A MORPHOMETRIC ANALYSIS OF THE GROWTH OF THE IMMATURE AND SUB-ADULT HUMAN PALATE

Nkemakonam Vincent Onwochei-Bolum

Student number: 2294793

A Dissertation Submitted to the Faculty of Health Sciences,

University of the Witwatersrand, Johannesburg, in fulfilment

of the requirements for the degree of Master of Science in Medicine.

Johannesburg

September 2021

DECLARATION

I Nkemakonam Vincent Onwochei-Bolum declare that this dissertation is my work. It is being submitted for the Degree of Masters of Science in Medicine at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

Nkemakonam Vincent Onwochei-Bolum

23rd Day of September 2021

This dissertation is dedicated to

My supervisors

Dr. Erin Hutchinson and Emeritus Professor Beverley Kramer

And

My family

Abstract

Postnatal nutrition in humans is associated with advancement in the mode of feeding from the neonatal and infancy period of growth to adulthood. During the neonatal and infancy periods, the palate functions in suckling, tongue manipulation and swallowing, while in adulthood and with dental eruption, the palate participates in both mastication and in the production of sound. It is anticipated that the transition in the role of the palate due to alterations in its function over time will cause morphological changes. Thus, the aim of this study was to analyse alterations in the shape and dimensions of the human palate from birth through the stages of dental eruption to the complete emergence of the permanent dentition in the sub-adult stages of life. Crania from 72 South African individuals were sourced from the Raymond A. Dart Collection of Human Skeletons, School of Anatomical Sciences, Faculty of Health Sciences, University of the Witwatersrand. The sample was divided into three age groups to correspond with the age ranges of the eruption of the deciduous dentition (birth to 5 years of age), mixed dentition (6 to 12 years of age) and the permanent dentition (13 to 20 years of age) respectively. A series of 14 osteological landmarks were digitized across the oral surface of the palate using an Immersion MicroScribe G2 unit. Landmark data were converted to linear distances and the length, width and elevation of the palate were assessed in relation to the state of the dentition. Analysis included both quantitative (linear measurements) and qualitative (wireframes) methods. The length and width of the palate in the permanent dentition group was significantly larger when compared to the mixed and deciduous dentition groups. While elevation of the palatal dome in the permanent dentition group was significantly greater than that of the palate in the mixed dentition group, no further significant differences were observed. Thus, changes in the morphology of the palate appear to be progressive with dental eruption and development across the different states of the dentition. By establishing the nature of the changes in the functional environment of the palate during development and growth, abnormalities in the postnatal development of the palate could be diagnosed.

Acknowledgements

I will be ever grateful to so many people who have been there to support me in my times of need while on this challenging and educative path. First and foremost, I want to thank my supervisors Dr. Erin Hutchinson and Professor Beverley Kramer who have both been inspiring and exemplary models. Dr. Hutchinson and Professor Kramer have been of great support to me through the length of this programme as they have shown me care and be patient with me while I was being trained and exposed to this field of research.

I am also very grateful to Prof. Amadi Ihunwo who is the head of the division of morphological anatomy. Prof Ihunwo has been very supportive and instrumental in my training as he offered me an opportunity to develop my teaching skills as a teaching assistant during the course of my programme.

I cannot fail to appreciate Dr. Brendon Billings and Mr. Mashudu Mulaudzi, who are respectively the curator and technician at the Raymond A Dart Collection of Human Skeletons. Despite the chaos accompanied by the uncertainties of the global pandemic last year 2020, Dr. Billings and Mr. Mulaudzi still made it possible for me to access the collection and not forestall my research.

To Mrs. Gital Patel the director of the international student's office, I say a big and well-deserved thanks to you. Right from the point of my admission Mrs. Patel has been very instrumental in making sure I am not encountered with so many hurdles as would an international student, Mrs. Patel would always give a listening ear and advice on how to proceed onwards no matter what the problem was.

Special thanks go to all my fellow postgraduate students and all the staff of the School of Anatomical Sciences as we have all been through these times together in one way or the other.

Last but in no way the least, I will like to extend deep gratitude from the bottom of my heart to my family. You have all been the best, and I say a big thanks to you all for always offering that shoulder to lean on whenever the need had arisen.

Table of Contents

List of figures

List of tables

List of abbreviations

2D	-	Two dimensions
3D	-	Three dimensions
CT	-	Computer tomography
Fig	-	Figure
FL	-	Floating landmarks
FX	-	Fixed landmarks
Geo_mean	-	Geometric mean
GPA	-	Generalized Procrustes analysis
HREC	-	Human Research Ethics Committee
IGF-1	-	Insulin-like growth factor
LM	-	Landmark
MANOVA	-	Multiple analysis of variance
MM	-	Millimeter
MRI	-	Magnetic resonance imaging
MUS	-	Microscribe utility software
MSV	-	Mosimann shape variable
MSV_H	-	Mosimann shape variable of height
MSV_L	-	Mosimann shape variable of length
MSV_W	-	Mosimann shape variable of width
PAST	-	Paleontological statistics
PC1	-	Principal component 1
PC2	-	Principal component 2
PCA	-	Principal component analysis
SD	-	Standard deviation

Chapter One

1.1 Introduction

Feeding is a characteristic of every living organism and is essential for survival. Structures involved in feeding have evolved over time to aid the mechanisms of prehension, mastication and deglutition in different organisms (Fish, 2019). The palate is one such structure. The palate has evolved in complexity from non-vertebrates to vertebrates, spanning from protostomes without a palate feeding by fluid filtration, through a short palate in fishes and birds, and finally in some reptiles (alligators and crocodile) and mammals into a long palate, completely separating the oral cavity from the nasal cavity (Li *et al.*, 2016; Fish, 2019). The latter separation is important in animals that have an advanced feeding mechanism such as mammalian suckling, in order for the respiratory system to be "closed off" from the oral cavity during feeding.

The palate, which forms the roof of the oral cavity in humans, consists of bones in its anterior twothirds and soft tissues, including skeletal muscles, in its posterior one-third. The bones contributing to the human adult palate are the palatine processes of the maxilla and the horizontal plates of the palatine bones, bordered by the alveolar region of the maxilla which is tooth bearing. The continuous intermaxillary and interpalatine sutures mark the line of palatal fusion (Cunningham *et al.,* 2016). The muscles of the soft palate such as the tensor veli palatini, levator veli palatini and the uvular muscles are all attached to the palate via the palatine aponeurosis, while the palatopharyngeus is directly attached to the horizontal plate of the palatine bone. The palatoglossus muscle attaches the palate to the tongue (Mu *et al.*, 2021). These muscles are of mechanical importance to the palate, particularly during swallowing.

During the neonatal and infancy periods, the palate functions in suckling, tongue manipulation and swallowing, while in adulthood, the palate participates in both mastication and in the production of sound. The importance of the palate in setting up a vacuum in the oral cavity and hence enabling suckling is realized in neonates with a cleft of the palate (Sperber *et al.*, 2010; Singh, 2018).

1.1.2 Development and ossification of the palate

The development of the palate in humans occurs as a highly regulated sequence of events beginning from 5 weeks of gestation (Humphrey, 1971; Sperber *et al.*, 2010). Neural crest cells migrating into the first pharyngeal arches contribute to the formation of the palate. At 5 weeks of gestation, the ectomesenchymal (neural crest) content of the median nasal process forms a median palatal process. The median palatal process gives rise to the premaxilla (primary palate) of the embryo and fetus (Humphrey, 1971; Allan and Kramer, 2010). The developing tongue occupies most of the stomodeal cavity at 5 weeks, and as a result, the lateral palatal process from each maxillary prominence lies vertically on each side of the tongue (Humphrey, 1971; Sperber *et al.*, 2010). As the tongue descends during week 6 of gestation, due to the growth of the stomodeal cavity (Humphrey, 1971; Allan and Kramer, 2010), the lateral palatal processes elevate to a horizontal position and join the median palatal process. The three shelves begin to fuse from anterior to posterior to form the palate at 9 weeks of gestation (Humphrey, 1971; Allan and Kramer, 2010; Sperber *et al.*, 2010).

Ossification of the palate occurs by means of intramembranous bone formation. At about 6 weeks of gestation, ossification of the palate proceeds from primary and secondary ossification centres in the median palatal process, thus producing a premaxilla (Allan and Kramer 2010). One primary ossification centre in each lateral palatal process appears at about 6 weeks, and will give rise to the horizontal part of the maxillary bone on either side of the midline (Allan and Kramer 2010; Sperber *et al.*, 2010). A primary ossification centre also appears at 8 weeks of gestation in the posterior region of each lateral palatal process and will give rise to the horizontal process of the palatine bone on either side of the midline (Allan and Kramer, 2010; Sperber *et al.*, 2010). The maxillary bone will overgrow the premaxillary bone superficially, so that the premaxilla is not evident after 16 weeks of gestation in humans (Singh, 2018). Ossification does not occur in the posterior “extremities” of the fused lateral palatal processes, resulting in the soft palate and the uvula (Sperber *et al.*, 2010).

1.1.3 Postnatal growth and development

As the oral cavity assumes full function during the early postnatal period of growth, the growth of the oral cavity during this period (birth – 5 years of age) is further complicated by the development and eruption of the dentition (Wise and King, 2008; Alqahtani *et al.*, 2010; Hutchinson *et al.*, 2017). During this period, the maxilla develops by increasing in size to accommodate dental eruption.

Skeletal growth within the oral cavity is thought to be continuous from birth through to adulthood (Alqahtani *et al.*, 2010; Martinez-Maza *et al.*, 2013; Amirabadi *et al.*, 2018). The maxilla grows more inferiorly in the early age of postnatal growth and during the eruption of the deciduous dentition. As the dentition transitions between the deciduous state and the permanent state (a period known as the "mixed dentition"), the cranial base grows in width and also inferiorly. Thus, the eruption and growth of the mixed dentition is thought to increase the width of the maxilla (Hesby, 2006; Martinez-Maza *et al.*, 2013). Further growth of the maxilla inferiorly in the region of the alveolar process during the stages of the mixed dentition results in an increase in the height of the palatal dome (Thilander, 1995; Amirabadi *et al.*, 2018). During the sub-adult stage of growth (14 – 20 years of age) in which the permanent dentition is fully erupted, the maxilla grows more anteriorly. This anterior growth of the maxilla results in an increase in the length of the palate (Martinez-Maza *et al.*, 2013).

Intake of nutrition is thought to be significant in the postnatal growth of the oral cavity, as there is local stimulation of blood by the activities of the tongue anteriorly, and by jaw movement and swallowing (Humphrey, 1971). The increased masticatory function is also characterised by further growth of the osteological structures of the oral cavity (Humphrey, 1971; Herring, 1985).

Drachman and Banker (1964) postulated that function has no effect on structural presentation or configuration. However, later studies have shown that the maturation of structures (such as bones and muscles) affect function by increasing their activities, and in turn influences further structural development and growth (Humphrey, 1971; Herring, 1985; Le Reverend *et al.,* 2014; Setiawati and Rahardjo, 2018). The juvenile stage of growth is characterised by extensive morphological changes in the maxilla as the deciduous dentition exfoliates, the permanent dentition erupts and a relative increase in the mass of the maxillary alveolar bone and growth of the inter-alveolar width occurs (Herring, 1985; Hesby *et.al,* 2006). Growth of the alveolar bone will be adjusted throughout life by bone modelling and remodelling (Wise and King, 2008; Chang *et al.*, 2012; Hutchinson *et al.*, 2017). Late changes in the maxillary region of the oral cavity such as appositional growth of the palate, may be triggered by bone loading.

Forces associated with the mechanical activities of the oral cavity such as mastication, occlusion, swallowing and dental eruption may stress and cause osteogenic loading of the associated bones. These weight bearing activities stimulate the building of bone and lead to an increase in bone mass (Li *et al.,* 2016) and also to bone remodelling in the palate (Li *et al.*, 2016). Remodelling of bones involves the constituent cells such as osteocytes, osteoblasts and osteoclasts. Osteocytes regulate the flow of fluid in bones which results from the mechanical forces on the bone (Seeman 2009) and signal the surrounding cells (Seeman 2009) when changes in the flow of fluid occur. This mechanotransduction by the osteocytes results from the forces and stress of the mechanical activities, which are translated into biomechanical signalling and which in turn stimulate bone formation by osteoblasts and bone resorption by osteclasts (Seeman 2009). The process of bone remodelling causes the release of growth factors which regulate this process (Crane and Cao, 2014). Growth hormone promotes osteoblast formation and osteoclast resorption which function through insulin-like growth factor – 1 (IGF – 1) secreted by the liver (Crane and Cao, 2014). The geometry of a bone is thus adjusted by osteoblasts and osteoclasts in order to adapt to mechanical forces and stress (Langdahl *et al.*, 2016).

Martinez-Maza *et al.* (2013) demonstrated variations in bone modelling of the maxilla by comparing the bone modelling pattern of the anterior and posterior craniofacial region in sub-adult (age 7 – 17 years) and adult (age 24 – 39 years) samples. They observed increased bone modelling towards the incisors in the sub-adult group. A further marked increase in the bone modelling activities of the anterior incisor region was observed during the transition between sub-adult and adult samples. The study concluded that the difference in bone modelling activities between the sub-adult and adult samples resulted in the change of the inferiorly directed growth of the face to an anterior direction in adulthood (Martinez-Maza *et al.,* 2013). The growth of the maxilla is thought to be associated with the growth of the alveolar bone, as a relative change in the dimensions of the dental arch of the maxilla due to an increase in length and width is observed during the stages of eruption and emergence of the dentition (Wise and King, 2008). Hesby *et.al.* (2006) observed that growth at the mid-palatal suture and remodelling along the lateral aspect of the posterior region of the maxilla and maxillary tuberosity, resulted in transverse alveolar growth during the stages of dental development. It was also observed that the inter-molar and inter-canine width increased continuously from childhood into adulthood (Hesby *et.al*, 2006). Thus, Hesby *et.al.* (2006) postulated that growth in the width of the alveolar process and palate may be age related.

Permanent teeth erupt earlier in females when compared to males (Kaczmarek, 1994; Nystrom *et al.,* 2001; Ekstrand *et al.,* 2003; Almonaitiene *et al.,* 2010). Morphological variation of the oral cavity attributed to sex is also observed in the alveolar bone (Alhldlaq, 2010). The alveolar bone in adolescent females is characterized by higher activities of bone modelling and remodelling compared to adolescent males (Alhldlaq, 2010). However, in adulthood the alveolar bone in males is characterized by higher activities of bone modelling and remodelling when compared to females (Alhldlaq, 2010). The marked difference in bone modelling and remodelling activities relative to sex further explains the greater alveolar bone cortical thickness observed in adolescent females compared to adolescent males (Hesby *et al.,* 2006). This difference may be a result of hormonal differences between males and females, as females assume the adolescent stage of growth earlier than their male counterparts. The alveolar bone cortical thickness may affect the morphology of the palate. Thus, changes in palatal morphology during the sub-adult stage of growth may vary from male to female individuals, and as such knowledge of the differences in palatal morphology between sexes may be of importance in determining the sex of unidentified human remains (Chovapoulou *et al.,* 2013).

Carter and McNamara (1988) and Thilander (2009) demonstrated marked changes in the length and width of the dentoalveolar arch relative to the stages of dental development. Other studies have also shown variations in the form and dimensions of the dental arch resulting from dental eruption and emergence (Moyers *et al.*, 1976; Van der Linden, 1983; Van der Linden, 1989; Ross-Powel and Harris, 2000). Amirabadi *et al.* (2018) evaluated palatal width and height at various stages of the dentition in children and adolescents ranging in age from 5 – 18 years, and observed an increase in palatal width from the deciduous to the permanent dentition. A decrease in palatal height occurred from the deciduous to the mixed dentition stage, and then increased from the mixed to the permanent dentition stage (Amirabadi *et al*., 2018). While Amirabadi *et al.* (2018) evaluated the postnatal changes in the height and width of the palate relative to the dental stages of eruption, they did not analyse these changes relative to the early stages of dental development and eruption beginning at about the third month postnatally (Sperber *et al.*, 2010).

1.1.4 Investigations of size and shape in the craniofacial region

Most craniometric studies (Moyers *et al.*, 1976; Van der Linden, 1983; Carter and McNamara, 1988; Van der Linden, 1989; Ross-Powel and Harris, 2000; Thilander, 2009; Amirabadi *et al*., 2018) analysing the morphology of the palate relative to dental development have studied the palate in two dimensions (2D). Most 2D studies make use of a caliper in collecting data and each measurement is carried out by measuring the distance between two landmarks. The 2D method usually produces metric data related to a biological structure which is limited to changes in size only and does not account for potential shape related changes in a structure. Previous craniometric studies (Chovalopoulou *et al.*,2013; Al-Shahrani *et.al.*,2014; Hutchinson *et al.,* 2015; Small *et al.*, 2016; Ghislanzoni *et al.*, 2017) have made use of geometric morphometrics, which takes into account the shape factor, to study different structures of the oral cavity in 3D orientation.

Geometric morphometrics provides information related to geometrical changes in a structure as studied in three-dimensional space, which may be expressed as either variations in the size and/or shape of the structure under investigation. The geometric information provided by this technique further allows for the complex shape analyses such as a Generalized Procrustes analysis as well as a principal component analysis which further facilitates three dimensional reconstructions of objects in space (Chovalopoulou *et al.*,2013; Al-Shahrani *et.al.*,2014; Hutchinson *et al.,* 2015; Small *et al.,* 2016; Ghislanzoni *et al.,* 2017).

Three-dimensional data can be captured using different methods and instruments, including a surface scan or volumetric scan, or coordinates captured directly with a digitizer such as a miroscribe or Polhemus. Data from volumetric scans are obtained from computer tomography (CT) or magnetic resonance imaging (MRI) scans, or from higher resolution scans such as microCT or micro-MRI. Tissue density can be linked to gray values on scan slices to provide a 3D orientation of the object in volumetric scans (Mitteroecker and Gunz, 2009). However, these techniques require extensive training and expertise, and are more expensive and time consuming when compared to using a microscribe. The microscribe is a tool used in the digitizing and recording of landmark data. The microscribe has the ability to capture data and represent them as coordinates (X, Y and Z). Data captured with a microscribe can be analysed without the influence of rotation or translation. In addition to its role in capturing landmark data, the microscribe is reported to have a high accuracy which effectively assists in minimizing the loss of biological information (Chovalopoulou *et al.*,2013; Al-Shahrani *et.al.*,2014; Hutchinson *et al.,* 2015; Small *et al.,* 2016; Ghislanzoni *et al.,* 2017). Due to the precision of the technique, the current study made use of geometric morphometrics with the aid of a microscribe to analyse the morphology of the palate in the sample population.

Knowledge of palatal growth relative to the stages of dental eruption and emergence is essential in diagnostics and subsequent treatment planning and management of patients in the fields of orthodontics and craniofacial surgery (Ghislanzoni *et al.,* 2017). Furthermore, knowledge of the dimensions of the palate relative to the dental stages of eruption and emergence may be of significance in the estimation of the age of immature skeletal samples and the identification of functional influences on the morphology of the palate (Chovalopoulou *et al.,* 2013).

The growth and morphology of the palate in humans may be better understood by studying palatal growth relative to the growth dynamics of the maxillary dentition and alveolar process with the aid of geometric morphometric. Thus, it is hypothesised that the morphological variation and growth of the palate is related to the stages of dental development and eruption of the maxillary dentition in immature, juvenile and subadult individuals.

1.2 Aims and objectives

1.2.1 Aim

The aim of this study was to analyse changes in the shape and dimensions of the human palate from birth through the stages of dental eruption to the complete emergence of the permanent dentition in the sub-adult stages of life.

1.2.2 Objectives

The objectives of the study were to:

1. Assess and compare changes in the dimensions i.e. maximum length, width and height of the human palate relative to the different states of the dentition.
2. Visualise and illustrate the relevant shape variations of the human palate between the different states of the dentition.

3. Compare the degree of change in shape of the human palate across the different states of the dentition.

Chapter Two

2.1 Materials and methods

Ethical clearance to use skeletonized human maxillae was obtained from the University of the Witwatersrand's Human Research Ethics Committee (HREC - Medical) (Appendix I). In addition, permission to use the ethical clearance waiver certificate for the use of skeletonized elements was obtained from the Head of the School of Anatomical Sciences, who is the custodian of the waiver. All materials used in this study were handled in accordance with the requirements of the South African National Health Act, Act 61 of 2003. Furthermore, permission to use specimens from the Raymond A. Dart Collection of Human Skeletons, was obtained from the Collections Committee of the School of Anatomical Sciences.

2.2 Study population

Crania from 72 South African individuals were sourced from the Raymond A. Dart Collection of Human Skeletons, School of Anatomical Sciences, Faculty of Health Sciences, University of the Witwatersrand. Individuals aged between 0 and 20 years of age, which included 44 males and 28 females, were analysed. Age estimation was based on the stages of dental eruption and emergence of the teeth of each specimen. The age of the individuals was also obtained from the available record at the time of death of the individual, as contained in the database of the Raymond A. Dart Collection.

As the eruption and emergence of the dentition is associated with the modeling and remodeling of the alveolar bone (Hutchinson *et al.,*2017), and as alveolar bone is closely associated with the postnatal development of the palate (Wise *et al.*, 2012), dental eruption and the emergence of the teeth were taken into account in the grouping of individuals for analysis. Thus, the sample was divided into three age groups to correspond with the age ranges of the eruption of the deciduous dentition (birth to 5 years of age), mixed dentition (6 to 12 years of age) and the permanent dentition (13 to 20 years of age) respectively (Alqahtani *et al.,* 2010). Maxillae with any congenital abnormalities, trauma, pathology or surgical interventions and general damage were excluded from this study. Specimens where sutures could not be visualised or with absence of landmarks were also excluded from the study.

2.3 Methodology

This study was conducted as a cross-sectional study with a quantitative approach.

2.3.1 Digitising of landmarks

Each cranium was placed in a fixed position with the oral surface of the palate exposed to show the basicranial surface of the skull, in order to facilitate the recording of each landmark. The cranium was protected and secured in place with the aid of a beanbag or oasis foam. A series of 14 osteological landmarks (Fig. 1) were digitized across the oral surface of the palate using an Immersion MicroScribe G2 unit (Solution technologies Oella, MD, USA), with an accuracy of 0.38mm. The landmarks were recorded in a pre-set anti-clockwise sequence (from LM1 towards LM14) (Fig. 1) as the microscribe captured and represented the coordinates in that order. The points necessary for calculating the linear measurement and defining the shape of the palate were all included in these landmarks. A total of 10 fixed (FX) landmarks (Table 1), selected for the purposes of calculating the linear measurements and defining the shape of the palate, and four floating landmarks (FL) (Table 1) to define the shape by replicating the angle of curvature of the palate of each specimen, were included in the 14 osteological landmarks selected for this study.

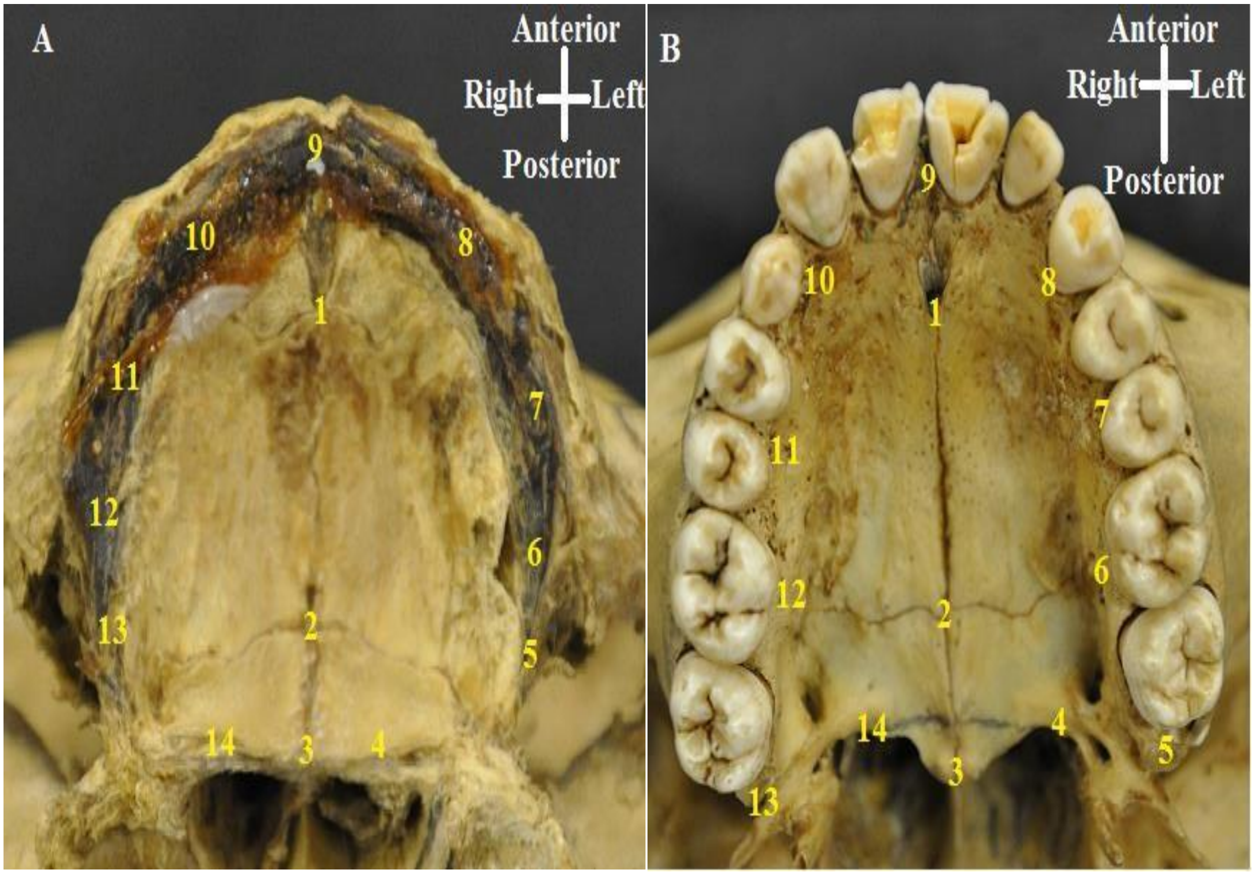


Figure 1: Inferior view of the human immature palate indicating the location of all 14 osteological landmarks used to assess size and shape differences. 1A: birth; 1B: 12 years of age.

Table 1: The 14 osteological landmarks.

Landmarks (FX / FL)	**Location**	**Description**
LM (FX) 1	Incisive foramen	The most posterior point of the incisive foramen along the midline palatal suture.
LM (FX) 2	Staurion	The point of intersection between the median and transverse palatine sutures (Chovalopoulou *et al.*,2013).
LM (FX) 3	Staphylion	The most posterior point on the spine of the palate.
LM (FL) 4	Midpoint between the staphylion and left postalverion	A point halfway between the staphylion and the most posterior part of the left alveolar process.
LM (FX) 5	Left Postalverion	The most posterior part of the left alveolar process (Chovalopoulou *et al.*,2013).
LM (FX) 6	Left Endomolare	A point on the lingual dental crypt of the left 2nd molar tooth for the palatal width measurement (Cordeiro *et al.*, 2015).
LM (FL) 7	Left 2nd premolar or 1st deciduous molar tooth (Lingual dental crypt).	Either location was chosen based on the age of the specimen.
LM (FX) 8	Left canine tooth (Lingual dental crypt).	This point was located in younger specimens by accessing the canine dental crypt.
LM (FX) 9	Orale	The midpoint on the prosthion.
LM (FX) 10	Lingual aspect of the dental crypt of the right canine tooth.	As described in LM 8
LM (FL) 11	Lingual aspect of the dental crypt of the right 2nd premolar or 1st deciduous molar tooth.	As described in LM 7
LM (FX) 12	Right Endomolare	As described in LM 6
LM (FX) 13	Right Postalverion	As described in LM 5
LM (FL) 14	Midpoint between the right postalverion and the staphylion.	As described in LM 4

Subsequent to the digitising of the landmarks using MicroScribe utility software (MUS) 7 (Revware inc. Raleigh, NC, USA), the 3D coordinates were imported into a Microsoft Excel worksheet. Each digitised landmark consisted of three coordinates (X, Y, and Z), which represented the horizontal, vertical and depth planes respectively. A Pythagorean formula was used to convert the recorded data into linear distances.

$$\text{Pythagorean formula} = \sqrt{}(X_1 - X_2)^2 + (Y_1 - Y_2)^2 + (Z_1 - Z_2)^2$$

where X_1, Y_1, Z_1 and X_2, Y_2, Z_2 refer to the coordinates of the first and second landmarks respectively (Hutchinson *et al.*, 2015).

2.3.2 Linear measurements

The length of the palate was measured by a linear measurement taken between LM9 and LM3 (Fig. 2). The width of the palate was measured at its widest point between LM6 and LM12 (Fig. 2).

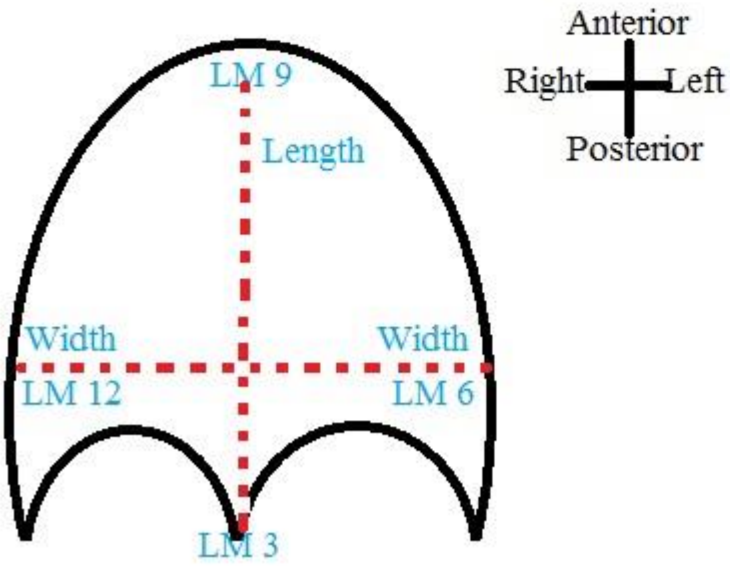


Figure 2: Schematic diagram illustrating the oral surface of the bony palate depicting the length and width measurements of the palate.

2.3.3 Palatal dome elevation

To calculate the posterior elevation of the palatal dome, landmarks LM3, LM5 and LM13 were used. The elevation calculation required two separate calculations as described below:

As the triangle created by the collective use of distances between LM3, LM5 and LM13 was not a right-angled triangle, the cosine rule was first used to calculate angle B (Fig. 3A).

$$\mathrm{Cos}B = (c^2 + a^2 - b^2) / (2ac)$$

Once angle B was calculated then a line was drawn perpendicular to side c, creating a 90^0 triangle (Fig. 3B). As angle B and side a were both known, the sine rule was then used to calculate the elevation of the dome as represented by side d (Fig. 3B).

$$a \times \mathrm{Sin}\ B = d \text{ (elevation of the palatal dome)}$$

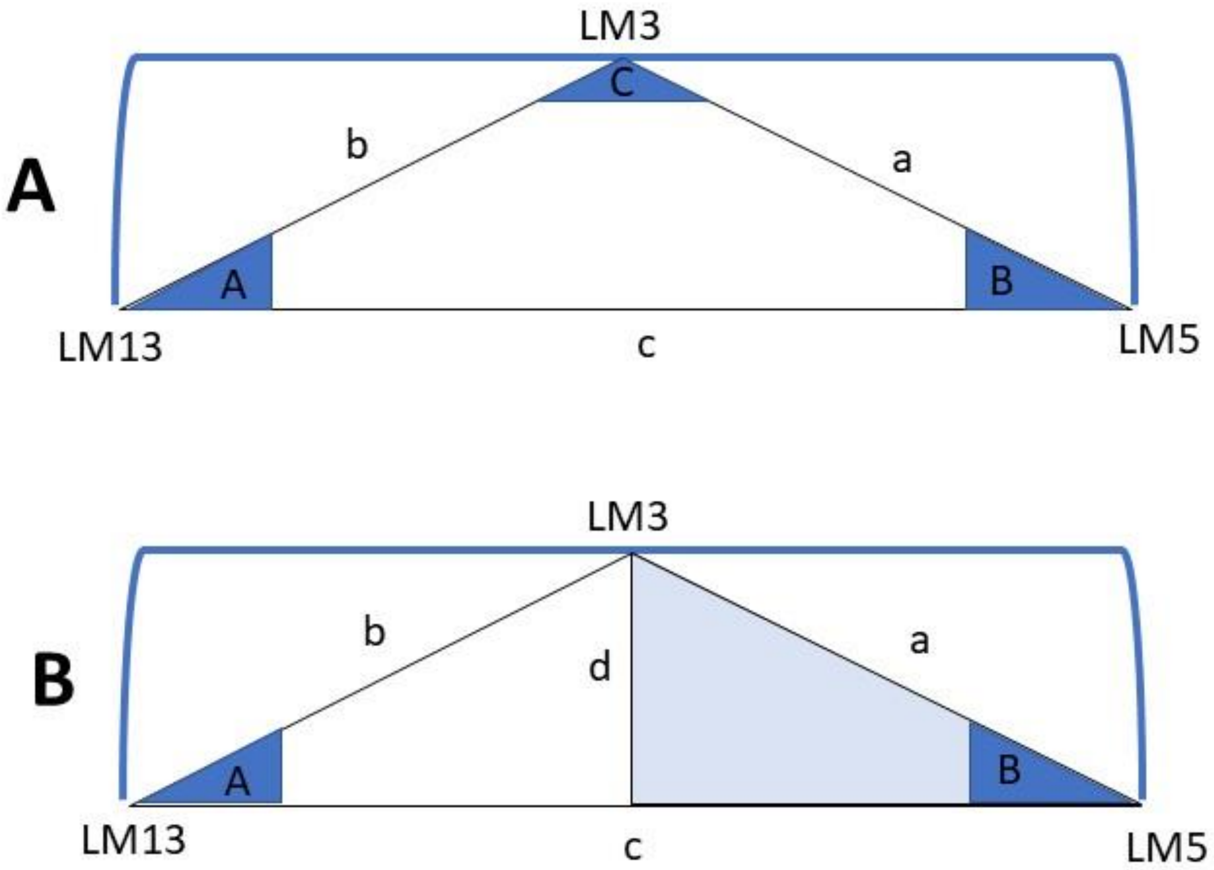


Figure 3: Schematic diagram illustrating the posterior view of the bony palate. 3A. Dimensions used to calculate angle B in an isosceles triangle. 3B. Parameters used to calculate the posterior elevation of the palatal dome using angle B and the sin rule.

2.3.4 Shape analysis

In order to visualise the digitised osteological landmarks in 3D, a wireframe model was constructed by creating a set of lines connecting the digitised osteological landmarks together in 3D space. The wireframes were generated by analysing the data through a Generalized Procrustes analysis (GPA). The osteological landmarks were digitized in 3D orientation. Each landmark coordinate was characterized by shape and size. In order to analyse the shape component a GPA was performed by centering the data on the average size known as the centroid size. The centroid size was calculated using the square root of the sum of the squared distance of each osteological landmark of the palate from the centre of gravity (the location was determined by taking the average of the X and Y coordinate of each landmark). The GPA removed the influence of size, rotation, and translation of the data, thus generating a new set of coordinates known as the Procrustes shape coordinate (Al-Shahrani *et.al.,* 2014; Klingenberg, 2016).

2.4 Data analysis

The 3D landmark measurements extracted from the data were subjected to a principal component analysis (PCA) using PAST statistical software to analyse the size and MORPHOLOGIKA 2 v. 2.5 (University College London, UK) to assess the shape. All analysis was conducted using Microsoft Excel for Windows and SPSS V20 (IBM, Armonk, NY, USA). A Shapiro–Wilk's test was conducted to assess the nature of the data. The partial eta squared was used to determine the effect of the group size on the level of significance for each measurement by running the data through MANOVA and performing the tests of between-subject effect. In the assessment of partial eta squared results, values ranged from 0 – 1 and the closer the values were to 1, the greater the effect group sizes had on the variable, values of 0 indicated no real effect. Thus, a value of 0.9 would translate to group sizes having a 90% effect on the variable.

Size analyses: Descriptive statistics, including means and standard deviations, were calculated. The data analysis included: a multivariate analysis of variance (MANOVA). A $p \leq 0.05$ was considered significant. The geometric mean was calculated, and it represented the size measure independent of the shape of the sample population. The geometric mean evaluated the total average of all values associated with a specimen and established the overall position of the size of the individual compared to the rest of the sample. MANOVA assessed the variations in the size of the palate relative to dental eruption and development by comparing the Scheffe posthoc variables. Scheffe posthoc test was used as the sample group sizes were unevenly distributed.

Shape analyses: The geometric mean was used as a scaling factor by dividing the measurement value by the geometric mean to give the Mosimann shape variable. This allowed for the analysis of shape as an independent variable. A MANOVA was performed using the Mosimann shape variable, and the Scheffe posthoc test was run to determine exactly where significance existed. The multivariate nature of shape as captured by the Procrustes shape coordinate were analysed using a principal component analysis (PCA) to show and compare shapes (Klingenberg, 2016). The data was then organized according to the stages of dental eruption and developmental age range (deciduous, mixed and permanent dentition) and the mean shape of each dental eruption and developmental age range was assessed using wireframes. Alteration in the wireframes across the different states of the dentition indicated changes in the shape of the palate.

Inter- and intra- observer errors were determined by two researchers on ten specimens and tested using Lin's concordance correlation coefficient of reproducibility. This provided information on the level of repeatability of the method and the degree of association between measurements.
Values ranging between 0.8 and 1 was considered acceptable levels of repeatability.

Chapter Three

3.1 Results

3.1.1 General morphology of the palate

General changes in the morphology of the palate were observed between the different states of the dentition. The palate appears to have a horseshoe-shape in the deciduous dentition group (Fig. 4A) when compared to a more oval-shape in the mixed and permanent dentition groups (Fig. 4B and 4C). In the posterior region of the palate in the mixed and permanent dentition groups, bilateral indentations (curvatures) and a formed palatal spine were observed when compared to the deciduous dentition group (Fig. 4B and 4C). The incisive foramen, and the greater and lesser palatine foramina were more visible in the mixed and permanent dentition groups when compared to the deciduous dentition group (Fig. 4). The incisive suture appeared to be longer and more evident in the palate of the permanent dentition group when compared to the mixed and deciduous dentition group (Fig. 4). The region of the incisive foramen was observed to be more posteriorly situated in the permanent dentition group when compared to the deciduous and mixed dentition groups (Fig. 4).

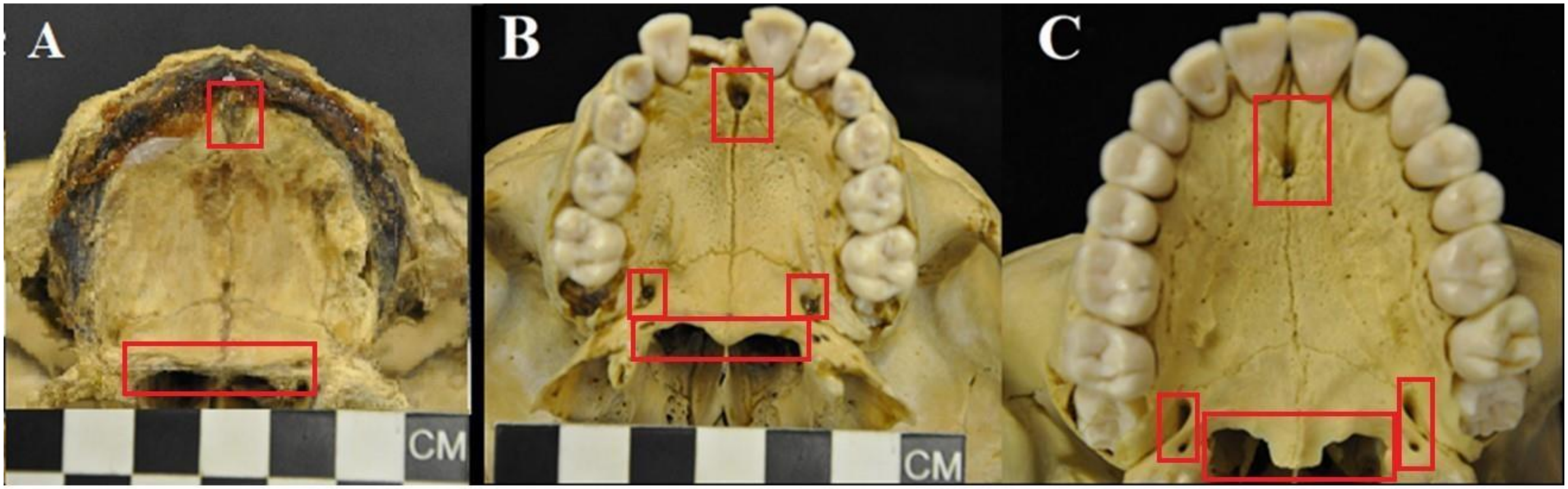


Figure 4: Oral surface of the immature human palate showing the general morphology. A: at birth; B: 10 years of age; C: 16 years of age. The figures are representative of the samples of the deciduous dentition group (A), the mixed dentition group (B) and the permanent dentition group (C) respectively. Red rectangles indicate areas of the palate with marked morphological changes.

3.1.2 Quantitative analysis of the palate

A high level of repeatability was observed across all measurements (height: 84%, width: 95.8%, length: 97.1%).

In the assessment of the overall change in the size and shape parameters of the palate, an increase in the size parameters was observed between the different states of the dentition (Table 2).

Table 2: Measurements (mean and standard deviation) of the palate according to the state of the dentition

	GROUP 1 (Deciduous dentition) n = 14	**GROUP 2** (Mixed dentition) n = 8	**GROUP 3** (Permanent dentition) n = 50	**Scheffe Post Hoc** *(P)*	
Measurements	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**	**Group 1 vs. 2**	**Group 2 vs. 3**
Width	26.26 (3.30)	31.70 (2.17)	38.83 (3.33)	0.001	0.001*
Height	3.02 (1.03)	4.60 (1.46)	7.75 (2.86)	0.366	0.006
Length	31.79 (3.24)	41.16 (2.71)	51.23 (4.37)	0.001*	0.001*
Geo_Mean	13.43 (2.38)	17.98 (1.87)	24.46 (4.22)	0.029	0.001*
MSV_W	1.99 (0.27)	1.78 (0.17)	1.64 (0.33)	0.303	0.495
MSV_H	0.22 (0.05)	0.25 (0.06)	0.31 (0.08)	0.571	0.146
MSV_L	2.42 (0.39)	2.31 (0.27)	2.16 (0.45)	0.846	0.640

*LENGTH, length of the palate; WIDTH, the width of the palate; HEIGHT, the height of the palate; Geo_Mean, geometric mean; MSV_L, Mosimann shape variable of the length of the palate; MSV_W, Mosimann shape variable of the width of the palate; MSV_H, Mosimann shape variable of the height of the palate. Scheffe Post Hoc p is significant at $p \leq 0.05$.*all indicated values of p were less than 0.001*

3.1.3 Size of the palate

The length and width measurements of the palate in the mixed dentition group were significantly larger ($p \leq 0.001$) when compared to the deciduous dentition group (Table 2). Similarly, the length and width measurements of the palate for the permanent dentition group were significantly larger ($p \leq 0.001$) than the mixed dentition group (Table 2) and thus, also larger than the deciduous dentition group. The height measurement of the permanent dentition group was significantly greater ($p \leq 0.006$) than that of the mixed dentition group. However, the difference in height between the mixed dentition and deciduous dentition was not statistically significant (Table 2). The geometric mean of the palate (geo_mean) was significantly greater when comparing the permanent dentition group to the mixed dentition group ($p \leq 0.029$) and when comparing the mixed dentition group to the deciduous dentition group ($p \leq 0.001$) (Table 2).

In determining the effect of each set of measurements on the variations in size observed in the sample by means of principal component analysis loading values, the length of the palate had the greatest influence, while the height of the palate had the smallest influence (Fig. 5).

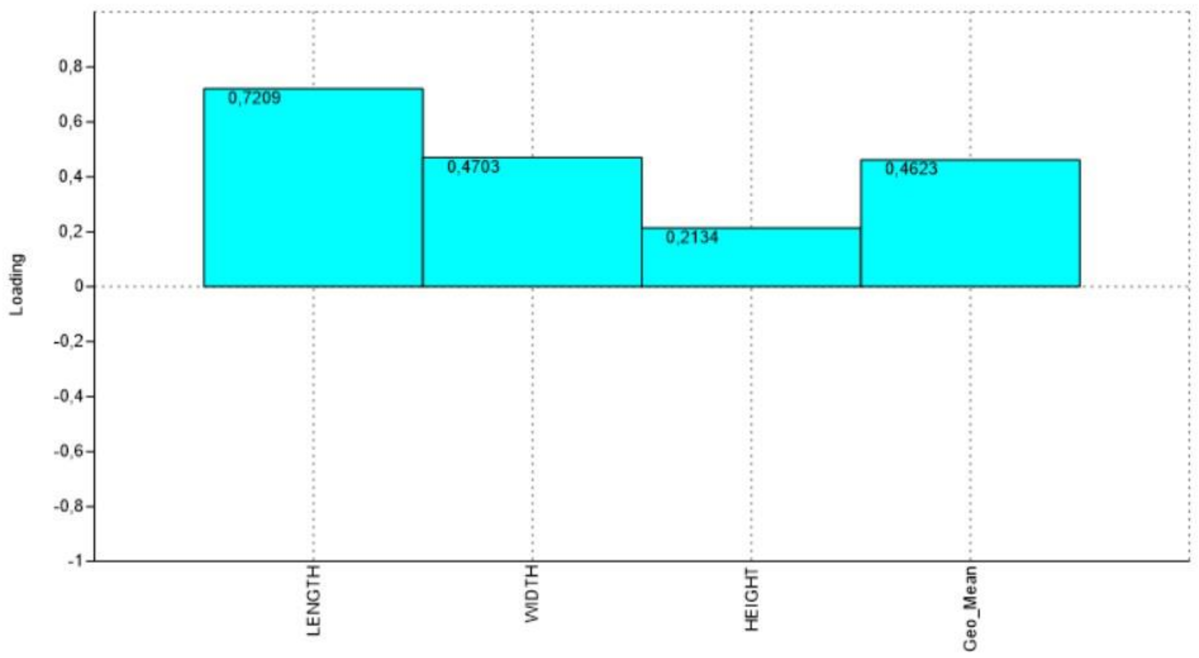


Figure 5: Principal component analysis (PCA) loading values indicating the influence of each set of variables and the geometric mean on the size variance of the palate.

The significant level of variance observed in terms of the length ($p \leq 0.001$), width ($p \leq 0.001$), and geo_mean ($p \leq 0.029$) when comparing the deciduous and mixed dentition groups (Table 2) was evident in the high degree of separation observed in the PCA between these groups (Fig. 6). While significant differences in the length ($p \leq 0.001$), width ($p \leq 0.001$), height ($p \leq 0.006$), and geo_mean ($p \leq 0.001$) were observed between the mixed and permanent dentition groups (Table 2), no significant level of variance was noted in the PCA between these groups (Fig. 6) as indicated by the degree of overlap observed between these groups (Fig. 6).

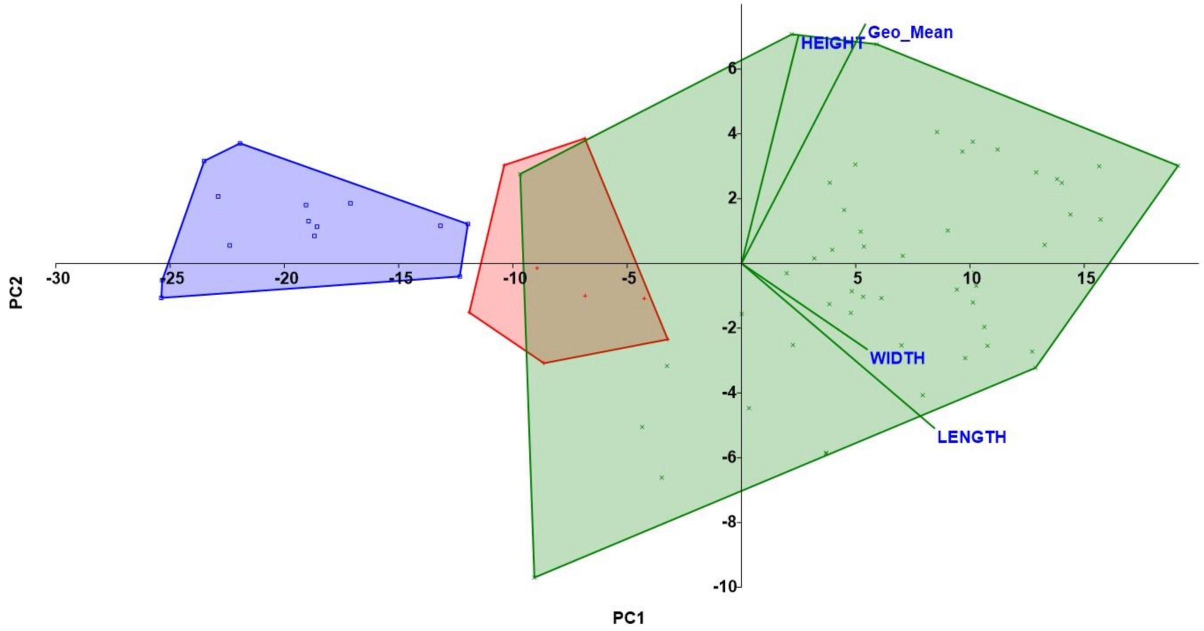


Figure 6: Principal component analysis (PCA) assessing the degree of variance in the size of the palate between the three states of the dentition: Group 1 (blue: deciduous dentition), group 2 (red: mixed dentition), group 3 (green: permanent dentition). Box plots illustrate the influence of each measurement and the geometric mean (Geo_Mean) on PC1 and PC2. In the PCA, an overlap of the group distribution map (coloured areas) indicates little to no variation between the represented groups, while a separation between groups indicates a high to moderate degree of variation which is proportional to the degree of separation between the represented groups.

3.1.4 Quantitative analysis of palatal shape

While a decrease in the parameters of the MSV_Length and the MSV_Width were observed between the different states of the dentition, an increase in MSV_Height occurred (Table 2). No statistically significant differences were found in the quantified shape parameters between the deciduous dentition group and the mixed dentition group, and between the mixed dentition group and permanent dentition group respectively (Table 2).

The MSV_Length of the palate had the greatest level of influence on the change in the palatal shape across the different states of the dentition, while the MSV_Height appeared to have the least level of influence (Fig. 7). A high degree of overlap between the different groups of the dentition in relation to the MSV_Length, MSV_Width and MSV_Height was observed, indicating no difference in terms of the quantified shape variance between the Mosimann shape variables (Fig. 8). The observed degree of overlap corresponds well with the absence of statistically significant differences between the Mosimann shape variables observed in the MANOVA assessment for shape (Table 2).

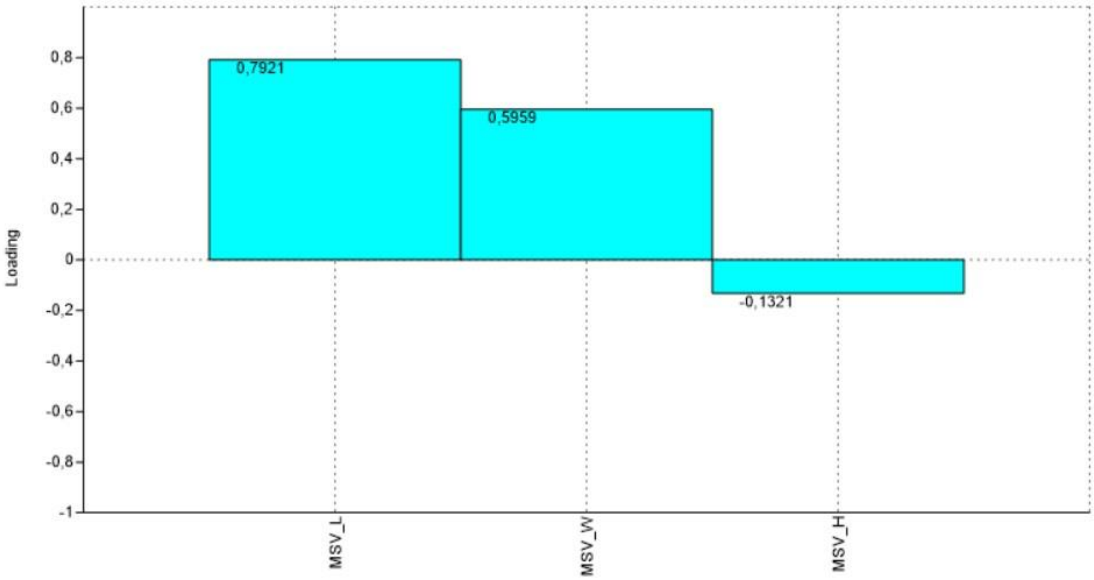


Figure 7: Principal component analysis (PCA) loading shape variables indicating the influence of the Mosimann variables on the shape variance of the palate. MSV_L, Mosimann shape variable of the length of the palate; MSV_W, Mosimann shape variable of the width of the palate; MSV_H, Mosimann shape variable of the height of the palate.

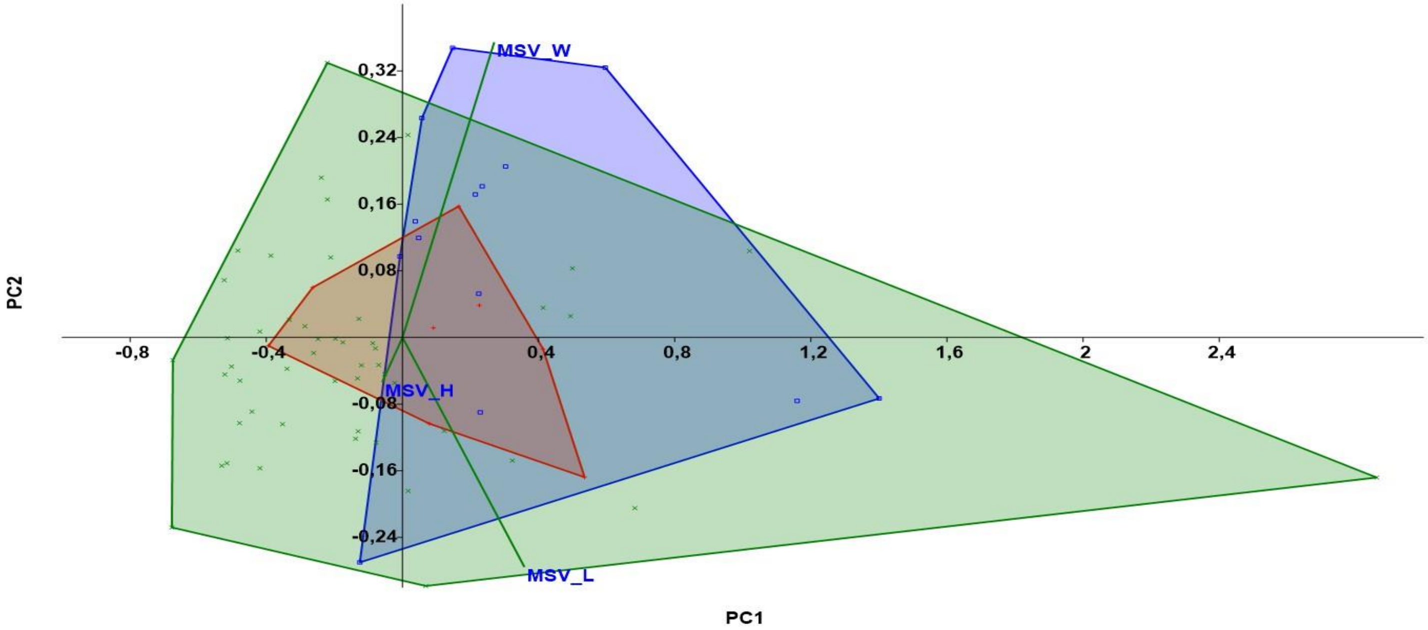


Figure 8: Principal component analysis (PCA) assessing the degree of shape variation of the palate across the different states of the dentition: Group 1(blue: deciduous dentition), group 2 (red: mixed dentition), group 3: permanent dentition). Box plots illustrate the effect of each Mosimann shape variable on PC1 and PC2. MSV_L, Mosimann shape variable of the length of the palate; MSV_W, Mosimann shape variable of the width of the palate; MSV_H, Mosimann shape variable of the height of the palate.

3.1.5 Qualitative analysis of palatal shape

On comparing the wireframes between the three dentition groups, the oral view of the palate shows that the left and right posterior alveolar regions (at LM6 and LM12 respectively) were directed towards the midline of the palate in the mixed dentition and permanent dentition groups (Fig. 9A). The medial orientation of the left and right alveolar regions towards the midline resulted in a narrower appearance of the wireframe of the palate in the permanent dentition group when compared to the mixed dentition and deciduous dentition groups respectively, as indicated by the distances between LM12 – LM6 and LM10 – LM8 (Fig. 9A). The palate was also observed to be longer along the median plane (distance between LM3 – LM9) in the permanent dentition group when compared to the deciduous and mixed dentition groups respectively (Fig. 9A). The long and narrow-looking palate of the permanent dentition group, resulted in a more acute angle anteriorly (LM8-LM9-LM10) and a protruded orale (LM9), when compared to the palate of the deciduous dentition group (Fig. 9A). In the posterior region of the permanent dentition group, an outward protrusion of the left and right postalverions (LM5 and LM13) was observed (Fig. 9A).

Shape changes in the posterior region of the palate such as the protrusion of the staphylion (LM3) were observed across the different states of the dentition (Fig. 9A). When comparing the posterior region (LM13-LM14-LM3-LM4-LM5) of the palate across each of the assessed dentition groups, particularly in the area of the posterior palatal indentation and staphylion in the deciduous dentition, a broad obtuse angle was observed relative to LM13-LM14-LM3 and LM3-LM4-LM5 on either side of the palatal spine. In the mixed dentition group the formation of bilateral indenting or curvature of the posterior region of the palate was observed at LM4 and LM14 respectively. The bilateral indenting was observed to be deeper in the permanent dentition group in comparison to the mixed dentition, and absent in the deciduous dentition group. As such a change in the obtuse angle of the bilateral indentations to an acute angle and a well defined "W" shape (LM13-LM14LM3-LM4-LM5) was observed at the posterior border of the palate in the permanent dentition group when compared to the palate of the deciduous dentition group (Fig. 9A).

When the wireframes were viewed from the lateral view, the height of the palate in the alveolar region was observed to have increased (LM13-LM3-LM5 and LM12-LM2-LM6) when the different dentition groups were compared (Fig. 9B). The observed increase in the height of the alveolar region in the lateral view of the wireframes as indicated at LM13-LM3-LM5 and LM12LM2-LM6 respectively, is associated with the more elevated roof of the palate in the permanent dentition group when compared to the mixed and deciduous dentition groups respectively (Fig.
9B).

From the posterior view of the wireframes (Fig. 9C), the roof of the palate changed from being flat in the deciduous dentition group (see line across the three groups indicated by: LM13-LM14-LM3LM4-LM5) to being deeper and forming a dome, as a marked elevation of LM14-LM3-LM4 was observed in the mixed and permanent dentition groups (Fig. 9C). The landmarks LM13 – LM14 and LM4 – LM5 respectively indicate a reorientation of the left and right alveolar regions from a horizontal orientation in the deciduous dentition group to a vertical orientation with a lateral inclination in the mixed and permanent dentition groups (Fig. 9C). The lateral divergence of the vertically oriented alveolar regions is associated with the observed significant increase in the width of the palate in the later dentition groups.

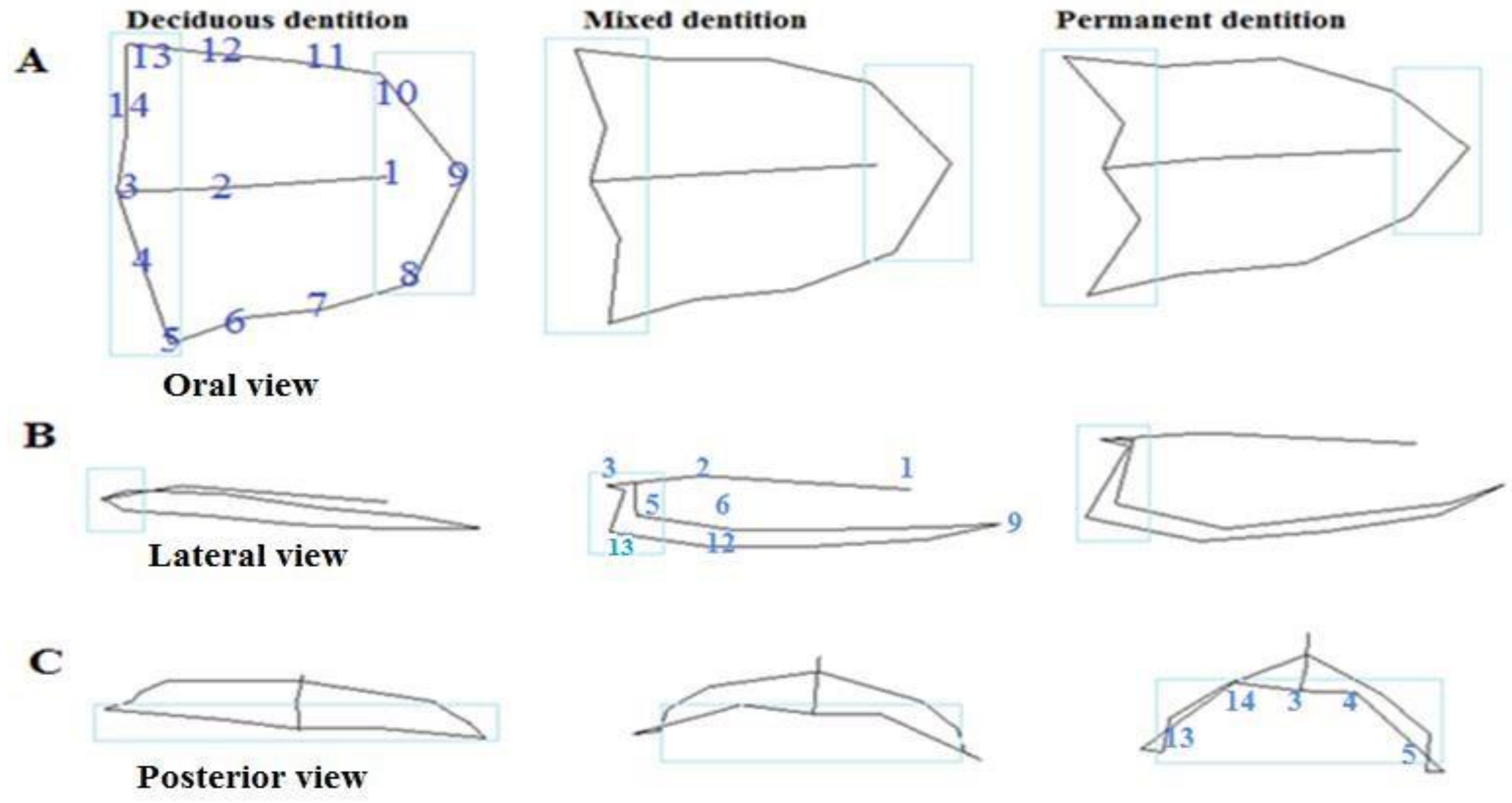


Figure 9: Wireframes illustrating the changes in the palatal shape between the varying stages of dental eruption and emergence. Oral view (A), illustrating the oral surface; lateral view (B), illustrating the right alveolar region and an overlapping of the left alveolar region; posterior view (C), illustrating the posterior region of the palate. Blue rectangles indicate areas of the palate with marked morphological changes. Numbers 1 – 14 indicates landmarks.

Chapter Four

4.1 Discussion

The development and growth of the palate is said to be a continuous process which is influenced by changes in the functional environment associated with the growth of the surrounding oral cavity structures (Cunningham *et al;* 2016; Li *et al;* 2017). This study investigated the morphological variations associated with the postnatal development and growth of the palate relative to the eruption and emergence of the maxillary dentition in immature, juvenile and subadult individuals. Significant changes in the shape and size of the palate were observed between the varying states of the dentition.

Changes were noted in the morphology of the palate such as the horseshoe-shape of the palate of the deciduous dentition group compared to a more oval-shaped palate in the later dentition groups, which may be due to an increase in the length and width of the palate in the posterior region. Studies by Yu *et al.* (2014) and Bushan *et al.* (2015) observed a distinct palatal spine due to lengthening of the palate in the mixed and permanent dentition groups. The increase in the length and width of the palate results in the oval-shape palate in the mixed dentition and permanent dentition groups (Yu *et al.*, 2014). The change in shape of the posterior palatal region from a relatively straight line to a bilaterally indented surface in the current study indicates that bone remodelling activities have occurred (Martinez-Maza *et al.*, 2013). Also in the current study, the more evident incisive suture and the posterior relocation of the incisive foramen may result from an increase in the size of the anterior alveolar region in the later dentition groups. (Yu *et al.*, 2014).

The palate was significantly longer in the permanent dentition group when compared to the mixed and deciduous dentition groups thus indicating growth of the palate across the different states of the dentition. The acute angulation of the anterior incisor region and the lengthening of the postalverions in the posterior region of the palate observed in this study, demonstrates the potential role of the permanent dentition in increasing the length of the palate through growth. The role of the eruption of the permanent dentition in the lengthening of the palate has been shown previously in children with delayed eruption of permanent teeth, who have shorter palatal lengths when compared to children with normal dental eruption patterns. (Suda *et al.,* 2002). Thus, eruption of the molar teeth and the transition from the deciduous dentition to the permanent dentition may lead to growth in the length of the palate. The biomechanical forces associated with the posterior movement of the molar teeth may stimulate osteoblasts to deposit bone in the posterior alveolar region, thus contributing to posterior growth and lengthening of the palate (Hesby *et al*., 2006). The forces of occlusion and increased masticatory activities which lead to movement of the molars in a posterior direction (Hesby *et al*., 2006) have also been shown to influence growth of the posterior palate.

The tongue has also been identified as playing a crucial role in craniofacial morphology (Fatima and Fida, 2019). During the stages of dental eruption, forces emanating from the tongue influence the reorientation of the maxillary incisors from a lingual to a more labial direction (Moss-Salentijn, 1997). This anterior orientation of the incisors as a result of an anterior drift of the anterior alveolar region may have contributed to the anterior palatal thrust (anterior palatal acute angulation) observed in this study. Increased bone mass which indicates bone remodelling has been observed in both the anterior (incisor region) and posterior (molar region) regions of the palate in the subadult stages of growth respectively (Martinez-Maza *et al.*, 2013). Thus, growth of the palate in response to mechanical pressure from the tongue on the anterior incisor region, and posterior movement of the molar teeth may be involved in the increase in the length of the palate.

In this study, the posterior palate of the permanent dentition group was significantly wider when compared to the palate of the deciduous and mixed dentition groups. The findings of the current study is consistent with that of Knott and Johnson (1970) and Amirabadi *et al.* (2018), who found increases in the posterior width of the palate in their respective samples of individuals aged between 5 – 18 years of age by measuring the inter-endomolar width (LM6 – LM12). Odajima (1990) observed a change in the dimension of the inter-endomolar palatal width up to the stage of the mixed dentition with no further significant increase thereafter. The findings of Odajima (1990) are in contrast with the current study which showed a significant increase in the palatal width between the mixed and permanent dentition groups. The increase in the inter-endomolar width of the palate coincides with the eruption of the permanent dentition and thus may trigger the widening of the alveolar region (Thilander, 2009; Amirabadi *et al.,* 2018). The alveolar region expands with the eruption of the permanent dentition, the teeth of which are larger in comparison to the deciduous dentition. The increase in the width and the divergence of the alveolar region laterally due to the eruption of the permanent dentition is responsible for the increase in the width of the palate in the later dentition groups. Thus the eruption of the permanent dentition contributes to the increase in width of the palate in the current study.

While the activities of the tongue have been identified in the lengthening of the palate, it may also be a significant factor in the growth of palatal width (Hesby *et al.,* 2006; Li *et al.,* 2016). The tongue may have contributed to the increase of the palatal width observed in this current study, as Li *et al* (2016) observed that the tongue creates a distortional force through suckling which coincides with the appearance of cartilage in the median palatal suture. This leads to growth at the median palatal suture and results in the expansion and growth in the width of the palate (Li *et al.,* 2016). Cases of aglossia and hypoglossia have been reported alongside an observed cleft of the palate and shortened or total absence of the soft palate (Rachmiel *et al.,* 1993; Mandai and Kinouchi, 2001; Salles *et al.,* 2008). An extremely high and narrow palate, malocclusion with bilateral buccal cross-bite and deep overbite, and receded facial growth with a short palate have been observed to be associated with aglossia (Rachmiel *et al.,* 1993; Salles *et al.,* 2008; Rasool *et al.,* 2009; Bommarito *et al.,* 2016; McMiken *et al.,* 2019). It is evident that the presence of the tongue is associated with the development and growth of the normal morphology of the palate, such as the increased width and length as opposed to the narrow and short palate in cases of aglossia (Rachmiel *et al.,* 1993; Rasool *et al.,* 2009; Bommarito *et al.,* 2016; McMiken *et al.,* 2019). The absence of the pressure created by the mechanical activity of the tongue which is associated with aglossia, results in the abnormal development of the oral cavity leading to the dysmorphology of the palate (Rachmiel *et al.,* 1993;

Rasool *et al.,* 2009; Bommarito *et al.*, 2016; McMiken *et al.*, 2019). Thus, forces emanating from the biomechanical activity of the tongue influence the increase in the length and width of the palate. The individual skeletal structures of the viscerocranium expand by growing at sutures due to growth of the associated organs with aging (Wei *et al.,* 2017). The expansion of the viscerocranium is characterised by the expansion of the body and the zygomatic process of the maxilla (Enlow, 1966), the anterior and lateral growth of the supraorbital regions, and the expansion and growth of the nasal regions. Thus, the growth of the viscerocranium may also influence growth in the length and width of the palate. As the supraorbital and nasal region grow anteriorly, they direct growth of the viscerocranium anteriorly. In order to achieve equilibrium of the craniofacial growth, the sphenoid bone moves posteriorly and apposition of new bone accrues in the posterior region of the maxillary tuberosity, which results in increasing the anterior-posterior dimension of the maxillary alveolar regions (Enlow and Bang, 1965; Wei *et al.*, 2017). The expansion of the zygomatic process of the maxilla also allows for bone growth in the lateral region of the palatine bone thus increasing the lateral dimension of the alveolar region and thus, increasing the palatal width. The growth processes involved in the expansion of the viscerocranium directly influence the increases in the anterior-posterior and lateral dimensions of the maxillary body and the alveolar region, which increase the length and width of the palate (Enlow and Bang, 1965). The increase of the alveolar region in its posterior direction is associated with the relocation of its resorptive surface towards the posterior direction of the maxilla, and thus termed "the concept of area relocation" (Enlow and Bang, 1965). The area relocation of the posterior alveolar region may indicate bone remodelling activity and the growth of the viscerocranium in the anterior-posterior dimension, which may also function to lengthen the palate.

A significant increase in the height of the palate was recorded in the permanent dentition when compared to the mixed dentition in the current study. Amirabadi *et al.* (2018) and Thilander (2009) observed an increase in the height of the palate in the mixed dentition and a subsequent increase in the permanent dentition. The increase in the height of the palate across the different states of the dentition may be attributed to the dental eruption which results in the growth of the alveolar bone inferiorly (Thilander, 2009). This is evident in the current study by observing the alteration of the palatal shape from the lateral view. The wireframes of the palate showed changes in shape morphology of the alveolar region from a horizontal orientation to a vertical orientation between the different states of the dentition. The change in shape of the alveolar region indicates growth of the alveolar region in an inferior direction and thus, increase in palatal height in the mixed and permanent dentition groups.

The palate forms both the roof of the oral cavity and the floor of the nasal cavity. Thus, growth and function of the nasal cavity during the stages of palatal development may also influence palatal morphology (Aziz *et al.,* 2015). Enlow (1966) postulated that growth in one region of the skull necessarily influences growth in other regions in order to maintain functional equilibrium. Thus, craniofacial skeletal growth is observed to be related across regions in structure and geometrics, and equilibrium growth is achieved if the regional structure and its counterpart structures grow to the same extent e.g. the oral cavity and the nasal cavity (Enlow and Bang, 1965). During the stages of postnatal development, deposits of new bone are accrued on the oral surface of the palate with corresponding bone removal from the nasal surface (Enlow and Bang, 1965). Thus, the expansion of the nasal cavity results in increase in the depth of the palatal dome while the eruption of teeth results in the growth of the alveolar region in an inferior direction (Enlow and Bang, 1965). This may also indicate the influence of the nasal cavity in the increase in height of the palate which is termed the “counterpart principle of craniofacial growth” by Enlow and Bang (1965). MossSalentijn (1997) suggested that breathing through the nose is crucial in the development of the craniofacial region. Baccetti *et al* (2001) were able to correlate growth of the palatal dimensions with the development of the nasal cavity during the stages of postnatal development and growth, and observed abnormally high depths of the palatal dome in individuals with nasal obstruction and a reduced nasal cavity. Nasal breathing may stimulate inferior growth of the palate, and the lateral expansion of the nasal cavity may stimulate growth of the maxilla, which will further lead to growth at the median palatal suture thus increasing the width of the palate (Enlow and Bang, 1965; Moss-Salentijn, 1997; Baccetti *et al.,* 2001).

The stages of dental development in humans are associated with an evolved feeding mechanism which is characterised by a shift from fluid-based feeding to a more solid-based feeding, with advancement in the muscles of mastication and swallowing (Li *et al.*, 2016). The swallowing mechanism in humans involves the functioning of the soft palate musculature which may influence growth in palatal dimensions and morphological shape changes (Li *et al.*, 2016). The levator veli palatini muscles of the soft palate elevate the palate, while the tensor veli palatini muscles aids the action of the levator veli palatini. The uvula also causes elevation to close off the naso-pharynx. Thus, the biomechanical pressure passed on to the palate by an upward pull of these muscles may result in an increase in the palatal height (Swartz *et al.*, 2012).

Alterations in craniofacial shape and reduced or abnormal cranial growth which result in a short and flat palate have been observed in individuals with craniofacial muscular abnormalities or degeneration (Sharir *et al.*, 2011). While the influence of the swallowing mechanism on the height of the palate has been identified from the activities of the soft palate musculature, the palatoglossus, palatopharyngeus and uvula muscles of the soft palate may also influence the increase in length and modification of the shape of the posterior palatal region. This can be understood by observing the actions of these muscles during swallowing, as the soft palate pulls the palate posteriorly towards the pharynx through the actions of the palatoglossus and palatopharygeus muscle. Thus, this posterior pull action of the soft palate musculature may stimulate the posterior appositional growth of the palate and result in lengthening of the palate. The uvula is also observed to cause lengthening of the posterior nasal spine (posterior palatal spine)
i.e. the point of the staphylion (LM3). The lengthening of the palate is indicated by the protrusion of the posterior palatal spine across the stages of dental eruption. The different shape patterns of the posterior alveolar region is an indication of alveolar growth in a posterior direction with increase in width. The posterior bilateral indentation of the palate ("W" shape) in the later dentition groups may be an indication of remodelling and growth in width resulting from the forces emanating from the soft palate musculature.

The muscles of the soft palate all originate from associated skeletal structures and insert into the palatal aponeurosis. However, in a cleft of the palate, the muscles insert into the posterior border of the hard palate which results in an abnormal muscular morphology, characterised by two bone attachments rather than one as is seen in the normal palate (Monroy *et al.*, 2012). This abnormal muscular attachment in cleft palate disrupts normal actions of soft palate musculature by restricting the isometric contractions. Thus the separated cleft palate is pulled laterally resulting in widening of the cleft and altering the height of the palate. This shows that abnormal development of the palatal morphology is correlated with the presence of abnormalities in dysfunction of the soft palate musculature, which may imply that normal palatal morphology may be influenced by the normal functioning of the soft palate musculature. However, no single oral structure or function in isolation can be said to influence the morphological variation of the palate. (Thilander, 2009; Sharir *et al.*,2011; Bommarito *et al.,* 2016; Amirabadi *et al.*, 2018; McMiken *et al.,* 2019).

4.2 Limitations

The nature of this study (cross-sectional) is considered a limitation as it restricts the extrapolations which can be made. This study was conducted on a limited sample of maxillae of South African individuals in the Raymond A Dart human skeletal collection within the School of Anatomical Sciences at the University of the Witwatersrand. Increasing the sample size may be of benefit to the study.

4.3 Conclusion.

Significant morphological changes were observed in the palate between the different states of the dentition, indicating that these changes may be progressive with dental eruption and development. By establishing the influence of the oral activities on the morphological variations and postnatal development of the palate during the stages of dental eruption and development, the diagnosis of abnormalities in the postnatal development of the palate is possible in other fields of dentistry and, can be applied in craniofacial rehabilitation.

Chapter Five

5.0 References

Alhadlaq A. (2010). Anterior alveolar dimensions among different classifications of sagittal jaw relationship in Saudi subjects. *Saudi Dent J*. 22(2):69-75.

Allan J, Kramer B. (2002). The Fundamentals of Human Embryology. *Second edition. Wits University Press.*

Almonaitiene R, Balciuniene I, Tutkuviene J. (2010). Factors influencing permanent teeth eruption: Part one – general factors. *Stomatologija, Baltic Dental and Maxillofacial Journal.* 12, 67 – 72.

Al-Shahrani I, Dirks W, Jepson N, Khalaf K. (2014). 3D-Geomorphometrics tooth shape analysis in hypodontia. *Frontiers in Physiology*, *5,* 154.

Alqahtani SJ, Hector MP, Liversidge HM. (2010). Brief communication: The London atlas of human tooth development and eruption. *Am J Phys Anthropol*. 142, 481 – 490.

Amirabadi GE, Golsha A, Derakhshn S, Khandan S, Saeidipour M, Nikkerdar N. (2018). Palatal dimensions at different stages of dentition in 5 to 18-year-old Iranian children and adolescent with normal occlusion. *BMC Oral Health.* 18, 87.

Aziz1 E, Ansari K, Lagravere1 MO, Major MP, Flores-Mir C. (2015). Effect of non-surgical maxillary expansion on the nasal septum deviation: a systematic review. *Progress in Orthodontics.* 16, 15.

Baccetti T, Franch L, Cameron CG, McNamara Jr JA. (2001). Treatment timing for rapid maxillary expansion. *Angle Orthod.* 71 (5), 343 - 343

Bhushan R, Kumar S, Chauhan AK, Mohan S, Shekhar M, Naronly A. (2015). Assessment of the relationship between maxillary rotation and nasal morphology in males. *Contemp Clin Dent.* 6(1), 12 – 17.

Bommarito S, Zanato LE, Viera MM, Angelieri F. (2016). Aglossia: Case Report. *Int Arch Otorhinolaryngol* 20, 87–92.

Carter GA, McNamara JA. (1998). Longitudinal dental arch changes in adults. *Am J Orthod Dentofac Orthop*. 114, 88–99

Chang HW, Huang HL, Yu JH, Hsu JT, Li YF, Wu YF. (2012). Effects of orthodontic tooth movement on alveolar bone density. *Clin Oral Investig*, 16(3), 679–688.

Chovaloupou ME, Efstratios D, Valakos, Manolis SK. (2013). Sex determination by threedimensional geometricmorphometrics of the palate and cranial base. *J. Biol. Clinic. Anthrop.* 70 (4), 407 – 425.

Cordeiro BA, Stefani FM, Goldfeder EM. (2015). Study of the correlation between the linear measurements of the skull and face and palatal wide and length measures. *Codas* 27 (5), 472 – 477.

Crane JL, Cao X. (2014). Function of matrix IGF-1 in coupling bone resorption and formation. *J Mol Med* 92, 107–115.

Cunningham C, Scheuer L, Blacks S. (2016). Developmental juvenile osteology (2^{nd} edition). *Academic Press Publication.*

Drachman DB, Banker BQ. (1964). Arthrogryposis multiplex congenital. *Arch Neuro,* 5, 77 – 93.

Enlow DH. (1966). A morphogenetic analysis of facial growth. *Am. J. Orthodontics.* 52 (4), 283 - 299.

Enlow DH, Bang S. (1965) Growth and remodeling of the human maxilla. *Am.J. Orthod.,* 51:446464.

Ekstrand KR, Christiansen J, Christiansen ME. (2003). Time and duration of eruption of first and second permanent molars: a longitudinal investigation. *Community Dent Oral Epidemiol*. 31, 344350

Fatima F, Fida M. (2019). The assessment of resting tongue posture in different sagittal skeletal patterns. *Dental Press J Orthod.* 24 (3), 55-63.

Fish JL. (2019). Evolvability of the vertebrate craniofacial skeleton. *Seminars in Cell & Developmental Biology*. Academic Press, 91, 13–22.

Ghislanzoni LH, Lione R, Cozza P, Franchi L. (2017). Measuring 3D shape in orthodontics through geometric morphometrics. *Progress in Orthodontics.* 18, 38.

Herring SW. (1985) The ontogeny of mammalian mastication. *Amer. Zool.,*25, 339 - 349.

Hesby RM, Marshall SD, Dawson DV, Southard KA, Casco JS, Franciscus RG, Southard TE. (2006). Transverse skeletal and dentoalveolar changes during growth. *Am J. Orthod and Dentofacial Orthop.* 130 (6), 721 - 731.

Humprey TA. (1971). Development of oral and facial motor mechanism in human fetuses and their relationship to craniofacial growth. *J Dent Res.* 50(6),1428 - 1441.

Hutchinson EF, Farella M, Kramer B. (2015). Importance of teeth in maintaining the morphology of the adult mandible in humans. *Eur J Oral Sci.* 123, 341 - 349.

Hutchinson EF, Farella M, Hoffman J, Kramer B. (2017). Variations in bone density across the body of the immature human mandible. *Journal of Anatomy*, *230*, 679–688.

Kaczmarek M. (1994). Variation in eruption sequence of permanent teeth in polish children. *Auxology'94 Humanbiol. Budapest*. 349-58.

Klingenberg CP. (2016). Size, shape, and form: concepts of allometry in geometric morphometrics. *Development Genes and Evolution, 226,113 - 137.*

Knott VB, Johnson R. (1970) Height and shape of the palate in girls. A longitudinal study. *Arch Oral Biol.*15(9):849 - 60.

Langdahl B, Ferrari S, Dempster DW. (2016). Bone modeling and remodeling: potential as therapeutic targets for the treatment of osteoporosis. *Ther Adv Musculoskelet Dis.* 8 (9), 2250 - 235.

Le Reverend GJD, Edelson LR, Loret C. (2014). Anatomical, functional, physiological and behavioural aspects of the development of mastication in early childhood. *British Journal of Nutrition*. 111, 403–414

Li J, Johnson CA, Smith AA, Hunter DJ, Singh G, Brunski JB, Helms JA. (2016). Linking suckling biomechanics to the development of the palate. *Scientific Reports*, *6*, 20419.

Mandai H, Kinouchi K. (2001). Perioperative management of a neonate with aglossia-adactylia syndrome. *Masui.* 50 (7), 773 - 775.

Martinez-Maza C, Rosas A, Nieto-Diaz M. (2013). Postnatal changes in the growth dynamics of the human face revealed from bone modelling patterns. *J Anat.* 223 (3), 228 - 41.

McMiken B, Vento-Wilson M, Warden M, Hall M, Rogers K. (2016). A child with congenital aglossia: a narrative review and descriptive case study. *Sage Open.* 9, 1 - 11.

Mitteroecker P, Gunz P. (2009). Advances in geometric morphometrics. *Evol Biol* 36, 235–247.

Monroy PLC, Grefte S, Kuijpers-Jagtman AM, Wagener FA, Von den Hoff JW. (2012). Strategies to improve regeneration of the soft palate muscles after cleft palate repair. *Tissue Eng Part B Rev.* 18 (6), 468 - 477.

Moss-Salentijn L. (1997). Melvin L. Moss and the functional matrix. *J Dent Res*. 76 (12):18141817

Moyers RE, van der Linden FPGM, Riolo ML, McNamara JA Jr. (1976). Standards of human occlusal development. *Ann Arbor, Mich: Center for Human Growth and Development, University of Michigan. Craniofacial Growth Series, Monograph 5*

Mu L, Chen J, Li J, Fowkes M, Benson B, Nyirenda T, Sobotka S, Christopherson M, Sanders I. (2021). Innervation of human soft palate muscles. *Anat Rec.* 304, 1054–1070

Nystrom M, Kleemola-Kujala E, Evalahti M, Peck L, Kataja M. (2001). Emergence of permanent teeth and dental age in a series of Finns. *Acta Odontol Scand* 59,49-56

Odajima TA. (1990) Longitudinal study on growth and development of dental arches of primary, mixed and permanent dentitions. *Shikwa Gakulho*.90(3), 369–409.

Rachmiel A, Jackson IT, Sabapathy SR, Forte RA. (1993). Severe congenital hypoplasia of tongue and abnormal shape of soft palate and tonsillar pillars. *Eur J Plast Surg* 16,149-153

Rasool A, Zaroo MI, Wani AH, Darzi MA, Bashir SA, Bijli AH, Rashid S. (2009). Isolated aglossia in a six year old child presenting with impaired speech: a case report. *Cases J.* 2, 7926.

Ross-Powel RE, Harris EF. (2000). Growth of the anterior dental arch in black American children: a longitudinal study from 3 to 18 years of age. *Am J Orthod Dentofac Orthop*. 118, 649–57

Salles F, Anchieta M, Bezerra PC, Lucia M, Torres, Queiroz E, Faber J. (2008). Complete and isolated congenital aglossia: case report and treatment of sequelae using rapid prototyping models. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod.* 105 (3), 41 - 47.

Seeman E. (2009). Bone modeling and remodeling. *Critical Reviews™ in Eukaryotic Gene Expression.* 19 (3), 219 - 233.

Setiawati R, Rahardjo P. (2018). Osteogenesis and bone regeneration. Bone development and growth. *Intechopen.*

Sharir M, Stern T, Rot C, Ron Shahar R, Zelzer E. (2011). Muscle force regulates bone shaping for optimal load-bearing capacity during embryogenesis. *Development*. 138 (15), 3247-3259

Singh I. (2018.) Human embryology (11th edition). *Jaypee Brothers Medical Publishers*.

Small C, Brits D, Hemingway J. (2016). Assessing the effects of tooth loss in adult crania using geometric morphometrics. *Int. J legal med.* 130, 233 - 243.

Sperber GH, Sperber SM, Guttmann GD. (2010). Craniofacial embryogenetics and development (2nd edition). *People's Medical Publishing House* USA, Shelton, CT.

Suda N, Hiyama S, Kuroda T. (2002). Relationship between formation/ eruption of maxillary teeth and skeletal pattern of maxilla. *Am J Orthod Dentofacial Orthop.* 121, 46 - 52.

Swartz ME, Sheehan-Rooney K, Michael J. Dixon MJ, Eberhart JK. (2011). Examination of a palatogenic gene program in zebrafish. *Dev Dyn*. 2011 September; 240(9): 2204–2220.

Thilander B. (2009). Dentoalveolar development in subjects with normal occlusion. A longitudinal study between the ages of 5 and 31 years. *Eur J Orthod.* 31:109–20

Van der Linden FPGM. (1983). Development of the dentition. *Chicago: Quintessence*.

Van der Linden FPGM. (1989). Facial growth and facial orthopedics. *Chicago: Quintessence*. 148–52

Wei X, Thomas N, Hatch NE, Hu M and Liu F. (2017). Postnatal craniofacial skeletal development of female C57BL/6NCrl Mice. *Front. Physiol*. 8:697

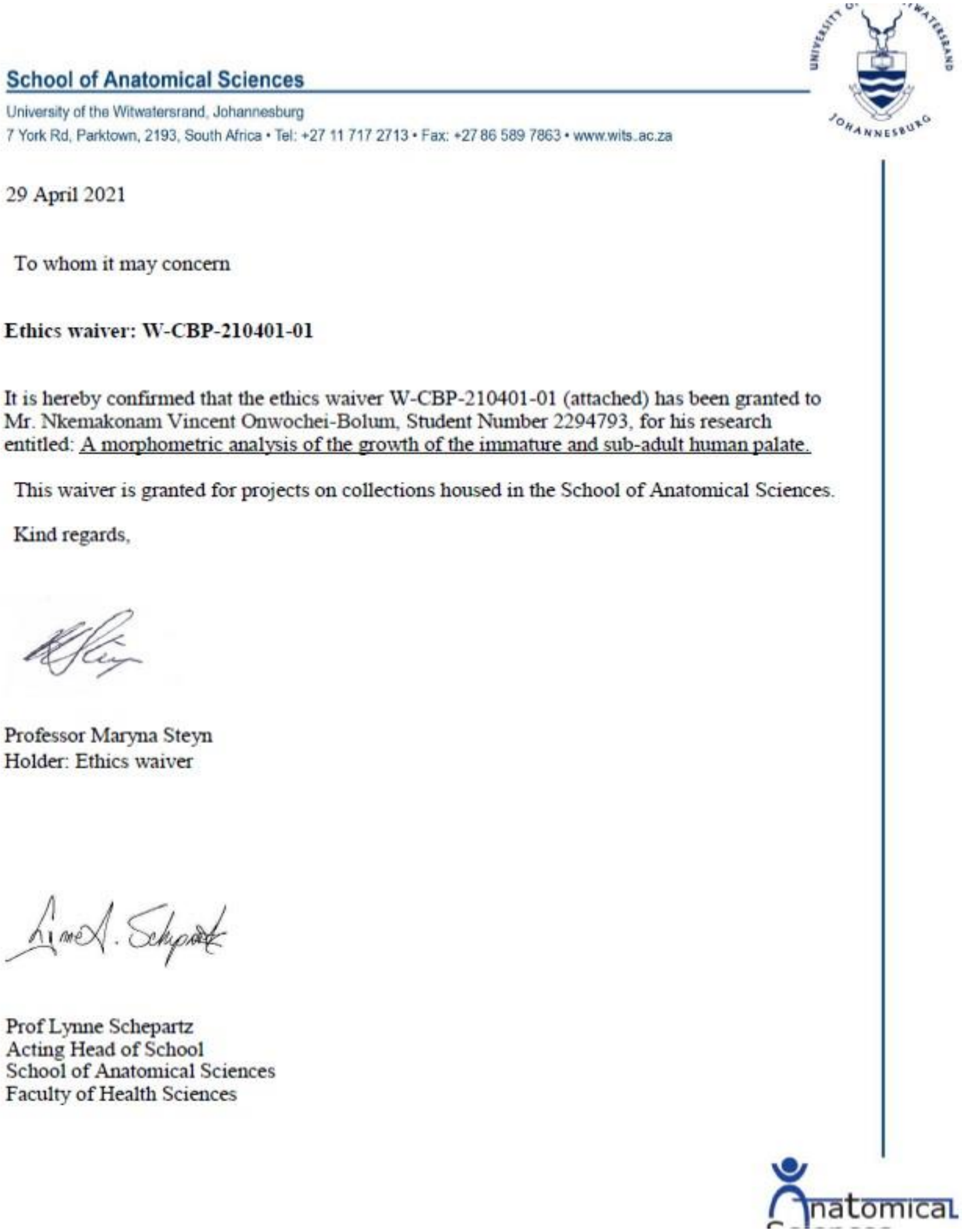
Wise GE, He H, Gutierrez DL, Ring S, Yao S. (2012). Requirement of alveolar bone formation for eruption of rat molars. *European Journal of Oral Science*, *119*(5), 333–338.

Wise GE, King GJ. (2008). Mechanisms of tooth eruption and orthodontic tooth movement. *Journal of Dental Research*, *87*(5), 414–434.

Yu SK, Lee MH, Park BS, Jeon YH, Chung YY, Kim HJ. (2014). Topographical relationship of the greater palatine artery and the palatal spine. Significance for periodontal surgery. *J Clin Periodontol* 41, 908–913.

Appendix I

Ethics waiver letter and certificate



School of Anatomical Sciences
University of the Witwatersrand, Johannesburg
7 York Rd, Parktown, 2193, South Africa • Tel: +27 11 717 2713 • Fax: +27 86 589 7863 • www.wits.ac.za

29 April 2021

To whom it may concern

Ethics waiver: W-CBP-210401-01

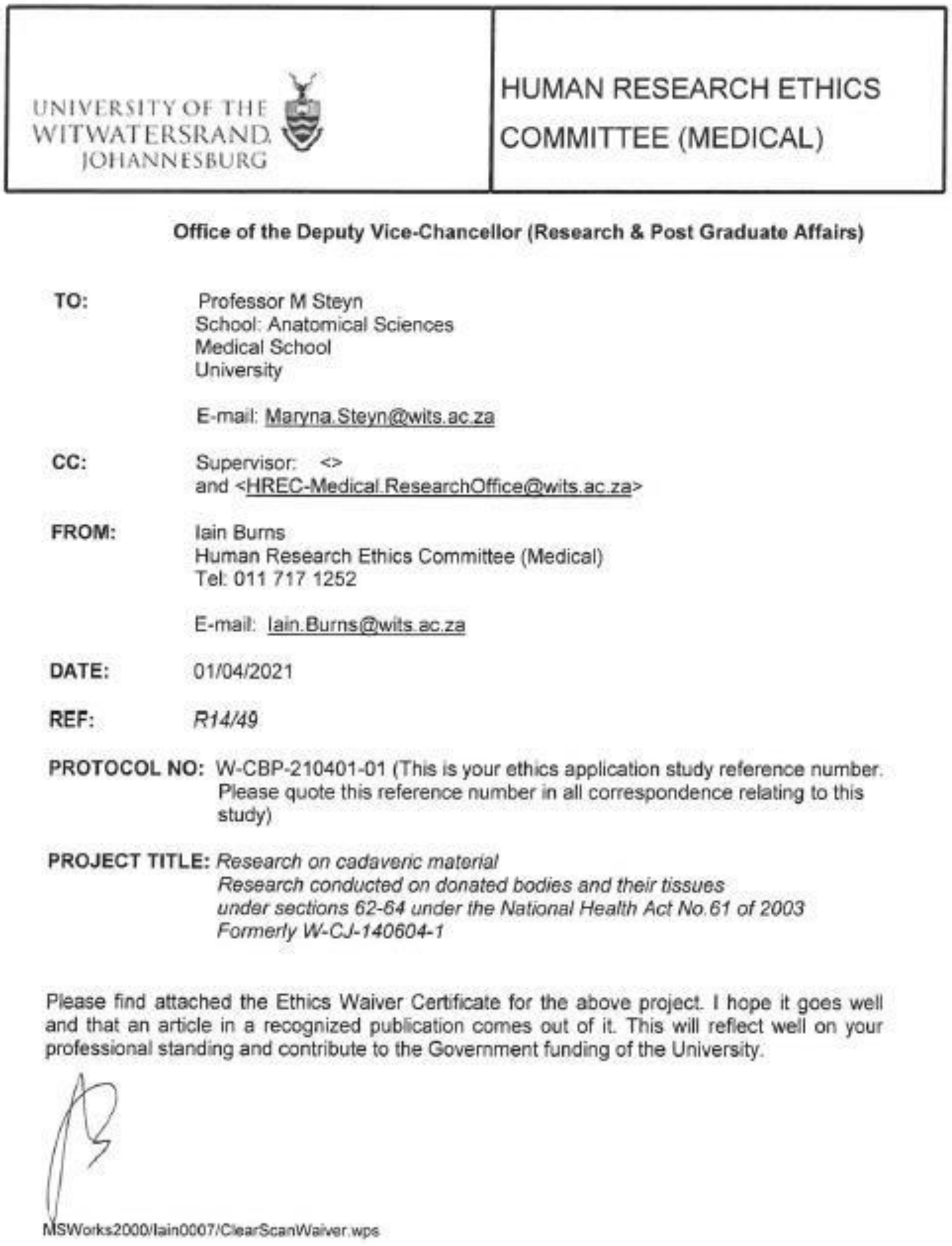
It is hereby confirmed that the ethics waiver W-CBP-210401-01 (attached) has been granted to Mr. Nkemakonam Vincent Onwochei-Bolum, Student Number 2294793, for his research entitled: A morphometric analysis of the growth of the immature and sub-adult human palate.

This waiver is granted for projects on collections housed in the School of Anatomical Sciences.

Kind regards,

Professor Maryna Steyn
Holder: Ethics waiver

Prof Lynne Schepartz
Acting Head of School
School of Anatomical Sciences
Faculty of Health Sciences



UNIVERSITY OF THE
WITWATERSRAND
JOHANNESBURG

HUMAN RESEARCH ETHICS COMMITTEE (MEDICAL)

Office of the Deputy Vice-Chancellor (Research & Post Graduate Affairs)

TO: Professor M Steyn
School: Anatomical Sciences
Medical School
University

E-mail: Maryna.Steyn@wits.ac.za

CC: Supervisor: <>
and <HREC-Medical.ResearchOffice@wits.ac.za>

FROM: Iain Burns
Human Research Ethics Committee (Medical)
Tel: 011 717 1252

E-mail: Iain.Burns@wits.ac.za

DATE: 01/04/2021

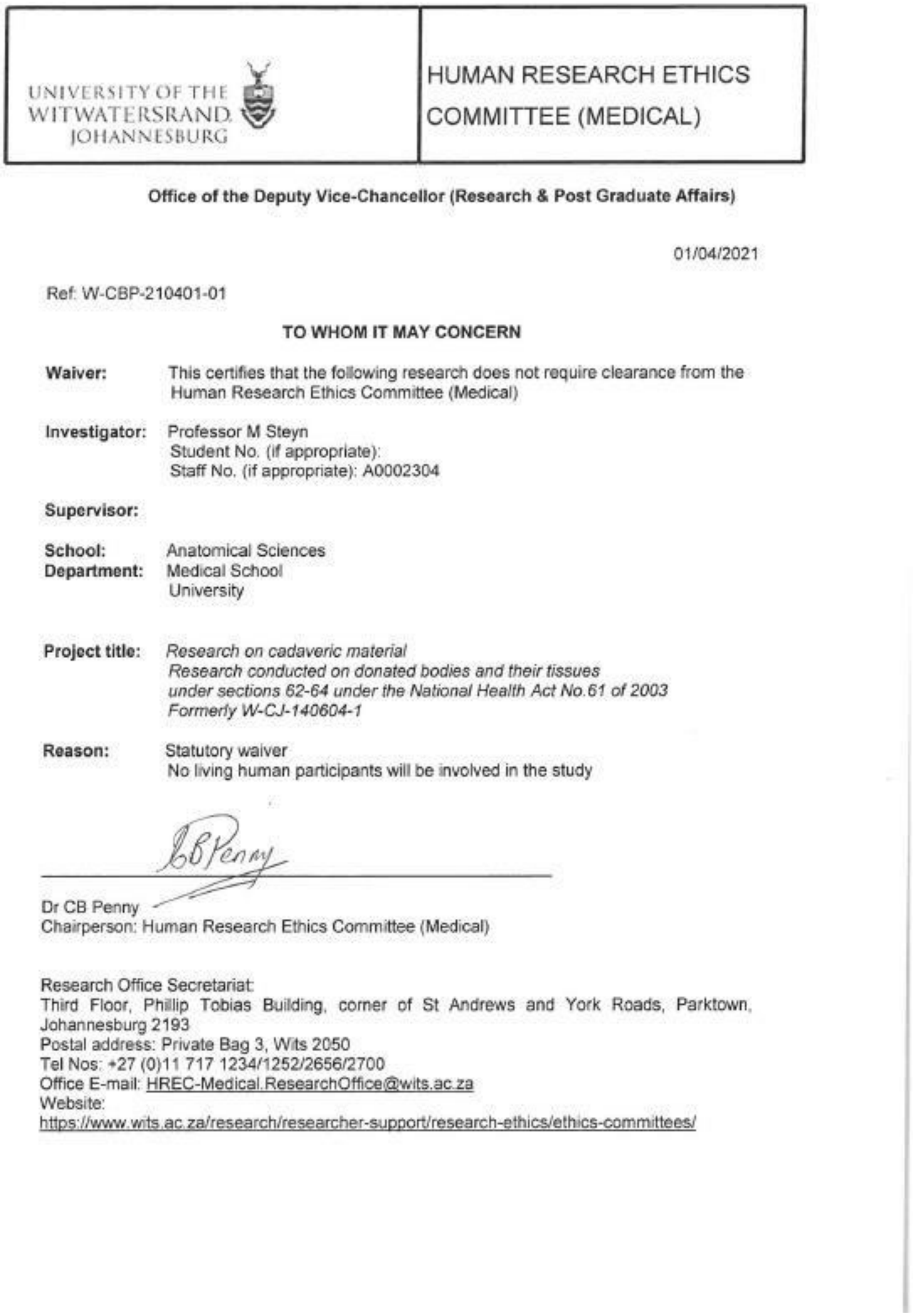
REF: *R14/49*

PROTOCOL NO: W-CBP-210401-01 (This is your ethics application study reference number. Please quote this reference number in all correspondence relating to this study)

PROJECT TITLE: *Research on cadaveric material*
Research conducted on donated bodies and their tissues
under sections 62-64 under the National Health Act No.61 of 2003
Formerly W-CJ-140604-1

Please find attached the Ethics Waiver Certificate for the above project. I hope it goes well and that an article in a recognized publication comes out of it. This will reflect well on your professional standing and contribute to the Government funding of the University.

MSWorks2000/Iain0007/ClearScanWaiver.wps



UNIVERSITY OF THE
WITWATERSRAND,
JOHANNESBURG

HUMAN RESEARCH ETHICS
COMMITTEE (MEDICAL)

Office of the Deputy Vice-Chancellor (Research & Post Graduate Affairs)

01/04/2021

Ref: W-CBP-210401-01

TO WHOM IT MAY CONCERN

Waiver:	This certifies that the following research does not require clearance from the Human Research Ethics Committee (Medical)
Investigator:	Professor M Steyn Student No. (if appropriate): Staff No. (if appropriate): A0002304
Supervisor:	
School: **Department:**	Anatomical Sciences Medical School University
Project title:	*Research on cadaveric material* *Research conducted on donated bodies and their tissues under sections 62-64 under the National Health Act No.61 of 2003* *Formerly W-CJ-140604-1*
Reason:	Statutory waiver No living human participants will be involved in the study

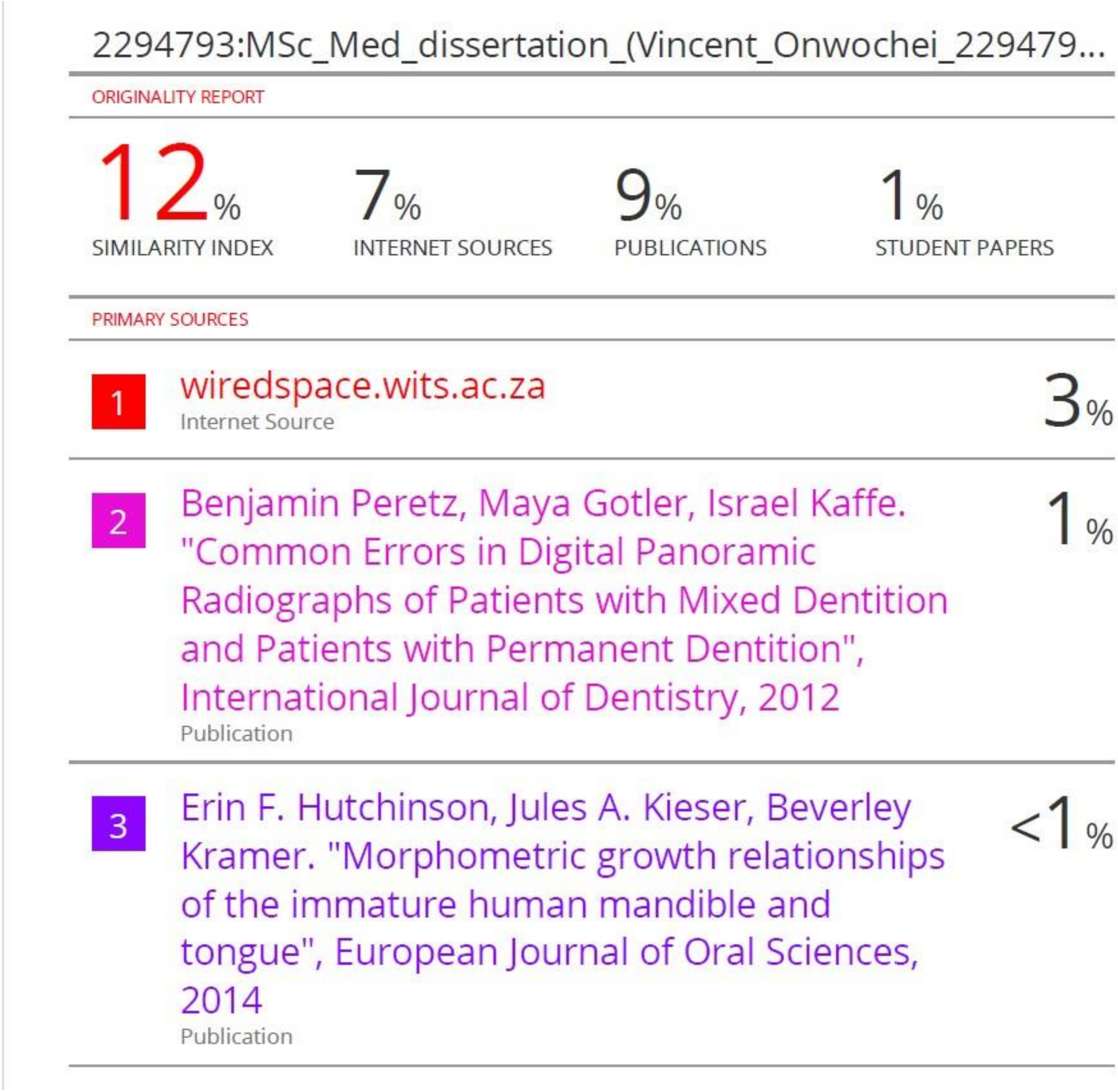
CB Penny

Dr CB Penny
Chairperson: Human Research Ethics Committee (Medical)

Research Office Secretariat:
Third Floor, Phillip Tobias Building, corner of St Andrews and York Roads, Parktown, Johannesburg 2193
Postal address: Private Bag 3, Wits 2050
Tel Nos: +27 (0)11 717 1234/1252/2656/2700
Office E-mail: HREC-Medical.ResearchOffice@wits.ac.za
Website:
https://www.wits.ac.za/research/researcher-support/research-ethics/ethics-committees/

Appendix II

Similarity index report



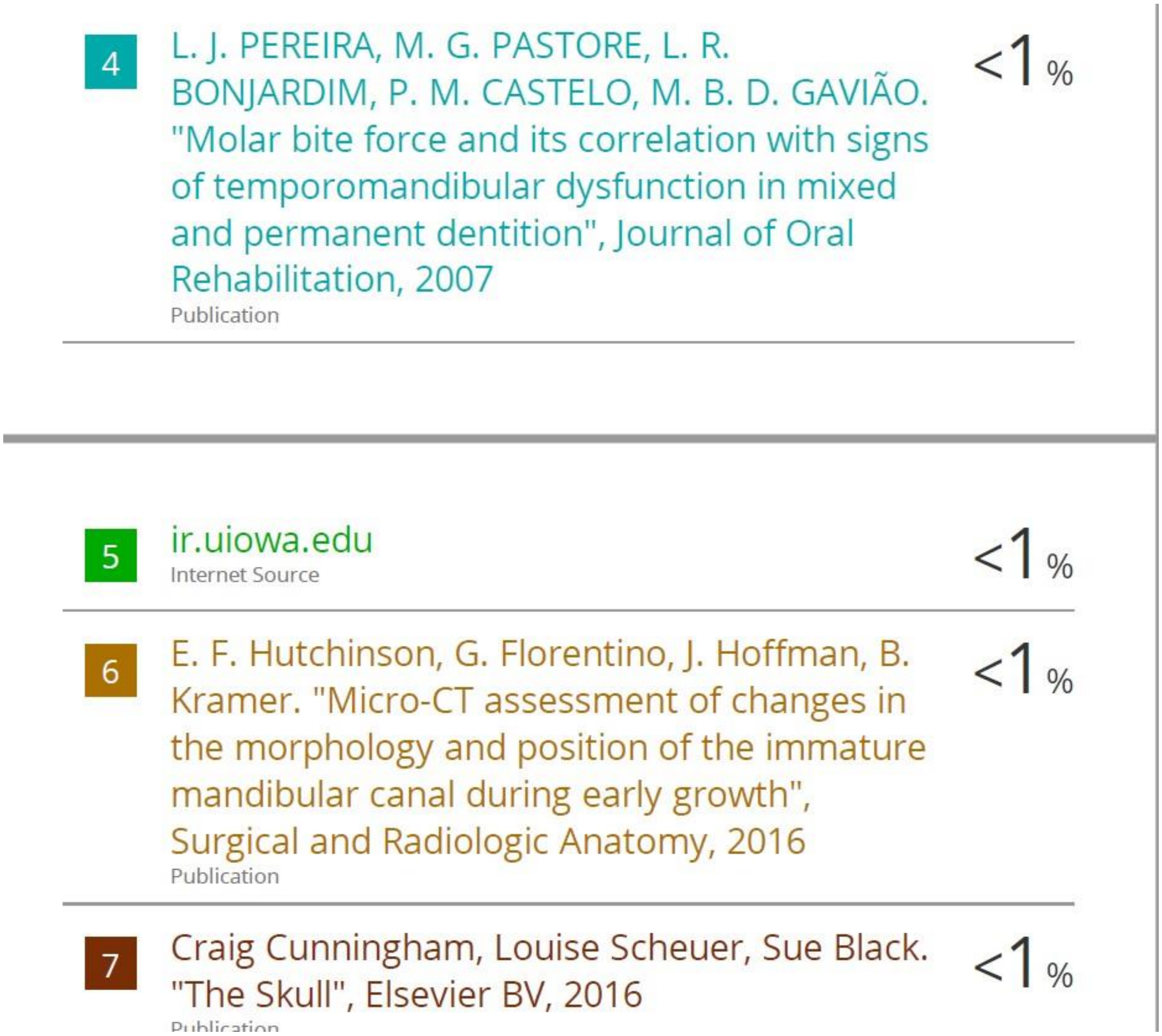
2294793:MSc_Med_dissertation_(Vincent_Onwochei_229479...

ORIGINALITY REPORT

12%	7%	9%	1%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

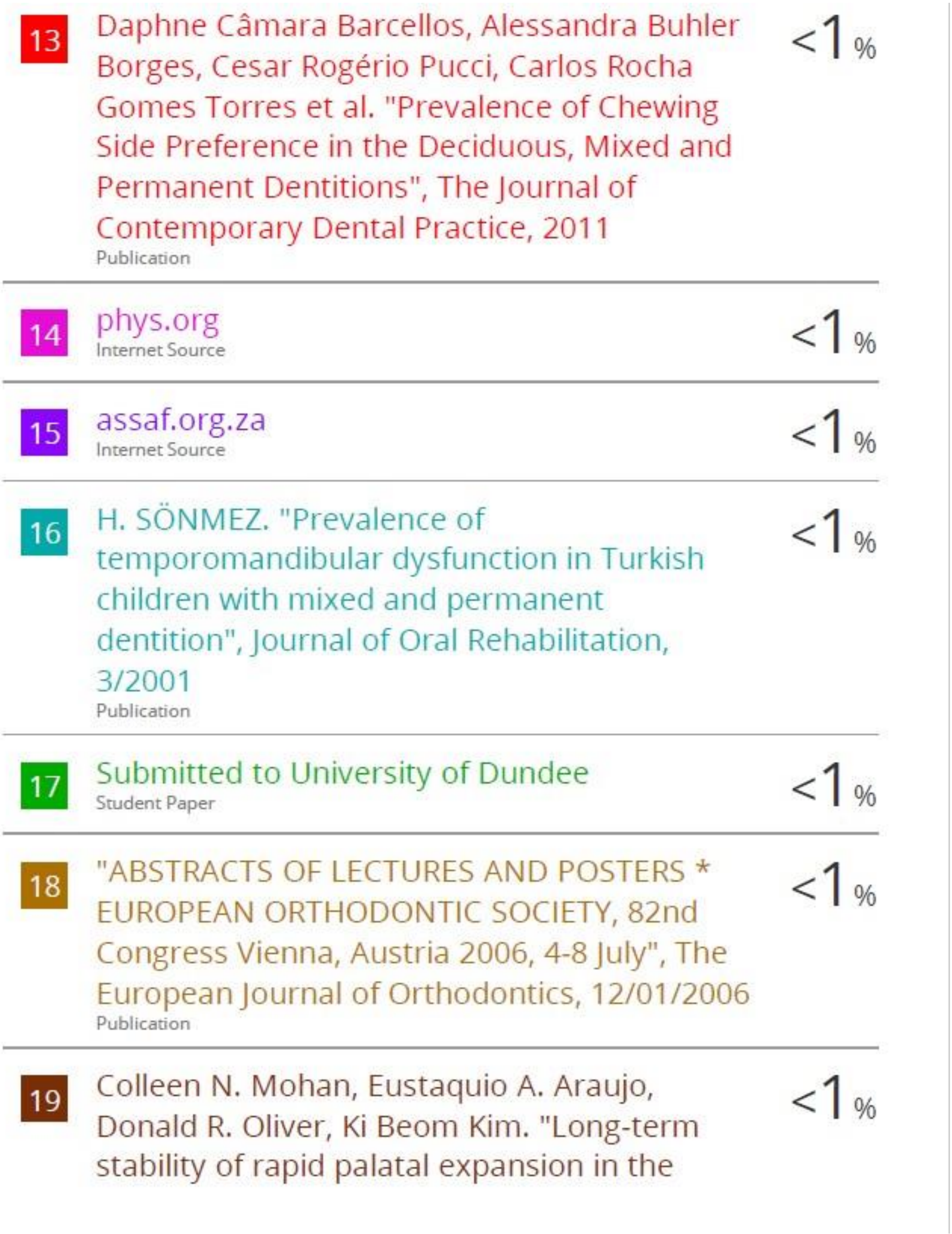
PRIMARY SOURCES

1	wiredspace.wits.ac.za Internet Source	3%
2	Benjamin Peretz, Maya Gotler, Israel Kaffe. "Common Errors in Digital Panoramic Radiographs of Patients with Mixed Dentition and Patients with Permanent Dentition", International Journal of Dentistry, 2012 Publication	1%
3	Erin F. Hutchinson, Jules A. Kieser, Beverley Kramer. "Morphometric growth relationships of the immature human mandible and tongue", European Journal of Oral Sciences, 2014 Publication	<1%

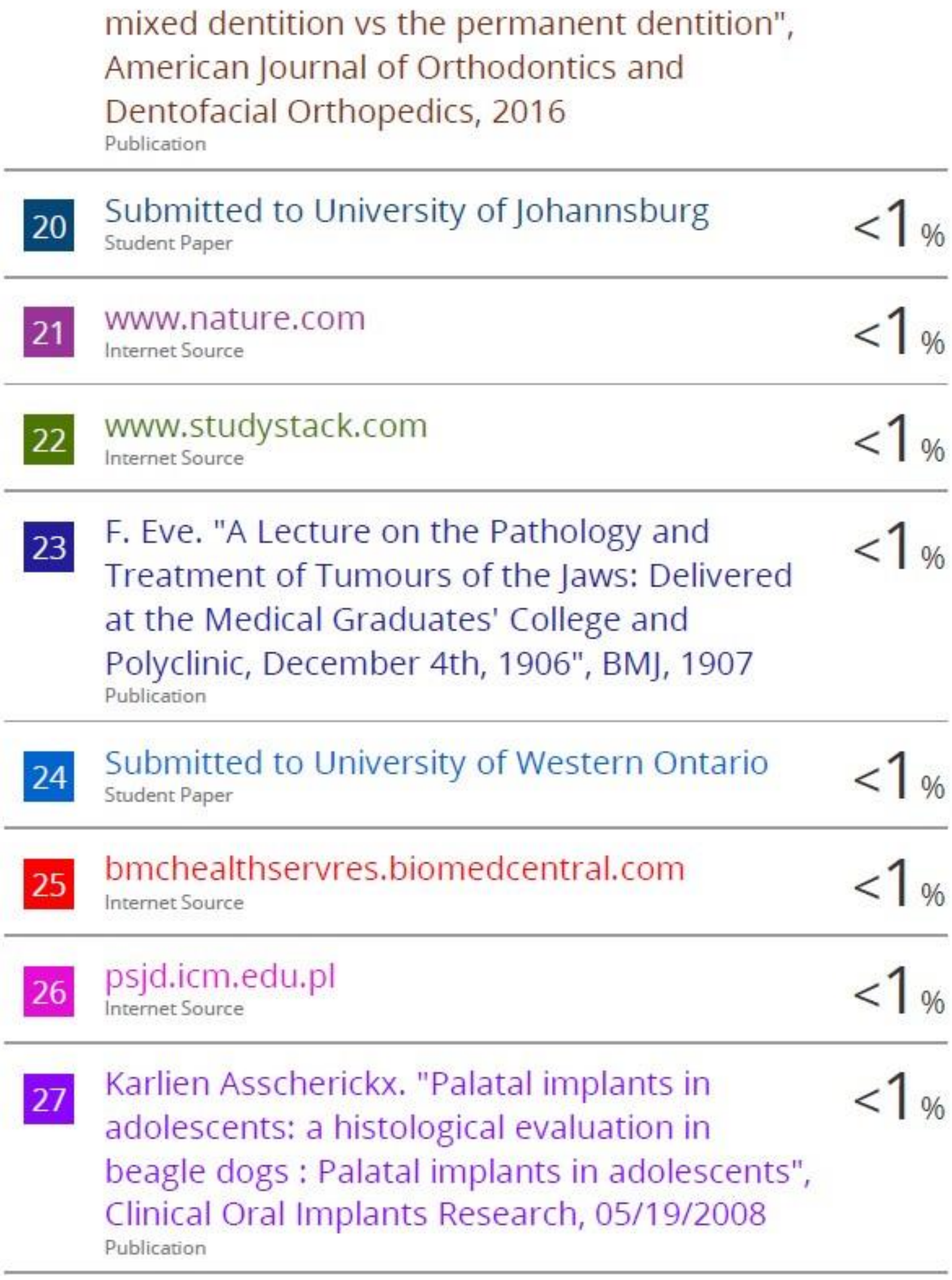


4	L. J. PEREIRA, M. G. PASTORE, L. R. BONJARDIM, P. M. CASTELO, M. B. D. GAVIÃO. "Molar bite force and its correlation with signs of temporomandibular dysfunction in mixed and permanent dentition", Journal of Oral Rehabilitation, 2007 Publication	<1 %
5	ir.uiowa.edu Internet Source	<1 %
6	E. F. Hutchinson, G. Florentino, J. Hoffman, B. Kramer. "Micro-CT assessment of changes in the morphology and position of the immature mandibular canal during early growth", Surgical and Radiologic Anatomy, 2016 Publication	<1 %
7	Craig Cunningham, Louise Scheuer, Sue Black. "The Skull", Elsevier BV, 2016 Publication	<1 %

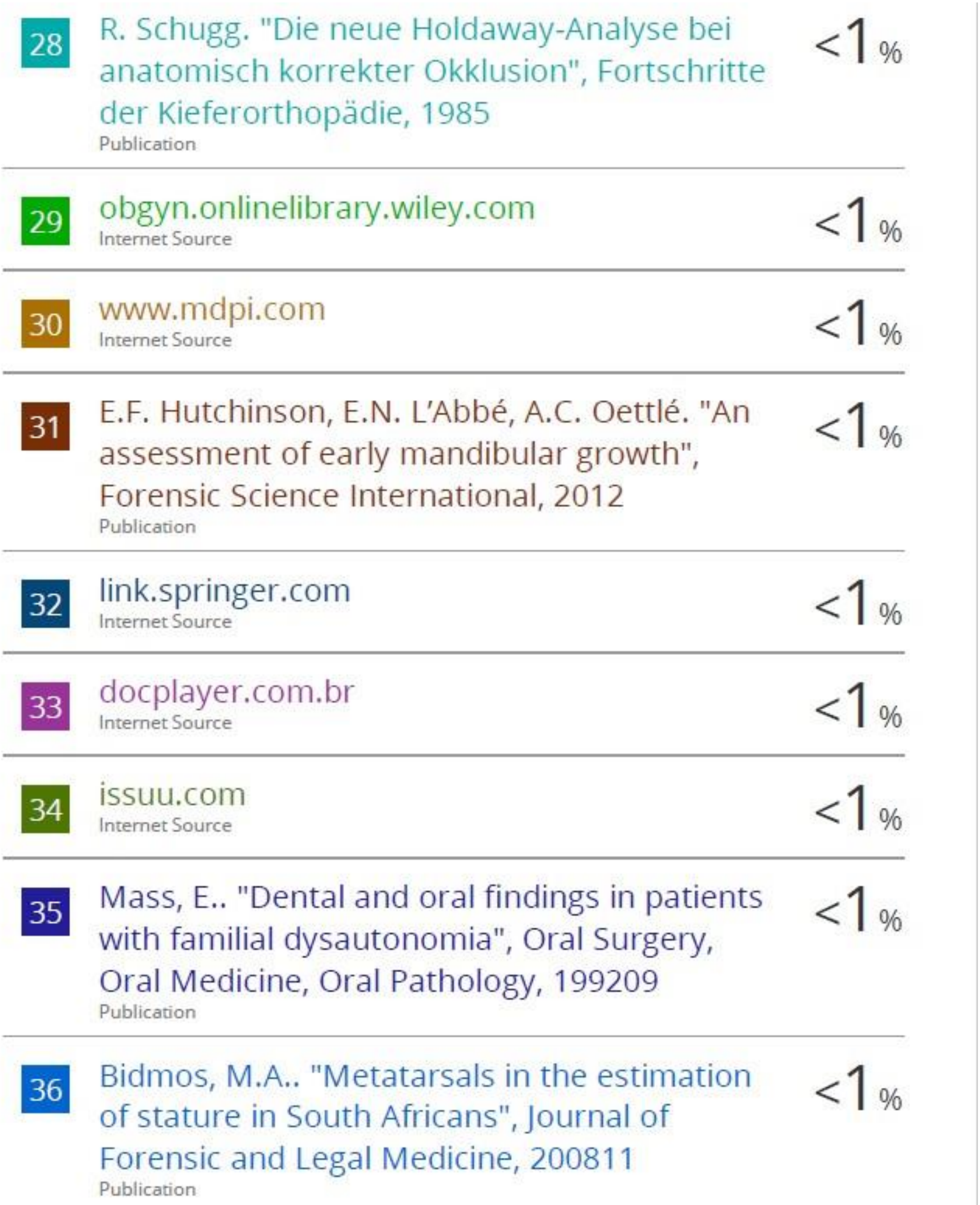
8	Franka Stahl, Rosemarie Grabowski. "Kieferorthop�dische Befunde im Milch- und fr�hen Wechselgebiss?Schlussfolgerungen f�r die Pr�vention", Journal of Orofacial Orthopedics/Fortschritte der Kieferorthop�die, 2003 Publication	<1 %
9	silo.pub Internet Source	<1 %
10	hdl.handle.net Internet Source	<1 %
11	dodgefamilychiropractic.com Internet Source	<1 %
12	bioone.org Internet Source	<1 %



13	Daphne Câmara Barcellos, Alessandra Buhler Borges, Cesar Rogério Pucci, Carlos Rocha Gomes Torres et al. "Prevalence of Chewing Side Preference in the Deciduous, Mixed and Permanent Dentitions", The Journal of Contemporary Dental Practice, 2011 Publication	<1 %
14	phys.org Internet Source	<1 %
15	assaf.org.za Internet Source	<1 %
16	H. SÖNMEZ. "Prevalence of temporomandibular dysfunction in Turkish children with mixed and permanent dentition", Journal of Oral Rehabilitation, 3/2001 Publication	<1 %
17	Submitted to University of Dundee Student Paper	<1 %
18	"ABSTRACTS OF LECTURES AND POSTERS * EUROPEAN ORTHODONTIC SOCIETY, 82nd Congress Vienna, Austria 2006, 4-8 July", The European Journal of Orthodontics, 12/01/2006 Publication	<1 %
19	Colleen N. Mohan, Eustaquio A. Araujo, Donald R. Oliver, Ki Beom Kim. "Long-term stability of rapid palatal expansion in the	<1 %



	mixed dentition vs the permanent dentition", American Journal of Orthodontics and Dentofacial Orthopedics, 2016 Publication	
20	Submitted to University of Johannsburg Student Paper	<1 %
21	www.nature.com Internet Source	<1 %
22	www.studystack.com Internet Source	<1 %
23	F. Eve. "A Lecture on the Pathology and Treatment of Tumours of the Jaws: Delivered at the Medical Graduates' College and Polyclinic, December 4th, 1906", BMJ, 1907 Publication	<1 %
24	Submitted to University of Western Ontario Student Paper	<1 %
25	bmchealthservres.biomedcentral.com Internet Source	<1 %
26	psjd.icm.edu.pl Internet Source	<1 %
27	Karlien Asscherickx. "Palatal implants in adolescents: a histological evaluation in beagle dogs : Palatal implants in adolescents", Clinical Oral Implants Research, 05/19/2008 Publication	<1 %



28	R. Schugg. "Die neue Holdaway-Analyse bei anatomisch korrekter Okklusion", Fortschritte der Kieferorthopädie, 1985 Publication	<1 %
29	obgyn.onlinelibrary.wiley.com Internet Source	<1 %
30	www.mdpi.com Internet Source	<1 %
31	E.F. Hutchinson, E.N. L'Abbé, A.C. Oettlé. "An assessment of early mandibular growth", Forensic Science International, 2012 Publication	<1 %
32	link.springer.com Internet Source	<1 %
33	docplayer.com.br Internet Source	<1 %
34	issuu.com Internet Source	<1 %
35	Mass, E.. "Dental and oral findings in patients with familial dysautonomia", Oral Surgery, Oral Medicine, Oral Pathology, 199209 Publication	<1 %
36	Bidmos, M.A.. "Metatarsals in the estimation of stature in South Africans", Journal of Forensic and Legal Medicine, 200811 Publication	<1 %

37	L. J. PEREIRA. "Molar bite force and its correlation with signs of temporomandibular dysfunction in mixed and permanent dentition", Journal of Oral Rehabilitation, 2/26/2007 Publication	<1 %
38	Sara Ghadimi, Mandana Tosifian, Ali Baghalian, Bahman Seraj. "The Effect of First Permanent Tooth Eruption on Dental Arch Dimension", Iranian Journal of Orthodontics, 2020 Publication	<1 %
39	cslide.ctimeetingtech.com Internet Source	<1 %
40	lume.ufrgs.br Internet Source	<1 %
41	dokumen.pub Internet Source	<1 %
42	Nabeel Almotairy, Abhishek Kumar, Nadia Welander, Anastasios Grigoriadis. "Age - related changes in oral motor - control strategies during unpredictable load demands in humans", European Journal of Oral Sciences, 2020 Publication	<1 %
43	University of Tennessee, Knoxville Publication	<1 %

Exclude quotes	On	Exclude matches	Off
Exclude bibliography	On		