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Dental Age Estimation of a Southern Nevada Hispanic Non-Adult Population Employing the London Atlas to Evaluate Archival Orthodontic Cone Beam Computed Tomography (CBCT) Images

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DENTAL AGE ESTIMATION OF A SOUTHERN NEVADA HISPANIC NON-ADULT POPULATION EMPLOYING THE LONDON ATLAS TO EVALUATE ARCHIVAL ORTHODONTIC CONE BEAM COMPUTED TOMOGRAPHY (CBCT) IMAGES

By

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Abstract

Age estimation is of societal importance for legal, forensic, and clinical reasons. The London Atlas of Human Tooth Development and Eruption, hereafter referred to as the London Atlas, was introduced as an improved method for determining dental age estimation. The London Atlas was developed from panoramic images of 528 living British Caucasian and Bangladeshi males and females aged 2 to 24 years and panoramic images of 176 archival human skeletal remains, aged 32 in utero to 2 years old, from two specimen collections (AlQahtani, Hector, & Liversidge, 2010). Further investigation is warranted to determine validity of the atlas's use in determining age estimation in specific ethnic subpopulations. Therefore, this project applied the use of the London Atlas to a Southern Nevada subadult Hispanic population to determine the validity of this technique as an instrument for age determination in this subpopulation. Additionally, since the London Atlas was developed using single plane, sagittal panoramic images, this study employed archival CBCT images of the chosen subpopulation (n=250, age range 8.5-20.7 years) to analyze tooth development stages from coronal, transverse, and sagittal projections to determine if CBCT technology can improve age estimation accuracy.

Estimated age (EA) was compared to true chronological age (TCA) and calculated chronological age (CCA). The latter represents the age ranges used by the London Atlas (AlQahtani et al., 2010). Data collected was analyzed using the following statistical analyses:

- paired t-test with a threshold of statistical significance set at $p < 0.05$ to evaluate age estimation accuracy,
- mean difference and absolute mean difference to calculate and evaluate bias and range of accuracy, respectively, and
- independent sample t-test to identify differences in age estimation accuracy between males and females.

A statistically significant bias of 0.30 years was found ($p< 0.001$), indicating a tendency to overestimate age in this population. The absolute mean difference was 1.0 years, indicating a range of accuracy of one year using the London Atlas. There was not a statistically significant difference of age estimation accuracy between males and females ($p= 0.408$). Results from this research indicated that mean difference and range of accuracy were not significantly improved compared to the AlQahtani research (mean difference= -0.1 years; absolute mean difference= 0.64 years) and other research analyzing the London Atlas (AlQahtani, Hector, & Liversidge, 2014; Alshihri, Kruger, & Tennant, 2015; Pavlović, Palmela Pereira, & Vargas de Sousa Santos, 2017; Baylis & Bassed, 2017; McCloe, Marion, da Fonseca, Colvard, & AlQahtani, 2018; Ghafari, Ghodousi, & Poordavar, 2018). Therefore, CBCT imaging for a Southern Nevada Hispanic male and female subadult population evaluated with the London Atlas does not significantly improve age estimation compared to panoramic images. Further research should be conducted to evaluate if an age estimation atlas developed from CBCT images instead of panoramic images would improve age estimation accuracy in other specific ethnic subpopulations.

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Chapter 1: Introduction

Age estimation is of societal importance for a number of legal, forensic, and clinical reasons. Human age estimation has been of interest since the early 1800's during England's Industrial Revolution when parliament enacted a child labor law setting the minimum working age at 9 years old and age verification for these children became necessary (Saunders, 1837). In the last several decades, relevance of age estimation has again become greatly important because of international refuge crises, human and migrant rights litigation, and individual and multiple fatality victim identification in forensic cases (Schmeling, Olze, Reisinger, & Geserick, 2004). This is especially true when related to age estimation of children (Schmeling, et al., 2004). Additionally, age estimation is important in medical and dental fields dealing with subadult populations (Demirjian, Goldstein, & Tanner, 1973).

AlQahtani in 2013 indicated that there are several methods available for age estimation, including the following:

- height/weight,
- secondary sex characteristics,
- bone development,
- analysis of the dentition, and
- social service assessments.

Each method has attributes and limitations. Thus, the Study Group for Forensic Age Diagnostics recommends a combination of physical examination, hand-wrist radiograph, and dental exam, including a panoramic radiograph for age estimation in criminal proceedings (Schmeling et al., 2004).

Use of the dentition addresses many desirable characteristics needed for age estimation. The dentition develops over a long period; has distinct stages over a short period of time; is minimally affected by environmental factors, socioeconomic stages, nutrition, diet and endocrine system stimuli; and survives after postmortem decomposition of soft tissues (AlQahtani, 2013). Because of these qualities the dentition is recognized as a useful tool for age determination. Both invasive and non-invasive dental methods have been employed in the determination of age estimation.

Invasive methods include the following:

- biomarkers,
- root dentine translucency, and
- incremental lines.

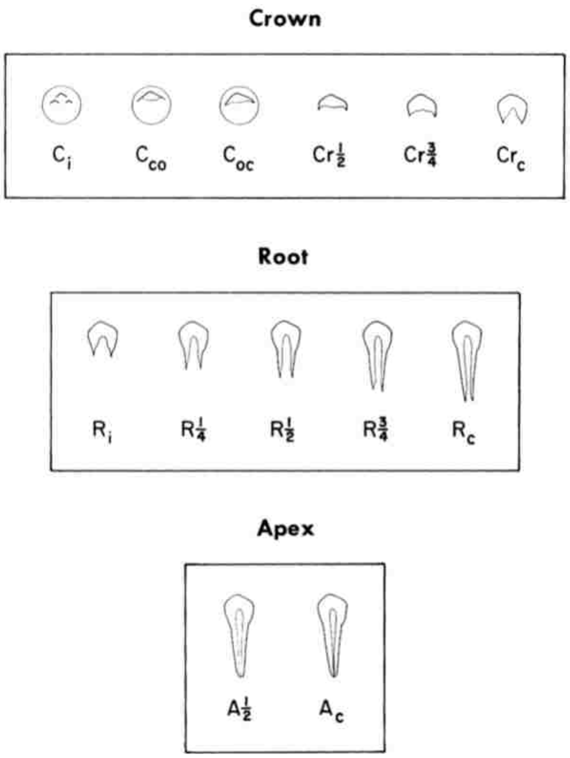
Invasive methods are complex, destructive, resource and knowledge extensive, and accurate for only a limited age range (AlQahtani, 2013). However, non-invasive estimation methods are more practical and harmless. Thus, they have become popular age estimation tools.

Non-invasive techniques include the following:

- sequential tooth eruption and/or emergence development by determination of calcification and/or root maturation,
- morphological tooth parameters, and
- tooth measurements.

Moorrees, Fanning, and Hunt developed a non-invasive dental age estimation tool in 1963 that continues to be a popularly utilized age estimation tool (Moorrees, Fanning, & Hunt, 1963). The researchers created and illustrated 14 arbitrary stages of tooth development from initial cusp formation to apex closing (Figure 1 & 2). When using the Moorrees, Fanning and Hunt technique for dental age estimation, the investigator assigns each tooth a stage based on its radiographic appearance. Developmental ratings are then correlated to age using a norm chart specific for gender (Moorrees et al., 1963). The rating of each tooth is taken into consideration to interpolate a final age estimation. Developmental stages created by Moorrees et al. are often modified for different age estimation techniques (AlQahtani, Hector, & Liversidge, 2010).

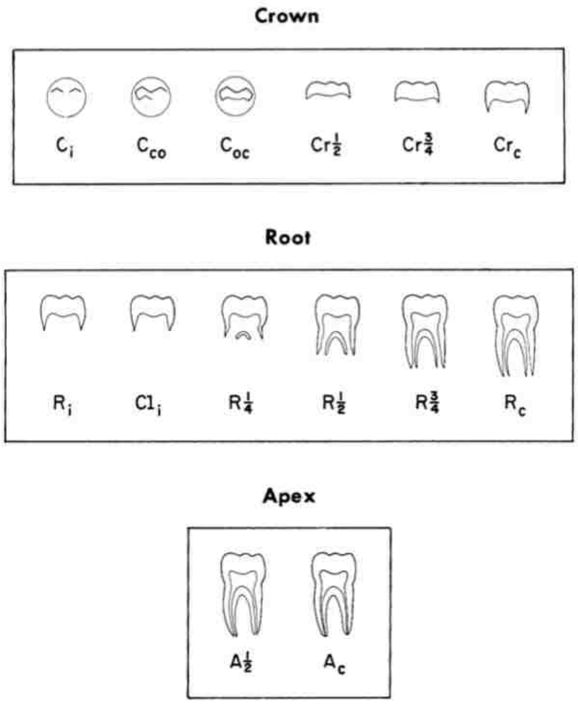
Figure 1. Moorrees, Fanning, and Hunt's stages of tooth formation for single-rooted teeth



TOOTH-FORMATION STAGES AND THEIR CODED SYMBOLS

Stage	Coded Symbol
Initial cusp formation	C_i
Coalescence of cusps	C_{co}
Cusp outline complete	C_{oc}
Crown ½ complete	$Cr_{\cdot 1/2}$
Crown ¾ complete	$Cr_{\cdot 3/4}$
Crown complete	$Cr_{\cdot c}$
Initial root formation	R_i
Initial cleft formation	$Cl_{\cdot i}$
Root length ¼	$R_{1/4}$
Root length ½	$R_{1/2}$
Root length ¾	$R_{3/4}$
Root length complete	R_c
Apex ½ closed	$A_{1/2}$
Apical closure complete	A_c

Figure 2. Moorrees, Fanning, and Hunt's stages of tooth formation for multi-rooted teeth



TOOTH-FORMATION STAGES AND THEIR CODED SYMBOLS

Stage	Coded Symbol
Initial cusp formation	C_i
Coalescence of cusps	C_{co}
Cusp outline complete	C_{oc}
Crown ½ complete	$Cr_{1/2}$
Crown ¾ complete	$Cr_{3/4}$
Crown complete	Cr_c
Initial root formation	R_i
Initial cleft formation	Cl_i
Root length ¼	$R_{1/4}$
Root length ½	$R_{1/2}$
Root length ¾	$R_{3/4}$
Root length complete	R_c
Apex ½ closed	$A_{1/2}$
Apical closure complete	A_c

The Smith method for dental age estimation is a modification of the Moorrees et al. technique (Smith, 1991). In this modified method, the developmental stage of each permanent mandibular tooth of a single quadrant is evaluated. Each tooth, assessed radiographically, is assigned a developmental stage based on the tooth formation stages illustrated by Moorrees et al. (Smith, 1991). The developmental stage of each tooth corresponds to a specific dental age estimation in years, which is shown in the gender-specific charts below (Figure 3 & 4) (Smith, 1991). The mean age estimation of the eight mandibular teeth is the final dental age estimation.

Figure 3. Smith chart for predicting age using the developmental stage of the permanent mandibular teeth (males)

Developmental stage	I1	I2	C	P1	P2	M1	M2	M3
Ci	—	—	0.6	2.1	3.2	0.1	3.8	9.5
Cco	—	—	1.0	2.6	3.9	0.4	4.3	10.0
Coc	—	—	1.7	3.3	4.5	0.8	4.9	10.6
Cr½	—	—	2.5	4.1	5.0	1.3	5.4	11.3
Cr¾	—	—	3.4	4.9	5.8	1.9	6.1	11.8
Crc	—	—	4.4	5.6	6.6	2.5	6.8	12.4
Ri	—	—	5.2	6.4	7.3	3.2	7.6	13.2
Rcl	—	—	—	—	—	4.1	8.7	14.1
R¼	—	5.8	6.9	7.8	8.6	4.9	9.8	14.8
R½	5.6	6.6	8.8	9.3	10.1	5.5	10.6	15.6
R⅔	6.2	7.2	—	—	—	—	—	—
R¾	6.7	7.7	9.9	10.2	11.2	6.1	11.4	16.4
Rc	7.3	8.3	11.0	11.2	12.2	7.0	12.3	17.5
A½	7.9	8.9	12.4	12.7	13.5	8.5	13.9	19.1
Ac	—	—	—	—	—	—	—	—

Key	
I1	Central incisor
I2	Lateral incisor
C	Canine
P1	First premolar
P2	Second premolar
M1	First molar
M2	Second molar
M3	Third molar

Figure 4. Smith chart for predicting age using the developmental stage of the permanent mandibular teeth (females)

Developmental stage	I1	I2	C	P1	P2	M1	M2	M3
Ci	—	—	0.6	2.0	3.3	0.2	3.6	9.9
Cco	—	—	1.0	2.5	3.9	0.5	4.0	10.4
Coc	—	—	1.6	3.2	4.5	0.9	4.5	11.0
Cr½	—	—	2.5	4.0	5.1	1.3	5.1	11.5
Cr¾	—	—	3.5	4.7	5.8	1.8	5.8	12.0
Crc	—	—	4.3	5.4	6.5	2.4	6.6	12.6
Ri	—	—	5.0	6.1	7.2	3.1	7.3	13.2
Rcl	—	—	—	—	—	4.0	8.4	14.1
R¼	4.8	5.0	6.2	7.4	8.2	4.8	9.5	15.2
R½	5.4	5.6	7.7	8.7	9.4	5.4	10.3	16.2
R⅔	5.9	6.2	—	—	—	—	—	—
R¾	6.4	7.0	8.6	9.6	10.3	5.8	11.0	16.9
Rc	7.0	7.9	9.4	10.5	11.3	6.5	11.8	17.7
A½	7.5	8.3	10.6	11.6	12.8	7.9	13.5	19.5
Ac	—	—	—	—	—	—	—	—

Key	
I1	Central incisor
I2	Lateral incisor
C	Canine
P1	First premolar
P2	Second premolar
M1	First molar
M2	Second molar
M3	Third molar

Demirjian, Goldstein, and Tanner developed a non-invasive dental age estimation method in 1973 using a rating system and panoramic radiographs (Demirjian et al., 1973). In this method, each tooth of the left mandible, as visualized on a panoramic radiographic image, is given a stage, A-H (Figure 5) (Demirjian et al., 1973). These stages are based on developmental status of the crowns and roots of the dentition in this arch. The stages are categorized by written criteria and visual diagrams using only relative values rather than absolute measurements. Each tooth is given a score based on its maturation stage illustrated in a developmental standards diagram designed by the researchers (Figure 6) (Demirjian et al., 1973). Demirjian et al. summated the scores of the individual teeth to create a total maturity score. The total maturity score is converted into a dental age estimation using a gender-specific conversion table created by the authors (Figure 7 & 8) (Demirjian et al., 1973). The estimated dental age for a patient can be compared to population norms using a gender-specific dental maturity percentile graph (Figure 9 & 10) (Demirjian et al., 1973).

Figure 5. Demirjian's developmental stages of the permanent dentition

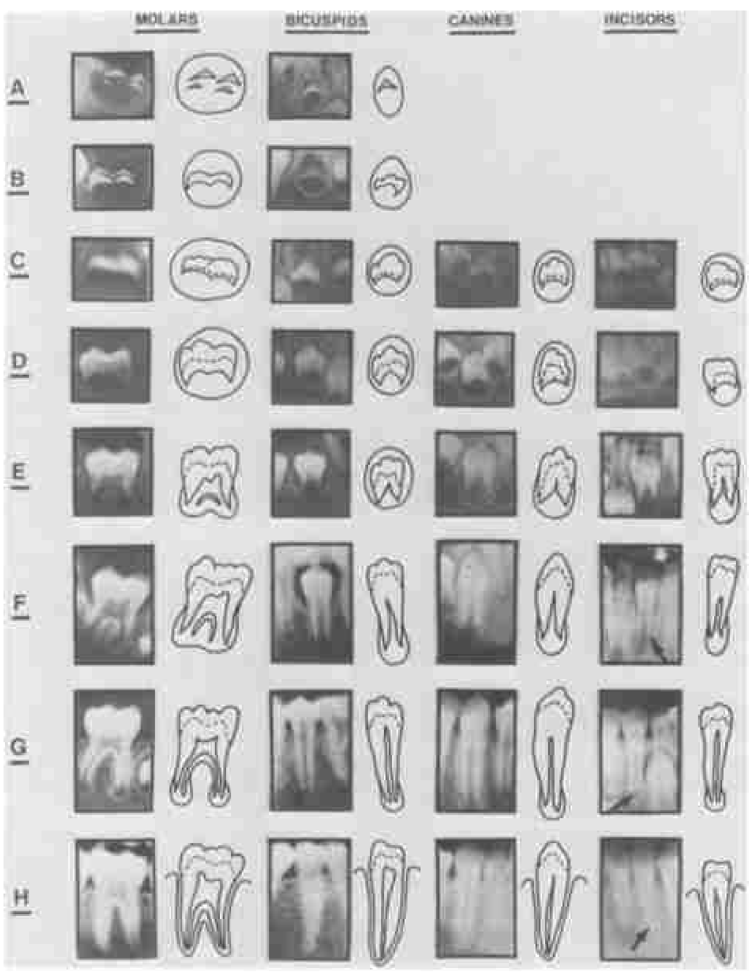


Figure 6. Individual scores for each dental stage of 7 teeth of the left side of the mandible, specific for males and females

Boys									
Tooth	Stage 0	A	B	C	D	E	F	G	H
M_2	0.0	2.1	3.5	5.9	10.1	12.5	13.2	13.6	15.4
M_1				0.0	8.0	9.6	12.3	17.0	19.3
PM_2	0.0	1.7	3.1	5.4	9.7	12.0	12.8	13.2	14.4
PM_1			0.0	3.4	7.0	11.0	12.3	12.7	13.5
C				0.0	3.5	7.9	10.0	11.0	11.9
I_2				0.0	3.2	5.2	7.8	11.7	13.7
I_1					0.0	1.9	4.1	8.2	11.8
Girls									
Tooth	Stage 0	A	B	C	D	E	F	G	H
M_2	0.0	2.7	3.9	6.9	11.1	13.5	14.2	14.5	15.6
M_1				0.0	4.5	6.2	9.0	14.0	16.2
PM_2	0.0	1.8	3.4	6.5	10.6	12.7	13.5	13.8	14.6
PM_1			0.0	3.7	7.5	11.8	13.1	13.4	14.1
C				0.0	3.8	7.3	10.3	11.6	12.4
I_2				0.0	3.2	5.6	8.0	12.2	14.2
I_1					0.0	2.4	5.1	9.3	12.9

NB: Stage 0 is no calcification

Figure 7. Chart for conversion of maturity score to dental age (males)

Age	Score	Age	Score	Age	Score	Age	Score
			Boys				
3.0	12.4	7.0	46.7	11.0	92.0	15.0	97.6
.1	12.9	.1	48.3	.1	92.2	.1	97.7
.2	13.5	.2	50.0	.2	92.5	.2	97.8
.3	14.0	.3	52.0	.3	92.7	.3	97.8
.4	14.5	.4	54.3	.4	92.9	.4	97.9
.5	15.0	.5	56.8	.5	93.1	.5	98.0
.6	15.6	.6	59.6	.6	93.3	.6	98.1
.7	16.2	.7	62.5	.7	93.5	.7	98.2
.8	17.0	.8	66.0	.8	93.7	.8	98.2
.9	17.6	.9	69.0	.9	93.9	.9	98.3
4.0	18.2	8.0	71.6	12.0	94.0	16.0	98.4
.1	18.9	.1	73.5	.1	94.2		
.2	19.7	.2	75.1	.2	94.4		
.3	20.4	.3	76.4	.3	94.5		
.4	21.0	.4	77.7	.4	94.6		
.5	21.7	.5	79.0	.5	94.8		
.6	22.4	.6	80.2	.6	95.0		
.7	23.1	.7	81.2	.7	95.1		
.8	23.8	.8	82.0	.8	95.2		
.9	24.6	.9	82.8	.9	95.4		
5.0	25.4	9.0	83.6	13.0	95.6		
.1	26.2	.1	84.3	.1	95.7		
.2	27.0	.2	85.0	.2	95.8		
.3	27.8	.3	85.6	.3	95.9		
.4	28.6	.4	86.2	.4	96.0		
.5	29.5	.5	86.7	.5	96.1		
.6	30.3	.6	87.2	.6	96.2		
.7	31.1	.7	87.7	.7	96.3		
.8	31.8	.8	88.2	.8	96.4		
.9	32.6	.9	88.6	.9	96.5		
6.0	33.6	10.0	89.0	14.0	96.6		
.1	34.7	.1	89.3	.1	96.7		
.2	35.8	.2	89.7	.2	96.8		
.3	36.9	.3	90.0	.3	96.9		
.4	38.0	.4	90.3	.4	97.0		
.5	39.2	.5	90.6	.5	97.1		
.6	40.6	.6	91.0	.6	97.2		
.7	42.0	.7	91.3	.7	97.3		
.8	43.6	.8	91.6	.8	97.4		
.9	45.1	.9	91.8	.9	97.5		

Figure 8. Chart for conversion of maturity score to dental age (females)

Age	Score	Age	Score	Age	Score	Age	Score
			Girls				
3.0	13.7	7.0	51.0	11.0	94.5	15.0	99.2
.1	14.4	.1	52.9	.1	94.7	.1	99.3
.2	15.1	.2	55.5	.2	94.9	.2	99.4
.3	15.8	.3	57.8	.3	95.1	.3	99.4
.4	16.6	.4	61.0	.4	95.3	.4	99.5
.5	17.3	.5	65.0	.5	95.4	.5	99.6
.6	18.0	.6	68.0	.6	95.6	.6	99.6
.7	18.8	.7	71.8	.7	95.8	.7	99.7
.8	19.5	.8	75.0	.8	96.0	.8	99.8
.9	20.3	.9	77.0	.9	96.2	.9	99.9
4.0	21.0	8.0	78.8	12.0	96.3	16.0	100.0
.1	21.8	.1	80.2	.1	96.4		
.2	22.5	.2	81.2	.2	96.5		
.3	23.2	.3	82.2	.3	96.6		
.4	24.0	.4	83.1	.4	96.7		
.5	24.8	.5	84.0	.5	96.8		
.6	25.6	.6	84.8	.6	96.9		
.7	26.4	.7	85.3	.7	97.0		
.8	27.2	.8	86.1	.8	97.1		
.9	28.0	.9	86.7	.9	97.2		
5.0	28.9	9.0	87.2	13.0	97.3		
.1	29.7	.1	87.8	.1	97.4		
.2	30.5	.2	88.3	.2	97.5		
.3	31.3	.3	88.8	.3	97.6		
.4	32.1	.4	89.3	.4	97.7		
.5	33.0	.5	89.8	.5	97.8		
.6	34.0	.6	90.2	.6	98.0		
.7	35.0	.7	90.7	.7	98.1		
.8	36.0	.8	91.1	.8	98.2		
.9	37.0	.9	91.4	.9	98.3		
6.0	38.0	10.0	91.8	14.0	98.3		
.1	39.1	.1	92.1	.1	98.4		
.2	40.2	.2	92.3	.2	98.5		
.3	41.3	.3	92.6	.3	98.6		
.4	42.5	.4	92.9	.4	98.7		
.5	43.9	.5	93.2	.5	98.8		
.6	45.2	.6	93.5	.6	98.9		
.7	46.7	.7	93.7	.7	99.0		
.8	48.0	.8	94.0	.8	99.1		
.9	49.5	.9	94.2	.9	99.1		

Figure 9. Dental maturity percentile graph (males)

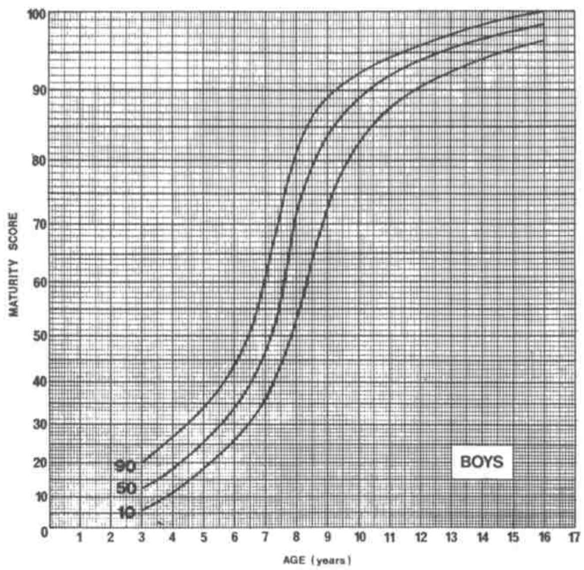
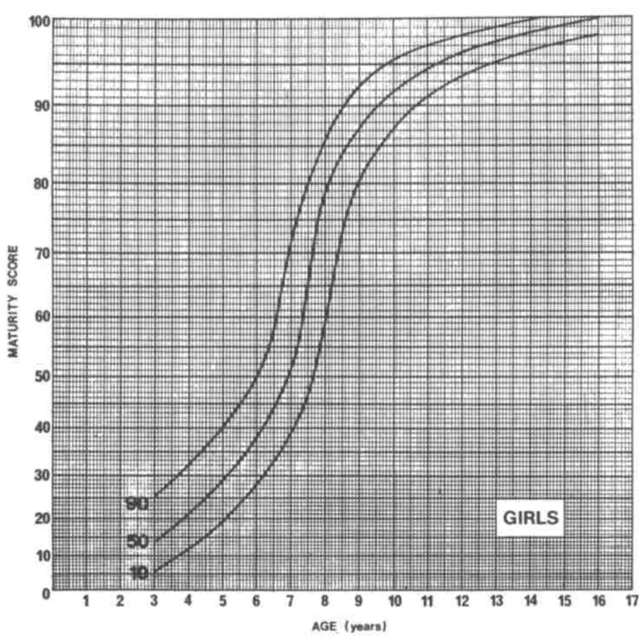


Figure 10. Dental maturity percentile graph (females)



An Italian study in 2006 investigated an alternative non-invasive age estimation technique that uses measurements of apices to estimate chronological age (Cameriere, Ferrante, & Cingolani, 2006). Cameriere et al. pointed out that the Demirijan age estimation technique evaluates individual age variation from the normal developmental pattern. Therefore, the Demirijan method is not fully appropriate for chronological age estimation (Cameriere et al., 2006). Cameriere developed an equation used to estimate chronological age by assessing apical development. In order to calculate the equation, the degree of apical closure of the seven left permanent mandibular teeth was evaluated radiographically. A value of one was assigned to teeth with complete apical closure. The sum of teeth with apical closure equaled $\mathbf{N_0}$ (e.g.: if four teeth in the radiograph exhibited this finding, then $\mathbf{N_0} = 4$).

Single rooted teeth with open apices were then evaluated by measuring the apical inner walls (Cameriere et al., 2006). Multi-rooted teeth with open apices were evaluated by measuring the apical inner walls of both roots, and the results were added together. The values derived for both single and multi-rooted teeth were then divided by the length of the respective tooth to minimize the variable created by radiographic distortion and magnification. This value was assigned a notation of $\mathbf{x_i}$, (i = 1,…, 5) for single rooted teeth and $\mathbf{x_i}$, (i = 6, 7) for multi-rooted teeth. From the measurements noted above, Cameriere et al. devised an equation for age estimation. The equation is shown below:

- $Age = 8.387 + 0.282g - 1.692x_5 + 0.835xN_0 - 0.116s - 0.139s\ xN_0$

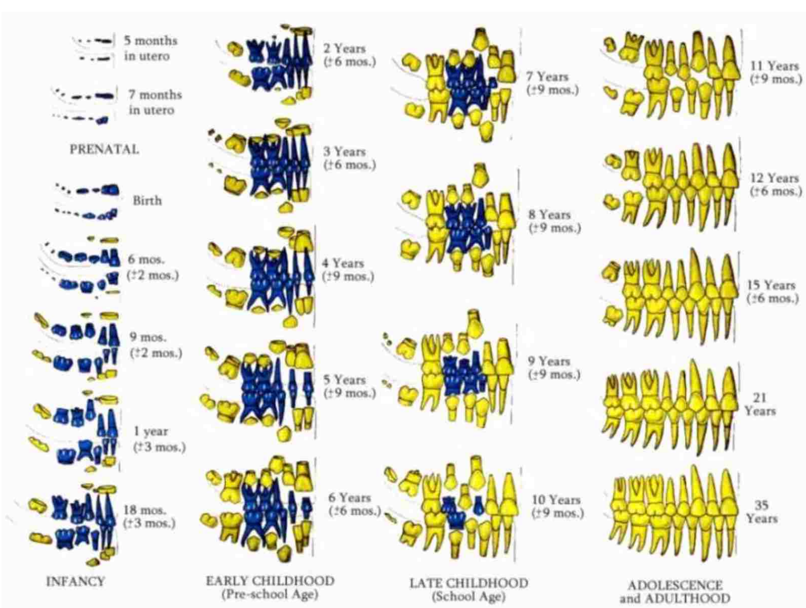
  Key:
  Males: $g = 1$
  Females: $g = 0$
  s = Sum of x_i (i = 1,…, 7)
  x_5 = 2nd premolar normalized measurement

Since its development in 1941, the Schour and Massler Atlas has been the benchmark diagram-based age estimation tool (Schour & Massler, 1941). Diagram-based age estimation tools are considered more user-friendly and efficient compared to other non-invasive techniques, previously cited (AlQahtani, 2012). The Schour and Massler Atlas includes 22 pictorial representations of the developing human dentition from age 5 months *in utero* to 35 years old (Figure 11) (Schour & Massler, 1941). The Atlas was developed from results of the 1933 research of Logan and Kronfeld regarding chronically ill and institutionalized children (Logan & Kronfeld, 1933; Blenkin & Taylor, 2012). Blenkin & Taylor in 2012 and AlQahtani, Hector, and Liversidge in 2014 identified weaknesses in the Schour and Massler Atlas, including the following:

- lack of description of the data source,
- missing ranges from 12-15 and 15-21 years of age,
- lack of internal dental structures, and
- minimal study subjects.

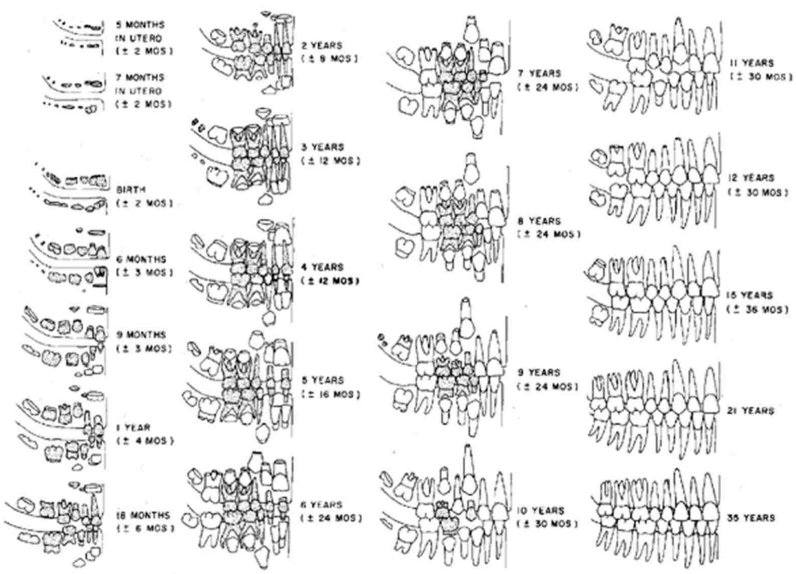
Despite these limitations, the Schour and Massler Atlas is still highly utilized for determination of dental age estimation.

Figure 11. The Schour and Massler Atlas for dental age estimation



Additionally, Ubelaker developed a pictorial diagram for age estimation that is a modification of the Schour and Massler Atlas (Figure 12) (Ubelaker, 1978). The Ubelaker Atlas incorporates data for North American subadult subpopulations (Native American and Canadian Inuit). However, some of the limitations of the Schour and Massler Atlas, including omission of 12-15 year and 15-21 year age ranges, are maintained (AlQahtani, 2012). Historically, these two atlases have been the principal diagrammatic age estimation tools used in research and practice.

Figure 12. The Ubelaker Atlas for dental age estimation



The London Atlas of Human Tooth Development and Eruption (London Atlas) was designed in 2010 at the Queen Mary University of London as an evidence-based, diagrammatic dental age estimation chart based on graduate research by AlQahtani, Hector, & Liversidge (AlQahtani et al., 2010). It has recently gained endorsement from the American Board of Forensic Odontology ("ABFO Standards and Guidelines for Dental Age Assessment", 2018). The London

Atlas sequentially diagrams the developmental stages of the human dentition from 30 weeks *in utero* to age 24 years with 31 illustrations (AlQahtani et al., 2010). The atlas was developed from 704 archived records of known-age individuals and skeletal remains (AlQahtani et al., 2010). The skeletal remains were part of two collections: the Spitalfields Collection at the Human Origins Group, Paleontology Department, Natural History Museum, London (N= 50) and the Maurice Stack's collection, Odonatological Collection at the Royal College of Surgeons of England (N= 126). The living individual archives (N= 528) were those of healthy patients, ages 2-24 years, from the Institute of Dentistry, Barts and the London School of Medicine and Dentistry. These individuals were of Caucasian British and Bangladeshi ethnic origins.

The London Atlas visualizes the right side of the maxilla and mandible, including sequential images of dental crown and root development, bony eruption, and primary tooth resorption (Figure 13). Representation of internal hard tissues is based on Moorrees' stages of tooth formation (Figure 14 & 15) (Moorrees et al., 1963). Eruptive patterns through the alveolar bone are based on modified Bengston's stages (Figure 16) (Bengston, 1935).

Figure 13. Atlas of human tooth development and eruption, the London Atlas

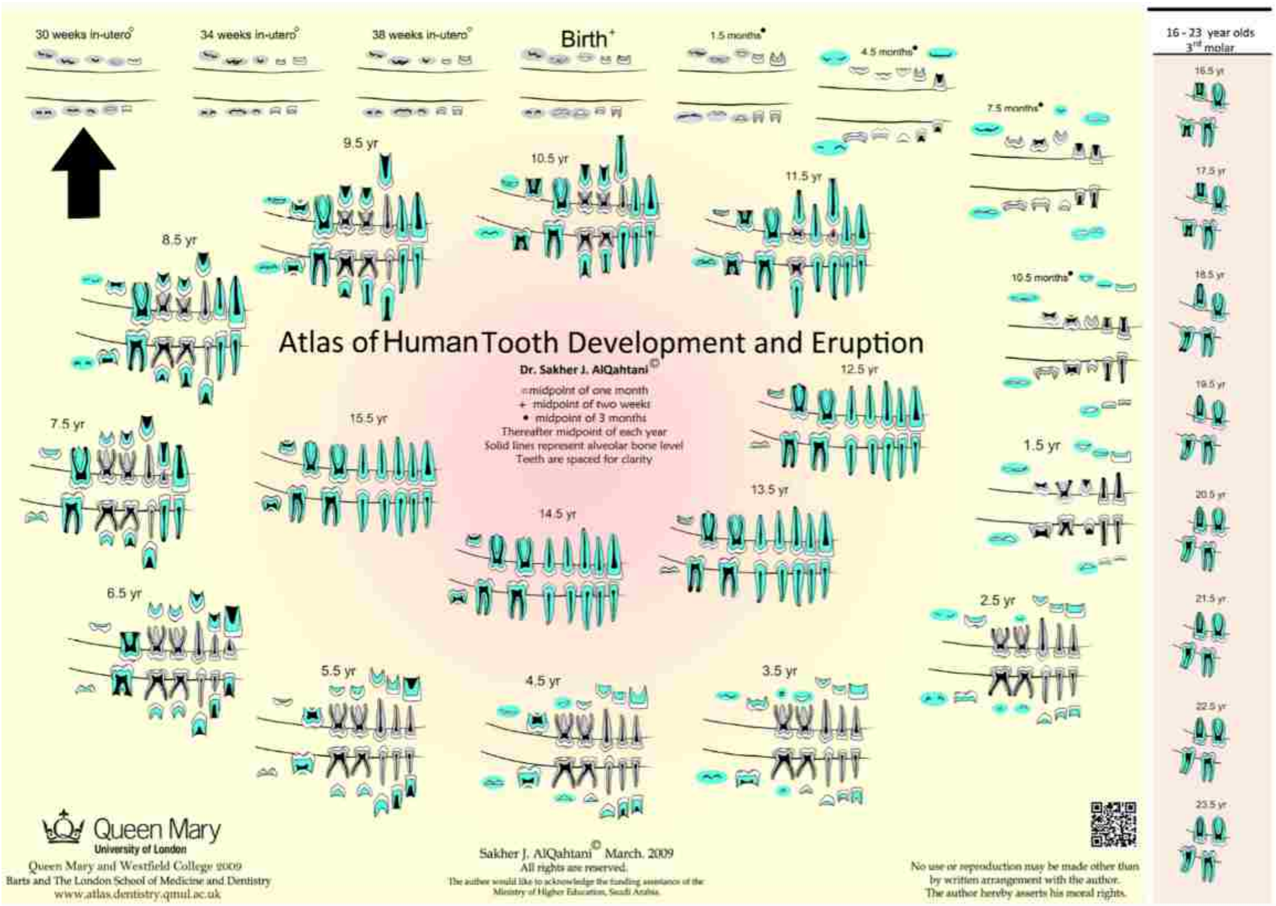


Figure 14. Moorrees, Fanning, and Hunt's stages of tooth formation for single-rooted tooth (illustrated in the London Atlas software)

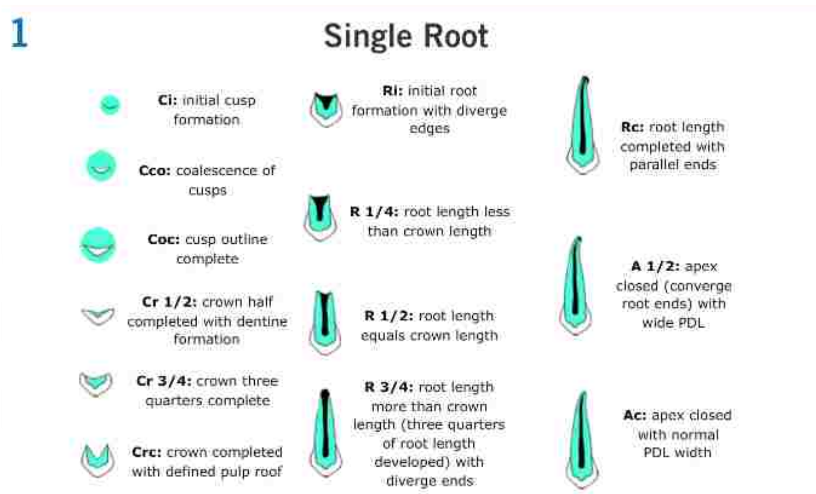


Figure 15. Moorrees, Fanning, and Hunt's stages of tooth formation for multi-rooted tooth (illustrated in the London Atlas software)

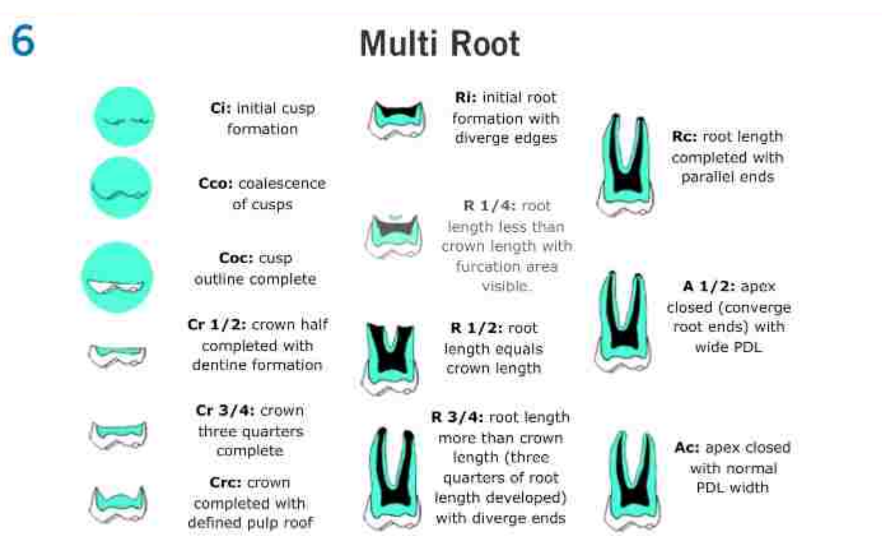
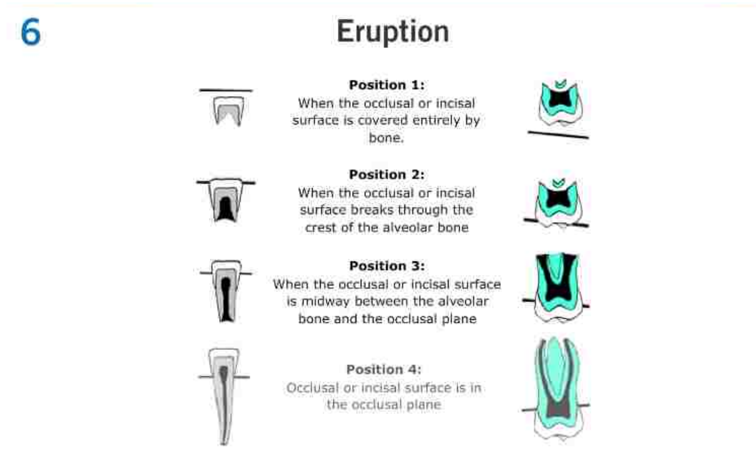
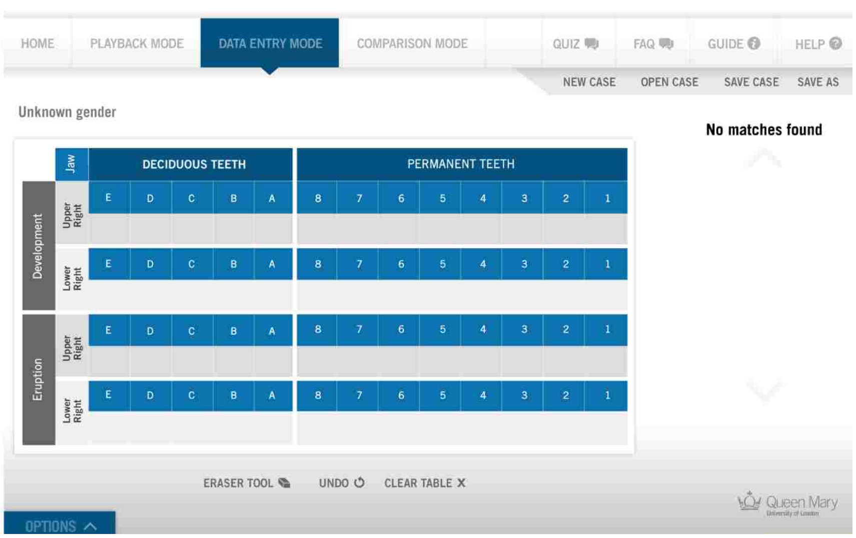


Figure 16. Bengston's stage of tooth eruption (illustrated in the London Atlas software)



Based on the London Atlas diagram, Dr. AlQahtani developed an interactive software (Figure 17) for dental age estimation to enable efficient and accurate age estimation while working under difficult conditions (i.e.: multiple fatality incidents, comingled body recovery, etc.) (AlQahtani, 2012).

Figure 17. The London Atlas interactive software: data entry mode



The accuracy of the London Atlas was compared to that of the Schour and Massler Atlas and the Ubelaker Atlas in a retrospective study in 2014 (N= 1,506) (AlQahtani, Hector, & Liversidge, 2014). Panoramic images of living patients (N= 1,323) of Caucasian British and Bangladeshi ethnicity and skeletal remains (N= 183), from Portuguese, Danish, Northern American, and French collections were collected and assessed; Ages ranged from 31 weeks *in utero* – 23.86 years (AlQahtani et al., 2014).

Results, analyzed by paired t-tests, indicated that all three atlases showed statistically significant bias to under-estimate age ($p < 0.001$) (AlQahtani et al., 2014). However, the London Atlas performed better in dental age estimation compared to the Schour and Massler Atlas and Ubelaker Atlas. The mean differences were -0.10 years, -0.76 years, and -0.80 years for the London, the Schour and Massler, and the Ubelaker Atlases, respectively.

The absolute mean difference was calculated to evaluate age estimation accuracy, independent of bias. The absolute mean differences were 0.64 years, 1.01 years, and 1.03 years for the London, the Schour and Massler, and the Ubelaker Atlases, respectively (AlQahtani et al., 2014). These results indicated that the London Atlas is more accurate in age estimation compared to the Schour and Massler and Ubelaker Atlases.

None of the three diagrammatic age estimation methods proved statistically valid for age estimation when relying solely on the third molars (AlQahtani et al., 2014). Therefore, researchers looked at age estimation accuracy (N= 1,034) in age ranges which excluded images that relied solely on third molar development for age estimation (ages 15 years and above). Results indicated a statistically significant difference in dental age estimation when utilizing the Schour and Massler Atlas ($p < 0.001$) and Ubelaker Atlas ($p < 0.001$) (AlQahtani et al., 2014). No statistically significant difference was found when utilizing the London Atlas for dental age estimation ($p = 0.872$). The mean differences were 0.00 years, -0.50 years, and -0.55 years for the London Atlas, the Schour and Massler, and the Ubelaker Atlases, respectively. The absolute mean differences were 0.50 years, 0.78 years, and 0.81 years for the London, the Schour and Massler, and the Ubelaker Atlases, respectively. These results indicated that the London Atlas was a statistically valid dental age estimation tool for ages under 15 years old in the tested subpopulation. Additionally, the London Atlas is more accurate in dental age estimation compared to the Schour and Massler and Ubelaker Atlases. Accuracy of estimations using the London Atlas varied by age (AlQahtani et al., 2014). A statistically significant difference in age estimation was noted in the following age ranges: 3.5, 4.5, 16.5, and 19.5-23.5 years.

Recently, studies have investigated the validity of the London Atlas when applied to ethnic and/or racial populations other than those included among its original sample populations (Alshihri, Kruger, & Tennant, 2015; Pavlović, Palmela Pereira, & Vargas de Sousa Santos, 2017; Baylis & Bassed, 2017; McCloe, Marion, da Fonseca, Colvard, & AlQahtani, 2018; Ghafari, Ghodousi, & Poordavar, 2018). In a Western Saudi Arabian 2-20 year-old subpopulation, a retrospective study utilizing panoramic images (N= 252) assessed the London Atlas as an age estimation tool (Alshihri et al., 2015). In this population, the estimated dental ages and chronological ages were significantly different ($p< 0.001$) when analyzed by a paired t-test. Results indicated the following:

- 65.5% of age estimations were within 12 months of the chronological ages of the subjects,
- 19% were overestimated by more than 12 months, and
- 15.5% were underestimated by more than 12 months.

Additionally, accuracy of estimations varied by age (Alshihri et al., 2015). The most accurate age range was found to be 10-12 years old. A statistically significant age estimation bias was found in age ranges 7-9 years and 13-15 years. Age estimation was more frequently overestimated in females than males in this study.

In 2017, the accuracy of the London Atlas as an age estimation tool was evaluated in a Portuguese subpopulation (N= 736) using panoramic images (Pavlović et al., 2017). Subjects ranged between 3-24 years old. Estimated age was compared to chronological age using a paired t-test. Additionally, right and left sides of the maxilla and mandible of each patient were compared for compatibility of dental development using a paired Student's t-test. No statistically significant difference was found between age estimation using the right or left side of the jaws ($p = 0.066$).

When investigators compared estimated age and chronological age for the entire sample population, there was a tendency to overestimate age by approximately 1 month (Pavlović et al., 2017). However, this was not a statistically significant difference (right $p = 0.104$; left $p = 0.052$). Researchers then separated participants into two age groups based on the use of third molars in age estimation using the London Atlas. These results indicated a statistically significant difference in subjects under 16 years old (right and left, $p = 0.00$); however, no statistically significant difference was found in subjects over 16 years old (right: $p = 0.105$; left: $p = 0.161$). Researchers also analyzed results based on gender and found a bias to overestimate age in males (right: $p = 0.008$; left: $p = 0.003$) and no bias in age estimation in females (right: $p = 0.765$; left: $p = 0.652$).

Another study performed in the United States in 2018 investigated age estimation accuracy of the London Atlas in a non-adult Hispanic population using panoramic images (McCloe et al., 2018). The investigators retrospectively evaluated 332 panoramic images of individuals aged 6 – 15.99 years. Estimated dental age and chronological age were compared using a paired t-test. The results indicated a statistically significant difference ($p < 0.001$) for the sample with a bias toward overestimation of 0.35 years.

The researchers found the following:

- 49% of subjects were estimated into the correct age group,
- 38% were overestimated,
- 13% were underestimated, and
- 72% of subjects were estimated within one year of chronological age.

Age estimation accuracy was found to vary based on age group (McCloe et al., 2018). A statistically insignificant bias was found in age groups 6, 8, 9, 10 and 15 years. Using an independent sample t-test, the difference in age estimation between males and females was not statistically significant (p= 0.324). This indicated that there was no difference in age estimation accuracy between males and females using the London Atlas.

A study performed in a New Zealand non-adult population compared the accuracy of the London Atlas, the Schour and Massler Atlas, and the Blenkin and Taylor charts using panoramic images (Baylis & Bassed, 2017). In this study, each chart was used to estimate age of the participants (N= 875). Their chronological ages ranged from 5-18 years

-. However, all subjects over age 15.5 were eliminated due to "difficulty in assigning appropriate stages without reference to third molars" (Baylis & Bassed, 2017). The estimated ages and chronological ages for each chart were independently evaluated using a paired t-test. The different age estimation charts were then compared using average mean differences and absolute mean differences to evaluate accuracy.

Results indicated that all three estimation charts showed low accuracy and precision (Baylis & Bassed, 2017). Age estimation accuracy was again found to vary based on age group and sex. A significant bias in age estimation utilizing the London Atlas was found in all females, except age 15.5 years. Similar bias in dental age estimation was noted for all males, except those 10.5-11.5 years old and 13.5-15.5 years old. Additionally, the mean difference in dental age estimation for females was -0.74 years and for males was -0.40 years. These results indicated a bias towards overestimation. Using the London Atlas, the mean absolute difference in dental age estimation was 0.93 years for females and 0.78 years for males (Baylis & Bassed, 2017). This research concluded that of all three age estimation tools the Blenkin and Taylor chart was the most accurate when evaluating dental age in the New Zealand population.

An age estimation comparison study in an Iranian non-adult population was studied in 2018 (Ghafari et al., 2018). This project was carried out to investigate the differences in age estimation accuracy between the London Atlas and the Smith's method. The researchers compared dental age findings using panoramic images (N= 339) of participants ranging from 5-15.99 years old. Dental age estimation was compared to chronological age with a paired t-test.

Results found no statistically significant difference in age estimation accuracy using the London Atlas (p= 0.150) or the Smith's method (p= 0.160) for the sample population (Ghafari et al., 2018). However, a tendency to overestimate dental age was seen when using the London Atlas. A tendency to underestimate age occurred when the Smith's method was employed. Additionally, paired t-tests results indicated no statistically significant difference in age estimation accuracy in males or females using the London Atlas or the Smith's method. Thus, the researchers concluded that both the London Atlas and Smith's method indicated high accuracy in age estimation in the non-adult Iranian population. However, the London Atlas diagram format and interactive software was more user-friendly for these investigators (Ghafari et al., 2018).

Based on the results and conclusions of the scientific literature cited, current knowledge regarding dental age estimation accuracy using the London Atlas is highly variable and warrants further investigation. Table 7, found in the appendix, summarizes the results and conclusions regarding age estimation using the London Atlas illustrated in previous studies. The literature review suggests that the London Atlas tends to overestimate age.

Currently, no studies have been undertaken to evaluate dental age estimation accuracy of the London Atlas utilizing three-dimensional (3D) Cone Beam Computed Tomography (CBCT) images rather than traditional two-dimensional (2D) panoramic images. Therefore, the objective of this study was to assess validity of the London Atlas as a dental age estimation tool in the age assessment of a Southern Nevada Hispanic non-adult subpopulation. The project employed CBCT imaging technology to assess coronal, transverse, and sagittal radiographic views of the dentition of this subpopulation to determine if this approach improved accuracy of age estimation.

Chapter 2: Materials and Methods

This study was a retrospective cross-sectional review of 395 anonymized archival CBCT records of self-identified Hispanic patients less than 21 years of age**.** The records were collected from the University of Nevada, Las Vegas School of Dental Medicine (UNLV SDM). The UNLV Institutional Review Board approved this study (1087051-1). A CB MercuRay, Hitachi Medical Corp. CBCT imaging machine was used for all CBCT images. Of the 395 images, 250 met the inclusion criteria when the following conditions were absent from the dentition of the entire left or right sides of the jaws:

- dental pathology in pulp canal and/or in periapical region,
- extensive restorations and/or endodontic treatment,
- evidence of trauma in the phase of tooth development,
- impacted teeth,
- orthodontic treatment (not including space maintainers), and
- dental anomalies.

Patient information was organized into a Microsoft Excel sheet with the following identifiers: sex, date of birth, and date of radiograph. Chronological age in years and months was calculated in this Excel worksheet. Each patient was given a randomized anonymization number generated by Excel software. To maintain confidentiality, this anonymization number was different from the patient number indicated in the clinic charting systems. To avoid bias, nonparticipating research assistants organized and identified the CBCT images based on the corresponding anonymized patient number assigned by the Excel software.

A sample size calculation was preformed using the Cochran formula for small sample sizes, using a confidence level of 95% ($p < 0.05$), a margin of error of 4%, and a standard deviation of 0.5. From this calculation, it was identified that 239 participants were needed for the sample population. However, there were 250 subjects without exclusion criteria; therefore, a sample size of 250 was used for the statistical analysis to increase power of the analysis.

Cohen's kappa assesses an investigator's calibration to an evaluation tool. This statistical analysis was employed to evaluate investigator consensus for both intra-rater and inter-rater reliability to the London Atlas. Cronbach's alpha assesses the reliability and consistency of a tool as a reliable measuring device. This statistical analysis was applied to evaluate reliability and consistency of the London Atlas as a dental age estimation tool.

The intra-rater reliability of the investigator was evaluated using 30% of the data for Cohen's kappa and Cronbach's alpha. This sample was re-analyzed 14 days after the initial analysis was concluded. The author trained a second qualified individual to evaluate 10% of the data for inter-rater reliability.

Dental age estimation was performed by a single observer (author) using the London Atlas diagram (Figure 13) and software found on the Queen Mary, University of London website (Figure 17) (AlQahtani, 2012). If no exclusion criteria were noted, the developmental and eruptive stage of each tooth on the right side of the maxillary and mandibular arches was identified from CBCT records using Anatomage viewing software. When exclusion criteria were found on the right side of the CBCT images, left side analysis was performed. Although the London Atlas diagram is observed from the right, no statistically significant difference in results was found between the right and left dentitions regarding dental age estimation (Pavlović et al., 2017).

The London Atlas designates age ranges for *in-utero*, postnatal, sub-adult, and adult sample populations (AlQahtani et al., 2010). During further development and testing of the London Atlas, Dr. AlQahtani converted chronological age into an age interval to evaluate the accuracy of the London Atlas within these ranges (AlQahtani, 2012; AlQahtani et al., 2014). Therefore, in this study, age estimation was evaluated by comparing the following:

- true chronological age (TCA) to estimated age (EA), and
- converted chronological age (CCA) to estimated age (EA).

The comparison of TCA to EA is significantly important when the London Atlas is applied to real life situations requiring age estimation. These may include, but are not limited to, age identification in refugee crises, determination of legal age requirements, and multiple fatality identification (MFI). The comparison of CCA to EA became important when the findings of the current study were related to Dr. AlQahtani's work and additional research (AlQahtani, 2012; AlQahtani et al., 2014, Alshihri et al., 2015; Pavlović et al., 2017; Baylis & Bassed, 2017; McCloe et al., 2018; Ghafari et al., 2018).

Difference in age estimation (DAE) for each subject was calculated using the following formula:

$$DAE = EA - TCA$$

A positive result indicated an overestimation of age, whereas a negative result indicated an underestimation of age. The mean difference was calculated to evaluate the tendency toward over- or underestimation and to compare results with previously reviewed research. The absolute difference and absolute mean difference were calculated to assess the range of accuracy of age estimation.

A paired t-test compared TCA and EA for the entire sample, regardless of sex and individually for male and female samples. Based on sexual dimorphism regarding dental age maturation, an independent sample t-test was also used to compare the mean differences between male and female age estimation. This evaluation was employed to identify a discrepancy between age estimation in males compared to females using the London Atlas.

TCA was then converted into a half year age interval (e.g., if the age of a subject was noted between 11.00-11.99, his or her age was recorded as 11.5 years). These converted values represent CCA. CCA was then compared to EA as previously described for TCA.

A significance level of 5% ($p = 0.05$) was used, and all statistical tests were performed with IBM Statistical Package of the Social Sciences (SPSS) Statistics software.

Chapter 3: Results

Intra-rater reliability of 30% of the data yielded a Cohen's kappa of 0.769, indicating substantial consensus. Cronbach's alpha for intra-rater comparison yielded 0.992, indicating high internal consistency. Inter-rater reliability of 10% of the data yielded a Cohen's kappa of 0.736, indicating substantial consensus. Cronbach's alpha for inter-rater comparison yielded 0.991, indicating high internal consistency. The Cohen's kappa values indicate the author is substantially calibrated to the London Atlas (Landis & Koch, 1977). Additionally, the Cronbach's alpha values confirm that the London Atlas is a consistent rubric from estimating age (Stelmer, 2004).

From the data set and inclusion criteria of this project, retrospective anatomized records from 110 males and 140 females were included (Table 1). The true chronological ages ranged from 8.5 – 20.7 years. The mean TCA was 13.2 years; the mean EA was 13.5 years (Table 1). The mean difference between the TCA and the EA was evaluated using a paired t-test. The mean difference (0.30 years) was statistically significant (p= 0.0004), indicating a significant difference between TCA and EA utilizing the London Atlas (Table 2). The bias was toward overestimation of age, indicated by a positive mean difference value (Table 2). The overestimation of EA compared to TCA can be visualized graphically in Figure 18. The mean absolute difference was 1.0 years, indicating a range of age estimation within 1 year.

Table 1. Mean true chronological age and estimated age for males and females

		TCA (years)	EA (years)
Male	Mean	13.2	13.6
	N	110.0	110.0
	Std. Deviation	2.4	2.5
Female	Mean	13.1	13.3
	N	140.0	140.0
	Std. Deviation	2.6	2.6
Total	Mean	13.2	13.5
	N	250.0	250.0
	Std. Deviation	2.5	2.5

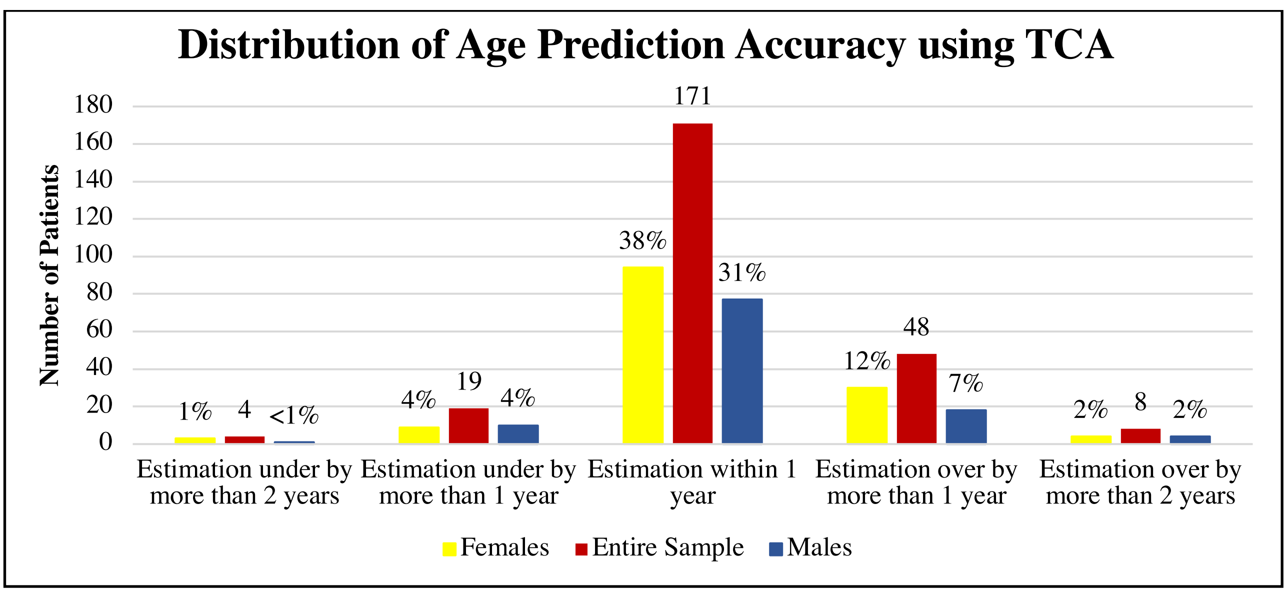
Figure 18. True chronological age vs. Estimated age in Southern Nevada Hispanic population

Table 2. Mean difference between EA and TCA for entire sample

	Paired Differences							
				95% Confidence Interval of the Difference				
	Mean Difference	Std. Deviation	Std. Error Mean	Lower	Upper	t	df	Sig. (2-tailed)
EA - TCA	0.30	1.30	0.08	0.13	0.46	3.603	249	0.0004

One hundred and seventy-one retrospective anatomized CBCT images (68%) were estimated within 1 year of TCA; twenty-three images (9%) were underestimated; Fifty-six images (23%) were overestimated (Figure 19).

Figure 19. Distribution of age prediction accuracy using TCA



The mean differences between males and females were compared using an independent sample t-test. For males, the mean TCA was 13.2 years; the mean EA was 13.6 years. For females, the mean TCA was 13.1 years; the mean EA was 13.3 years (Table 1). This research found no statistically significant difference in age estimation between males and females based on results of the independent sample t-test (p= 0.408) (Table 3). Thus, there is no statistically significant difference in age estimation accuracy between males and females using the London Atlas.

Table 3. Mean difference between EA and TCA between males and females

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Differences: males vs. females	Equal variances assumed	0.098	0.755	0.829	248	0.408	0.14	0.17	-0.19	0.46
	Equal variances not assumed			0.842	244.855	0.400	0.14	0.16	-0.18	0.46

TCA was changed to CCA for all subjects as noted in the materials and methods section. The mean CCA was 13.2 years (Table 4). The difference between the CCA and the EA was evaluated using a paired t-test. The mean difference (0.29 years) was statistically significant (p= 0.001), indicating a significant difference between the CCA and EA utilizing the London Atlas

(Table 5). The bias was towards overestimation of age, indicated by a positive mean difference. The mean absolute difference was 0.97 years, indicating a range of age estimation within 1 year.

Table 4. Mean EA and CCA

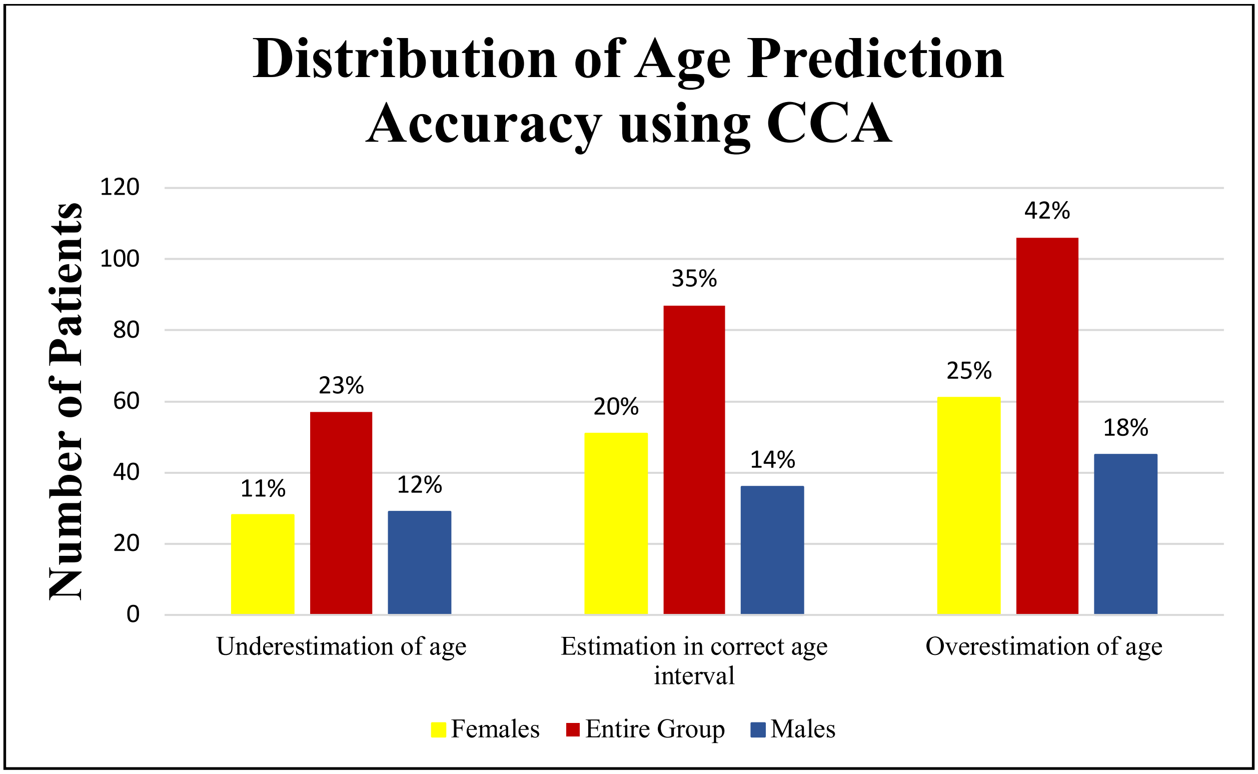
	Mean Age	N	Std. Deviation	Std. Error Mean
EA	13.5	250.00	2.524	0.160
CCA	13.2	250.00	2.556	0.162

Table 5. Mean difference between EA and CCA for entire sample

	Paired Differences							
	Mean Difference	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference Lower	95% Confidence Interval of the Difference Upper	t	df	Sig. (2-tailed)
EA - TCA	0.29	1.30	0.08	0.12	0.45	3.413	249	0.001

Eighty-seven CBCT images (35%) were estimated to the accurate age interval, fifty-seven images (23%) were underestimated, and one hundred and six images (42%) were overestimated (Figure 20) One hundred and ninety-one images (76%) were estimated within 1 year of chronological age.

Figure 20. Distribution of age prediction accuracy using CCA



The mean differences between males and females were compared using an independent sample t-test. No statistically significant difference in age estimation was found between males and females (p= 0.589), indicating no statistically significant difference in age estimation between males and females using the London Atlas when using CCA (Table 6).

Table 6. Mean difference between EA and CCA between males and females

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Differences: males vs. females	Equal variances assumed	0.127	0.721	-0.542	248	0.589	-0.09	0.17	-0.43	0.24
	Equal variances not assumed			-0.549	243.458	0.584	-0.09	0.17	-0.42	0.24

Chapter 4: Discussion

This study evaluated the validity of the London Atlas by comparing both TCA and CCA to EA in a non-adult Southern Nevada Hispanic population using archival CBCT images instead of traditional 2D panoramic radiographs.

A statistically significant difference was found between EA and TCA when using the London Atlas to estimate age in a Southern Nevada Hispanic non-adult population. The mean difference was 0.30 years, indicating a tendency to overestimate age by 3.6 months in our population. Therefore, it should be recognized by clinicians and researchers that, when utilizing the London Atlas in our population or similar populations, there is a tendency to overestimate age by several months. The mean differences in age estimation of TCA and CCA were very similar at 0.30 and 0.29 years, respectively. Results for the mean absolute differences were likewise similar at 1.0 and 0.97 years, respectively. Surprisingly, the percentage of estimates within 1 year using TCA (68%) was approximately double the percentage of estimates within the accurate age interval using CCA (35%).

It is important to remember that the London Atlas is an estimation tool designed to approximate the chronological age of an individual within a six-month range. The absolute mean difference for both EA to TCA and EA to CCA was approximately 1.0 year. This result indicated that the London Atlas assesses age within a 1-year range of accuracy. This is supported by the fact that 68% of patients were estimated within 1 year of chronological age using TCA and 76% when using CCA. Although a statistically significant difference was present between EA and TCA, estimating age within several months to one year is clinically useful for legal, medical, and dental purposes. Therefore, the London Atlas remains a valuable tool for age estimation in a Southern Nevada Hispanic non-adult population when CBCT technology is employed.

To simplify the remaining discussion, TCA and CCA will be abbreviated to chronological age (CA). In 2014 AlQahtani et al. obtained a mean difference of -0.10 years when utilizing the London Atlas to estimate age (AlQahtani et al., 2014). The mean difference found in this research (0.30 years) was compared to those found by AlQahtani et al. in 2014 (-0.10 years). This comparison indicated that the use CBCT images does not improve age estimation accuracy compared to standard panoramic images when utilizing the London Atlas. Therefore, panoramic images will suffice when investigators utilize the London Atlas to estimate age.

Importantly, the London Atlas was developed using traditional sagittal plane panoramic images. Therefore, this age estimation tool lends itself to the use of panoramic images and the details present in this plane. CBCT images, however, present extensively more details in dental developmental and eruptive stages by assessing all three anatomical planes (sagittal, coronal, and axial) compared to panoramic images. For example, a maxillary second molar with two buccal roots and one palatal root will only exhibit the buccal roots in a panoramic radiograph. The palatal root is often obscured by overlapping structures. Therefore, the developmental status of the palatal root of this tooth is not accounted for when investigators utilize the London Atlas to assess dental age from panoramic images.

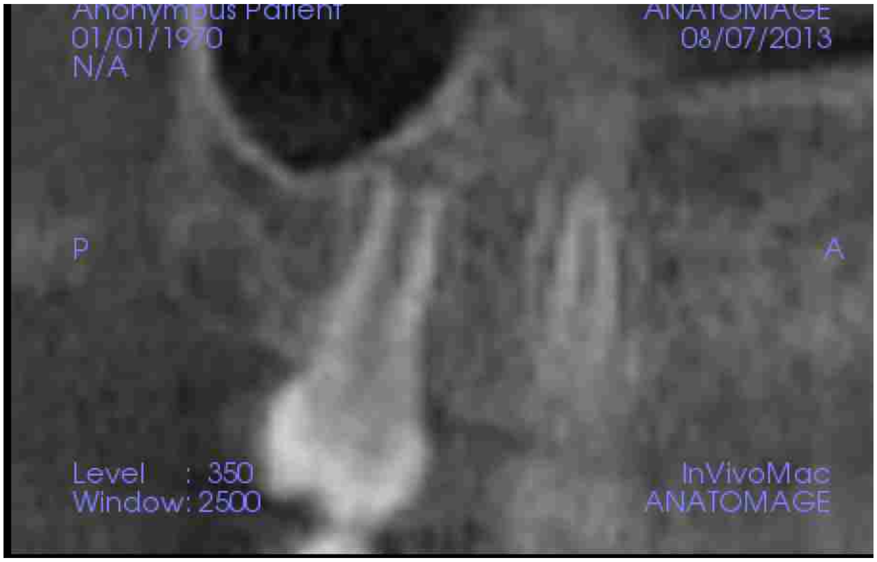
However, the developmental status of each root can be individually identified and recorded in CBCT imagery. Thus, assessment of simultaneous or asynchronous development of all three roots of a maxillary second molar can be determined. Findings of this CBCT project indicated that the development of the maxillary second molar roots were often asynchronous. Since the London Atlas does not provide imagery for the palatal root of this tooth, this study only assessed development of its buccal roots to comply with the London Atlas dental age estimation tool.

An example of this phenomenon is shown in Figures 21-23. Visualized in the panoramic image of patient A (Figure 21), the right maxillary second molar is in developmental stage Rc. In the CBCT image of patient A, made one month later, the buccal roots of this tooth are in developmental stage Rc (Figure 22). However, the second molar palatal root of patient A is in developmental stage R ¾ (Figure 23).

Figure 21. Panoramic image of patient A

Figure 22. CBCT image of buccal roots of maxillary second molar in patient A

Figure 23. CBCT image of palatal root of maxillary second molar in patient A



CBCT imaging permits the assessment of the maxillary second molar palatal root as an additional variable for evaluation. As mentioned previously, development of this root often did not occur at the same time as the buccal roots of this tooth. Therefore, if an age estimation diagram was developed based on CBCT rather than panoramic images, would dental age estimation accuracy improve?

The London Atlas has been tested in six different populations since its introduction in 2010 (AlQahtani et al., 2014; Alshihri et al., 2015; Baylis & Bassed, 2017; Pavlović et al., 2017; Ghafari et al., 2018; McCloe et al., 2018). A statistically significant difference between chronological and estimated age was found in the following populations: Caucasians and Bangladeshi in Great Britain, Western Saudi Arabians, New Zealanders, Hispanics in the United States, and Portuguese <16 years old (AlQahtani et al., 2014; Alshihri et al., 2015, Baylis & Bassed, 2017; McCloe et al., 2018; Pavlović et al., 2017). Among the following populations, the London Atlas was identified to overestimate age: Western Saudi Arabians, New Zealanders, Hispanics in the United States, and

Portuguese <16 years old (Alshihri et al., 2015, Baylis & Bassed, 2017; McCloe et al., 2018; Pavlović et al., 2017). Although not statistically significant, the London Atlas also tended to overestimate age in the Iranian non-adult population (Ghafari et al., 2018).

Most relevant to the current project, the study of Hispanic patients performed in Chicago, Illinois, in 2018 found a statistically significant tendency to overestimate age (McCloe et al., 2018). In the Chicago study, the mean difference in age estimation was 0.35 years and the absolute mean difference was 0.73 years. These values corroborate those found in the current research (for CCA: mean difference= 0.29 months; mean absolute difference= 0.97 months), thus indicating a commonality to overestimate age by approximately 3 months in two Hispanic populations found in the United States.

The archival large field of view CBCT images used for this study included the entire craniofacial complex. It is recommended that future studies use CBCT images with a smaller field of view including only the dentition and developing dentition. This would be beneficial by avoiding scatter radiation and improving image contrast. Scatter radiation in the following areas of the large field CBCT images used in this study made it difficult to visualize the development stage of the dentition:

- mandibular incisor regions,
- mandibular and maxillary canine regions, and
- maxillary molars regions with roots in close proximity to the maxillary sinus

This was especially true when attempting to discern between the two final root development stages (i.e.: apex closure with PDL widening and apex closed with normal PDL width).

Age estimation using the dentition has its limitations, as do all methods of age estimation including the London Atlas. Because the dentition develops over an age range, there is a point where the dentition can no longer be used for age estimation in diagram form. This is specifically apparent when the third molars are fully developed and erupted. Additionally, the use of third molars for age estimation contributes to inaccuracies because of the variability in third molar development, morphology, and position. The London Atlas relies solely on third molars for age estimation from ages 16.5-23.5 years (AlQahtani et al., 2010). Therefore, its accuracy is reduced when attempting to determine critical dental age in adult groups for legal and social reasons.

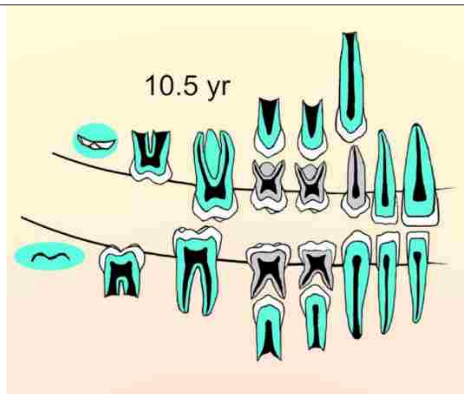
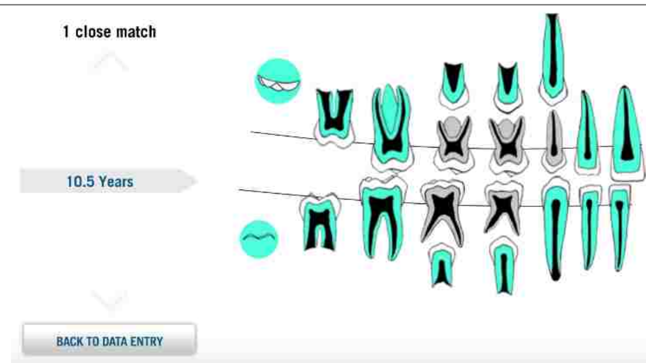
Additionally, age estimation using the dentition represents an idealized oral environment. Many patients do not have an "ideal" dentition and are affected by impactions, genetically missing teeth, and premature tooth loss. These common anomalies affect the accuracy of age estimation utilizing a dental age estimation diagram like the London Atlas.

Minor discrepancies were noted between the online diagram and PDF diagram of the London Atlas (AlQahtani, 2012). For example, at age 10.5 the mandibular second premolars appear to be at different developmental stages when comparing the PDF and software illustrations (Figure 24). In the PDF version, the mandibular second premolar appears to have one half of the root developed. The software version presents the mandibular second premolar with only one fourth of the root developed.

This led to a conundrum in estimating dental age utilizing the London Atlas in this study. Further anomalies regarding the London Atlas were described by Drs. Baylis and Bassed in 2017 in a study testing the London Atlas as a dental age estimation tool for a New Zealand population (Baylis & Bassed, 2017). They identified the following:

- In age 12.5, the mandibular first permanent molar show more apical development than in age 13.5.
- In age 14.5, the mandibular first permanent molar shows normal PDL width while in age 15.5, the mandibular first permanent molar shows widened PDL.

Figure 24. Comparison of PDF and Software Version of the London Atlas

The London Atlas PDF	The London Atlas Software
	

A limitation of this study was the narrow age range among the subjects. The project was limited to patients < 21 years of age whose archival CBCT radiographs were obtained from the UNLV SDM orthodontic residency database. Thus, the age range mirrored ages of patients requiring orthodontic treatment. After all images with exclusion criteria were eliminated, age ranges of the subjects in this study included those 8.5 – 20.7 years old. Therefore, in this study, the London Atlas was untested for subjects falling outside of the age ranges indicated above. Besides this age limiting constraint, the investigator was also aware of the fact that patients in the study could not be over 21 years old. Therefore, a bias was potentially created against overestimating age in those >21 years old.

The generalization of patients' ethnic background was an additional limitation of this project. From an anthropological stand point, it is difficult to define a homogenous ethnic population. This is especially true for the "melting pot of the United States" population. Ethnicity can seldom be isolated to a common national or cultural tradition. The population in the sample chosen for this study was broadly described as a Southern Nevada Hispanic population. This group included self-reported Hispanic participants of diverse backgrounds that were not ethnically defined. A limitation of this study is the broad generalization of Hispanic ethnicity. Many cultures are potentially tested in this analysis; however, the subjects were considered to represent one ethnicity. Future studies would be improved by identifying a more precisely defined ethnic population.

Chapter 5: Conclusions

Conclusions inferred from this research indicated the following:

- The London Atlas has a bias to overestimate age by approximately three months in a non-adult Southern Nevada Hispanic population for both females and males.
- No difference in age estimation accuracy between males and females was observed using the London Atlas.
- CBCT images do not currently improve age estimation accuracy using the London Atlas.

Therefore, panoramic images remain preferable to CBCT images when using the London Atlas to assess dental age because the atlas was designed based on panoramic images. Additionally, further research should investigate the validity of using the London Atlas to evaluate dental age estimation in a more ethnically defined non-adult Southern Nevada Hispanic population for both females and males including larger samples sizes. A diagram-based age estimation tool similar to the London Atlas should be created from data collected from CBCT images to determine if this technology improves dental age estimation accuracy.

Appendix

Table 7. Review of current literature on the London Atlas

Research Title	Authors	Publication Year/Type of Study	Population Description	Age Range	N value	p-value	Mean difference	Mean abs. difference	Variations in ages range	Conclusion
Accuracy of dental age estimation charts: Schour and Massler, Ubelaker and the London Atlas	AlQahtani, Hector, Liversidge	2014/ Retrospective	British Caucasian, British Bangladeshi, Portuguese, Danish, Northern American, and French	31 weeks in utero - 23.86 years	Total: 1,506 Skeletal remains: 183 Living patients: 1,323 (674 females, 649 males)	LA/SM/ Ub: p< 0.001	(in years) LA: -0.10 SM: -0.76 Ub: -0.80	(in years) LA: 0.64 SM: 1.01 Ub: 1.03	Bias in ages: 3.5, 4.5, 16.5, 19.5-23.5	-LA, SM, and Ub has bias to underestimate age. -LA is more accurate than SM and Ub -If exclude third molars, no bias in age estimation using LA
Dental age assessment of Western Saudi children and adolescents	Alshihri, Kruger, Tennant	2015/ Retrospective	Western Saudi Arabian	2-20 years	252 (142 females, 110 males)	Entire sample: p< 0.001	Not reported for entire sample, only age ranges	Not reported	-Bias in ages: 7-9, 13-15 -No bias in ages: 4-6, 10-12, ≥16	-Overall, bias in age estimation -Bias to overestimate age was higher in females than males
Precision and accuracy of commonly used dental age estimation charts for the New Zealand population	Baylis, Bassed	2017/Not reported	New Zealand	5-15.5 years	875 (439 females, 436 males)	Not reported per sample, only per age ranges	(in years) LA/females: -0.741 LA/males: -0.396 BT/females: -0.339 BT/males: -0.071 SM/females: 0.030 SM/males: 0.391	(in years) LA/females: 0.928 LA/males: 0.776 BT/females: 0.889 BT/males: 0.772 SM/females: 0.836 SM/males: 0.858	Non-biased ages: -LA/females: 15.5 -LA/males: 10.5, 11.5, 13.5-15.5 -BT/female: 5.5, 6.5, 9.5, 10.5, 14.5 -BT/males: 5.5, 6.5, 10.5, 13.5 -SM/females: 9.5-11.5 -SM/males: 6.5-9.5	-LA had bias to overestimate age -SM had bias to underestimate age -BT most accurate, although still low accuracy and precision

Age estimation in Portuguese population: The application of the London atlas of tooth development and eruption	Pavlović, Palmela Pereira, & Vargas de Sousa Santos	2017/ Retrospective	Portuguese	3-24 years	736 (498 females, 238 males)	Entire sample: p= 0.104 (right) p= 0.052 (left) <16 y: p= 0.00 (both sides) >16 y: p= 0.105 (right) p= 0.161 (left) Females: p= 0.765 (right) p= 0.652 (left) Males: p= 0.008 (right) p= 0.003 (left)	(in months) For entire sample: 1.05 (right) 1.24 (left) <16 y: 3.55 (right) 3.67 (left) >16 y: -2.21 (right) -1.83 (left)	Not reported	Bias to overestimate age in patients below 16 y	-No significant difference between age estimation using the right or left side of jaw -No bias in entire sample or in patients over 16 yr. -Bias to overestimate in patients under 16y -Bias toward overestimation in males, no bias in females
Comparison of the accuracy of the London atlas and Smith method in dental age estimation in 5–15.99-year-old Iranians using the panoramic view	Ghafari, Poordaver	2018/ Prospective	Iranian	5-15.99 years	339 (194 females, 145 males)	LA -- Entire sample: p= 0.150 Males: p= 0.196 Females: p= 0.203 SmM – Entire sample: p= 0.160 Males: p= 0.204 Females: p= 0.200	Not reported	(in years) LA – Entire sample: 0.60 Males: 0.59 Females: 0.63 SmM -- Entire sample: 0.70 Males: 0.65 Females: 0.73	LA & SmM: -Accuracy decreased at ages 12+.	LA & SmM -No bias in entire sample, males or females -LA has tendency to overestimate age -SmM has tendency to underestimate age -LA is easier to use -No difference in accuracy between males and females

Age estimation of Hispanic children using the London Atlas	McCloe, Marion, Da Fonseca, Colvard, AlQahtani	2018/ Retrospective	American Hispanic	6-15.99 years	332 (164 females, 168 males)	$p < 0.001$	(in years) 0.35	(in years) 0.73	-Bias in ages: 7, 11, 12, 13, 14 -No bias in ages: 6, 8, 9, 10, 15	-Bias to overestimate age -No difference in accuracy between males and females

***LA: the London Atlas; SM: Schour and Massler Atlas; Ub: Ubelaker Atlas; BT: Blenkin and Taylor Australian charts; SmM: Smith's Method*

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Academic Excellence Scholarship, University of Kentucky
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