INVESTIGATING THE PREVALENCE OF TAURODONTISM IN AN ADOLESCENT POPULATION USING DENTAL PANORAMIC RADIOGRAPHS

by

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Abstract

Purpose: Taurodontism was thought to be associated mainly with oro-facial syndromes but studies in normal Chinese and Brazilian adult populations have shown that this trait is relatively common. We hypothesize that taurodontism is a variation of normal root morphology that may be present in an adolescent population as an incidental finding.

Methods: Digital dental panoramic radiographs (DPRs) taken of 124 adolescents aged between 15 and 20 years old (male: female; 59:65), attending the University of British Columbia's Faculty of Dentistry Clinic between July 2006 and June 2019 were examined. Unrestored first and second permanent molars with closed apices were measured digitally and a taurodont ratio index was obtained using the Shifman and Chanannel criteria.

Results: The total number of teeth examined was 992 and the proportion of taurodont teeth was 16.6%. Of the 124 cases, 68 (54.8%) had at least one taurodont tooth. There were 43 cases with bilateral taurodont teeth. Taurodontism had a higher predilection for females (63.1%) as compared to males (45.8%). This difference was significant for all molars with a *P* value ranging from $P = .003$ to $P = .043$, where $P < .05$, except for the upper left second permanent molar (tooth #27) and the lower left second permanent molar (tooth #37). The extent of taurodontism was mostly mild.

Conclusions: Our results suggest that mild taurodontism is relatively common in the local adolescent population similar to what was reported elsewhere. The ability to identify these teeth and diagnose them early can help inform treatment planning decisions.

Lay Summary

This retrospective research study examined whether taurodontism was an incidental finding in a local adolescent population. The anatomical shape of these teeth can have an impact in endodontic, orthodontic, and prosthodontic considerations during treatment planning.

The unfilled, decay-free, first and second adult molars of one hundred and twenty-four dental panoramic radiographs (DPRs) were analyzed and classified on a ratio scale of mild, moderate to severe taurodontism.

Our results suggest that mild taurodontism is relatively common in the local adolescent population similar to what was reported elsewhere. As dentists, the ability to identify these teeth and diagnose them early can help inform treatment planning decisions.

Preface

Dr. Zahra Samji conducted this retrospective research project under the direct supervision of Dr. David MacDonald. Committee members included Dr. Adrianna Manso and Dr. Joy Richman.

Dr. Samji performed all data collection and analysis of the research data with the guidance of Dr. MacDonald and meetings with Dr. Jolanta Aleksejuniene (statistics).

Although no direct contact with patients was required, to ensure proper protocol was adhered to and no violation of patient privacy was committed, ethics approval was obtained from the UBC Clinic Research Ethics Board (Certificate Number: 19-0917) approved on 6th July 2019 and renewed in July 2020.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

AAPD: American Association of Pediatric Dentistry

AD: Autosomal dominant

AR: Autosomal recessive

ASA: American Society of Anesthesiologists

CB: Crown-body

CEJ: Cementoenamel junction

CI: Confidence interval

CNCC: Cranial neural crest cell

DLX3: Distal-less 3 homeobox

DPR: Dental Panoramic Radiograph

ED: Ectodermal Dysplasia

EDA: ectodysplasin

EVC: Ellis–Van Creveld

FGFR3: fibroblast growth factor receptor 3

HERS: Hertwig's epithelial root sheath

ICC: Intraclass Correlation Coefficient

IEE: Inner enamel epithelium

OEE: Outer enamel epithelium

OMIM: Online Mendelian Inheritance in Man

PHEX: Phosphate regulating endopeptidase homolog X-Linked

R: Root

SD: Standard deviation

SI: Stratum intermedium

SR: Stellate reticulum

TDO: Tricho-dento-osseous

TI: Taurodont Index

T1: Variable 1: Measured from the lowest point of the roof of the pulp chamber to the highest point of the floor of the pulp chamber

T2: Variable 2: Measured from the lowest point of the roof of the pulp chamber to the apex of the longest root

T3: Variable 3: Measured from the cementoenamel junction to the lowest point of the pulp chamber

UBC: University of British Columbia

WNT: canonical Wingless-related

2D: Two-dimensional

Glossary

Antimere: A pair of opposite corresponding symmetrical body parts. Tooth #17 and tooth #27 are antimeres.

Brachydont: Short crowns located above the alveolar bone and well-developed roots with narrow canals (as in humans).

Hypsodont: High-crowned teeth and enamel extending past the gingival margin, providing extra material for wear and tear (as in horses and cows).

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I would like to express my sincerest gratitude to my supervisor, Dr. David MacDonald for his guidance, patience, and timely constructive feedback. His patience and clarity with my neve-ending questions during our long in-person M.Sc. meetings that later transitioned to zoom meetings, was instrumental. His calm leadership in our M.Sc. committee meetings was invaluable. Dr. MacDonald's continual pursuit of excellence is and will continue to be a source of inspiration throughout my career.

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I owe Dr. Adrianna Manso my gratitude as well for her support and guidance as a member of my research committee who brought a unique and important perspective to the team.

I would like to acknowledge Dr. Jolanta Aleksejuniene, for committing hours to teaching me how to run my own statistics and guiding me through this process with utmost patience.

Dedication

This is dedicated to my incredible family who have always been there for me. Their support, selfless love and constant sacrifices have allowed me to pursue my dreams. Without them none of my accomplishments would be possible, and none would mean as much.

A special note of gratitude to my mother who has always been my rock and always had faith in me. I dedicate this in memory of my loving father who was not there with me on this adventure but continues to guide me always.

And finally, my gratitude to God for His kindness, mercy, and strength along this journey.

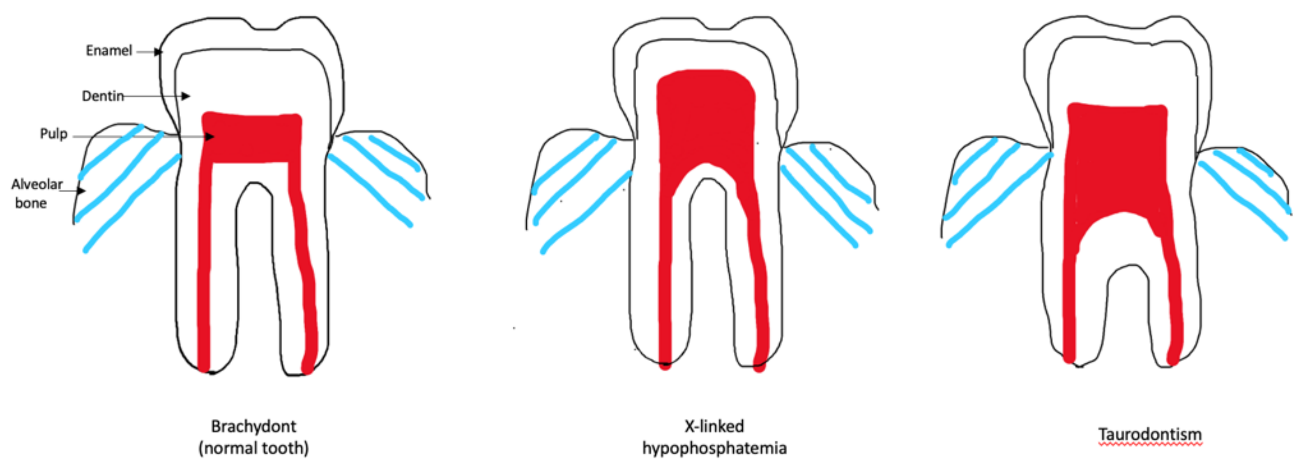
Chapter 1: Introduction

1.1 **Introduction to Taurodontism**

Taurodontism (Online Mendelian Inheritance in Man OMIM #272700), has been described as a dental anomaly defined as a distortion of the internal morphology of the pulp chamber (Haskova et al., 2009). Its characteristic features are a larger pulp chamber, apical displacement of the pulpal floor, proportionally shortened roots and the lack of constriction at the level of the cementoenamel junction in premolars and molars (Jafarzadeh et al., 2008). This results in the displacement of the furcation in an apical direction, and essentially in the elongation of the pulp chamber overall (Shifman and Chanannel, 1978). Taurodontism is a condition that primarily affects the root development; however, these teeth present with normal dentin thickness in the crown and root (Li et al., 2017). In contrast, conditions that are affected by reduced dentin secretion such as X-linked hypophosphatemia, due to mutations in the *PHEX* (phosphate regulating endopeptidase homolog X-Linked) gene, also have enlarged pulp cavities but the position of the furcation is normal (Li et al., 2017). Dentinogenesis Imperfecta Type III ("Brandywine isolate"), in which the *DSPP* gene is affected, can also present with enlarged pulp chambers with a thin surrounding dentinal layer and a normal tooth furcation (Kim and Simmer, 2007).

Figure 1: Normal molar, X-Linked hypophosphatemic molar and Taurodont molar

Figure 1 below depicts a normal molar also known as a brachydont, an X-Linked hypophosphatemic molar with an enlarged pulp, normal furcation and a taurodont molar, also with an enlarged pulp in addition to apical displacement of the tooth furcation.



In multi-rooted molars as the furcation is displaced more apically, it results in the overall morphological change from a more common "cynodont" shape to a more cylindrical taurodont shape (MacDonald, 2020). Taurodontism was initially described by Gorajnovic-Kramburger in 1908. The word taurodontism has a combined origin from the Latin word, *tauros,* meaning "bull" and the Greek word *odus,* meaning "tooth", hence, "bull tooth" (MacDonald, 2020). Cynodont is a combination of the Greek words *cyno* meaning "dog" and *odus* meaning tooth, hence "dog-tooth"(MacDonald, 2020). In 1913, the term taurodontism was first initiated by Sir Arthur Keith to describe molar teeth that looked similar to hypsodont teeth of hooved animals such as bulls (Keith, 1913). Taurodontism has been observed in both deciduous and permanent dentitions, but to a lesser degree in deciduous teeth (Jamshidi et al., 2017). It can also present in single or multiple teeth unilaterally or bilaterally in molars and premolars (Haskova et al., 2009).

1.1 Development of multirooted teeth

In order to comprehend the variation in normal tooth development seen in taurodontism, it is first essential to review the steps of root formation. Teeth are structurally divided into two parts: the crown and the root (Ma et al., 2021). Tooth development comprises of the bud, cap, bell stages, root development and tooth eruption (Huang and Chai, 2012). Sequential reciprocal epithelial and mesenchymal cellular interactions regulate these developmental processes (Thesleff and Sharpe, 1997). The enamel organ gives rise to the crown of the tooth and the cervical loop (Liu et al., 2016). The crown is comprised of the outer enamel epithelium (OEE), inner enamel epithelium (IEE), stellate reticulum (SR) and stratum intermedium (SI) (Liu et al., 2016). Following crown formation, the process of the development of the root is initiated (Li et al., 2017). At this stage, the apical extension of the developing enamel organ reaches the boundary of the future cementoenamel junction (CEJ) and ceases enamel formation (Li et al., 2017). The place where the outer enamel epithelium and inner enamel epithelium join, is known as the cervical loop (Liu et al., 2016). The inner enamel epithelium of the cervical loop is no longer capable of forming ameloblasts and the epithelial-derived cervical loops extend apically to form the root (Li et al., 2017).

As the apical projection of the enamel organ extends a few millimeters beyond the crown, the cervical loops bend towards the center of the tooth resulting in separation of one root into two or three roots (Li et al., 2017). The coronal-apical position of the bend in the cervical loops determines the position of the furcation (Li et al., 2017). Tissue interactions are necessary between the dental epithelium and the cranial neural crest cell (CNCC)-derived mesenchyme to form the root dentin (Li et al., 2017). Without this interaction, no dentin forms resulting in root agenesis which has been observed in conditions such as dentin dysplasia type I (Alhilou et al., 2018).

There is likely migration of the dental epithelium towards the center of the tooth since studies in mouse molar organ culture have demonstrated that the use of a drug that blocks cell movement (cytochalasin-D), blocked furcation formation (Sohn et al., 2014). The mechanism that controls the epithelial invagination is still unclear. After the furcation has been established, the cervical loop epithelium extends further apically and breaks down to form a discontinuous sheath of epithelial cells called Hertwig's epithelial root sheath (HERS) (Li et al., 2017). This breakthrough of mesenchyme induces the formation of periodontal ligament and cementum along the root surface (Li et al., 2017). The furcation also induces the alveolar bone and PDL underneath. It takes several years to complete root formation (Li et al., 2017). Any delay in the timing of when the cervical loop turns medially will cause an increase in pulp chamber depth or taurodontism (Jing et al., 2019).

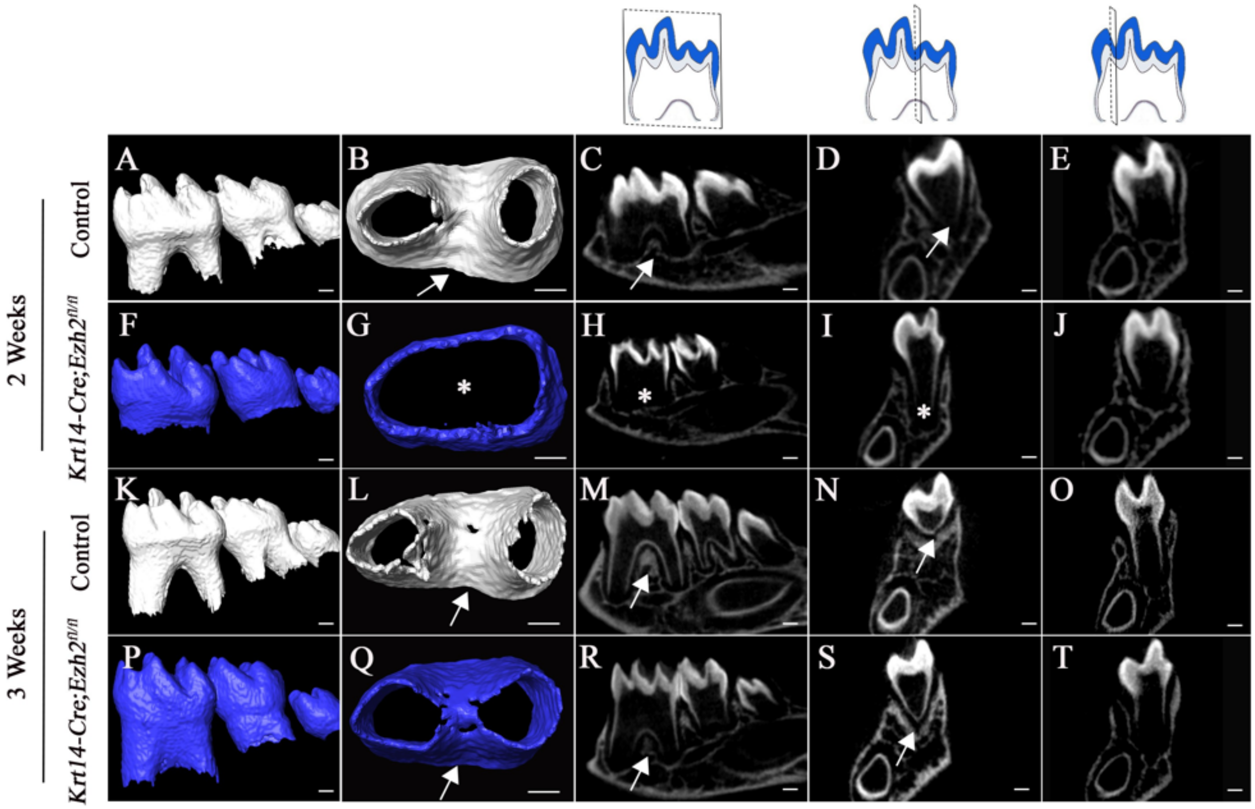
1.1.1 Molecular controls of root number and pattern

The epithelium signals to the mesenchyme to control the number and pattern of the roots (Li et al., 2017). There are several mouse models showing that disrupting gene expression specifically in the epithelium (Fons Romero et al., 2017, Jing et al., 2019), or mesenchyme (Jing et al., 2019) leads to single rooted molars, hence both tissues may play a role. Cell proliferation is the key to furcation development (Yang et al., 2015). If cell proliferation is reduced, particularly in the mesenchyme (Jing et al., 2019), then single rather than multiple roots develop. The molecular pathways with the most evidence to support a role in root patterning are the ectodysplasin pathway (EDA); (Fons Romero et al., 2017), and the canonical Wingless-related pathway (WNT) (Du et al., 2021) (Yang et al., 2015). Root morphogenesis seems to be directed by molecular regulation involving the interaction of epithelial and mesenchymal derived tissues (Gomes et al., 2012).

In Figure 2 below from Jing et al., (2019), the authors observed the role that a protein, Ezh2, important in the development of facial bones, to determine if the lack of this protein had any impact on the development the molar teeth in a mouse model (Jing et al., 2019). At 2 weeks after birth in control mice, the molar furcation with two roots can be observed (Figure 2A-2E), but in the affected mice Osr2-Cre;Ezh2$^{fl/fl}$, the furcation was not present (Figure 2F-2J). The furcation developed later when the mice were 3 weeks postnatal (Figure 2P-2T), similar to what we see in taurodontism where the constriction of the furcation is more apical (Jing et al., 2019). The loss of Ezh2 in the tooth mesenchyme converted a multi-rooted molar into a single-rooted tooth in the mouse model, signifying the importance of the dental mesenchyme in regulating root pattern and furcation development (Jing et al., 2019). However, when Ezh2 was not present in the epithelium, this caused a delay in the development of the furcation but did not affect the number of roots (Jing et al., 2019).

Figure 2: Loss of EZh2 in the dental mesenchyme leading to single-rooted molars

Acknowledgement (Jing et al., 2019)



Loss of Ezh2 in the dental mesenchyme leads to single-rooted molars. Micro CT images of control (white) and Osr2-Cre;Ezh2$^{fl/fl}$ (blue) molars at postnatal (PN) 2 and 4 weeks of age. A, F, K, P, lateral view of mandibular molars; B, G, L, Q, apical view of mandibular first molars; C, H, M, R, sagittal sections of mandibular molars; D, I, N, S, coronal sections of mandibular molars in the furcation region; E, J, O, T, coronal sections of mandibular molars in the root forming region. The schematic drawings indicate where the CT section were taken. Arrows indicate furcation and asterisks indicate absence of furcation.

(Jing J, Feng J, Li J, Han X, He J, Ho TV, Du J, Zhou X, Urata M, Chai Y. Antagonistic interaction between Ezh2 and Arid1a coordinates root patterning and development via Cdkn2a in mouse molars. *Elife. 2019 Jul 1;8: e46426. doi: 10.7554/eLife.46426.* Available at: https://pubmed.ncbi.nlm.nih.gov/31259687/)

1.2 Etiology

Taurodontism is caused by the failure or delay of HERS to invaginate at the proper horizontal level (Hamner et al., 1964). This results in the elongation of the pulp chamber and consequently, shortening of the roots (Witkop et al., 1988).

1.2.1 Non-syndromic and syndromic forms of taurodontism

Taurodontism has been reported as an isolated trait (Jaspers and Witkop, 1980), or occurring concomitantly with multiple syndromes (Seow et al., 1995). In addition, taurodontism has been associated with several dental anomalies such as amelogenesis imperfecta (OMIM# 104510) (Price et al., 1999) and hypodontia (tooth agenesis) (OMIM# 106600) (Seow and Lai, 1989, Schalk-van der Weide et al., 1993). Taurodontism has been frequently observed in syndromes such as those listed below in Table 1.

Table 1: Syndromes associated with taurodontism

Syndromes associated with taurodontism	OMIM #	Gene	Inheritance Pattern	Reference
Ectodermal Dysplasia (ED)	305100	*EDA*	X-linked recessive, AD, AR	Torres et al. (2019)
Tricho-dento-osseous syndrome (TDO)	190320	*DLX3*	AD	Jagtap et al. (2019)
Trisomy 21	190685	Multiple	Trisomy 21	Jaspers (1981)
Klinefelter syndrome	400045	46, XX	De novo	Giambersio et al. (2019)
Ellis-van Creveld syndrome (EVC)	225500	*EVC/EVC2*	AR	Peña-Cardelles et al. (2019)
X-linked hypophosphatemia	307800	*PHEX*	X-linked dominant; De novo	Seow et al. (1995)
Otodental dysplasia	166750	*FGFR3*	AD	Gregory-Evans et al. (2007)

OMIM: Online Mendelian Inheritance in Man
AD: Autosomal dominant
AR: Autosomal recessive

In these syndromes, additional dental phenotypes can be observed such as hypodontia, which suggests that ectodermal defects may also be present (Schalk-van der Weide et al., 1993). Some studies propose that taurodontism may have a genetic basis (Witkop et al., 1988). Multiple genes and signaling pathways have been implicated in tooth development and genetic mutations may impact this process (Thesleff, 2000). One such gene implicated in root morphogenesis associated with taurodontism is the distal-less 3 homeobox gene (*DLX3*) (Wright et al., 2008). *DLX3* gene mutations have been identified in syndromes that present with taurodontism such as tricho-dento-osseous syndrome as well as amelogenesis imperfecta with taurodontism (OMIM# 104510) (Wright et al., 2008). Among patients with more severe forms of taurodontism there has been an increased tendency for X chromosomal polyploidy, which lends credence to further supporting the genetic underpinning of taurodontism (Jaspers and Witkop, 1980). Nonetheless more studies need to be done and the genetics of taurodontism may in fact be polygenic (Gomes et al., 2012).

1.2.2 Evolution of human molars

An alternative theory suggests that taurodontism may be rooted in Neanderthal and Inuit populations whereby teeth were utilized as tools and the shape of the taurodont molar would serve as an evolutionary advantage (Macchiarelli et al., 2006). This is because the attrition would encourage the enlarged pulps to deposit secondary dentin, thereby enhancing tooth longevity (Kupczik and Hublin, 2010). The other selective advantage is the apical displacement of the furcation reduces the likelihood of periodontal disease (Blumberg et al., 1971). This is in direct contrast with findings that suggest that taurodontism has been reported mostly in modern populations, namely Caucasians (Jaspers and Witkop, 1980).

In order to understand the evolution of teeth, fossilized remains of hypsodont teeth seen in horses were examined. Hypsodont teeth are those where the crown extends below the level of the alveolar bone whereas in humans, we have brachydont teeth where the crowns are above the alveolar bone level (Jheon et al., 2013). Brachydont teeth are thought to have evolved in humans to adapt to dietary needs (Jheon et al., 2013).

1.2.3 External factors

External factors, during early childhood can affect root development. These factors can include osteomyelitis (Reichart and Quast, 1975), antineoplastic therapy and trauma as potential causative factors (Carrillo et al., 2014). If there is trauma to the HERS, that can potentially affect the surrounding neurovascular structures which can lead to a disruption of the root and dentin development (Andreasen and Kahler, 2015). Tooth dilaceration, a root malformation, defined as a steep curvature of the root that is sometimes found in permanent teeth, caused indirectly by trauma in the primary dentition (Andreasen et al., 1971). With chemotherapy and radiotherapy, the proliferating cells can be destroyed and hence affect root morphogenesis (Minicucci et al., 2003). This depends on the dosage and duration as well as the age of the patient a range of abnormalities can result (Minicucci et al., 2003). These range from agenesis of teeth to blunted roots and even the premature arrest of root development (Minicucci et al., 2003).

1.3 Taurodontism – Prevalence in various populations

Remarkably, taurodontism has been reported in the multiple studies, as an incidental finding in non-syndromic populations (MacDonald-Jankowski and Li, 1993, Weckwerth et al., 2016, Jamshidi et al., 2017). The prevalence of taurodontism has been examined in various populations in the literature. Most studies prefer to quantify taurodontism in a subjective assessment as opposed to an objective analysis (Jafarzadeh et al., 2008). The methods used to quantify taurodontism differs between studies in terms of criteria, the types of radiographs used, types of teeth measured and analytical measured employed (Jaspers and Witkop, 1980, Shifman and Chanannel, 1978, Hegde et al., 2013) leading to a lack of consistency in the prevalence data reported (Table 2).

Table 2: Prevalence of taurodontism

Study	Population	Type of teeth	Sample size	Prevalence (%)	Type of Image
Shifman and Chanannel (1978)	Israeli	All posterior molars	1200 patients 10,204 teeth	5.6% (patients) 1.5% (teeth)	Periapical and bitewing radiographs
Jorgenson (1982)	African American	Deciduous and permanent molars	1074 patients	4.3% (patients)	Dental panoramic radiographs
Ruprecht et al. (1987)	Saudi Arabian	Molars	1581 patients 1647 teeth	11.3% (patients) 43.2% (teeth)	Full mouth series & Dental panoramic radiographs
MacDonald-Jankowski and Li (1993)	Chinese	All posterior molars	196 patients 1093 teeth	46.4% (patients) 21.7% (teeth)	Dental panoramic radiographs
Darwazeh et al. (1998)	Jordanian	All posterior molars	875 patients 2636 teeth	8.0% (patients) 4.4% (teeth)	Posterior periapical radiographs
Touré et al. (2000)	Senegalese	All posterior molars	150 patients 1027 teeth	48.0% (patients) 18.8% (teeth)	Dental panoramic radiographs
Bürklein et al. (2011)	German	All posterior molars	800 patients 4,885 teeth	2.25% (patients) 0.61% (teeth)	Full mouth series
Patil et al. (2013)	Indian	All posterior molars	4143 patients	0.41% (patients)	Dental panoramic radiographs
Gonçalves Filho et al. (2014)	Brazilian	All posterior molars	503 patients	27.19% (patients)	Dental panoramic radiographs
Puttalingaiah et al. (2014)	Indian	First mandibular molars	946 patients	17.30% (patients)	Dental panoramic radiographs
Weckwerth et al. (2016)	Brazilian	All posterior molars	974 patients	42.8% (patients)	Dental panoramic radiographs
Jamshidi et al. (2017)	Iranian	All posterior molars	2630 patients	22.9% (patients)	Dental panoramic radiographs
Bilge et al. (2018)	Turkish	All posterior molars	1200 patients	11.27% (patients)	Dental panoramic radiographs

1.4 Diagnosis - A radiographic phenomenon

From a clinical perspective a taurodont tooth appears as a normal tooth (Giambersio et al., 2019). Taurodontism is primarily a radiographic diagnosis, since a taurodont tooth clinically does not have any unique features and cannot be differentiated from other teeth (Giambersio et al., 2019). Shaw (1928) proposed that taurodontism should be defined in more precise terms with reference to the increasing order of severity as hypotaurodontism (mild), mesotaurodontism (moderate) and hypertaurodontism (severe). Nonetheless, in order to quantify taurodontism, multiple indices have been suggested as displayed in Table 3 below:

Table 3: Categorization of taurodont teeth

Study	Method of Assessment	Classification	Observations
Shaw (1928)	Based on the external morphologic tooth form: Severity of apical displacement of the floor of the pulp chamber.	4 categories a) Cynodont (no taurodontism) b) Hypotaurodont c) Mesotaurodont d) Hypertaurodont	Assessed second molars only Pioneering study to quantify taurodontism Does not distinguish between prismatic (roots are undifferentiated) and taurodont teeth
Keene (1966)	Taurodont index (TI): comparison of the vertical height of the pulp chamber with the length of longest root	4 categories based on the TI a) Cynodont: Index: 0-24.9% b) Hypotaurodont: Index: 25-49.9% c) Mesotaurodont: Index; 50-74.9% d) Hypertaurodont: Index: 75 – 100%	Limitations: Use of biological landmarks that may be subject to change
Blumberg et al. (1971)	Used 5 variables defined as: Variable 1: mesiodistal diameter of the crown at contact points Variable 2: mesiodistal diameter of the crown at the level of the cementoenamel junction (CEJ) Variable 3: distance from the CEJ to the highest point on pulp chamber floor Variable 4: distance from the CEJ to the apex of longest root Variable 5: distance from CEJ to the lowest point of the root of the pulp chamber.	No categories (Blumberg et al., 1971) described taurodontism as being a continuous trait and cannot be separated into categories	A biometric study

Shifman and Chanannel (1978)	Used 3 variables: Variable 1 (T1): the distance between the lowest point of the roof of the pulp chamber and the highest point of the floor of the pulp chamber (vertical height of the pulp chamber) Variable 2 (T2) - the distance between the lowest point of the roof of the pulp chamber to the apex of the longest root. Taurodont index (TI) = $\frac{\text{Variable 1}}{\text{Variable 2}}$ X 100 Variable 3 (T3)- the distance from the CEJ to the highest point of the floor of the pulp chamber	3 categories based on the TI: a) Hypotaurodontism: TI = 20-30 a) Mesotaurodontism: TI = 30-40 a) Hypertaurodontism: TI = 40-75	Advantages: Used anatomical landmarks that were constant as opposed to being in continual flux (Keene's Index) Excluded teeth affected by reparative dentin Limitations: Variable 3: range of measurement of the distance from the CEJ to the highest point of the pulp chamber is small and thus can be inaccurate
Seow and Lai (1989)	Mandibular first permanent molars: crown-body (CB): root (R) ratios (1989). CB: length measurement along the vertical axis of the tooth perpendicular to the occlusal pit to a perpendicular line drawn through the furcation R: length measurement along the vertical axis of the tooth from the furcation to the root apex.	4 categories based on CB:R ratios a) Normal (cynodont): ratio of <1.10 b) Hypotaurodont: 1.10 -1.29 c) Mesotaurodont: 1.30 -2.00 d) Hypertaurodont: > 2.00	Only assessed mandibular first permanent molars which may not be an accurate representation since taurodontism can affect multiple teeth (Keith, 1913)

With regards to Shifman and Chanannel (1978), they used periapical radiographs to radiologically detect taurodontism. Tulensalo et al. (1989), pioneered the use of DPRs to manually evaluate taurodontism. The use of a younger age group (10-16 years old) may have limited their ability to use Variable 2 (T2), which is the distance between the lowest point of the roof of the pulp chamber to the apex of the longest root, due to incomplete root development in multiple molars which is characteristic of that cohort (MacDonald, 2020). By contrast the age group assessed by Shifman and Chanannel (1978) was between 20-30 years of age. A limiting factor in this study is the teeth measured in an older cohort may have been subject to attrition, resulting in deposition of secondary dentin, which may be a confounding variable. In indigenous southern African populations, increased occlusal wear has been associated with a reduction in the size of the pulp cavity, presumably due to the deposition of secondary dentin (Constant and Grine, 2001). The study done by MacDonald-Jankowski and Li (1993), was the first to use digital measurements directly measuring DPRs. These digital measurements increased the accuracy of the measurements to 2 decimal places, as opposed to rounding off to the closest half millimetre (MacDonald-Jankowski and Li, 1993).

1.4.1 Dental implications

Taurodontism poses a clinical challenge to dental treatment and may warrant an interdisciplinary approach. The pulp and root morphology in a taurodont tooth is diverse with multiple variations depending on the degree of severity of taurodontism (Dineshshankar et al., 2014).

Negotiating the complicated anatomy of the root canal system coupled with multiple roots of a taurodont tooth is potentially problematic from an endodontic perspective (Jafarzadeh et al., 2008). There may be difficulty in locating canal orifices, due to the apical displacement of the pulpal floor, as well as the increased risk of hemorrhage due to the voluminous pulp which can be mistaken for a perforation (Mohan et al., 2013). However, advances using magnification, better quality images including the use of cone beam computerized tomography have shown to improve the visualization of the furcation area as well as individual roots (Marques-da-Silva et al., 2010). This can aid in alleviating some of these endodontic challenges.

From a prosthodontic viewpoint, due to the limited amount of tooth surface that is implanted in the alveolus, the concern is that a taurodont tooth may not have as much anchorage as a cynodont tooth when used as a prosthetic or an orthodontic abutment when laterally displacing forces are applied (Durr et al., 1980). This however may make extractions of these teeth easier, since not much of the tooth is embedded in the alveolus, provided the roots are not significantly divergent (Durr et al., 1980). Notably, the change in the apical displacement of the furcation of a taurodont tooth to the apical third may mean a change in extraction approach would be needed as would be harder to position the forcep beaks, and potentially surgical tooth elevators would need to be utilized (Durr et al., 1980).

With regards to periodontal considerations, in certain cases, taurodont teeth potentially can have a favourable outcome (Shifman and Buchner, 1976, Shifman and Chanannel, 1978). Due to the apical displacement of the furcation, the likelihood of furcation involvement is less compared to cynodont teeth, unless there is severe periodontal destruction of the surrounding tissues (Shifman and Chanannel, 1978).

Evidently, taurodontism and its management does lend itself to various complications and as such care must be taken to diagnose these teeth early on and incorporate their treatment nuances in a comprehensive treatment plan to minimize future concerns.

1.4.2 Taurodontism and sexual dimorphism

In two prominent studies done by MacDonald-Jankowski and Li (1993) in a Chinese population, and in a Brazilian population by Weckwerth et al. (2016), have shown that females exhibit a significantly higher predilection for taurodontism. In the Chinese study, a 56% prevalence in females was noted in contrast to 36% in males ($P < 0.001$) (MacDonald-Jankowski and Li, 1993). In the Brazilian study, a 49% prevalence in females was observed as compared to 32% in males ($P < 0.01$) (Weckwerth et al., 2016).

The rationale for a female predilection may be rooted in genetics and be associated with the X-chromosome (MacDonald, 2020). Taurodontism has been highly reported in cases of XXY Finnish Klinefelter syndrome in males (Alvesalo and Varrela, 1991, Varrela and Alvesalo, 1988) and in X-linked polyploidy in XXX and XXXX Finnish females (Varrela and Alvesalo, 1989). There is an additive effect with each increasing X-chromosome on the severity of taurodontism expressed (Varrela and Alvesalo, 1989).

1.4.3 Symmetry and taurodontism

The genetic contribution to non-syndromic taurodontism can be tested by evaluating symmetry between antimeres. Previous work on twins showed a high degree of concordance of taurodontism with 41% concordance in monozygotic and dizygotic twins (Laatikainen and Ranta, 1996). It also revealed high degree of symmetry for this trait, indicating a possible genetic influence (Kan et al., 2010).

Bilateral symmetry in taurodontism has been revealed in multiple studies in the literature (Laatikainen and Ranta, 1996, Awadh et al., 2020, Shifman and Chanannel, 1978). In the study done by Awadh et al. (2020), they looked at unrelated individuals with cleft palate that were syndromic and their non -syndromic matched controls. They used the taurodontism index developed by Shifman and Chanannel with the Tulensalo modification ((Tulensalo et al., 1989, Shifman and Chanannel, 1978) and found more subjects with bilateral symmetry of taurodonts as opposed to unilateral (Awadh et al., 2020).

1.5 Study hypotheses

The overall goal of this study was to determine whether taurodontism is present as an incidental finding in a local adolescent population. The rationale for considering sex-related differences was based on the literature reported, that there was a female predilection for the presence of taurodontism (Alvesalo and Varrela, 1991, Varrela and Alvesalo, 1989, Varrela and Alvesalo, 1988, MacDonald-Jankowski and Li, 1993, Toure et al., 2000).

Null Hypothesis: There is no difference between males and females in the frequencies of taurodontism in the general adolescent population of UBC Dentistry patients.

The rationale for secondary hypothesis originated from the possibility that taurodontism does has a strong genetic tendency. This can be implied by the bilateral symmetric manifestation of the trait, as reported in several twin studies (Laatikainen and Ranta, 1996, Awadh et al., 2020). It is also worth noting that these studies were done on syndromic populations. If indeed there is a genetic component, we would expect to see a bilateral symmetrical presentation of taurodontism in the same individual in our present study.

Secondary hypothesis: There is no symmetrical manifestation of taurodontism in the general adolescent population of UBC Dentistry patients.

Chapter 2: Materials and Methods

2.1 Ethics approval

The ethics approval was obtained, Certificate number 19-019117 from UBC Clinical Research Ethics Board (CREB) on 6th July 2019, prior to commencing this retrospective study and reviewing patient charts. In the event that there was a need to re-access patient records to confirm data, the ethics approval was renewed in July 2020.

2.1.1 Dental Panoramic Survey

This retrospective study was based on a convenience sample of DPRs taken of adolescent patients seen between the ages of 15 to 20 years old from 1st July 2006 when digital dental panoramic radiography was first used at the University of British Columbia (UBC) to 30th June 2019. All the DPRs were taken with the ProMax Planmeca digital panoramic machine (Helsinki, Finland) at UBC with the standard adolescent settings (Time: 16s; 62kvp; 5mA). Using an electronic health record (EHR), Romexis, a total of 412 DPRs were elicited. A total of 124 DPRs met our inclusion criteria **(Section 2.2.1)**. There were 59 males and 65 females. All the DPRs were downloaded from the electronic patient record, Romexis in a DICOM format without patient identifiers. These were then analyzed on a 13-inch MacBook Pro (Retina) using ImageJ Software Analysis.

2.2 Criteria

2.2.1 Inclusion Criteria

Our study included patients that were healthy. Our parameters for defining a healthy individual was based on their physiological status which was classified using the American Society of Anesthesiologists (ASA) physical status classification system (Doyle et al., 2020) **(Appendix 1)**. We included patients that were ASA I, which referred to a normal healthy patient that was a non-smoker and had no alcohol consumption (Doyle et al., 2020). We also included patients that were ASA II, which included patients with a mild systemic disease that was well controlled with medication such as mild asthma, hypothyroidism, attention deficit hyperactivity disorder (ADHD) as well as any social drinking and smoking.

Table 4: Classification of physiologic status

	ASA I	ASA II
Number of patients	112	12

Table 5: Allocation of categories based on physiologic status

ASA I	ASA II
No medications (91)	Mild asthma well controlled (last inhaler use within a year) (1)
Allergies: cat/dust/pollen/lactose/bees/soy/peanut/ Gluten (16)	Mild asthma (no medications) (2)
Allergies to amoxicillin/penicillin/sulfa (4)	Hypothyroidism well controlled with medication (1)
Birth control (1)	ADHD well controlled with medication (1)
	Social drinker/smoker (6)

With regards to teeth analyzed, we included first and second maxillary and mandibular molars that had not been previously restored (apart from sealants), had no endodontic therapy and no carious lesions. The presence of carious lesions has shown to cause reduction of the size of the pulp chamber due to the formation of secondary dentin. This is due to pulpal shrinkage away from the carious insult (Bjørndal et al., 2019).

According to the American Association of Pediatric Dentistry (AAPD), the anticipated time of eruption of the first permanent molars ranged from 5.5 years to 7 years and the second permanent molars ranged from 12 to 14 years (Logan and Kronfeld, 1933). The apical closure of roots of permanent teeth is expected to occur two to three years after the tooth emerges into the oral cavity (Logan and Kronfeld, 1933). Therefore, with regards to our patients who were between 15 and 20 years of age, we could reasonably anticipate completed root development for both the first and second permanent molars, thus fulfilling our inclusion criteria.

2.2.2 Exclusion Criteria

Third molars, any first or second molars that have been restored previously, presence of caries, root canal treated teeth, oral habits, craniofacial anomalies, cleft lip with or without palate and poor contrast of DPRs.

Table 6: Number of DPRs excluded out of a total number of DPRs obtained (N=412)

Exclusion Criteria	Number of DPRs
Caries, restorations, root canal treated teeth	251 DPRs
Poor contrast	32 DPRs
Orthodontic treatment	5 DPRs
Total # of DPRs excluded	288 DPRs

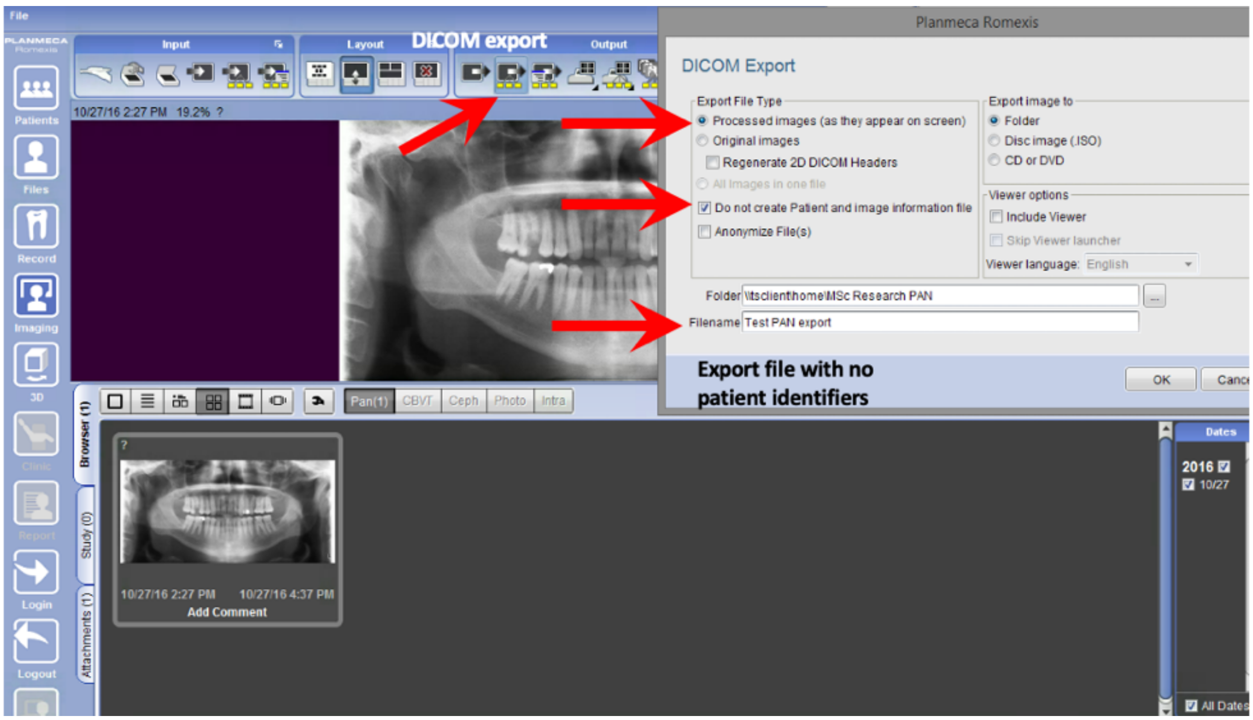
Poor contrast was seen in 32 DPRs out of the 412 DPRs that obtained initially. Attempts to adjust the brightness and sharpness of the image did not aid in improving image quality. In addition, majority of the DPRs (N = 251) were excluded due to the presence of caries, restorations and root canal treated teeth. 5 DPRs were excluded due to the presence of orthodontic brackets obscuring the pulp chambers of the first and second permanent molars which hindered us from measuring the pulp chamber accurately.

2.3 Methods of measurement

2.3.1 Dental Panoramic Radiograph Protocol

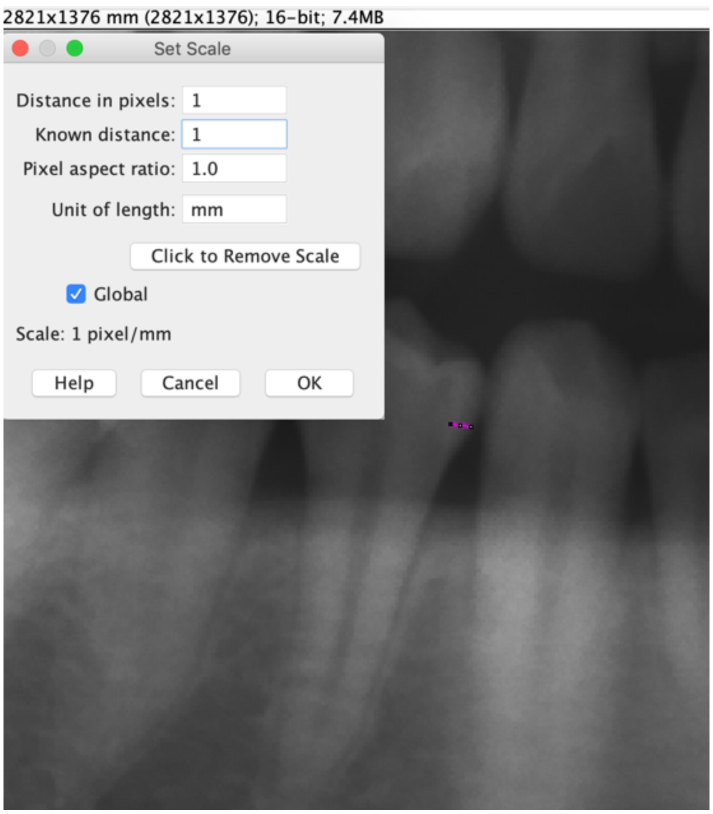
1. Download the DPR from Romexis in DICOM format without patient identifiers.

Figure 3: Importing the DPR from Romexis without patient identifiers



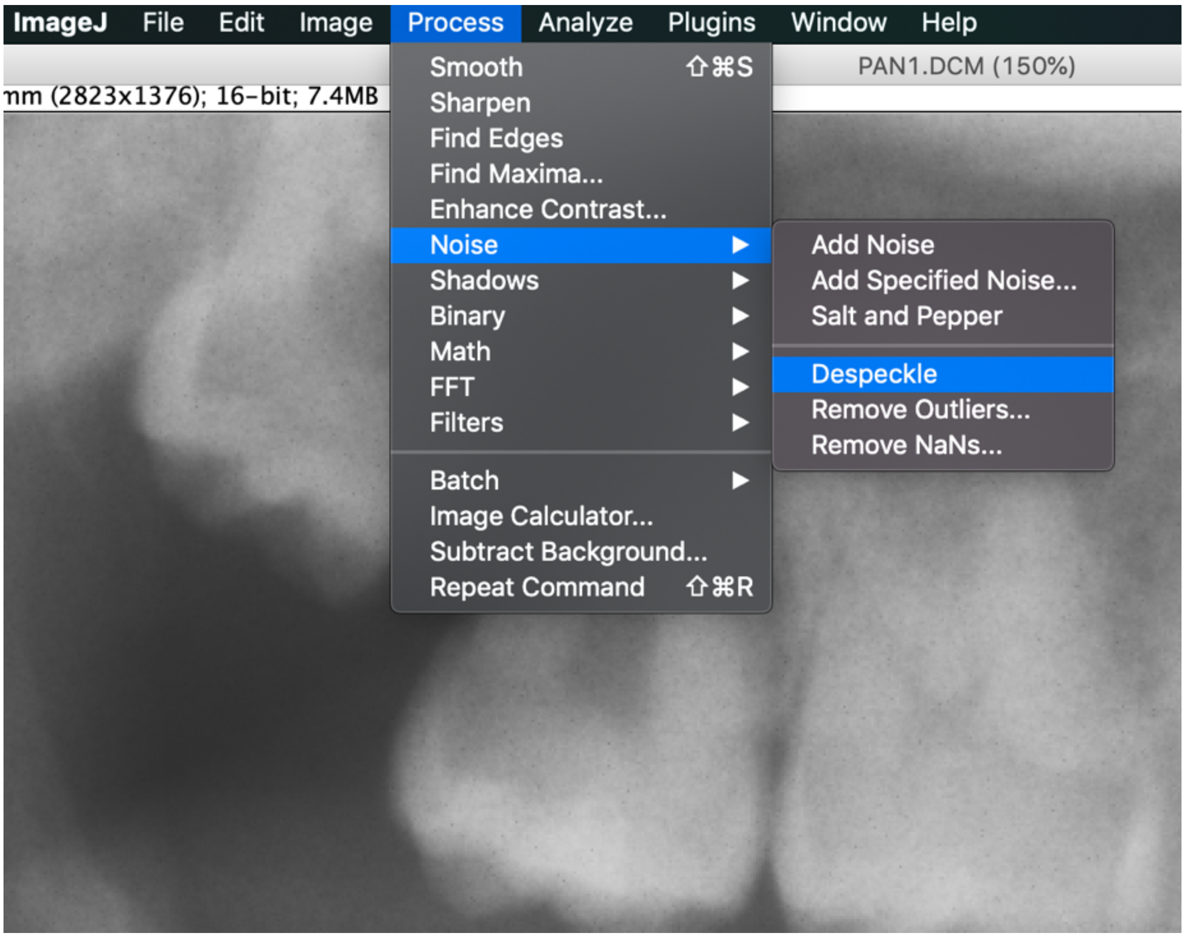
2. Open the DPR using ImageJ software. Calibrate the image using a known distance. The permanent bicuspid teeth interproximal enamel is usually 1 mm (Stroud et al., 1998).

Figure 4: Image J: Calibration of DPR



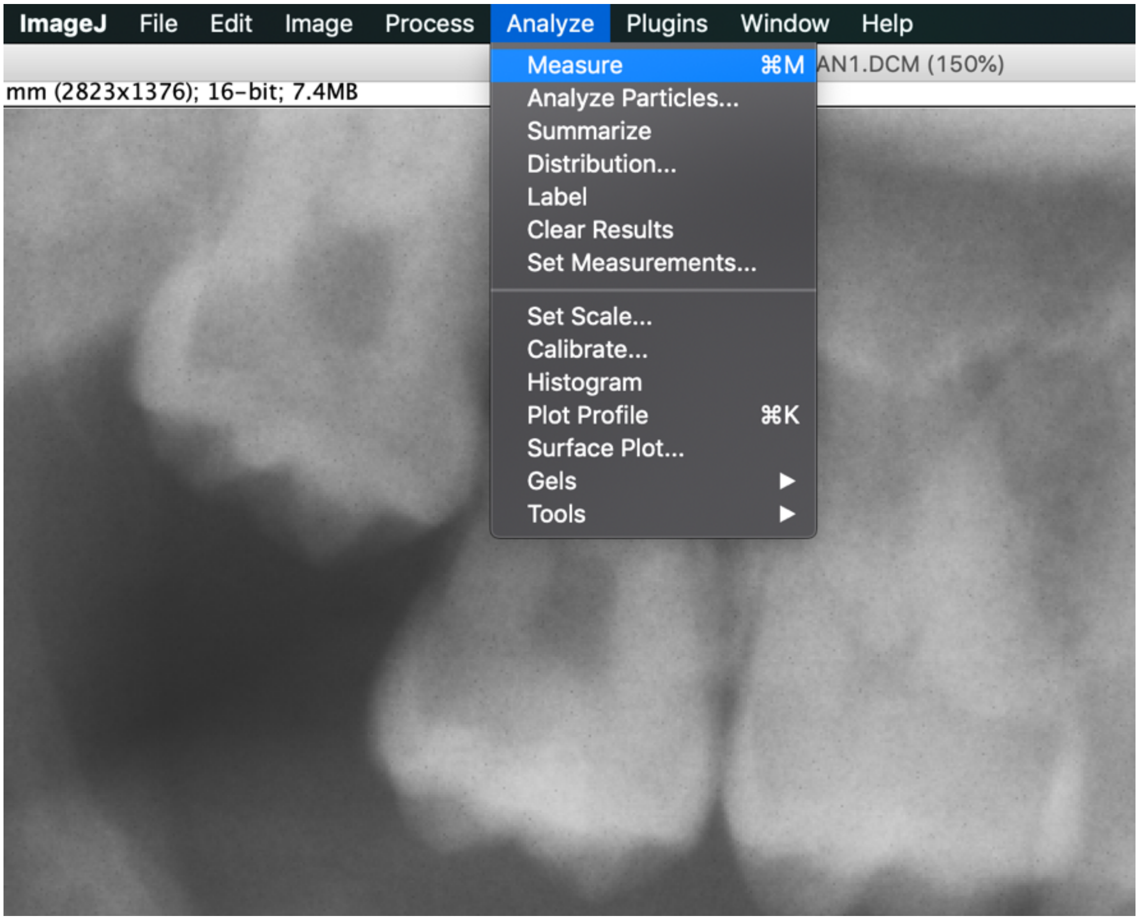
3. On the dropdown menu: Process > Noise > Despeckle (which removes some of the grainy aspects of the image).

Figure 5: Image J: Despeckle function to increase clarity of DPR



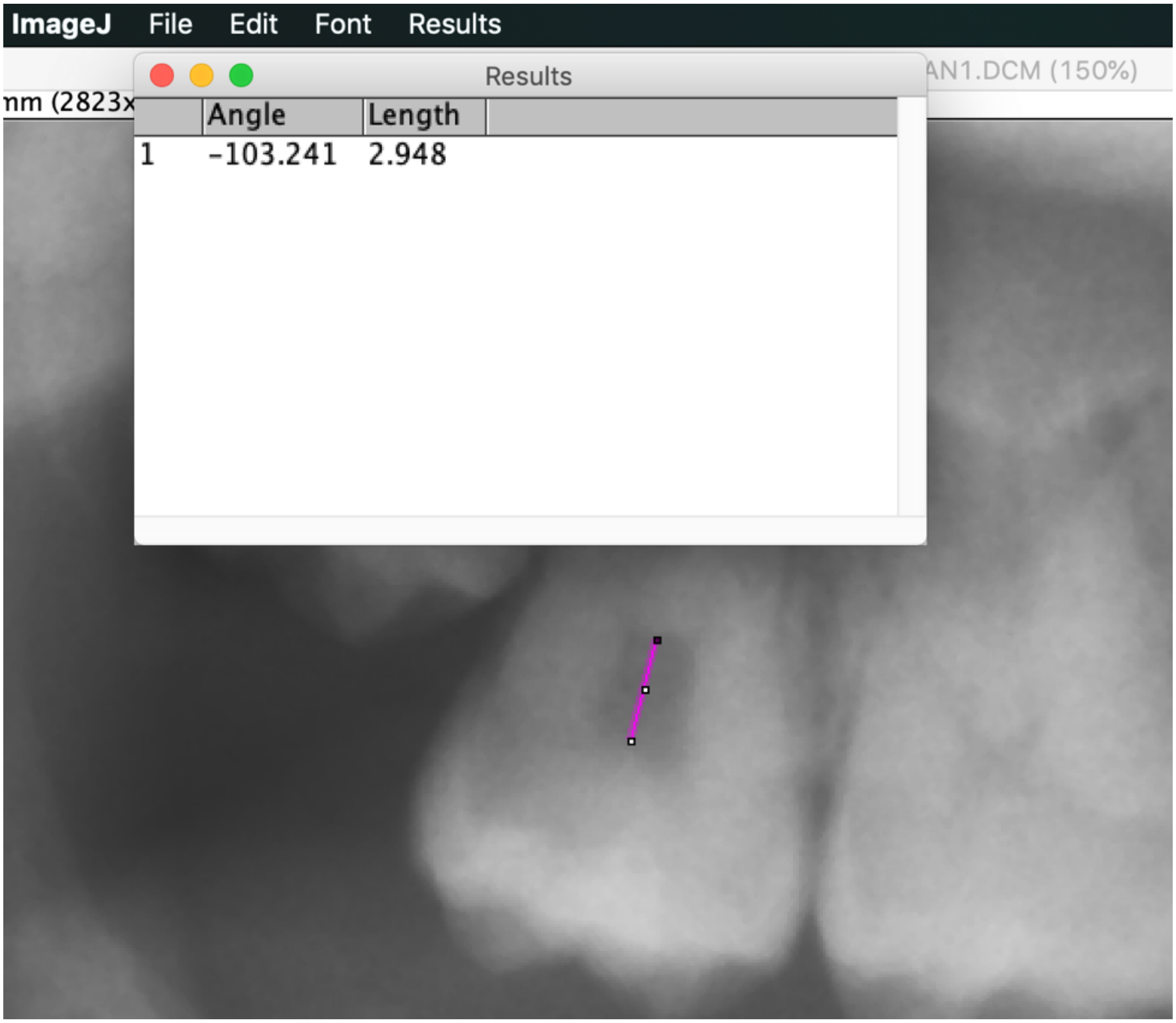
4. Click on the measuring tool.

Figure 6: Image J: Tooth #17: Measurement of DPR



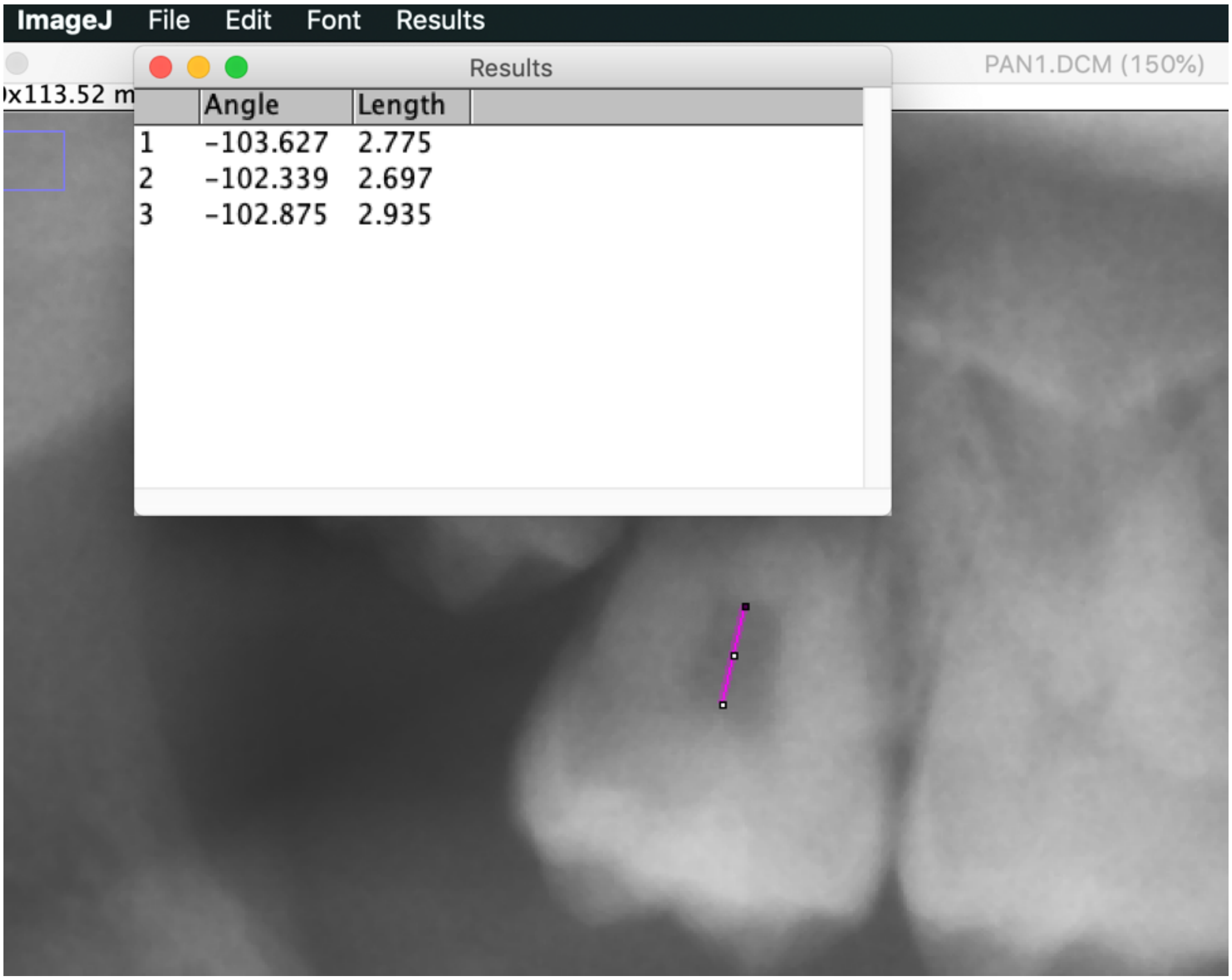
5. Draw a line measuring Variable 1 (T1) (from the lowest point of the root of the pulp chamber to the highest point of the floor of the pulp chamber).

Figure 7: Image J: Tooth #17: Measurement of Variable 1 (T1)



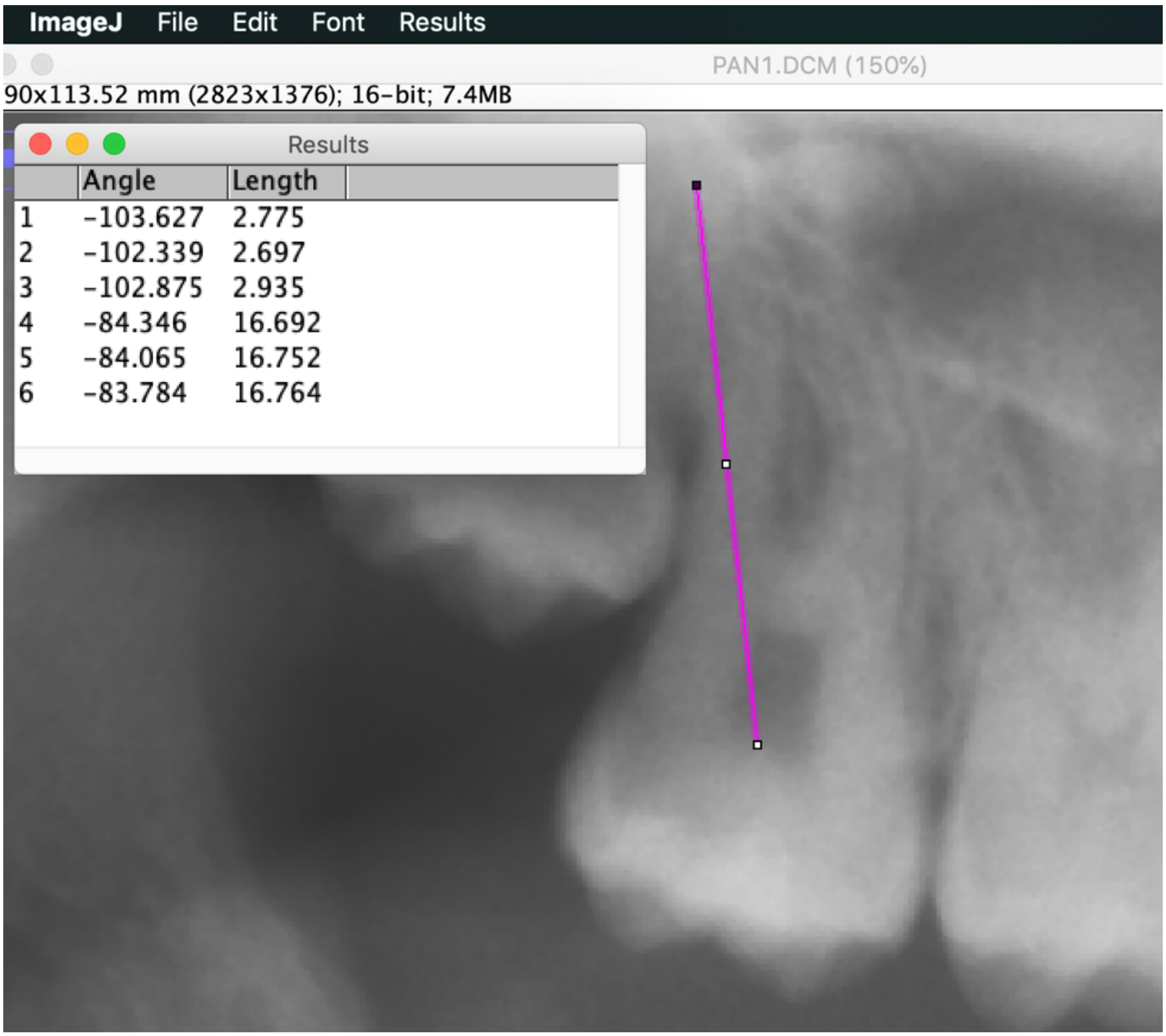
6. Repeat 3 times.

Figure 8: Image J: Tooth #17: Measurement repeated 3 times



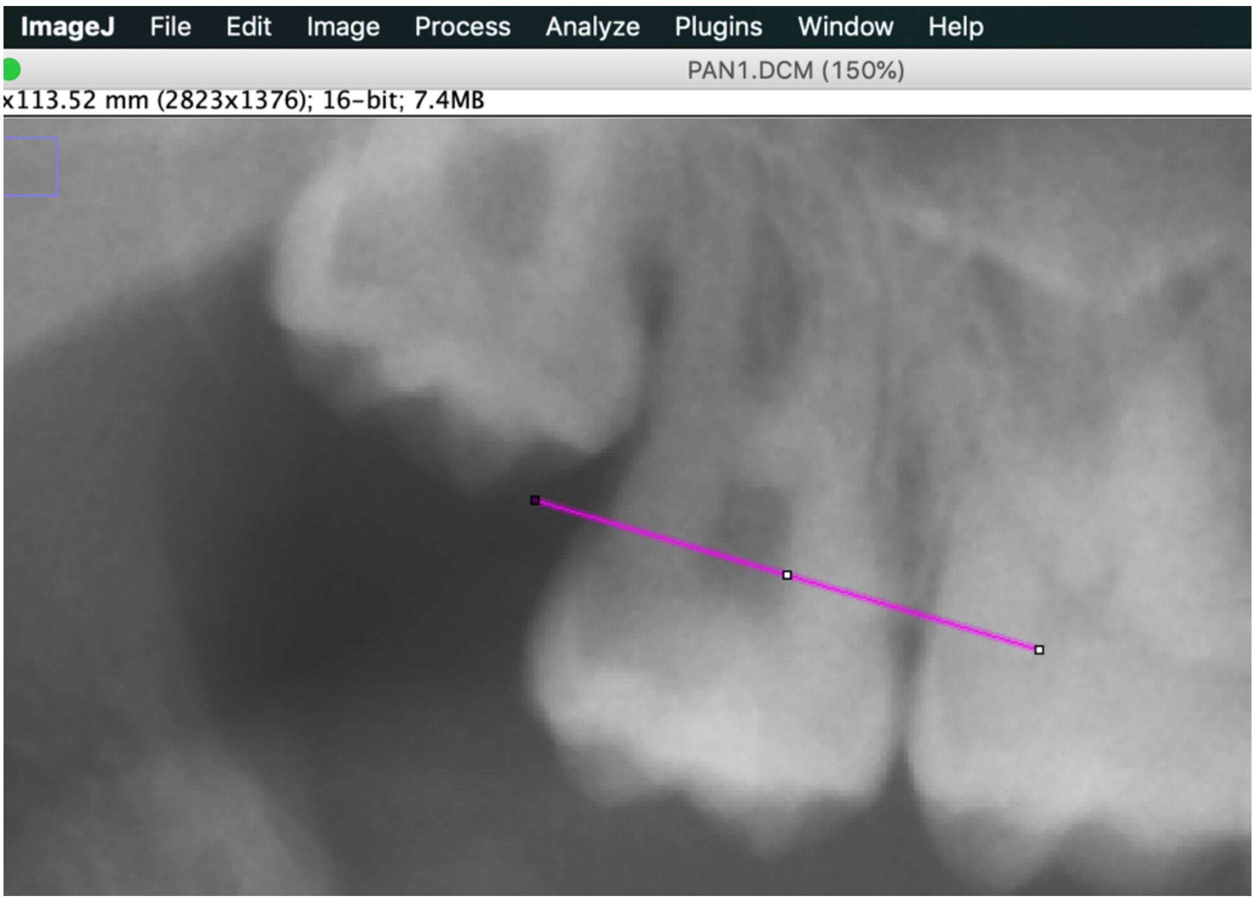
7. Repeat the process for Variable 2 (T2) (the lowest point of the roof of the pulp chamber to the apex of the longest root) In this case the palatal root was used).

Figure 9: Image J: Tooth #17: Measurement of Variable 2 (T2)



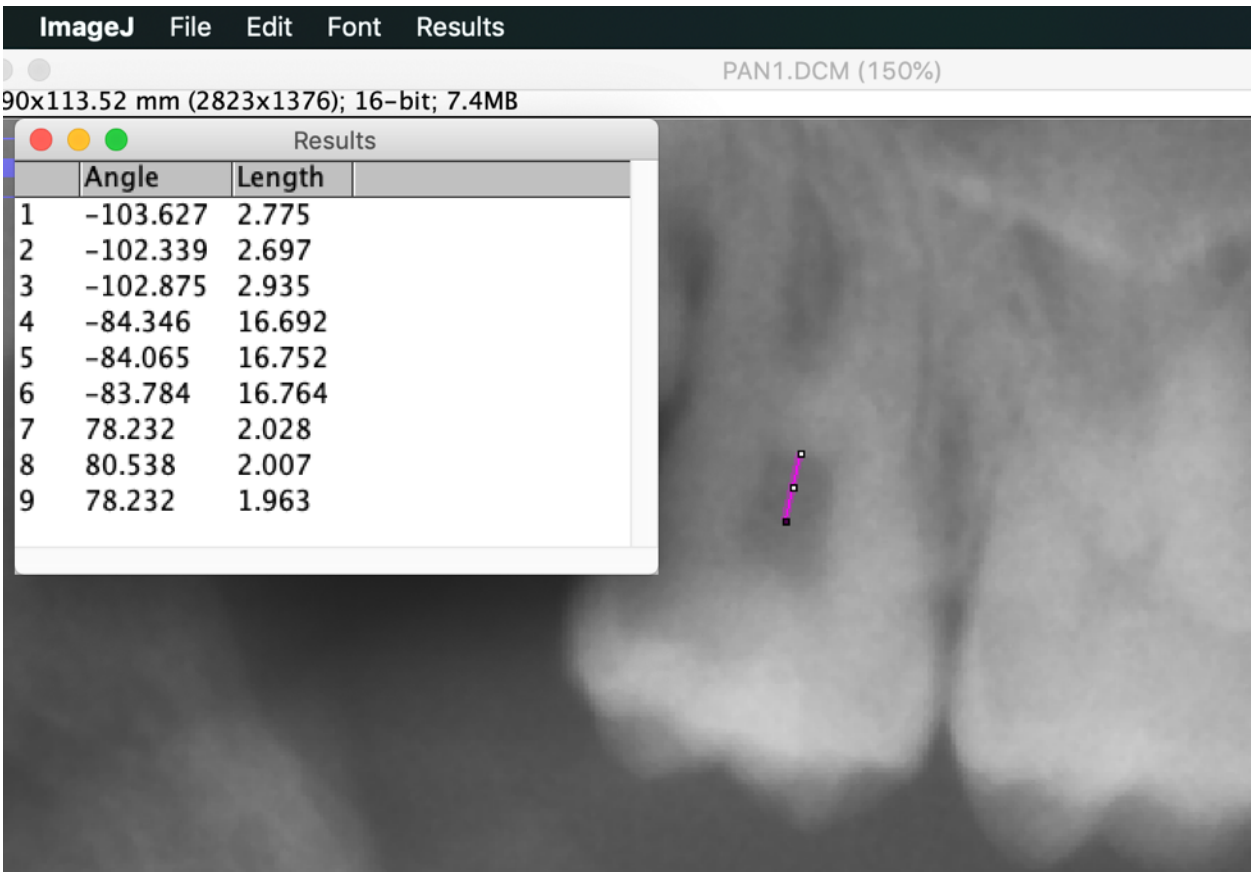
8. Repeat the process for Variable 3 (T3) (the distance from the line of the CEJ to the floor of the pulp chamber).

Figure 10: Image J: Tooth #17: Measurement of Variable 3 (T3)



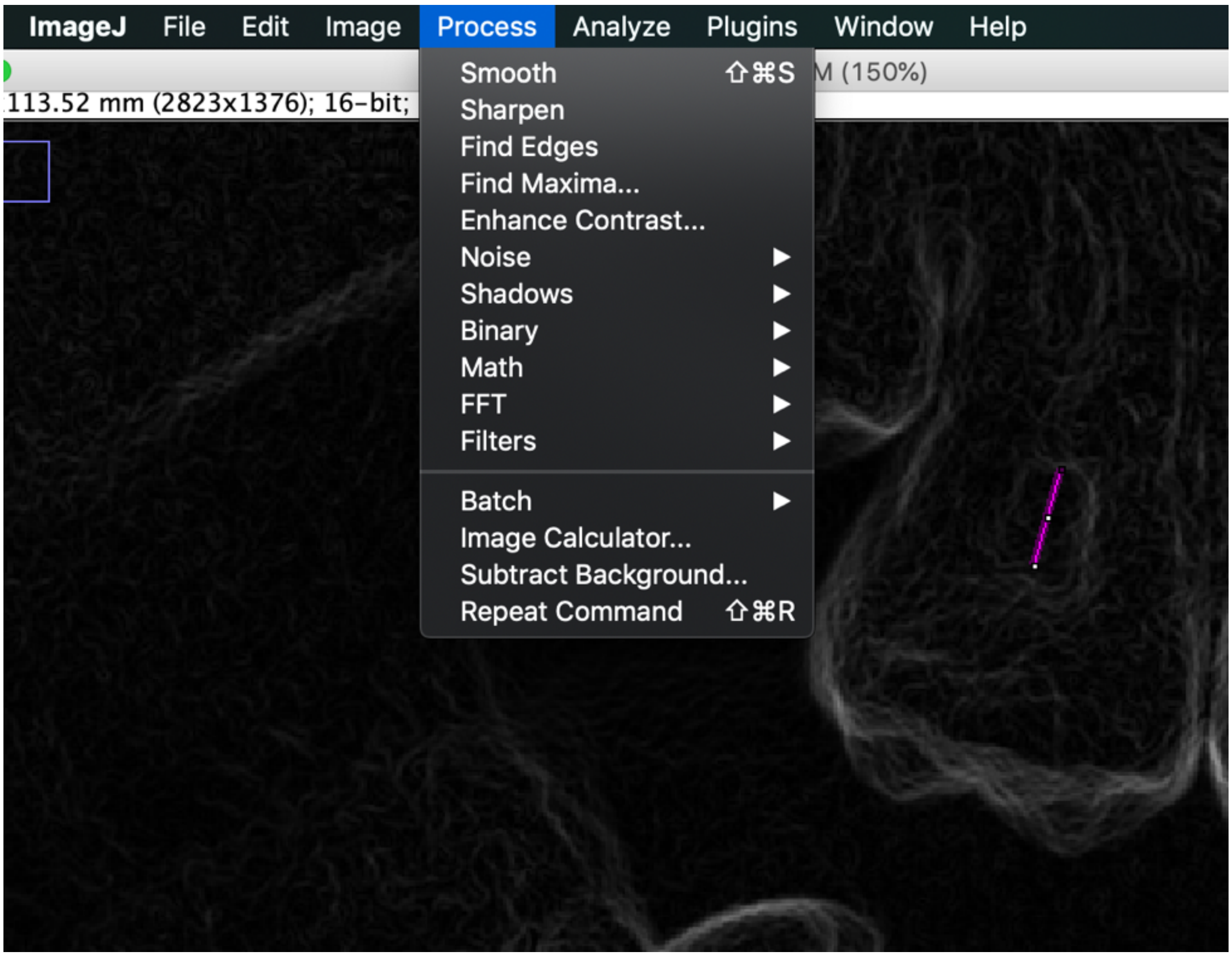
9. Obtain 9 measurements per tooth. The measurements were done in quick succession and the angulation was kept within 5 degrees to maintain accuracy of measurement. For the purposes of this study, keeping the vertical angulation when measuring Variable 1(T1), Variable 2 (T2) and Variable 3 (T3) within 5 degrees of the three consecutive measurements tended to increase the repeatability and accuracy of measurements obtained.

Figure 11: Image J: Tooth #17: 9 measurements obtained



10. In certain cases, it was difficult to see the images due to overlapping structures, hence the “Find Edges” tool was employed to make it easier to delineate the structures.

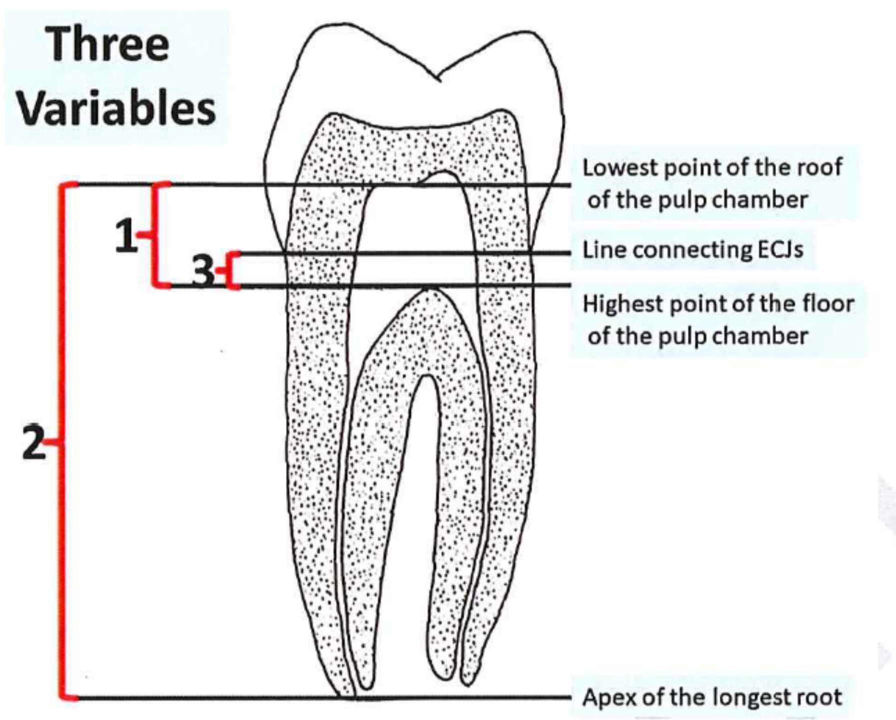
Figure 12: Image J: Use of Find Edges tool



2.3.2 Methods of measurement

The use of DPRs to measure taurodontism was beneficial because it enabled the examination of all the maxillary and mandibular structures, teeth and dental anomalies at the same time (Bilge et al., 2018). We used the method described by Shifman and Chanannel (Shifman and Chanannel, 1978) to calculate the taurodont index for each of these teeth.

Figure 13: An adaptation of Shifman and Chanannel's three variables to objectively measure taurodontism. ***Acknowledgment: MacDonald D (MacDonald, 2020)***



Variable 1 (T1) was obtained by measuring the distance from the lowest point of the roof of the pulp chamber and the highest point of the floor of the pulp chamber (Shifman and Chanannel, 1978). Variable 2 (T2) was the distance between the lowest point of the roof of the pulp chamber and the apex of the longest root (Shifman and Chanannel, 1978). Variable 3 (T3) was the measurement of the distance between the cementoenamel junction (CEJ) and the highest

point of the floor of the pulp chamber (Shifman and Chanannel, 1978). The Taurodont Index (TI) was obtained by Variable 1 (T1) divided by Variable 2 (T2) x 100 (Shifman and Chanannel, 1978). The teeth were then categorized according to the taurodont index as below:

Figure 14: Changing root morphology depicting the increase in severity of taurodontism as reflected by the taurodont index. ***Acknowledgment: MacDonald D (MacDonald, 2020)***

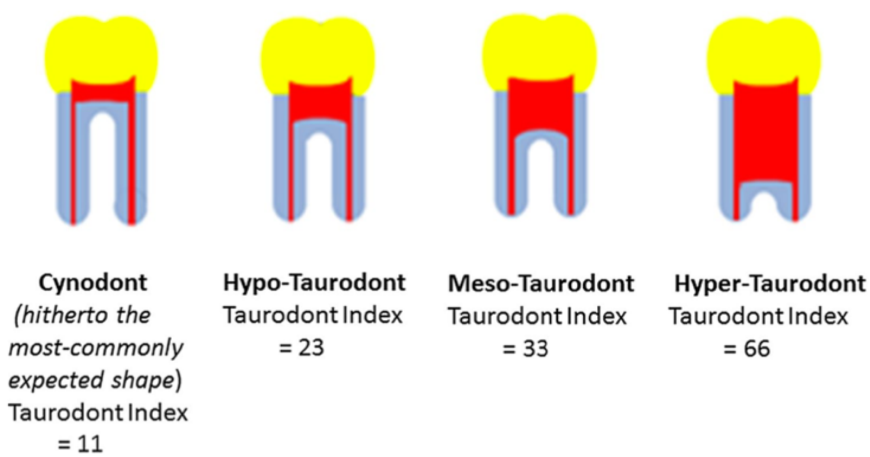


Table 7: Taurodont Index: ***Acknowledgment: MacDonald D (MacDonald, 2020)***

Root Shape	Taurodont Index
Normal (Cynodont)	Less than 20
Hypotaurodont (mild)	From 20 up to 30
Mesotaurodont (moderate)	Over 30 up to 40
Hypertaurodont (severe)	Greater than 40

2.4 Intra and Inter-examiner reliabilities

One observer ZS (author of the thesis) performed all measurements. A second observer, Dr. David MacDonald (DM) measured ten DPRs that had been selected randomly from those that fulfilled the inclusion criteria. It was necessary to determine if there were any major discrepancies in measurements between the two observers to ensure the validity of the results.

Chapter 3: Results

3.1 Intrarater reliability

The definition of reliability is the degree to which measurements can be replicated (Koo and Li, 2016). To determine the intra-examiner reliability, the intraclass correlation coefficient (ICC) was used to compare three repeated measurements done by the same observer (ZS).

Table 8: Intraclass correlation of the all the measurements taken for each variable per tooth

Reliability		Intraclass Correlation Coefficient (ICC)	95% Confidence interval	
			Lower	Upper
Tooth #17	T1.17	**0.93**	0.91	0.95
	T2.17	**0.98**	0.98	0.99
	T3.17	**0.97**	0.96	0.98
Tooth #16	T1.16	**0.97**	0.96	0.98
	T2.16	**0.99**	0.99	0.99
	T3.16	**0.98**	0.98	0.99
Tooth #47	T1.47	**0.98**	0.97	0.98
	T2.47	**0.97**	0.98	0.98
	T3.47	**0.98**	0.98	0.98
Tooth #46	T1.46	**0.96**	0.96	0.98
	T2.46	**0.98**	0.98	0.99
	T3.46	**0.98**	0.98	0.99
Tooth #26	T1.26	**0.98**	0.97	0.98
	T2.26	**0.99**	0.99	0.99
	T3.26	**0.98**	0.98	0.99
Tooth #27	T1.27	**0.98**	0.97	0.98
	T2.27	**0.97**	0.96	0.98
	T3.27	**0.98**	0.97	0.99
Tooth #37	T1.37	**0.98**	0.97	0.99
	T2.37	**0.99**	0.98	0.99
	T3.37	**0.98**	0.98	0.99
Tooth #36	T1.36	**0.97**	0.95	0.97
	T2.36	**0.99**	0.99	0.99
	T3.36	**0.94**	0.91	0.95

This analysis was done using the SPSS statistical package version 27 (SPSS Inc, Chicago, IL). The intraclass correlation (ICC) is a reliability index that shows the amount of correlation as well as agreements between measurements. In this model which assessed the intra-rater reliability of the repeated measurements, the ICC ranged between 0.93 to 0.99 which is indicative of excellent reliability. The high level of intra-examiner agreement is also reflected in the 95% confidence intervals of the ICC coefficients.

3.2 Levels of Inter-rater agreement

Table 9: Inter-rater agreement of the all the measurements taken for each variable per tooth

Reliability		Intraclass Correlation Coefficient (ICC)	95% Confidence interval	
			Lower	Upper
Tooth #17	T1.17	**0.96**	0.91	0.99
	T2.17	**0.98**	0.96	0.99
	T3.17	**0.95**	0.89	0.98
Tooth #16	T1.16	**0.87**	0.73	0.96
	T2.16	**0.91**	0.78	0.98
	T3.16	**0.95**	0.87	0.98
Tooth #47	T1.47	**0.90**	0.74	0.97
	T2.47	**0.90**	0.75	0.97
	T3.47	**0.92**	0.79	0.97
Tooth #46	T1.46	**0.92**	0.79	0.98
	T2.46	**0.98**	0.94	0.99
	T3.46	**0.94**	0.83	0.98
Tooth #26	T1.26	**0.97**	0.92	0.99
	T2.26	**0.98**	0.96	0.99
	T3.26	**0.95**	0.87	0.98
Tooth #27	T1.27	**0.96**	0.90	0.99
	T2.27	**0.98**	0.96	0.99
	T3.27	**0.95**	0.87	0.98
Tooth #37	T1.37	**0.93**	0.83	0.98
	T2.37	**0.93**	0.81	0.98
	T3.37	**0.77**	0.76	0.93
Tooth #36	T1.36	**0.83**	0.75	0.94
	T2.36	**0.96**	0.87	0.99
	T3.36	**0.89**	0.72	0.97

The inter-rater reliability refers to the agreement between different individuals performing the same measurements. The intraclass correlation coefficient (ICC) is a reliability index that reflects both degree of correlation and agreement between 2 or more raters (Koo and

Li, 2016). In our reliability testing, the ICC ranged from 0.77 to 0.98 which is indicative of good to excellent inter-examiner reliability. Similarly, this high level of agreement between the two examiners was reflected in the 95% confidence intervals of the ICCs that ranged from 0.72 to 0.99. This also suggested a high level of calibration between the two examiners.

3.3 Statistical Analyses:

The total number of teeth examined was 992. The corresponding proportions of taurodont teeth (hypo-, meso- and hyper) was 16.6%, found in 165 teeth.

Table 10: Frequency of severity of type of taurodont presented per tooth type (N=124)

Tooth Type (N=992)	Normal	Hypotaurodont (Mild)	Mesotaurodont (Moderate)	Hypertauront (Severe)
Tooth #17	77	42	4	1
Tooth #16	105	18	1	0
Tooth #47	105	16	1	2
Tooth #46	124	0	0	0
Tooth #26	104	17	3	0
Tooth #27	78	38	6	2
Tooth #37	111	10	1	2
Tooth #36	123	1	0	0
TOTAL	**827 (83.4%)**	**142 (14.3%)**	**16 (1.6%)**	**7 (0.7%)**

Among the 165 taurodont teeth, 142 (86.0%) teeth exhibited hypotaurodontism, a mild form of taurodontism, 16 teeth (9.7%) were mesotaurodont and severe hypertaurodontism was found in 7 teeth (4.2%). The proportion of taurodont teeth was greater in the maxilla, 132 teeth (80.0%), whereas the mandible elicited only 33 taurondont teeth (20.0%).

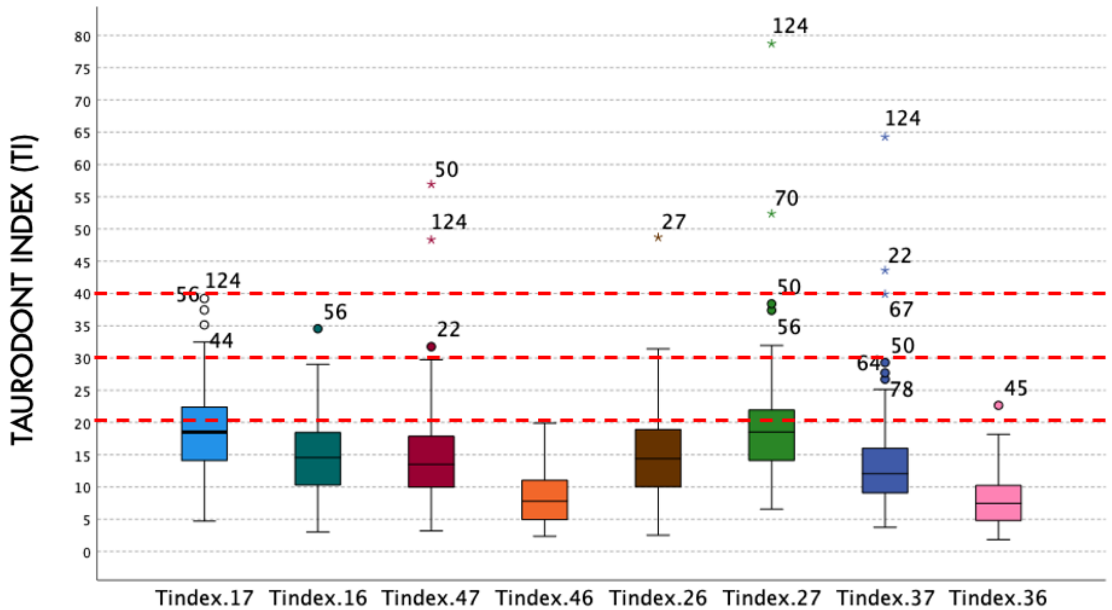
Table 11: Number and types of taurodonts per DPR (N = 124)

#s of Taurodont per patient	Any Taurodont (Total N = 124 cases)		Hypotaurodont		Mesotaurodont		Hypertaurodont	
	Frequency	Percentage	Frequency	Percentage	Frequency	Percentage	Frequency	Percentage
0	56	45.0	58	46.8	111	89.5	119	96.0
1	22	17.7	24	19.4	12	9.7	4	3.2
2	18	14.5	23	18.5	0	0.0	1	0.8
3	12	9.5	8	6.5	0	0.0	0	0.0
4	10	8.1	8	6.5	1	0.8	0	0.0
5	5	4.0	2	1.6	0	0.0	0	0.0
6	1	0.8	1	0.8	0	0.0	0	0.0

As is evident from the table, of the 124 DPRs examined, 68 cases (54.8%), presented with at least one taurodont tooth.

3.4 Taurodont Index (Males and Females combined)

Figure 15: Taurodont Index: Males (N=59) and Females (N =65)



From Figure 15, we were able to identify those DPRs (indicated by case numbers) that consistently exhibited a more severe form of taurodontism in multiple teeth. For example, DPR 124 (an outlier in the boxplot) displayed hypertaurodontism, in all second permanent molars with a taurodont index of above 40. The majority of teeth however, fell into the normal or cynodont category with a taurodont index threshold below 20. In addition, second permanent molars tended to more frequently exhibit mesotaurodontism (1.2%) and hypertaurodontism (0.7%) as compared to the first permanent molars, of which 0.4% were mesotaurodonts and none were hypertaurodonts.

3.5 Sexual dimorphism: Frequencies in males and females

Null Hypothesis: There is no difference between males and females in frequencies of taurodontism in the general adolescent population of UBC Dentistry patients.

Table 12: Frequency of taurodontism in males (N=59) and females (N=65)

	No Taurodont	Any Taurodont
Males (N=59)	32/59 = 54.2%	27/59 = 45.8%
Females (N=65)	24/65 = 36.9%	41/65= 63.1%

Taurodontism was found at a higher proportion in females (63.1%) as compared to males (45.8%) in our study.

3.5.1 Non-parametric test: Chi-squared test

This test was used to compare the proportions of taurodonts between males and females, in order to determine if there was sex-related difference in taurodontism.

For this test the following online calculator was used:

https://www.socscistatistics.com/tests/chisquare2/default2.aspx

Table 13: Comparison of taurodontism between males and females#

	No Taurodont	Any Taurodont	Total
Males	32	27	59
Females	24	41	65

Chi-Square test, P = 0.053

The null hypothesis (no difference between males and females) could not be rejected as there was a marginally significant relationship when the *P* value was less than or equal to 0.05.

3.6 Parametric tests: Independent sample t-test

This test was employed to compare the means of the Taurodont Index (TI) between the two-independent sex-related groups.

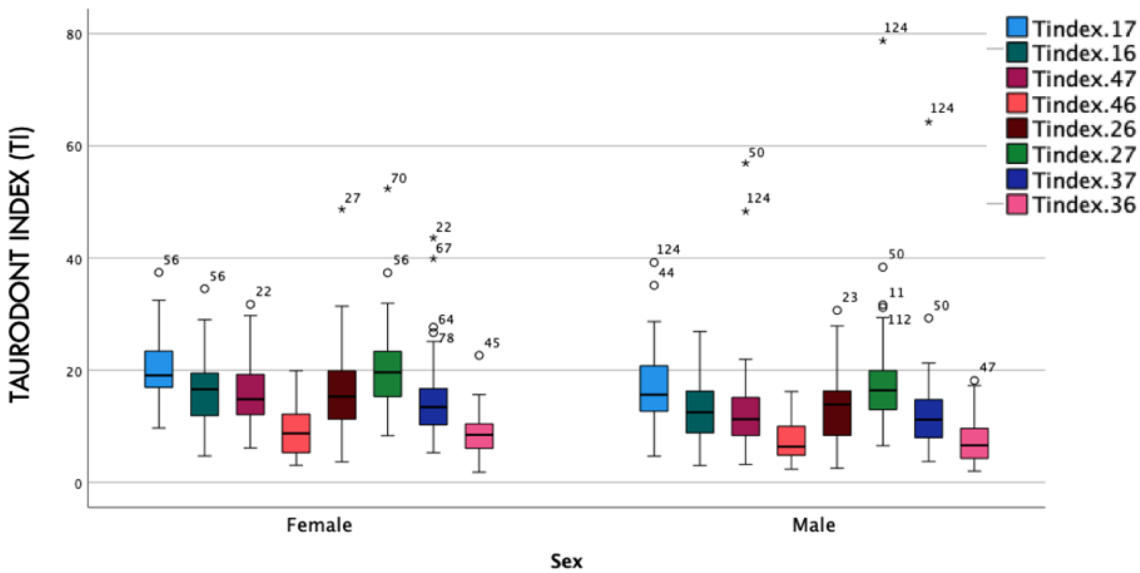
Table 14: Independent sample t-test: Taurodont Index (TI) comparisons between males (N=59) and females (N=65)

Taurodont Index (TI)	Taurodont Index Mean ± 1 SD		*P* value	95% CI of difference
	Males Mean (SD)	Females Mean (SD)		
Tindex.17	17.3 (6.5)	20.2(5.3)	0.007	0.80; 5.01
Tindex.16	13.01 (5.4)	16.1 (5.7)	0.003	1.08; 5.03
Tindex.47	13.0 (8.9)	16.1 (5.9)	0.020	0.50; 5.76
Tindex.46	7.5 (3.6)	9.1 (4.1)	0.021	0.25; 3.01
Tindex.26	12.9 (5.8)	16.1(7.3)	0.009	0.80; 5.52
Tindex.27	18.3 (10.0)	20.3 (7.3)	0.236	-1.24; 4.97
Tindex.37	12.6 (8.3)	14.7 (7.1)	0.130	-0.63; 4.84
Tindex.36	7.2 (3.9)	8.6 (3.66)	0.043	0.042; 2.27

This 2-tailed t-test showed that there were significant differences ($P < .05$) in the means of the Taurodont Index between males and females concerning all teeth, except for teeth #27 and #37.

Taurodontism in females was more severe than in males.

Figure 16: Taurodont Index: Males (N=59) compared to Females (N =65)



Visual assessment of the boxplot above, with regards to the median values showed that the severity of taurodontism was higher in females as compared to males. However, in our study, one male (DPR case 124) demonstrated a more severe form of taurodontism in multiple teeth (17, 47, 27 and 37). This can be depicted in Figure 16 where DPR 124 can be observed as an outlier in all the second permanent molars.

3.7 Symmetry

Secondary hypothesis: There is no symmetrical manifestation of taurodontism in the general adolescent population of UBC Dentistry patients.

Table 15: Paired samples t-test: Taurodont Index (TI) comparisons between males (N=59) and females (N=65)

	Taurodont Index	Mean ± 1 SD)	*P* value	95% CI of difference
Pair 1	Tindex.17	18.8 (6.1)	**0.349**	-1.77;0.63
	Tindex.27	19.4 (8.7)		
Pair 2	Tindex.16	14.6 (5.7)	**0.980**	-0.93; -0.03
	Tindex.26	14.6(6.8)		
Pair 3	Tindex.47	14.6(7.5)	**0.072**	-0.09;1.97
	Tindex.37	13.7(7.7)		
Pair 4	Tindex.46	8.3(4.0)	**0.176**	-0.17;0.91
	Tindex.36	7.9(3.8)		

When the means of the Taurodont Index of antimeric pairs of teeth were compared, all *P* values were < .05. Given there were no statistically significant mean differences between the right and left sides, was indicative that taurodontism had a symmetrical manifestation.

3.7.1 Differences in symmetry in females

We chose the paired samples t-test to compare two measurements taken from the same subjects (Kim, 2015). A paired sample t-test compares the means of the two measurements taken within the same individual. The paired sample t-test was used to determine if there was any statistically significant mean difference between antimeric pairs of teeth on the right and left sides of the mouth.

Table 16: Paired samples t-test: Taurodont Index (TI) for females (N=65)

		Mean ± 1SD)	***P* value**	**95% CI of difference**
Pair 1	Tindex.17	20.2(5.3)	**0.915**	-1.5;1.3
	Tindex.27	20.3(7.3)		
Pair 2	Tindex.16	16.1(5.7)	**0.931**	-1.4;1.3
	Tindex.26	16.1(7.3)		
Pair 3	Tindex.47	16.1(6.0)	**0.056**	-0.4;2.8
	Tindex.37	14.8(7.1)		
Pair 4	Tindex.46	9.1(4.1)	**0.210**	-0.3;1.3
	Tindex.36	8.6(3.7)		

3.7.2 Differences in symmetry in males

Table 17: Paired samples t-test: Taurodont Index (TI) for males (N=59)

		Mean ± 1SD	*P* value	95% CI of difference
Pair 1	Tindex.17	17.3(6.5)	**0.275**	-3.1;0.9
	Tindex.27	18.4(10.0)		
Pair 2	Tindex.16	13.0(5.4)	**0.953**	-1.3;1.4
	Tindex.26	13.0(5.8)		
Pair 3	Tindex.47	13.0(8.7)	**0.569**	-1.1;1.9
	Tindex.37	12.6(8.3)		
Pair 4	Tindex.46	7.5(3.6)	**0.535**	-0.5;1.0
	Tindex.36	7.2(3.9)		

In both tables, females (Table 16) and males (Table 17), no significant differences were found when comparing the means of the Taurodont Index in antimeric pairs of teeth within the same sex group. This indicated no significant difference in symmetry were found between males and females which was in accordance with our secondary hypothesis.

3.7.3 Antimeric pairs

From our data we observed 43 (34.7%) cases out of 124 cases exhibited at least one bilateral symmetrical taurodont pair of antimeric teeth. We wanted to determine if one tooth, for example, tooth #17 presented with taurodontism, whether its antimeric pair (tooth #27) would also display taurodontism. We counted the frequencies of bilateral taurodont presentation in each antimeric pair. For all of the pairs, except for one, if hypotaurodontism was present in one tooth, its antimeric pair presented with hypotaurodontism as well. There was only one pair where a difference was noted in DPR 52 where tooth #17 presented hypotaurodontism and tooth #27 presented with mesotaurodontism. With regards to severity of the trait (hypo-, meso-, hyper -), it seems that for 42 cases (97.6%), if one tooth presented with hypotaurodontism, then the corresponding antimere tooth also presented with the same severity of taurodontism.

Table 18: Bilateral symmetry of taurodontism: Antimeric pairs

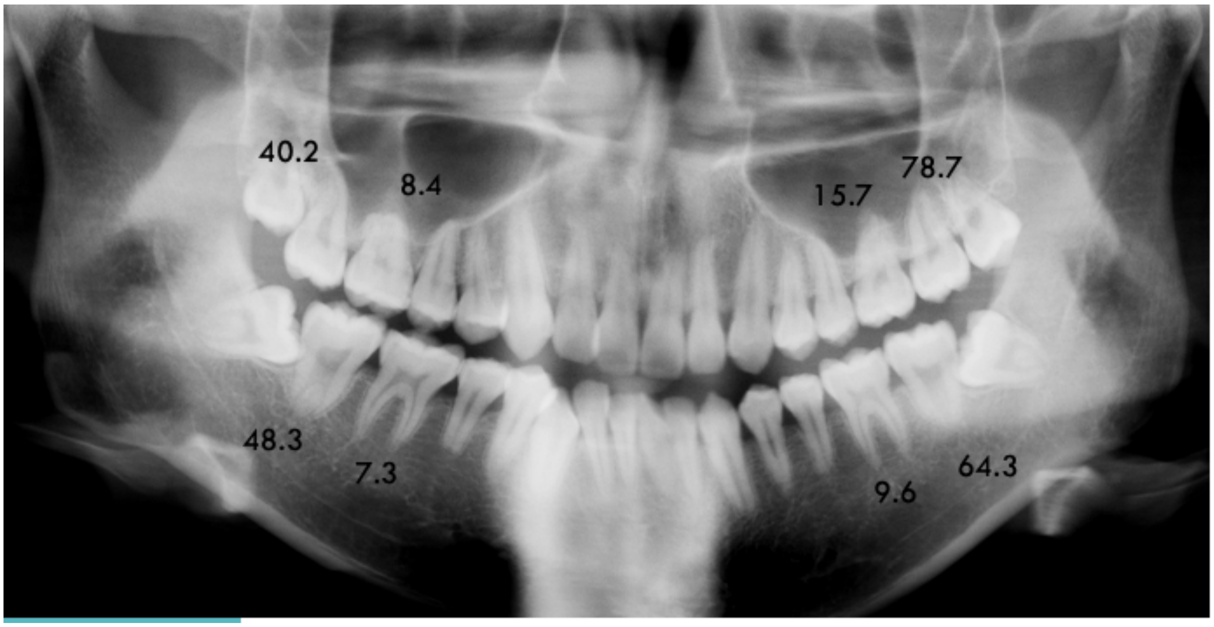
Antimeric pairs	Number of pairs	Frequency (%)
Teeth #17/Teeth #27	31/124	25.0
Teeth #16/Teeth #26	12/124	9.6
Teeth #37/Teeth #47	8/124	6.5
Teeth #36/Teeth #46	0/124	0.0

From our table above, the antimeric pairs of teeth #17 and #27 had the highest frequency of bilateral taurodontism with 31 (25.0%) out of 124 possible pairs. In addition, we also wanted to assess whether this was more common in the maxillary or the mandibular teeth. There was a higher frequency of antimeric bilateral symmetric pairs observed in the maxilla (34.6%) as compared to the mandible (6.5%).

3.8 Outliers

3.8.1 Dental Panoramic Radiograph 124

Figure 17: DPR 124



As observed previously in Figure 15, this DPR 124, coincidentally was a male who expressed hypertaurodontism in all his second permanent molars and was ASA I. From Figure 17, it is evident that all the second permanent molars have a Taurodont Index of above 40. In addition, we observed that the roots of the second permanent premolars, namely tooth #45, #35 and the first permanent molar #46 exhibited a degree of possible root resorption and blunting of roots.

3.9 Incidental finding

Figure 18: The lowest point of the roof of the pulp chamber was found below the CEJ

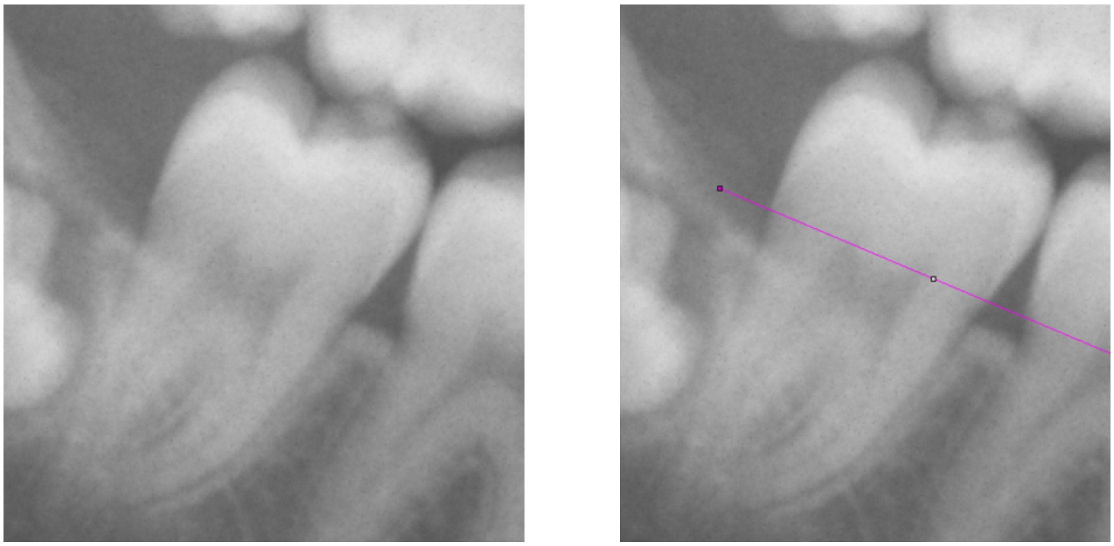


Figure 18 showed that in certain cases, the lowest point of the roof of the pulp chamber was found below the CEJ, illustrated by tooth #47. The proportion of cases in our study that displayed this phenomenon was 2%.

Chapter 4: Discussion

4.1 Limitations of the study

The assessment of taurodontism using DPRs allowed the imaging of all the jaw structures and teeth at the same time (Bilge et al., 2018). This in turn upheld the ALARA (As Low As Reasonably Possible) mandate for imaging in children as per the American Dental Association with regards to limiting radiation exposure in our younger patients (American Dental Association (Council on Scientific Affairs) and Services, Revised 2012). The gold standard of assessing root length is a periapical radiograph obtained by the paralleling technique (Sameshima and Sinclair, 2001). However, the paralleling technique is prone to multiple inaccuracies due to vertical radiograph positioning, angulation errors leading to distortions such as elongation or foreshortening of the image which can ultimately skew linear measurements in 2D radiography (Adarsh et al., 2018). In contrast, by using DPRs, due to the central ray being orientated in a buccal-lingual manner and mesiodistal position of the roots, taurodontism can be imaged with clarity (MacDonald, 2020). A study done by Adarsh et al. (2018), in single rooted teeth found that DPRs tended to overestimate root lengths by 0.5-0.8mm when compared to the periapical images. For our purposes, for this study, all the images used were calibrated to a known distance and additionally our calculations were done on a ratio scale that would account for these minimal distortions.

Some of the limitations of using DPRs are difficulties in determining the end of the apex of the longest root in maxillary molars due to the overlap of the zygomatic processes (Seow, 1993). Positioning errors such as the chin being too high results in the superimposition of the hard palate on the roots of the maxillary teeth, as well as if the chin is tilted down then the teeth are prone to overlap (Adarsh et al., 2018). This can affect the visualization of important structures that may impact measurement accuracy. By using the ImageJ software "Find Edges" tool this helped us to visualize apices and dental landmarks that were otherwise challenging to see. Another difficulty encountered by using DPRs is the challenge in identifying the CEJ for the measurement of Variable 3, in particular when the occlusal plane was slightly angulated. In order to overcome this, when the line connecting the CEJs was measured, care was taken to ensure that this line was in accordance with the occlusal surface of the tooth. Another important point to mention the angulation of the tooth, when measuring Variable 1, 2 and 3 in the vertical plane, can affect the tooth length measurement. Care was taken to ensure that when the measurements were repeated three times per variable measured that this angulation was kept within 5 degrees to ensure accuracy. Notably, with DPRs, the magnification factor is fairly constant in the vertical dimension as compared to the horizontal dimension (Adarsh et al., 2018). Taken together, our approach of only using DPRs in this study was justified.

Another limitation of this study is that we were unable to calculate a statistical power for our sample size in order to reach statistical significance. The reason for this, is our study is one of the first done in a mixed ethnic population whereas previous studies have been done in single ethnic populations. Hence, we were unable to utilize those studies to enable us to calculate a sample size.

We had to exclude a number of DPRs that had molars with caries and restorations which were more prevalent in our UBC adolescent population as compared to the Hong Kong study done by MacDonald-Jankowski and Li (1993), where water fluoridation has been present since 1961.

4.1.1 Digital Imaging Software.

All the images imported were in a DICOM format which enabled any imaging software to visualize the image without loss of diagnostic information and is considered to be the universal standard for image transmission of files (Farman, 2005). The use of digital imaging analysis software such as ImageJ achieved a more accurate measurement by allowing us to obtain measurements to 2 decimal places.

4.2 Taurodontism in an adolescent population of UBC patients drawn from the greater Vancouver area

Our results showed the total proportion of all taurodont teeth (hypotaurodont, mesotaurodont and hypertauront) was 16.6% or 165 teeth. Out of the 124 individuals assessed, 68 cases had at least one taurodont tooth. Therefore 54.8% of individuals presented with taurodontism. Clinically, the more meaningful value, is the proportion of individuals with at least one taurodont tooth. The dentist or hygienist practicing in Vancouver is likely to have a greater than 1:2 chance of finding a taurodont tooth in any given patient. Furthermore, in our study we found that 86% of the teeth exhibited mild (hypotaurodontism), consistent with studies by others (Marques Fernandes et al., 2018).

The prevalence of taurodontism was higher in our study as compared to a Chinese population (MacDonald-Jankowski and Li, 1993) . These authors, found a prevalence of 46.4% in individuals in 21.7% of teeth assessed (MacDonald-Jankowski and Li, 1993). Similarly, Weckwerth et al. (2016), also found a lower prevalence of 42.8% in individuals in their study compared to ours. Similar studies using Shifman and Chanannel's (1978), criteria to examine taurodontism depicted variable prevalence proportions. One of the concerns with assessing previous prevalence studies in different populations was the differing methods of measurements, sample size and also whether it was the number of people or the number of teeth assessed. In an Israeli population, the prevalence of taurodontism, was slightly lower at 6% (Shifman and Chanannel, 1978). Germans displayed a similar prevalence at 2% (Bürklein et al., 2011). There was a slight increase in the Turkish population at 11% (Bilge et al., 2018) and prevalence in an Iranian community was 23% (Jamshidi et al., 2017). These values range from 2-23% which cannot be explained by differences in analysis methods.

One possibility is that gene flow may potentially affect the varying prevalence of taurodontism in different populations. Population genetic models show colonization and immigration lead to mixing of populations and changing the dynamics of gene flow (Hedrick, 2017). For example, in Antioquia, Columbia, a Latin American population demonstrated a 69% European X-chromosome ancestry (Hedrick et al., 2002). This can potentially impact the presence of taurodontism since we know from Finnish studies, that the severity of taurodontism increases with each increasing X-chromosome (Laatikainen and Ranta, 1996).

In 2016, a census of the ethnicity in Vancouver showed the following composition: European Canadians: 48.2%: Chinese: 28.3%: South Asian (Indian/Pakistani/Punjabi/Srilankan): 6.1%, Filipino: 6%: Southeast Asian (Malaysian, Vietnamese, Taiwanese): 3%, Japanese: 1.7%, Latin American (Brazilian, Columbian): 1.6%, Korean: 1.5%, Aboriginal: 2% (1.3% First Nations, 0.6% Metis) and West Asian (Persians, Turkish): 1.2% (Canada, 2016).

The dentistry clinic at UBC provides a lower cost for service which makes it attractive to individuals who are recent immigrants, financially challenged and refugees. Patients come from the greater Vancouver area and are not limited to the immediate vicinity of the University. The prevalence of taurodontism is consistent with the composition of the general British Columbia population.

In our study we were unable to do a sub analysis of the proportions of the various ethnicities in our population sample due to ethical considerations. The reported prevalence of taurodontism is variable amongst different populations. Understanding the contribution of different ethnic proportions within our population sample could have enabled us to make inferences with regards to the increased prevalence found in our study.

Another reason to explain the higher rate of taurodontism in our study could be the inclusion of maxillary molars and second molars which tend to be more frequently affected (Weckwerth et al., 2016) (Laatikainen and Ranta, 1996).

4.3 Taurodontism and sex-related dimorphism

In our study we determined that taurodontism had a higher predilection for females (63.1%) as compared to males (45.8%). This difference was statistically significant for all teeth except for tooth #27 and #37. A possible reason for this is that there may be a statistical difference among these teeth, but we did not have enough cases to reach statistical significance. Other studies have shown a female predilection for taurodontism, particularly in a Chinese population whereby taurodontism was considerably more prevalent in females (56% in comparison to 36% in males, $P < 0.001$) (MacDonald-Jankowski and Li, 1993). Similar findings were observed in the Brazilian study done by Weckwerth et al. (2016), in their control group: 49% in females to 32% in males ($P < 0.01$).

The reason for taurodontism being more prevalent females is possibly related to the genes located on the X-chromosome (MacDonald, 2020, Laatikainen and Ranta, 1996). Taurodontism is also frequently described in a multitude of X-linked conditions such as Klinefelter syndrome (XXY) (Komatz et al., 1978), X-linked ectodermal dysplasia (Torres et al., 2019), X-linked hypophosphatemic rickets (Seow et al., 1995) and X-chromosome polyploidy in XXX and XXXX Finish females (Varrela et al., 1990). It has been proposed that the degree of severity of taurodontism increases with each additional X-chromosome (MacDonald-Jankowski and Li, 1993).

Our null hypothesis was not rejected in this case as there was no statistical difference between males and females in frequencies of taurodontism. With regards to the chi-squared test, the difference was marginally significant and using our independent samples t-test, statistical significance was achieved for all teeth except for tooth #27 and #37. We attempted to run the same statistical tests again, while removing the outlier DPR 124, but our results were similar and there was no appreciable change in results.

4.3.1 Clinical challenges posed by taurodontism

In a Chinese population, the authors reported that the pulp chamber was lower than the CEJ (MacDonald-Jankowski and Li, 1993). We also observed this phenomenon in 2% of our cases. The clinical impact is that should there be a need to perform endodontic treatment, such teeth would need a deeper access preparation in order to reach the pulp chamber (Mohan et al., 2013). Recognizing this phenomenon radiographically would help prepare the clinician for such a situation. Molars with a more apical position of the pulp chamber can appear to a lesser extent less taurodont, which can be misleading (MacDonald-Jankowski and Li, 1993).

4.3.2 Incidental finding of hypertaurodontism in one case

Taurodontism could be one of the constellation of features leading to a diagnosis of Klinefelter syndrome (Giambersio et al., 2019). Klinefelter syndrome is a genetic disorder in which there are three sex chromosomes (47, XXY) (Bonomi et al., 2017). Individuals appear male but have hypogonadism and androgen insensitivity usually rendering them infertile (Cangiano et al., 2021, Kanakis and Nieschlag, 2018). The diagnosis is often missed and in one study, 1 in 28 males presenting with Klinefelter syndrome were diagnosed before 11 years of age (Abramsky and Chapple, 1997). Early diagnosis is essential because it can enable one to prepare the parents of the affected individual for subsequent developmental challenges. In addition, studies have demonstrated that early replacement of testosterone at the start of puberty may alleviate some of the symptoms of Klinefelter syndrome by increasing bone mineral density, improving the metabolic profile, and decreasing cardiovascular risk which can improve the overall quality of life (Pizzocaro et al., 2020). One case included in our study had hypertaurodont second permanent molars in all quadrants. As per their medical history they had no reported concerns. This degree of severity of taurodontism might be indicative of Klinefelter syndrome however more than one phenotype is needed before genetic testing is indicated. In a study done by Schulman et al. (2005), they concluded that the positive predictive value for a male patient with taurodontism and a learning disability is 84%. In those situations, they suggest recommending karyotyping to the patient, parent or physician (Schulman et al., 2005). As dentists, it is important that we are able to pick up on these small nuances which may not have any dental treatment considerations at present but may or may not result in medical concerns for the patient in the future.

4.4 Symmetry in taurodontism

A study done on monozygotic and dizygotic twins by Laatikainen and Ranta (1996), revealed a high concordance of taurodontism as well as a high degree of symmetry for this trait (91.0%), indicating a potential genetic influence. Another study done by Awadh et al. (2020), in unrelated individuals, found symmetric bilateral taurodontism was more common than unilateral taurodontism.

Our study in unrelated individuals revealed 43 cases (35.0%) that presented with bilateral taurodontism. With regards to severity of the trait (hypo-, meso-, hyper -), it seems that for 42 cases (97.6%), if one tooth presented with hypotaurodontism, then the corresponding antimere tooth also presented with the same severity of taurodontism. Based on these results, it seems that the similarity in the type of taurodont tooth expressed in antimeric teeth may indicate a potential genetic role in the expression of taurodont severity within the same individual. Our study was the first study to compare antimeric teeth within the same individual. Previous studies have only compared taurodontism within different subjects. We found no statistically significant differences when comparing corresponding antimeric pairs of teeth between males and females. Additionally, we found a higher frequency of symmetry in the maxillary permanent second molars (25.0%), and overall in the maxilla (34.6%). This is consistent with what has been found in the literature (Sarr et al., 2000, MacDonald-Jankowski and Li, 1993).

Hence our secondary hypothesis was rejected as there was a symmetrical manifestation of taurodontism in the general adolescent population of UBC Dentistry patients.

Chapter 5: Future directions

Further research in this area will be required to increase our knowledge of the etiology regarding taurodontism and the roles that genes contribute to the manifestation of this trait. Studies involving familial inheritance patterns of specific gene variants are needed (multiple family members affected across several generations). Several promising candidate genes have been identified in recent mouse knockout studies where taurodontism has been induced (Ma et al., 2021, Jing et al., 2019). However, it is likely based on the variability of taurodontism that the genetic contributions are complex. There may be multiple gene variants contributing to the phenotypes as is the case for cleft lip with or without cleft palate.

Chapter 6: Conclusions

Our results suggest that:

- Mild taurodontism is relatively common in the local adolescent population similar to what was reported elsewhere. In previous studies, taurodontism was found in the Chinese and Brazilian populations in 46.4% and 42.8% respectively, of their normal controls.
- Our study is unique in that it looks at a Canadian adolescent population with a mixed ethnicity. It was the first study to assess the symmetrical manifestation of taurdontism within the same subject.
- Taurodontism was found in 68 (54.8%) of the 124 DPRs examined.
- The ability to identify these teeth and diagnose them early can help inform treatment planning decisions that are beneficial for both the clinician and the patient.
- Early detection of taurodontism in male patients can potentially point towards an underlying diagnosis of Klinefelter syndrome which can be further explored by their physician. It can lead to timely treatment with modalities such as testosterone replacement therapy and genetic counselling which ultimately will change the quality of life for these patients.

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Appendix:

ASA Physical Status Classification System

https://www.asahq.org/standards-and-guidelines/asa-physical-status-classification-system.

Accessed April 25th, 2021

Current Definitions and ASA-Approved Examples

ASA PS Classification	Definition	Adult Examples, Including, but not Limited to:	Pediatric Examples, Including but not Limited to:	Obstetric Examples, Including but not Limited to:
ASA I	A normal healthy patient	Healthy, non-smoking, no or minimal alcohol use	Healthy (no acute or chronic disease), normal BMI percentile for age	
ASA II	A patient with mild systemic disease	Mild diseases only without substantive functional limitations. Current smoker, social alcohol drinker, pregnancy, obesity (30<BMI<40), well-controlled DM/HTN, mild lung disease	Asymptomatic congenital cardiac disease, well controlled dysrhythmias, asthma without exacerbation, well controlled epilepsy, non-insulin dependent diabetes mellitus, abnormal BMI percentile for age, mild/moderate OSA, oncologic state in remission, autism with mild limitations	Normal pregnancy*, well controlled gestational HTN, controlled preeclampsia without severe features, diet-controlled gestational DM.
ASA III	A patient with severe systemic disease	Substantive functional limitations; One or more moderate to severe diseases. Poorly controlled DM or HTN, COPD, morbid obesity (BMI ≥40), active hepatitis, alcohol dependence or abuse, implanted pacemaker, moderate reduction of ejection fraction, ESRD undergoing regularly scheduled dialysis, history (>3 months) of MI, CVA, TIA, or CAD/stents.	Uncorrected stable congenital cardiac abnormality, asthma with exacerbation, poorly controlled epilepsy, insulin dependent diabetes mellitus, morbid obesity, malnutrition, severe OSA, oncologic state, renal failure, muscular dystrophy, cystic fibrosis, history of organ transplantation, brain/spinal cord malformation, symptomatic hydrocephalus, premature infant PCA <60 weeks, autism with severe limitations, metabolic disease, difficult airway, long term parenteral nutrition. Full	Preeclampsia with severe features, gestational DM with complications or high insulin requirements, a thrombophilic disease requiring anticoagulation.

			term infants <6 weeks of age.	
ASA IV	A patient with severe systemic disease that is a constant threat to life	Recent (<3 months) MI, CVA, TIA or CAD/stents, ongoing cardiac ischemia or severe valve dysfunction, severe reduction of ejection fraction, shock, sepsis, DIC, ARD or ESRD not undergoing regularly scheduled dialysis	Symptomatic congenital cardiac abnormality, congestive heart failure, active sequelae of prematurity, acute hypoxic-ischemic encephalopathy, shock, sepsis, disseminated intravascular coagulation, automatic implantable cardioverter-defibrillator, ventilator dependence, endocrinopathy, severe trauma, severe respiratory distress, advanced oncologic state.	Preeclampsia with severe features complicated by HELLP or other adverse event, peripartum cardiomyopathy with EF <40, uncorrected/decompensated heart disease, acquired or congenital.
ASA V	A moribund patient who is not expected to survive without the operation	Ruptured abdominal/thoracic aneurysm, massive trauma, intracranial bleed with mass effect, ischemic bowel in the face of significant cardiac pathology or multiple organ/system dysfunction	Massive trauma, intracranial hemorrhage with mass effect, patient requiring ECMO, respiratory failure or arrest, malignant hypertension, decompensated congestive heart failure, hepatic encephalopathy, ischemic bowel or multiple organ/system dysfunction.	Uterine rupture.
ASA VI	A declared brain-dead patient whose organs are being removed for donor purposes			