5-1-2011

A Methodology for Three-Dimensional Quantification of Anterior Tooth Width

L. Thomas Johnson
Marquette University, thomas.johnson@marquette.edu

Thomas W. Radmer
Marquette University, thomas.radmer@marquette.edu

Alexis D. Visotcky
Medical College of Wisconsin

Kwang Woo Ahn
Medical College of Wisconsin-Milwaukee

Daniel D. Blinka
Marquette University

See next page for additional authors

Published version. *Journal of Forensic Identification*, Vol. 61, No. 3, (May-June 2011): 296-310.

Authors
L. Thomas Johnson, Thomas W. Radmer, Alexis D. Visotcky, Kwang Woo Ahn, Daniel D. Blinka, and Thomas Wirtz

Technical Note

A Methodology for Three-Dimensional Quantification of Anterior Tooth Width

L. Thomas Johnson [1]
Thomas W. Radmer [1]
Alexis D. Visotcky [2]
Kwang W. Ahn [2]
Daniel D. Blinka [3]
Thomas Wirtz [1]

Abstract: The use of cone-beam computed tomography (CBCT) technology has been shown to be more accurate in measuring individual incisor tooth widths than the use of wax exemplars. There were fewer differences by investigators using CBCT than others using an F-test in a mixed model of the measurement differences of investigators, wax type, and which tooth was measured. In addition, the frequency of outliers was less in the CBCT method (a total of 5) as compared to the two-dimensional measurements in ether Aluwax (a total of 8) or Coprwax (a total of 12). Both results indicate that CBCT measurements accounted more precisely for tooth width and level of eruption.

Introduction

The National Research Council's report underscored the need to bring more scientific rigor and objectivity to an array of forensic sciences, especially when they are used to identify suspects [1]. We have reported results in two dimensions [2]. However, maxillary and mandibular tooth relationships can be expressed in the third plane because of anatomical relationships affected by the erution of natural teeth. The resultant patterns may have excluded a tooth from being present when incisal imprints are considered in the x/y axis alone.

[1] Marquette University School of Dentistry, Milwaukee, WI
[2] Medical College of Wisconsin, Milwaukee, WI
[3] Marquette University Law School, Milwaukee, WI

Received June 3, 2010; accepted September 25, 2010

Working methodically in previous studies, a template for the measurement of dental characteristics in two-dimensions was developed [2]. During the course of this investigation, an automated measurement software application was also written, tested, and validated. A dataset of six dental characteristics was established, and a protocol was developed that measured a seventh dental characteristic: displacement either in front of, or behind, the physiologic dental arch [3–4].

Cone-beam computed tomography (CBCT) technology has been used for a number of years. Its accuracy in measuring linear spatial objects in two-dimensional images has been reported by a number of investigative studies. Kim reported, "... using cone-beam geometry produced true 3D images of the structure of small samples and suggested that the images were accurate enough for experimental endodontology" [5]. Of course, sectioning teeth would be the most accurate method of measurement, but that route of investigation was invasive and restricted measurements to predetermined levels of tooth morphology [5]. In the Kim study, measurements obtained by a three-dimensional surface scanner were comparable with direct measurements made with calipers [5]. This was substantiated in two additional studies that indicated that measurements based on three-dimensional CBCT surface images were accurate and that small variations in head position did not influence measurement accuracy [6, 7]. No measurement of linear characteristics can be completely identical between investigators. Asquith reported that even direct caliper measurement – the "gold standard" in orthodontic measurements – has its limitations in that the direct measurements cause damage by the repeated use of the device on teeth during the gathering of data [8]. Kim went on to report, "Measurements using photography, however, resulted in exaggerated values compared with the other methods. There are many reasons that may account for this, including the fact that the distance between the measuring surface or point and the camera could differ from the distance between the ruler and the camera. Such differences could magnify the tooth in a different ratio relative to the ruler." [5] In his study, Kim found, "... the values obtained using the photographic method were significantly overestimated ..." [5]. Although photographic error is possible, photographic documentation by a trained forensic imaging specialist following the guidelines of the Scientific Working Group on Imaging Technology can eliminate most from occurring.

With regard to three-dimensional volume rendering and accuracy, Lopes, Brown, and Rahim all found that in computerized tomography generations, data acquisition and parameters such as slice thickness and interval reconstruction all lead to a high degree of accuracy between three-dimensional and actual linear measurements of a dental model [9–11]. In the Brown study, the most clinically significant finding "... was that there was no difference in accuracy between measurements obtained from 3D volumetric renderings, no matter how many projection images were used to create the reconstruction" [10]. With regards to angular measurements, the Moreira study has shown that the results of the angular assessment did not demonstrate a statistically significant difference being observed for comparison between CBCT and physical measurements for two independent examiners [7].

Finally, the accuracy of measurements on three-dimensional scanned models versus direct caliper measurements to these models has been reported in a number of studies. Redlich, Bell, and Keating have reported in independent assessments that the accuracy of three-dimensional imaging systems has shown no statistically significant differences in measurements of linear dimensions when comparing direct caliper measurements to measurements using three-dimensional imaging techniques [12-14].

Our previous studies have indicated that it is possible to quantify the individual characteristics of the human dentition in two dimensions [2–4]. A rapid and accurate method of doing so may be included in the analysis using a validated computer software application called Tom's Toolbox.

Null Hypothesis

There is no difference in quantifying width as a tooth characteristic by using either two-dimensional or three-dimensional methodology.

Method

Fifty sets of dental casts were chosen from models submitted by dental students at Marquette University School of Dentistry. A set of models was composed of a gypsum cast replica of the entire maxillary and mandibular teeth. The models were chosen based on the presence of all of the six anterior teeth in the maxilla and mandible. To limit the sample size "n", only males were selected from the collection of models submitted, based on the quality of the models. This selection was made only if there were no chips, cracks, or bubbles. Only the ethnicity, gender, and age of the individual were recorded on the model. The fifty sets of models were scanned using a Sorodex Scanora CBCT scanner (Figure 1).

The scanned images produced by InVivo ANATOMAGE demonstrate a point cloud model (Figure 2).

The three-dimensional images were converted to a standard template for stereo lithography (STL) format. The conversion was necessary to enable the use of tools for the measurement of three-dimensional images in a prototyping software (Materialise' MiniMagics) on the incisal level, or "Z" plane (Figure 3).

Each of the sets of fifty models was also used to create imprints of the incisal edges of the anterior teeth in both Coprwax Bite Wafers (Heraeus Kulzer) and Aluwax (Aluwax Dental Products, Allendale, Michigan), both standard dental bite registration materials (Figure 4).

The use of Coprwax Bite Wafers was described in a previously reported two-dimensional analysis [2–4]. The imprints were scanned using an Epson 1680 Pro flatbed scanner and saved in a tiff format as original images. Duplicated images were measured by each investigator, using Tom's Toolbox (Figure 5). The calculated files were then saved by capturing the screen image in a jpeg format. Tom's Toolbox records all measurements and angulations in an internal data set.

The three-dimensional virtual images of the dental models derived from the CBCT scans were measured using Materialise' MiniMagics. The measurements were taken after establishing the level of the first point of contact, represented by a tiny blue marker on the incisal edge of one of the teeth. This established the base level of the Z plane. That level was recorded for each investigator. Subsequent measurements of tooth width for each of the incisor teeth were then recorded at 0.5, 1.0, 1.5, and 2.0 millimeters from that base. Each level of a three-dimensional scan measured in the Z plane was recorded as a screen capture and saved in jpg format for reproducibility by other investigators (Figure 6).

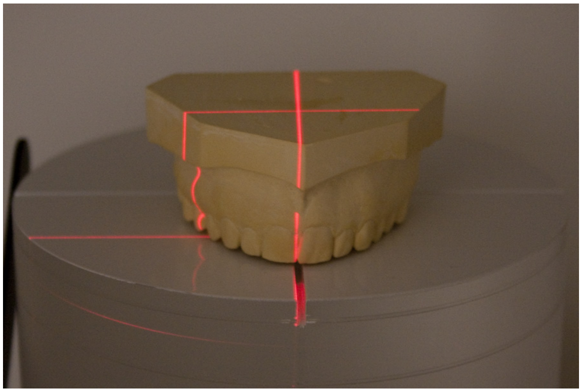


Figure 1

Orientation of the castone dental models prior to scanning by the Sorodex Scanora CBCT.

Figure 2

Scanned model in DICOM format.

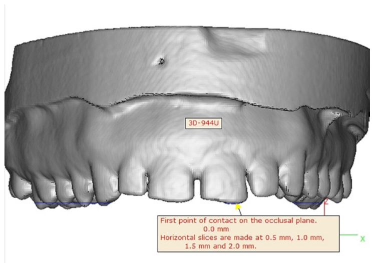
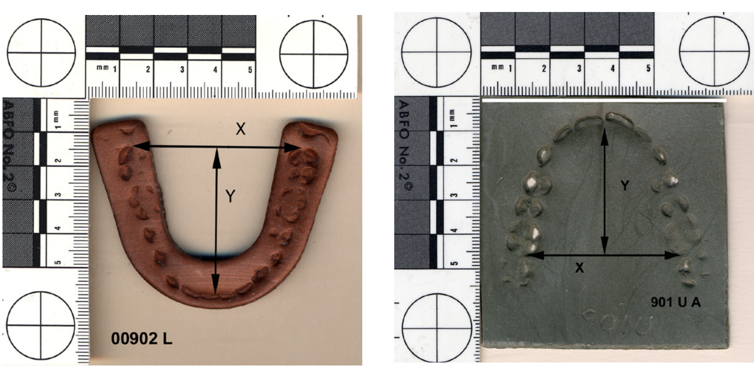


Figure 3

The base position on the Z plane is established by the first point of contact of one of the incisor teeth.



(a) *(b)*

Figure 4

Dental imprints in Coprwax (a) and Aluwax (b).

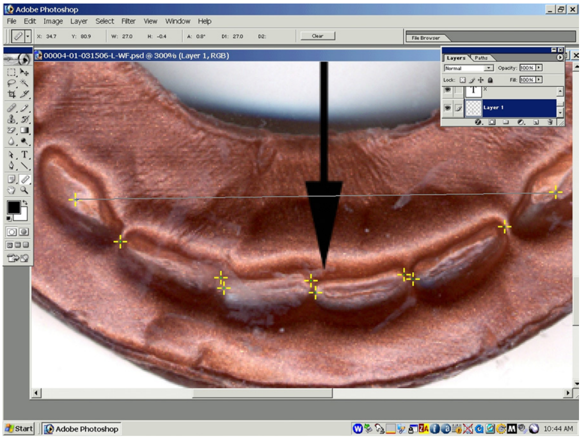


Figure 5

Using a series of ten markers, the application recognizes the location of each marker by column and row, calculating distance and angle of rotation. These calculations were then compared and verified using the measure tool in Adobe PhotoShop.

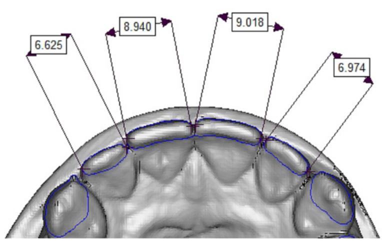


Figure 6

Measurements were made at 0.5, 1.0, 1.5, and 2.0 mm levels and recorded as screen captures in jpg format. The data was then entered into an Excel spreadsheet.

Results and Statistical Analysis

We investigated three-dimensional widths of teeth at four levels (0.5, 1.0, 1.5, and 2.0 mm) and compared them to two-dimensionl measurements in Aluwax and Coprwax and considered the 1.5 mm level in the Z plane (CBCT at 1.5 mm), Aluwax, and Coprwax in the multivariate analysis. The depth of 1.5 mm was selected for comparison because it represented the actual thickness of the two wax exemplars investigated. The dependent variable was the width measured by two investigators. Table 1 demonstrates the descriptive statistics including mean, median, and standard deviation of each wax type and CBCT level of penetration. The Aluwax, Coprwax, and CBCT measurements at 1.5 mm and 2.0 mm were similar, and the measurement of CBCT at the 0.5 mm levels had the least mean. Investigators, wax type, and tooth position were considered as explanatory variables in the multivariate analysis. Mixed model analysis was utilized to account for repeated measurements. All analyses were performed using Statistical Analysis Software (SAS Institute, Cary, NC). Table 2 shows F-test results from the mixed model. All explanatory variables were statistically significant. Table 3 shows comparison results. The measurements from two investigators showed significant difference. The CBCT was the least among the three types, and Coprawax was the greatest. All differences among the three measurement types were statistically significant. To see which wax type showed more consistency between two investigators, we performed mixed model with measurement differences between two investigators as dependent variable and wax type and tooth position as explanatory variables. Table 4 shows means and standard deviations of measurement differences of three wax types. Aluwax and Coprwax showed big measurement differences between two investigators compared to the CBCT model. In addition, the CBCT model had the least standard deviation among three methods of measurement. Table 5 shows mixed model results. Wax type and tooth position were all statistically significant, and there was no interaction between the two variables. Table 6 shows comparison results. Although Aluwax and Coprwax showed no difference, Aluwax and Coprwax showed much greater measurement differences between two investigators than the CBCT model. We also investigated outliers of two investigator-measurement differences, which were defined as differences larger than three standard deviation away from the mean of them (Table 7). Figure 7 shows the distributions of the two investigators' differences. The three distribution curves at 1.5 mm were similar, but Aluwax and the CBCT model showed a slight skew, whereas Coprwax was symmetric.

The standard deviations between investigators were minimal when comparing the three methods of measurements, given the fact the measurements were small. There was less of a significant difference by investigator than by either measurement type or tooth width as a variable. Measurement type had a highly significant difference, whereas the significant difference between investigators was not as great.

There were four hundred measurements, and the percent of outliers for Aluwax, Coprwax, and CBCT were 2%, 3%, and 1.25%, respectively, indicating the CBCT method had more precise measurements and more agreement between investigators. There were a total of 25 outliers by all methods. Aluwax accounted for 32%, Coprwax accounted for 48%, and CBCT accounted for 20%, further indicating there was more agreement by investigator using CBCT three-dimensional measurements of tooth width.

There was not a great deal of variability between investigators, when considering the three measurement types. The two-dimensional method in Aluwax and the CBCT both skewed slightly.

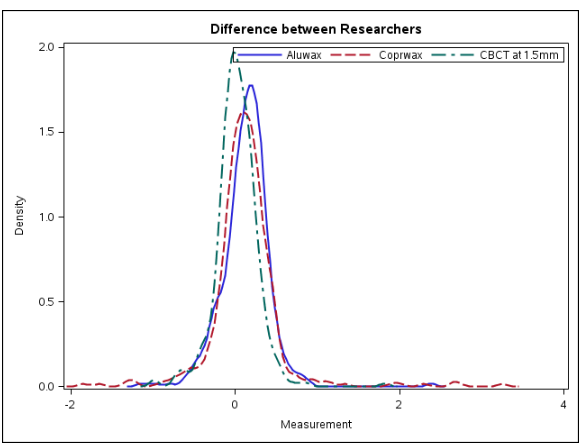


Figure 7

Distribution of outliers determined by investigators measuring in two dimensions from wax impressions in Aluwax or Coprwax compared to measurements obtained with the three-dimensional method from the CBCT scans.

Measurement Type	Mean	Median	Standard Deviation
Aluwax	6.36	6.00	1.68
Coprwax	6.56	6.21	1.54
CBCT@0.5 mm	4.16	4.11	1.85
CBCT@1.0 mm	5.39	5.20	1.80
CBCT@1.5 mm	5.91	5.66	1.64
CBCT@2.0 mm	6.19	5.83	1.47

Table 1

Descriptive statistics.

	P-value
Investigators	0.0387
Measurement Type	<0.0001
All Teeth	<0.0001

Table 2

F-test results of mixed model.

Variable	Comparison	Estimate (as a difference)	P-value
Investigator	Investigator 1 vs Investigator 2	0.08319	0.0387
Measurement Type	Aluwax vs CBCT @ 1.5 mm	0.4937	<.0001
	Coprwax vs CBCT @ 1.5 mm	0.6927	<.0001
	Aluwax vs Coprwax	-0.1990	<.0001

Table 3

Comparison results for investigator and measurement type.

Measurement Type	Mean	Standard Deviation
Aluwax	0.1294	0.288
Coprwax	0.1280	0.439
CBCT at 1.5mm	0.0200	0.253

Table 4

The means and standard deviations for the difference of measurements between investigators.

	P-value
Measurement Type	<0.0001
All Teeth	0.0162

Table 5

F-test results of mixed model for measurement type with the outcome being the difference in measurements.

Comparison	Estimate	P-value
Aluwax vs CBCT @ 1.5 mm	0.1086	<.0001
Coprwax vs CBCT @ 1.5 mm	0.1074	<.0001
Aluwax vs Coprwax	0.0012	0.9602

Table 6

Comparison results of measurement type with the outcome being the difference in measurements.

Measurement Type	Outliers Below 3 Standard Deviations	Outliers Above 3 Standard Deviations
Tom's Toolbox Aluwax	7	1
Tom's Toolbox Coprwax	6	6
CBCT @ 1.5 mm	3	2

Table 7

Frequency table of outliers.

Discussion

As previously reported, tooth widths can vary from the very uncommonly small to very uncommonly large when considering incidence rates in the 1st, 5th, 95th, and 99th percentile of occurrence [3]. Additionally, in the first reported study, the most common missing tooth was found to be the maxillary lateral incisor [3]. This is not surprising when measurements are made in the two-dimensional plane only, because the maxillary lateral incisor frequently is found to be at an eruption level in the third dimension (Z plane) that is higher than that of the adjacent central incisors. The distal incisal marginal ridge is also more rounded than that of the central incisors [15]. To the untrained observer, this might be interpreted as a tooth that is more narrow and shorter than it actually is. For the forensic odontologist, this may present a problem when evaluating the presence, absence, or uncommonly small appearance of characteristics in the patterned injury. This could also occur for other anterior teeth in each of the dental arches.

The use of CBCT and the incorporation of MiniMagics, along with the positioning of the pixel marker found in Tom's Toolbox, has allowed the investigators to add another individualized dental characteristic for the evaluation of patterned bitemark evidence in that the verticle position of teeth in the Z plane can be quantified. The values reported in Table 1 show that the differences in the standard deviation were very minimal, especially when evaluating the two wax types with the 1.5 mm level of tooth widths incorporated in the CBCT. For the Aluwax, CoprWax, and CBCT values at 1.5 mm, these were 1.68, 1.54, and 1.64, respectively. When evaluating the significant differences between investigators in a mixed model, there was a more highly significant difference in the wax measurements and tooth selection than there was with the individual investigators, with P-values of 0.0001, 0.0001, and 0.0387, respectively. Another multivariate analysis with measurement differences between investigators as dependent variable was performed. Aluwax and Coprwax showed much greater measurement differences between investigators than the CBCT. The conclusion drawn with these results indicate that the CBCT method of characterizing tooth width provides for greater investigator agreement than either media choice of bite mark replication or the individual tooth being evaluated. The skewnesses of the illustrative graphs found in Figure 7 are minimal and indicate the precise measurements achieved with each measurement in either wax or the CBCT. This figure shows only minor skews in variability between the two investigators when considering outliers. However, the measurement differences were minimal, less than 0.1 mm in most cases, for the various methodologies used in recording tooth width. Because the distribution curves of outliers fits patterns previously reported, this skewing can be discounted, because there is no significant difference.

Conclusion

The use of statistical evidence in court room proceedings with a jury that may lack expertise may be the next formidable task facing the forensic odontologist. How material is gathered, presented, and then evaluated by a jury can be a problem. For the scientific community, confidence intervals of 95% are accepted evaluations of data when using a scientific basis of reporting. For the jury, this may indicate that there is a 5% chance that an individual in question is not the perpetrator. Based only on our limited data set from the quantification of the eight individual characteristics of the human dentition reported, a single tooth with outliers in all categories with regards to a tooth's width, displacement, rotation, damage, presence, spacing, vertical position, and intercupid arch width has a factorial of 1:40,320 if all outlier characteristics are present. Expanding the factorial to the eight teeth presently evaluated, this becomes 1:1.626 billion (8 factorial X 8 factorial) or 5.27 times the 2010 United States population figure estimates of 308.75 million.

The final direction to be taken in evaluation of bite mark evidence is the ability of the forensic odontologist to evaluate patterned evidence and to link that pattern to an individual data set in a known data base. With this in mind, the need for an ever-expanding data base becomes apparent. This will require other researchers in the forensic community to aide in the expansion of data collected in a uniform, reproducible, and quantifiable format. We believe a template has been established that can now be modified and expanded to analyze not only bite marks but other types of patterned evidence.

Acknowledgments

Major funding for the development of the data in this paper was provided by the U. S. Department of Energy Award # DE-AC02-07CH11358, via a sub-award from the Midwest Forensic Resources Center, Ames Laboratory Iowa State University.

We wish to express our appreciation to the MFRC for their continued support in funding our research; Dr. Lisa Koenig, Associate Professor, for the use of the Department of Radiology's cone-beam equipment; and Mr. James Brozek, photographer, for his technical support in providing illustrations.

For further information, please contact:

L. Thomas Johnson
Marquette University School of Dentistry
P.O. Box 1881
Milwaukee, WI 53201-1881
thomas.johnson@marquette.edu

References

1. Committee on Identifying the Needs of the Forensic Sciences Community, National Research Council. *Strengthening Forensic Science in the United States: A Path Forward*, The National Academies Press: Washington, DC, 2009.
2. Johnson, L. T.; Blinka, D. D.; VanScotter-Asbach, P.; Radmer, T. W. Quantification of the Individual Characteristics of the Human Dentition: Methodology. *J. For. Ident*. **2008**, *58* (4), 409–418.
3. Johnson, L. T.; Radmer, T. W.; Wirtz, T. S.; Pajewski, N. M.; Cadle, D. E.; Brozek, J.; Blinka, D. D. Quantification of the Individual Characteristics of the Human Dentition. *J. For. Ident*. **2009**, *59* (6), 609–625.
4. Radmer, T.; Johnson, L. T.; Yang, M.; Wirtz, T. The Quantification of Tooth Displacement. *J. For. Ident*. **2010**, *60* (3), 4–18.
5. Kim, I; Paik, K; Lee, S. Quantitative Evaluation of the Accuracy of Micro-Computed Tomography in Tooth Measurement. *Clinical Anat*. **2007**, *20* (1), 27–34.
6. Hassan, B; van der Stelt, P; Sanderink, G. Accuracy of Three-dimensional Measurements Obtained from Cone Beam Computed Tomography Surface-rendered Images for Cephalometric Analysis: Influence of Patient Scanning Position. *Europ. J. of Orthodonttics* **2009**, *31* (2), 129–134.
7. Moreira, C. R.; Sales, M. A. O.; Lopes, P. M. L.; Cavalccanti, M. G. P. Assessment of Linear and Angular Measurements on Three-dimensional Cone-beam Computed Tomographic Images. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontology* **2009**, *108* (3), 430–436.
8. Asquith, J; Gillgrass, T; Mossey, P. Three-dimensional Imaging of Orthodontic Models: A Pilot Study. *Europ. J. Orthodontics* **2007**, *29* (5), 517–522.
9. Lopes, P. M. L; Moreira, C. R.; Perrella, A. 3-D Volume Rendering Maxillofacial Analysis of Angular Measurements by Multislice CT. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontology* **2008**, *105* (2), 224–230.
10. Brown, A. A.; Scarfe, W. C.; Scheetz, J. P.; Silveira, A. M.; Farman, A. G. Linear Accuracy of Cone Beam CT Derived 3D Images. *Angle Orthod*. **2009**, *79* (1), 150–157.
11. Rahimi, A.; Keilig, L.; Bendels, G.; Klein, R.; Buzug, T. M.; Abdelgader, I.; Abboud, M.; Bourauel, C. 3D Reconstruction of Dental Specimens from 2D Histological Images and CT-Scans. *Comput. Methods Biomech. Biomed. Engin*. **2005**, *8* (3), 167–176.

12. Redlich, M; Weinstock, T; Abed, Y; Schneor, R; Holdstein, Y; Fischer, A. A New System for Scanning, Measuring and Analyzing Dental Casts Based on a 3D Holographic Sensor. *Orthod. Craniofac. Res.* **2008**, *11* (2), 90–95.
13. Bell, A; Ayoub, A. F.; Siebert, P. Assessment of the Accuracy of a Three-dimensional Imaging System for Archiving Dental Study Models. *J. Orthod.* **2003**, *30* (3), 219–223.
14. Keating, A. P.; Knox, J.; Bibb, R.; Zhurov, A. I. A Comparison of Plaster, Digital and Reconstructed Study Model Accuracy. *J. Orthod.* **2008**, *35* (3), 191–201.
15. Wheeler, R. C. The Permanent Maxillary Incisors. In *A Textbook of Dental Anatomy and Physiology*, 4th ed.; W. B. Saunders Company: Philadelphia, 1965; p 138.