The London Atlas: developing an atlas of tooth development and testing its quality and performance measures

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"وما أوتيتم من العلم إلا قليلا"

The London Atlas: developing an atlas of tooth development and testing its quality and performance measures

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Abstract

Aim:
To develop a comprehensive, validated, evidence based, practical, user-friendly atlas of dental age estimation and compare its performance with two widely used atlases.

Methods:
Based on the radiographic appearance of tooth development in 528 individuals aged 2-23 years and 176 neonates, the median stage of tooth development for each tooth in each age category/chronological year was used to construct diagrams representing ages between 28 weeks *in-utero* and 23 years were developed (The London Atlas)

Accuracy was determined by ageing skeletal remains/radiographs of 1514 individuals (aged 32 weeks in-utero to 23 years) using The London Atlas (LA), the Schour and Massler (SM) and Ubelaker (Ub) atlases. Estimated age was compared to real age. Bias, absolute mean difference and proportion of individuals correctly assigned by age were calculated. Intra-observer variation (Kappa) was measured by re-assessment of 130 radiographs.

To test the application of The London Atlas, a questionnaire was used to validate its use. Ninety 3rd year dental students were divided randomly into three subgroups, and blinded from the researcher. Each group used one of the 3 atlases to estimate the radiographic age of 6 individuals and complete a questionnaire focussed on the design, clarity, simplicity and self-explanation of the three atlases.

Results:
Excellent reproducibility was observed for all three atlases (Kappa: LA 0.879, SM 0.838 and Ub 0.857). LA showed no bias (P=0.720) and correctly estimated 53% of cases. SM and Ub showed significant bias by consistently underestimating age (P=0.026 and P=0.002) with 35% and 36% correctly estimated for SM and Ub respectively. The mean absolute difference for LA (0.72 years) was smaller than SM (1.15 years) and Ub (1.17 years).

LA was preferred over the other two atlases in all quality measures tested (clarity, design, simplicity and self-explanation).

Conclusion:
The London Atlas represents a substantial improvement on existing atlases facilitating accurate age estimation from developing teeth. Development of interactive online and mobile app versions is complete.

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Glossary

Chronological age: refers to the period that has elapsed beginning with an individual's birth and extending to any given point in time. Chronological age is used in research and in monitoring development as a measure to group individuals (Kraemer, Korner *et al.*, 1985).

Physiological age: Physiologic age is estimated by the maturation of one or more tissue systems, and it is best expressed in terms of each system studied. Maturation is scaled by the occurrence of one or the sequence of multiple events that are irreversible (Moorrees, Fanning *et al.*, 1963b).

Dental age: refers to the morphological state of an individual's dentition without reference to their chronological age, involving both the formation and the emergence of teeth (Moorrees *et al.*, 1963b).

Age estimation: age estimation is comparing the developmental status of a selected system in a person of known, or unknown, chronological age with developmental surveys or standard charts compiled from a large number of persons of known age (Braga, Heuze *et al.*, 2005).

Chapter One: Literature review

1.1 Importance of age

Estimating the age of an individual when it is unknown is of great importance in Paediatric Endocrinology and Orthodontic treatment planning. It determines legal responsibility or social rights such as school attendance, social benefits, employment, marriage and most importantly for asylum seekers. Knowing the age at death is crucial in identifying deceased individuals in crime scene investigations or in mass disasters and it provides information regarding past populations (Hillson, 1996; Hoppa and Fitzgerald, 1999; Olze, Schmeling *et al.*, 2004; Kvaal, 2006; Tassi, Franchi *et al.*, 2007; Turchetta, Fishman *et al.*, 2007).

Age is determined by the date of birth and the period of time or number of years elapsed after that to any point of time, which is then called the chronological age (Krogman, 1968; Kraemer *et al.*, 1985). It is documented in birth certificates, hospital records, and governmental databases and many more, but in the absence of these documents, other ways to establish age are of great importance especially in the light that 50 million births are unregistered in the world where 70% of births are registered in developed countries and only 50% in developing countries (UNICEF, 2012).

1.2 Physiological age

Chronological age can be estimated by determining physiological age, which is the age at which a developing system or organ reaches a specific stage (Braga *et al.*, 2005). A previous knowledge of the developmental stages of that organ or system and the time needed for each stage to be achieved is needed for physiological age to be concluded, along with population norms or standards. Therefore, not all body systems or organs can be used for age estimation.

A set of criteria should exist in the organ or system for it to be an ideal age indicator:

- It has to develop over a long period of time.
- It has to have recognisable and/or measurable stages that can be assessed in the living as well as the dead.
- The stages have to happen over a short period of time.
- It has to be stable, not be affected by environmental or racial factors.
- It has to survive inhumation well.

Many organs or body systems have been used to estimate chronological age. Starting from the most obvious and less complex: height, weight and secondary sex characters, to the less obvious and more complex: molecular methods using biomarkers; passing through methods of moderate complexity: bone and dental development.

What attracted scientists to these organs and systems is the ability to recognise changes that happen over time to all people at more or less the same age. These observations led to countless studies on different organs and body systems in the quest to find the ideal system that will enable the determination of chronological age. All studies began by observing the development of a specific system and/or organ, identifying its developmental stages, the time it takes for each stage to be completed in relation to chronological age. They then studied the population to find standards for the organ's and/or the system's development.

1.3 Height, weight and secondary sex characteristics

The journey of a growing child from birth up to adulthood is filled with landmarks that scientists observed and were eager to record to monitor the process. The norms of height and weight are available for different races (Onis, Garza *et al.*, 2004), standards of puberty for boys and girls are tabulated (Green, 1961; Bjork and Helm, 1967; Fishman, 1979; Hägg and Taranger, 1980; 1982; 1985b). While these tables provide great importance in monitoring growth and development in general, they lack the sensitivity to estimate the chronological age because they are highly affected by the environment. A malnourished 12 year old boy from Mexico may correspond to a healthy 10 year old boy from Germany (Haas and Campirano, 2006). A rural 12 year old girl at menarche may correspond to an urban 13 year old girl from the same race (Delavar and Hajian-Tilaki, 2008) and sexual abuse can influence maturation (Trickett and Putnam, 1993). Height, weight and secondary sex characteristics, therefore, are best used for monitoring healthy development but not for age estimation purposes.

1.4 Biomarkers

Biomarkers, which are biochemical features, can be used to examine the aging process. They measure the degeneration of the RNA ends that happens every time the cell divides (Ritz-Timme, Cattaneo *et al.*, 2000; Bauer, 2007; Heinrich, Matt *et al.*, 2007; Jiang, Schiffer *et al.*, 2008; Griffin, Chamberlain *et al.*, 2009; Ren, Li *et al.*, 2009). Racemisation of aspartic acid in dentine or tooth enamel can determine the date of death and radiocarbon dating of postnatal tooth enamel can determine the date of birth (Alkass, Buchholz *et al.*, 2009). The combination of these two techniques can provide chronological age estimation up to ± 1.6 years (Alkass *et al.*, 2009). The drawback, however, is that it requires a sample from the tooth, which is an invasive procedure in living individuals, and is very expensive, time consuming and laborious.

1.5 Bone development

Bone development in the form of suture fusion and ossification of cartilage is somewhat better than the previous methods at estimating chronological age, and is widely used (Işcan, Loth *et al.*, 1985; Lovejoy, Meindl *et al.*, 1985a; Lovejoy, Meindl *et al.*, 1985b; Nawrocki, 1998; Bull, Edwards *et al.*, 1999; Hoppa *et al.*, 1999; Vallejo-Bolaños, España-López *et al.*, 1999; Scheuer and Black, 2000; Sasaki, Motegi *et al.*, 2003; Osborne, Simmons *et al.*, 2004; Caldas, Ambrosano *et al.*, 2007). Nevertheless, it has several limitations. The fact that it depends on a suture to be fused or a cartilage to be ossified suggests that the individual has passed a certain age and gives large age ranges (Prince and Konigsberg, 2008), moreover, it lacks the sensitivity to know how much time has passed since suture fusion (Lovejoy *et al.*, 1985a; Brooks and Suchey, 1990). Bone development is also highly affected by the environment; nutrition and activity in particular highly affect bone development. The more an individual is malnourished, the slower the rate of bone development (Specker, 2004). The more active an individual is, the faster the rate of bone development (Janz, Burns *et al.*, 2001). Most importantly, delayed bone development at a young age can 'catch up' as the individual grows (Clark, Zawadsky *et al.*, 1988; Rogol, Clark *et al.*, 2000). Bones are also vulnerable to environmental or storage factors after death as they are predestined to degeneration in various rates, depending on conditions, leading to inaccurate age estimations (Murray and Murray, 1991).

If bone development is to be used for age estimation, several indicators of bone development at different body parts have to be used together and weighted according to their reliability to overcome the variation in each one (Bedford, Russell *et al.*, 1993) due to the difficulty in perceiving changes accurately in cases with too young or too old individuals (Alkhal, Wong *et al.*, 2008). While this is applicable in skeletal remains, it might be a hazard to living individuals because of X-ray exposure, or simply inapplicable because of the need for direct observation.
Using bone development for age estimation "might best be described as more of a "gestalt", with our intuitive hunches being moderated by an informed understanding of the underlying statistical realities and limitations of our methods." (Osborne *et al.*, 2004)

1.6 Dental development

With humans having two sets of teeth, deciduous and permanent, developing over nearly a third of the average human life with easily detected stages, it made sense to study dental development (Krogman and Işcan, 1986; Aka, Canturk *et al.*, 2009). Teeth also survive inhumation very well because of their minimal organic content, which is only 4% in dental enamel. Tooth development is very stable and minimally affected by environmental factors, socio-economic status, nutrition, dietary habits and even by endocrine factors (Garn, Lewis *et al.*, 1965a; Garn, Lewis *et al.*, 1965b; Voors, 1973; Demirjian, Buschang *et al.*, 1985; Hillson, 1996; Gutiérrez-Salazara and Reyes-Gasgaa, 2003). These characteristics made the dentition the best indicator of chronological age compared with other systems, and for that reason, extensive research has been done on tooth development to provide simple and accurate ways of estimating the physiological dental age.

Early records that date back to the first half of the 19^{th} century by factories who employed children, and by legal bodies in the United Kingdom to impose legal responsibility on children older than seven years, showed that dental development was used as an age indicator (Saunders, 1837).

1.6.1 Methods that use dental development

Dental age can be obtained from assessing growth in the form of: crown and/or root length (Stack, 1967), crown and root weight (Stack, 1960), development by means of calcification or maturation (Gleiser and Hunt, 1955; Garn, Lewis *et al.*, 1958; Garn, Lewis *et al.*, 1959; Nolla, 1960; Moorrees, Fanning *et al.*, 1963a; Moorrees *et al.*, 1963b; Haataja, 1965; Nanda and Chawla, 1966; Wolanski, 1966; Haavikko, 1970; Fanning and Brown, 1971; Liliequist and Lundberg, 1971; Demirjian, Goldstein *et al.*, 1973; Gustafson and Koch, 1974; Haavikko, 1974; Anderson, Anderson *et al.*, 1976; Demirjian and Goldstein, 1976; Nyström, Kilpinen *et al.*, 1977; Cameriere, Ferrante *et al.*, 2006) and by assessing the incremental lines of dental root cementum (Jankauskas, Barakauskas *et al.*, 2001; Czermak, Czermak *et al.*, 2006; Aggarwal, Saxena *et al.*, 2008). Dental age also can be obtained using the sequential tooth appearance in the oral cavity in the form of tooth eruption and shedding (Nyström, Kleemola-Kujala *et al.*, 2001; Foti, Lalys *et al.*, 2003). Moreover, dental age can be obtained from measuring the time elapsed after eruption in the oral cavity in the form of attrition to the tooth crown (Miles, 1978; Brothwell, 1981; Lovejoy, 1985; Constandse-Westermann, 1997).

1.6.2 Techniques using dental development

Several techniques have been developed to utilise dental development to estimate chronological age, from charts of tooth formation and eruption to mathematical formulae that calculate dental age. Many studies testing each and every method have also been done in the quest to find the method with the best performance measures. What performs well in one population doesn't appear to perform well in another; what is simple to one scientist is complicated to another. Methods have been modified, re-modified, tested and retested. Diagrams have been redrawn and adopted, yet there are still problems associated with most of these techniques. Lack of evidence behind the technique is the most profound problem (Smith, 1991; Braga *et al.*, 2005); even with the most widely used techniques. The lack of documented details of the studied sample (Fass, 1969), the restriction to a small age range (Gustafson *et al.*, 1974), the insufficient sample size or the absence of samples all together are just examples (Schour and Massler, 1941). Some of these techniques were even based on estimates (Ubelaker, 1978).

1.6.3 Accuracy of dental age estimation techniques:

The accuracy of dental age estimation is defined by how closely the difference between real age and estimated age is to zero and how closely that can be predicted (Cardoso, 2007b; Butti, Clivio *et al.*, 2008; Cameriere, Ferrante *et al.*, 2008c). Statistically, a *t*-test on the difference between estimated age and chronological age is calculated or using paired t-test on estimated age and chronological age (Cruz-Landeira, Linares-Argote *et al.*, 2010).

Many studies have tested the accuracy of different age estimation techniques based on dental development with varying results (Hägg and Matsson, 1985a; Hägg and Hägg, 1986; Staaf, Mörnstad *et al.*, 1991; Thorson and Hägg, 1991; Saunders, DeVito *et al.*, 1993; Davis and Hagg, 1994; Liversidge, 1994; Kullman, 1995 ; Willems, 2001; Solari and Abramovitch, 2002; Liversidge, Lyons *et al.*, 2003; Chaillet and Demirjian, 2004a; Chaillet, Nystrom *et al.*, 2004b; Chaillet, Willems *et al.*, 2004c; Brkic, Milicevic *et al.*, 2006; Cameriere *et al.*, 2006; Maber, Liversidge *et al.*, 2006b; Smith, Reid *et al.*, 2006; Bhat and Kamath, 2007; Cardoso, 2007b; a; Halcrow, Tayles *et al.*, 2007; Tao, Wang *et al.*, 2007; Cardoso, 2009; Griffin *et al.*, 2009; Shi, Lie *et al.*, 2009 ; Cruz-Landeira *et al.*, 2010) (for full descriptions refer to appendix 4). However, very few studies tested the accuracy of diagram-based techniques (Liversidge, 1994; Smith, 2005).

1.6.4 Schemas of dental development

There are several methods of age estimation based on dental age, but most of them are based on formulae and lengthy techniques only a specialist can deliver (Demirjian *et al.*, 1973; Roberts, Parekh *et al.*, 2008), sometimes using special equipment (Bauer, 2007; Heinrich *et al.*, 2007). In mass disaster situations, the need for an accurate, reliable, cheap, fast and easy to use technique is imperative for the victim identification process, especially when the lack of personnel or resources dictates the help of non-trained volunteers. In these cases, using a comparison method in the form of a diagram or computer software with the radiograph of developing teeth that would give an estimate of chronological age would be ideal.

Various schemas have been compiled throughout the last century to show dental development. One of the first schemas to be used widely is Schour and Massler's Atlas (1941) and it has been the bench mark for the past 70 years. Gustafson and Koch (1974) used data from 20 sources combining anatomical, radiographic and gingival eruption data and constructed a schematic representation of tooth formation and eruption from prenatally to the age of 16. Although Gustafson and Koch's method is a diagrammatic non pictorial scheme, it doesn't offer anatomical tooth outlines; but presents the age range and average of developmental stages for individual teeth based on data from previous studies rather than actual data average of tooth developmental stages. Dental age is estimated by placing a ruler horizontally through the average of a single tooth's developmental stage and moving it up and down depending on the teeth in question. It is not easy to obtain an overview of dental development for a specific age cohort. Gustafson and Koch's scheme therefore is not suitable for direct comparison between dental developmental stages seen in a radiograph or isolated teeth because it doesn't provide anatomical tooth outlines. Ubelaker's chart (1978) was loosely based on Schour and Massler's Atlas using additional North American Indian population data. Brown (1985) demonstrated permanent tooth development using anatomical tooth illustrations tabulated for the ages three to 12 years based on Schour and Massler's atlas. Kahl and Schwarze (1988b) updated Schour and Massler's Atlas using 993 radiographs of children aged 5 to 24 and produced anatomical charts for separate sexes.

All the past schemas cover a limited age range, except for Schour and Massler's and Ubelaker's schemas that cover dental development from prenatal to early adulthood, which made them the most wildly used ones.

1.6.4.1 Schour and Massler atlas of tooth development

Schour and Massler published their atlas of tooth development in 1941 as an attachment in the Journal of the American Dental Association. It was based on anatomical and radiographic data but with little or no description of their source, but probably based on Logan and Kronfeld's previous work of 26 to 29 individuals, 20 of whom were younger than two years of age (Logan and Kronfeld, 1933). It consists of 21 diagrams covering ages from 5 months *in utero* to 35 years. This method has several limitations with the missing ages between 12 and 15 and between 15 and 21, also the fact it was based on a very small number of individuals makes the evidence behind it very weak (Appendix 1).

1.6.4.2 Ubelaker's chart of tooth development

Ubelaker's chart of tooth formation and eruption among American Indians was compiled from data published in 16 different papers by different researchers. He used the "early end of the published variation in preparing the chart" because he argues that "some studies suggest that teeth probably form and erupt earlier among Indians" (Ubelaker, 1978). Ubelaker's chart has the same missing ages as Schour and Massler's and therefore the same limitation (Appendix 2).

1.6.5 Limitations of dental development schemas

The common drawbacks of the previous schemas are the lack of uniform age distribution and/or the limited age range that fails to cover the entire developing dentition. A uniform age distribution with similar numbers for each year of age improves variance across the age range(Bocquet-Appel and Masset, 1982; Konigsberg and Frankenberg, 2002). Whereas a normal age distribution has high precision around the mean value but with low precision at the age extremes.

Other limitations are the lack of clarity in identifying crown and root developmental stages as almost all of these schemas were based on dental radiographical description of tooth development directly or indirectly, yet they presented anatomical drawings, concealing the internal tooth developmental stages.

When assessing tooth development from dental radiographs, one can distinguish between consecutive developmental stages more easily using internal hard tissues, such as the shape of the pulp chamber or root canal, improving sensitivity and performance measures (Moorrees *et al.*, 1963a; b; Demirjian, 1973; Haavikko, 1974), yet no schematic technique delivers that. All the previously mentioned schemas used anatomical representations of teeth that mask internal tooth structures and with no information regarding eruption reference, with the exception of Ubelaker (1978), who used gingival emergence as a reference, which can be altered by local factors, systemic diseases, and nutritional habits. Also, emergence is an instant process, whereas calcification of the teeth is an ongoing process that can be used in skeletal remains or through radiographs.

1.7 Criminal responsibility

Scientists became accustomed to some methods with all their limitations and drawbacks, probably because the results when using them were often good enough at the time, with one or two years difference from the actual chronological age being acceptable (Liliequist *et al.*, 1971; Hägg *et al.*, 1985a; Thorson *et al.*, 1991; Mincer, Harris *et al.*, 1993; Saunders *et al.*, 1993; Kullman, 1995 ; Foti *et al.*, 2003). For this current time, with all the immigration and forensic problems the modern society is facing, especially with the surge of teenage asylum seekers from Kosovo in 1990 onwards and with the age of criminals getting younger and younger, not being accurate is no longer sufficient (Ritz-Timme *et al.*, 2000).

Children have unique rights under international law and societies are based on legislation that uses age, therefore denying age is denying identity, which is a human rights violation (UNICEF, 1989) and correct age estimation is not just for the child's rights, but also for those around him/her (other children).

Age assessment is done when there is a reasonable doubt and it is the last resource keeping the best interest of the child as the main priority and giving the benefit of the doubt. Although Law is biased towards social services assessment using Merton Age Compliance Guidelines published 2003 (Crawley, 2012) it has never been validated. The Merton Compliant Age assessment includes the assessment of physical appearance, the interaction of the individual during the assessment process, social history, family composition, how the individual responds to authority/instruction, education, Independent/Self Care Skills, health, medical assessment and information from documentation and other sources.

There is considerable variation in age of criminal responsibility that can be as young as 7 years in Switzerland and South Africa, to as old as 18 years in Belgium and the United States of America. Currently, the age of criminal responsibility in Scotland is 12 years whereas in England, Wales and Northern Ireland it is 10 years where 10-12 year olds can be convicted but not imprisoned, 12-15 year olds can be convicted and incarcerated in special units, 16 years is a milestone for sexual consent and assault, 15-17 year olds will be juvenile offenders, 18-21 year olds will be young offenders and 21-25 year olds will be young adult offenders (Janes, 2008), therefore knowing the right age in the absence of documents can be life changing. No finalized government guidelines and no protocol are in place so far and no country has got it right as they are all different, therefore a reproducible protocol is required.

The forensic academy recommendation for using teeth in age estimation is that the technique has to give results within 6 months of the actual age for it to be legally acceptable (Schmeling, Reisinger *et al.*, 2006; Rösing, Graw *et al.*, 2007; Peiris, Roberts *et al.*, 2009) and "Many studies reached the central conclusion that no universal system for dental age assessment has been achieved" (Braga *et al.*, 2005).

1.8 Aim

The aim of this thesis was to develop a comprehensive, validated, evidence based, practical, user-friendly atlas of dental age estimation that avoids all the previous limitations and compare its performance with two widely used atlases. It should cover all ages of dental development with uniform age distribution and be based on a large and well documented sample size to be representative. It should show the developing tooth internal structures and be self explanatory. It should be easily used with reproducible results. These criteria can be summarised as:

1- Comprehensive.

2- Evidence based.

3- Accurate.

4- Sensitive.

5- Reliable.

6- Clear.

7- Easy to use.

1.9 Objectives

- Produce a comprehensive, evidence based, easy to use Atlas of tooth development that has good measures of performance, and fill an important gap in current knowledge.
- Test the performance measures of the Atlas (Reliability, Bias and standard deviation, mean absolute difference between estimated and real age, proportion of individuals correctly estimated to be in the correct age group, sensitivity, specificity and likelihood ratios.
- Apply a qualitative study on the Atlas in the form of a survey to assess user satisfaction and ease of use along with reliability.
- Identify problems and limitations of the Atlas and amend them.
- Produce an interactive computer software version of the Atlas.

1.10 Null hypotheses

- There are no differences between the old schemas of dental development (Schour and Massler's Atlas and Ubelaker's chart) and the new atlas in measures of performance, ease of use and user satisfaction.

1.11 Design and setting of the study

This thesis is divided into two main parts:

- Quantitative part: developing a new atlas of tooth development in two forms (Schematic and computer program), test the performance measures and compare them to existing old schemas.

- Qualitative part: In the form of a survey to explore and evaluate the experience of using the new Atlas of tooth development in its two forms to test the ease of use, user satisfaction and clarity.

Chapter Two: The London Atlas

The quantitative part of this thesis was done in several stages, starting with a systematic review of the literature, then developing the atlas of tooth development and finally testing its performance measures (validity, reliability and reproducibility).

2.1 Background

Literature review in chapter one was written in the light of the results of the systematic search, identified references and discussions that took place at different scientific meetings, workshops attended and comments received during the presentation process of the draft atlas.

2.1.1 Systematic search on dental age estimation methods

A review was prepared using a systematic approach to minimise bias in literature selection (Egger, Smith *et al.*, 2001). A search strategy was developed and conducted to identify relevant studies using key research words to supply initial keywords: developing or development, age or aging or old or growing or chronological, estimation or prediction or determination, dental or teeth or tooth or dentition, accuracy or test or assessment, atlas or chart or method or stage or length or width or size, atlas or chart or method, accuracy or test or assessment. The keyword list was further added from scientific articles identified from the initial search results and by using the OvidMD subject headings (mapped terms). The search strategies used have been conducted in December 2010 (updated in July 2012) and saved for further use if required. Medline, World Health Organization and United Nations websites were searched to identity any additional resources / issues (Appendix 3).

2.1.1.1 Search results

An initial search of the literature found 2134 published articles, which were all assessed for their relevance to this project. After reviewing the abstract / description, only 150 articles were found to be relevant as they were new methods for age estimation, assessing existing age estimation methods or reviewing existing methods. Articles in languages other than English were translated. Citation tracking added an extra 50 articles and books. The identified documents were compiled within a reviewing log to enable tracking of the review process and were entered into an Endnote (16.0) Library.

2.1.1.2 Assessment of evidence and data extraction

All 200 Identified references were read thoroughly and their quality assessed (Egger *et al.*, 2001). There were 82 papers that presented new methods for dental age estimation; an overview of these articles is presented in (Appendix 4), it includes authors' names, title, year of publication, method of age estimation, population, study sample, age, sex and weakness and strength of each method ; only four were diagram based methods:

- Non-invasive methods:
    - Sequential tooth eruption and/or emergence (nine methods) (Demirjian, 1973; Carvalho, Ekstrand *et al.*, 1989; Nyström *et al.*, 2001; Foti *et al.*, 2003; Moslemi, 2004; Franchi, Baccetti *et al.*, 2008; Olze, Peschke *et al.*, 2008; Aggarwal, Kaur *et al.*, 2011; Feraru, Rãducanu *et al.*, 2011).

The strengths of using tooth eruption to estimate dental age is that it is based on simple and few eruption stages and counting of teeth. In situations where tooth emergence is used, a simple oral examination is all that is needed. The weaknesses of using tooth eruption and emergence, however, lies in the fact that it observes a single event in time for each tooth. Also eruption is affected by early extractions, tooth crowding, tooth impaction and missing teeth. Moreover, tooth eruption can only apply to certain age groups (between six months and two years then between six and 13 years) and methods based on gingival emergence are not applicable on skeletal remains.

- Development by means of calcification and/or root maturation:
    - Developmental schemas (four methods) (Schour *et al.*, 1941; Gustafson *et al.*, 1974; Ubelaker, 1978; Kahl *et al.*, 1988b; AlQahtani, Hector *et al.*, 2010)
    - Dental developmental stages (31 methods) (Kronfeld, 1935; Gleiser *et al.*, 1955; Garn *et al.*, 1958; Garn *et al.*, 1959; Nolla, 1960; Moorrees *et al.*, 1963b; a; Haataja, 1965; Nanda *et al.*, 1966; Wolanski, 1966; Fass, 1969; Haavikko, 1970; Fanning *et al.*, 1971; Liliequist *et al.*, 1971; Demirjian *et al.*, 1973; Haavikko, 1974; Anderson *et al.*, 1976; Demirjian *et al.*, 1976; Nyström *et al.*, 1977; Van der Linden, Wasenberg *et al.*, 1985a; b; Van der Linden, Wassenberg *et al.*, 1985a; b; Nyström, Haataja *et al.*, 1986; Carels, Kuijpers-Jagtman *et al.*, 1991; Smith, 1991; Mincer *et al.*, 1993; Köhler,

Schmelzle *et al.*, 1994; Mörnstad, Staaf *et al.*, 1994; Mesotten, Gunst *et al.*, 2002)

- Root developmental stages (four methods) (Harris and Nortjé, 1984; Kullman, Johanson *et al.*, 1992; Gunst, Mesotten *et al.*, 2003; Rai, Krishan *et al.*, 2008)

The strengths of using dental developmental stages to estimate dental age are that they provide a point estimate based on calculations where different estimates for teeth are averaged or given different weights. Schemas of dental development are the exception, although they use dental developmental stages, they provide an overview of the overall dental development for age cohort and the age estimation they provide is an age category. Using dental development has the advantage of observes a continues process of tooth development.

Limitations of methods based on dental developmental stages are that most of them are based on permanent teeth only and evidence is scarce for the initiation of development of lower permanent anterior teeth and lower posterior deciduous teeth (Smith, 1991). Moreover, they are applicable on limited age range (Gustafson *et al.*, 1974; Kahl and Schwarze, 1988a) or having missing age cohorts (Schour *et al.*, 1941; Ubelaker, 1978). Schemas of dental development are simpler to use due to the fact that they are based on direct comparison between an illustration of dental development of a certain age cohort and a radiograph or isolated teeth. Gustafson and Koch (1974) is an exception. In this diagram each tooth is represented by a triangle where the base of the triangle representing the range, based on both histological and radiographical data, and the peak indicates the average of developmental stages in each age category.

- Morphological tooth parameters (11 methods) (Gustafson, 1950; Dalitz, 1962; Johanson, 1971; Moore and Corbett, 1971; 1973; Miles, 1978; Brothwell, 1981; Lovejoy, 1985; Solheim, 1993; Kvaal and Solheim, 1994; Constandse-Westermann, 1997)
- Tooth measurements (seven methods) (Stack, 1960; 1967; Liversidge, Dean *et al.*, 1993; Kullman, Martinsson *et al.*, 1995; Kvaal, Kolltveit *et al.*, 1995; Liversidge and Molleson, 1999b; a; Cameriere *et al.*, 2006; Aka *et al.*, 2009)

- Invasive methods:
    - Biomarkers (three methods) (Wehner, Secker *et al.*, 2007; Alkass *et al.*, 2009; Griffin *et al.*, 2009)
    - Root dentine translucency (four methods) (Dalitz, 1962; Bang and Ramm, 1970; Solheim, 1993; Prince *et al.*, 2008)
    - Incremental lines (nine methods) (Solheim, 1990; 1993; FitzGerald, 1998; Jankauskas *et al.*, 2001; Bojarun, Garmus *et al.*, 2003; Smith and Avishai, 2005; Czermak *et al.*, 2006; Aggarwal *et al.*, 2008; Antoine, Hillson *et al.*, 2009).

Many studies have tested the accuracy of different dental age estimation methods with varying results, but in general the methods are more accurate in children because of the high number of developing teeth and as the number of developing teeth decreases, so does the accuracy (Hägg *et al.*, 1985a; Hägg *et al.*, 1986; Staaf *et al.*, 1991; Thorson *et al.*, 1991; Saunders *et al.*, 1993; Davis *et al.*, 1994; Liversidge, 1994; Kullman, 1995 ; Willems, 2001; Solari *et al.*, 2002; Liversidge *et al.*, 2003; Chaillet *et al.*, 2004a; Chaillet *et al.*, 2004b; Chaillet *et al.*, 2004c; Smith, 2005; Brkic *et al.*, 2006; Cameriere *et al.*, 2006; Maber *et al.*, 2006b; Smith *et al.*, 2006; Bhat *et al.*, 2007; Cardoso, 2007b; a; Halcrow *et al.*, 2007; Tao *et al.*, 2007; Cardoso, 2009; Griffin *et al.*, 2009; Shi *et al.*, 2009 ; Cruz-Landeira *et al.*, 2010).

The common drawbacks of dental age estimation methods are the lack of uniform age distribution and/or the limited age range that fails to cover the entire developing dentition. A uniform age distribution with similar numbers for each year of age improves variance across the age range (Bocquet-Appel *et al.*, 1982; Konigsberg *et al.*, 2002).

Very few studies evaluated schemas of tooth development (Hägg *et al.*, 1985a; Hillson, 1992; Liversidge, 1994; Smith, 2005; Smith *et al.*, 2005; Thevissen, Pittayapat *et al.*, 2009; Blenkin and Evans, 2010; Thevissen, Alqerban *et al.*, 2010; Blenkin and Taylor, 2012). They criticised the very small biased samples they were based on. The results when these schemas were tested revealed that they are more reliable on males.

The most studied method was Demirjian *et al.*'s; these studies concluded that a modification of the technique to allow for standardisation against a sample from a given population is necessary. (Nyström *et al.*, 1977; Hägg *et al.*, 1985a; Staaf *et al.*, 1991; Mincer *et al.*, 1993; Gaethofs, Verdonck *et al.*, 1999; Liversidge, 1999; Lehtinen, Oksa *et al.*, 2000; Nyström *et al.*, 2001; Krailassiri, Anuwongnukroh *et al.*, 2002; McKenna, James *et al.*, 2002; Solari *et al.*, 2002; Olze, Taniguchi *et al.*, 2003; De Salvia, Calzetta *et al.*, 2004; Olze *et al.*, 2004; Braga *et al.*, 2005; Leurs, Wattel *et al.*, 2005; Neves, Pinzan *et al.*, 2005; Prieto, Barbería *et al.*, 2005; Dhanjal, Bhardwaj *et al.*, 2006; Liversidge, Chaillet *et al.*, 2006; Maber *et al.*, 2006b; Naidoo, Norval *et al.*, 2006; Jamroz, Kuijpers-Jagtman *et al.*, 2006 ; Başaran, Özer *et al.*, 2007; Orhan, Ozer *et al.*, 2007; Sisman, Uysal *et al.*, 2007; Bai, Mao *et al.*, 2008; Cameriere, Ferrante *et al.*, 2008a; Heuzé and Cardoso, 2008; Introna, Santoro *et al.*, 2008; Mani, Naing *et al.*, 2008; Martin-de las Heras, García-Fortea *et al.*, 2008; Martin, Li *et al.*, 2008; Moananui, Kieser *et al.*, 2008; Olze *et al.*, 2008; Tunc and Koyuturk, 2008; Mitchell, Roberts *et al.*, 2009; Peiris *et al.*, 2009; Blenkin *et al.*, 2010; Chen, Guo *et al.*, 2010; Cruz-Landeira *et al.*, 2010; Liversidge, Smith *et al.*, 2010; Bagherian and Sadeghi, 2011; Jayaraman, King *et al.*, 2011; Nik-Hussein, Kee *et al.*, 2011; Ogodescu, Zetu *et al.*, 2011; Blenkin *et al.*, 2012; Nur, Kusgoz *et al.*, 2012).

2.2 Atlas of tooth development

As part of a Masters program in Paediatric Clinical Dentistry (MCliDent) in the Institute of Dentistry, Queen Mary University of London, the researcher (SA) developed diagrams of dental development between birth and 23 years as a research thesis (AlQahtani, 2008).

It was a retrospective cross- sectional study of selected 308 archived radiographs of healthy children aging between two and 23 years who had their panoramic dental radiographs taken as part of their dental treatment at the Dental Hospital, Queen Mary, University of London. For each chronological year, seven radiographs each for males and females were selected. The individuals were of mixed ethnic group (White British and Bangladishi). In addition, all available skeletal remains of infants from the Spitalfield's Collection of known age-at-death skeletal remains at the Natural History Museum, London, who died before they reached the age of two, were assessed. There were 50 skeletal remains (15 females, 31 males and 4 unknown sex) (Molleson and Cox, 1993).

In the "Atlas of tooth form" there are tables containing the measurements of ideal teeth in millimetres (Wheeler, 1984). For each tooth in both dentitions, Wheeler provided detailed measurements of crown and root lengths and enamel, dentine and pulp thickness. Based on these measurements and in isolation from radiographs, each tooth was hand drawn by the examiner (SA) magnifying each millimetre into a centimetre to get exact replica of ideal teeth enlarged to fit A4 scale using a pigment liner (Staedtler®) size 0.8 on a tracing pad over a 5mm isometric graphic pad. A total of 26 drawings of teeth were made representing teeth in their final mature shape, which is the final stage of Morreess, Fanning and Hunt's dental developmental stages, stage (AC). (Figure 2.1)

Figure 2. 1: Final stage of tooth development (AC).

Tooth formation stages were then created using transparent tracing paper over the full ideal tooth form drawn previously by the examiner (SA). The outlines of the developmental stages based on Moorrees' stages (Moorrees, Fanning *et al.*, 1963a; b) were recreated as followes:

- Stage initial cusp formation (Ci): the illustration of this stage is made by tracing only incisal edges of anterior teeth or only isolated cusp tips of posterior teeth as black lines. (figure 2.2)

Figure 2. 2: Stage initial cusp formation (Ci).

- Stage coalescence of cusps (Cco): The illustration of this stage is made by tracing the incisal edge of anterior teeth with added mesial and distal angles as black lines with no enamel or connecting the cusp tips for posterior teeth with no enamel.

Figure 2. 3: Stage coalescence of cusps (Cco).

- Stage cusp outline completed (Coc): The illustration of this stage is made by tracing the outline of the incisal/occlusal third of tooth crown height with enamel shown as white area. (Figure 2.4)

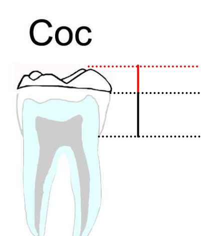

Figure 2. 4: Stage cusp outline completed (Coc).

- Stage crown half (Cr ½): The illustration of this stage is made by tracing half of the crown height with part of dentine shown. (Figure 2.5)

Cr 1/2

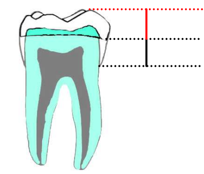

Figure 2. 5: Stage half crown (Cr ½).

- Stage crown three quarters (Cr ¾): The illustration of this stage is made by tracing three quarters of the crown height. (Figure 2.6)

Cr 3/4

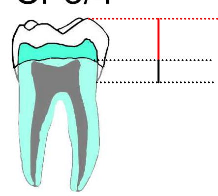

Figure 2. 6: Stage crown three quarters (Cr ¾).

- Stage crown complete (Crc): The illustration of this stage is made by tracing the outline of the whole crown with pulp roof well defined. The edges of the cervical crown edges are thin and converged. (Figure 2.7)

Figure 2. 7: Stage crown complete (Crc).

- Stage initial root formation (Ri): The illustration of this stage is made by tracing the outline of the whole crown with spicules of the root outline extending from the cervical crown edges. (Figure 2.8)

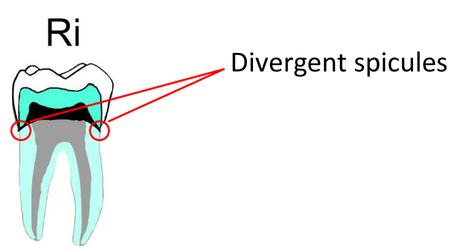

Figure 2. 8: Stage root initiation (Ri).

- Stage root quarter (R ¼): The illustration of this stage is made by tracing the outline of the whole crown and part of the root equivalent to half the height of the crown. In posterior teeth, the first sign of the bifurcation area is visible. Root edges are divergent. (Figure 2.9)

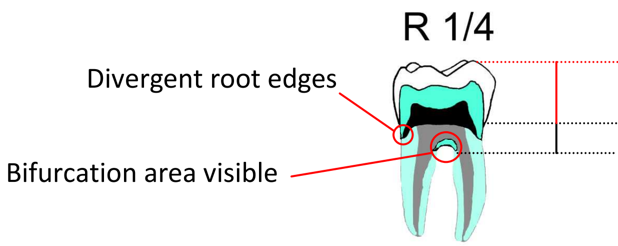

Figure 2. 9: Stage root quarter (R ¼).

- Stage root half (R ½): The illustration of this stage is made by tracing the outline of the whole crown and part of the root equivalent to the whole length of the crown. Root edges are divergent. (Figure 2.10)

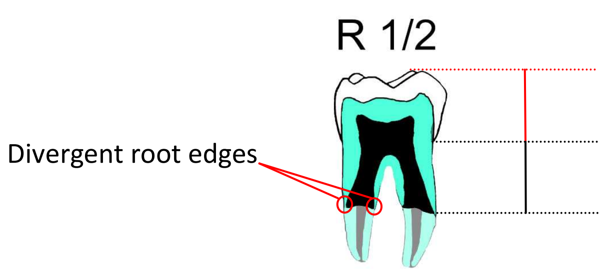

Figure 2. 10: Stage root half (R ½).

- Stage root three quarters (R ¾): The illustration of this stage is made by tracing the outline of the whole crown and part of the root longer than the length of the crown. Root edges are divergent. (figure 2.11)

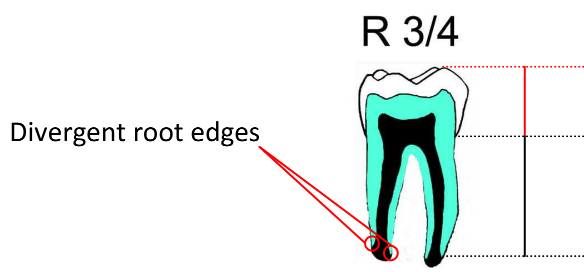

Figure 2. 11: Stage root three quarters (R ¾).

- Stage root complete (Rc): The illustration of this stage is made by tracing the outline of the whole tooth, crown and root. Root edges are parallel. (Figure 2.12)

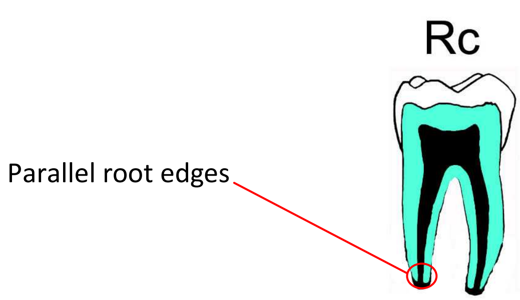

Figure 2. 12: Stage root complete (Rc).

- Stage apex half closed (A ½): The illustration of this stage is made by tracing the outline of the whole tooth, crown and root. Root edges are convergent with wide apical periodontal ligament space. (Figure 2.13)

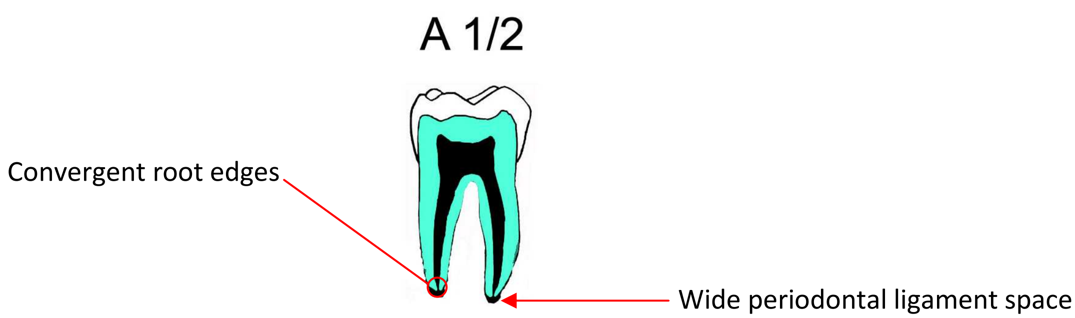

Figure 2. 13: Stage apex half closed (A ½).

Each tooth had all developmental stages drawn on A4 scale; resulting in a total of 756 drawings. Preliminary drawings were discussed with supervisors, colleagues and clinical staff regarding the shape of crown, root and pulp cavity. Moreover, dentine and enamel thickness were discussed in the same manner along with the developing aspects and resorption of each tooth. After much discussion, the decision to accentuate and adjust the root ends of developing teeth was made to make the stages distinctive to the non trained eye, and the reason being that identifying the correct stage is the aim rather than having a realistic replica of teeth seen on the radiograph. Then all drawings were scanned into the computer, finished and coloured using Adobe Photoshop® software 7.0.

Eruption of teeth through the alveolar bone was assessed according to modified Bengston's stages (Bengston, 1935; Liversidge, 2001) and was replicated in the diagrams in relation to a black line representing the alveolar bone.

The aim was to develop diagrams that are easy to interpret rather than having a realistic replica of normal tooth positions seen in radiographs, taking a different approach from Schour and Massler's and Ubelaker's schemas (Schour *et al.*, 1941; Ubelaker, 1978). Presenting a two dimensional illustration of a three dimensional structure resulting in considerable overlap of normal teeth positioned within the alveolar bone. After discussion with supervisors, colleagues and clinical staff, the decision to space teeth for clarity within the alveolar bone in the illustrations was taken to ease the identification of the tooth developmental stages.

After all teeth were assessed, the median developmental stages were identified for each tooth for every age category and were used to illustrate diagrams for each chronological year for males, females and for mixed sex. A midway point was selected to be at 6 months of every chronological year with a range of plus and minus 6 months. An example of these diagrams for a five year old child is shown in figure 2.14.

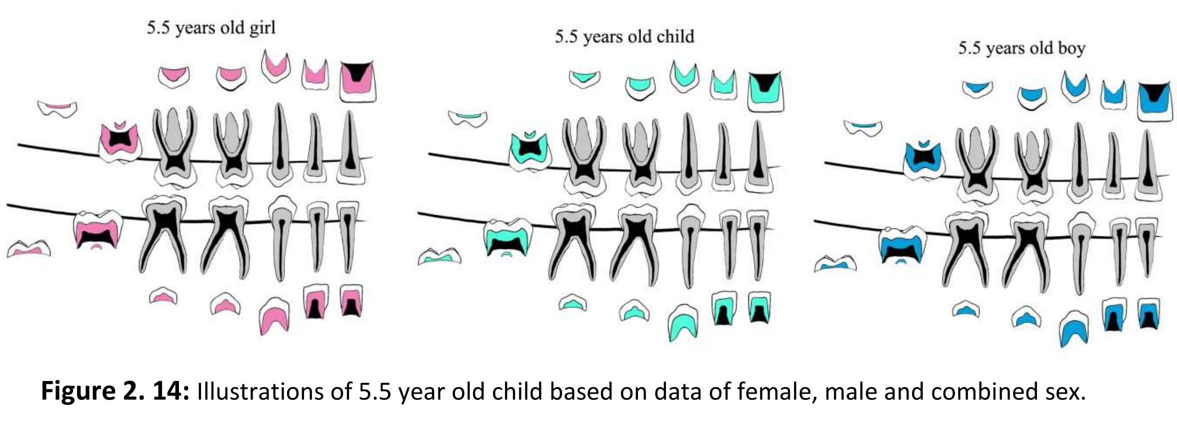

Figure 2. 14: Illustrations of 5.5 year old child based on data of female, male and combined sex.

The first year of life was represented by two diagrams, midpoint at three and nine months (Fig. 2.15).

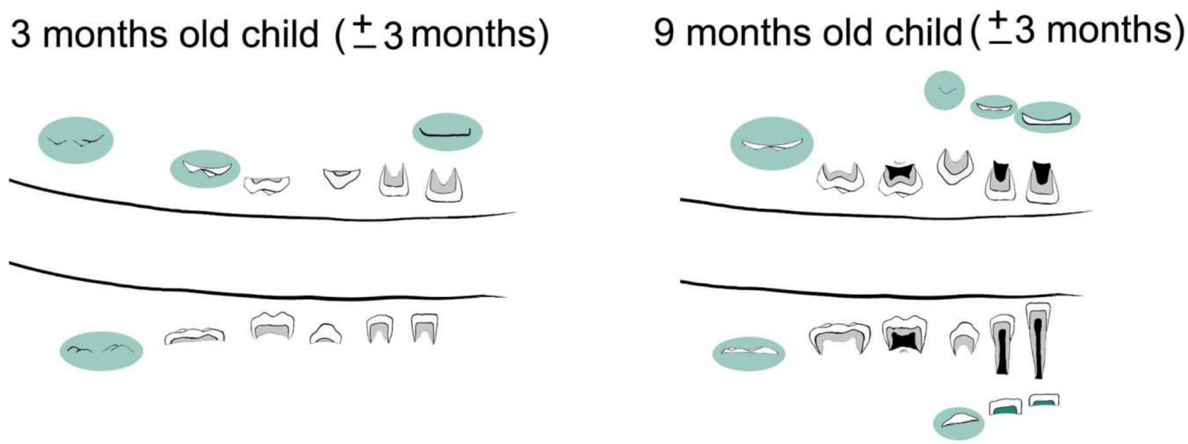

Figure 2. 15: original illustrations of younger than one year: three months old child and 9 months old child.

Teeth were drawn and presented in their radiographic appearance with detailed inner structures. This preliminary work provided possibilities to build on, especially after it attracted interest from different disciplines. When this PhD project was first started, it was decided to use these diagrams to produce an atlas and expand it more and test its performance measures on individuals of known age. There were 14 individuals in each chronological age between two and 23 (308 radiographs), and 50 known age-at-death skeletal remains from Spitalfield's collection for the younger than two.

2.2.1 Newark bay collection of human remains

A collection of skeletal remains of 68 infants were excavated from Norse Christian cemetery on the eastern edge of Newark Bay, Deerness in Scotland, where it was found by chance by Dr. Brothwell in the late 1960s (Brothwell and Krzanowski, 1974). It is dated back to the 10th century and placed at the British Natural History Museum, London. Three methods have been used to estimate the age at death of these infants. The first method was done by Theya Molleson, where she assessed tooth formation stages according to Moorrees and Demirjian and then referred to the original Schour and Massler atlas of 1941 but with an extra stage at 3 months of age that she added. The other two methods were done by Dr. Helen Liversidge, where she used formulae of tooth length in one method, and tooth stage in another. Although the actual age at death is unknown, it was decided that comparing methods and testing the diagrams on this collection would be beneficial for further development as it might shed some light on limitations that could be improved or issues to be addressed.

When age estimation process was started on Newark Bay collection, it was evident that dental age in numerous individuals was more advanced than three months but less advanced than nine months. This fast rate of deciduous tooth development indicated the need for shorter age group intervals; therefore, it was decided to add diagrams to the first year of life and design a single page Atlas for easy reference.

2.2.2 Maurice Stack collection of developing teeth

Increasing the number of diagrams that represent dental development in the first year of life from two to four necessitated dividing individuals from the Spitalfield’s collection into four subgroups rather than two, but when that was applied, however, each subgroup ended up containing too few individuals (Appendix 5), which would ultimately affect how accurately they represent dental development. To overcome this problem, increasing sample size for these age groups was vital.

The Royal College of Surgeons of England, London, UK houses an invaluable collection of isolated developing teeth that were dissected from the jaws following autopsies in cases of stillbirths and infant deaths where pathological examination had not shown features likely to be associated with retarded growth of 168 known age-at-death neonates with an age range starting from still born foetuses to one year olds (Appendix 5). It was collected by Maurice Stack in 1960 for forensic estimation of age in infancy by gravimetric observations. He also recorded gestation age and cause of death (Stack, 1960).

Access to the museum was granted, and assessing tooth formation stages of the whole collection was done by the researcher (SA) according to Moorrees's stages (Moorrees *et al.*, 1963b; a). Adding data from Stack's collection extended the age range to include the last trimester and the data were sufficient enough to have three one-month age groups prenatally and one at birth (39 to 41 weeks) (Appendix 5).

The aim was to have a uniform age distribution for the new diagrams with similar numbers of males and females in each age group; however four age groups were uneven (Appendix 5). This is reflected by a jump in tooth formation stages from 1.5 to 2.5 years for the deciduous canine and deciduous second molar from root initiation stage (Ri) to root three quarters (R ¾) stage, nevertheless, the Spitalfield's and Maurice Stack's collections of known age–at–death reference samples are unique and valuable and fill an important age gap for which radiographic data are scarce.

2.2.3 Gestation age

In Maurice Stack's collection, some babies were prematurely born, while others had longer than 40 weeks gestation periods. To decide how to tackle this issue, a literature search regarding the effect of birth on tooth formation was foreseeable. Several studies have examined the effect of premature birth on tooth formation and eruption. All of them concluded that when using the corrected age, which is 40 weeks (representing full gestational period) minus the actual chronological age (age from premature birth), dental development was the same as for those who were born in full term. In other words, premature birth doesn't affect the progress of dental development, except for the position of neonatal line (Backstrom, Aine *et al.*, 2000; Paulsson, Bondemark *et al.*, 2004; O'Neill, 2005; Ramos, Gugisch *et al.*, 2006; Sardi, Ventrice *et al.*, 2007; Rythén, Norén *et al.*, 2008). For that reason, it was decided to use the corrected age for all neonates in the collection and then treat them according to their new age to be either as foetus or as a full term born baby. The data from Maurice Stack's collection was added to those from the Spitalfield's collection. Age groups for younger than one were devised to be: three one-month groups prenatally, one group around a full gestation birth, four three-month groups for the first year of life. Median tooth developmental stages were identified and tabulated accordingly. In other words, if a child is born at 36 weeks and survives one month, its dental age would correspond to the diagram of a full term birth dentition.

2.2.4 Eruption data

Alveolar tooth eruption was not assessed from the used known age-at-death collections as the Spitalfield's collection was fragmentary, and many had isolated teeth and all teeth from Maurice Stack's collection were isolated teeth with no skulls. To overcome the issue of missing data of alveolar eruption for individuals aged younger than 2 years, a referral to previous studies on that matter was essential (Liversidge and Molleson, 2004), and then used to develop new diagrams for the younger than two years. A total of 8 diagrams were constructed and added rather than the two diagrams constructed initially (Figures 2.15 and 2.16).

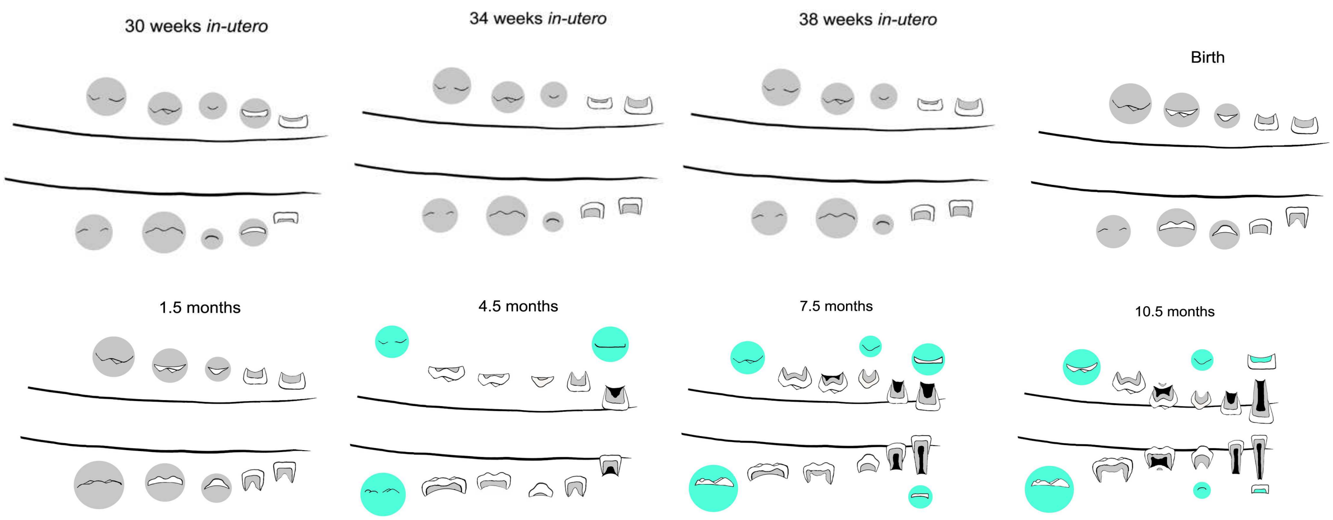

Figure 2. 16: New figures for children younger than one year after the addition of Mauric Stack's collection data.

2.2.5 Increasing sample size

When the sample size was increased for the first year of life, median developmental stages changed, which was expected because of the previous small sample size. Therefore, a judgment to increase the sample size from 14 to 24 for each chronological year between the ages two and 24 was made to include 12 males and 12 females for each chronological year. The median tooth formation and alveolar eruption stages were identified, and compared to the old median stages. The new median stages didn't differ from the previous ones, except for root resorption of a single tooth: the lower deciduous central incisor at age 5.5 where the median changed from tooth developmental stage AC (root completed) to tooth resorption stage Res¼ (resorption of apical ¼ of the root) (Fig. 2.17).

5.5 years old child based on 12individuals **5.5 years old child based on 24 individuals**

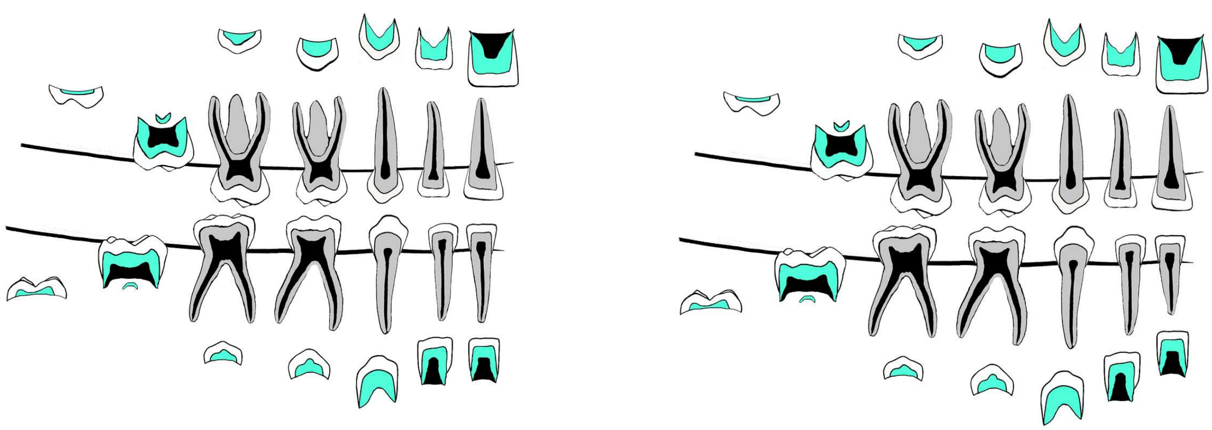

Figure 2. 17: Five year old child based on 12 individuals and after increasing the number to 24.

2.2.6 The London Atlas of tooth development

All 31 diagrams that represent median stages of dental development and alveolar eruption were compiled to form The London Atlas of tooth development. A spiral flow schema was designed beginning with the 30 weeks *in utero* diagram that is underlined with an arrow to demonstrate the ongoing development up to the age of 15 years; this is a departure from the columns used historically in previous schemas (Schour *et al.*, 1941; Gustafson *et al.*, 1974; Ubelaker, 1978). Third molar development between the ages 16 and 23 were presented separately in a column on the side of the Atlas for easy reference and the diagrams included only the second and third molars as all other teeth have reached maturity. The London Atlas consists of two pages; the first one is the atlas of dental development for the ages between 28 weeks *in utero* up to 23 years (Appendix 6). The second page presents tables explaining tooth formation and eruption stages that were used to construct the atlas (Bengston, 1935; Moorrees *et al.*, 1963b; a) with added written description (Appendix 7). Worldwide copyrights were reserved and registered in the Library of Congress with registration Number VAu000979741 on the 30th of March 2009 (AlQahtani, 2009) (Appendix 8).

The London Atlas of tooth development was published in the American Journal of Physical Anthropology (AlQahtani *et al.*, 2010) (Appendix 9).

2.3 Testing the performance of The London Atlas

This was a retrospective cross sectional study of archived materials.

2.3.1 Materials

Individuals included in this part of the study were all of documented known age. Dental development was assessed from archived dental panoramic radiographs except for individuals younger than two, where taking radiographs are either clinically impractical or not needed; therefore collections of known age-at-death human remains were utilised to test the performance of dental methods of age estimation. Since two collections of known age-at-death already had been used to construct The London Atlas (Spitalfield's and Stack's), it was decided that different collections would have to be assessed. An extensive search for other collections worldwide revealed very few numbers that have individuals younger than the age of two. There were five available collections identified: Luis Lopes collection (Portugal), De Froe and Vrolik collection (The Netherlands), Hamann-Todd collection (USA), Belleville's collection (Canada) and the collection d'anthropologie biologique (France). They contain 154 human remains between them (Table 2.1).

Table 2. 1: Number and sex of individuals from known age-at-death skeletal remains and archived radiographs up to the age of four used to test the performance of The London Atlas, Schour and Massler's and Ubelaker's schemas.

Age	Collection						
	Luis Lopes (Portugal)	De Froe (Amsterdam, Netherlands)	Hamann-Todd (Cleveland, USA)	Belleville (Montreal, Canada)	CAB** (Paris, France)	Archived Radiographs	Total
28 -- < 32 w*	-	-	-	-	2	-	2
32 -- < 36 w*	-	-	-	-	6	-	6
36 -- < 39 w*	-	-	-	-	12	-	12
39 w* -- < 1 week	6	-	4 m	-	6	-	16
1 w -- < 3 months	1	2	-	-	25	-	28
3 m -- < 6 m	4	2	-	2	1	-	9
6 m -- < 9 m	-	2	-	3	1 m, 1	-	7
9 m -- < 12 m	1	1 m	-	6	2	-	10
1+ year	20	3 m, 4 f, 2	8 m, 1 f	19	1 m, 6	-	64
2+ years	9	-	1 f	1	10	41	62
3+ years	8	-	-	-	-	67	75
4+ years	1	-	-	-	-	66	67
Total	50	16	14	31	73	174	358

*Weeks *in utero*.
**CAB: Collection d'anthropologie biologique.
M : male, F : female.

Table 2. 2: Number and sex of individuals from archived radiographs between five and 23 years used to test the performance of The London Atlas, Schour and Massler's and Ubelaker's.

Age	Males	Females	Total
5+	40	42	82
6+	39	38	77
7+	40	36	76
8+	29	35	64
9+	34	31	65
10+	32	32	64
11+	28	37	65
12+	25	31	56
13+	27	35	62
14+	32	27	59
15+	30	32	62
16+	34	30	64
17+	27	30	57
18+	29	27	56
19+	28	30	58
20+	25	31	56
21+	27	28	55
22+	25	24	49
23+	18	11	29

2.3.1.1 The Luís Lopes Collection

This collection of known age-at-death human remains is also known as the Lisbon Collection and it is placed at the Bocage Museum (National Museum of Natural History), Lisbon, Portugal. It consists of human remains that were abandoned by relatives and destined for communal graves at local cemeteries in Lisbon, Portugal. The museum collected the remains before they were destroyed or reburied. Because all individuals were identified through coffin plates, grave numbers, and cemetery registers, a whole suite of biographic and other data were collected (Cardoso, 2006). The collection has 50 very young individuals, access was given to photographs of both radiographs and isolated teeth (Table 2.1).

2.3.1.2 De Froe and the Vrolik collections

In Amsterdam, the Netherlands, a collection of human remains was gathered by father Gerard Vrolik (1775-1859) and his son Willem (1801-1863) between the years 1800 and 1863, both professors of anatomy. Another collection of human remains, the De Froe collection, was collected by Lodewijk Bolk (1866-1930), who was also a professor of anatomy in Amsterdam between 1898 and 1930.

These collections were mainly achieved during the 1910s and 1920s after the excavation of cemeteries in Amsterdam, Netherlands, and contain 16 neonates (Oostra, 1999) (Table 2.1). All skeletal remains in this collection were in the form of intact skulls; therefore radiographs were taken by the radiology team in the department of Radiology at the Academic Medical Centre, Meibergdreef, Amsterdam, The Netherlands. Each skull was mounted by the researcher (SA) and digital radiographs were taken from different angles: two laterals to view posterior dental development and one anterior to view anterior dental development.

2.3.1.3 Hamann – Todd collection

This collection is held at the Natural History Museum, Cleveland, USA. It came from retained skeletons and other specimens from the cadavers that the medical students dissected. They are supported by extensive documentation, hence, one of the largest, modern, documented human skeletal collections in the world (Brown, 1977). It contained 14 very young individuals in the form of either whole skulls or jaw sections (Todd, 1925)(Table 2.1). Radiographs were taken for all individuals by the researcher (SA).

2.3.1.4 Belleville's collection

When St. Thomas' Anglican Church in Belleville, Ontario, Canada was given permission to close in 1989, all skeletal remains from the nineteenth century cemetery located on land adjacent to the church property were excavated and identified by records of burials as well as baptisms. Age, death date, name of the registrar, burial date, and occasional notes on family relationships as well as cause of death were all preserved making the register data confidently treated as a reliable source for comparison to skeletally derived sex and age profiles. In the Department of Anthropology, McMaster University, Ontario, Canada, the collection was studied and radiographs were taken for all skeletal remains before reburial. There are 31 very young individuals in this collection (McKillop, 1995) (Table 2.1), but the skeletal remains of this collection have been reburied and only radiographs were available, access was given to photographs of these radiographs.

2.3.1.5 Collection d'anthropologie biologique

Held at the Musée de l'Homme in Paris, France, this collection is of many pieces that were recovered during the great works ordered by the Georges Haussmann (1809-1891) when the cemeteries were moved. It included skulls and skeletons, foetuses and mummies. It has 73 very young individuals. Radiographs were taken for all individuals by the researcher (SA) using a portable x-ray machine (NOMAD Intraoral, Dental X-Ray System, Aribex, Inc, USA) (Table 2.1).

2.3.1.6 Individuals aged two years

Archived dental panoramic radiographs of two year old children, total number 41, held at the Institute of Dentistry, Queen Mary, University of London, were used (Table 2.1).

2.3.2 Individuals aged three to 16 years

The sample of individuals aged three to 16 came from a collection of archived dental panoramic radiographs that has been collected and tested by Maber *et al*. (2006b; 2010). The radiographs are of 930 healthy children (452 males and 478 females). The ethnic origin of the sample was Bangladeshi (238 boys and 231 girls) and white British (214 boys and 247 girls). The added advantage of using this collection of radiographs was that the results can be utilised to compare the accuracy of many more methods, which was what Maber *et al*. (2006b; 2010) had done in their papers where they tested different methods of age estimation using this same collection of radiographs (Tables 2.1 and 2.2).

2.3.3 Individuals older than 16

Archived dental panoramic radiographs of 17 to 23 year old individuals from the Institute of Dentistry, Queen Mary, University of London, were used, total number is 360. (Table 2.2)

Chapter Three: Methods

3.1 Methodology

To test the accuracy of the new Atlas (The London Atlas), a comparison with similar previously used methods is necessary, but the limitations of the diagram based methods made the choice very limited. Only two schemas of dental development covered a wide age range, and therefore were the most widely used schemas and included in almost all dental anatomy textbooks. They are Schour and Massler's Atlas of tooth development published in 1941 and Ubelaker's Chart of dental development published in 1978 (Appendices 1 and 2).

Therefore, age estimation schemas tested in this study were:

1- The London atlas (AlQahtani *et al.*, 2010)

2- Schour and Massler's Atlas (1941).

3- Ubelaker's Chart (1978).

These methods were used to estimate the age of known- age individuals using developing teeth. The assessment was for each method on all ages as a whole, for each age group and based on sex. Missing age groups from Schour and Massler's and Ubelaker's will be dealt with separately. Performance measures were calculated for each schema in terms of:

- Reliability: assessed by how different results were when using it by the same examiner on different occasions after a wash out period measured using Cohen's kappa (Landis and Koch, 1977).

- Mean difference between estimated and real age (Bias) and standard deviation in age groups.

- Mean absolute difference between estimated and real age in age groups.

- Proportion of individuals correctly estimated to be in the correct age group.

- Sensitivity, specificity and likelihood ratios of positive and negative test results.

3.2 Testing methods

All radiographs were assessed on a radiographic viewer, photographed radiographs were assessed on a computer monitor using Microsoft office picture manager; isolated teeth were examined visually and photographed by the researcher (SA). The magnification that is associated with radiographs or photographs was not an issue because what was assessed is the developmental stage that depends on proportions rather than measurements.

To test the intra examiner reliability, 10% of all cases was assessed again using each method after a wash out period of two months by the researcher (SA) and Kappa was calculated (Landis *et al.*, 1977) as it more accurately represents reliability (Hunt, 1986).

All cases were numbered and real age was blinded from examiner. Sex of individuals was recorded along with the time needed to estimate age using each method. Data were entered into SPSS (16.0) program immediately.

Performance of each method tested was compared to the other two. Because the age intervals for the groups were not equal under the age of one as prenatal age groups had one month age interval, around birth it had two weeks age interval and younger than one it had three months age interval. This made it necessary to divide the whole sample according to age groups before analysis for the groups to be comparable.

Real age was converted into an age interval for it to be comparable with estimated age, which is always an age group. For example, all individuals aged 1.00 to 1.99 were recoded to be in one age group.

3.2.1 Bias

This is the mean difference between the estimated age and the real age. The analysis was then calculated using a one sample *t*-test.

3.2.2 Absolute mean difference:

This is the absolute value of the difference between the estimated age and the real age then analysed using simple mean test.

3.2.3 Proportion of individuals correctly estimated to be in the same age group

This was calculated using Wilcoxon test on real age groups and estimated age groups using The London Atlas, Schour and Massler's and Ubelaker's. This test gives the number of cases that were estimated to be in the correct age group, underestimated and overestimated.

3.2.4 Sensitivity and specificity

Sensitivity measures the proportion of individuals estimated correctly in their age group, or the probability that the method estimates the correct age of an individual. **Specificity** measures the proportion of individuals estimated correctly to not be in a specific age group, or the method estimates that an individual is not at a specific age.

True positives are cases correctly estimated to be in a specific age group, true negatives are cases correctly estimated not to be in a specific age group, false positives are cases estimated wrongly to be in a specific age group and false negatives are cases that belong to a specific age group but estimated not to be.

3.2.5 Likelihood ratios

The positive likelihood ratio for a result indicates how much the probability of the specific age when the age estimation gives that age. A likelihood ratio greater than 1 indicated that the estimated age is associated with real age, whereas a result of 1 means absence of diagnostic performance. The further likelihood ratios are from 1, the stronger the evidence for the estimated age; likelihood ratios above 10 are considered to provide strong evidence for age estimation.

3.3 The survey, qualitative test

The qualitative part of testing The London Atlas was in the form of an analytical survey.

3.3.1 Study design

This was a population based matched unpaired cross sectional study design to explore the experience of participants when using age estimation methods. This survey was designed to gather information regarding the experience of using one of three age estimation methods. Participants were divided randomly and assigned to groups using Random Allocation software (Saghaei, 2004). The groups were:

1- Group (A) to use The London atlas.
2- Group (B) to use Ubelaker's chart.
3- Group (C) to use Schour and Massler's atlas.

Each group was assigned a code letter (A,B and C). The groups' methods were blinded from the researcher (SA). All groups were shown the same seven photographs of dental panoramic radiographs on a large computer screen or a large TV, and asked to estimate the age of each case. Since this is an analytical survey, a representative sample of the population is not required, therefore a convenience sample is used (Oppenheim, 1992). Sample size was calculated for significance level 0.05 and statistical power 0.95 using GPower software (Mayr, Erdfelder *et al.*, 2007); this was 90 individuals with 30 individuals randomly allocated in each group. Third year dental students (45 males and 45 females) at Queen Mary, University of London, were chosen to be the target group because although they had begun clinical dentistry and were able to a basic interpretation of radiographs they had very limited or no experience of age estimation using radiographs; therefore the risk of bias towards one method was minimal.

3.3.2 Ethical approval

Ethical approval was granted from Queen Mary Research Ethics Committee on 19th of May 2009 (QMREC2009/14) (Appendix 10).

3.4 Survey questionnaire

The first part was designed to collect information about the participant's past experience, providing an easy way into the survey. There were 10 questions to gather information such as sex, age, the participants' history in age estimation, their preferred method of choice, rational for choosing that method, their satisfaction with it and what they look for in methods of age estimation in general.

The second part asked the participant to use the assigned method of age estimation to seven different photographs of dental panoramic radiographs of individuals selected at random from the tested collections and clearly numbered. The participants were asked to give their age estimation answers in a table in the survey.

The third part had 13 questions designed to collect information regarding their experience with the assigned method they have just been asked to use in regards to its clarity, design, simplicity, if it had been self explanatory, time consumption, their satisfaction with it and how that reflects on their future use. There were some questions that allowed participants to write their comments and feelings.

It was written in English and included nine pages starting with a well-written introduction and the title (Atlas of tooth development) on top of each page. The survey was designed so that participants were anonymous. (Appendices 11 and 12)

3.4.1 Pilot study

To make sure that the designed survey was usable and providing the information needed, a pilot study was carried out on 20 students who volunteered to participate. The main issues to test were the wording of questions and their clarity. Participants did not interpret some items as intended. Some items posed problems to respondents because of their wording or because they were considered not applicable to the respondents' circumstances. Amendments were carried out accordingly (Appendices 11 and 12).

3.4.2 Survey outline

The survey started with easy to understand, clear and concise instructions on how to complete the questions. The questions were as brief as possible. Adequate space was provided for the participant to make comments, which also made the survey easier to read. To hold the participant's interest, the small exercise of using the assigned method of age estimation was placed in the middle of the survey (Appendix 13). Questions were designed to be placed into coherent categories and maintain a smooth flow from one question to the next avoiding questions that may ask for a response on more than one dimension.

Answers were provided for most questions in the form of multiple choices to make it easier to complete, but when the choices were thought not to accommodate all possible answers, a choice of writing the answer by participants was provided. Answers were also made variable as possible to enable measuring the differences between participants, and when assuming a certain condition, an added response category for participants who don't fulfil the condition was included. Attitudinal answers had a scale of five answers to choose one, with a neutral answer in the middle (Oppenheim, 1992; Fowler, 1993; Aday, 1996).

3.5 Conducting the survey

The setting of the study was in the Institute of Dentistry, Queen Mary University of London, over several days in groups of 10-12 students at a time. Consent was obtained from all participants prior to taking part in the study. Participants were allowed to withdraw from taking part at any point without any consequences. All information collected was treated with the outmost confidence in accordance to the data protection act. All data sheets and files were stored in the researcher's locked office or on a password protected computer, both located in an area of limited access within the Institute of Dentistry.

Chapter Four: Results

4.1 Atlas of tooth development and eruption

The Atlas of tooth development and eruption has been designed and published in the American Journal of Physical Anthropology (AlQahtani *et al.*, 2010) and is available to download for free through the Institute of Dentistry's website: www.atlas.dentistry.qmul.ac.uk in 17 languages: Arabic, traditional Chinese, Simplified Chinese, Dutch, English, Farsi, French, German, Greek, Hindi, Japanese, Malay, Portuguese, Romanian, Russian, Spanish and Urdu. It has been used in many workshops, incorporated into several universities' curricula around the world and adopted by several forensic societies (Appendix 14).

4.1.1 Performance

4.1.2 Intra-observer measurement error

Intra-observer error was assessed by retesting a random 10% of the whole sample (160 cases). Selecting the random sample was by generating random numbers using random allocation software then allocating the radiographs accordingly. Excellent reproducibility was observed for all three methods (Kappa: The London Atlas 0.879, Schour and Massler 0.838 and Ubelaker 0.857).

4.1.3 Performance analysis on the whole sample

4.1.3.1 Bias

Mean difference (Bias) for the whole sample (N: 1514) in age groups between real age and estimated age using The London Atlas, Schour and Massler's and Ubelaker's for each age cohort is tabulated in (Table 4.1) along with the standard deviation of mean difference, standard error of mean, 95% confidence interval of mean difference and the *P* value. Bias for males and females was only done between ages one and 23 years because in the other age cohorts the small number didn't allow for that kind of analysis. The results are explained in detail for each age cohort below.

Table 4. 1: Mean difference (Bias) for the whole sample (N: 1514) in age groups between real age and estimated age using The London Atlas (LA), Schour and Massler (SM) and Ubelaker (Ub) for each age cohort, standard deviation (SD) of mean difference, standard error of mean (SEM), 95% confidence interval of mean difference and the *P* value.

Age category	Number of cases	Method		Mean (Bias)	Standard deviation	SEM	95%CI	*P* value
Prenatal	20	LA		0.03	± 0.08 m	0.018	-0.003, 0.71	0.097
		SM		-0.14	± 0.08 m	0.017	-0.143, -0.073	0.000*
		Ub		-0.14	± 0.08 m	0.017	-0.143, -0.073	0.000*
Birth	16	LA		0.15	± 0.62 w	0.078	-0.019, 0.315	0.078
		SM		0.09	± 0.68 w	0.096	-0.069, 0.339	0.287
		Ub		0.06	± 0.64 w	0.091	-0.096, 0.289	0.451
1 week – less than a year	54	LA		-0.03	± 0.48 m	0.022	-0.079, 0.009	0.122
		SM		-0.02	± 0.83 m	0.037	-0.098, 0.054	0.578
		Ub		-0.05	± 0.89 m	0.041	-0.137, 0.026	0.177
One to 23 years	1424	LA	Total	-0.01	± 1.14 y	0.030	-0.071, 0.047	0.700
			Males	0.05	± 1.08 y	0.042	-0.031, 0.133	0.219
			Females	-0.07	± 1.24 y	0.047	-0.161, 0.025	0.154
		SM	Total	-0.09	± 1.53 y	0.040	-0.169, -0.010	0.027*
			Males	-0.04	± 1.47 y	0.057	-0.155, 0.069	0.449
			Females	-0.13	± 1.65 y	0.063	-0.256, -0.008	0.036*
		Ub	Total	-0.12	± 1.53 y	0.030	-0.202, -0.043	0.003*
			Males	-0.08	± 1.48 y	0.058	-0.192, 0.033	0.168
			Females	-0.18	± 1.65 y	0.063	-0.301, -0.053	0.005*

4.1.3.1.1 Bias for prenatal

There are 20 prenatal foetuses. Age interval is one month. The London Atlas showed no bias with mean difference of 0.03 (± 0.079 months, p=0.097) whereas Schour and Massler's and Ubelaker's consistently underestimated age with significant bias with mean difference being -0.14 (± 0.084 months, p= 0.000) for both methods (Figures 4.1 and 4.2).

Figure 4. 1: Bias in months for The London Atlas, Schour and Massler and Ubelaker on 20 prenatal foetuses (3 prenatal age groups combined.

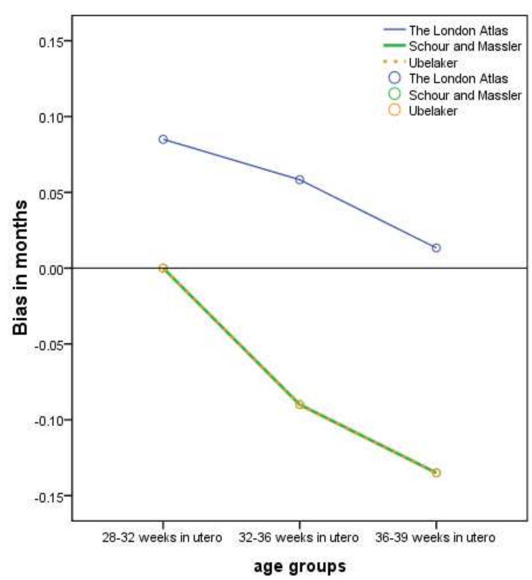

Figure 4. 2: Bias in months for The London Atlas, Schour and Massler and Ubelaker for each prenatal age group.

4.1.3.1.2 Bias for birth

There are 16 individuals at full term birth (40 weeks gestation using corrected age). Age interval is two weeks. All methods showed no bias. The London Atlas had a mean difference of 0. 15 (± 0.31 age groups: 0.62 weeks, p= 0.078), Schour and Massler's had a mean difference of 0.093 (± 0.34 age groups: 0.68 weeks, p= 0.287). Ubelaker's had a mean difference of 0.063 (± 0.32 age groups: 0.64 weeks, p= 0.451) (Fig. 4.3).

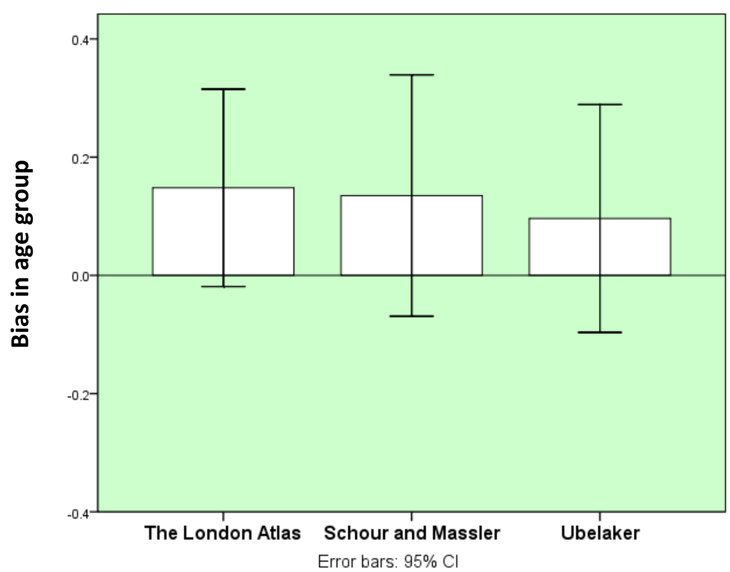

Figure 4. 3: Bias in age group (two weeks) for The London Atlas, Schour and Massler and Ubelaker on full gestation birth individuals.

4.1.3.1.3 Bias for one week to less than a year

There are 54 individuals younger than the age of one. Age interval is three months. All methods show no bias. The London atlas has a mean difference of -0.035 (± 0.16 age groups: 0.48 months, p= 0.122). Schour and Massler's has a mean difference of -0.021 (± 0.28 age groups: 0.84 months, p= 0.578). Ubelaker's has a mean difference of -0.055 (± 0.29 age groups: 0.87 months, p= 0.177) (Figures 4.4 and 4.5)

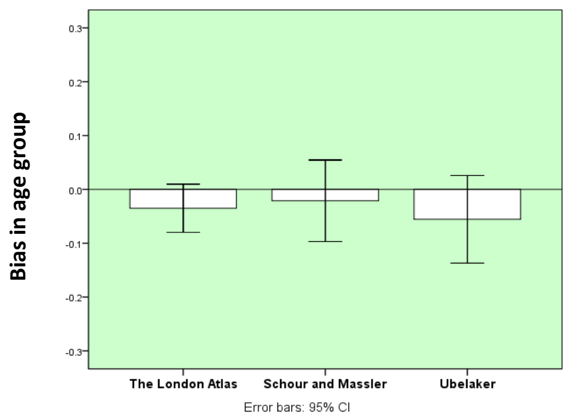

Figure 4. 4: Bias in age groups (3 months) for The London Atlas, Schour and Massler and Ubelaker on individuals aged one week to just below one year.

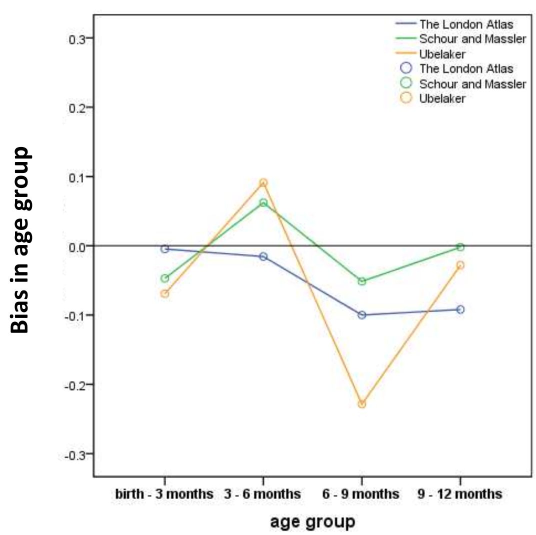

Figure 4. 5: Bias in age groups (3 months) for each of the groups for The London Atlas, Schour and Massler and Ubelaker on individuals aged one week to just below one.

4.1.3.1.4 Bias for one to 23 years

There are 1424 individuals between the ages one and 23 years. Age interval is one year. The London Atlas shows no bias with mean difference of -0.012 (± 1.14 years, p= 0.7). Both Schour and Massler's and Ubelaker's systematically underestimate age with significant bias. Schour and Massler's has a mean difference of -0.09 (± 1.53 years, p= 0.027). Ubelaker's has a mean difference of -0.12 (± 1.53 years, p= 0.003) detailed in Figure 4.6.

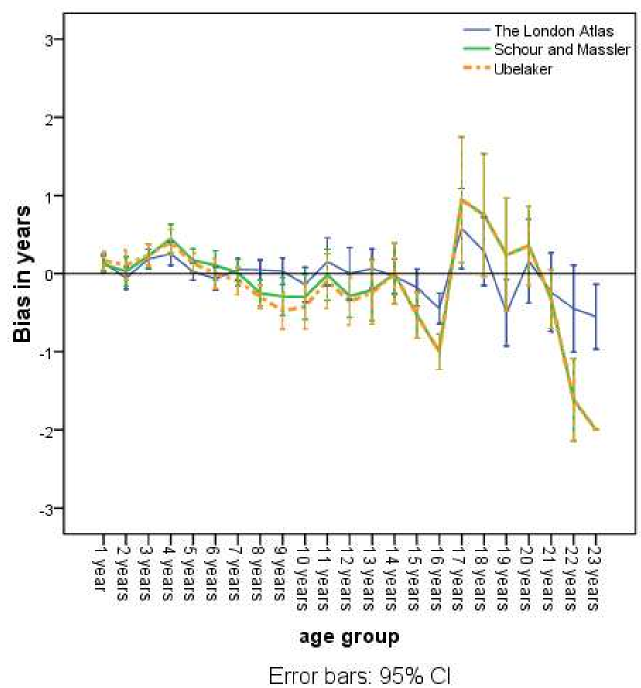

Figure 4. 6: Bias in years for The London Atlas, Schour and Massler and Ubelaker on individuals between one and 23 years.

4.1.3.1.4.1 Bias for males and females

Calculating the bias for the three methods on only males (N: 664) using a one sample *t*-test shows that there is no bias for all three methods: The London Atlas has a mean difference of 0.051 (± 1.07 years, p= 0.219), Schour and Massler's has a mean difference of -0.043 (± 1.48 years, p= 0.449) and Ubelaker's chart has a mean difference of -0.079 (± 1.48 years, p= 0.168) (Figure 4.7).

Calculating the bias for the three methods on only females (N: 684) using a one sample *t*-test shows that the London Atlas has no bias with a mean difference of -0.068 (± 1.24 years, p= 0.154). Schour and Massler's and Ubelaker's systematically underestimate age with significant bias. Schour and Massler's has a mean difference of -0.13 (± 1.65 years, p= 0.036) and the Ubelaker's has a mean difference of -0.18 (± 1.65 years, p= 0.005) (Figure 4.7).

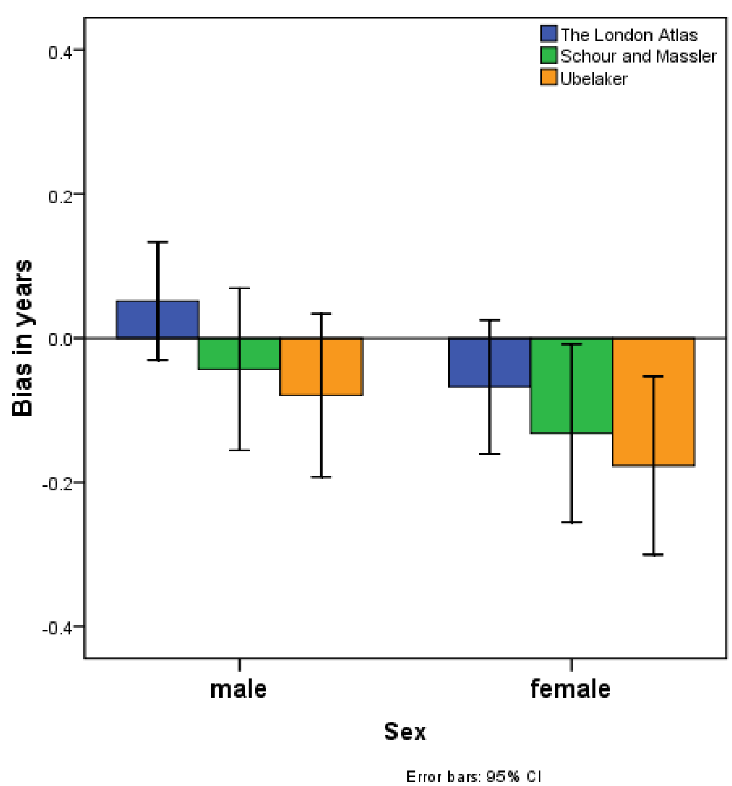

Figure 4. 7: Bias in years for The London Atlas, Schour and Massler and Ubelaker on individuals between one and 23 year based on sex.

4.1.3.2 Mean absolute difference

An overview of absolute mean difference in age cohorts for the whole sample (N: 1514) in age groups between real age and estimated age using The London Atlas, Schour and Massler's and Ubelaker's for each age cohort is shown in (Table 4.2 and Figures 4.8-4.11). Absolute mean difference for males and females was only done between ages one and 23 years because in the other age cohorts the small number didn't allow for that kind of analysis. The results are explained in detail for each age cohort below.

Table 4. 2: Absolute mean difference in age groups (years (y), months (m) or weeks (w)) between real age and estimated age using The London Atlas, Schour and Massler's and Ubelaker's for each age cohort.

Age category	Number of cases	Method		Absolute mean difference
Prenatal	20	The London Atlas		0.07 m (0.006 y)
		Schour and Massler		0.12 m (0.01 y)
		Ubelaker		0.12 m (0.01 y)
Birth	16	The London Atlas		0.38 w (0.0079 y)
		Schour and Massler		0.48 w (0.01 y)
		Ubelaker		0.40 w (0.0083 y)
1 week – less than a year	54	The London Atlas		0.36 m (0.03 y)
		Schour and Massler		0.63 m (0.05 y)
		Ubelaker		0.72 m (0.06 y)
One to 23 years	1424	The London Atlas	Total	0.65 y
			Males	0.61 y
			Females	0.73 y
		Schour and Massler	Total	1.03 y
			Males	1.02 y
			Females	1.12 y
		Ubelaker	Total	1.03 y
			Males	1.02 y
			Females	1.12 y

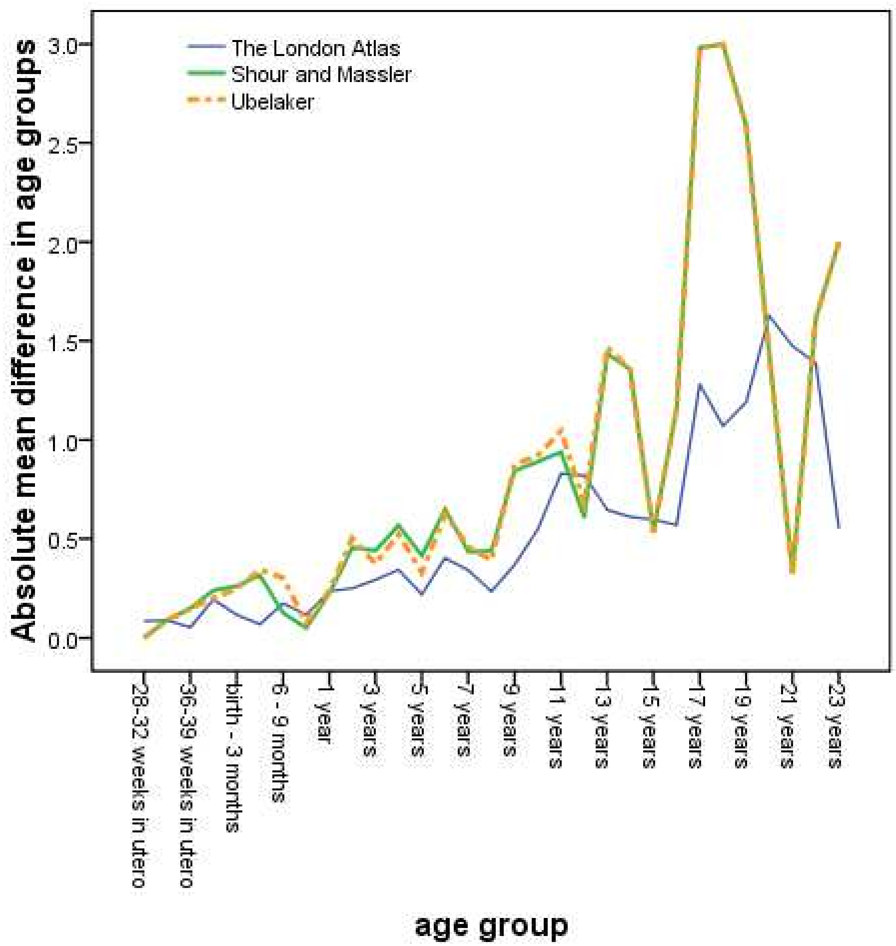

Figure 4. 8: Absolute mean difference between real and estimated age in age groups when using The London Atlas, Schour and Massler and Ubelaker on individuals between the ages 28 week *in utero* and 23 years

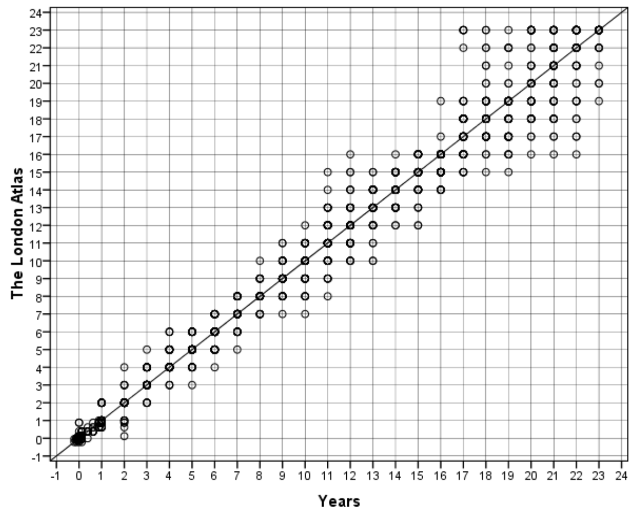

Figure 4. 9: Distribution of The London Atlas age estimation (y axis) in relation to real age (x axis)

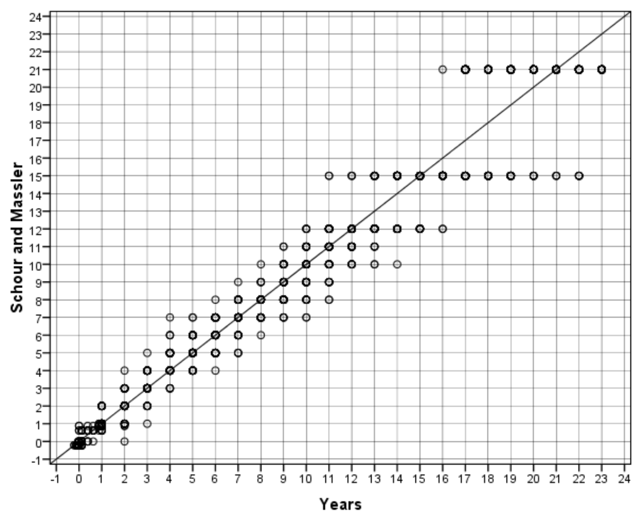

Figure 4. 10: Distribution of Schour and Massler's age estimation (y axis) in relation to real age (x axis)

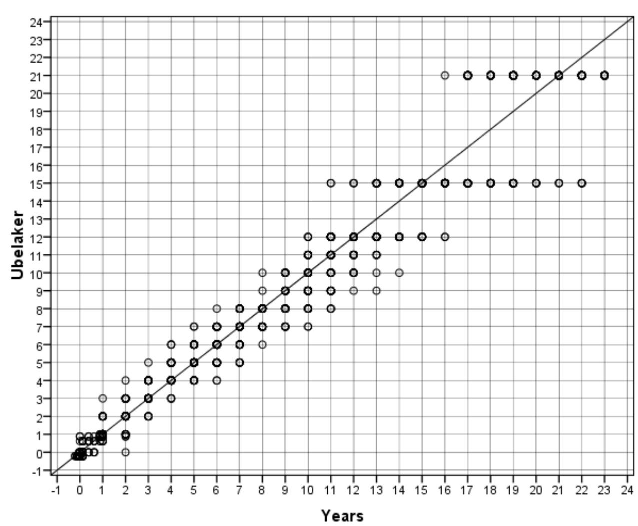

Figure 4. 11: Distribution of Ubelaker's age estimation (y axis) in relation to real age (x axis)

4.1.3.2.1 Absolute mean difference for prenatal

There are 20 prenatal individuals. Age interval is one month. The London Atlas has an absolute mean difference of 0.067 months. Schour and Massler's and Ubelaker's both have the same absolute mean difference of 0.12 months (Figures 4.12).

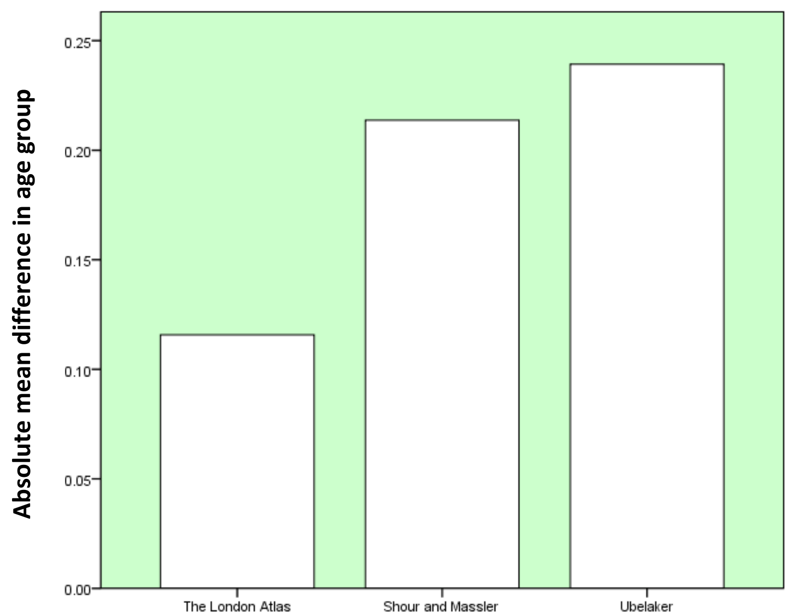

Figure 4. 12: Absolute mean difference between real and estimated age in months when using The London Atlas, Schour and Massler and Ubelaker on prenatal individuals.

4.1.3.2.2 Absolute mean difference for birth

There are 16 individuals at full term birth (40 weeks gestation using corrected age). Age interval is two weeks. The London Atlas has an absolute mean difference of 0.19 age groups (0.38 weeks), Schour and Massler's has an absolute mean difference of 0.24 age groups (0.48 weeks) and Ubelaker's has an absolute mean difference of 0.2 age groups (0.4 weeks) (Figure 4.13).

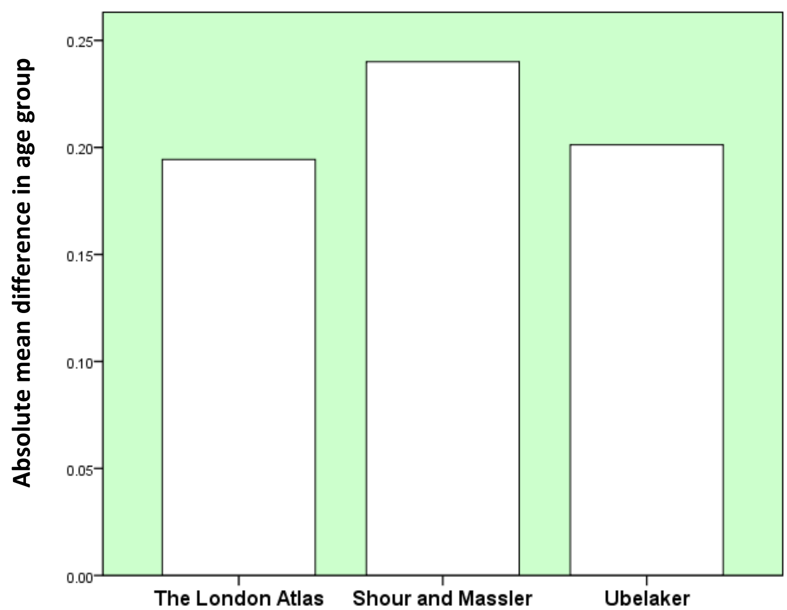

Figure 4. 13: Absolute mean difference between real and estimated age in age groups (2 weeks) when using The London Atlas, Schour and Massler and Ubelaker on newly born babies at full gestation.

4.1.3.2.3 Absolute mean difference for one week to less than one year

There are 54 individuals younger than the age of one year. Age interval is three months. The London Atlas has an absolute mean difference of 0.12 age groups (0.36 months). Schour and Massler's has an absolute mean difference of 0.21 age groups (0.63 months) and Ubelaker's has an absolute mean difference of 0.23 (0.69 months) (Figures 4.14 and 4.15).

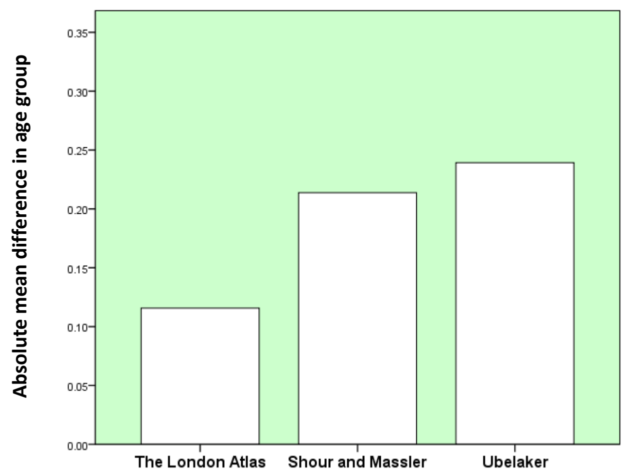

Figure 4. 14: Absolute mean difference between real and estimated age in age groups (3 months) when using The London Atlas, Schour and Massler and Ubelaker between 1 week of age and just less than one year.

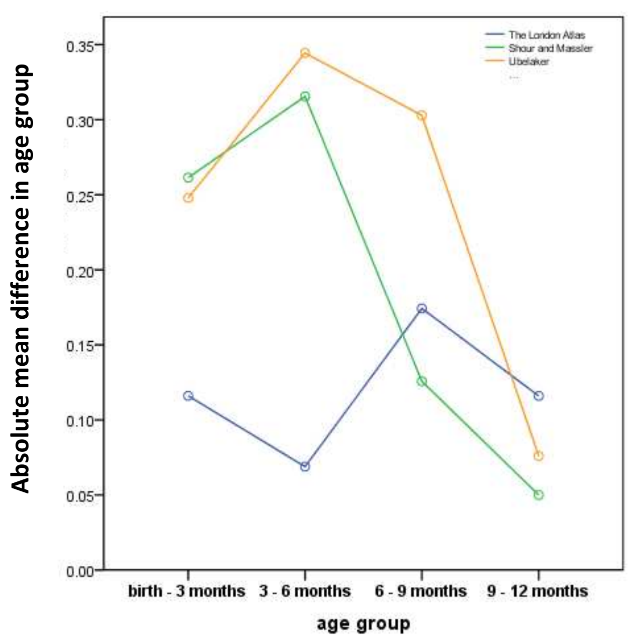

Figure 4. 15: Absolute mean difference between real and estimated age in age groups (3 months) when using The London Atlas, Schour and Massler and Ubelaker between 1 week of age and just less than one year.

4.1.3.2.4 Absolute mean difference for one to 23 years

There are 1425 individuals between the ages one and 23 years. Age interval is one year. The London Atlas shows an absolute mean difference of 0.65 years. Both Schour and Massler's and Ubelaker's have an absolute mean difference of 1.03 years (Figures 4.16 and 4.17).

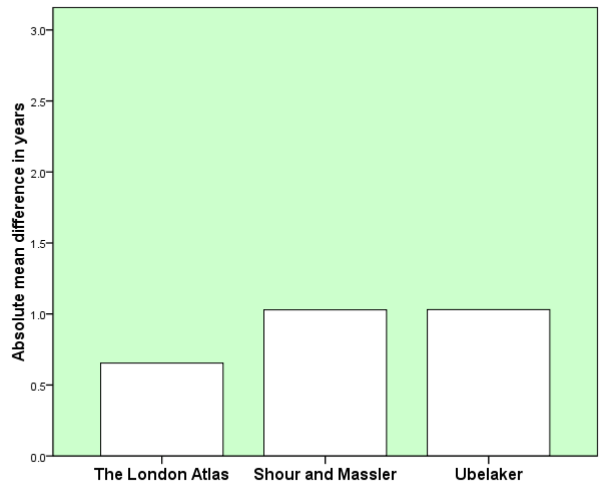

Figure 4. 16: Absolute mean difference between real and estimated age in years when using The London Atlas, Schour and Massler and Ubelaker between one and 23 years according to age groups.

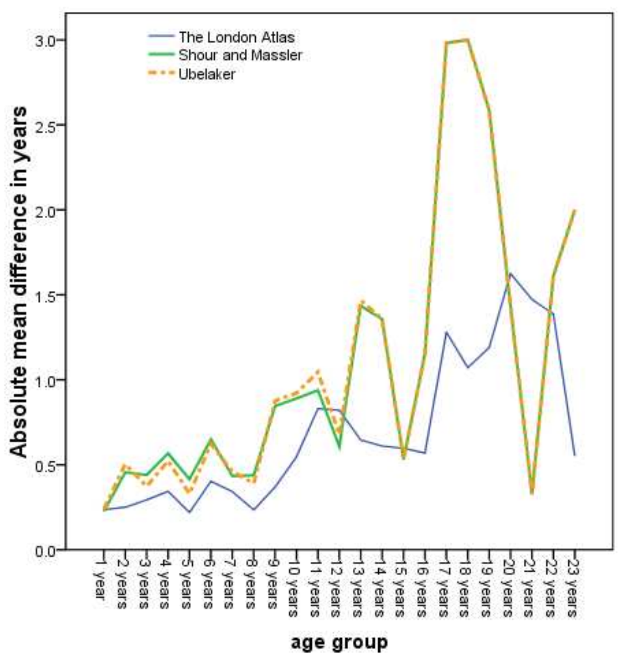

Figure 4. 17: Absolute mean difference between real and estimated age in years when using The London Atlas, Schour and Massler and Ubelaker between one and 23 years according to age groups.

4.1.3.2.4.1 Absolute mean difference for males and females

The absolute mean difference for males in the sample (N: 665) using a one sample *t*-test: The London Atlas has an absolute mean difference of 0.61 years, both Schour and Massler's and Ubelaker's have an absolute mean difference of 1.02 years (Figure 4.18).

The absolute mean difference for females in the sample (N: 684) using a one sample *t*-test: The London Atlas has an absolute mean difference of 0.73 years, both Schour and Massler's and Ubelaker's have an absolute mean difference of 1.12 years (Figure 4.18).

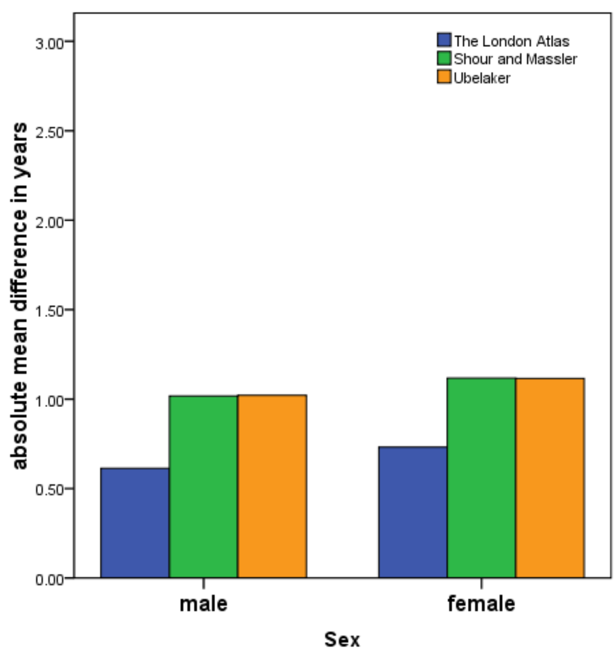

Figure 4. 18: Absolute mean difference in years for individuals between the ages 1 and 23.

4.1.3.3 Proportion of individuals correctly estimated to be in the same age group

Of the 1514 cases tested, The London Atlas estimated 52.8% of cases to be in the correct age group (N: 800). Schour and Massler's atlas had estimated 35.0% of cases to be in the correct age group (N: 530). Ubelaker's chart had estimated 35.7% of the cases to be in the correct age group (N: 541). The test also confirmed that The London Atlas has no bias (p: 0.503), whereas the Schour and Massler's and Ubelaker underestimate age (p: 0.031 and 0.002 respectively) (Table 4.3 and Figure 4.19).

Table 4. 3: Proportion of cases estimated to be younger, older or in the same age group as real age for The London Atlas, Schour and Massler's and Ubelaker's using Wilcoxon signed ranks test.

Method	**Age estimation**	**Number of cases**	**Percentage of cases**	**Z***	**Significance**
The London Atlas	Underestimated	364	24.04%	-0.678	0.503
	Correctly estimated	**800**	**52.84%**		
	Overestimated	350	23.12%		
Schour and Massler	Underestimated	543	35.87%	-2.153	0.031
	Correctly estimated	**530**	**35.01%**		
	Overestimated	441	29.12%		
Ubelaker	Underestimated	551	36.40%	-3.11	0.002
	Correctly estimated	**541**	**35.73%**		
	Overestimated	422	27.87%		

*Based on correctly estimated cases compared to the pooled underestimated and overestimated cases.

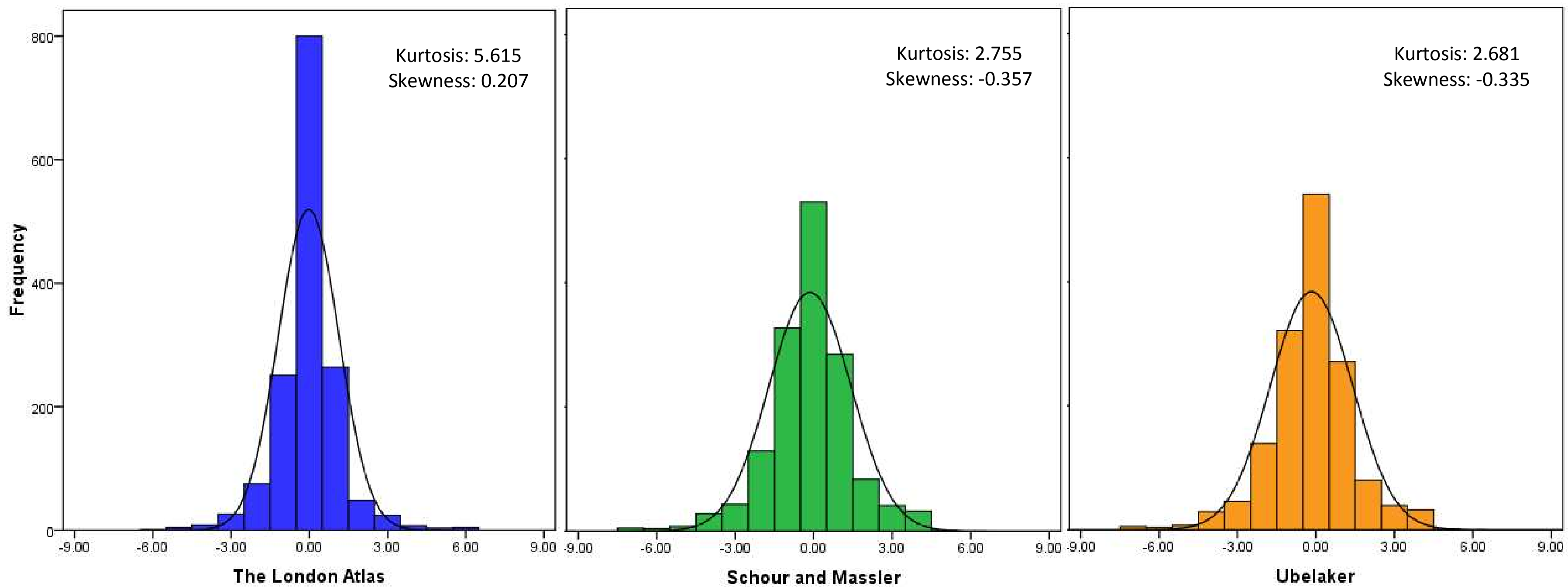

Figure 4. 19: Proportion of cases estimated to be younger, older or in the same age group as real age for The London Atlas, Schour and Massler's and Ubelaker's with Kurtosis and Skewness.

Skewness values for the three methods are close to zero, which indicates a normal distribution of estimated ages around zero (where estimated and real ages are the same). However, the negative skewness values of Schour and Massler's and Ubelaker's (-0.357 and -0.335 respectively) suggest that they tend to underestimate age whereas The London Atlas has positive value (0.207) meaning that it tends to overestimate age, although with a lesser degree than Schour and Massler's and Ubelaker's underestimate age.

Kurtosis is considered normal if it was three, meaning that Schour and Massler's and Ubelaker's show a normal distribution in regard to the spread of estimated age around zero (2.755 and 2.681 respectively) , whereas the kurtosis for The London Atlas is almost the double (5.615) showing that most of the differences between estimated and real ages are equal to zero.

4.1.3.4 Sensitivity and specificity

Number of cases of correct estimation, incorrect estimation, false estimation when using The London Atlas, Schour and Massler's and Ubelaker's are tabulated in (Tables 4.4, 4.6 and 4.7). The sensitivity, specificity, positive and negative likelihood ratios and predictive values for The London Atlas, Schour and Massler's and Ubelaker's according to age groups are tabulated in (Tables 4.5, 4.8 and 4.9). The results are explained in detail for each age cohort below.

Table 4. 4: Number of cases of correct estimation, incorrect estimation, false estimation when using The London Atlas (LA), Schour and Massler's (SM) and Ubelaker's (Ub).

Age	Method	Correct age (True positive)	Incorrect estimation (false negative)	False estimation (false positive)	Correct not to be (true negative)
Prenatal	LA	4	16	26	1468
	SM	2	18	28	1466
	Ub	2	18	28	1466
Birth	LA	5	11	16	1482
	SM	8	8	21	1477
	Ub	9	7	24	1474
1 week – less than a year	LA	25	30	16	1443
	SM	12	24	14	1464
	Ub	9	18	14	1473
1 – 23 years	LA	766	638	1	109
	SM	508	897	2	108
	Ub	521	888	2	103

Table 4. 5: Sensitivity (%), specificity (%), Likelihood ratios and predictive values (%) for The London Atlas (LA), Schour and Massler's (SM) and Ubelaker's (Ub) according to age groups under the age of one.

Age group	Method	sensitivity	Specificity	Likelihood ratio positive	Likelihood ratio negative	Positive predictive value	Negative predictive value
Prenatal	LA	20	99.26	11.49	0.81	13.33	98.92
	SM	10	98.12	5.35	0.92	6.67	98.78
	Ub	10	98.12	5.35	0.92	6.67	98.78
Birth	LA	31.25	98.93	29.48	0.69	23.8	99.26
	SM	50	98.59	35.46	0.51	27.58	99.46
	Ub	56.25	98.39	38.82	0.44	27.27	99.53
1 week – less than a year	LA	45.45	98.90	41.44	0.55	60.97	97.96
	SM	33.33	99.05	35.08	0.67	39.13	98.39
	Ub	33.33	99.66	98.02	0.67	39.13	98.79

Table 4. 6: Number of cases of correct estimation, incorrect estimation, false estimation when using The London Atlas (LA), Schour and Massler's (SM) and Ubelaker's (Ub) between one and 23 years (Total N: 1514).

Age	Method	Correct age (True positive)	Incorrect estimation (false negative)	False estimation (false positive)	Correct not to be (true negative)
1 years	LA	35	29	5	1445
	SM	35	29	12	1438
	Ub	39	25	10	1466
2 years	LA	49	13	16	1436
	SM	36	26	17	1435
	Ub	33	29	16	1436
3 years	LA	54	21	8	1431
	SM	44	31	17	1422
	Ub	48	27	22	1417
4 years	LA	47	20	24	1423
	SM	34	33	35	1412
	Ub	35	32	32	1415
5 years	LA	65	17	32	1400
	SM	50	32	48	1384
	Ub	57	32	51	1374
6 years	LA	47	30	22	1415
	SM	29	48	34	1403
	Ub	32	45	30	1407
7 years	LA	51	25	21	1417
	SM	47	29	56	1382
	Ub	46	30	53	1385
8 years	LA	50	14	29	1421
	SM	38	26	54	1396
	Ub	41	23	57	1393
9 years	LA	44	21	22	1427
	SM	16	49	50	1399
	Ub	15	50	31	1418
10 years	LA	36	28	27	1423
	SM	22	42	34	1416
	Ub	21	43	33	1417
11 years	LA	28	37	30	1419
	SM	21	44	32	1417
	Ub	18	47	27	1422
12 years	LA	24	32	26	1432
	SM	33	23	94	1364
	Ub	33	23	93	1363
15 years	LA	32	30	49	1403
	SM	51	11	207	1245
	Ub	51	11	207	1245
21 years	LA	12	43	13	1446
	SM	52	3	228	1231
	Ub	52	3	228	1231

Table 4. 7: Number of cases of correct estimation, incorrect estimation, false estimation when using The London Atlas (LA) for ages missing from (SM) and (Ub) (Total N: 1514).

Age	Method	Correct age (True positive)	Incorrect estimation (false negative)	False estimation (false positive)	Correct not to be (true negative)
13 years	LA	30	32	31	1421
14 years	LA	26	33	39	1416
16 years	LA	35	30	36	1413
17 years	LA	16	41	33	1424
18 years	LA	20	36	43	1415
19 years	LA	23	35	39	1417
20 years	LA	11	45	15	1443
22 years	LA	10	39	23	1442
23 years	LA	21	8	56	1429

Table 4. 8: Sensitivity (%), specificity (%), Likelihood ratios and predictive values (%) for The London Atlas (LA), Schour and Massler's (SM) and Ubelaker's (Ub) according to age groups older than one year that are present in all three methods.

Age group	Method	sensitivity	Specificity	Likelihood ratio positive	Likelihood ratio negative	Positive predictive value	Negative predictive value
1+	LA	54.69	99.66	158.59	0.45	87.50	98.03
	SM	54.69	99.17	66.08	0.45	74.47	98.02
	Ub	60.94	99.32	89.94	0.39	79.59	98.32
2+	LA	79.03	98.89	71.72	0.20	75.38	99.10
	SM	58.06	98.83	49.59	0.41	67.92	98.22
	Ub	53.23	98.89	48.30	0.46	67.35	98.02
3+	LA	72.00	99.44	129.51	0.28	87.09	98.55
	SM	58.67	98.82	49.66	0.41	72.13	97.87
	Ub	64.00	98.47	41.86	0.35	68.57	98.13
4+	LA	70.15	98.34	42.29	0.29	66.19	98.61
	SM	50.75	97.58	20.98	0.48	49.28	97.72
	Ub	52.24	97.79	23.62	0.47	52.24	97.79
5+	LA	79.27	97.77	35.47	0.19	67.01	98.80
	SM	60.98	96.65	18.19	0.37	51.02	97.74
	Ub	64.04	96.42	17.89	0.34	52.78	97.72
6+	LA	61.04	98.47	39.87	0.38	68.12	97.92
	SM	37.66	97.63	15.92	0.61	46.03	96.69
	Ub	41.56	97.91	19.91	0.58	51.61	96.90
7+	LA	67.11	98.54	45.95	0.32	70.83	98.27
	SM	61.84	96.11	15.88	0.36	45.63	97.94
	Ub	60.53	96.31	16.42	0.37	46.46	97.88
8+	LA	78.13	98.00	39.06	0.20	63.29	99.02
	SM	59.38	96.28	15.94	0.38	41.30	98.17
	Ub	64.06	96.07	16.29	0.33	41.84	98.38
9+	LA	67.69	98.48	44.58	0.31	66.67	98.55
	SM	24.62	96.55	7.133	0.75	24.24	96.62
	Ub	23.08	97.86	10.79	0.76	32.61	96.59
10+	LA	56.25	98.14	30.21	0.43	57.14	98.07
	SM	34.38	97.66	14.66	0.65	39.29	97.12
	Ub	32.81	97.72	14.42	0.66	38.89	97.05
11+	LA	43.08	97.93	20.81	0.56	48.28	97.46
	SM	32.31	97.79	14.63	0.67	39.62	96.99
	Ub	27.69	98.14	14.86	0.72	40.00	96.80
12+	LA	42.86	98.22	24.03	0.56	48.00	97.81
	SM	58.93	93.55	9.14	0.37	25.98	98.34
	Ub	58.93	93.61	9.23	0.37	26.19	98.34
15+	LA	51.61	96.63	15.29	0.47	39.51	97.91
	SM	82.26	85.74	5.77	0.04	19.77	99.12
	Ub	82.26	85.74	5.77	0.04	19.77	99.12
21+	LA	21.82	99.11	24.49	0.78	48.00	97.11
	SM	94.55	84.37	6.05	0.06	18.57	99.76
	Ub	94.55	84.37	6.05	0.06	18.57	99.76

Table 4. 9: Sensitivity (%), specificity (%), Likelihood ratios and predictive values (%) for The London Atlas (LA), Schour and Massler's (SM) and Ubelaker's (Ub) according to age groups missing from (SM) and (Ub).

Age group	Method	sensitivity	Specificity	Likelihood ratio positive	Likelihood ratio negative	Positive predictive value	Negative predictive value
13+	LA	48.39	97.87	22.66	0.51	49.18	97.79
14+	LA	44.07	97.32	16.44	0.55	40.00	97.72
16+	LA	53.85	97.52	21.67	0.45	49.29	97.92
17+	LA	28.07	97.74	12.39	0.71	32.65	97.20
18+	LA	35.71	97.05	12.11	0.63	31.75	97.52
19+	LA	39.66	97.32	14.80	0.59	37.09	97.59
20+	LA	19.64	98.97	19.09	0.80	42.31	96.98
22+	LA	20.41	98.43	12.99	0.79	30.30	97.37
23+	LA	72.41	96.23	19.20	0.25	27.27	99.44

4.1.3.4.1 Sensitivity and specificity for prenatal

The London Atlas:

Sensitivity is 20% with type II error of 80%, **Specificity** is 99.26% with type I error of 1.74%, **Likelihood ratio positive** is 11.49, **Likelihood ratio negative** is 0.81, **Positive predictive value** is 13.33% and **Negative predictive value** is 98.92%.

Schour and Massler:

Sensitivity is 10% with type II error of 90%, **Specificity** is 98.12% with type I error of 1.87%, **Likelihood ratio positive** is 5.35, **Likelihood ratio negative** is 0.92, **Positive predictive value** is 6.67% and **Negative predictive value** is 98.78%.

Ubelaker:

Sensitivity is 10% with type II error of 90%, **Specificity** is 98.12% with type I error of 1.87%, **Likelihood ratio positive** is 5.35, **Likelihood ratio negative** is 0.92, **Positive predictive value** is 6.67% and **Negative predictive value** is 98.78%.

These results show that The London Atlas provides a strong evidence to correctly estimate the age, almost twice as much as Schour and Massler's and Ubelaker's. The similarities between Schour and Massler's and Ubelaker's results are due to the fact that Ubelaker's diagrams are based on Schour and Massler's. All methods are better in identifying that an individual doesn't belong to this age group.

4.1.3.4.2 Sensitivity and specificity for birth

The London Atlas:

Sensitivity is 31.25% with type II error of 68.75%, **Specificity** is 98.93% with type I error of 1.06%, **Likelihood ratio positive** is 29.48, **Likelihood ratio negative** is 0.69, **Positive predictive value** is 23.8% and **Negative predictive value** is 99.26%.

Schour and Massler:

Sensitivity is 50% with type II error of 50%, **Specificity** is 98.59% with type I error of 1.41%, **Likelihood ratio positive** is 35.46, **Likelihood ratio negative** is 0.507, **Positive predictive value** is 27.58% and **Negative predictive value** is 99.46%.

Ubelaker:

Sensitivity is 56.25% with type II error of 43.65%, **Specificity** is 98.39% with type I error of 1.61%, **Likelihood ratio positive** is 38.82, **Likelihood ratio negative** is 0.44, **Positive predictive value** is 27.27% and **Negative predictive value** is 99.53%

These results show that Schour Massler's and Ubelaker's performed better than The London Atlas. These results, however, have to be dealt with care because of the small number tested in this age group.

4.1.3.4.3 Sensitivity and specificity for one week to less than one year

The London Atlas:

Sensitivity is 45.45% with type II error of 54.55%, **Specificity** is 98.90% with type I error of 1.10%, **Likelihood ratio positive** is 41.44, **Likelihood ratio negative** is 0.55, **Positive predictive value** is 60.97% and **Negative predictive value** is 97.96%.

Schour and Massler:

Sensitivity is 33.33% with type II error of 66.67%, **Specificity** is 99.05% with type I error of 0.95%, **Likelihood ratio positive** is 35.08, **Likelihood ratio negative** is 0.67, **Positive predictive value** is 39.13% and **Negative predictive value** is 98.39%.

Ubelaker:

Sensitivity is 33.33% with type II error of 66.67%, **Specificity** is 99.66% with type I error of 0.34%, **Likelihood ratio positive** is 98.02, **Likelihood ratio negative** is 0.67, **Positive predictive value** is 39.13% and **Negative predictive value** is 98.79%

These results show that The London Atlas provides strong evidence to correctly estimating the age than that of Schour and Massler's and Ubelaker's. The similarities between Schour and Massler's and Ubelaker's results are due to the fact that Ubelaker's diagrams are based on Schour and Massler's. All methods are better in identifying that an individual doesn't belong to this age group.

4.1.3.4.4 Sensitivity and specificity for age 10

The London Atlas:

Sensitivity is 56.25% with type II error of 43.75%, **Specificity** is 98.14% with type I error of 1.86%, **Likelihood ratio positive** is 30.21, **Likelihood ratio negative** is 0.43, **Positive predictive value** is 57.14% and **Negative predictive value** is 98.07%.

Schour and Massler:

Sensitivity is 34.38% with type II error of 65.62%, **Specificity** is 97.66% with type I error of 2.34%, **Likelihood ratio positive** is 14.66, **Likelihood ratio negative** is 0.65, **Positive predictive value** is 39.29% and **Negative predictive value** is 97.12%.

Ubelaker:

Sensitivity is 32.81% with type II error of 67.19%, **Specificity** is 97.72% with type I error of 2.28%, **Likelihood ratio positive** is 14.42, **Likelihood ratio negative** is 0.66, **Positive predictive value** is 38.89% and **Negative predictive value** is 97.05%.

These results show that The London Atlas provides a strong evidence to correctly estimate the age, almost twice as much as Schour and Massler's and Ubelaker's. The similarities between Schour and Massler's and Ubelaker's results are due to the fact that Ubelaker's diagrams are based on Schour and Massler's. All methods are better in identifying that an individual doesn't belong to this age group.

4.1.3.4.5 Sensitivity and specificity for age 12

The London Atlas:

Sensitivity is 42.86% with type II error of 57.14%, **Specificity** is 98.22% with type I error of 1.78%, **Likelihood ratio positive** is 24.03, **Likelihood ratio negative** is 0.56, **Positive predictive value** is 48.00% and **Negative predictive value** is 97.81%.

Schour and Massler:

Sensitivity is 58.93% with type II error of 41.07%, **Specificity** is 93.55% with type I error of 6.45%, **Likelihood ratio positive** is 9.14, **Likelihood ratio negative** is 0.37, **Positive predictive value** is 25.98% and **Negative predictive value** is 98.34%.

Ubelaker:

Sensitivity is 58.93% with type II error of 41.07%, **Specificity** is 93.61% with type I error of 6.39%, **Likelihood ratio positive** is 9.23, **Likelihood ratio negative** is 0.37, **Positive predictive value** is 26.19% and **Negative predictive value** is 98.34%.

These results show that The London Atlas provides a strong evidence to correctly estimate the age, over twice that of Schour and Massler's and Ubelaker's. The similarities between Schour and Massler's and Ubelaker's results are due to the fact that Ubelaker's diagrams are based on Schour and Massler's. All methods are better in identifying that an individual doesn't belong to this age group.

4.1.3.4.6 Sensitivity and specificity for age 15

The London Atlas:

Sensitivity is 51.61% with type II error of 48.39%, **Specificity** is 96.63% with type I error of 3.37%, **Likelihood ratio positive** is 15.29, **Likelihood ratio negative** is 0.47, **Positive predictive value** is 39.51% and **Negative predictive value** is 97.91%.

Schour and Massler:

Sensitivity is 82.26% with type II error of 17.74%, **Specificity** is 85.74% with type I error of 14.26%, **Likelihood ratio positive** is 5.77, **Likelihood ratio negative** is 0.04, **Positive predictive value** is 19.77% and **Negative predictive value** is 99.12%.

Ubelaker:

Sensitivity is 82.26% with type II error of 17.74%, **Specificity** is 85.74% with type I error of 14.26%, **Likelihood ratio positive** is 5.77, **Likelihood ratio negative** is 0.04, **Positive predictive value** is 19.77% and **Negative predictive value** is 99.12%.

These results show that The London Atlas provides a strong evidence to correctly estimate the age, almost three times that of Schour and Massler's and Ubelaker's. The similarities between Schour and Massler's and Ubelaker's results are due to the fact that Ubelaker's diagrams are based on Schour and Massler's. All methods are better in identifying that an individual doesn't belong to this age group.

4.1.3.4.7 Sensitivity and specificity for age 16

The London Atlas:

Sensitivity is 53.85% with type II error of 46.15%, **Specificity** is 97.52% with type I error of 2.48%, **Likelihood ratio positive** is 21.67, **Likelihood ratio negative** is 0.45, **Positive predictive value** is 49.29% and **Negative predictive value** is 97.92%.

These results show that The London Atlas provides a strong evidence to correctly estimate the age and good in identifying that an individual doesn't belong to this age group. Schour and Massler's and Ubelaker's results cannot be analysed because this age group is missing from them.

4.1.3.4.8 Sensitivity and specificity for age 17

The London Atlas:

Sensitivity is 28.07% with type II error of 71.93%, **Specificity** is 97.74% with type I error of 2.26%, **Likelihood ratio positive** is 12.39, **Likelihood ratio negative** is 0.71, **Positive predictive value** is 32.65% and **Negative predictive value** is 97.20%.

These results show that The London Atlas provides a strong evidence to correctly estimate the age and good in identifying that an individual doesn't belong to this age group. Schour and Massler's and Ubelaker's results cannot be analysed because this age group is missing from them.

4.1.3.4.9 Sensitivity and specificity for age 18

The London Atlas:

Sensitivity is 35.71% with type II error of 71.93%, **Specificity** is 97.05% with type I error of 2.26%, **Likelihood ratio positive** is 12.11, **Likelihood ratio negative** is 0.63, **Positive predictive value** is 31.75% and **Negative predictive value** is 97.52%.

These results show that The London Atlas provides a strong evidence to correctly estimate the age and good in identifying that an individual doesn't belong to this age group. Schour and Massler's and Ubelaker's results cannot be analysed because this age group is missing from them.

4.1.3.4.10 Sensitivity and specificity for age 21

The London Atlas:

Sensitivity is 21.82% with type II error of 78.18%, **Specificity** is 99.11% with type I error of 0.89%, **Likelihood ratio positive** is 24.49, **Likelihood ratio negative** is 0.78, **Positive predictive value** is 48.00% and **Negative predictive value** is 97.11%.

Schour and Massler:

Sensitivity is 94.55% with type II error of 5.45%, **Specificity** is 84.37% with type I error of 15.63%, **Likelihood ratio positive** is 6.05, **Likelihood ratio negative** is 0.06, **Positive predictive value** is 18.57% and **Negative predictive value** is 99.76%.

Ubelaker:

Sensitivity is 94.55% with type II error of 5.45%, **Specificity** is 84.37% with type I error of 15.63%, **Likelihood ratio positive** is 6.05, **Likelihood ratio negative** is 0.06, **Positive predictive value** is 18.57% and **Negative predictive value** is 99.76%.

These results show that The London Atlas provides a strong evidence to correctly estimate the age, almost three times that of Schour and Massler's and Ubelaker's. The similarities between Schour and Massler's and Ubelaker's results are due to the fact that Ubelaker's diagrams are based on Schour and Massler's. All methods are better in identifying that an individual doesn't belong to this age group.

4.2 Survey questionnaire:

4.2.1 Participants:

The survey was conducted on 3rd year dental students (N: 90, 45 males and 45 females) (Figure 4.20). Table 4.10 shows the characteristics of participants and their past experience in age estimation, 67.8% of them had never done age estimation and only 7.8% have less than a year of experience using tooth eruption. Previous experience in age estimation methods was mainly using tooth eruption. Only two participants out of 90 used Schour and Massler's method (Table 4.11).

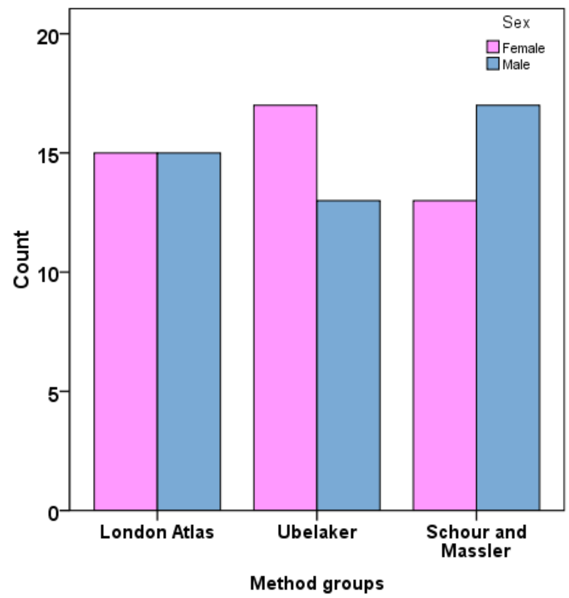

Figure 4. 20: Number and sex of participants in the survey in each group.

Table 4. 10: Distribution of age and past experience across participants based on gender.

	Age					**Past experience**			
	18-24	25-34	35-44	Prefer not to say	**Total**	Never	Less than 6 months	Less than a year	**Total**
Males	37	7	1	0	45	30	13	2	45
Females	37	7	0	1	45	31	9	5	45
Total	74	14	1	1	90	61	22	7	90

Table 4. 11: Participants' past experience in dental age estimation, their satisfaction with that method and their attitude towards searching for new methods of dental age estimation.

Number of participants **Total N: 90**	**Age estimation method**	**Reason for choosing the method**	**Previous training**	**Satisfaction**					**Search for new methods**		
				Very satisfied	Somewhat satisfied	Neutral	Somewhat dissatisfied	Very dissatisfied	Sometimes	Rarely	Never
52	None	Never done it before	No	-	-	100 %	-	-	-	-	100 %
2	Schour and Massler's	Easy to use	No	-	-	100 %	-	-	-	-	100 %
36	Tooth emergence	Only known method	64 %	5.5 %	25 %	64 %	5.5 %	-	8 %	20 %	72 %

4.2.2 Past experience

There were 64% of the participants who said they had some kind of training in using tooth emergence as an age estimation method, 30.5% of those are satisfied with this method whereas 64% were neutral and 5.5% were dissatisfied with tooth eruption method. Only 8% search for new methods for age estimation, whereas 72% never searched.

Table 4. 12: Participants' preference in general when choosing a dental age estimation method.

		Rank
Preference when choosing a dental age estimation method	Accuracy	**1**
	Reproducibility	**2**
	Availability	**3**
	Time consumption	**4**
	Need for training	**5**
	Convenience	**6**

When participants were asked to rank their preference when choosing a dental age estimation method from one to six in regard to accuracy, reproducibility, availability, time consumption, need for training and convenience, accuracy came on top of the list and convenience at the bottom (Table 4.12).

Table 4. 13: Participants' satisfaction of The London Atlas' (LA), Schour and Massler's (SM) and Ubelaker's (Ub) design, clarity, simplicity and being self explanatory (N: 30 in each group).

Quality measure	**Age estimation method**	**Satisfaction**				
		Very satisfied	Somewhat satisfied	Neutral	Somewhat dissatisfied	Very dissatisfied
Design	LA	13	15	1	1	0
	SM	9	15	1	4	1
	Ub	5	16	4	2	3
Clarity	LA	12	15	1	2	0
	SM	5	9	4	9	3
	Ub	2	9	4	12	3
Simplicity	LA	13	13	3	1	0
	SM	9	11	3	3	3
	Ub	9	11	4	5	1
Self explanation	LA	19	8	2	1	0
	SM	16	8	2	3	1
	Ub	14	8	1	7	0

4.2.3 Quality assessment:

Evaluating the quality of the three methods in regard to: design, clarity, simplicity and self explanation, revealed that The London Atlas came on top in all measure, with numbers of satisfied individual almost the double compared to Schour and Massler's Atlas or Ubelaker's Chart. (Table 4.13)(Figures 4.21 to 4.25)

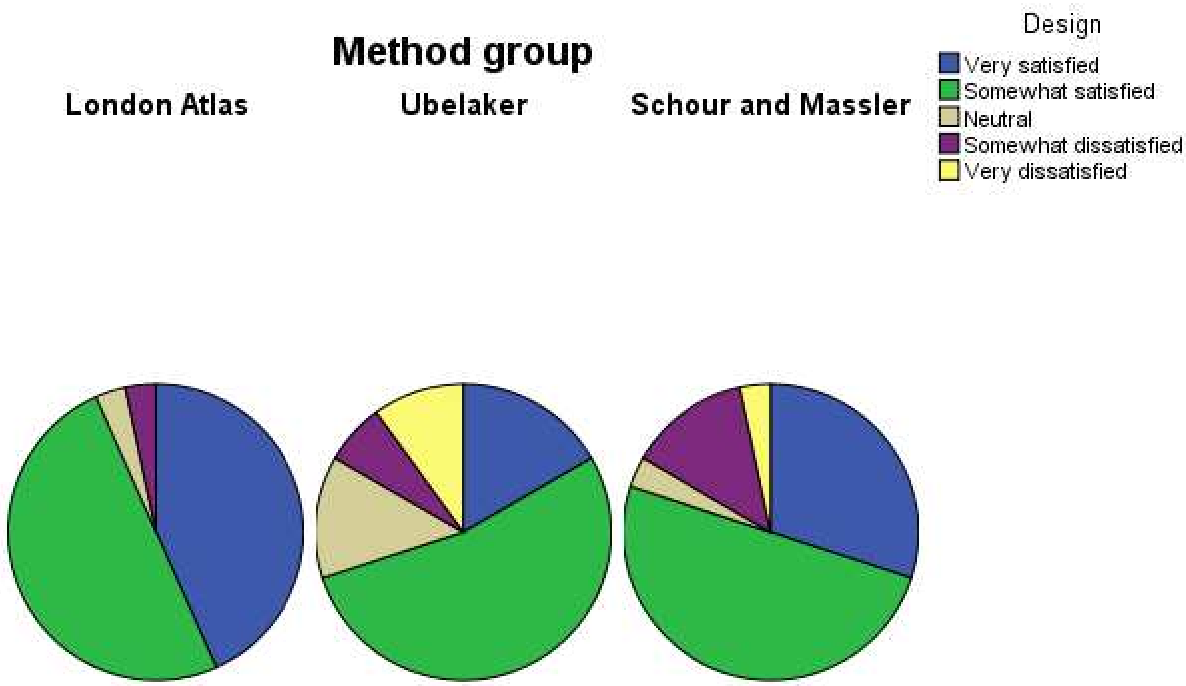

Figure 4. 21: Participants response regarding their satisfaction in relation to the schema's design.

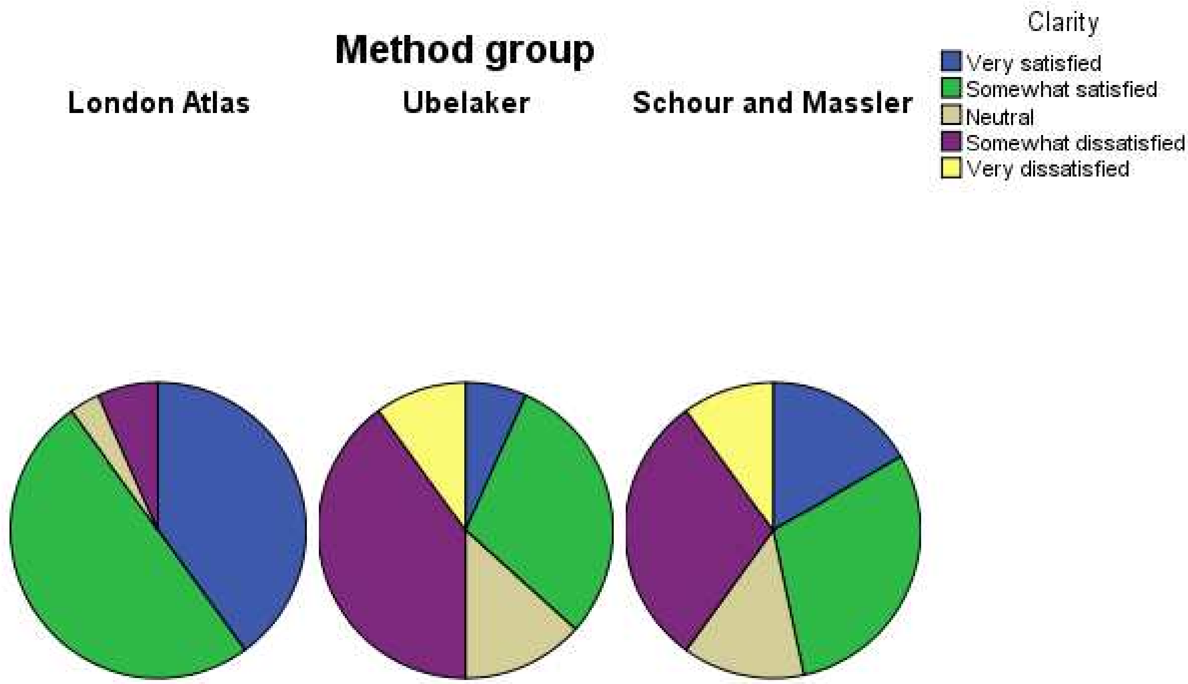

Figure 4. 22: Participants response regarding their satisfaction in relation to the schema's clarity.

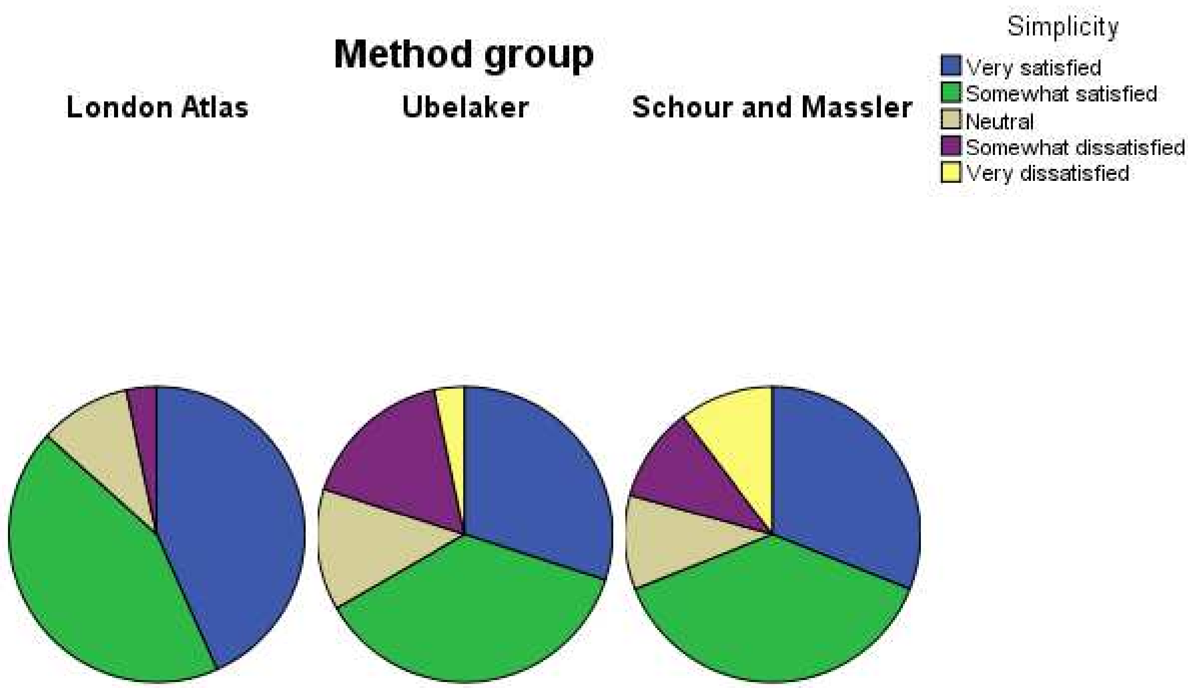

Figure 4. 23: Participants response regarding their satisfaction in relation to the schema's simplicity.

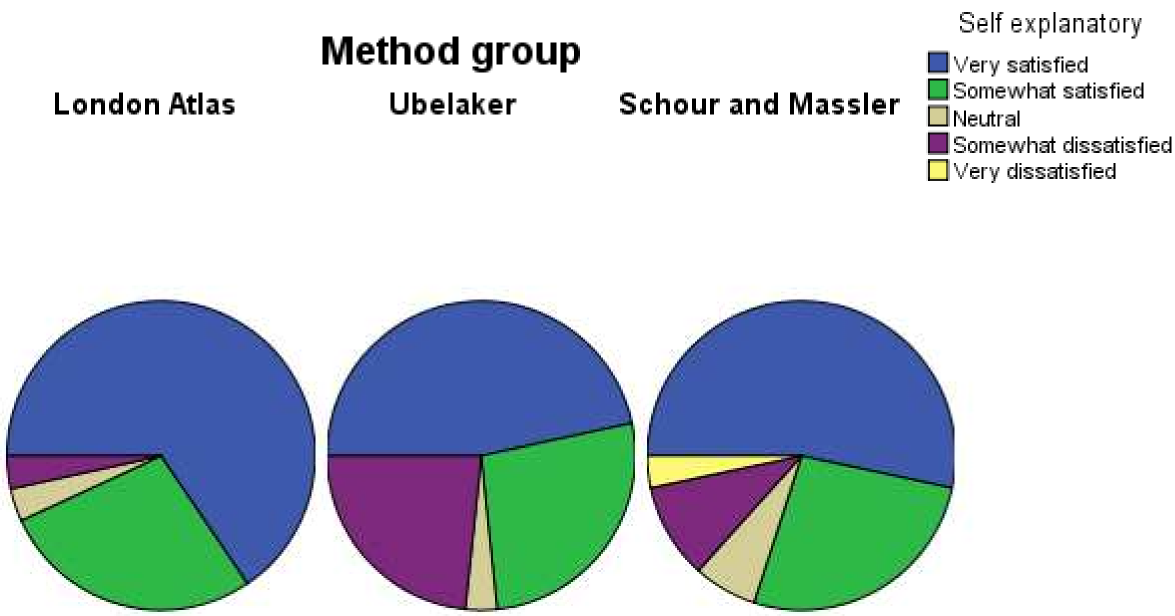

Figure 4. 24: Participants response regarding their satisfaction in relation to the schema's self explanation.

Chapter Five: The London Atlas computer software

To take the London Atlas a step further, a decision to develop an interactive software computer program was taken using the data sheets of median stages of tooth development and all hand illustrations of tooth formation. The software program was designed by the examiner (SA) to have three sections (Appendices 15):

5.1 Playback mode

This section is to feature dental development for males, females and mixed sex covering all age ranges present in The London Atlas (31 age categories). In this section the user can follow the development of all teeth along the time line or select specific tooth/teeth or dentition and follow their development through time. Moreover, this mode will present dental developmental stages with written description for reference purposes. The idea of this mode is to make it an excellent teaching aid as well as an excellent research tool, especially for those who have little or no background in dental development and anatomy.

5.2 Data entry mode

This section will feature a dental age calculator that enables the user to enter data for tooth formation and eruption according to Moorrees *et al.* (1963a; b) and modified Bungsten's stages (Bengston, 1935; Liversidge *et al.*, 2004). The dental age calculator will demonstrate half the jaw of the upper and lower permanent and deciduous dentitions. There will be two sections in the table, one for tooth formation and the other is for alveolar eruption. This calculator will be in the form of a table with each cell linked to a certain tooth. By clicking on any cell in the table, all illustrations of dental developmental stage with written description would appear allowing the user to select the right stage, therefore minimising guess work and enhancing performance measures. After the user enters as much data as possible, the software would present an age estimate accordingly. If sex was not selected, the software would give a sex approximation depending on the data entered. The age estimation result is to be linked to dental development diagrams from the Atlas enabling the user to assess it further and compare the diagrams with the case in question. This section is to be equipped with all three dental notation systems: Palmer, FDI, and Universal, permitting a choice to what the user is most familiar with.

5.3 Comparison mode

This section is to allow the user to compare tooth/teeth development between two different ages from the same sex or between different sexes at the same age. The user will have the liberty to dim down the unwanted tooth/teeth and highlight the tooth/teeth of interest. The interface is to show two diagrams where the user can control individually and independently by changing the age or sex, moreover, the user will be able to link these two diagrams together and compare dental development through time.

5.4 Program development:

After the design was made, it was decided to outsource the development process to a software developing company, 3wise-solutions, Surrey, United Kingdom. Meetings with the developers underwent with the researcher (SA) to discuss the design, features and the interface. It was agreed to write the program in Adobe® Flash® using Actionscript 2.0 and an application called mProjector® which extends the functionality available in Flash for maximum visual impact and ease of use.

5.5 Piloting The London Atlas software program

An online questionnaire was designed (appendix 16) to assemble information from specialists who practice age estimation as part of their job in different disciplines. They were given access to password protected software program through Queen Mary University of London's website and asked to use it for age estimation or teaching purposes. The questionnaire was designed to assess their experience and feedback regarding all features.

Targeted experts for this survey were professionals who use age estimation in their field including Forensic Personnel, Dentists, Archaeologists and Anthropologists:

1. Professor Jenz Andreasen, Specialist Consultant in Dental Trauma, University Hospital (Rigshospitalet), Copenhagen, Denmark.
2. Dr. Zaf Khouri, Dental Surgeon & Consultant Forensic Odontologist, President, NZ Society of Forensic Dentistry.
3. Stephen P. Nawrocki, Distinguished Professor of Forensic Studies, Professor of Biology & Anthropology, Co-Director, University of Indianapolis Archeology & Forensics Laboratory.
4. Dr. Phil Marsden. President elect of the British Association for Forensic Odontology.
5. Julia Beaumont, British Association for Forensic Odontology.
6. Dr. Eric Dykes, Forensic Consultant, President, Institute of Emergency Management, U.K. Honorary Senior Lecturer, Cameron Forensic Medical Sciences, QMUL.
7. Dr. B. Holly Smith, Associate Research Scientist, University of Michigan Museum of Anthropology.
8. Professor Tony Smith, editor in chief of the Journal of Dental Research.
9. Professor Richard Welbury, Professor of Paediatric Dentistry at the University of Glasgow Dental School, UK.
10. Professor Nigel King, Paediatric Dentistry University of Hong Kong.

All candidates were contacted by emails. The researcher (SA) sent a link to a password protected website that has the software program of The London Atlas and an electronic survey to be completed. The candidates were asked to access the software program, use and get familiar with it before answering the questionnaire. The answers were automatically sent to the researcher (SA) using Monkey Survey website (Finley, 2009). There were also two one-to-one meetings with Dr. Phil Marsden, President elect of the British Association for Forensic Odontology (2010 – 2012), and Dr. Anu Anttila, Forensic Odontologist, Helsinki, Finland. The meetings took place in the researcher's office (SA) at the Institute of Dentistry, Queen Mary University of London, where the candidates sat with the researcher (SA) and used the software program and gave their feedback directly on each section, raised various questions from the user's point of view and suggested more features to be added to make the experience better, easier and more informative.

5.6 Pilot results:

The feedback from eight out of the 12 candidates requested to participate were similar. The issues they raised were almost the same and their questions were pointing at the same thing. After reviewing all the responses, the software program was redesigned to have the following features:

5.6.1 Changes to be made in all modes:

- Add mouse-over information that displays information on what a certain button does or where it leads (same information as in the "?" pages). And when the mouse is over the guide buttons, a minimized guide should appear without pressing the button, so that if the user wants the full guide then he can press the button. The same goes for the help button.

- Change “?” button to the word “HELP”.
- Add a section in the menu called: frequently asked questions.
- Change the home button from a house icon to the word: “HOME” or “MAIN MENU”.
- Change the “X” button in the guide pages to say the word “BACK”.
- Open the guide pages in a separate window that can be moved to the side while working on the mode interface. Same goes for the help figure.
- When pressing the “X” button that closes the program, add a warning box that the user has to agree to close the program.

5.6.2 Changes to be made in playback mode:

- Selected sex should be clearly labelled on the interface, next to the guide menu, with an option to change the sex without going back to the main menu.
- In the lower menu, change the word “Ages” to “VIEW AGES”.
- The slider on the bottom should change to resemble the slider in the comparison mode where the age is written directly over the slider.

5.6.3 Changes to be made in data entry mode:

- The button “clear tooth” should be changed to a menu that has:
    - Clear selected cell
    - Clear all developmental stages
    - Clear all eruption stages
    - Clear all upper
    - Clear all lower

- The “options” button should be changed into “notation systems” having only these:
    - Palmer
    - Universal
    - FDI
- In the FDI notation system, add a period (.) Between the numbers, to be: 1.1, 1.2, 1.3, etc.
- Add anthropology notation system. (Appendices 28-35)
- Add an “Undo” button.
- Add a “save case” button in the menu.
- Add a “new case” button in the menu.
- On the interface, change “data entry” into “sex”.
- Add option to change sex without going back to the main menu.
- If the user pressed the main menu button, an option to save data should be given.
- Remove the word “median” from the table.
- The data entry table should be constructed following three steps selected by the user:
    - The first step is selecting “dentition”:
        - Deciduous
        - Permanent

  Both can be selected together, the minimum is one and the maximum is two.

    - The next step is selecting “quadrant”:
        - Upper right
        - Upper left
        - Lower right
        - Lower left

Only one upper and one lower can be selected, doesn't matter which ones, the minimum number of quadrant selected is one and the maximum is two. Then construct the table accordingly, labelling the quadrants on the table.

    - The last step is selecting the notation system

- Then a table would be constructed depending on the options selected.
- When entering the data into the table:
    - The tooth number of the selected cell should be labelled on the chart given to select the stage depending on the notation system selected, such as: permanent upper right 5 (if the Palmer notation system was selected).
    - Change the "X" button to "back".
    - When selecting the stages, the mouse icon should change from a hand to an arrow between stages to avoid entering the wrong stage and to make it easier for the user.
    - When entering stages for the upper teeth only, the images of the dental stages should be upside down.
    - The selected cell should be framed or highlighted more so that it makes it easier for the user.
- If the sex selected was unknown, the answer in the evaluation should be from the combined sex diagrams "the green teeth", the sex should be optional on the side as some researchers said if they didn't know the sex and the program gave the answer with the sex directly then they can become bias, so having the sex in the answer should be optional, but the default answer for the unknown sex should be from the "green teeth" or combined sex diagrams.

- The “evaluate these teeth” button, when pressed to get the results, should change to (x close matches found) where x is the number of the matches found.
- The menu for the answers was advised by many to be on the right rather than the bottom as on some smaller screen formats it can be missed; also the answers should all be visible or if there were too many, the drag down button should be highlighted more.
- The result diagrams should be presented on a pop-up screen, each result on a separate screen.
- Add an option in the result diagrams to view two selected diagrams side by side for comparison.
- Add a “print report” option, the format of the single page report is based on Lalwani *et al.* (2004).

5.6.4 Changes to be made in comparison mode:

- The buttons that show the sex should be coloured in blue, pink or green according to the teeth of the selected sex.
- The “link” button should change colour if selected or become highlighted more.

5.6.5 The new London Atlas software program:

The new software program of The London Atlas was an improvement from the primary version. It was developed by a new company: NXT Digital Solutions, Surrey, UK. The interface has changed completely taking into account all the comments and ideas that came after piloting the primary version (Appendix 17). It is available to access for free through Queen Mary, University of London, Institute of Dentistry’s website: www.atlas.dentistry.qmul.ac.uk

The London Atlas software program allows the user to create an account enabling features like saving a case and creating a dental age estimation report. It has been well received from dentists and forensic odontologists around the world from the feedback that keeps coming on a daily basis. Moreover, it is the most visited page on the site, with more than 40 visits a day. (Appendices 18)

Application for smart phones (Apple and Android only) were designed based on the online software program and they are linked to the web based program. The user can create cases, save them or access saved cases and email reports through their handheld devices.

Chapter Six: Discussion

Knowing the age is a basic human right and having it documented is what gives identity to the individual. In the society we live in, date of birth is the epitome of one's entity. It is required to enter school, work, getting married and getting the pension. It also plays a role in unfortunate events in pertaining justice and incriminating offenders rightfully according to their age and protect them and the people around them by knowing their appropriate age group. In other words it drives the journey of life from birth to death.

With the importance of knowing the age highlighted in every aspect of any society, it is shocking to know that 30 to 50% of births are still unrecorded (UNICEF, 2012), violating those babies' human rights and setting up a dark rocky road for their future life. Moreover, with the increase in armed conflicts around the world, especially in the last two decades up to the recent Arab spring, more and more people flee their homeland without their documents because they left unexpectedly fearing for their lives, their documents got lost or stolen after their homes got attacked, or simply to avoid being identified by their oppressive regimes. This problem became clear to the safe developed countries that faced a surge of asylum seekers with no documents during the war in Bosnia in the early 1990. This movement of immigrants seeking shelter in developed countries is on the increase by people fleeing famine in east Africa, ethnic cleansing in middle and west Africa, genocides in the middle east and oppressive regimes in the near and far east.

The need to accurately age unidentified asylum seekers to make sure that they are who they claim to be is not only for the benefit of the hosting country, but also to protect those seekers from sexual abuse, getting taken advantage of and to get the support they need. Moreover, developed countries sometimes need to age their own citizens who were not recorded at birth, got their documents stolen or those who have been kidnapped at some point. Because of the overwhelming numbers of all these cases, an easy to apply method for age estimation is vital to minimize the time needed for processing those cases and the time needed to train personnel.

Social services that deal with asylum seekers favour the use of social parameters along with physical development charts. The problem when using those, however, is that social parameters haven't been evaluated and the physical development is highly affected by the environment.

Dental development is extensively researched and evaluated, but to be able to use the dentition in the living, a radiograph is investable and many social workers are lobbying against taking radiographs because of the risks associated with x-ray exposure, not knowing that if asylum seekers from poor countries apply for a legitimate visa to enter Australia, Canada, United Kingdom, United States of America and New Zealand, they would be asked to present a chest radiograph as part of their visa application for individuals older than 11 years (IOM, 2012).

Knowing the correct age goes beyond the living to the dead. In the past 100 years, the world has experienced an increase in mass disasters both natural and manmade. Mass graves from the late 20th century are still being discovered in Bosnia and Africa; new mass graves are being created in the Middle East to oppress the Arab spring movement for freedom. Identifying victims of mass murders not only brings closure to relatives but also help incriminates people responsible for those atrocities. With the huge numbers in victims of mass murders, which could be thousands in one grave, the need for a simple to use method of age estimation is crucial because of the limited resources and the use of volunteers.

The rise in the number of tsunamis is evident and accelerated in a worrying level. In the 19th century there were eight recorded tsunamis compared to 20 in the 20th century and since the beginning of this millennium there were nine devastating tsunamis in only 12 years. Because of the nature of this natural disaster: salty water, heat and massive force, dentition plays an invaluable role in victim identification because the DNA gets damaged and physical features distorted. Again, the need for a reliable easy to use method of age estimation is much needed and was exactly the motive for this project after the 2004 tsunami that revealed to the forensic teams the difficulty in using existing methods at the time that were either inaccurate or difficult to use.

The aim of this thesis was to develop a comprehensive, validated, evidence based, practical, user-friendly atlas of dental age estimation that avoids all the previous limitations and compare its performance with two widely used atlases. One of the aims was to cover all ages of dental development with uniform age distribution and be based on a large and well documented sample size to be representative. It should show the developing tooth internal structures and be self explanatory. It should be easily used with reproducible results.

When this project started, the decision to make the age groups uniform in numbers and sex distribution was taken to avoid the limitations of previous methods: relying on previous studies for data, small sample size, narrow age range and not having a normal age distribution. When The London Atlas was being developed, the median for tooth developmental stages was used to give a representative picture of the development in each age group, which in effect makes The London Atlas **evidence based**.

Although the development of The London Atlas has been based on similar numbers of white and Bangladeshi origin individuals living in London, UK, its applicability to other ethnic groups is still to be explored. Several studies have tested dental age estimation methods that were based on Caucasian standards on other populations including South African (Chertkow and Fatti, 1979; Phillips and van Wyk Kotze, 2009), Venezuelan (Cruz-Landeira, Linares-Argote *et al.*),Chinese (Davis *et al.*, 1994), South Indian (Koshy and Tandon, 1998), Somali (Davidson and Rodd, 2001), Thai (Raungpaka, 1988; Krailassiri *et al.*, 2002), Turkish (Celikoglu, Cantekin *et al.*; Nur, Kusgoz *et al.*; Uysal, Sari *et al.*, 2004; Tunc *et al.*, 2008), Brazilian (Maia, Martins *et al.*; Eid, Simi *et al.*, 2002; Kurita, Menezes *et al.*, 2007), Korean (Teivens and Mörnstad, 2001; 2001), Malay (Nik-Hussein, Kee *et al.*; Mani *et al.*, 2008), Southeast Asian (Halcrow *et al.*, 2007), Chilean (Flores, Sanhueza *et al.*), Ivory Coast and Iran (Braga *et al.*, 2005), Iran (Bagherian and Sadeghi; Bagherpour, Imanimoghaddam *et al.*),New Zealand (TeMoananui, Kieser *et al.*, 2008) and Saudi (Baghdadi and Pani; Al-Emran, 2008), but with varying results.

Highly significant differences (P<0.01) between estimated and chronological age have been interpreted as population differences, but many factors influence any study of accuracy and precision of age estimation (see (Liversidge *et al.*, 2010)) including poor sampling at younger ages that increases error of estimates for all studies, regardless of method of computation (Smith, 1991).

This controversy in finding intra- and inter-population differences in dental age estimation could be attributed to several methodological issues including sample size, weighted values and the fact that many of these studies assessed developmental stage of attainment of selected teeth or dental maturity rather than an overall dental age estimation. These sources of variation haven't been controlled for between studies, therefore discrepancies between studies cannot be attributed to population differences (Smith, 1991; Braga *et al.*, 2005; Liversidge, 2012).

Highly significant differences (P<0.01) between estimated and chronological age when applying Caucasian based methods on non Caucasians, however, are similar to differences reported when the same methods were tested on Caucasian populations (Burt, Sauer *et al.*; Cruz-Landeira *et al.*; Mörnstad, Reventlid *et al.*, 1995; Nykanen, Espeland *et al.*, 1998; Liversidge, Speechly *et al.*, 1999c; Hegde and Sood, 2002; Chaillet *et al.*, 2004a; Chaillet *et al.*, 2004c; Nyarady, Mornstad *et al.*, 2005; Prieto *et al.*, 2005; Liversidge *et al.*, 2006; Maber, Liversidge *et al.*, 2006a; Cameriere, Ferrante *et al.*, 2008b; Thevissen *et al.*, 2009). This suggests that population specific methods do not improve accuracy and precision.

Most reported population differences in dental formation for most tooth types are small with the exception of the most variable tooth, the third molar (Liversidge 2008). This means that if The London Atlas is used to estimate age in different populations, the median tooth stage for each tooth type is unlikely to differ considerably and justifies the selection of one year age cohort in The London Atlas.

The diagrams presented in The London Atlas show the right side of the upper and lower jaws, going in accordance with all previously published schemas of tooth development. The difference was in the layout of the diagrams where it is a spiral in the London Atlas compared to columns in the previous ones. The reason for that was to give the sense of time and by that reminding the user of the continuous nature of the process of development. Presenting the third molar development in a column on the side of The London Atlas, however, is to accentuate the sensitivity associated with dealing with that tooth alone.

One of the challenges in testing The London Atlas was to find as many materials as possible from individuals under the age of two. An extensive research was done to identify collection of known age-at-death skeletal remains that have that age group. the researcher (SA) had to travel around the world to assess these collections and by doing so gaining knowledge by working with people from different backgrounds and working in different environments, which taught the researcher (SA) to think outside the box and be adaptable and resourceful.

Evaluating performance measures of The London Atlas was done in alignment with published literature. Studies testing methods of dental age estimation used numerous different measures, which made comparing the results between different studies difficult. Some studies looked at bias and standard deviation, other studies looked at the absolute mean difference and error means or proportion of cases correctly estimated, sensitivity and specificity or likelihood ratios. A decision to include all performance measure was made so that the results can be comparable with the existing body of evidence.

The results then were compared to the two schemas that cover the widest range of ages, Schour and Massler's Atlas (1941) and Ubelaker's chart (1987). Both schemas are widely used and printed in most text books of dental development.

Schour and Massler's atlas and Ubelaker's chart performed similarly across the ages; this could be explained by the fact that Ubelaker's diagrams were loosely based on Schour and Massler's.

In regard to bias, The London Atlas performed better than Schour and Massler's Atlas and Ubelaker's, across all ages except for foetal to younger than one, where they all performed similarly. This could be attributed to their good sample size for this age group.

When bias was calculated for males and females separately for individuals older than one, however, there was a different picture all together. All three methods had no significant bias for males, but Schour and Massler's Atlas and Ubelaker's chart both significantly underestimated the age of females, similar to findings by Smith (2005) and Blenkin and Taylor (2012) who both suggested having a modified method for females. This emphasises the importance of The London atlas that had no significant bias for both males and females, attributed to the large sample size and equal number of males and females.

The London Atlas being applicable for both sexes with good measures of performance makes it one of the best Atlas method available to this date with results even comparable to techniques that give point age estimates based on stages of tooth development (Gleiser *et al.*, 1955; Nolla, 1960; Moorrees *et al.*, 1963b; Demirjian *et al.*, 1973; Demirjian *et al.*, 1976), which makes it a **practical** method.

The London Atlas covers all ages from 30 weeks in utero to 23 years, which covers all the ages of dental development based on a uniform age and sex distribution. Moreover, The London Atlas provides not only the median tooth development stage for all teeth in both dentitions, it also gives the range of dental development for all teeth in the published paper (AlQahtani *et al.*, 2010). This feature is unique to The London Atlas amongst all the other dental age methods available, both diagram and measurements based methods, which makes The London Atlas a **comprehensive** method.

Clarity, ease of use and satisfaction are a major improvement from all the past available methods of dental age estimation. Many methods have been criticised because of their complexity or poor reproducibility (Demirjian and Levesque, 1980; Nyström, Ranta *et al.*, 1988; Staaf *et al.*, 1991; Liversidge *et al.*, 1999c; Dhanjal *et al.*, 2006). By testing The London Atlas on Dental students, not only it **validates** it, but also revealed that it is **user-friendly**.

Designing a software program and smart phone apps based on the London Atlas revolutionise the Forensic Odontology and Anthropology fields. With the personnel of these disciplines always working on the scene, "an immediate access to information can be vital. The Tooth Atlas app will prove to be invaluable as a ready source of instant detail for the forensic odontologist, forensic anthropologist and forensic pathologist" as Professor of Anatomy and Forensic Anthropology at the University of Dundee, Prof. Sue Black, has said in a letter (Black, 2012).

Satisfaction with The London Atlas software was measured by the feedback from users around the world. Currently it is one of the most visited website on the Institute of Dentistry's website with about 40 visits a day. It is accessed from around the world as the website monitor reveals, and not only does it help the forensic odontologists and anthropologists, but also dentists who discuss their patients' oral health using the software program.

Areas for future research:

This project has set a new standard in dental age estimation from developing teeth with its two interfaces, the printed and the electronic. It opens up new areas of research such as:

- Validating The London Atlas by different researchers on the same population it was developed from and on different populations.
- Evaluating the electronic use and results of the electronic version of The London atlas.
- Testing The London Atlas on patients with syndromes that affect tooth development.
- Using the London Atlas to compare human dental development with extinct species of hominid.
- Develop a dental atlas based on both alveolar eruption and emergence.
- Develop a new method for dental age estimation after teeth have reached maturity.

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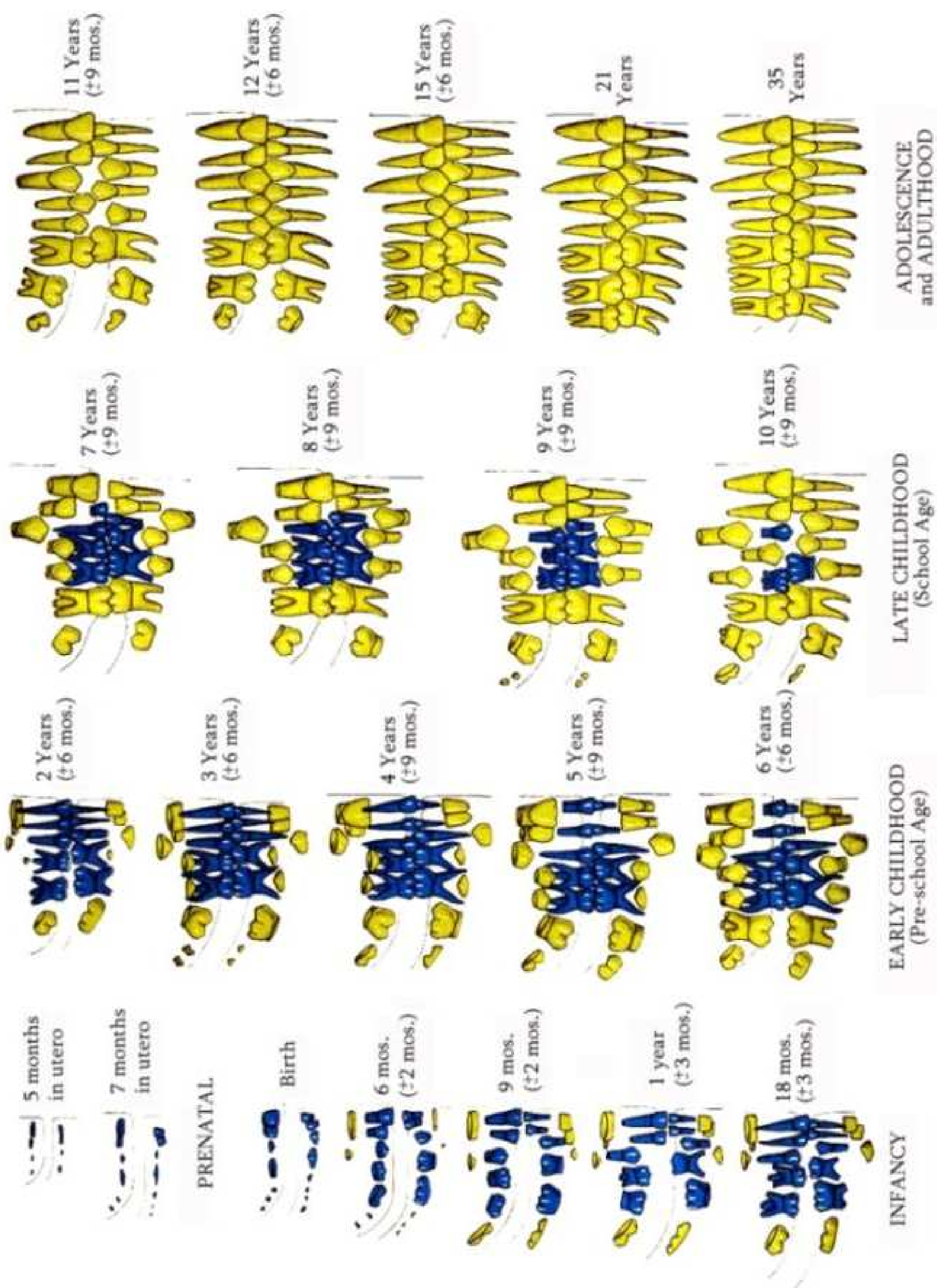
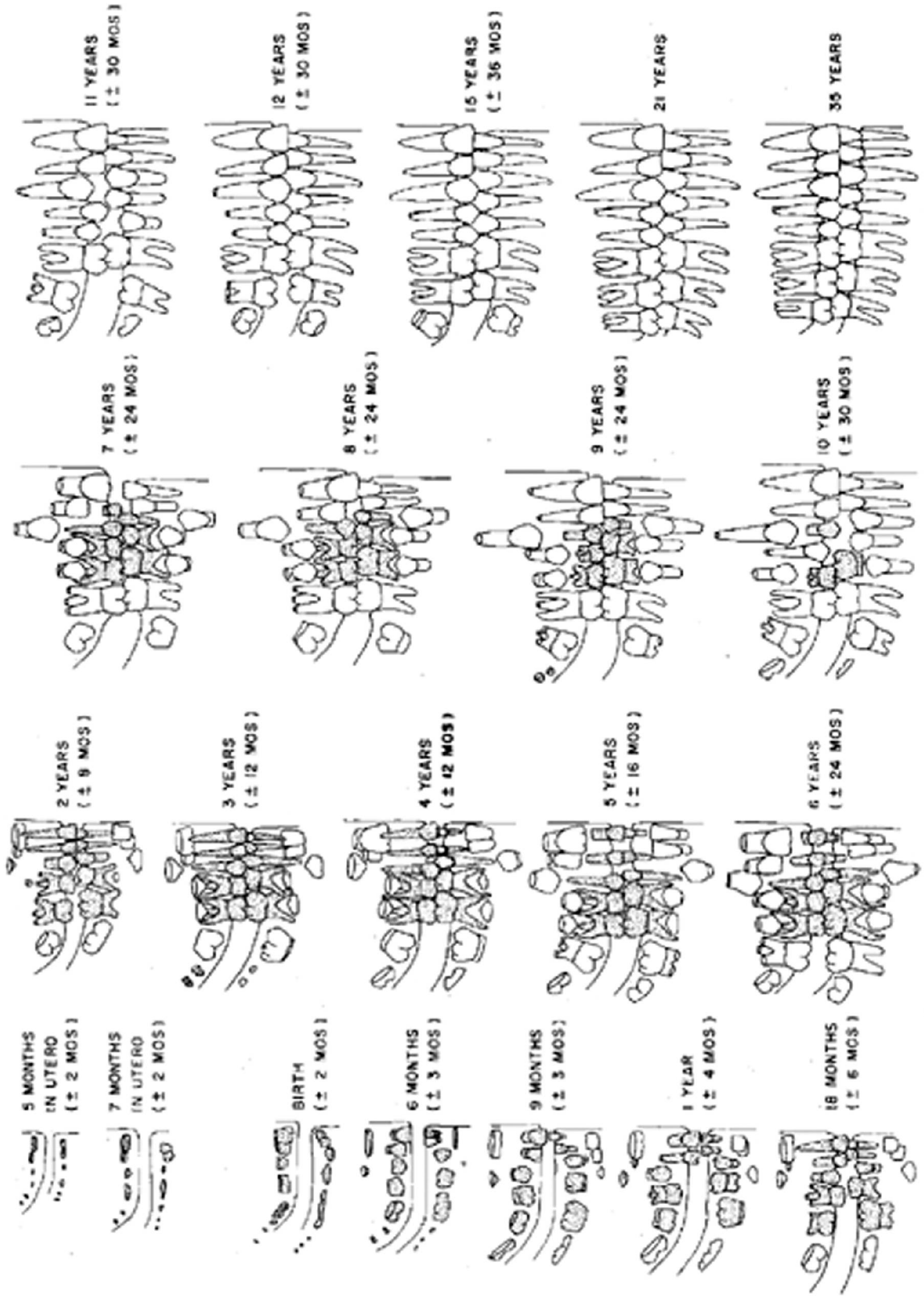
Appendices

Appendix 1: Schour and Massler's Atlas of tooth development



Appendix 2: Ubelaker's chart of dental development.



Appendix 3: Systematic search strategy.

Search step	Search terms	Number of articles
1	age OR grow* OR old OR chronological OR physiological	3736171
2	estimat* OR predict* OR determin*	3346819
3	teeth OR tooth OR dent* OR crown OR root	609895
4	Develop* OR matur* OR grow*	3870148
5	stage OR length OR width OR rate OR size OR weight	3458741
6	atlas* OR chart* OR method* OR schem* OR standard* OR table*	5761960
7	Test* OR assess* OR use*	3369269
8	Accura* OR reliab* OR applicab*	727508
9	Search 1 AND 2 AND 3 AND 4 AND 5 AND 6	2426
10	Search 9 AND 7	1978
11	Search 9 AND 8	404
12	Search 10 OR 11	2134

Appendix 4: An overview of new methods for dental age estimation.

Author	Year	Method	Title	Population	Study sample	Age	Weakness/strength
Aggrawal *et al.*	2008	Incremental cementum lines	Incremental lines in root cementum of human teeth: An approach to their role in age estimation using polarizing microscopy	Indian	Thirty no restorable teeth were extracted from 20 people	13-69 years	Weakness: - Small sample size - Invasive
Aggrawal *et al.*	2011	Tooth emergence	Chronological pattern of eruption of permanent teeth in the adolescent age group in Patiala district, Punjab	Indian	554 (305 males and 249 females)	10-19 years	Weakness: - Emergence is affected by external and internal variables - Not applicable on deciduous teeth
Aka *et al.*	2009	Metric tooth development	Age determination from central incisors of foetuses and infants	Turkish	76 maxillary and mandibular central incisors	16–108 weeks after conception	Weakness: - Applies to only central deciduous incisors - Invasive
Alkass *et al.*	2009	Biomarkers	Age estimation in forensic sciences: Application of combined aspartic acid racemization and radiocarbon analysis	Swedish	44 teeth from 41 individuals	13.4 – 70.6 years	Weakness: - Applies to permanent teeth - Small sample size - Invasive - Laborious - Expensive
Anderson *et al.*	1976	Dental development	Age of attainment of mineralization stages of the permanent teeth	Canadian	121 males and 111 females	3.5 – 18 years	Weakness: - Small sample size - Applies only to permanent teeth
Antoine *et al.*	2009	Prism cross-section	The developmental clock of dental enamel: a test for the periodicity of prism cross-striations in modern humans and an evaluation of the most likely sources of error in histological studies of this kind	Skeletal remains	5 children	between birth and 6 years	Weakness: - Small sample size - Invasive
Bang *et al.*	1970	apical translucency	Determination of age in humans from root dentin transparency	Norwegian	926 teeth comprising 978 roots including 450 extracted teeth from 201	20 – 80 years	Weakness: - Applies only on mature teeth - Invasive

					patients, 112 men and 89 women, in a mental institution and 476 teeth collected from 64 persons, 46 men and 18 women, at autopsy		
Bojarun *et al.*	2003	Microstructure of dental cementum lines	Dental cement microstructure and individual biological age setting (Lithuanian)	Lithuanian	178 individuals (227 teeth)	11-78 years	Weakness: - Applies only on mature teeth - Invasive
Cameriere *et al.*	2006	Formula	Age estimation in children by measurement of open apices in teeth	Italian	455 children	5-15 years	Weakness: - Limited age range
Carels *et al.*	1991	Dental development	Age reference charts of tooth length in Dutch children	Dutch	486 children	4-14 years	Weakness: - Limited age range
Carvalho *et al.*	1989	Tooth eruption	Dental plaque and caries on occlusal surfaces of first permanent molars in relation to stage of eruption	Danish	57 children	6 – 8 years	Weakness: - Limited age range - Applies on only permanent teeth - Based on eruption only
Chaillet *et al.*	2005	Tooth maturity scores	Comparison of dental maturity in children of different ethnic origins: international maturity curves for clinicians	8 countries	9577	2 and 25 years	Strength: - Large sample size - Sample from different countries
Constandse-Westermann *et al.*	1997	Attrition	Age estimation by dental attrition in an independently controlled early 19th century sample from Zwolle, The Netherlands	Netherlands	138 skeletal sample	Adults	Weakness: - Based on old collection of skeletal remains that may had different food habits affecting attrition - Small sample size
Czermak *et al.*	2006	Tooth cementum annulation	A new method for the automated age-at-death evaluation by tooth-cementum annulation (TCA)	Skeletal remains	26 individuals	11 – 70 years	Weakness: - Small sample size - Invasive
Demirjian *et al.*	1973	Dental development	A new system of dental age assessment	French Canadian	1446 boys and 1482 girls	2 – 20 years	Strength: - Large sample size Weakness: - Applicable to permanent teeth
Demirjian *et al.*	1976	Dental development	New systems for dental maturity based on seven and four	French Canadian	2407 boys and 2349 girls	2.5 – 17 years	Strength: - Large sample size

			teeth				Weakness: Applicable to certain teeth
Feraru *et al.*	2011	Tooth eruption	The Sequence and Chronology of the Eruption of permanent Canines and Premolars in a Group of Romanian Children in Bucharest	Romanian	2081	8 – 13 years	Strength: - Large sample size Weakness: - Limited age range - Applicable to selected permanent teeth - Based on eruption only
FitzGerald *et al.*	1998	Circaseptan interval	Do enamel microstructures have regular time dependency? Conclusions from the literature and a large-scale study	Native Americans (35), Medieval Britons (31), and contemporary South Africans (30)	158 anterior teeth from 96 individuals (M=62, F=32, US=2)	-	Weakness: - Applicable to anterior teeth - Small sample size - Invasive
Foti *et al.*	2003	Tooth eruption equation	New forensic approach to age determination in children based on tooth eruption	French	397 boys and 413 girls	6.10–21.08 years	Strength: - Large sample size Weakness: - Applicable to permanent teeth - Limited age range - Based on eruption only
Franchi *et al.*	2008	Tooth eruption	Phases of the dentition for the assessment of skeletal maturity: A diagnostic performance study	Italian	1000 subjects	250 (125 boys, 125 girls) in each of the 4 dentition phases	Strength: - Large sample size Weakness: - Based on eruption only
Garn *et al.*	1958	Dental development	Sex differences in tooth calcification	White Americans	255	children	Weakness: - Limited age range
Garn *et al.*	1958, 1959	Dental development	Variability of tooth formation	White Americans	255	children	Weakness: - Limited age range
Griffin *et al.*	2008	Aspartic Acid Racemization	Age Estimation of Archaeological Remains Using Amino Acid Racemization in Dental Enamel: A Comparison of Morphological, Biochemical, and Known Ages-At-Death	early medieval cemetery of Newcastle Blackgate	13 human teeth	5 years to 30–40 years	Weakness: - Small sample size - Limited age range
Gunst *et al.*	2003	root development	Third molar root development in relation to chronological age: a large sample sized retrospective study	Belgian	2513	15.7 – 23.3 years	Strength: - Large sample size Weakness: - Limited age range - Applicable only to third molars
Gustafson and	1950	Thickness of cementum	Age determination on teeth	-	-	Adults	Weakness: - Limited age

Johanson							range - Invasive
Gustafson and Koch	1974	Atlas	Age estimation up to 16 years of age based on dental development	From previous studies	-	Intra utero to 16 years	Weakness: - Limited age range
Haataja *et al.*	1965	Dental development	Development of the mandibular permanent teeth of helsinki children	Finish	-	Children	Weakness: - Limited age range - Applicable to permanent teeth only
Jankauskas *et al.*	2001	Incremental lines of dental cementum	Incremental lines of dental cementum in biological age estimation	Lithuanian	51teeth from 49 individuals	12 – 72 years	Weakness: - Small sample size - Limited age range - Invasive
Kahl and Schwarze	1988	Atlas	Updating of the dentition tables of i. Schour and m. Massler of 1941	German	940 children	5 – 16 years	Weakness: - Limited age range
Kronfeld	1935	Dental development	Postnatal development and calcification of the anterior permanent teeth	White American	-	Birth to adolescents	Weakness: - Limited age range - Applicable only to anterior permanent teeth
Kvaal and Solheim	1995	Formula	Age estimation of adults from dental radiographs	Norwegian	100	20 – 87 years	Weakness: - Small sample size - Applicable to only mature teeth
Liversidge and Molleson	2004	scoring system	Variation in Crown and Root Formation and Eruption of Human Deciduous Teeth	Skeletal remains	121 individuals And 61 healthy living children	2–5 years	Weakness: - Limited age range
Liversidge *et al.*	1999	Tooth size	Deciduous tooth size and Morphogenetic fields in children from Christ Church, Spitalfield's	Skeletal remains	37 boys, 18 girls and 88 children of unknown sex	Children	Weakness: - Limited age range
Moorreess	1963a,b	Dental development	Age Variation of Formation Stages for Ten Permanent Teeth	Americans	48 males and 51 females	??	Weakness: - Small sample size - Applicable to permanent teeth only
Mörnstad *et al.*	1994	Dental development	Age estimation with the aid of tooth development: a new method based on objective measurements	Swedish	541 children (270 boys and 271 girls)	5.5 – 14.5 years	Weakness: - Limited age range
Moslemi *et al.*	2004	Tooth eruption	An epidemiological survey of the time and sequence of eruption of permanent teeth in 4–15-year-olds in	Iranian	3744 (1786 girls and 1958 boys)	4–15 years	Strength: - Large sample size Weakness: - Limited age range

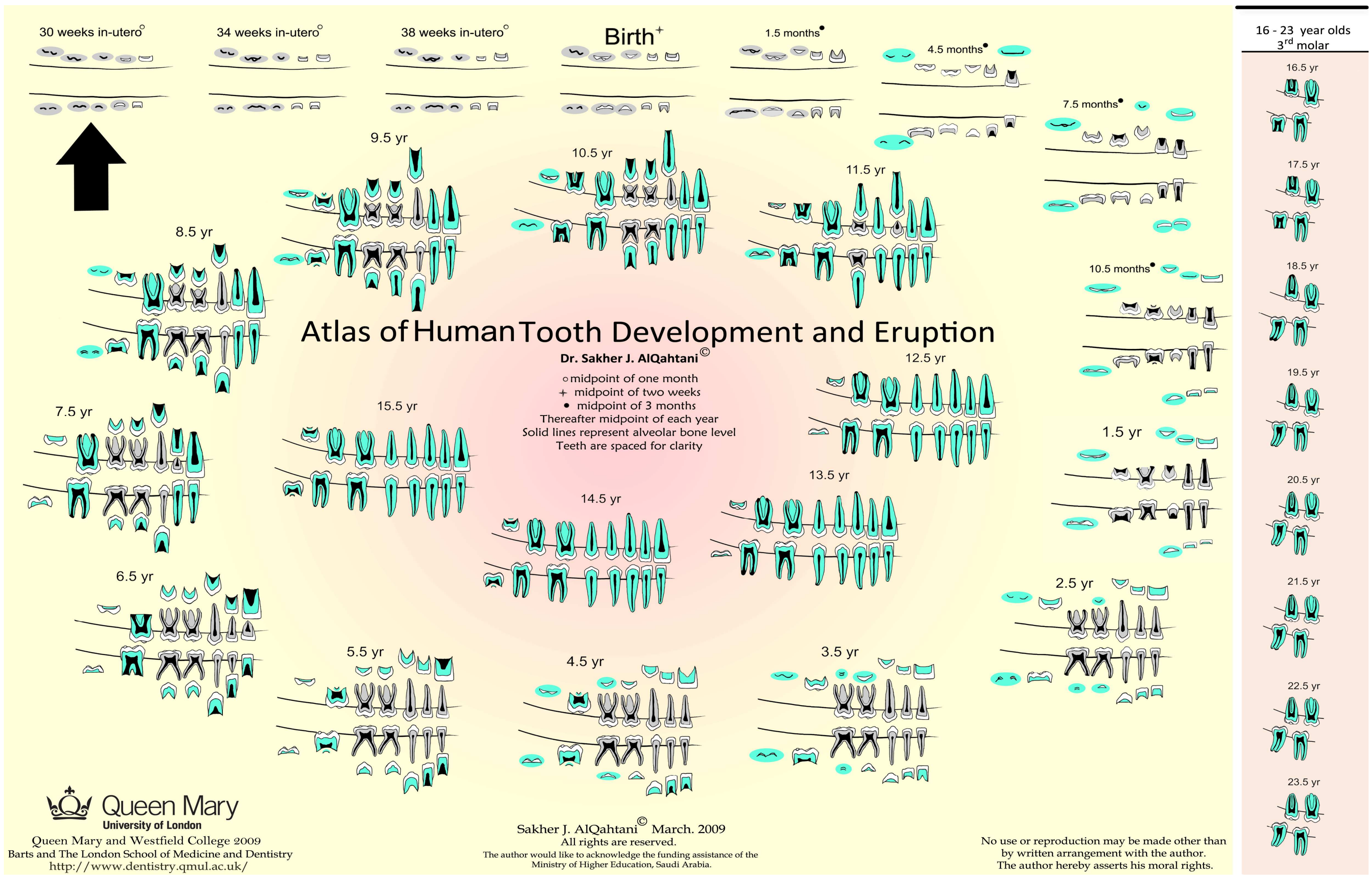
			Tehran, Iran				- Based on eruption only - Applicable to permanent teeth only
Nyström *et al.*	1977, 1986	Dental development	A radiographic study of the formation of some teeth from 0.5 to 3 years of age Dental maturity in finnish children, estimated from the development of seven permanent mandibular teeth	Finnish	65 children	0.5 to 3 years	Weakness: - Limited age range - Applicable to selected mandibular permanent teeth
Olze *et al.*	2008	Tooth eruption	Studies of the chronological course of wisdom tooth eruption in a German population	German	144 male and 522 female	12–26 years	Weakness: - Limited age range - Based on eruption only
Prince *et al.*	2008	apical translucency Formula	New Formulae for Estimating Age-at-Death in the Balkans Utilizing Lamendin's Dental Technique and Bayesian Analysis	Kosovo	401 single rooted teeth (359 males, 42 females)	18 to 90 years	Weakness: - Applicable to mature teeth only - Invasive
Rai *et al.*	2008	measurement of the open apices in teeth and derived regression equations	Age Estimation in Children from dental Radiograph: A Regression Equation	India	435 children (218 boys: 217 girls)	4-16 years	Weakness: - Limited age range - Applicable to permanent teeth only
Roberts *et al.*	2008	mathematical manipulation based on meta-analysis	Dental age assessment (DAA): a simple method for children and emerging adults	British	1,547 subjects	1.8 to 26.1 years	Strength: - Large sample size Weakness: - Very complicated method
Schour and Massler	1941	Atlas	The development of the human dentition	American	??	5 months in utero to 35 years	Strength: - Covers all ages of developing dentition Weakness: - Missing ages - Unknown sample size - No reference for eruption
Smith *et al.*	2005	Neonatal line	The use of dental criteria for estimating postnatal survival in skeletal remains of infants	Roman, ottoman	Upper first deciduous molar tooth germs were present in 14 infants from Ashqelon and 13 infants from Dor	Neonates	Strength: - Useful for postnatal survival Weakness: - Limited age range - Invasive
Solheim *et al.*	1993	Formulae	A new method for dental age estimation	Norway	1000 teeth	-	Strength: - Large sample

			in adults				size Weakness: - Limited age range
Stack	1960	gravimetric observations	Forensic estimation of age in infancy by gravimetric observations on the developing dentition	British	126 neonates	24th week in utero to birth	Weakness: - Limited age range - Invasive
Wehner *et al.*	2007	Amelogenin	Immunohistochemical proof of amelogenin in teeth--a contribution to the evaluation of the age in the identification of unknown corpses	-	-	-	Weakness: - Laborious - Invasive

Appendix 5: Sample and sex distribution for each age group used to develop the atlas of tooth development and eruption.

Age	Spitalfields			Stacks		Radiographs		Total		
	Male	Female	Unknown	Male	Female	Male	Female	Male	Female	Sum
28 -- < 32 weeks *in utero*	-	-	-	8	4	-	-	8	4	12
32 -- < 36 weeks *in utero*	-	-	-	8	7	-	-	8	7	15
36 -- < 39 weeks *in utero*	-	-	-	15	15	-	-	15	15	30
39 weeks *in utero* -- < 1 week after birth	-	-	-	15	15	-	-	15	15	30
1 week -- < 3 months	1	7	1	14	11	-	-	15	18	34
3 months -- < 6 months	4	1	1	6	2	-	-	10	3	14
6 months -- < 9 months	3	3	1	1	2	-	-	4	5	10
9 months -- < 12 months	5	-	6	2	1	-	-	7	1	14
1+ year [a]	9	4	4	-	-	-	-	9	4	17
2+ years	-	-	-	-	-	12	12	12	12	24
3+ years	-	-	-	-	-	12	12	12	12	24
4+ years	-	-	-	-	-	12	12	12	12	24
5+ years	-	-	-	-	-	12	12	12	12	24
6+ years	-	-	-	-	-	12	12	12	12	24
7+ years	-	-	-	-	-	12	12	12	12	24
8+ years	-	-	-	-	-	12	12	12	12	24
9+ years	-	-	-	-	-	12	12	12	12	24
10+ years	-	-	-	-	-	12	12	12	12	24
11+ years	-	-	-	-	-	12	12	12	12	24
12+ years	-	-	-	-	-	12	12	12	12	24
13+ years	-	-	-	-	-	12	12	12	12	24
14+ years	-	-	-	-	-	12	12	12	12	24
15+ years	-	-	-	-	-	12	12	12	12	24
16+ years	-	-	-	-	-	12	12	12	12	24
17+ years	-	-	-	-	-	12	12	12	12	24
18+ years	-	-	-	-	-	12	12	12	12	24
19+ years	-	-	-	-	-	12	12	12	12	24
20+ years	-	-	-	-	-	12	12	12	12	24
21+ years	-	-	-	-	-	12	12	12	12	24
22+ years	-	-	-	-	-	12	12	12	12	24
23+ years	-	-	-	-	-	12	12	12	12	24

Appendix 6: The London Atlas of human tooth development, the front page.



Appendix 7: The London Atlas of human tooth development, the back page.

Description of Moorrees' stages (1963)
used to identify tooth developmental stages of single rooted teeth

	ci: initial cusp formation			Ri: initial root formation with diverge edges
	Cco: Coalescence of cusps			R 1/4: root length less than crown length
	Coc: Cusp outline complete			R 1/2: root length equals crown length
	Cr 1/2: crown half completed with dentine formation			R 3/4: three quarters of root length developed with diverge ends
	Cr 3/4: crown three quarters completed			Rc: root length completed with parallel ends
	Crc: crown completed with defined pulp roof			A 1/2: apex closed (root ends converge) with wide PDL
				Ac: apex closed with normal PDL width

Description of Moorrees' stages (1963)
used to identify tooth developmental stages of multirooted teeth

	Ci: initial cusp formation			
	Cco: Coalescence of cusps			R 1/4: root length less than crown length with visible bifurcatio area
	Coc: Cusp outline complete			R 1/2: root length equals crown length
	Cr 1/2: crown half completed with dentine formation			R 3/4: three quarters of root length developed with diverge ends
	Cr 3/4: crown three quarters completed			Rc: root length completed with parallel ends
	Crc: crown completed with defined pulp roof			A 1/2: apex closed (root ends converge) with wide PDL
	Ri: initial root formation with diverge edges			Ac: apex closed with normal PDL width

Description of Moorrees' stages (1963)
used to identify root resorbtion
in single and multirooted teeth

	Ac: apex closed with normal PDL width	
	Res 1/4: resorbtion of apical quarter of the root	
	Res 1/2: resorbtion of half the root	
	Res 3/4: resorbtion of three quarters of the root	

Description of modified Bengston's stages
used to identify tooth eruption

	position 1: when the occlusal or incisal surface is covered entirely by bone	
	position 2: when the occlusal or incisal surface breaks through the crest of the alveolar bone	
	position 3: when the occlusal or incisal surface is midway between the alveolar bone and the occlusal plane	
	position 4: occlusal or incisal surface is in the occlusal plane	

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Appendix 8: Copyright registration certificate.

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This Certificate issued under the seal of the Copyright Office in accordance with title 17, *United States Code*, attests that registration has been made for the work identified below. The information on this certificate has been made a part of the Copyright Office records.

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Registration Number:

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Effective date of registration:

March 30, 2009

Title

Title of Work: Atlas of tooth development and eruption

Completion/ Publication

Year of Completion: 2009

Author

- **Author:** Sakher Jaber AlQahtani, dba PhD student

Author Created: 2-D artwork, map/technical drawing, text

Citizen of: Saudi Arabia **Domiciled in:** Saudi Arabia

Year Born: 1978

Copyright claimant

Copyright Claimant: Sakher Jaber AlQahtani

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Certification

Name: Sakher Jaber AlQahtani

Date: March 30, 2009

Appendix 9: Published article: Brief Communication: The London Atlas of HumanTooth Development and Eruption. American Journal of Physical Anthropology. 2010

AMERICAN JOURNAL OF PHYSICAL ANTHROPOLOGY 142:481–490 (2010)

Brief Communication: The London Atlas of Human Tooth Development and Eruption

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KEY WORDS dental; age; estimation; forensic; odontology

ABSTRACT The aim of this study was to develop a comprehensive evidence-based atlas to estimate age using both tooth development and alveolar eruption for human individuals between 28 weeks in utero and 23 years. This was a cross-sectional, retrospective study of archived material with the sample aged 2 years and older having a uniform age and sex distribution. Developing teeth from 72 prenatal and 104 postnatal skeletal remains of known age-at-death were examined from collections held at the Royal College of Surgeons of England and the Natural History Museum, London, UK (M 91, F 72, unknown sex 13). Data were also collected from dental radiographs of living individuals (M 264, F 264). Median stage for tooth development and eruption for all age categories was used to construct the atlas. Tooth development was determined according to Moorrees et al. (J Dent Res 42 (1963a) 490–502; Am J Phys Anthropol 21 (1963b) 205–213) and eruption was assessed relative to the alveolar bone level. Intraexaminer reproducibility calculated using Kappa on 150 teeth was 0.90 for 15 skeletal remains of age <2 years, and 0.81 from 605 teeth (50 radiographs). Age categories were monthly in the last trimester, 2 weeks perinatally, 3-month intervals during the first year, and at every year thereafter. Results show that tooth formation is least variable in infancy and most variable after the age of 16 years for the development of the third molar. Am J Phys Anthropol 142:481–490, 2010. © 2010 Wiley-Liss, Inc.

Age estimation for humans plays an important role in mass disasters and unaccompanied or asylum-seeking minors in the absence of proper documents. It also contributes to anthropology and forensic sciences, where age at death is estimated for skeletal remains (Hillson, 1996). Teeth survive inhumation well and show less variability than skeletal age, and the developing dentition is therefore better than other developmental indicators available for age estimation up to maturity (Garn et al., 1960; Demirjian, 1986; Smith, 1991). Humans have two generations of teeth: the deciduous dentition, which begins to develop around the sixth week in utero, and the permanent dentition, which reaches completion in early adult life. This long span of tooth development, eruption, shedding, and maturing is an orderly and sequential process. Crown or root growth and maturation stages as well as eruption relative to the alveolar bone level can be used to estimate dental age in both living and skeletal remains. (Demirjian, 1986) The aim of this study was to develop a comprehensive evidence-based atlas to estimate age using both tooth development and alveolar eruption for individuals between 28 weeks in utero and 23 years.

MATERIALS AND METHODS

Materials

This was a cross-sectional retrospective study of 704 archived records: radiographs of known age individuals and known age-at-death skeletal remains.

Individuals aged 28 weeks in utero to less than two years of age. All available individuals aged between 28 weeks in utero and 2 years of age were examined from two collections of known age-at-death human remains detailed in Table 1. The first was the Spitalfields Collection at the Human Origins Group, Paleontology Department, Natural History Museum, London (Molleson and Cox, 1993), that consists of 15 females, 22 males, and 13 unknown sex ($N = 50$); the second was Maurice Stack's collection, which is part of the Odontological Collection at the Royal College of Surgeons of England (Stack, 1960) made up of 69 males and 57 females ($N = 126$).

Individuals aged 2–24 years of age. Good quality archived dental panoramic radiographs were selected, with all teeth in focus, of healthy individuals ($N = 528$) aged 2–24 years from the Institute of Dentistry, Barts and the London School of Medicine and Dentistry. All radiographs had previously been taken for diagnosis and treatment. The sample was made up of two ethnic groups: about half were white and half Bangladeshi. Mean ages of tooth development are not significantly different in these groups (Liversidge, 2009). Each chronological year was represented by 12 males and 12 females. A uniform age distribution was chosen to equalize accuracy over all age groups (Konigsberg and Frankenberg,

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TABLE 1. Sample and sex distribution for each age group used to develop the atlas of tooth development and eruption

	Spitalfields			Stacks		Radiographs		Total		
Age	Male	Female	Unknown	Male	Female	Male	Female	Male	Female	Sum
Skeletal remains										
28 to <32 weeks in utero	–	–	–	8	4	–	–	8	4	12
32 to <36 weeks in utero	–	–	–	8	7	–	–	8	7	15
36 to <39 weeks in utero	–	–	–	15	15	–	–	15	15	30
39 weeks in utero to <1 week after birth	–	–	–	15	15	–	–	15	15	30
1 week to <3 months	1	7	1	14	11	–	–	15	18	34
3 months to <6 months	4	1	1	6	2	–	–	10	3	14
6 months to <9 months	3	3	1	1	2	–	–	4	5	10
9 months to <12 months	5	–	6	2	1	–	–	7	1	14
1+ year [a]	9	4	4	–	–	–	–	9	4	17
Radiographs										
2+ years	–	–	–	–	–	12	12	12	12	24
3+ years	–	–	–	–	–	12	12	12	12	24
4+ years	–	–	–	–	–	12	12	12	12	24
5+ years	–	–	–	–	–	12	12	12	12	24
6+ years	–	–	–	–	–	12	12	12	12	24
7+ years	–	–	–	–	–	12	12	12	12	24
8+ years	–	–	–	–	–	12	12	12	12	24
9+ years	–	–	–	–	–	12	12	12	12	24
10+ years	–	–	–	–	–	12	12	12	12	24
11+ years	–	–	–	–	–	12	12	12	12	24
12+ years	–	–	–	–	–	12	12	12	12	24
13+ years	–	–	–	–	–	12	12	12	12	24
14+ years	–	–	–	–	–	12	12	12	12	24
15+ years	–	–	–	–	–	12	12	12	12	24
16+ years	–	–	–	–	–	12	12	12	12	24
17+ years	–	–	–	–	–	12	12	12	12	24
18+ years	–	–	–	–	–	12	12	12	12	24
19+ years	–	–	–	–	–	12	12	12	12	24
20+ years	–	–	–	–	–	12	12	12	12	24
21+ years	–	–	–	–	–	12	12	12	12	24
22+ years	–	–	–	–	–	12	12	12	12	24
23+ years	–	–	–	–	–	12	12	12	12	24

[a] Sample is 1 year to <2 years, and the same applies to all ages to the age of 24.

2002). Exclusions were the following: retained deciduous tooth, an impacted tooth, or a resorbing deciduous root associated with a permanent tooth other than its successor. Other exclusions were the presence of a developmental anomaly, a developmental absence of a tooth, or extracted tooth/teeth.

Methods

Stage identification was done by the first author (SJA). Tooth developmental and alveolar eruption stages of the right side of the jaw from each radiograph were identified on a radiographic viewer with the help of a magnifying glass. Isolated teeth for the human skeletal remains collections were observed directly when radiographs were not available. Each developing tooth (crown and root) was assessed according to modified Moorrees stages (Moorrees et al., 1963a,b) shown in Figures 1–3. The last three stages of tooth development (Rc, A 1/2, and Ac) are differentiated by subtle differences that relate to the dentin edges at the root end, the apex width, and the width of the periodontal ligament space (PDL). Root length is complete (Rc) when the dentin edges are parallel with an open apical end and a wide PDL. Apex half (A 1/2) is the stage where the root terminal is maturing by narrowing at the apical end and making the dentin root ends converge but still having the PDL space wide. Tooth development reaches completion (Ac) when the root apex is closed radiographically with normal PDL space.

The remaining root and the distal root of molars were selected when root resorption and formation stages were assessed. Modified Bengston's stages (Bengston, 1935; Liversidge and Molleson, 2004) were used in assessing tooth eruption stage in relation to bone level, ranging from occlusal or incisal surface of a tooth below bone for mandibular teeth or above bone for maxillary teeth, at alveolar crest, at midway between alveolar bone and occlusal plane, and at occlusal plane (see Fig. 4). After assessing the developmental and eruption stages, the median was identified from minimum to maximum stages for each stage and for each tooth. These were tabulated for males, females, and combined sex for each of the following age groups: the seventh, eighth, and ninth month of gestation; birth at midpoint of 2 weeks; the first, second, third, and fourth 3 months of life; and for each chronological year over the age of 1 up to the age of 23 years. Tooth development and eruption stages were assessed twice for 15 skeletal remains (150 teeth) and 50 radiographs (605 teeth) at different occasions to determine the intraexaminer reliability calculated using Kappa.

Each tooth was drawn by hand by the first author (SJA) as an international paper size A4 scale using a pigment liner (Staedtler®) size 0.8 on a tracing pad over a 5-mm isometric graphic pad. Each drawing was

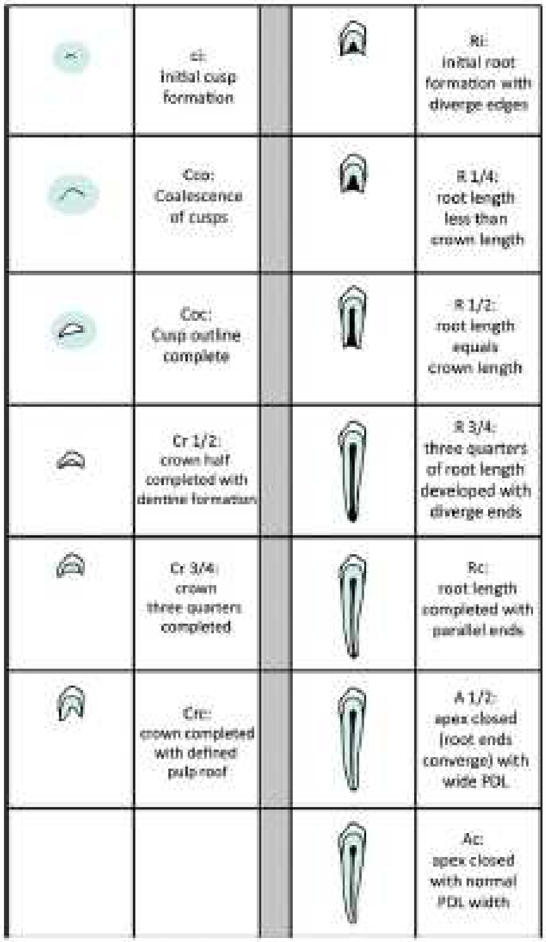

Fig. 1. Description of modified Moorrees' stages (Moorrees et al., 1963a,b) used to identify tooth developmental stages of single rooted teeth. PDL refers to "periodontal ligament space." [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

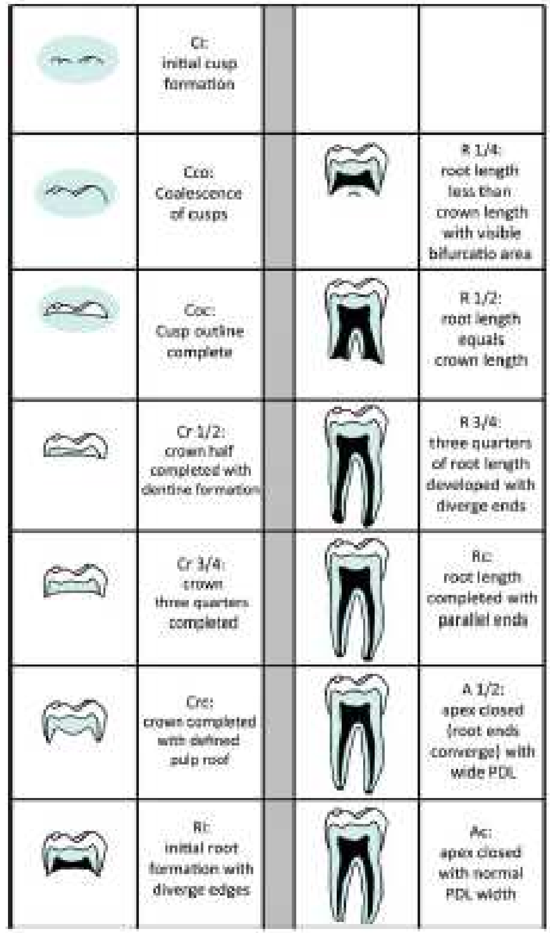

Fig. 2. Description of modified Moorrees' stages (Moorrees et al., 1963a,b) used to identify tooth developmental stages of multirooted teeth. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

based on the "ideal" or "model" tooth supplied in the Wheeler's Atlas of Tooth Form (Wheeler, 1984). The drawing was then scanned, finished, and colored using Adobe Photoshop® software 7.0. Three drawings were made for the prenatal dentition each representing a midpoint of 1 month for the last 3 months of pregnancy and one drawing was made for birth representing a midpoint of 2 weeks around a full-term pregnancy birth; corrected age around 40 gestational weeks was used (O'Neill, 2005); four drawings for the first year of life each representing a midpoint of 3 months for each quadrant of the year were done and one drawing for each chronological year thereafter was made representing midpoint of 1 year each. The diagrams illustrate the median tooth developmental and alveolar eruption stages. Diagrams were made for males, females, and combined sex.

RESULTS

Kappa value was 0.90 and 0.81 for skeletal material and radiographs, respectively (combined 0.85), indicating excellent agreement (Landis and Koch, 1977). Figure 5 shows the dentition of a 5-year-old child with explanation of the illustration. The full atlas for combined sex is shown in Figure 6. Teeth in this new atlas mimic the radiographic presentation with the pulp area black and the enamel white; the dentin is gray for deciduous teeth and green for permanent. Teeth were spaced with accentuated developmental stages to ease identification. Developing third molars for the ages 16–23 years were presented separately on the right hand side with the second molars, because the rest of the permanent dentition was fully matured by the age of 15. Data from males and females were pooled in view of the fact that the median of tooth development in females preceded males between the ages 6 and 14, but by usually only one stage and not in all teeth, and this was not consistent. The

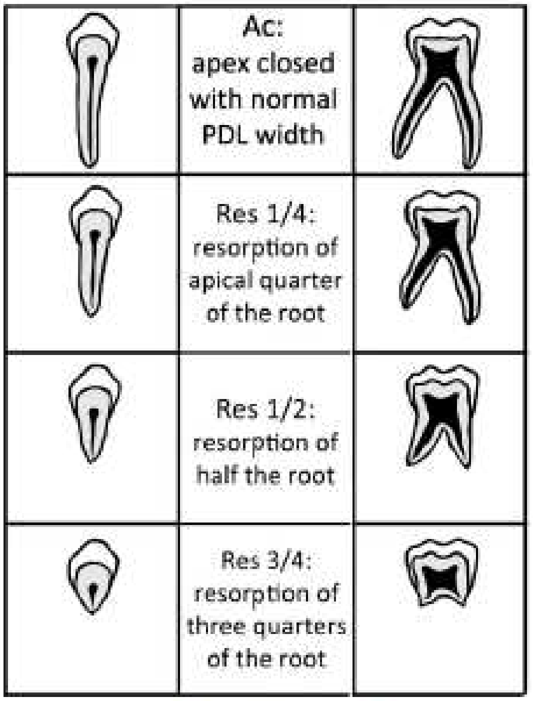

Fig. 3. Description of modified Moorrees' stages (Moorrees et al., 1963b) used to identify root resorption in single and multi-rooted teeth.

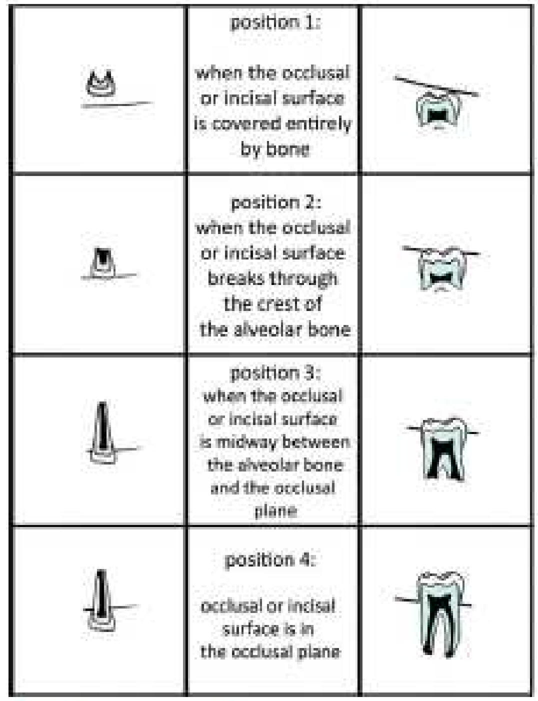

Fig. 4. Description of modified Bengston's stages (Bengston, 1935) used to identify tooth eruption. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

combined sex data are presented in Tables 2–9 with minimum, maximum, and median stages. The spread of the stages around the median was minimal and was usually limited to plus or minus one stage, which is expected in regard to the biological variation between different individuals. Females in general preceded males in tooth development; this was particularly noticeable between the ages 6–14 years. After the age of 15, males were more advanced in third molar maturation; this was also the tooth with the most pronounced variation between subjects in the same age group. Tables 10 and 11 give median age of alveolar eruption and full eruption from our study with estimated clinical emergence from Lysell et al. (1962) and Haavikko (1970).

DISCUSSION

The early history of illustrating tooth development during childhood is reviewed by Smith (1991). The best known atlas is by Schour and Massler (1941) consisting of 21 diagrams with an age range from 5 months in utero to 35 years. Each diagram is an anatomical drawing showing whole teeth in their developmental position. Each diagram is labeled with an age in months or years with a range of ±3, 6, or 9 months, some of which overlap. No details of sample size are given, but Smith (1991) points out it was probably based on Logan and Kronfeld's anatomical and radiographic data of 26 or 29 autopsy specimens, 20 of whom were younger than two (Logan and Kronfeld, 1933; Kronfeld, 1935a,b,c; Logan, 1935). This atlas or adaptations of it thereof are to be found in most standard dental anatomy textbooks.

Gustafson and Koch (1974) constructed a schematic representation of tooth formation and eruption from 20 sources combining anatomical, radiographic, and gingival eruption data. This extends from prenatal to 16 years and shows the range and peak age for each stage. Ubelaker's atlas (Ubelaker, 1978) of dental formation and eruption among American Indians was also compiled from a variety of sources, and it used the "early end of the published variation in preparing the chart" because "some studies suggest that teeth probably form and erupt earlier among Indians" (Ubelaker, 1978). Kahl and Schwarze (1988) updated Schour and Massler's atlas using 993 radiographs of children aged 5–24 and produced charts for separate sex for each age. Both Kahl and Schwarze (1988) and Ubelaker (1978) present anatomical drawings with no internal dental structure, yet are based fully or partly on the radiographic data. Internal hard tissues of a developing tooth can help distinguish between developmental stages thus improving sensitivity and accuracy.

Previous atlases and charts are hampered by inadequate age ranges not covering the entire developing dentition. The new atlas covers as much of the developing dentition as possible and all ages are represented. Each illustration in the new atlas from ages 1 to 23 shows tooth development and eruption at the midpoint of the chronological year. Developmental stages were illustrated as radiographic representations and clarified by the addition of written descriptions. Teeth were spaced to ease stage assessment making it applicable to both radiographs and direct observation. Initially, we based the atlas on data from Spitalfields and archived radiographs, and the first year of life was represented by only two illustrations of 6 months duration, with midpoints at 3 and 9 months. Pilot testing of this on neonatal skeletal remains revealed numerous individuals dentally more advanced than 3 months but less advanced than 9 months. This fast rate of deciduous tooth development indicated the need for shorter age group intervals of 3 months for the first year. Adding data from Stack's collection extended the age range to include the last trimester and the data were sufficient to have 1 month age groups for the prenatal and birth (39–41 weeks) age categories. We aimed for a uniform age distribution for the new atlas by selecting similar numbers of males and females in each age group from radiographic data and by using all available data from the skeletal remains; however, four age groups were uneven (see Table 1). The Spitalfields and Maurice Stack's collections of known age-at-death reference samples are unique and valuable and fill an important age gap for which radiographic data are scarce. However, some skeletal remains from Spitalfields are fragmentary with an incomplete developing dentition. Few individuals were aged between 6 months and less than 2 years, and as a result, the sex and age distribution for children in those age groups in our atlas is not ideal. This is reflected by a jump in tooth formation stages from 1.5 to 2.5 years for the deciduous canine and deciduous second molar from root initiation stage (Ri) to root three quarters (R 3/4) stage. From the radiographic sample, the maximum age was determined from the age where all teeth have reached maturity; our data showed this to be

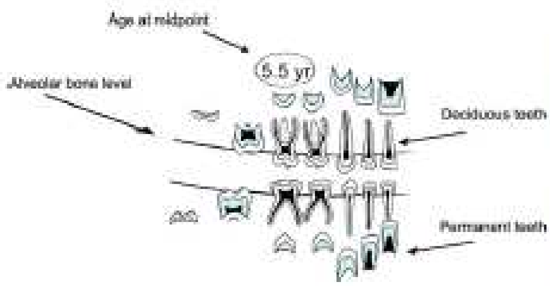

Fig. 5. Explanation of the illustration of a 5-year-old child's dental development. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

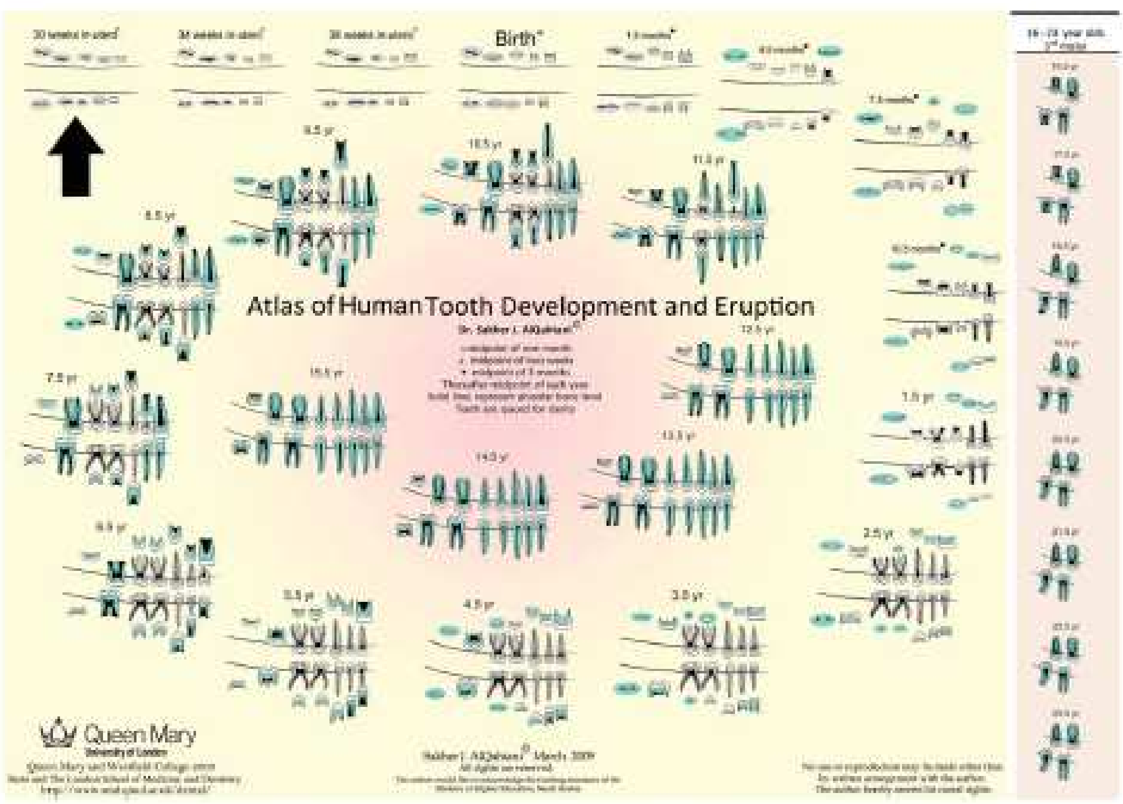

Fig. 6. Atlas of human tooth development and eruption. The arrow indicates the starting point. The dentine is presented in gray for deciduous teeth and in green for permanent.

TABLE 2. Tooth development data from autopsied infants[a] (combined sex)

	Maxilla					Mandible				
			Tooth formation stage					Tooth formation stage		
Age	Tooth	Number of teeth	Minimum	Median	Maximum	Tooth	Number of teeth	Minimum	Median	Maximum
30 weeks in utero[b]	i^1	12	Coc	Cr ½	Cr ¾	i_1	12	Coc	Cr ½	Cr ¾
	i^2	12	Cco	Coc	Cr ¾	i_2	12	Cco	Coc	Cr ¾
	c^1	12	Ci	Ci	Coc	c_1	12	Ci	Ci	Coc
	m^1	12	Ci	Cco	Coc	m_1	12	Ci	Cco	Coc
	m^2	12	Ci	Ci	Cco	m_2	12	Ci	Ci	Cco
34 weeks in utero[b]	i^1	13	Cr ½	Cr ¾	Cr ¾	i_1	15	Cr ½	Cr ¾	Crc
	i^2	13	Cr ½	Cr ½	Cr ¾	i_2	7	Cr ½	Cr ¾	Cr ¾
	c^1	13	Ci	Ci	Coc	c_1	12	Ci	Ci	Coc
	m^1	15	Cco	Cco	Coc	m_1	14	Cco	Cco	Coc
	m^2	13	Ci	Ci	Cco	m_2	12	Ci	Ci	Cco
38 weeks in utero[b]	i^1	26	Cr ½	Cr ¾	Crc	i_1	23	Cr ½	Cr ¾	Crc
	i^2	20	Cr ½	Cr ½	Cr ¾	i_2	15	Cr ½	Cr ¾	Crc
	c^1	26	Ci	Ci	Coc	c_1	26	Ci	Cco	Coc
	m^1	29	Cco	Cco	Cr ½	m_1	29	Cco	Cco	Cr ½
	m^2	27	Ci	Ci	Cco	m_2	26	Ci	Ci	Cco
Birth[c]	i^1	23	Cr ¾	Cr ¾	Crc	i_1	27	Cr ¾	Crc	Crc
	i^2	20	Cr ½	Cr ¾	Cr ¾	i_2	18	Cr ¾	Cr ¾	Crc
	c^1	30	Ci	Coc	Cr ½	c_1	28	Ci	Coc	Coc
	m^1	25	Cco	Coc	Cr ½	m_1	29	Cco	Coc	Cr ½
	M^2	29	Ci	Cco	Coc	m_2	26	Ci	Ci	Coc

[a] Twelve children from 28 to <32 weeks in utero, 15 children from 32 to <36 weeks in utero, 30 children from 36 to 39 weeks in utero, and 30 children from >39 weeks in utero to <1 week after birth.
[b] Midpoint of 4 weeks.
[c] Midpoint of 2 weeks.

TABLE 3. Tooth development data from skeletal remains[a] (combined sex)

	Maxilla					Mandible				
			Tooth formation stage					Tooth formation stage		
Age (months)	Tooth	Number of teeth	Minimum	Median	Maximum	Tooth	Number of teeth	Minimum	Median	Maximum
1.5[b]	i^1	34	Cr ¾	Crc	Ri	i_1	29	Cr ¾	Crc	Ri
	i^2	31	Cr ½	Cr ¾	Crc	i_2	25	Cr ¾	Crc	Ri
	c^1	34	Coc	Coc	Cr ½	c_1	29	Coc	Coc	Cr ½
	m^1	33	Cco	Coc	Cr ½	m_1	28	Cco	Coc	Cr ½
	m^2	27	Ci	Cco	Coc	m_2	25	Ci	Cco	Cr ½
	M^1	4	–	–	Ci	M_1	3	–	–	Cco
4.5[b]	i^1	13	Crc	Ri	R ¼	i_1	11	Crc	Ri	R ¼
	i^2	11	Crc	Crc	Ri	i_2	13	Cr ¾	Ri	R ¼
	c^1	14	Coc	Cr ½	Cr ¾	c_1	16	Coc	Cr ½	Cr ¾
	m^1	7	Cr ½	Cr ½	Cr ¾	m_1	11	Cr ½	Cr ¾	Crc
	m^2	8	Coc	Cr ½	Cr ¾	m_2	11	Cr ½	Cr ¾	Crc
	I^1	4	Ci	Ci	Coc	I_1	1	–	–	Ci
	M^1	4	Ci	Ci	Ci	M_1	5	Ci	Ci	Cco
7.5[b]	i^1	6	Ri	R ¼	R ½	i_1	5	R ¼	R ½	R ½
	i^2	6	Crc	R ¼	R ¼	i_2	4	Ri	R ¼	R ¼
	c^1	8	Cr ¾	Crc	Crc	c_1	6	Cr ½	Cr ¾	Crc
	m^1	9	Crc	Ri	Cr ½	m_1	10	Cr 3/4	Crc	Ri
	m^2	5	Cr ¾	Crc	Crc	m_2	10	Cr ½	Cr ¾	Cr ¾
	I^1	4	Coc	Coc	Cr ½	I_1	3	Coc	Coc	Cr ½
	C^1	4	Ci	Ci	Ci	C_1	1	–	–	Ci
	M^1	4	Cco	Cco	Coc	M_1	4	Cco	Coc	Coc
10.5[b]	i^1	5	Ri	R ½	R ½	i_1	9	R ¼	R ¾	R ¾
	i^2	4	Ri	R ¼	R ¼	i_2	10	Ri	R ½	R ½
	c^1	6	Cr ¾	Crc	Ri	c_1	12	Cr ¾	Crc	Crc
	m^1	4	Crc	R ¼	R ¼	m_1	12	Crc	R ¼	R ½
	m^2	6	Cr ¾	Crc	Ri	m_2	12	Cr ¾	Crc	Ri
	I^1	4	Coc	Cr ½	Cr ½	I_1	5	Cr ½	Cr ½	Cr ½
	C^1	4	Ci	Ci	Ci	C_1	4	Ci	Ci	Ci
	M^1	4	Cco	Coc	Coc	M_1	10	Cco	Coc	Coc

[a] Thirty-four children from 1 week to <3 months, 14 children from 3 to <6 months, 10 children from 6 to <9 months, and 14 children from 9 to <12 months.
[b] Midpoint of 3 months.

TABLE 4. Combined sex tooth development data for 17 children (skeletal remains) from 1 to <2 years, 24 children from 2 to <3 years, and 24 children from 3 to <4 years

	Maxilla					Mandible				
			Tooth formation stage					Tooth formation stage		
Age (years)	Tooth	Number of teeth	Minimum	Median	Maximum	Tooth	Number of teeth	Minimum	Median	Maximum
1.5*	i^1	5	R ¼	R ¾	R ¾	i_1	7	R ¾	R ¾	Rc
	i^2	6	Ri	R ½	R ¾	i_2	7	R ¾	R ¾	Rc
	c'	6	Crc	Ri	R ½	$c_,$	7	Cr ¾	Ri	R ½
	m^1	7	Ri	R ½	R ¾	m_1	8	Ri	R ½	R ¾
	m^2	8	Crc	Ri	R ¼	m_2	8	Cr ¾	Ri	R ¼
	I^1	6	Cr ½	Cr ½	Cr ½	I_1	6	Cr 1/2	Cr ½	Cr ¾
	I^2	4	—	Coc	Coc	I_2	6	Coc	Cr ½	Cr ¼
	C'	8	Coc	Coc	Coc	$C_,$	4	—	Coc	Coc
	M^1	4	—	Coc	Cr ½	M_1	8	Cco	Coc	Cr ½
2.5*	i^1	24	Rc	Ac	Ac	i_1	24	Rc	Ac	Ac
	i^2	24	Rc	Ac	Ac	i_2	24	Rc	Ac	Ac
	c'	24	R ¾	Rc	Rc	$c_,$	24	R ¾	Rc	Rc
	m^1	24	R ¾	Rc	Ac	m_1	24	R ¾	Rc	Ac
	m^2	24	R ¼	R ¾	Ac	m_2	24	R ½	R ¾	Ac
	I^1	24	Cr ½	Cr ¾	Cr ¾	I_1	24	Cr ½	Cr ¾	Crc
	I^2	24	Coc	Cr ½	Cr ¾	I_2	24	Cr ½	Cr ¾	Crc
	C'	21	—	Cr ½	Cr ½	$C_,$	24	Coc	Cr ½	Cr ½
	P^1	19	—	Ci	Cco	P_1	20	—	Cco	Cco
	P^2	10	—	—	Ci	P_2	18	—	Ci	Ci
	M^1	24	Cr ½	Cr ¾	Cr ¾	M_1	24	Cr ½	Cr ¾	Crc
	M^2	16	—	Ci	Ci	M_2	15	—	Ci	Ci
3.5*	i^1	24	Ac	Ac	Ac	i_1	24	Ac	Ac	Ac
	i^2	24	Ac	Ac	Ac	i_2	24	Ac	Ac	Ac
	c'	24	Ac	Ac	Ac	$c_,$	24	Ac	Ac	Ac
	m^1	24	Ac	Ac	Ac	m_1	24	Ac	Ac	Ac
	m^2	24	Ac	Ac	Ac	m_2	24	Ac	Ac	Ac
	I^1	24	Cr ¾	Cr ¾	Ri	I_1	24	Cr ¾	Crc	Ri
	I^2	24	Cr ½	Cr ½	Crc	I_2	24	Cr ½	Cr ¾	Crc
	C'	24	Cr ½	Cr ½	Cr ¾	$C_,$	24	Coc	Cr ½	Crc
	P^1	24	Ci	Coc	Cr ½	P_1	24	Ci	Cr ½	Cr ½
	P^2	20	—	Ci	Cco	P_2	22	—	Ci	Coc
	M^1	24	Cr ½	Crc	R ¼	M_1	24	Cr ½	Ri	Ri
	M^2	20	—	Cco	Coc	M_2	22	—	Cco	Coc

* Midpoint of 1 year.

TABLE 5. Tooth development data (combined sex) for 24 children in each age group: 4 to <5 years, 5 to <6 years, and 6 to <7 years

	Maxilla					Mandible				
			Tooth formation stage					Tooth formation stage		
Age (years)	Tooth	Number of teeth	Minimum	Median	Maximum	Tooth	Number of teeth	Minimum	Median	Maximum
4.5*	i^1 to m^2	24 each	Ac	Ac	Ac	i_1 to m_2	24 each	Ac	Ac	Ac
	I^1	24	Cr ¾	Crc	Ri	I_1	24	Cr ¾	Ri	R ¼
	I^2	24	Cr ¾	Cr ¾	Ri	I_2	24	Cr ¾	Ri	Ri
	C'	24	Cr ¾	Cr ¾	Ri	$C_,$	24	Cr ½	Cr ¾	Ri
	P^1	24	Cr ½	Cr ½	Cr ¾	P_1	24	Cr ½	Cr ½	Crc
	P^2	24	Coc	Cco	Cr ¾	P_2	24	Ci	Coc	Cr ½
	M^1	24	R ¼	R ¼	R ½	M_1	24	R ¼	R ¼	R ½
	M^2	24	Ci	Coc	Cr ½	M_2	24	Cco	Coc	Cr ½
5.5*	i^1	24	Ac	Ac	Res 1/4	i_1	24	Ac	Ac	Res 1/2
	i^2	24	Ac	Ac	Res 1/4	i_2	24	Ac	Ac	Res 1/4
	c' to m^2	24 each	Ac	Ac	Ac	$c_,$ to m_2	24 each	Ac	Ac	Ac
	I^1	24	Crc	Ri	R ¼	I_1	24	Ri	R ¼	R ½
	I^2	24	Crc	Crc	Ri	I_2	24	Crc	R ¼	R ¼
	C'	24	Cr ¾	Crc	Ri	$C_,$	24	Cr ¾	Crc	Ri
	P^1	24	Cr ½	Cr ¾	Crc	P_1	24	Coc	Cr ¾	Crc
	P^2	24	Cco	Cr ½	Cr ¾	P_2	24	Cco	Cr ¾	Cr ¾
	M^1	24	R ¼	R ¼	R ½	M_1	24	R ¼	R ¼	R ½
	M^2	24	Coc	Cr ½	Cr ¾	M_2	24	Coc	Cr ½	Cr ¾
6.5*	i^1	14	Ac	Res ¾	—	i_1	11	Ac	—	—
	i^2	22	Ac	Res ¼	Res ¾	i_2	13	Ac	Res ½	—
	c'	24	Ac	Ac	Ac	$c_,$	24	Ac	Ac	Ac
	m^1	24	Ac	Ac	Res ¼	m_1	24	Ac	Ac	Res ¼
	m^2	24	Ac	Ac	Ac	m_2	24	Ac	Ac	Res ¼
	I^1	24	Crc	R ¼	R ¾	I_1	24	R ¼	R ½	Rc
	I^2	24	Crc	Ri	R ½	I_2	24	Ri	R ¼	R ¾
	C'	24	Crc	Ri	R ¼	$C_,$	24	Cr ¾	Ri	R ¼
	P^1	24	Cr ¾	Crc	Ri	P_1	24	Cr ½	Crc	Ri
	P^2	24	Cr ½	Crc	Crc	P_2	24	Coc	Crc	Ri
	M^1	24	R ¼	R ½	R ¾	M_1	24	R ¼	R ½	R ¾
	M^2	24	Coc	Cr ½	Crc	M_2	24	Coc	Cr ½	Crc

* Midpoint of 1 year.

TABLE 6. Tooth development data (combined sex) for 24 children in each age group: 7 to <8 years, 8 to <9 years, and 9 to <10 years

	Maxilla					Mandible				
		Number	Tooth formation stage				Number	Tooth formation stage		
Age (years)	Tooth	of teeth	Minimum	Median	Maximum	Tooth	of teeth	Minimum	Median	Maximum
7.5*	i^1	2	Res ¾	–	–	i_1	–	–	–	–
	i^2	13	Res ½	Res ¾	–	i_2	2	Ac	–	–
	c'	24	Ac	Ac	Ac	$c_,$	24	Ac	Ac	Ac
	m^1	24	Ac	Ac	Res ½	m_1	24	Ac	Ac	Res ½
	m^2	24	Ac	Ac	Res ½	m_2	24	Ac	Ac	Res ¼
	I^1	24	R ¼	R ¾	Rc	I_1	24	R ¾	Rc	A ½
	I^2	24	R ¼	R ½	Rc	I_2	24	R ¼	R ¾	A ½
	C'	24	Ri	R ¼	R ½	$C_,$	24	Ri	R ¼	R ½
	P^1	24	Cr ¾	Ri	R ¼	P_1	24	Ri	Ri	R ¼
	P^2	24	Cr ¾	Crc	R ¼	P_2	24	Crc	Crc	R ¼
	M^1	24	R ¼	R ¾	A ½	M_1	24	R ¾	R ¾	A ½
	M^2	24	Cr ½	Cr ¾	R ¼	M_2	24	Cr ½	Cr ¾	R ¼
	M^3	4	–	–	Ci	M_3	8	–	–	Ci
8.5*	i^2	6	Res ¾	–	–	i_2	–	–	–	–
	c'	24	Ac	Ac	Res ¼	$c_,$	24	Ac	Ac	Res ½
	m^1	24	Res ¼	Res ½	Res ½	m_1	24	Res ¼	Res ½	Res ½
	m^2	24	Ac	Res ½	Res ½	m_2	24	Ac	Ac	Res ¼
	I^1	24	R ½	Rc	A ½	I_1	24	R ¾	Ac	Ac
	I^2	24	R ¼	R ¾	Rc	I_2	24	R ¼	A ½	Ac
	C'	24	Ri	R ¼	R ¾	$C_,$	24	R ¼	R ¼	R ¾
	P^1	24	Ri	Ri	R ½	P_1	24	Ri	R ¼	R ½
	P^2	24	Ri	Ri	R ½	P_2	24	Crc	Ri	R ¼
	M^1	24	R ½	Rc	Ac	M_1	24	R ¾	R ¾	A ½
	M^2	24	Crc	Ri	R ¼	M_2	24	Cr ¾	Ri	R ¼
	M^3	13	–	Ci	Coc	M_3	20	–	Ci	Cco
9.5*	c'	22	Ac	Ac	–	$c_,$	22	Ac	Res ¼	–
	m^1	24	Res ¼	Res ½	Res ¾	m_1	24	Res ¼	Res ¼	Res ¾
	m^2	24	Res ¼	Res ½	Res ¾	m_2	24	Ac	Res ¼	Res ½
	I^1	24	R ¾	Rc	A ½	I_1	24	Rc	Ac	Ac
	I^2	24	R ½	Rc	A ½	I_2	24	Rc	A ½	Ac
	C'	24	R ¼	R ½	R ¾	$C_,$	24	R ¼	R ½	R ¾
	P^1	24	R ¼	R ¼	R ¾	P_1	24	R ¼	R ½	R ¾
	P^2	24	Ri	R ¼	R ¾	P_2	24	Ri	R ¼	R ¾
	M^1	24	Rc	Ac	Ac	M_1	24	R ¾	A ½	Ac
	M^2	24	Ri	R ¼	R ½	M_2	24	Ri	R ¼	R ½
	M^3	17	–	Coc	Cr ¾	M_3	22	–	Cco	Cr ¾

* Midpoint of 1 year.

TABLE 7. Tooth development data (combined sex) for 24 children in each age group: 10 to <11 years, 11 to <12 years, and 12 to <13 years

	Maxilla					Mandible				
		Number	Tooth formation stage				Number	Tooth formation stage		
Age (years)	Tooth	of teeth	Minimum	Median	Maximum	Tooth	of teeth	Minimum	Median	Maximum
10.5*	c'	20	Ac	Res ¼	–	$c_,$	–	–	–	–
	m^1	17	Res ¼	Res ½	–	m_1	16	Res ¼	Res ½	–
	m^2	21	Res ¼	Res ½	–	m_2	18	Ac	Res ¼	–
	I^1	24	Rc	A ½	Ac	I_1	24	A ½	Ac	Ac
	I^2	24	Rc	A ½	Ac	I_2	24	Rc	Ac	Ac
	C'	24	R ½	R ¾	R ¾	$C_,$	24	R ¾	R ¾	Rc
	P^1	24	R ¼	R ½	Rc	P_1	24	R ¼	R ½	Rc
	P^2	24	Ri	R ½	Rc	P_2	24	R ¼	R ½	R ¾
	M^1	24	Rc	Ac	Ac	M_1	24	Rc	Ac	Ac
	M^2	24	R ¼	R ½	R ½	M_2	24	R ¼	R ½	R ½
	M^3	23	–	Coc	Cr ½	M_3	23	–	Cco	Cr ½
11.5*	c'	17	Ac	Res ¾	–	$c_,$	4	Res ¼	–	–
	m^1	8	Res ½	–	–	m_1	6	Res ¼	–	–
	m^2	17	Res ¼	Res ¾	–	m_2	18	Ac	Res ½	–
	I^1	24	Rc	Ac	Ac	I_1	24	Rc	Ac	Ac
	I^2	24	R ¾	Ac	Ac	I_2	24	A ½	Ac	Ac
	C'	24	R ½	R ¾	Rc	$C_,$	24	R ¾	R ¾	A ½
	P^1	24	R ½	R ¾	A ½	P_1	24	R ½	R ¾	A ½
	P^2	24	R ¼	R ¾	Rc	P_2	24	R ¼	R ¾	A ½
	M^1	24	A ½	Ac	Ac	M_1	24	A ½	Ac	Ac
	M^2	24	R ¼	R ½	Rc	M_2	24	R ¼	R ½	R ¾
	M^3	24	Ci	Cr ½	Ri	M_3	24	Ci	Coc	R ¼
12.5*	m^2	2	Res ¾	–	–	m_2	10	Res ¼	–	–
	I^1	24	Rc	Ac	Ac	I_1	24	A ½	Ac	Ac
	I^2	24	Rc	Ac	Ac	I_2	24	A ½	Ac	Ac
	C'	24	R ¾	Rc	Rc	$C_,$	24	R ¾	A ½	Ac
	P^1	24	R ¾	Rc	A ½	P_1	24	R ¾	Rc	Ac
	P^2	24	R ½	R ¾	A ½	P_2	24	R ½	Rc	Ac
	M^1	24	Ac	Ac	Ac	M_1	24	Ac	Ac	Ac
	M^2	24	R ¼	R ¾	Rc	M_2	24	R ½	R ¾	Rc
	M^3	24	Cco	Cr ¾	R ¼	M_3	24	Ci	Cr ½	R ¼

* Midpoint of 1 year.

TABLE 8. Tooth development data (combined sex) for 24 children in each age group: 13 to <14 years, 14 to <15 years, 15 to <16 years, 16 to <17 years, and 17 to <18 years

	Maxilla					Mandible				
			Tooth formation stage					Tooth formation stage		
Age (years)	Tooth	Number of teeth	Minimum	Median	Maximum	Tooth	Number of teeth	Minimum	Median	Maximum
13.5[a]	I^1	24	Ac	Ac	Ac	I_1	24	Ac	Ac	Ac
	I^2	24	Ac	Ac	Ac	I_2	24	Ac	Ac	Ac
	$C^\prime$	24	Rc	Rc	A ½	$C_\prime$	24	Rc	A ½	Ac
	P^1	24	Rc	A ½	Ac	P_1	24	R ¾	A ½	Ac
	P^2	24	R ½	Rc	Ac	P_2	24	R ¾	Rc	Ac
	M^1	24	Ac	Ac	Ac	M_1	24	Ac	Ac	Ac
	M^2	24	Coc	R ¾	A ½	M_2	24	R ½	R ¾	A ½
	M^3	24	Ci	Cr ¾	R ½	M_3	24	Ci	Cr ½	R ½
14.5[a,b]	$C^\prime$	24	Rc	A ½	Ac	$C_\prime$	24	A ½	Ac	Ac
	P^1	24	A ½	Ac	Ac	P_1	24	A ½	Ac	Ac
	P^2	24	Rc	Ac	Ac	P_2	24	Rc	Ac	Ac
	M^2	24	Rc	Rc	Ac	M_2	24	Rc	Rc	Ac
	M^3	24	Cr ¾	R ½	R ½	M_3	24	Cr ½	R ½	R ½
15.5[a,b]	$C^\prime$	24	R ¾	Ac	Ac	$C_\prime$	24	Ac	Ac	Ac
	P^1	24	Ac	Ac	Ac	P_1	24	Ac	Ac	Ac
	P^2	24	Ac	Ac	Ac	P_2	24	Ac	Ac	Ac
	M^2	24	Rc	A ½	Ac	M_2	24	Rc	A ½	Ac
	M^3	24	Cr ½	R ½	R ¾	M_3	24	Cr ½	R ½	R ¾
16.5[a,c]	$C^\prime$	24	Ac	Ac	Ac	$C^\prime$	24	Ac	Ac	Ac
	M^2	24	A ½	Ac	Ac	M_2	24	A ½	Ac	Ac
	M^3	24	Ri	R ½	R ¾	M_3	24	Crc	R ½	R ¾
17.5[a,c]	M^2	24	Ac	Ac	Ac	M_2	24	Ac	Ac	Ac
	M^3	24	Crc	R ½	Rc	M_3	24	R ½	R ½	Rc

[a] Midpoint of 1 year.
[b] Teeth that reached radiographic apical closure stage (Ac) are permanent upper and lower incisors and first molars.
[c] Teeth that reached radiographic apical closure stage (Ac) are permanent incisors, premolars, and first molars.

TABLE 9. Third molar development for 24 individuals (combined sex) from 18 to <24 years

	Maxilla					Mandible				
			Tooth formation stage					Tooth formation stage		
Age (years)	Tooth	Number of teeth	Minimum	Median	Maximum	Tooth	Number of teeth	Minimum	Median	Maximum
18.5[a]	M^3	24	Crc	R ¾	Rc	M_3	24	R ½	R ¾	Rc
19.5[a]	M^3	24	R ½	Rc	A ½	M_3	24	R ½	Rc	A ½
20.5[a]	M^3	24	R ½	A ½	A ½	M_3	24	R ¾	A ½	A ½
21.5[a]	M^3	24	Rc	A ½	Ac	M_3	24	Rc	A ½	Ac
22.5[a]	M^3	24	Rc	A ½	Ac	M_3	24	Rc	A ½	Ac
23.5[a]	M^3	24	Ac	Ac	Ac	M_3	24	Ac	Ac	Ac

Teeth that reached radiographic apical closure stage (Ac) are permanent incisors, canines, premolars, first and second molars.
[a] Midpoint of 1 year.

TABLE 10. Median age of eruption for deciduous teeth (combined sex)[a]

Maxilla				Mandible			
Tooth	Alveolar eruption	Clinical emergence[b]	Full eruption	Tooth	Alveolar eruption	Clinical emergence[b]	Full eruption
i^1	4.5 months	9.96 months	10.5 months	i_1	4.5 months	8.04 months	10.5 months
i^2	7.5 months	11.4 months	1.5 years	i_2	7.5 months	1.08 years	1.5 years
$c^\prime$	10.5 months	1.58 years	2.5 years	$c_\prime$	10.5 months	1.67 years	2.5 years
m^1	10.5 months	1.33 years	1.5 years	m_1	10.5 months	1.33 years	1.5 years
m^2	1.5 years	2.42 years	2.5 years	m_2	1.5 years	2.25 years	2.5 years

[a] Midpoint of 3 months for younger than 1 year and midpoint of 1 year otherwise.
[b] From Lysell et al. (1962).

23 years of age. It is important to note that corrected age around 40 gestational weeks was used (O'Neill, 2005), and the new atlas should be interpreted with this in mind. Birth is not an age, but an event that has no effect on dental formation stage (Backstrom et al., 2000; Paulsson et al., 2004; Ramos et al., 2006). If a child is born at 36 weeks and survives 1 month, its dental development will correspond to a full-term dentition.

Eruption in this atlas refers to emergence from *alveolar bone*, which contrasts to Ubelaker's atlas (Ubelaker, 1978) where "eruption refers to emergence through the gum, not to emergence from the bone or to reaching the

TABLE 11. Median age (years) of eruption for permanent teeth (combined sex)[a]

	Maxilla					Mandible				
Tooth	Alveolar eruption	Clinical emergence[b] Boys	Clinical emergence[b] Girls	Full eruption		Tooth	Alveolar eruption	Clinical emergence[b] Boys	Clinical emergence[b] Girls	Full eruption
I^1	6.5	6.9	6.7	7.5		I_1	5.5	6.3	6.2	7.5
I^2	7.5	8.3	7.8	9.5		I_2	6.5	7.3	6.8	7.5
C'	11.5	12.1	10.6	12.5		C_1	9.5	10.4	9.2	11.5
P^1	10.5	10.2	9.6	11.5		P_1	10.5	10.3	9.6	11.5
P^2	11.5	11.4	10.2	12.5		P_2	11.5	11.1	10.1	12.5
M^1	5.5	6.4	6.4	6.5		M_1	5.5	6.3	6.3	6.5
M^2	10.5	12.8	12.4	13.5		M_2	10.5	12.2	11.4	12.5
M^3	16.5	–	–	20.5		M_3	16.5	–	–	20.5

[a] Midpoint of 1 year.
[b] From Haavikko (1970).

occlusal plane". Allowance should be made for gingival eruption when using this atlas in the presence of oral soft tissues (see Tables 10 and 11).

ACKNOWLEDGMENTS

We are grateful to Robert Kruszynski at the Human Origins Group, Paleontology Department, Natural History Museum, London, for access to the Spitalfield's Collection. Theya Molleson also contributed to the development of Figure 6 in our choice of age groups for younger individuals. We also thank Milly Farrell, Assistant Curator of the Odontological Collection, and Simon Chaplin, Senior Curator of the Museums of The Royal College of Surgeons of England, for access to Stack's collection of fetal and neonatal teeth.

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Appendix 10: Ethical approval:

Queen Mary Research Ethics Committee

To: Dr Helen Liversidge (Principal Investigator)

Mr Sakher Jaber AlQahtani

Ref no: QMREC2009/14
Title of study: Atlas of tooth development and eruption was considered by QMREC on 13th May 2009
The Committee **approved** this proposal (with an advisory point).
The Committee advised that:- The researcher should make it clear; when writing up his research; by what method he selected specific radiographs (out of all of the collection available) to be given to the participants in all of the experimental groups. Subject to this point being made the researcher, the Committee **approved** this proposal.
Further action: None. In the event of any problems or queries, do not hesitate to contact Ms Covill direct – 020 7882 2207 or ext. 5070.
Signed: Hazel Covill, Secretary to QMREC (on behalf of the Committee) Dated: 19th May 2009

Appendix 11: Pilot survey

Atlas of tooth development and eruption

Dear Mr. /Ms.

We would like to invite you to be part of this research project, if you would like to.

Please ask if there is anything that is not clear or if you would like more information.

If you decide to take part, please make sure that you signed the attached form to say that you agree.

You are still free to withdraw at any time and without giving a reason.

This is a survey on methods of age estimation by using developing teeth.

Please fill in the first 4 pages according to your previous experience in age estimation.

Then you will find attached photocopies of 6 radiographs and be asked to estimate the age of each individual according to an attached method; and you will be asked to fill the rest of the questionnaire regarding your experience with it.

It is up to you to decide whether or not to take part in this survey. Please ask if there is anything that is not clear or if you would like more information.

Best wishes

Please circle the appropriate answer:

Please indicate your gender:

Female

Male

Prefer not to answer

Which range includes your age?

18 - 24

25 - 34

35 - 44

45 - 54

55 - 64

65 or older

Prefer not to answer

Rank what is most important to you in any method of age estimation:

Convenience

Accuracy

Reproducibility

Need of training

Time needed to do age estimation

Availability

How long have you been doing age estimation?

Never ⟶ *go to page 94*

Less than 6 months

1 year to less than 3 years

3 years to less than 5 years

5 years or more

How often do you use age estimation methods?

Very frequently

Frequently

Was not aware of

Infrequently

Very infrequently

Which of age estimation methods do you use?

Demirjian et al (1973)

Gustafson and Koch (1974)

Haavikko (1970)

Liliequist and Lundberg (1971)

Moorrees et al (1963)

Root width

Schour and Massler atlas of (1941)

Tooth eruption

Tooth length

Other: ____

Please indicate your reasons for using this method in the past:

more accurate

easier to use

easy access to it

Better understanding of it

Other: ____

How would you rate your overall satisfaction with the method you have been using?

Very satisfied

Somewhat satisfied

Neutral

Somewhat dissatisfied

Very dissatisfied

Did you receive any kind of training to use that method of age estimation?

Yes

No

How often do you look for new methods for age estimation?

Always

Frequently

Sometimes

Rarely

Never

You will find attached 6 photocopied radiographs of different individuals.

Please use the attached method to estimate the age of each individual then answer the following questions:

How long did it take you to figure out how to do age estimation using attached method?

Less than 1 minute

1 to less than 3 minutes

3 to less than 5 minutes

5 to less than 10 minutes

10 minutes or over

How long did it take you to do age estimation for each radiograph?

Less than 5 minutes

5 minutes to less than 10 minutes

10 minutes to less than 20 minutes

20 minutes to less than 30 minutes

30 minutes or more

More than a day

Could not do age estimation with this method

Please rate the attached method on the following attributes:

Design:

Very satisfied

Somewhat satisfied

Neutral

Somewhat dissatisfied

Very dissatisfied

Clarity:

Very satisfied

Somewhat satisfied

Neutral

Somewhat dissatisfied

Very dissatisfied

Simplicity:

Very satisfied

Somewhat satisfied

Neutral

Somewhat dissatisfied

Very dissatisfied

Very dissatisfied

Self explanatory:

Very satisfied

Somewhat satisfied

Neutral

Somewhat dissatisfied

Very dissatisfied

How relevant do you find this method in your field of work?

Very relevant

Somewhat relevant

Not at all relevant

Please complete the following:

This method of age estimation ….

is better than expected

Matches expectations

is worse than expected

How likely are you to continue using this method?

Very likely

Somewhat likely

Neutral

Somewhat unlikely

Very unlikely

How likely is it that you would recommend this method to a friend/colleague?

Very likely

Somewhat likely

Neutral

Somewhat unlikely

Very unlikely

How likely are you to use a different method that you think is better than this method?

Very likely

Somewhat likely

Neutral

Somewhat unlikely

Very unlikely

Is there an unaddressed need that this method should focus on?

No

Yes: ____

Do you have any suggestions for improving this method?

____
____
____
____
____
____

Appendix 12: Survey on methods of age estimation by using teeth.

Please fill in the first 4 pages according to your previous experience in age estimation.

Then you will be given a set of radiographs and be asked to estimate the age of each individual according to an attached atlas; and you will be asked to fill the rest of the questionnaire regarding your experience with it.

It is up to you to decide whether or not to take part in this survey. Please ask if there is anything that is not clear or if you would like more information.

Please circle the answer most closely match your personal opinions:

Please indicate your gender:

Female

Male

Prefer not to answer

Which range includes your age?

Younger than 18

18 - 24

25 - 34

35 - 44

45 - 54

55 - 64

65 or older

Prefer not to answer

How long have you been doing age estimation?

Never

Less than 6 months

1 year to less than 3 years

3 years to less than 5 years

5 years or more

How often do you use age estimation methods?

Very frequently

Frequently

Was not aware of

Infrequently

Very infrequently

Do not use

Rank what is most important to you in any method of age estimation:

Convenience

Accuracy

reproducibility

need of training

Time consumption

Availability

Which of age estimation methods do you usually use?

Do not use

Demirjian et al (1973)

Gustafson and Koch (1974)

Haavikko (1970)

Liliequist and Lundberg (1971)

Moorrees et al (1963)

Root width

Schour and Massler atlas of (1941)

Tooth eruption

Tooth length

Other: ____

Please indicate your reasons for using this method:

more accurate

easier to use

easy access to it

Better understanding of it

Other: ____

How would you rate your overall satisfaction with the method you have been using in the past?

Very satisfied

Somewhat satisfied

Neutral

Somewhat dissatisfied

Very dissatisfied

Did you receive any kind of training to use the method of age estimation that you have been using in the past?

Yes

No

How often do you look for new methods for age estimation?

Always

Frequently

Sometimes

Rarely

Never

Now please use the attached atlas of tooth development and eruption to estimate the age of the individuals given then answer the following questions:

Radiograph No.	Age estimation	Radiograph No.	Age estimation
1		**2**	
3		**4**	
5		**6**	
7			

How long did it take you to understand how to use the atlas?

Less than 1 minute

1 to less than 3 minutes

3 to less than 5 minutes

5 to less than 10 minutes

10 minutes or over

How long did it take you to do age estimation using the atlas for each sample?

Less than 5 minutes

5 minutes to less than 10 minutes

10 minutes to less than 20 minutes

20 minutes to less than 30 minutes

30 minutes or more

Could not do age estimation with this atlas

Please rate the atlas on the following attributes

Design:

Very satisfied

Somewhat satisfied

Neutral

Somewhat dissatisfied

Very dissatisfied

Simplicity:

Very satisfied

Somewhat satisfied

Neutral

Somewhat dissatisfied

Very dissatisfied

Clarity:

Very satisfied

Somewhat satisfied

Neutral

Somewhat dissatisfied

Very dissatisfied

Self explanatory:

Very satisfied

Somewhat satisfied

Neutral

Somewhat dissatisfied

Very dissatisfied

How relevant do you find this atlas in your field of work?

Very relevant

Somewhat relevant

Not at all relevant

Please complete the following sentence:

This atlas of tooth development and eruption….

Was better than expected

Matched expectations

Was worse than expected

How likely are you to continue using this atlas?

Very likely

Somewhat likely

Neutral

Somewhat unlikely

Very unlikely

How likely is it that you would recommend this atlas to a friend/colleague?

Very likely

Somewhat likely

Neutral

Somewhat unlikely

Very unlikely

How likely are you to use the old method that you have been using in the past again?

Very likely

Somewhat likely

Neutral

Somewhat unlikely

Very unlikely

Is there an unaddressed need that the atlas should focus on?

No

Yes: ____

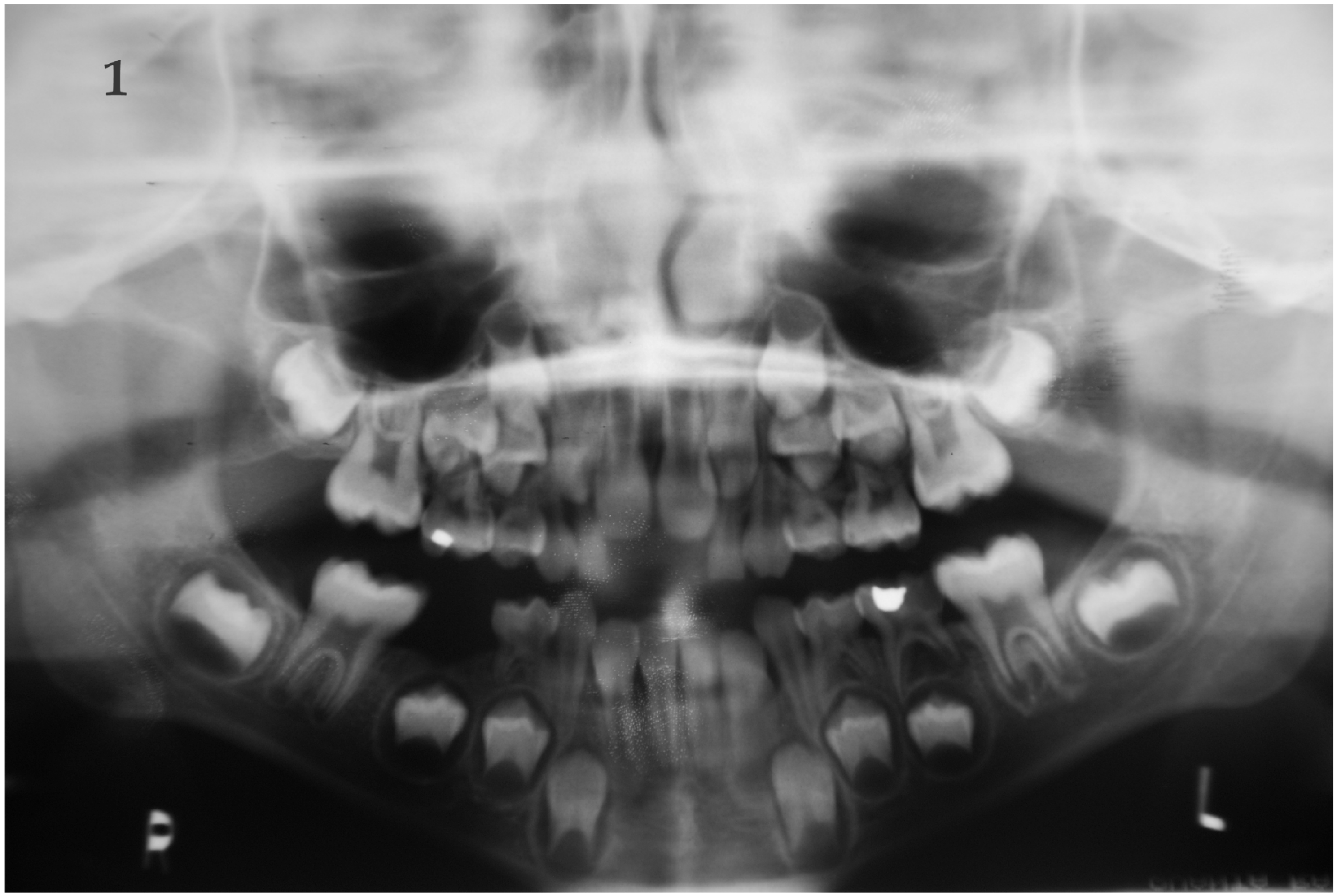
Do you have any suggestions for improving this atlas?

____

____
____
____
____
____
____

Thank you for taking part in this survey

Appendix 13: an example of the dental panoramic radiographs used in the survey.



Appendix 14: current uses of The London Atlas.

Meetings that featured The London Atlas:

- **2011** British Society for Oral and Dental Research, Sheffield, UK
- **2011** The 15th International Symposium on Dental Morphology, Newcastle, UK
- **2010** The International Organisation of Forensic Odontology meeting; Leuven, Belgium
- **2010** The 1835th Scientific Meeting of the Anthropological Society of Paris Brussels Institute (Museum) Royal Natural Science, Brussels, Belgium
- **2010** William Harvey Day, London, UK
- **2010** Dubai International Dental Conference, UAE
- **2010** The 7th international congress on the archaeology on the ancient near east, The British museum, London, UK
- **2010** American Association of Physical Anthropology, New Mexico, USA
- **2010** Society for the Study of Human Biology, London, UK
- **2009** British Association of Forensic Odontology, Edinburgh, UK
- **2009** The only Dentist selected to be a science ambassador in the Big Bang event to excite, educate, stimulate and enthuse young people about opportunities in science and to encourage them to follow careers in science
- **2008** Presented in the Human Identification course organised by the Met Police and Queen Mary University of London, London, UK
- **2008** The London Oral Biology Club, QMUL, London, UK
- **2008** Presented in the 3rd International Saudi Conference, Surry, UK

- **2007** Presented in the Saudi Innovation Conference, Newcastle, UK

Workshops that utilized The London Atlas:

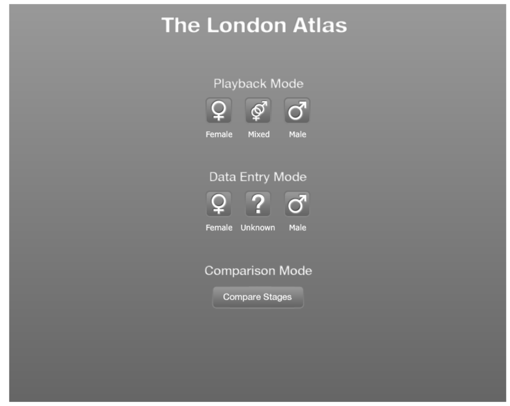
- **2011** Dental Age Estimation workshop: American Academy of Forensic Sciences meeting, Chicago, USA
- **2010** workshop called: 'Human remains in the Ancient Near East: Advances, problems and potential' in The 7th international congress on the archaeology on the ancient near east, The British museum, London, UK
- **2010** Dental Age Estimation workshop: The International Organisation of Forensic Odontology meeting; Leuven, Belgium.
- **2009** Dental Anthropology Short Course, The Biological Anthropology Research Centre, Archaeological Sciences, University of Bradford
- **2009** Postgraduate teaching course, Department of Bioarchaeology, Institute of Archaeology, University of Warsaw, Poland

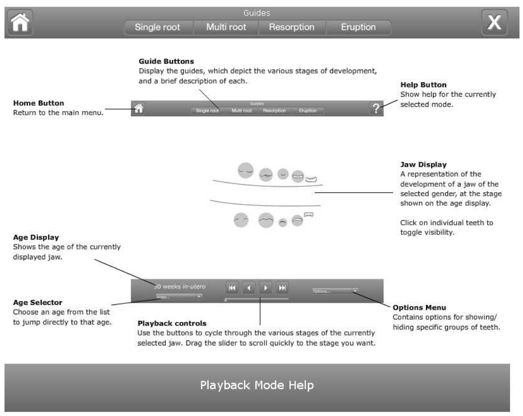
Awards received for The London Atlas:

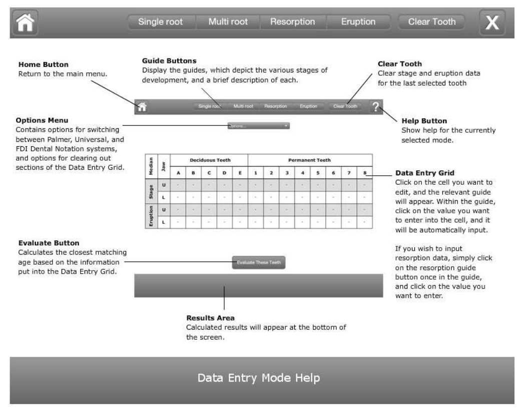
- **2010** Received the high achievement award from the Ministry of Higher Education, Saudi Arabia. The award was given by the Saudi Ambassador H.R.H Prince Mohammed bin Nawaf Al-Saud
- **2010** Won the first prize by the Society for the Study of Human Biology, London
- **2010** The researcher (SA) was selected to be an honorary member of the Royal College of Surgeons of England

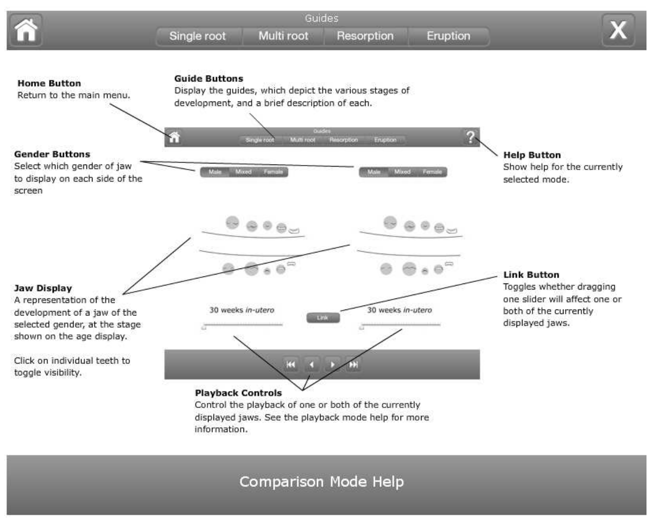
- **2009** Best research award in the UK and Ireland by a Saudi student, Saudi Cultural Bureau, London, UK
- **2008** Semi-finalist for the President's prize, Royal College of Surgeons of England, London, UK
- **2008** Awarded a scientific excellence Award by the 3^{rd} International Saudi Conference, Surry, UK
- **2007** Awarded by the Saudi Innovation Conference, Newcastle, UK

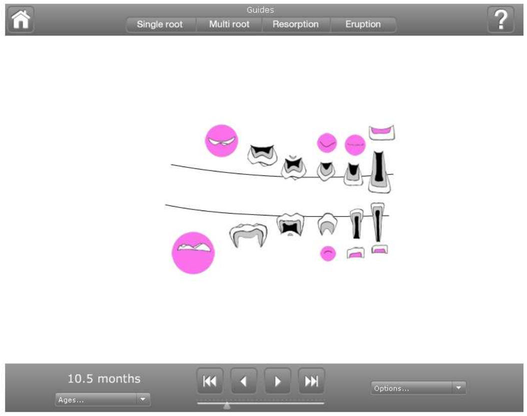
Appendix 15: The London Atlas primary software

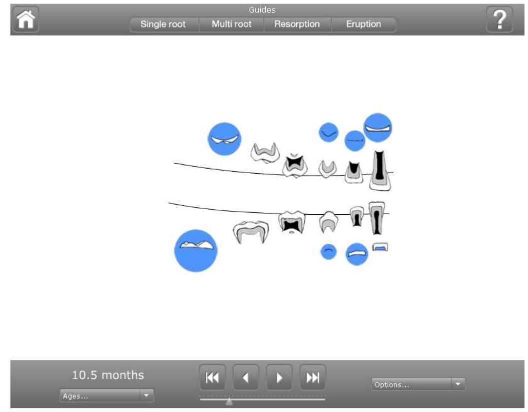


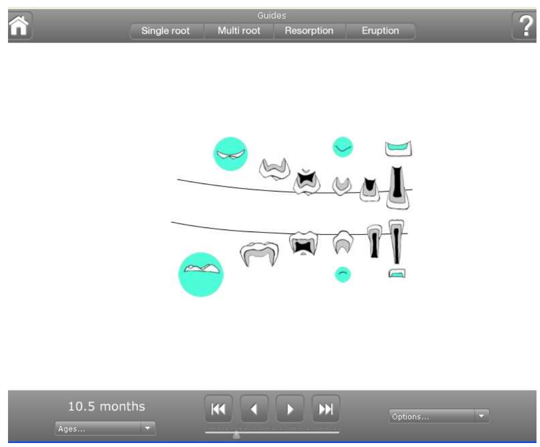


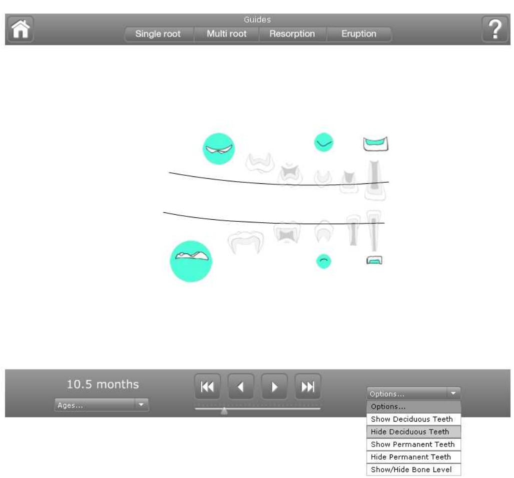


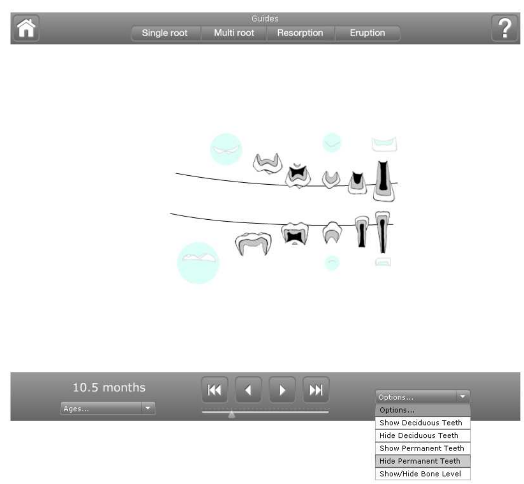


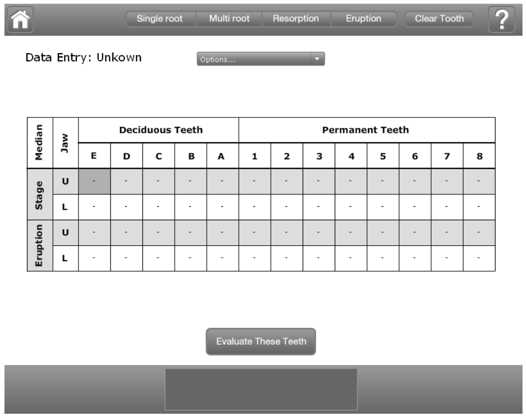

Guides
Single root
Multi root
Resorption
Eruption
10.5 months
Ages...
Options...

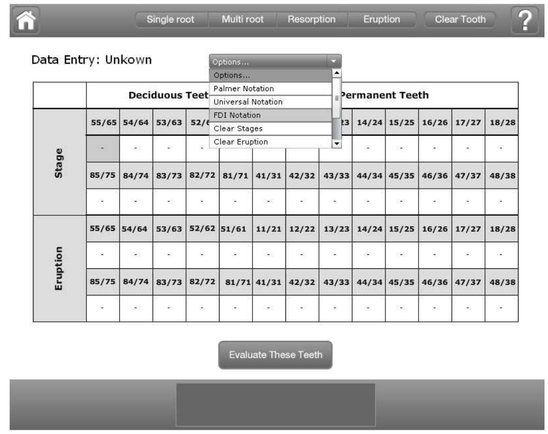

Guides
Single root
Multi root
Resorption
Eruption
10.5 months
Ages...
Options...

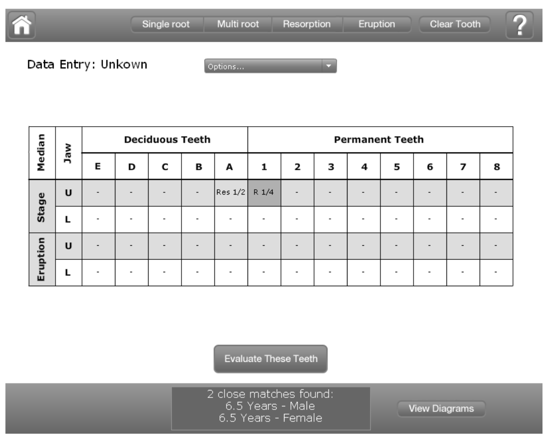

Guides
Single root
Multi root
Resorption
Eruption
10.5 months
Ages...
Options...

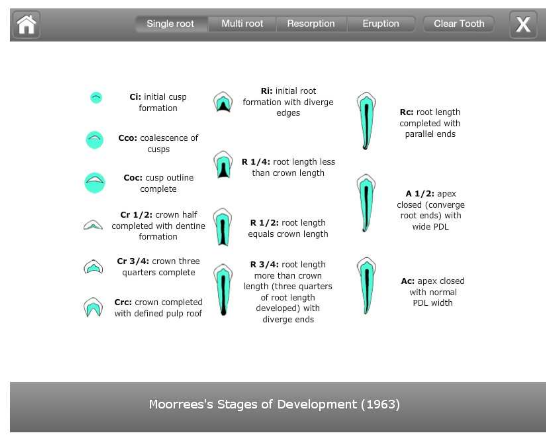

Guides
Single root
Multi root
Resorption
Eruption
10.5 months
Ages...
Options...
Options...
Show Deciduous Teeth
Hide Deciduous Teeth
Show Permanent Teeth
Hide Permanent Teeth
Show/Hide Bone Level

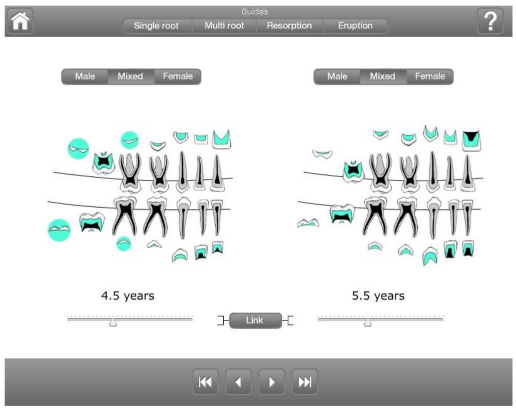

Guides
Single root
Multi root
Resorption
Eruption
10.5 months
Ages...
Options...
Options...
Show Deciduous Teeth
Hide Deciduous Teeth
Show Permanent Teeth
Hide Permanent Teeth
Show/Hide Bone Level

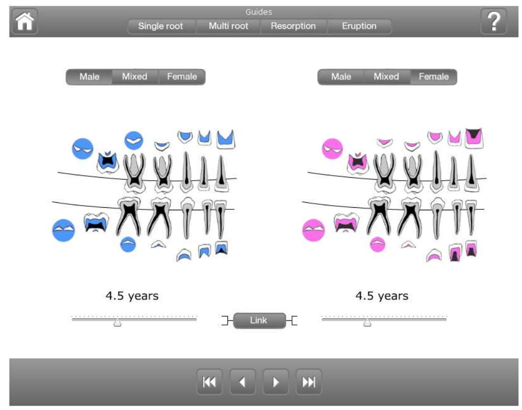

Single root
Multi root
Resorption
Eruption
Clear Tooth
Data Entry: Unkown
Options...
Deciduous Teeth
Permanent Teeth
Median
Jaw
Stage
Eruption
Evaluate These Teeth

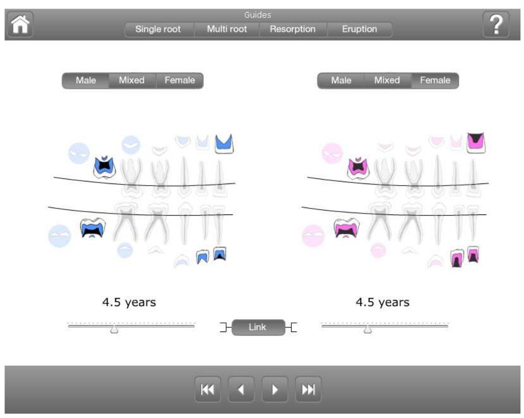

Single root
Multi root
Resorption
Eruption
Clear Tooth
Data Entry: Unkown
Options...
Palmer Notation
Universal Notation
FDI Notation
Clear Stages
Clear Eruption
Deciduous Teeth
Permanent Teeth
Stage
Eruption
Evaluate These Teeth

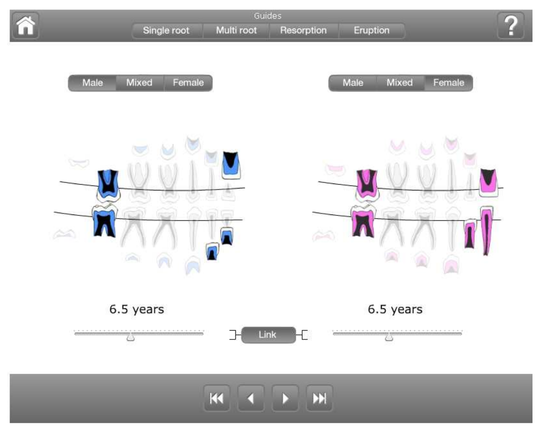

Single root
Multi root
Resorption
Eruption
Clear Tooth
Data Entry: Unkown
Options...
Deciduous Teeth
Permanent Teeth
Median
Jaw
Stage
Eruption
Res 1/2
R 1/4
Evaluate These Teeth
2 close matches found:
6.5 Years - Male
6.5 Years - Female
View Diagrams


Single root
Multi root
Resorption
Eruption
Clear Tooth
Ci: initial cusp formation
Cco: coalescence of cusps
Coc: cusp outline complete
Cr 1/2: crown half completed with dentine formation
Cr 3/4: crown three quarters complete
Crc: crown completed with defined pulp roof
Ri: initial root formation with diverge edges
R 1/4: root length less than crown length
R 1/2: root length equals crown length
R 3/4: root length more than crown length (three quarters of root length developed) with diverge ends
Rc: root length completed with parallel ends
A 1/2: apex closed (converge root ends) with wide PDL
Ac: apex closed with normal PDL width
Moorrees's Stages of Development (1963)


Guides
Single root
Multi root
Resorption
Eruption
Male
Mixed
Female
Male
Mixed
Female
4.5 years
5.5 years
Link


Guides
Single root
Multi root
Resorption
Eruption
Male
Mixed
Female
Male
Mixed
Female
4.5 years
4.5 years
Link


Guides
Single root
Multi root
Resorption
Eruption
Male
Mixed
Female
Male
Mixed
Female
4.5 years
4.5 years
Link


Guides
Single root
Multi root
Resorption
Eruption
Male
Mixed
Female
Male
Mixed
Female
6.5 years
6.5 years
Link

Appendix 16: Online questionnaire

Please complete this short feedback questionnaire after you explore The London Atlas application:

Name [ ]

Do you want your feedback to be quoted?

( ) Yes ( ) No

You work in (choose more than one if applicable):

[ ] Teaching Institute [ ] Archaeology [ ] Anatomy [ ] Forensics

[ ] Anthropology [ ] Clinical Dentistry [ ] Health sciences

[ ] Other [ ]

1. How often do you deal with dental development:

( ) Daily ( ) Weekly ( ) Monthly ( ) Yearly ( ) Always ( ) Sometimes ( ) Never

2. Which of these statements applies to you?

( ) I prefer interactive electronic applications

( ) I prefer to work from a hard copy

3. Does The London Atlas application reduce time needed for age estimation compared to other methods?

☐ Yes ☐ No ☐ I don't know

- Reason

- What methods do you usually use?

4. Does The London Atlas application make age estimation easier than using other methods?

☐ Yes ☐ No ☐ I don't know

- Reason

5. Could The London Atlas application provide a good teaching aid?

☐ Yes ☐ No ☐ I don't know

- Reason

6. Would you recommend The London Atlas application to colleagues and/or students?

☐ Yes ☐ No

7. With respect to the application, how useful was each section to you?

Playback mode

☐ Not useful ☐ Somewhat useful ☐ Useful ☐ Very useful ☐ Most useful

Data entering mode

☐ Not useful ☐ Somewhat useful ☐ Useful ☐ Very useful ☐ Most useful

Comparison mode

☐ Not useful ☐ Somewhat useful ☐ Useful ☐ Very useful ☐ Most useful

Tooth development guides

☐ Not useful ☐ Somewhat useful ☐ Useful ☐ Very useful ☐ Most useful

8. Would you prefer to use The London Atlas application through a website rather than a personal copy?

☐ Yes ☐ No

9. Would you buy a license to use The London Atlas application?

☐ Yes ☐ No

10. In your opinion, do you think it would be appropriate to pay to use this program?

☐ Yes ☐ No

11. If so, which groups/categories of individuals should pay (Choose more than one if applicable)?

☐ Academic, teaching institutions

☐ Human Identification agencies

☐ Undergraduate/Postgraduate students

☐ Child care agencies/Social services

☐ Researchers centers

☐ Health agencies

☐ Police/Immigration agencies

☐ Other ____________

12. Do you think The London Atlas application is applicable for (Choose more than one if applicable):

- ☐ Undergraduate students
- ☐ Postgraduate students
- ☐ Researchers
- ☐ Forensic scientists
- ☐ Human Identification agencies
- ☐ Pathologists
- ☐ Schools
- ☐ Child care agencies/Social services
- ☐ Dental Clinics/ GP clinics
- ☐ Police/Immigration
- ☐ Other ______

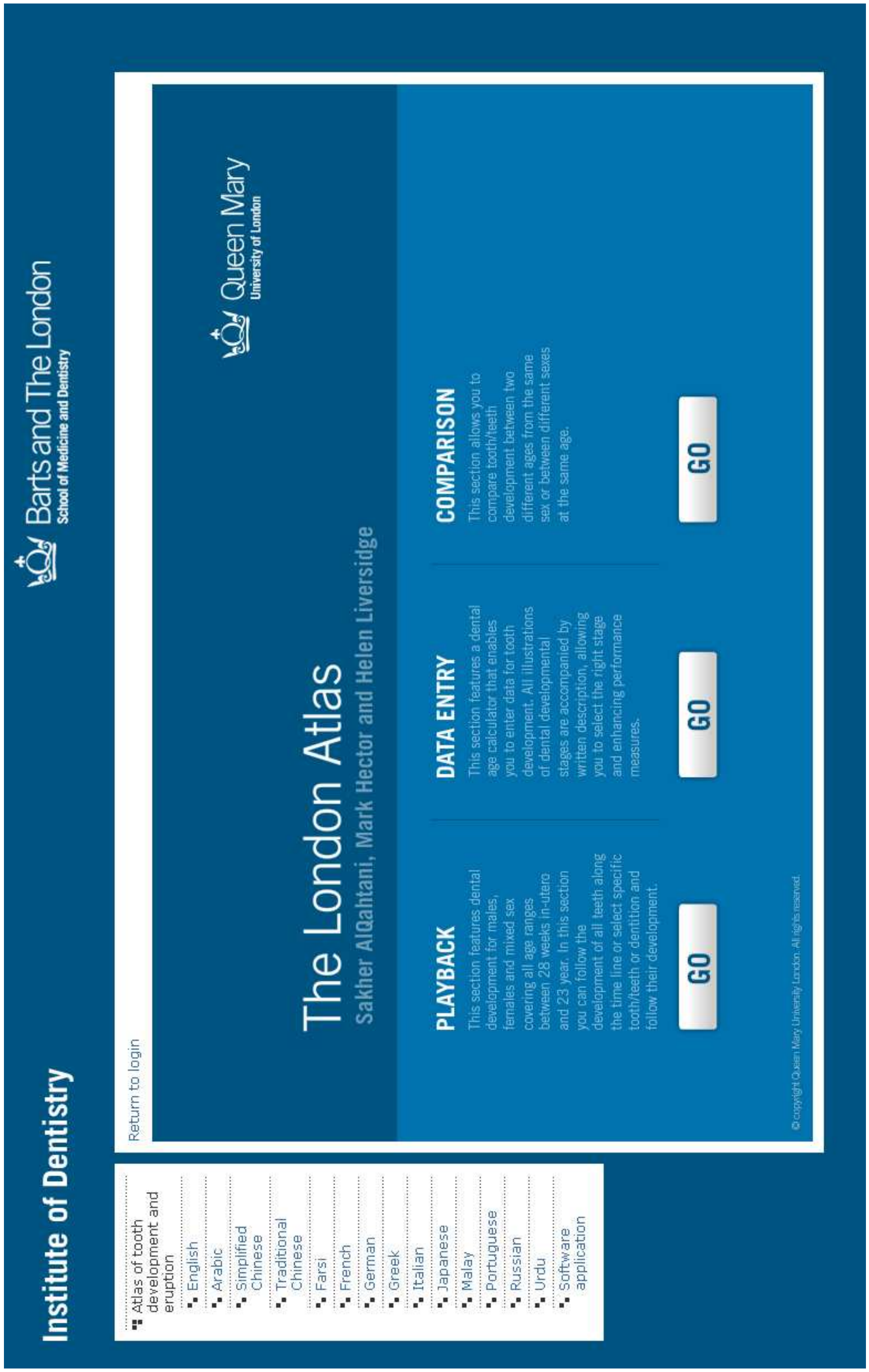
13. Do you have any other comments or suggestions regarding The London Atlas application?

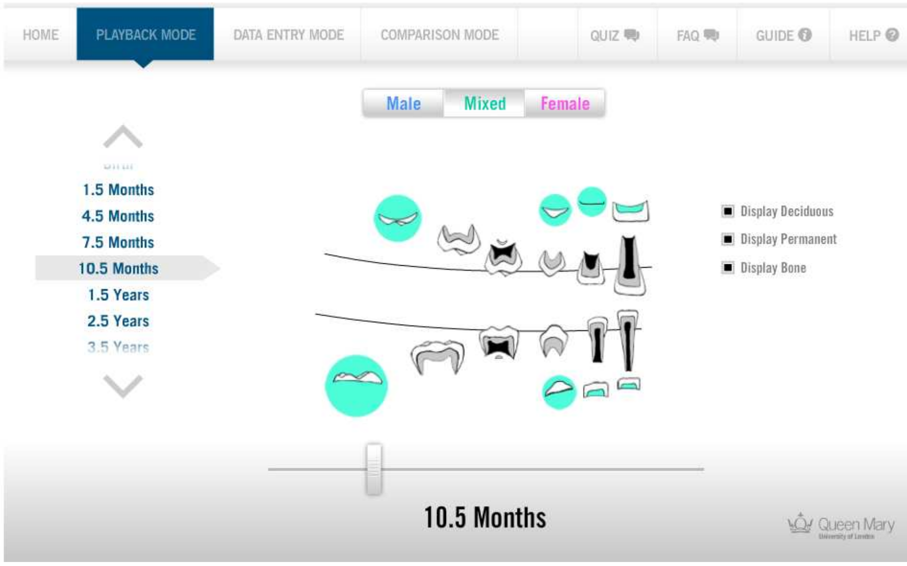
______

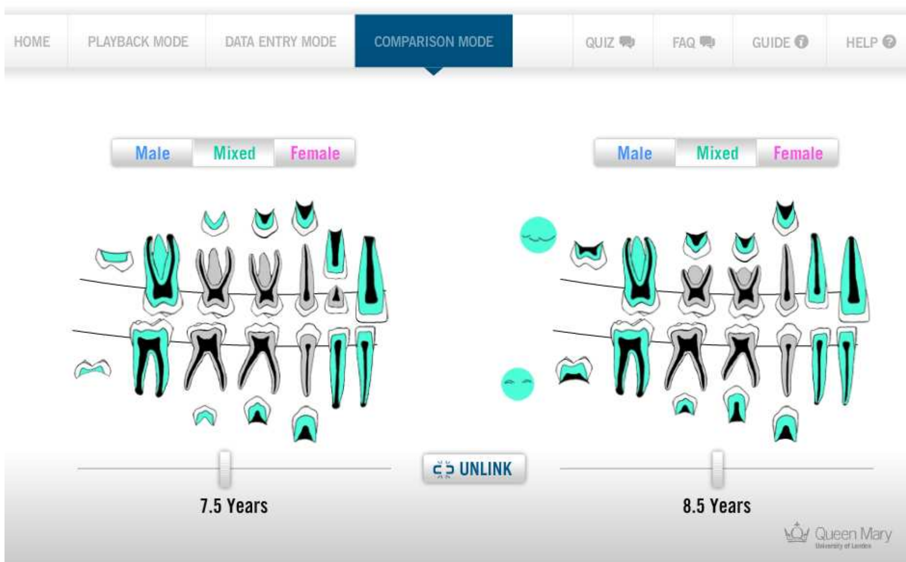
14. Compared to other age estimation systems available, how much should be charged for the London Atlas application?

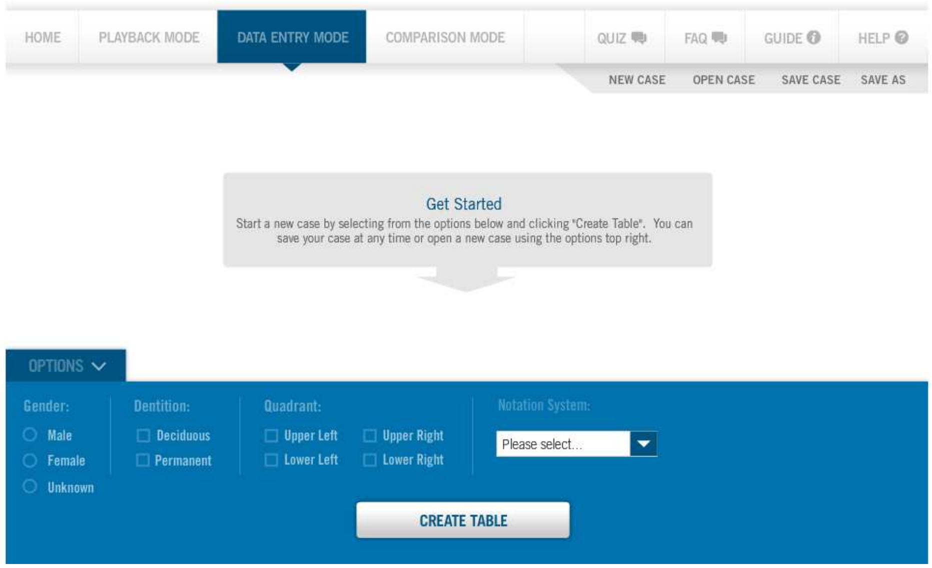
○ Less ○ Similar amount ○ More

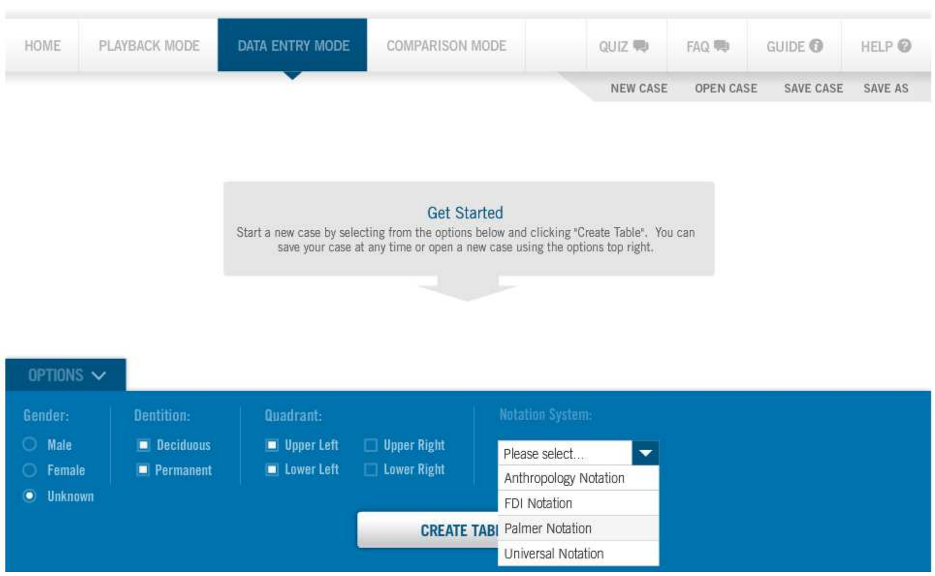
Appendix 17: The new version of The London Atlas software program.

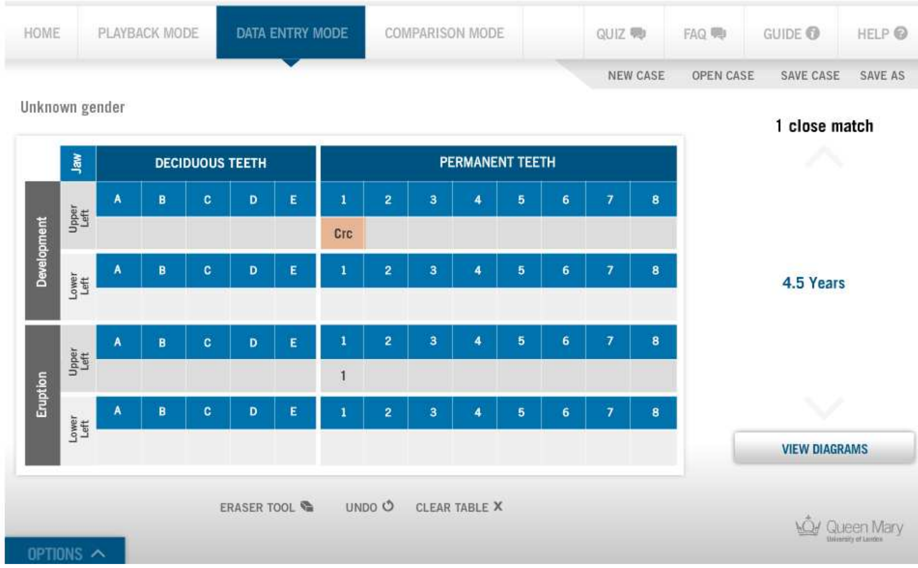



HOME
PLAYBACK MODE
DATA ENTRY MODE
COMPARISON MODE
QUIZ
FAQ
GUIDE
HELP
Male
Mixed
Female
1.5 Months
4.5 Months
7.5 Months
10.5 Months
1.5 Years
2.5 Years
3.5 Years
Display Deciduous
Display Permanent
Display Bone
10.5 Months
Queen Mary

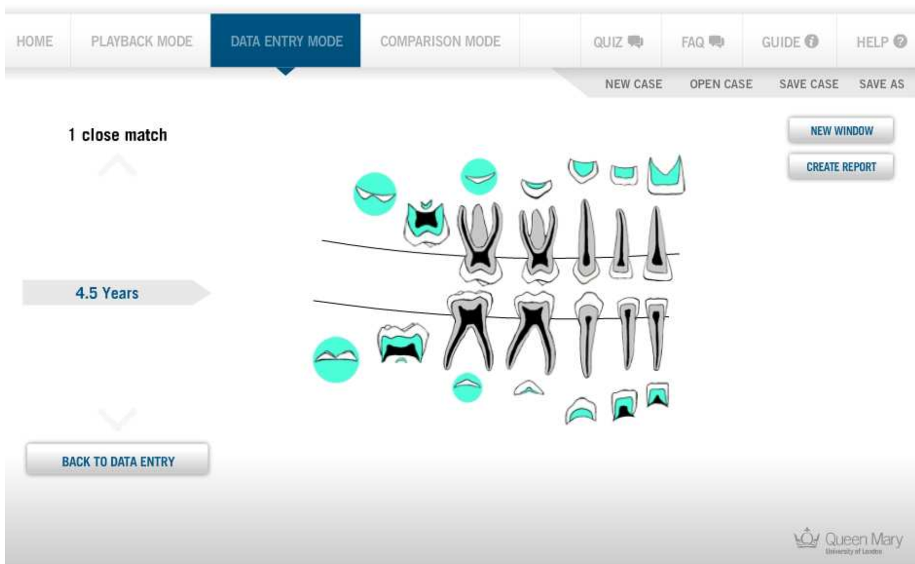

HOME
PLAYBACK MODE
DATA ENTRY MODE
COMPARISON MODE
QUIZ
FAQ
GUIDE
HELP
Male
Mixed
Female
Male
Mixed
Female
UNLINK
7.5 Years
8.5 Years
Queen Mary


HOME
PLAYBACK MODE
DATA ENTRY MODE
COMPARISON MODE
QUIZ
FAQ
GUIDE
HELP
NEW CASE
OPEN CASE
SAVE CASE
SAVE AS
Get Started
Start a new case by selecting from the options below and clicking "Create Table". You can save your case at any time or open a new case using the options top right.
OPTIONS
Gender:
Male
Female
Unknown
Dentition:
Deciduous
Permanent
Quadrant:
Upper Left
Upper Right
Lower Left
Lower Right
Notation System:
Please select...
CREATE TABLE

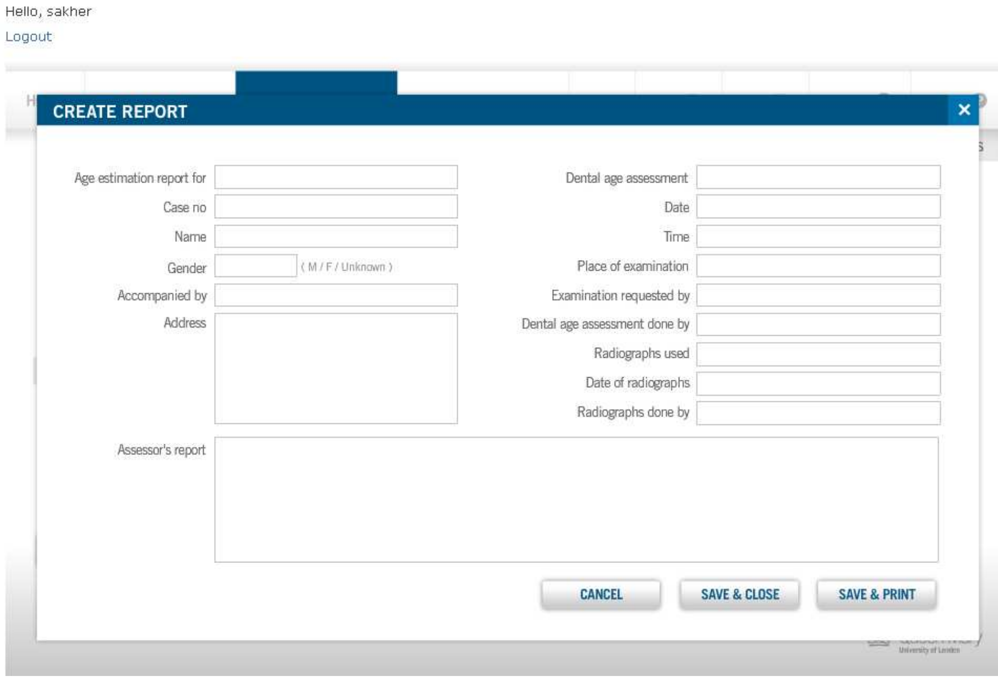

HOME
PLAYBACK MODE
DATA ENTRY MODE
COMPARISON MODE
QUIZ
FAQ
GUIDE
HELP
NEW CASE
OPEN CASE
SAVE CASE
SAVE AS
Get Started
Start a new case by selecting from the options below and clicking "Create Table". You can save your case at any time or open a new case using the options top right.
OPTIONS
Gender:
Male
Female
Unknown
Dentition:
Deciduous
Permanent
Quadrant:
Upper Left
Upper Right
Lower Left
Lower Right
Notation System:
Please select...
Anthropology Notation
FDI Notation
Palmer Notation
Universal Notation
CREATE TABL



HOME
PLAYBACK MODE
DATA ENTRY MODE
COMPARISON MODE
QUIZ
FAQ
GUIDE
HELP
NEW CASE
OPEN CASE
SAVE CASE
SAVE AS
Unknown gender
1 close match
Jaw
DECIDUOUS TEETH
PERMANENT TEETH
Development
Upper Left
Lower Left
Eruption
A B C D E
1 2 3 4 5 6 7 8
Crc
1
4.5 Years
VIEW DIAGRAMS
ERASER TOOL
UNDO
CLEAR TABLE X
OPTIONS
Queen Mary



HOME
PLAYBACK MODE
DATA ENTRY MODE
COMPARISON MODE
QUIZ
FAQ
GUIDE
HELP
NEW CASE
OPEN CASE
SAVE CASE
SAVE AS
1 close match
NEW WINDOW
CREATE REPORT
4.5 Years
BACK TO DATA ENTRY
Queen Mary


Hello, sakher
Logout
CREATE REPORT
Age estimation report for
Case no
Name
Gender
(M / F / Unknown)
Accompanied by
Address
Dental age assessment
Date
Time
Place of examination
Examination requested by
Dental age assessment done by
Radiographs used
Date of radiographs
Radiographs done by
Assessor's report
CANCEL
SAVE & CLOSE
SAVE & PRINT

Appendix 18: List of countries that accessed the London Atlas software program since May 2012

Statistics for:
www.atlas-dentistry.qmul.ac.uk

Summary
When:
Monthly history
Days of month
Days of week
Hours
Who:
Countries
- Full list

Hosts
- Full list
- Last visit
- Unresolved IP Address

Robots/Spiders visitors
- Full list
- Last visit

Navigation:
Visits duration
File type
Viewed
- Full list
- Entry
- Exit

Operating Systems
- Versions
- Unknown

Browsers
- Versions
- Unknown

Referrers:
Origin
- Referring search engines
- Referring sites

Search
- Search Keyphrases
- Search Keywords

Others:
Miscellaneous
HTTP Status codes
- Pages not found

United Kingdom	uk	968	2560	294.38 MB
Network	net	873	1853	391.19 MB
Australia	au	435	765	239.13 MB
Spain	es	259	397	87.74 MB
France	fr	120	206	51.66 MB
Finland	fi	119	206	31.27 MB
Israel	il	107	209	36.93 MB
Canada	ca	101	185	35.54 MB
Netherlands	nl	94	170	40.58 MB
USA Educational	edu	85	154	29.96 MB
New Zealand	nz	83	140	31.89 MB
Greece	gr	58	104	34.03 MB
Colombia	co	52	92	14.27 MB
Switzerland	ch	50	125	20.77 MB
Italy	it	47	83	24.14 MB
Germany	de	46	83	19.58 MB
Portugal	pt	34	72	21.52 MB
Belgium	be	34	60	17.59 MB
Venezuela	ve	33	57	15.74 MB
Paraguay	py	29	42	12.34 MB
Turkey	tr	28	47	11.19 MB
Japan	jp	23	37	2.92 MB
Chile	cl	22	40	7.28 MB
Peru	pe	22	34	10.16 MB
Norway	no	20	39	421.52 KB
Argentina	ar	18	34	7.03 MB
Brazil	br	17	36	13.26 MB
Croatia	hr	17	26	9.74 MB
Pakistan	pk	15	28	2.93 MB
Ireland	ie	14	28	9.93 MB
Cyprus	cy	14	22	4.21 MB
Poland	pl	14	26	7.76 MB
Saudi Arabia	sa	13	32	5.02 MB
United Arab Emirates	ae	13	23	2.83 MB
Yemen	ye	10	14	4.09 MB
Guatemala	gt	10	19	2.38 MB
USA Military	mil	9	20	4.10 MB
Nicaragua	ni	9	14	2.28 MB
Republic of Serbia	rs	8	13	2.39 MB
India	in	8	19	4.37 MB
Denmark	dk	8	19	2.29 MB
South Africa	za	8	12	4.35 MB
USA Government	gov	8	17	8.15 MB
Russian Federation	ru	6	10	4.34 MB
Mexico	mx	5	15	4.60 MB
Uruguay	uy	5	10	4.55 MB
Lithuania	lt	4	7	4.23 MB
Malaysia	my	3	6	2.40 MB
Bulgaria	bg	3	6	227.49 KB
Taiwan	tw	2	6	1.91 MB
Unknown	adsl	2	2	7.70 KB
Czech Republic	cz	1	1	5.58 KB
Macedonia	mk	1	3	99.07 KB
Unknown	iad1	1	1	2.07 MB
Iran	ir	1	3	129.41 KB
United States	us	1	1	0
Ukraine	ua		3	1.91 MB
Others		0	0	0

Advanced Web Statistics 6.9 (build 1.925) - Created by awstats