A longitudinal study of dental arch dimensions in Australian Aboriginals using 2D and 3D digital imaging methods

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3. Literature Review

3.1 Introduction

Man evolved in an environment in which the occlusion was worn down quickly, resulting in flattened occlusal and interproximal surfaces. Some believe this rapid wear is essential for normal development of the dentition and a lack of this process due to the evolution of food preparation and processing techniques over the last 250 years or more has led to teeth not being worn down as 'programmed', resulting in an increase in malocclusions and other dental problems such as periodontal disease, caries and TMD[1]. Should we recreate these severe wear patterns to aid in improving modern dental conditions? The answer is no, but it is an important concept of our past to understand that will improve our understanding of the development of dental arch dimensions and functional occlusions.

3.1.1 Attrition

Dental attrition, both interproximal and occlusal, can be thought of as resulting from a series of interactions between the teeth, their supporting structures and the masticatory apparatus. It is wear produced by tooth-on-tooth contact between neighboring teeth or opposing teeth. The effects of dental attrition are not limited to the reduction of individual tooth dimensions alone[2]. Skeletal changes are evident, dental arch morphology is altered and the associated inter-relationships between the upper and lower jaws and their supporting structures are modified [2]. Interproximal or interstitial wear has been described in many mammalian species including man and has been suggested as a diagnostic characteristic of hominids [3] and by some as essential to anatomically correct occlusion [4]. The stability of the treated occlusion is closely dependent on biologic arch dimension changes that occur with growth and aging.

Relatively recent hunter gatherer populations such as the Australian aborigines experienced considerable tooth wear before being influenced by the western way of life. Begg [4] studied skeletal remains of Australian Aborigines and found the difference in total arch length between worn and unworn groups to be at least 10.6mm in the mandibular arch and slightly less in the maxillary arch. Lysell [5] examined medieval skull remains from northern Sweden and found loss in total arch length to be approximately 8.28mm in the lower jaw and 7.6mm in the maxilla. Wolpoff [6] found considerable interproximal wear in Eskimo and American Indian populations and claimed wear among Australian aborigines could exceed 21mm of arch length. Murphy [7] investigated mature Australian Aboriginal skulls and found approximately 3.5mm of arch length reduction in the buccal segments.

Mehta and Carnot [8], on the other hand, measured pre-Columbian Arkansas Indian skulls and found no difference in mesio-distal widths of the teeth between the prehistoric skulls and modern man. Corruccini [9] in testing Begg’s theory found no interproximal attrition in the Australian aboriginal sample from the Yuendumu collection.

Begg's [4] theory surmises that for the normal development of the dentition, an extensive amount of attrition is necessary to compensate for an excess amount of tooth material. Begg believed that attritional tooth reduction and compensatory physiological tooth migration occurred throughout life. He hypothesized that physiological or mesial migration occurred to maintain contact between adjacent teeth by closing the spaces generated by the interproximal attrition and thus ensure good occlusal function [4]. Although Begg's work was carried out on the severely worn dentitions of pre-European contact indigenous Australian skulls [4], he considered attritional occlusion to be the original type of human occlusion and thus applicable to any race. Begg believed the lack of this function was the primary reason for the extent of malocclusion associated with crowding that exists in modern man. Crowding in pre-historic man is not unheard of but is not as common as regular well aligned arches. This discussion has brought about much debate and researchers since have found evidence to support and dispute his original findings. This hypothesis by Begg offers an important insight into understanding why the dentitions and occlusions of prehistoric and contemporary people differ. There is evidence that technologically primitive populations have a low incidence and degree of crowding [10] [11] [4] . What is frequently seen in most of the societies with little crowding is a high degree of interproximal and occlusal attrition [12].

It can be assumed that selection pressures for teeth big enough to withstand the rigours of a tough and abrasive diet have been suspended only in modern populations that have adopted a soft and refined diet, a consequence of advances in food preparation and tool technology. Even in these advanced populations, without significant tooth wear, there has not yet been sufficient time for the slow pace of evolutionary tooth reduction to eliminate crowding and the impaction of the third molars in the absence of attrition. Therefore, the genetic programming for sufficient tooth size to withstand the inevitable wear caused by the diet of the past would now be functionally maladaptive. What does appear to be clear is that in modern man what appears to be dental crowding because of oversized teeth is in primitive man a balancing compensation for interproximal attrition resulting from a tough and abrasive diet [12].

Dental and craniofacial studies on historic and contemporary populations can be mistakenly considered to have a limited application to the solution of problems in dentistry today and thus would be of little importance or interest to practicing clinicians [13]. Research investigations involving aboriginal people living in isolated regions at primitive or near primitive level of material culture and society might seem to be of academic interest only. However, comparative studies on the face, jaws and teeth of human groups can help clarify practical dental problems as well as providing information on the racial aspects of the dentition and problems in evolution. These data together with others can be assembled to give us a broad biological background of man’s masticatory system in relation to environment and function [13]. This is of course invaluable to a clinician as it can have relevance to problems of facial growth, dental development, arch form, tooth occlusion, aetiology of dental disease and abnormalities, dental genetic problems and in this manner influence orthodontic treatment planning, restoration of teeth and replacement of missing teeth.

3.1.2 Methods of measuring teeth on study models

The second component of this study involves a comparative assessment of 2D measurements of dental study models compared with measurements made on computer generated 3D images of the same study models.

The use of study models is an integral part of practical orthodontics and dental research. The measurement of teeth on study models involves the direct physical identification of specific landmarks anthropometrically [14]. This system while reliable and accurate, is limited by the number of points the probe touches the object, as well as the inter and intra operator reliability in identifying the correct landmarks. The University of Adelaide houses an impressive longitudinal collection of study models of native Australians dating back to the 1950s that have immense research and historical value. Ways are being sought to avoid physical manipulation and possible distortion of the models when they are measured for research purposes.

In the past, standardised digital photographs have been taken of the study models and digitised on a customized software program. This system, while simple and effective, is handicapped by the operator's inability to compensate for tipped, tilted teeth or a caved in occlusion. Virtual or digital models offer orthodontists an alternative to the plaster study models routinely used. Surface laser scanners are able to capture a complete digital data image of the study model and transform it into a 3 dimensional virtual model for further analysis. It is advantageous in that it avoids any contact or distortion of the surface of the models. Previous studies have shown that the dimensional accuracy of laser scanned digital models is high, within 0.05mm [15] [16] [17]. As the need for evidence-based orthodontics is increasing, the accuracy and reliability of different measurement methods used for research purposes need to be evaluated [18]. Clinical decisions cannot otherwise be justified.

In this study, a subset of 5 individuals from the original sample, at ages 8, 12, 15 and 18 years were first duplicated and then scanned using the Minolta Vivid 900, which is a 3D surface scanner. The scanned images were digitized using the Rapidform software package (Inus Technology, Seoul, Korea). The measurements obtained from the computer generated 3D images were then compared with the measurements of the same teeth obtained from the 2D images. We hypothesized that there would be no difference in the reliability of measuring tooth widths on 2D digital images when compared with computer generated 3D images.

The purpose of this study, therefore, was to investigate arch dimension changes associated with growth and tooth wear in Australian Aboriginals aged from age 8 to 15years using a 2D and a 3D digital imaging system (Refer Section 6: Aims/Hypotheses).

3.2 The Australian aboriginal dentition

It is thought that aborigines first came to Australia at least 15000 years ago [13] It has been reported that the primary and permanent teeth of Aborigines are large and exhibit a number of primitive features in crown and root form[19]. In the Yuendumu group, crown dimensions were found to be greater than those reported for other contemporary populations [20] [13]. However, there are wide variations in tooth size among Aboriginal populations, the Yuendumu subjects displaying smaller teeth when compared with earlier groups represented by skeletal material from various regions of Australia. Sexual dimorphism in tooth size has been noted within the Yuendumu Aborigines, especially the canine teeth [21]. The dental arch dimensions of Australian aborigines tend to be large and the teeth are usually arranged in well-formed symmetrical arches (Figure 1)

Figure 1: Example of broad symmetrical arch form of an Australian Aboriginal from the Yuendumu sample.

Barrett, Brown and MacDonald [22] studied dental casts obtained from a group of adolescent and adult Australian aborigines. Dental arch dimensions of the subjects were compared with those of Swedes and Aleuts and were found to be larger. In general, they found dental arch dimensions were greater for males than females during adolescence while arch depth was smaller for adults in both arches[22]. They also found no significant sex differences in arch depth for adults [22]. They reported that crowding of teeth and other irregularities in tooth position were not infrequent in that population.

Kaidonis et al[2] examined the interproximal surfaces of over 200 individual teeth from Australian Aboriginals and Caucasians. They reported that interproximal surfaces were generally more extensive on the mesial surfaces of teeth than adjacent distal surfaces. They also noted that the mesial surfaces tended to develop a concavity while distal surfaces tended to be convex (Figure 2). They concluded that vertical displacement of teeth combined with simultaneous mesial tipping, rather than bucco-lingual movement, is an important determinant of interproximal tooth wear in humans.

Figure 2: Occlusal and Interproximal wear. (Note broad contact areas)

The people used in the present study was part of the Wailbri tribe based at the Yuendumu settlement in the Northern Territory of Australia. Yuendumu was established in 1946 as a ration depot for aborigines who had abandoned their tribal way of life. A general account of the settlement at Yuendumu as of 1972 was given by Barrett and Williamson [23]. Over the last fifty years extensive studies have been done looking at the dental and craniofacial features of the Yuendumu population [13,21] [20,22,24] [25,26]. Barrett [22] found that, with few exceptions, the mean values of these dimensions are significantly larger than those recorded for other population groups. He reported that aborigine males have larger teeth than the females and the most marked sex difference in size was shown by permanent mandibular canines.

3.3 Dental attrition

The degree and rate of tooth wear has long been of interest and concern in both dentistry and anthropology. Kaifu [27] reported on the trend for extreme tooth wear in our genus for over 2 million years. Tooth wear appears to have been a persistent, if somewhat variable feature throughout human evolution [27]. Numerous attempts have been made to quantify and compare the worn occlusal surfaces of prehistoric and contemporary dentitions [28] [29] [30]. Most research has been focused on the contribution of tooth wear to disease or its affect on occlusion, while others have investigated the influence of diet and culture on the destruction of the enamel crown and the non-masticatory function of the teeth. Attempts have been made to correlate attrition with alterations in tooth position, arch form and its relationship to supporting bone [31].

Dental attrition is wear produced by tooth-on-tooth contact between neighboring teeth or opposing teeth. It produces wear facets on the occlusal surface or on the contacting mesial and distal surfaces of adjacent teeth. As previously mentioned, the effects of dental attrition are not limited to the reduction of individual tooth dimensions alone [2]. Skeletal changes are evident, dental arch morphology is altered and the associated inter-relationships between the upper and lower jaws and their supporting structures are modified [2]. Interproximal or interstitial attrition has been described in many mammalian species including man and has been suggested as a diagnostic characteristic of hominids and by some as essential to anatomically correct occlusion [3] [4].

The rate and extent of tooth wear is determined by biological factors such as the morphology of teeth and dental arches, the force and direction of masticatory movements and the hardness of enamel and dentine [32]. Methods used for food preparation and cooking also influence dental attrition which may increase substantially when abrasive material is incorporated into food. Tooth wear can also result from bruxism or tooth grinding and other non-masticatory acts. Dental attrition is progressive and should ideally be rated on a continuous scale rather than according to discrete stages.

Interproximal wear in Australian aboriginals has been estimated at rates of about 1mm per year before the eruption of third molars, 0.3mm per year during adult life and 0.1mm per year during old age [7] [2]. Richards [32] reported rates of 0.9mm per decade per quadrant in the lower arch and 1.1mm per decade per quadrant in the maxilla[7].

Among those who believe interproximal attrition to be a major player in the development of the normal dentition was Percy Raymond Begg, who in many ways played a pivotal role in introducing the idea to the scientific world. His 1954 paper on Stone Age man's dentition has been widely cited in orthodontic, dental and anthropological literature [6 8 32 12].

Begg [4] investigated occlusions found in Australian aboriginals and reported extensively on these findings. He stated that for the normal development of the dentition, an extensive amount of attrition is necessary to compensate for an excess amount of tooth material. He maintained that teeth migrate occlusally and mesially as attrition progresses [4]. Interproximal attrition associated with mesial migration could have had an important function in prehistoric man, as the adjustment mechanism providing close proximal contact between teeth in the buccal segments, attritional occlusal planes developed early in adult life.

Begg felt that horizontal replacement of worn anterior teeth by mesial migration of posterior teeth was a survival adaptation that natural selection has favoured to maintain adequate masticatory function over a reproductive lifetime in many mammalian species [12]. This attritional occlusion allowed for the changing anatomy of teeth which is essential for correct occlusion and that the function of cusps is to guide the eruption of teeth into occlusion during the early years [31]. It appears reasonable to suggest that the apparent vigorous mastication of an adult occlusion would have demanded a high level of denture stability for functional longevity.

Begg felt that, after wear extends below the proximal contact areas, arch length is markedly reduced [4]. He observed that the molars establish a Class III relationship to each other. He found the difference in total arch length between worn and unworn groups to be at least 10.6mm in the mandibular arch and slightly less in the maxillary arch. It should be pointed out that these measurements were derived from measuring only nine skulls and those of true nomadic Aboriginal hunter gatherers. Begg[4] demonstrated how the teeth are designed to resist attrition so that time is available for the formation of secondary dentine as a defence mechanism. The greatest amount of enamel and dentine is on the occlusal, incisal and proximal surfaces. Before occlusal attrition progresses far, the posterior plane of occlusion slopes downwards from the buccal to lingual surfaces. The occlusal plane then becomes horizontal because of the resistance afforded by the cusp of carabelli, and eventually slopes downward from lingual to buccal.

Whilst investigating the patterns of wear as related to mandibular paths of eruption in populations that use their jaws more vigorously than is demanded by a civilized diet, Brodie [33] noted that the occlusal surfaces of all the posterior teeth became more concave and more tooth structure was lost on the lingual half of the upper teeth and buccal half of the lower teeth. Interproximal wear was extensive indicating independent movement of the teeth. This helicoidal plane of dental occlusion is a composite feature involving axial inclination of teeth and effects of dental attrition. Increasing axial inclination of molars from first molar to third is primarily responsible for the helicoidal plane, although attrition acts to increase its expression. In hominoids, increased molar axial tilt appears to be associated with facial shortening and dental attrition [34].

Leigh[30] wrote about the dental pathology of the Eskimo. He examined Eskimo crania and found that the lingual margins of the maxillary teeth wore deeper than the facial. As attrition progressed, this plane of wear reversed direction [30]. The mandibular plane of occlusion slanted from lingual to buccal surface [30]. This is in accordance with Begg's findings. Bjőrk [35] has discussed the effects evolution has had on the shortening of the dental arches. He considered the reduction of facial prognathism to be the most significant change associated with the decrease in arch length.

Pre-Columbian Arkansas Indian skulls, 3-5000 years old, were measured by Mehta and Carnot [8] to determine the exact amount of attrition that existed. Buccal and lingual crown heights and mesio-distal widths were measured and compared with modern man. Occlusal heights were less in the attrition group, but the widths did not differ. The mesio-distal widths between the maxillary premolars were greater than the canine fossa measurements indicating the probability that these Indians had an inherent excess of tooth material over basal bone. Malocclusion was rare in their sample.

Lysell[5] examined medieval skull remains from northern Sweden. He measured the width of the dental arches between first premolars and first molars, the length and height of the arches, incisor inclination and evaluated available arch length. Overjet, overbite and molar relations were also examined. The skulls exhibited marked attrition. Their widths were less than similar measurements on present day material, although the validity of this conclusion is questionable. The juvenile skull exhibited more overjet and overbite than the mature skulls. Using the same material, Lysell [5] investigated the effects of the attrition to a greater degree. He studied the relation of attrition to age and sex, the distribution of attrition within the dentition, the degree of proximal tooth reduction and the amount of tooth migration. He determined the mesio-distal widths of the teeth prior to attrition by means of the existing buccal-lingual widths which were not particularly subjected to the forces of attrition. A limitation of this method is that it assumes tooth shape has not changed over the millenia.

Lysell's results revealed that attrition increased with age with no sex differences [5]. The incisors demonstrated the most attrition, the third molars the least. The mandibular molars and incisors showed more attrition than the maxillary teeth. He found the loss in total arch length to be approximately 8.28mm in the lower jaw and 7.6mm in the maxilla [5]. These values are somewhat less than those found by Begg. Those skulls possessing a large amount of attrition did not demonstrate spacing. The upper incisor tipped lingually in the severe attrition group, rather than the molars drifting mesially. Lysell postulated the cause of this change in incisal inclination to be due to an increased use in the perioral musculature because food was more difficult to tear as the incisors become shorter through attrition. It can be argued that this reasoning of Lysell's is flawed as worn teeth can be sharp and easily utilized for tearing foods.

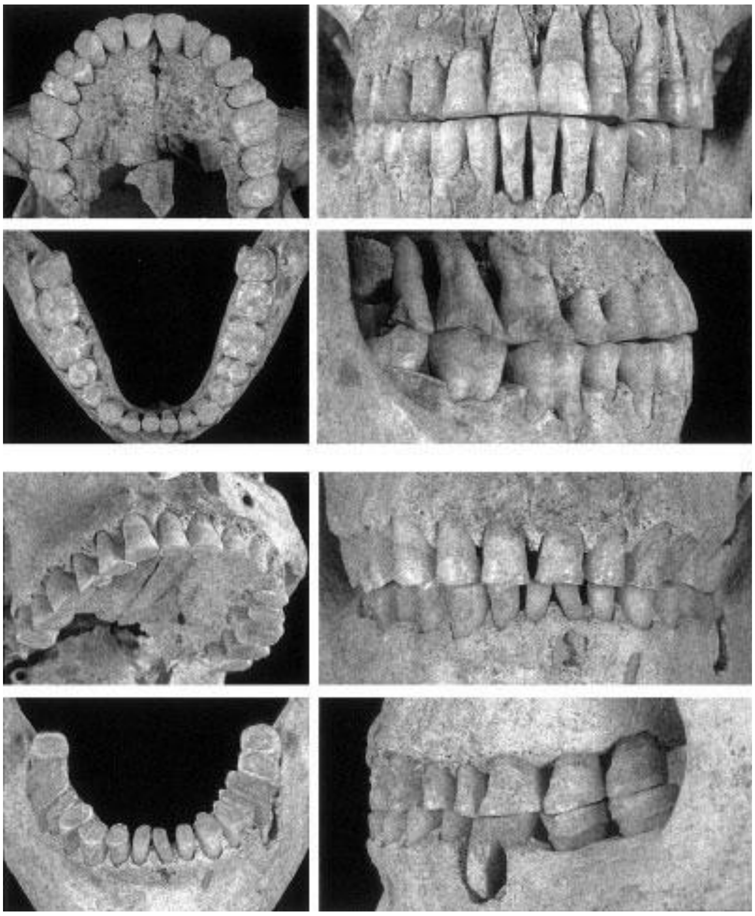


Figure 3: Two cases of attritional occlusion seen in prehistoric hunter-gatherers in Japan [27].

Lundstrőm and Lysell [36] studied a group of medieval Danish skulls. In addition to measurements similar to the previous study, anthropological measurements of cranial width, facial width and height and mandibular width were taken.

Overbite was less in the mature skull and this was felt to be related to the additional attrition in the older group. Arch width was found to be the wider in the medieval skull group compared with present day material.

Murphy [7] noted that Begg's measurements of arch length reduction were made on immature Australian Aboriginal groups. Murphy[7] investigated adult Australian aboriginal skulls, but limited his attention to only the posterior teeth. The length of the buccal segment and arch width between the first molars were measured. These findings were then compared with present-day aboriginal communities. Approximately 3.5mm of arch length reduction was found in the buccal segments [7]. Arch width was found to increase slightly. Wolpoff [6] claims that the wear among Australian aborigines can exceed 21mm of arch length, he also found considerable interproximal wear in Eskimo and American Indian populations.

Fishman [31] studied American Indian crania spanning eight hundred years from excavation sites in the central regions of New York state. He found that the mesial and distal surfaces of the teeth became flatter and the arch length was altered. He noted that both the maxillary and mandibular molars drifted anteriorly. His study also found that midsagittal arch length decreased for both arches, but less for uppers. As arch length decreased, proximal contact relationships did not always maintain themselves and spacing often developed, particularly in the anterior regions. Lysell[5] observed the opposite result and described no interproximal spacing. The upper anteriors moved anteriorly as the degree of attrition progressed while the lower incisors maintained a more stable relationship. He also noted that the intra-arch width dimensions decreased as attrition progressed. This was contradictory to observations made by Lundstrőm [36] and Murphy [29].

As the occlusal and proximal attrition progressed, the occlusal plane moved more vertically within the cranio-facial complex. Subsequently, the mandibular gonial angle and total face height is decreased. Begg observed similar changes.

Mehta and Carnot [8], conversely, measured pre-Columbian Arkansas Indian skulls and found no difference in mesio-distal widths of the teeth between the prehistoric skulls and modern man. Corruccini [9] in testing Begg's theory found no interproximal attrition in an Australian aboriginal sample from the Yuendumu collection. Corruccini [9] makes no mention of his methods in measuring this lack of attritrion.

Begg's contention that attritional occlusion is more normal and the lack of attrition in civilized society is the primary aetiologic factor in malocclusion, is worthy of consideration. Most investigators have reported that many excellent occlusions existed in skulls that demonstrated both slight and advanced attrition [12,31,36]. What does seem to be an indisputable fact is that attrition does generally provide additional arch length to accommodate teeth at the distal extremities of the arches.

3.4 Mastication and tooth wear

The main cause of tooth wear in prehistoric populations appears to have been due to some combination of friction of foreign material forced over tooth surfaces and an increase in the number of power strokes during mastication when less refined, tougher foods are consumed [27].

Historically, the Australian aborigines were nomadic hunters and food gatherers. Harsh living conditions with infrequent rainfall and the consequent low food productivity demanded considerable time, effort and skill for survival. Their methods of food preparation and cooking were simple and crude. Many foods were eaten raw [4,13]. Those that were cooked received minimal heat treatment over an open fire or were buried in the hot sands and ashes after the fire had burnt down. The aborigines had no cooking or eating utensils, they managed with their teeth and hands.

This unrefined native foods and primitive methods of food preparation demanded vigorous effort in mastication [13]. Consequently the teeth of Australian aborigines living under natural conditions were subject to continual wear throughout life [4,13,37]. Attrition was a characteristic feature of the functioning dentition. Wear took place both on the occlusal and approximal surfaces of the teeth. Interproximal attrition reduced the mesio-distal crown diameters of the teeth to a considerable extent and formed wear facets on the approximal surfaces [13,38] (Figure 4). This led to a reduction in dental arch length.

NOTE:
This figure is included on page 30
of the print copy of the thesis held in
the University of Adelaide Library.

Figure 4: Interproximal wear facets. Picture courtesy of Kaidonis J, University of Adelaide.

Occlusal attrition obliterated cusps and occlusal surfaces grooves, exposed dentine to wear and considerably reduced crown height [13]. The occlusal surfaces of the teeth were also subject to continual change throughout life. The interlocking cuspal occlusion of adolescence with its overbite incisor relation was progressively modified by the loss of cusps and reduction in crown height.

Broad masticatory surfaces were thus developed. This extensive wear led to a helicoidal wear pattern. Typically the adult incisor relation was edge to edge [4,13].

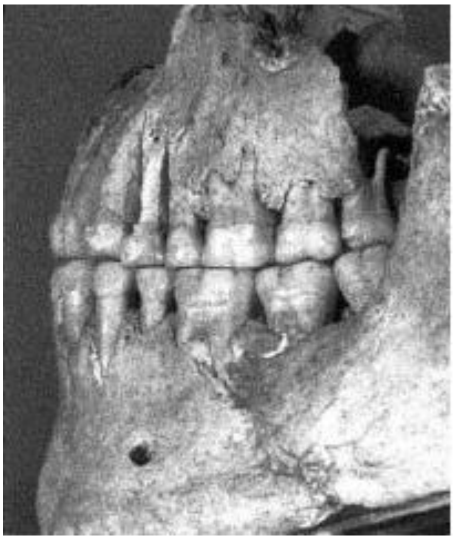


Figure 5: Edge to edge occlusion seen in an adult individual from the prehistoric Jomon population of Japan. Picture courtesy of Kaifu et al [27].

The obliteration by attrition of fissures likely contributed to the very low if any occurrence of caries by eliminating lodgment areas for cariogenic food material. The closely contacting approximal surface attrition facets also reduced stagnation areas interproximally. An important factor in the caries free dentition was the scarcity of indigenous sources of fermentable carbohydrate foods.

Almost all of the aboriginal communities in Australia since the early 1920's, including the Yuendumu population have been in continual contact with Caucasian civilization for many years [20]. Their environment, mode of life, food and methods of food preparation, and eating habits all differ markedly from the native situation and primitive conditions of their predecessors. While most tribes had broken up by the 1950s, there were still a few groups living under near primitive conditions at government settlements in the outback. Yuendumu is one such settlement where the Wailbri people receive clothing, food rations, medical care and schooling for their children.

Yuendumu was found to be very suitable for dental studies as the settlement is relatively isolated geographically. Its population consists of a static self-contained group of people almost free of non-aboriginal mingling[13] . In their general mode of life, methods of food preparation and eating habits, this group in the 1950-60's were at an intermediate stage of transition from their previous hunting and food gathering existence to the adoption of a civilized way of life. This is the population group that is being studied in this study.

Wolpoff [6] claimed that the wear among Australian aborigines can exceed 21 mm. He also found considerable interproximal wear in Eskimo and American Indian populations and in chimpanzees [6]. His analysis indicates that interproximal wear is highly correlated with the chewing force required by the diet. A diet consisting largely of tough foods, such as nuts, seeds, fibrous vegetables, and partially cooked meats, requires high chewing forces that cause lateral movement of the teeth relative to each other. This rubbing of adjacent teeth is the main cause of interproximal wear [12]. Lombardi[12] believed that the amount of particulate matter or grit in the diet was a secondary factor in interproximal wear, although it accounted for most of the occlusal wear. Lombardi stated that advanced populations that consume a diet composed largely of cooked meats and vegetables, as well as processed foods, did not require the large chewing forces that lead to lateral movement of the teeth and interproximal wear. He contended that the low incidence of crowding in primitive populations seemingly resulted from the high degree of interproximal attrition and not from a more harmonious concordance of tooth and jaw size. Barret[22] [13] also spoke of cross-occlusion, where there was a alternating left to right pattern of occlusion, preventing bilateral buccal tooth contact in centric which would have led to considerable lateral excursive chewing patterns.

3.5 Animal Experiments, Chewing Activity and Malocclusion

Several authors have found a correlation between reduced chewing activity and malocclusion. In animal experiments, it has been possible to correlate a diet of low chewing resistance to narrower arches, which predispose the subject to crowding and irregular teeth. Larsson et al [39] showed that chewing hard food caused considerable occlusal and approximal attrition in experimental animals.

The dental arches were shorter due to this attrition and to mesial migration of the molars and premolars. The approximal attrition also reduced the tendency for crowding and rotation of the teeth. Posterior crossbites were found to be more common among the hard-chewing animals. Lindsten et al [40] [41] compared dental arch dimensions in 9-year-olds from different time periods. They observed narrower arches in children born in the 1980s compared with those born in the

1960s and the skulls of medieval children. A reason suggested for the variations was differences in chewing consistency of modern diets.

Several investigators have found lower prevalence of severe malocclusions in people living in traditional non-urbanized settings compared with those living in urban industrialized societies. In comparing Chinese, Americans in Kentucky, and Punjabis, living traditionally in rural areas with those who have a modern, urban, fast-food lifestyle, Corruccini et al [42] found an increased prevalence of malocclusions, especially mal-alignment, after just one generation with the new eating habits. One reason for this development was thought to be a narrower maxilla caused by decreased chewing activity associated with more refined food. Less appositional bone growth might have resulted from lack of stimulation from growth of the masticatory muscles. It has also been suggested that chewing a soft diet would reduce or even obliterate the growth of the internasal suture. A narrow maxilla could also be the result of reduced growth caused by lack of functional stimuli.

Malocclusion is prevalent in modern man, but there is no conclusive evidence in the literature that the modern soft diet results in reduced craniofacial and dentofacial development and thus an increased likelihood of developing malocclusion compared with the ancient hard-chewing diet. Larsson et al [39] conducted their study on growing pigs as they are reasonably similar to primates in their feeding apparatus. The mesio-distal tooth sizes were measured at the anatomic contact points when the tooth was in a correct position. In case of attrition, which was severe in some hard-food animals, the new anatomic contact point was used. Attrition was evaluated in the first permanent molars. The maxillary teeth were judged separately from the mandibular teeth. Approximal attrition was pronounced in the hard-diet group. Most affected were the mandibular first molars. As reported by some authors [4 2], the approximal surface was worn to a degree that it became concave. Notably, the distal surfaces of the maxillary first molar and, to some extent, the mandibular fourth premolar were the most affected. This was postulated to have been due to the strength of the mesial migration of the teeth in the jaws. Similar to Begg's[4] study, the rotations were less in the hard-diet group. In Begg's study, the probable explanation was the reduction of space needed for the teeth because of the approximal attrition. The greater variability of the fourth premolar's rotation in the soft-diet group was also a sign of crowding in some animals [39]. According to Lindsten et al [40] , mesial drift of the first permanent molars in children who have lost the second deciduous molars also will reduce the transverse width.

Teeth in posterior crossbite or edge-to-edge position were significantly more prevalent in the hard-diet group, a common finding in jaws with heavy attrition. The mesial migration of the molars seemed to force the mandibular first molar into a more buccal position, thereby creating a crossbite or a cusp-to-cusp position. Hard food caused considerable occlusal and approximal attrition in the experimental animals. The lengths of the dental arches were reduced because of this attrition and mesial migration of the molars and premolars.

The approximal attrition also reduced the tendency for crowding and rotation of the teeth. Posterior crossbite was more common in the hard-diet animals. They concluded that teeth and chewing muscles appear to be compensating structures that can take up heavy loads during chewing and that as long as teeth and chewing muscles can compensate for the external loads during chewing, the craniofacial and dentofacial complex is not necessarily influenced during growth and development.

3.6 Mesial migration, occlusion and malocclusion

Normal occlusion in the biologic sense implies a range of variation in the alignment of the teeth and jaws compatible with normal function and the absence of disease [12]. There is a changing set of social and cultural values that motivate individuals to seek orthodontic treatment. To many, increased fitness and improved appearance become of paramount importance to a sense of well-being and social adjustment. This complexity of factors involved makes it difficult to make biologically valid definitions of normal occlusion and malocclusion. The best clinicians recognize that malocclusion is an expression of biologic variation, and they consciously and unconsciously assimilate the information needed to make a sound clinical decision.

The modern day concept of normal occlusion is much oriented toward specific anatomical characteristics of the teeth. Cuspal relationships are used to describe and treat normal occlusions and malocclusions. Every phase of dental therapy is concerned with the restoration, alteration or orientation of cusps on the occlusal surfaces of teeth.

Man did not always demonstrate marked occlusal-cusped anatomy. Civilised man exhibits relatively little dental attrition, but primitive societies possessed teeth with marked degrees of wear. This attrition was, as we now know due to many factors, primarily the abrasiveness of the food consumed. The wear was caused by the type of food, lack of food refinement and the nature of the cooking and eating utensils. In some situations teeth were also used for performing tasks such as the working of animal hides.

Modern man demonstrates innumerable problems related to tooth alignment. Malocclusion associated with inadequacy of arch length to accommodate full dentitions is common. Third molars are often unable to take their proper places at the distal ends of the arch. It is important to note that malocclusion has been reported in prehistoric man, but many investigations have reported on the surprisingly high incidence of occlusions that demonstrate no form of malocclusion [31].

It is significant that some degree of malrelation of occlusal variables is a widespread phenomenon. It is also relevant that the incidence of malocclusion is not distributed equally among world populations. Technologically advanced populations seemingly have a higher occurrence of malocclusion than do technologically primitive peoples[10,11]. This observation has led to a widely held erroneous concept of dental crowding, the occlusal variable with the most frequent and greatest range of variability.

The concept declares that primitive populations represent “pure” races, that they are genetically homogeneous and thus have close concordance between tooth and jaw size, whereas the high incidence of crowding in advanced populations is attributable to the breakdown of “pure” races, resulting in the mating of individuals who differ widely in tooth and jaw size[12].

Crowding as we now know, is influenced by both genetic and environmental factors and is extremely widespread, affecting to some degree the majority of the people of advanced societies with complete dentitions [10]. It is associated more frequently with large teeth [43] [44]. There is evidence that technologically primitive populations have a low incidence and degree of crowding [10] [11] [4] . What is frequently seen in most of the societies with little crowding is a high degree of interproximal and occlusal attrition [12].

Mesial drift can be defined as the bodily mesial migration of individual teeth within the alveolar bone. As a result of this process, interproximal spaces generally do not occur even when there is severe interproximal attrition [27]. The lack of interproximal spaces in situations of advanced tooth wear is often accepted as being a consequence of mesial drift. In favorable circumstances, the differential mesial migration of the first permanent molars following exfoliation of the second deciduous molars will result in a Class 1 molar occlusion[12 4]. In unfavorable circumstances, the mesial migration of the posterior teeth leads to pressures that cause the anterior teeth to overlap or it will block late erupting teeth, such as the upper canines or lower second premolars, from full eruption.

Begg[4] postulated that the interproximal attrition that occurs in the dentition of primitive man compensates for the progressive mesial migration of the posterior teeth. There is general agreement that mesial drift occurs in contemporary human populations and that it occurs both in developing and established dentitions[45]. Histological studies have shown that there are signs of bone resorption on the mesial alveolar wall and bone apposition on the distal alveolar wall [46 47]

The proposed mechanisms of mesial drift are varied and include; the transseptal fibers tending to pull the teeth together [48], mesially; the action of the masticatory muscles and tongue produces a mesial force vector on the dentition; the permanent teeth erupt in an approximately antero-posterior sequence, so that the eruption forces of the late-erupting posterior teeth push forward the erupted teeth;

the roots of the posterior teeth are inclined forward in the jaws, so that chewing forces create a mesial force vector. The last explanation is favored by Wolpoff [6], who concludes that the greater the chewing forces, which are determined by the nature of the diet, the higher the mesial force vector. The extent to which some or all of the proposed mechanisms account for mesial drift is still to be determined.

From the viewpoint of the evolutionary biologists, these biologic features, be they anatomic structures or physiologic processes, are affected by the forces of natural selection. They, therefore, have an effect on the survival or differential reproduction of the individual; mesial migration of the teeth must have adaptive value that enhances survival in a certain environment [12]. Horizontal replacement of worn and lost anterior teeth by the mesial migration of posterior teeth is a survival adaptation that natural selection has favored to maintain adequate masticatory function over a reproductive lifetime in many mammalian species [4] [12,31]. It appears to be an adaptive process that maintains a close correspondence between chewing surface area and jaw size. In the immature individual the sequential eruption of the teeth allows occlusal area to keep pace with the growing jaws and with increasing body size and nutritional demands.

In the mature individual of some species, sequential replacement of worn teeth through mesial migration permits jaw and body size to be adapted to the particular environment without regard to the loss of chewing surface through wear [12]. Without this concept of sequential eruption and mesial migration, there would have to be sufficient tooth structure in the jaws at the start to withstand future wear throughout the reproductive years. The more efficient adaptation as Begg [4] and Lombardi [12] believe is to have the potential for replacement of tooth structure only as it is needed. The programmed timing of normal development keeps the reserve teeth in an immature form until the appropriate stages of physical development and environmental demand cause their eruption.

Human evolution began with the adoption of upright bipedal locomotion and thousands of years later, the gradual enlargement of the brain. These crucial adaptations led to selection pressures that better balanced the head on a vertical spine [12]. This included a shortening and retraction of the jaws and reduction of facial prognathism.

Because closely related structures have overlapping genetic control, the phenomenon of pleiotropy, it is thought that selection pressures for the reduction of jaw size also reduced tooth size [12]. According to Lombardi [12], the most significant reduction in mesio-distal diameter of the molars occurred about 500,000 years ago, at a time where there is evidence that fire had begun to be used for cooking. Cooking would have a tenderizing effect on food, especially meat, making it more easily chewed. Further advances in food technology led to selection pressures for smaller teeth, or at least relaxed the selection pressures for large teeth. During all of mankind's prehistory the heavy chewing forces created strong mesial force vectors and mesial migration of the teeth, much as was seen by Begg [4] and Barret

[13 20] in Australian aborigines living in primitive circumstances. With gritty, abrasive material in the food, extensive interproximal and occlusal wear occurred. Because of the coarse, demanding diet, it was postulated that adequate functioning occlusal area, that is large crown dimensions enhanced survival [4,12,13,20].

The horizontal replacement of the posterior teeth by mesial migration was a positive biologic adaptation to maintain sufficient chewing surface in the face of tooth loss by attrition [4 6,12]. The continuous vertical eruption of teeth throughout life and the formation of a secondary dentition in response to occlusal stress are also adaptations that serve to maintain sufficient tooth structure in the face of wear [31]. What in modern populations appears to be dental crowding because of oversized teeth, in primitive man was a balancing compensation for interproximal attrition resulting from a tough and abrasive diet. Because of interproximal wear and mesial migration, the third molars erupted and were important functioning teeth in primitive man. Thus, what now appears as maladaptive dental crowding was of crucial adaptive value in the long period of mankind's past [12].

It can be assumed that selection pressures for teeth big enough to withstand the rigours of a tough and abrasive diet have been suspended only in modern populations that have adopted a soft and refined diet, a consequence of advances in food preparation and tool technology. Even in advanced populations, without significant tooth wear, there has not yet been sufficient time for the slow pace of evolutionary tooth reduction to eliminate crowding and the impaction of the third molars in the absence of attrition [12]. Therefore, the genetic programming for sufficient tooth size to withstand the inevitable wear caused by the diet of the past would now be functionally maladaptive. As dental crowding is a cause of malocclusion and is, therefore, maladaptive it is likely that selection pressures are operating to reduce dental arch length. This may manifest as an increased rate of tooth agenesis, especially of the third molars, which are the last teeth to seek room in the jaws [12].

In the midst of all these theories on dental wear and malocclusions it is important to realize that the proposed evolutionary model for dental crowding does not necessarily account for all aspects of dental crowding. We know that it is not apparent that early incisor crowding results simply from mesial drift and a lack of interproximal wear [10] and may well be due to other factors such as a lack of space in the alveolar bone and dento-alveolar development with tooth eruption.

Van Beek's [49] experimental study on functional occlusion and mesial drift using a monkey model was reviewed recently and confirmed that occlusion plays an important role in mesial drift. Van Beek concluded that mesial drift was not merely a compensatory mechanism for loss of tooth substance, but could cause crowding, depending on axial inclination and occlusal morphology [50].

It is important to realise that the size of the teeth and the amount of space available for them in the tooth bearing parts of the jaws are vital factors in determining the positions taken up by the teeth in the dental arches [20]. Tooth crowding and spacing are most frequently associated with discrepancies in this size-space relation but irregularities in the positions of teeth sometimes occur which are seemingly independent of this relation. Moorrees and Reed [43] have also shown that crowding or spacing of teeth depend in large measure on the relation between the size of the teeth and the size of the bony dental arch.

Corruccini [9] believed that there were theoretical and practical problems with the Begg model. The theoretical difficulties revolved around the integration of deciduous versus permanent tooth attrition with the sequence of deciduous tooth replacement. He also noted that practical attempts to repeat Begg's research in Australian aborigines and in prehistoric Amerindians have consistently produced estimates of permanent mandibular tooth reduction of only twenty to forty percent of Begg's discovery of 10.54mm [9]. He expressed surprise at other investigators findings of dental crowding and overjet increases in these populations although Begg in 1935 and 1954 clearly stated that attrition is just as marked in aborigines who show crowding as those with regular alignment and that malocclusions occur in occlusions that present with attrition in these pre-modern men.

Corruccini[9] reexamined Begg's theory using a collection of dental casts obtained from Australian aborigines living at the Yuendumu Settlement in the Northern territory of Australia. He assumed the Yuendumu sample was of the same general type of humanity on which Begg based his thinking but this was an incorrect assumption as the Yuendumu population is different to the sample of hunter-gatherers used by Begg in the 1950s. The Yuendumu population was a transitional group based only half of the time at the government settlement, that provided food and rations very different from their hunter gatherer practices of food preparation or type of food. It has to be surmised, therefore, that there is bound to be markedly different levels of attrition and wear in the modern Australian aborigine sample. But being in a stage of life style transition, we might still expect to see some amount of attrition. Nevertheless, Corruccini [9] found no attrition in the Yuendumu population. His study longitudinally compared tooth/arch variables in Australian aborigines 'lacking' interproximal attrition to test Begg's Theory. He noted that only adult dentition incisor overjet in the absence of attrition bore any relation to crowding status [9]. Corruccini [9] concluded that there appeared to be some validity to the idea that failure of attrition and mesial drift to bring the mandibular incisors more toward the anterior plane of maxillary incisors related to an increased crowding tendency especially of anterior teeth. While not tested in his study, he did note that mandibular incisor mesio-distal dimensions appeared to positively correlate with crowding of those teeth [9]

Contrary to popular thought, Begg did not advocate the extraction of teeth to suit his theory on the attrition, tooth size and crowding. He believed that in an earlier population group with a different diet and food preparation techniques, severe attrition resulted in the reduction of some developing occlusal problems, including crowding. It is important to note that Begg did not report that attrition would be the same for all individuals nor did he surmise that it would eliminate all causes of malocclusion.

3.8 Dental Attrition and craniofacial morphology

The preservation and maintenance of healthy masticatory function requires continual adaptive and compensatory changes in the teeth, their supporting tissues, the facial skeleton and associated musculature and the temperomandibular joint [37]. Because attrition of the occlusal surfaces of the teeth is continuous, progressive and can be an extensive dental change which is relatively easy to quantify, it provides an opportunity to study adaptive and compensatory changes in other components of the masticatory system[37]. The best described of the facial changes associated with dental attrition is that of anterior face height. Whether anterior face height increases, remains constant or decreases depends on the balance between the rate of attrition and the rate of compensatory tooth eruption and alveolar bone growth[29].

In addition to changes in anterior face height, several other features of facial morphology have been shown to be related to dental attrition. Fishman[31] found that in American Indians with advanced attrition, maxillary alveolar prognathism increased, the gonial angle decreased and the inter-incisor angle increased. But not all observations of the facial changes associated with attrition support Fishman's conclusions. For example, Mohlin et al [51], found that the loss of facial height observed in their Swedish sample was not associated with any significant maxillary change but that the occlusal and mandibular plane angles increased and a degree of mandibular alveolar prognathism developed.

Richards' [37] study observed that groups with different craniofacial morphology and different patterns of tooth wear responded in different ways to advancing dental attrition. The evidence of compensatory and adaptive changes seen in the groups considered in his study are important for a number of reasons. It illustrates the complex nature of the human masticatory system and the way in which variation in one component is closely related to variation in other components. An appreciation of these types of relationships is important not only in physical anthropology but also in clinical dentistry where the effects on other components of the masticatory system need to be considered when changes affecting the occlusion of the teeth are contemplated [37]. Studies of the associations between attrition and facial morphology based on correlations are complicated by the difficulties inherent in determining cause-and-effect relationships between the observed changes. It cannot be assumed that attrition is always the cause of observed differences in facial morphology, and as a result observed associations need to be interpreted carefully.

Differences in patterns of tooth wear could also arise as a result of differences in the mechanics of the masticatory system arising from differences in facial morphology and associated differences in the magnitude and direction of forces acting on the teeth. Despite information provided by Moller [52] and the work of Hylander [53-55] and Brehnan et al [56], the relative importance of differences in masticatory function in determining patterns of tooth wear is difficult to determine.

Kiliaridis et al [57] looked at craniofacial morphology , occlusal traits, and bite force in persons with advanced occlusal tooth wear. Their cephalometric findings were in agreement with those found by Krogstad and Dahl [58]. They surmised that the reduced mandibular-palatal plane angle in the occlusal wear sample, and specially in men, may have been explained by the assumption that the rate of the dental wear exceeds the rate of compensatory tooth eruption and dentoalveolar bone growth causing an anterior rotation of the mandible with reduction of the lower anterior facial height. However, this explanation contradicts the findings of studies on skull materials and in certain contemporary non-western population groups. For example, Australian aborigines and Eskimos with extensive wear, where the loss of vertical dimensions after wear of the teeth was compensated for by tooth eruption and vertical growth of the alveolar bone [4,6,12].

The other significant cephalometric finding in their sample was the small gonial angle of the mandible found in both men and women. That finding reflected the local effect of the excessive function of the masticatory muscles on the region of their insertion. The facial structure of their sample was similar to the medieval skulls studied by Mohlin et al[51] . The characteristic facial structure in the medieval skulls was found to comprise a small intermaxillary angle, a small gonial angle and broad jaws. The severity of wear of the teeth in medieval skulls suggested an excessive function of the masticatory muscles, a factor they considered could, in turn, have influenced facial structure. Since the degree of wear in many of their subjects could be compared with that found in the medieval skulls, they suggested that a similar function/wear- facial structure interrelationship to that of the medieval material accounted for the observations made in their sample [51]. Although that was in contrast to most contemporary populations, it conformed with that of all primitive societies in which extensive occlusal and approximal wear seem to have been the norm, and the process of "wearing in" started early during the deciduous dentition. Other features of the developing primitive facial skeleton were a compensatory growth to improve the vertical facial dimensional deficit accompanying wear, and an anterior rotation of the mandible that, together with an uprighting of the incisors, manifested in an "edge-to-edge" bite early in life. Mohlin et al [51] reported the significant interdependence between muscle function, occlusal wear, and dentofacial structure in their sample and concluded that the relationship differed little from that seen in earlier populations.

3.9 Dental arch changes

Understanding the normal changes in dental arch dimensions with growth is vital for orthodontic treatment planning. There are a number of studies investigating changes in the dental arches during the period of growth and adulthood, and they provide strong evidence of individual mechanisms that influence the form of the dental arch. Cassidy et al [59] showed different heritability ratios in the main arch parameters and concluded that arch size and shape are seen to be more subject to environmental influences than to heredity. Because the dental arch is under the influence of all supporting and neighboring structures as well as under a strong environmental influence, it is important to note some hereditary factors that are more difficult to treat in comparison to extrinsic influences. For phenotypic expression of all genetic and environmental influences, time is an important additional factor that should be considered [60].

The stability of the treated occlusion is closely dependent on biologic arch dimension changes that occur with growth and aging. Dental arch dimensions change systematically during the period of intensive growth and development and less so in adulthood. In the mixed dentition, dental arch form and, consequently, the occlusion changes systematically because of tooth movement as teeth migrate into shorter and broader arch forms in the deciduous dentition and again in the permanent dentition and the growth of the supporting bone.

Many studies report a moderate increase in dental arch width before the eruption of the permanent canines and a systematic decrease thereafter [60,61] [62] [63] [64]. It is generally understood that changes in arch width vary between males and females and that more growth in width occurs in the upper than the lower arch [63]. Lee [63] stated that this growth occurs mainly between the ages of 7 and 12 years of age. He also reported that the lower intercanine width increases significantly in the changeover dentition but does not increase in the permanent dentition after 12 years of age.

Bishara et al [61] , carried out a longitudinal study to assess the changes in intercanine and intermolar widths over a 45 year span. They reported that intercanine and intermolar widths increased significantly between 3 and 13 years of age in both maxillary and mandibular arches. They found that after the eruption of the permanent dentition, there was a slight decrease in dental arch widths, more in the intercanine than intermolar widths. Bishara et al [61] concluded that although dental arch widths undergo changes from birth until adulthood, the arch dimensions returned to closely approximate the dimensions established at the time of the eruption of the permanent canines and molars.

Similarly, Odajima et al [62] studied the dental arches of 127 Japanese children from 6 months after birth until the age of 15. They found the dental arch widths increased slightly from about the age of 6 years and the period of mixed dentition and then remained stable until the permanent dentition stage [62]. From the primary dentition stage, the width of the dental arch in the region of the maxillary and mandibular canines and first and second molars was reported to gradually increase[62]. They reported that the intermolar width gradually increased and attained a stable condition at about 12 years of age [62].

In a longitudinal study, Knott [64] noted that intercanine width showed little change after eruption of the permanent dentition and in the transition stage from complete deciduous to permanent dentition; least mean change (~ 1mm) was in width from mandibular deciduous second molars to width of their successors.

Ross-Powell and Harris [65] described changes in arch form in a cohort of 52 black American children between the ages of 3 and 18 years. Incisor-to-canine depth remained static in both arches between 3 and 5 years but shortened significantly between 12 and 18 years. They noted that intercanine width broadened significantly in both arches, first during the deciduous dentition, then again as the primary teeth were replaced by the permanent incisors and canines [65]. No change in intercanine width was noted once the permanent canines were in functional occlusion around the ages of 11 to 18 years [65].

In 1925, Campbell [66] described various features of the dentition and palate of the Australian aboriginal from an investigation of 630 skull specimens. He found that average values of dental arch breadth increased with age but arch depth decreased with age. Moorrees [67] conducted a longitudinal study of growth and developmental changes of the dentition of 184 North American white children. He found that the average arch depth decreased with increasing age except during the eruption of permanent incisors. The maxillary and mandibular arch depths decreased from age three to eighteen years for both sexes and the total decrease appeared to be more in the mandible and in girls. The arch breadth increased irregularly with age and it was generally associated with the eruption of the permanent incisors, canines and premolars. Moorrees pointed out that there were wide individual variations in size and directional changes, especially during the eruption of permanent teeth.

Understanding and predicting changes in arch form is clinically vital for planning treatment and retention strategies to ensure long term stability of treatment results.

3.10 Methods of study model analysis

Stone or plaster models are a standard component of orthodontic records, and they are fundamental to diagnosis and treatment planning, case presentations, evaluation of treatment progress and results and record keeping. Virtual or digital models offer orthodontists an alternative to the plaster study models routinely used.

Tooth measurement is important in clinical orthodontics, anthropology and in developmental biology. In the past measurement techniques have been based around the manual measurement of erupted teeth on study models. Investigators have used the contact method using simple instruments such as a pair of dividers with a millimeter ruler [68,69] or sliding calibrated calipers for dental cast measurements [70]. Hand held calipers have the advantage of being simple to use and transport and studies have confirmed that manual measurements made from dental casts, are reasonlably accurate and reproducible [71]. Unfortunately, the sharpened beaks of calipers can damage the casts and this is unacceptable when studying valuable historic samples.

Researchers have for years used several other non-contact methods including standardized photographs [72], photocopies of casts [73], occlusograms and laser holograms [74] of the occlusal aspects of the teeth. Schrimer and Wiltshire [75], and Champagne [76] compared measurements made manually on casts with those made on digitised casts obtained from the photocopier. They concluded that, although photocopies are easy to handle, manually measuring teeth with a calibrated gauge produces the most “accurate, reliable and reproducible” measurements. The photocopier method still requires a traditional study model and only provides a 2 dimensional image of a 3 dimensional image. Bhatia and Harrison [77], studied the performance of the “traveling microscope” which is an apparatus modified to measure dental casts and concluded that the method was more precise than some alternatives. Martensson and Ryden [78] investigated a holographic system for measuring dental casts. The method was shown to be more precise that previous methods and they believed that it would also save storage space. However, although microscopes and holographic systems had some advantages, they did not prove to be practical in a clinical practice and have never become popular.

Mok and Cooke [79] compared the use of sonic digitization using the DigiGraph Workstation and the digital caliper in space analysis. The DigiGraph Workstation permits the use of sonic digitization to measure lateral cephalometric values, mesio-distal tooth size and arch perimeter discrepancy as a one-stop diagnostic record taking set-up. Their study compared the reproducibility of mesio-distal total tooth widths and arch perimeter values obtained from plaster casts as determined by the DigiGraph Workstation and by digital calipers. Compared with manual measurement, there was an over-estimation of the total tooth widths by 1 mm in the mandible and 0.5 mm in the maxilla, and an arch perimeter discrepancy of 1.6 mm in the mandible and 0.4 mm in the maxilla when using the sonic method [79]. The sonic digitization was found to be not as reproducible as the digital caliper [79] .

Three dimensional systems have been available for over 40 years. Early approaches include the use of stereophotogrammetry, the Optocom and reflex metrography. These methods were limited by poor measurement accuracy due to difficulties identifying landmarks and by the length of time needed to collect data. More recent advents have included Moire photography, micro computed tomography and confocal microscopy. The introduction of laser scanning and computer aided tomography has been of great interest in dentistry. These new systems allow easy manipulation of the images and enable a wider range of measurements to be made plus the information can be stored as 3 dimensional data creating virtual study models of the dentition.

Because the need for evidence-based orthodontics is increasing, the accuracy and reproducibility of different measurement methods ought to be evaluated [18]. Clinical decisions cannot otherwise be justified. With the ultimate aim of a ‘paperless’ orthodontic office and with the already existing possibilities of incorporating digital photos and radiographs into the electronic patiens file, the need for replacement of the plaster casts has emerged. Thus there has been marked interest over the last fifteen years in developing a computerized study model database and analysis software. Yamamoto et al [80] described an optical method for creating 3D computerized models using a laser beam on a cast. Surface laser scanners are able to capture a complete digital data image of the object and transform it into a 3 dimensional virtual model for further analysis. It has the advantage of image acquisition without any contact or distortion of surface tissues and is entirely non-invasive and safe to the patient [14]. Several attempts have been made to transfer the dental cast into a 3D virtual model [81] [82] [17] or even to create an apparatus for intraoral direct scanning. These computerized models are the platform for calculating distances by using designated software and estimating treatment effects and tooth movements in this way [83] [18].

In the late nineties OrthoCAD (Cadent, Carlstadt, NJ) developed virtual digital dental casts. In early 2001, emodels (GeoDigm, Chanhassen, Minn) was introduced into the orthodontic market. The technology of digital study models allows an orthodontist to send a patient’s alginate impression or existing plaster study model to one of several companies for processing into a virtual 3-dimensional (3D) computerized image. This image is then available to the orthodontist for downloading from the company’s web-site within 5 days. Software from the imaging companies allows the orthodontist to view the image and manage it in a virtual 3D environment.

OrthoCAD provides software the orthodontist can use to make routine measurements such as tooth size, overjet, overbite and Bolton's analysis on the digital images. This system as with any other 3D system offers many advantages, including elimination of model breakage and storage problems (this is of particular relevance to historic samples), instant retrieval of models, ease of communication with patients and colleagues, and model access from many locations. It enables the orthodontist to email images if desired and is a convenient presentation tool. Disadvantages include lack of tactile input for the orthodontist and time needed to learn how to use the system. It must also be noted that computer failure, software failure, or manufacturer insolvency could possibly mean that the models may become inaccessible for some time [84].

Santoro et al [83] compared measurements made on digital (OrthoCAD) and plaster models and found that the digital measurements were smaller than the manual measurements and the magnitude of these differences ranged from 0.16 mm to 0.49 mm. While the authors concluded that the magnitude of the differences did not appear to be clinically relevant, in research investigations such as the present study, measurement differences of such magnitude can significantly affect our findings. Santoro et al [83] felt that alginate shrinking during transportation to OrthoCAD laboratories and different pouring times may have been the most likely explanations for the differences [83]. Another possibility discussed was the intrinsic difference between the 2 methods. 3 dimensional analysis systems utilize 3D visual pointing tools to interproximal contacts on an enlarged image and digital tools to measure diameters and distances along selected planes. Depending on the orthodontists training , abilities and preferences, measuring on a computer screen can be more or less accurate than the traditional gauge-on-cast method. Zilberman et al [18] compared measurements from digital models and manual measurement using calipers and found that all measurements were highly correlated. They found that within a confidence interval of 95%, they could not prove that measurements carried out with the various methods differed from each other but measurements made directly on cast with electronic calipers were found to be the most accurate and repeatable. Foong et al's [85] work has also shown good reliability and accuracy of 3D analysis of 3D models.

Stevens et al's [86] validation study compared standard plaster models with their digital counterparts made with emodel software (version 6.0,GeoDigm, Chanhassen, Minn). Measurements were made with a digital caliper to the nearest 0.01 mm from plaster models and with the software from the digital models. They found the difference between the measurements means for plaster and 'emodels' were 0.01 to 0.21 mm and concluded that Digital models are a clinically acceptable replacement for plaster casts for the routine measurements made in most orthodontic practices.

Quimby et al[84] carried out a study to determine the accuracy, reproducibility, efficacy, and effectiveness of measurements made on computer-based models. They reported that measurements made from computer-based models appeared to be generally as accurate and reliable as measurements made from plaster models [84]. They found efficacy and effectiveness were similar to those of plaster models[84].

Tomassetti et al [87] compared four methods of conducting overall and anterior Bolton tooth-size analyses. The mean Vernier caliper results were compared with each of the following computerized methods: QuickCeph, Hamilton Arch Tooth System (HATS), and OrthoCad. They found no statistically significant error was present for any of the methods at $p \leq 0.05$. The results from the different systems ranged from 0mm to 5.6mm (orthoCAD versus venier calipers) [87]. They also found the range of measurements were greater for OrthoCad than for the other systems [87]. Such a large range in mean measurement differences is not suitable for research purposes and may not be clinically relevant either.

Brook et al [88,89] [90] have over the years developed a 2D image analysis system that they have shown to be comparable to manual methods of study model analysis. They recently carried out a study to validate a new 3D approach against their established 2D image analysis system [91]. They found a high correlation between their 2D and 3D imaging systems with the mean differences between the two systems ranging from 0 to 0.6mm. Brook et al[92] validated their image analysis system against results obtained using manual methods. Their findings validated the 2D system and found it comparable in accuracy with manual methods[92].

The Minolta Vivid 900 was selected to be used in this study. The Minolta Vivid 900 is a surface laser scanner that uses 2 high resolution 3D cameras to capture different sets of images and mesh them into a complete virtual model. The scanner employs laser light sectioning technology using a slit beam. 1881 points (x = 0.17 mm, y = 0.17 mm, z = 0.047 mm / ±0.02 mm) can be measured per scan and is recorded using an incorporated CCD (640×480 points) camera in colour mode. The digitizer works with a Laser class 2 using a galvanometer driven rotating mirror and light receiving lens using a focal distance of f = 14 mm with a 670 nm red laser and a maximal power of 30 mW. The information from the scanner is turned into a polygonal mesh using the Polygon Editing Tool, the accompanying software to the Minolta Vivid 900.

A recent study evaluated the accuracy of the Minolta Vivid 900 by comparing it to direct measurements of physical anthropometric landmarks obtained from the Coordinate Measuring Machine, a gold standard [93]. Ho et al [93] found the accuracy levels to be very similar to the reported manufacturing accuracy of 0.3mm. The Rapidform (Inus Technology, Seoul, Korea) software package was used to analyse the images and obtain measurements.

Whichever technique is used, the reliability of each system is affected by many factors. Sources of measurement error include the type of device or technique used, the skill of the operator/examiner, impression and casting procedures as study models are often used and the condition of the tooth and related gingiva. Different factors may influence the accuracy and repeatability of measurements of individual teeth within the dental arch. Among these factors are, the existing spacing condition, the inclination of the teeth, rotations, presence of interproximal contacts and anatomical variations such as the presence of deep undercuts.

4. Aims/Hypothesis

The purpose of this study was to investigate arch dimension changes associated with growth and tooth wear in Australian Aboriginals living at the Yuendumu settlement in the Northern Territory of Australia aged from age 8 to 15.years using 2D and 3D digital imaging systems. The null hypothesis was that there would be no discernible interproximal attrition or associated reduction in arch length in the selected sample. Changes in arch length, depth and width in this sample from the ages 8 to 15 years will be described.

The second component of this study was to compare measurements made of teeth from digital photographs of dental models with those obtained using the Minolta Vivid 900 surface laser scanner. A subset of 40 study models (5 individuals at 4 time periods with upper and lower models available at each time interval) derived from the main sample were used for this aspect of the study. The null hypothesis was that there would be no difference in the accuracy of measuring tooth widths on 2D digital images when compared with computer generated 3D images.

5. Material and Methods

5.1 Sample

Subjects in the sample were Australian Aborigines known as Wailbri, living at the Yuendumu settlement, 185 miles north-west of Alice Springs in the Northern Territory of Australia (Fig 6). This population was of pure Aboriginal ancestry. The settlement was provided rations of mainly flour and sugar by the government and was markedly different from the traditional raw and coarse foods of the older generations of nomadic hunters and gatherers. This population base retained a partly nomadic lifestyle and chose to move in and out of the settlement.

Members of the School of Dentistry at the University of Adelaide carried out a longitudinal growth study at Yuendumu from the 1960s to the 1970s [13 20 22]. Collection of dental casts and serial x-rays of this population was initiated ten years prior to the start of the study. Several of the individuals involved in the study had extensive longitudinal series of models (Figure 7). A sample of 49 subjects (24 males and 25 females) was found to be suitable for the present study (please refer to section 5.2 for the inclusion criteria).

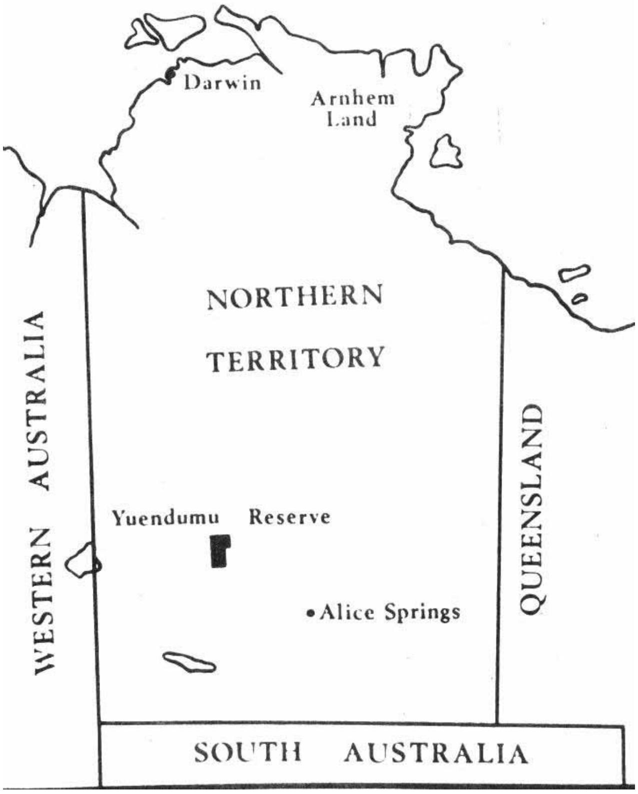


Figure 6: Map showing location of Yuendumu settlement.

Figure 7: Example of a storage drawer with sets of dental casts for an individual subject (Subject 253).

5.2 The selection criteria

5.2.1 Inclusion criteria

i. Upper and lower study models of good quality available at recorded ages of 8, 12 and 15years (or within a 1 year range) for the same individual.

ii. A sub-sample of the main sample to have study models at age periods of 8, 12, 15 and 18 years.

iii. Information on the sex and estimated birth date of each subject.

5.3 Ethical Clearance

Ethical clearance was sought and obtained from the University of Adelaide on 8 June 2006; Project no: H-079-2006 (Appendix 11.1)

The research protocols were submitted and accepted by the University of Adelaide Research Committee. Agreement was obtained from the Human Ethics Committee for use of historical material obtained longitudinally from a population of Australian aborigines in the 1950s – 1970s.

Permission to study the high quality study models and other records was granted by Professor G. Townsend, custodian of the collection housed in the Murray Barrett Laboratory, School of Dentistry, University of Adelaide. The author was required to:

1. Attend a basic information session on the use of the laboratory and the care of the models.
2. Ensure the models be studied only within the Murray Barrett Laboratory where they are stored.

5.4 Methodology

The study was set up to use a sample of 49 individuals (25 females and 24 males) with upper and lower study models at three time periods (which amounted to 294 study models). The models were photographed in a standardized manner and the images were digitized using a customized software program developed by Dr. T. Hughes at the School of Dentistry, University of Adelaide. Measurements of tooth widths, arch width and depth were made from these digitized images. A second component of the study was carried out at the National University of Singapore and used a subset of 40 study models (5 individuals at 4 time periods with upper and lower models available at each time interval) selected from the main sample. The same variables were measured from a 3D image obtained using the Minolta Vivid 900, surface laser scanner and the Rapidform Software package(Inus technology, Seoul, Korea).

Measurements of mesio-distal crown diameters were obtained at the points of contact with adjacent teeth but if no such contact existed then the maximum mesio-distal diameter of the dental crown was measured (Figure 8). A system of centroids was used to calculate the most reliable midpoints for canines and first molars and these were then used to measure arch width dimensions (please refer to section 7.5.2 for details on centroid determination). All right and left teeth, mesial to the first permanent molar were measured.

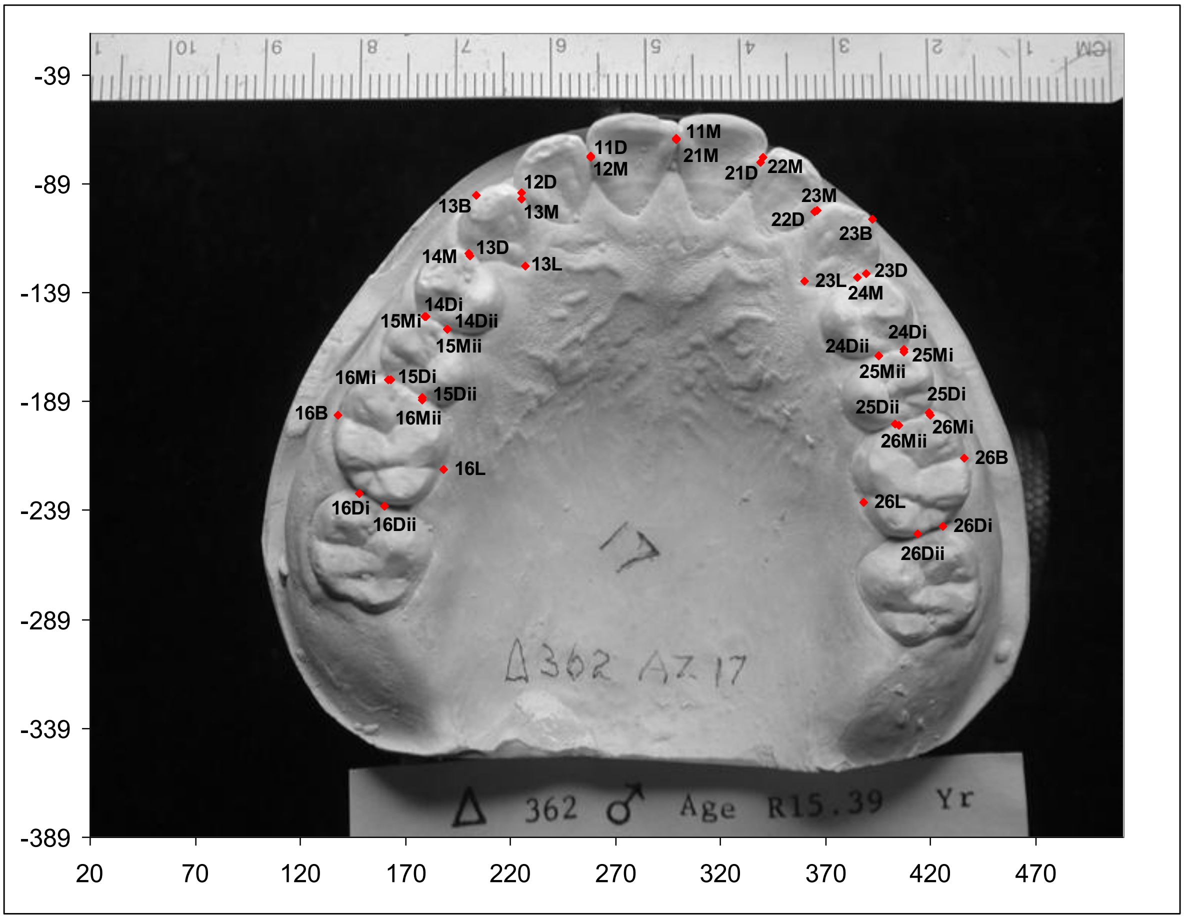


Figure 8: Example of 2D image with landmarks illustrated. Most distal(D) and mesial (M) points on adjacent teeth were identified. Where there is a broad contact, 2 points were located at the ends of the contact area (Mi and Mii or Di and Dii). A midpoint was then calculated and used to calculate mesio-distal width of the crown. Most buccal(B) and most lingual (L) points were marked on canines and first molars to aid in location of centroid used for arch width measurements.

5.4.1 Methods of study model analysis

Two methods of capturing images and analysis of study models were used. The first technique involved obtaining standardized digital photographs of the models and digitizing the landmarks using an Apple IIGS computer and a customized software program developed by Dr. T. Hughes, School of Dentistry, University of Adelaide.

The models of a sub-sample of 5 individuals at four time periods was duplicated and then scanned using the Minolta 900 Vivid, 3 dimensional surface scanner and digitized using the Rapidform software package(INUS technology, National University of Singapore).

5.4.2 Model analysis using standardized, digitised photographs of the study models.

The photographs were taken according to the method described by previous investigators at the University of Adelaide [94 72].

Photographic set up

Equipment:

a. Photographic height adjustment tripod - LPL Copystand (LPL, Co Ltd, Tokyo, Japan)

b. Digital Camera – Nikon Coolpix E995. Zoom Nikkor lens 8-32mm 1:2.6-5.1
c. Model clamp with a universal joint.
d. Leveling tripod – a flat plane and spirit level with tripod jig to be placed on the occlusal fissures of the first molars and the tips of the incisors.
e. Fluid levels – used to calibrate the lens of the camera to a true horizontal angulation.
f. Millimeter scale – Codman 15 cm ruler.
g. Lighting – 32 Watt, cool white fluorescent lamp to ensure no shadowing of the casts.

Each dental model was first securely placed on a model clamp (Figure 9);

Utilizing a leveling tripod and spirit level, the dental casts were leveled with respect to the central incisors and the first molars (Figures 9 and 10);

Figure 9: Model clamp and tripod device for leveling the occlusal plane

Figure 10: Dental casts were leveled with respect to the central incisors and the first molars.

- The focal length was predetermined and standardized for all models by fixing the camera on a height adjustment tripod (Figure 11);

Figure 11: White fluorescent lamp used to reduce shadowing effects.

- Utilising a spirit level, the photographic unit was leveled (Figure 12).

Figure 12: Spirit level used to ensure camera is leveled.

- A millimeter scale, at the same vertical level as the occlusal plane, and the patients' details were placed alongside the casts during the photographic process to allow calculation of magnification and identification (Figure 13).

Figure 13: Millimeter ruler maintained at occlusal height

5.4.3 Digitisation Process

The following digitizing procedure was employed:

1. The images were randomly selected for measurement (with no sequence for age, arch or sex to reduce examiner bias)
2. Endpoints (10mm) on the millimeter ruler were digitized to enable calibration and correction of magnification
3. All landmarks were digitized in a specific order by aligning the cursor cross-hairs over the landmark and pressing the button on the cursor which recorded the X and Y coordinates of the selected landmark. Anatomic contact points were digitized for all teeth (Please refer to Sections 7.5 – 7.5.3 for definition of landmarks). Buccal and lingual points were recorded for first molars, and canines (Figure 8);
4. This procedure was repeated for each photograph of upper and lower models.

5.4.4 Model analysis using the Minolta Vivid 900 3D surface scanner and Rapidform software (Inus Technology, Seoul, Korea)

As the sample used in this study is a collection of museum quality longitudinal study models, the author was not allowed to remove the stone models from the School’s premises. Therefore, it was decided that a sub-sample from the original sample group would be analysed using a 3D scanner.

First the subset of study models were duplicated using the highest quality impression material and stone. To investigate the reliability of the 2D and 3D techniques of study model analysis, the duplicated subset of study models were digitized using the Minolta Vivid 900 non-contact surface laser. The laser emits a beam of light that reflects off a mirror spreading the beam to capture the surface of the model being scanned. The information was then turned into a polygonal mesh using the Polygon Editing Tool, the accompanying software to the Minolta Vivid 900. These polygonal meshes were then imported into the Rapidform 2006 (Inus, technology, Seoul, Korea) software package for digitisation of landmarks and obtaining measurements.

5.4.5 Duplication Process

The process involved:

1. Duplication of the selected subsample was performed using Wirosil (Bego, Germany), a poly-vinyl siloxane impression material (Figure 14). This was followed by pouring up the impression moulds with high grade Diestone.

Figure 14: Wirosil duplicate mould

2. The models were then observed for any obvious differences such as pitting and distortion of cuspal anatomy against the original stone casts.

3. The duplicated sub-sample was then packed and sent to the DSO laboratories at National University Singapore (NUS), Singapore.
4. The models were scanned by the author using the Minolta Vivid 900 3D surface scanner at NUS, Singapore. (Figure 15).
5. The scanned images were then exported to the Rapidform software program (INUS Technology, Seoul, Korea) for analysis. Please see below for more details of the software analysis process.

5.4.5.1 Accuracy of duplication of study models – Error of method

To test the accuracy of the duplicate study models obtained by the method described in Section 5.4.5, a spare study model was duplicated with the exact same method and mesial-distal tooth widths were measured on both the original and duplicated model. Paired t tests were carried out and no significant differences were found. The mean difference between crown width measurements comparing the two methods ranged between -0.09mm to 0.16mm measured using digital calipers (Whitworth Vernier Calipers Digital 0-150mm). The results proved the duplication system to be highly accurate and the duplicates produced to be a very close twin of the original model.

5.4.6 Model scanning using the Minolta Vivid 900 3D surface scanner

Equipment set up at the DSO Laboratory, National University, Singapore (Figure 15):

a. The Minolta VIVID-900 stationary scanner mounted on a tripod;

   - 0.0016"-0.0035" Resolution

   - 640 x 480 output pixels (3-D data)

   - Accuracy (tele lens): x: +-0.22 mm y: +-0.16 mm z: +-0.10mm

b. Desktop workstation with a 2 GHz Pentium 4 processor and a standard computer mouse.

c. Turntable and wedge for study model positioning.

d. Reverse modeling software package Rapidform 2004 (INUS Technology Inc, Seoul, Korea)

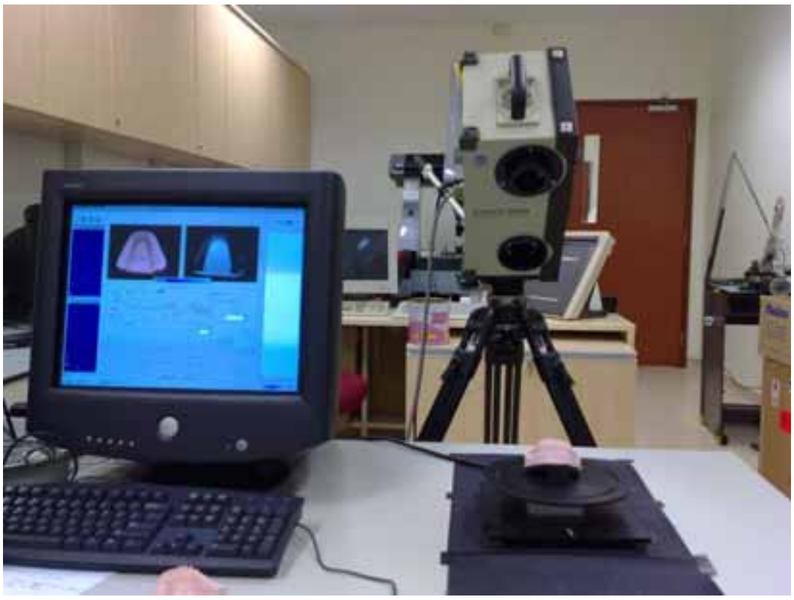


Figure 15: Minolta Vivid Scanner, cast stand and computer set up at NUS, Singapore.

Procedure

1. The Scanner was turned on and then the PC was switched on.
2. The model was placed on a turntable on a 45° pyramid shaped wedge to maintain parallelism with the 45 degree angle of the Minolta lens (Fig 16).

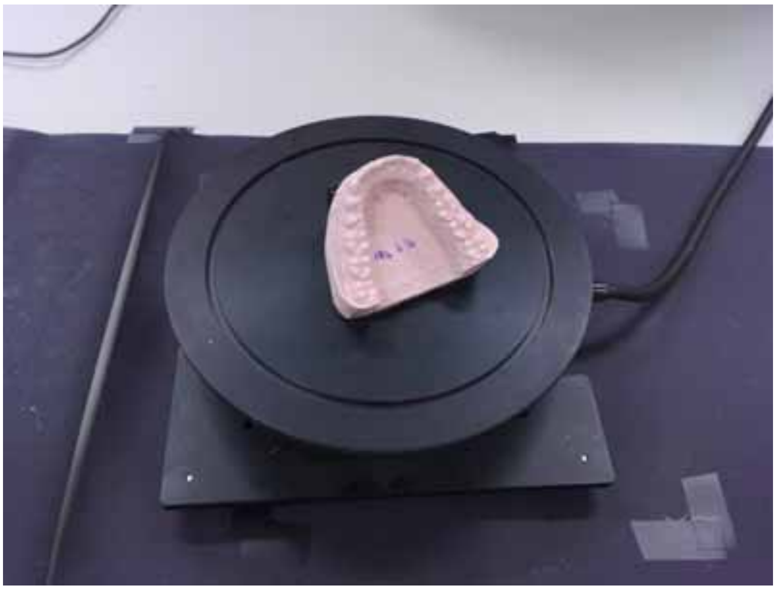


Figure 16: Turntable with cast placed on a 45 degree wedge.

2. The Scanner lens was focused and the number of image captures selected. 60 degree turns was selected for this study. (Six images for each model are thus obtained at the completion of a full 360 degree revolution)
3. A calibration platform was used to set the position of the images (Figure 17). This was used to align and coordinate the various images.

Figure 17: Calibration platform.

4. The individual images captured were merged together to form one full scanned image using the Polygon Mesh acquisition software (Minolta, Japan).
5. The image was then saved and exported to a secure location (portable hard drive).

5.4.7 Analysis of the images using the Rapidform software

The following digitization protocol was used:

1. Each image was individually imported into the software program. The software allowed the images to be viewed in a variety of outer shells.

2. The mesio-distal widths of all the teeth from first molar to first molar in both upper and lower jaws were measured using the line measure tool. A standard computer mouse was used to draw the distances from point to point on the computer models.
3. A graphic measure tool was used to outline the circumference of the molars and canines which created spheres from which centroids were calculated (Figure 18).

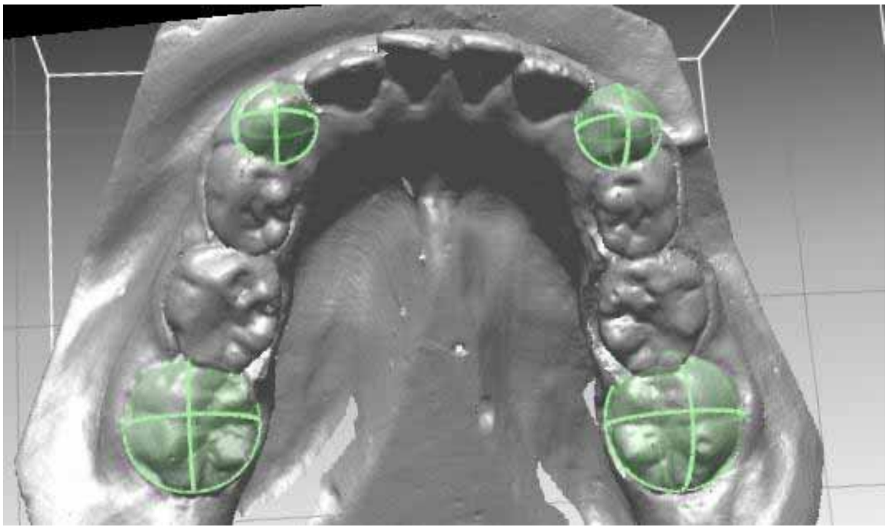


Figure 18: A graphic measure tool used to plot the circumference of the crown and calculate centroids.

4. The vector tool was then used to calculate linear measurements for the intermolar, intercanine widths and arch depth as was done in the 2D photographic digitization method (Figure 19).

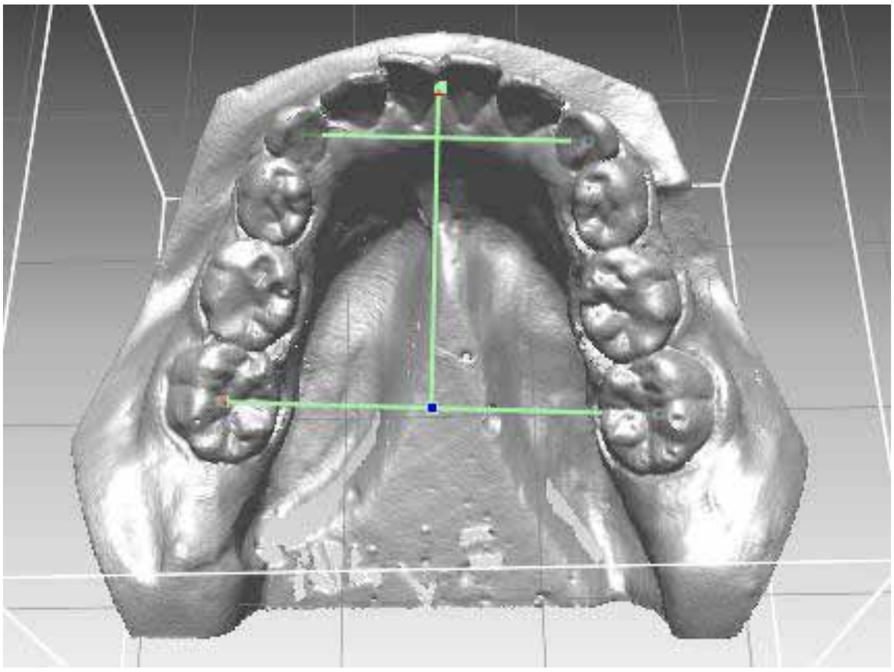


Figure 19: Arch width and depth linear measurements.

5.5 Definitions of measurements

All landmarks were standardized for both techniques. The landmarks used were based primarily on reference points described in Moyers' Standards of Human Occlusal Development [95], but were modified for the current study. (Please refer to paragraphs below)

For molars and canines, four points were recorded; distal midpoint, most buccal point, most lingual point and mesial midpoint. For incisors, the distal and mesial midpoints were recorded.

The following are the points used for the x and y coordinates: (adapted from Moyers *et al*:[95])

1. Distal contact point: The distal point of contact with the adjacent tooth. When a diastema was present, the point where the tooth is closest to the adjacent one was used.
2. Mesial contact point: The mesial point of contact with the adjacent tooth. Again, when a diastema is present, the point where the tooth is closest to the adjacent one is used.

If a broad area of contact was present between two teeth then the midpoint of the contact area was calculated and used as the final as the ‘contact point’ (Figure 8). For malaligned teeth, the most anatomically correct mesial and distal points were chosen.

3. Most buccal point: the point at the buccal fissure location for the permanent molars. For the cuspids, this point is the most labial on the labial surface.
4. Most lingual point: the point at the lingual fissure location for the permanent molars. For the cuspids, this point is the most lingual on the lingual surface.

5.5.1 Centroid determination

For the 2D photographic digitization method, the centroid was determined by using the four points located on the circumference of the dental crown for the molars and canines (Figure20)

NOTE:
This figure is included on page 83
of the print copy of the thesis held in
the University of Adelaide Library.

Figure20: Schematic illustration of centroid determination [96].

A. midpoint between the approximal midpoints

B. point halfway between the buccal and lingual points

C. the centroid: halfway between A. and B.

The real position of the crown could then be better determined independent of the number and location of cusps and crown tipping or tilting.

The arch width measurements were obtained from these constructed centroids as described by Moyers *et al.* [95]. It was felt that this method of measurement would be less affected by any attritional changes to the dentition.

5.5.2 The following measurements were determined for both upper and lower arches (Figure 21)

1. Mesio-distal widths of all teeth from first permanent molar on the right side to the first permanent molar on the left side. If there was a broad area of contact then the midpoint of the area of interproximal contact was used).
2. Inter-canine width (ICW): distances between the canines defined at the constructed centroids.
3. Inter-molar width (IMW): distances between the first permanent molars defined at the constructed centroids.
4. Arch depth (AD): distances measured from the midpoint of the most labial points of the central incisors to a line joining the centroids of the first molars.

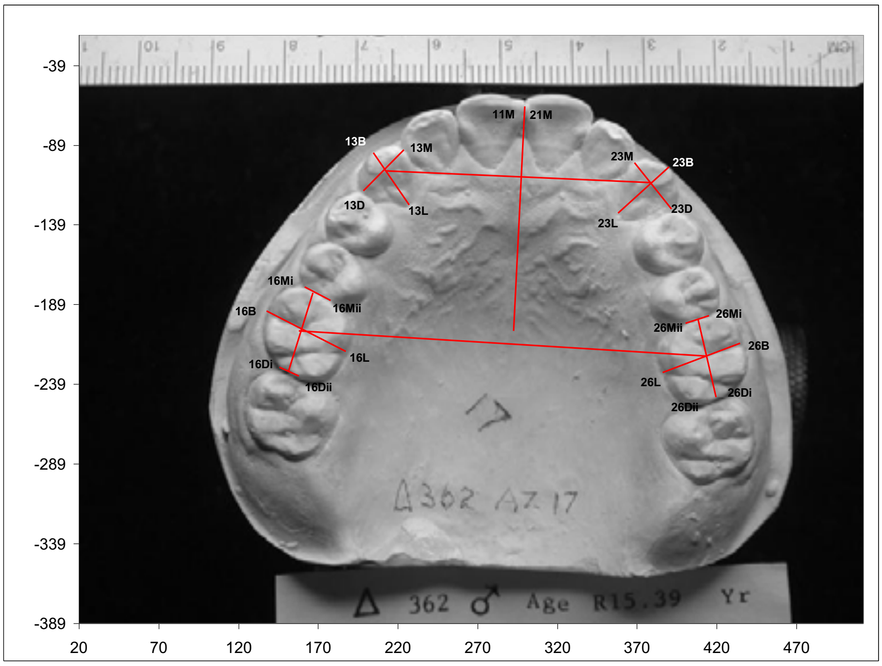


Figure 21: Arch dimensions calculated using centroids.

5.5.3 Tooth type labels used is shown in Table 1.

Table 1: Labels for tooth type used in this study.

11	Upper right central incisor
12	Upper right lateral incisor
13	Upper right canine
14	Upper right first premolar
15	Upper right second premolar
16	Upper right first molar
21	Upper left central incisor
22	Upper left lateral incisor
23	Upper left canine
24	Upper left first premolar
25	Upper left second premolar
26	Upper left first molar
31	Lower left central incisor
32	Lower left lateral incisor
33	Lower left canine
34	Lower left first premolar
35	Lower left second premolar
36	Lower left first molar
41	Lower right central incisor
42	Lower right lateral incisor
43	Lower right canine
44	Lower right first premolar
45	Lower right second premolar
46	Lower right first molar

5.6 Power Study

The power of a statistical analysis is the ability to show a difference when there is a true difference (i.e. reject the null hypothesis). A statistical power test calculates the probability of not committing a type II statistical error at a chosen level of type 1 error.

The numbers in this study were limited by availability and thus formal power studies were not performed. Nevertheless, the sample size was large enough to expect that clinically significant differences in study variables would also be statistically significant.

5.7 Estimation of Method Error

Reproducibility can be defined as the closeness of successive measurements of the same object [97]. Reliability is often used as a synonym for reproducibility. The reproducibility of the measurement varies according to the quality of records, the conditions under which they are measured and the care and skill of the examiner [97]. For this reason an assessment of reproducibility was done even though standardized measurements were used.

Errors of measurement may be systematic or random. As Houston [97] defines it, a systematic error refers to a consistent entry into the data, in a conscious or subconscious fashion, incorrect values which may over or underestimate the “true” values.

Errors associated with the present investigation could arise from several sources including:

- Landmark identification and thus tooth size measurement
- Digitisation;
- Model casting, photographic and measurement errors.

Method error studies were carried out to substantiate the initial measurements. To minimize variation in preparation and digitization, one individual examiner carried out all measurements.

To determine error of the overall method (in the photographic digitization method) 24 study models were randomly selected. These were rephotographed and remeasured not less than three months after the original recordings. To determine the method error in the 3D digitization process, eight study models were randomly selected from the all male subsample. These images were redigitised using the Rapidform software not less that two months after the original measurements were carried out and compared with the first determinations.

Systematic error was determined by calculating the mean difference and standard deviation of the differences, then paired Students t-test were performed. Random errors were quantified by calculating the standard error of a single observation or Dahlberg value, S(i) and also the percentage error variance, E(var). The Dahlberg statistic is also know as the ‘technical error of measurement’ [98]. The percentage error variance E (var) is the variance due to measurement error expressed as a percentage of the total observed variance.

5.8 Statistical Methods

The measurements obtained from the standardized digital pictures were converted from xy coordinate format into scaled numerical measures of mesio-distal tooth widths. The Apple IIGS disk operating system (PRODOS) format was converted to a Microsoft Windows XP format using a Macintosh Power PC computer and then converted to a Microsoft Excel spreadsheet format. The measurements made on the 3D images were generated automatically and entered into a Microsoft Excel spreadsheet.

Basic descriptive statistical analysis was carried out for each variable. Study variables included mesio-distal crown diameters, arch widths, arch depths and arch lengths. In this study, arch length was calculated by summing up the mesio-distal tooth widths of all teeth (first molar to first molar) in each arch.

Single pass Z-score analysis was carried out to look for frank errors and to identify any outlying values.

F-tests were carried out to determine whether there were any significant sex differences in variance for each variable (tooth type). F values were calculated by dividing the square of the larger male or female standard deviations by the smaller one.

Paired t-tests were carried out to determine any significant differences in tooth size between right and left sides and between the sexes. While unpaired t-tests were used to make comparisons.

5.8.1 Bland-Altman Limits of Agreement

To assess the reliability of measuring tooth size with 2D or 3D digital images, the Bland Altman Test was used.

Bland and Altman proposed a simple technique to assess the agreement between two sets of observations derived from the same sample[99]. The Bland-Altman technique consists of analysis and graphical visualization of the differences between two sets of observations. Graphical techniques are useful in method comparison studies, as the visual representations may be easily understood and appreciated. The plots are commonly used to distinguish whether two measurement techniques are comparable.

The plots were used to determine:

1. The agreement between the two methods. That is, whether the two methods were comparable in their measuring of the tooth widths.
2. Which of the two methods was the most reproducible and hence accurate.

Reproducibility or reliability is the closeness of successive measurements of the same object.

The generation of the Bland and Altman plots was achieved as follows:

1. Compute the differences between each pair of observations.
2. Compute the mean and standard deviation of the differences.
3. Plot the differences of each observation against their mean.
4. Include the 95% limits of agreement, i.e., 2 standard deviations either side of the mean difference.

Plotting the differences of each observation against their mean is considered a better way of displaying data, as it allows the investigation of any possible relationship between the discrepancies and the true value [99]. If the measurements are comparable, the differences should be small, scattered tightly around zero and show no systematic variation with the mean of the measurement pairs.

6. Results

6.1 Method Error

Method error tests were carried out for both 2-dimensional photographic data and 3D surface scanner data to assess the degree of error attributed to the method of producing data. The basis of the error study consisted of double determination of variables through repetition of landmark identification and the digitization process for 20% of the original sample chosen randomly. The working level of significance was set at $p<0.05$ for all statistical tests. Each variable was tested for systematic (paired t tests) and random error (Dahlberg values). The Dahlberg value quantifies the magnitude of random error and allows us to locate where the true value will lie.

6.1.1 Error of overall method -

2D photographic digitisation system

Each variable was tested for systematic (paired t tests) and random error (Dahlberg values) as shown in Table 2 & 3.

Table 2: Method error for 2D digitisation process : Results for double determinations for mesio-distal individual tooth widths in the upper arch (mm).

Tooth	*N*	*Mean Difference*	*SD*	*SE*	*Dahlberg*	*E(var) %*	*t value*	*p-value*	*Sig*
16	22	0.16	0.47	0.18	0.316	9.9	0.94	0.38	
15	22	-0.06	0.38	0.14	0.125	1.6	-0.46	0.66	
14	22	0.02	0.57	0.21	0.045	0.2	0.11	0.91	
13	22	-0.22	0.58	0.22	0.425	18.0	-1.03	0.34	
12	22	-0.13	0.25	0.09	0.254	6.4	-1.40	0.21	
11	22	0.09	0.61	0.23	0.181	3.2	0.42	0.69	
21	22	0.06	0.35	0.13	0.123	1.5	0.50	0.63	
22	22	-0.20	0.74	0.28	0.383	14.6	-0.73	0.49	
23	22	-0.22	0.49	0.18	0.420	17.6	-1.20	0.27	
24	22	-0.03	0.35	0.13	0.065	0.4	-0.26	0.80	
25	22	0.01	0.38	0.14	0.015	0.02	0.06	0.95	
26	22	0.06	0.43	0.16	0.122	1.4	0.40	0.70	

Table 3: Method Error 2D digitisation process Method Error : Results for double determinations for individual mesio-distal tooth widths in the lower arch (mm).

Tooth	*N*	*Mean Difference*	*SD*	*SE*	*Dahlberg*	*E(var) %*	*t value*	*p-value*	*Sig*
36	22	0.32	0.34	0.13	0.601	36.1	2.44	0.05	*
35	22	0.14	0.18	0.07	0.270	7.2	2.06	0.08	
34	22	0.38	0.13	0.05	0.719	31.6	7.60	0.01	*
33	22	-0.10	0.50	0.19	0.192	3.6	-0.53	0.61	
32	22	0.28	0.29	0.11	0.529	27.9	2.58	0.04	*
31	22	0.28	0.44	0.16	0.537	28.8	1.71	0.13	
41	22	0.25	0.18	0.06	0.484	23.4	3.79	0.01	*
42	22	0.23	0.31	0.12	0.436	19.0	1.93	0.10	
43	22	0.28	0.45	0.17	0.537	28.8	1.65	0.14	
44	22	0.14	0.45	0.17	0.273	7.4	0.85	0.42	
45	22	0.03	0.20	0.07	0.072	0.5	0.50	0.63	
46	22	-0.02	0.52	0.19	0.045	0.2	-0.12	0.90	

Significant t-tests are starred

The critical t value for N= 22 (df = 21) and p = 0.05 was 2.45. The variables that showed systematic error (t > 2.45) in mesio-distal tooth width measurements were the lower right central, left lateral, first premolars and left first molar . No evidence of significant systematic error was found in the upper arch measurements.

The following variables showed error variance values, E(var), greater than 10% of observed variance,

Upper arch:

- Canines (Teeth 13, 23)
- Left lateral incisor (Tooth 22)

Lower Arch:

- Left molar (Tooth 36)
- Left first premolar (Tooth 34)
- Incisors (Teeth 31, 32, 41, 42).

These findings indicate that error in the overall method had the potential to bias the results, in particular the arch length measurement as it is a summation of the mesio-distal widths of all the teeth in one arch. Therefore, any interpretation of results for the following variables should take into account the possible effect of systematic error,

- Mesio-distal widths of the lower central incisors
- Mesio-distal widths of the lower lateral incisors
- Mesio-distal widths of the lower first premolars
- Mesio-distal widths of the lower left first molars

6.1.2 Error of overall method - 3D digitization system

The basis of the error study for the 3D digitization method was the same as that done for the 2D method. Double determination of variables through repetition of landmark identification and digitization process for 20% of the original sample chosen randomly was carried out. The working level of significance was again set at $p<0.05$ for all statistical tests. Each variable was tested for systematic (paired t tests) and random error (Dahlberg values) as shown in Table 4 & 5.

Table 4: Method error for 3D digitisation process (n=4) : Results for double determinations for mesio-distal tooth widths of the upper arch (mm).

Tooth	*N*	*Mean Difference*	*SD*	*SE*	*Dahlberg*	*E(var)%*	*t value*	*p-value*	*Sig*
16	4	-0.25	0.42	0.21	0.354	12.5	-1.19	0.32	
15	4	0.05	0.32	0.16	0.071	0.5	0.31	0.77	
14	4	-0.04	0.14	0.07	0.060	0.3	-0.58	0.60	
13	4	0.04	0.68	0.34	0.060	0.3	0.13	0.90	
12	4	0.29	0.90	0.45	0.421	17.7	0.66	0.55	
11	4	-0.05	0.39	0.19	0.081	0.6	-0.29	0.78	
21	4	-0.14	0.05	0.02	0.209	4.3	-5.91	0.01	*
22	4	-0.22	0.32	0.16	0.322	10.3	-1.42	0.25	
23	4	0.07	0.73	0.36	0.103	1.0	0.20	0.85	
24	4	0.11	0.46	0.23	0.156	2.4	0.47	0.67	
25	4	-0.12	0.13	0.06	0.173	2.9	-1.84	0.16	
26	4	-0.12	0.41	0.20	0.173	2.9	-0.59	0.59	

Significant t-tests are starred

Table 5: Method error for 3D digitisation process (n=4 lowers) : Results for double determinations for mesio-distal tooth widths of the lower arch (mm).

Tooth	*N*	*Mean Difference*	*SD*	*SE*	*Dahlberg*	*E(var)%*	*t value*	*p-value*	*Sig*
36	4	0.00	0.15	0.09	0.004	0.0	-0.04	0.97	
35	4	0.09	0.27	0.15	0.114	1.2	0.60	0.61	
34	4	-0.12	0.45	0.26	0.155	2.4	-0.48	0.67	
33	4	-0.02	0.30	0.17	0.033	0.1	-0.15	0.89	
32	4	0.06	0.61	0.35	0.073	0.5	0.17	0.88	
31	4	-0.37	0.11	0.06	0.457	20.8	-5.54	0.03	*
41	4	-0.09	0.35	0.20	0.118	1.3	-0.47	0.68	
42	4	0.06	0.54	0.31	0.078	0.6	0.20	0.85	
43	4	-0.47	0.69	0.40	0.580	33.6	-1.18	0.35	
44	4	-0.18	0.26	0.15	0.220	4.8	-1.19	0.35	
45	4	-0.58	0.30	0.17	0.714	50.9	-3.37	0.07	
46	4	0.23	0.46	0.26	0.286	8.1	0.87	0.47	

Significant t-tests are starred

The critical t value for N =4 (df = 3) and p = 0.05 is 3.18.

The only variables that showed systematic error (t > 3.18) in mesio-distal tooth width measurements were:

- Upper left central incisor
- Lower left central incisor

The variables that showed significant error variance (E(var) >10%) were:

Upper:

Right first molar (tooth 16)

Lateral incisors (tooth 12 and 22)

Lower:

Left central incisor (tooth 31)

Right lower canine (tooth 43)

Right second premolar (tooth 45)

6.2 Sample size and age groups studied

A total of 49 subjects were selected from the collection held at the University of Adelaide. The total sample consisted of 25 females and 24 males who met the selection criteria. All of these subjects were found to have upper and lower study models at or close to the age groups being studied; 8, 12 and 15 years as shown below (Tables 6 & 7).

Table 6: Male subjects at observed ages
(x indicates the ages at which study models were available for the subject)

		AGE					
MALE	**7**	**8**		**12**		**15**	**16**
184	**x**			**X**		**x**	
253	**x**			**X**			**X**
254		**x**		**X**		**x**	
300		**x**		**X**		**x**	
301		**x**		**X**		**x**	
302		**x**		**X**		**x**	
303		**x**		**X**		**x**	
304		**x**		**X**		**x**	
320		**x**		**X**			**X**
330		**x**		**X**		**x**	
357		**x**		**X**		**x**	
359		**x**		**X**		**x**	
361		**x**		**X**		**x**	
362		**x**		**X**		**x**	
363		**x**		**X**		**x**	
366		**x**		**X**		**x**	
367	**x**			**X**		**x**	
368	**x**			**X**		**x**	
451	**x**			**X**		**x**	
525		**x**		**X**		**x**	
572		**x**		**X**		**x**	
574		**x**		**X**		**x**	
581	**x**			**X**		**x**	
600		**x**		**X**		**x**	
Total	**6**	**17**		**21**		**21**	**2**
Grand Total		**24**		**24**		**24**	

Table 7: Female subjects at observed ages.

(x indicates the ages at which study models were available for the subject)

			AGE					
FEMALE	**7**	**8**	**9**		**12**		**15**	**16**
40		**x**			**x**		**x**	
155		**x**			**x**		**x**	
252			**x**		**x**		**x**	
313		**x**			**x**		**x**	
321		**x**			**x**		**x**	
322			**x**		**x**		**x**	
324		**x**			**x**			**x**
327	**x**				**x**		**x**	
371		**x**			**x**		**x**	
376		**x**			**x**		**x**	
379		**x**			**x**		**x**	
380		**x**			**x**		**x**	
381		**x**			**x**		**x**	
413		**x**			**x**		**x**	
414			**x**		**x**			**x**
415	**x**				**x**		**x**	
473	**x**				**x**		**x**	
479		**x**			**x**		**x**	
507		**x**			**x**		**x**	
549		**x**			**x**		**x**	
550		**x**			**x**		**x**	
571	**x**				**x**		**x**	
576			**x**		**x**			**x**
585		**x**			**x**		**x**	
632		**x**			**x**		**x**	
Total	**4**	**17**	**4**		**25**		**25**	
Grand Total		**25**			**25**		**25**	

The age groups were labeled T1, T2, T3 (and T4: present in subsample measurements) as shown below:

Age 7-9	**T1**
Age 12	**T2**
Age 15+	**T3**
Age 18+	**T4**

6.2.1 Subsample for 3D digitization Method

Due to financial and logistical problems the sub-sample used to test the 3D digitiization method was restricted to 5 male individuals who had records obtained at four age groups, 8, 12, 15, 18 years as shown below (Table 8).

Table 8: Subsample for 3D digitisation.

MALE	Age 7-8	12	15	18
184	x	x	X	X
253	age 6	x	X	X
254	x	x	X	X
303	x	x	X	X
320	x	x	X	X
Total sample = 5				
Total U + L models	10	10	10	10

6.3 Statistical Analysis

6.3.1 Normality Testing

All data were first tested for normality. This was performed using histogram analysis and box and whisker plots for each variable (mesio-distal tooth widths) (Figure 22). For all variables (MD tooth widths), the data appeared to be evenly distributed with no significant deviation from normality. Estimates of skewness and kurtosis showed no clear trends of significant lack of normality in data distribution for the variables. The variables could, therefore, be accepted as being normally distributed and described adequately in terms of means and standard deviations.

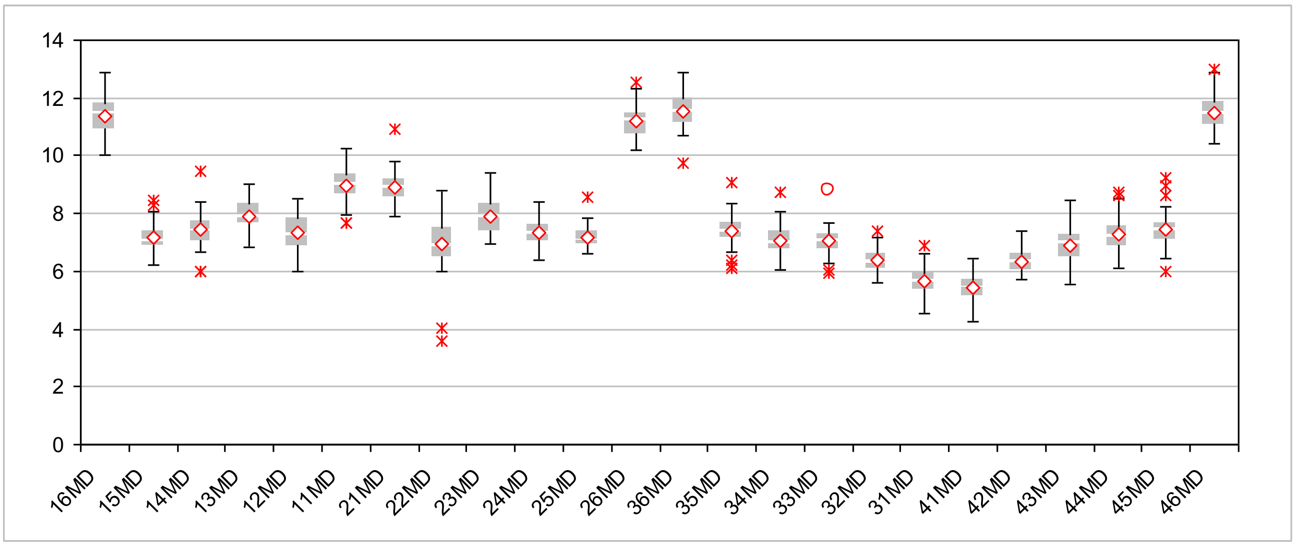
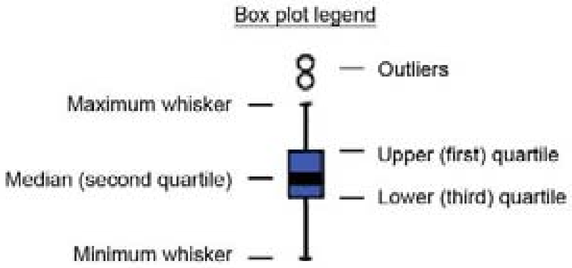


Figure 22: Box and Whisker chart of mesio-distal tooth widths (mm).



6.3.2 Descriptive Statistics – Mesio-distal tooth widths (2 D method)

Descriptive statistics are outlined below for all mesio-distal tooth widths at Age 12 (T2). This age was selected as most representative of the full width of each tooth calculated for each tooth type at T2. Descriptive statistics were initially determined by sex for males (Table 9) and females (Table 10).

Table 9: Descriptive statistics for males for mesio-distal tooth widths.

		(mm)				
	Tooth	**n**	**Mean**	**sd**	**Min**	**Max**
Male	**11**	20	8.9	0.6	7.7	10.2
	12	21	7.3	0.6	6	8.5
	13	21	7.9	0.7	6.8	9.0
	14	21	7.4	0.7	6	9.4
	15	18	7.1	0.5	6.2	8.4
	16	21	11.4	0.5	10	12.9
	21	21	8.9	0.7	7.9	10.9
	22	21	6.9	0.8	3.6	8.8
	23	21	7.9	0.6	7.0	9.4
	24	20	7.4	0.5	6.4	8.4
	25	17	7.2	0.4	6.6	8.6
	26	21	11.2	0.6	10.2	12.6
	31	24	5.7	0.5	4.5	6.9
	32	24	6.4	0.4	5.6	7.4
	33	23	7.1	0.6	5.9	8.8
	34	22	7.1	0.6	6.1	8.8
	35	20	7.4	0.6	6.1	9.0
	36	24	11.5	0.7	9.8	12.9
	41	24	5.4	0.4	4.3	6.4
	42	24	6.4	0.3	5.7	7.4
	43	23	6.9	0.6	5.5	8.5
	44	22	7.3	0.6	6.1	8.7
	45	21	7.4	0.6	6.0	9.2
	46	24	11.5	0.6	10.4	13

Table 10: Descriptive statistics for females for mesio-distal tooth widths.

		(mm)				
	Tooth	**n**	**Mean**	**sd**	**Min**	**Min**
Female	**11**	20	8.9	0.6	7.7	9.8
	12	21	7.3	0.7	6.3	8.5
	13	20	7.8	0.4	7.2	8.6
	14	21	7.4	0.6	6.0	8.4
	15	20	7.2	0.5	6.6	8.4
	16	21	11.4	0.7	10.0	12.9
	21	19	8.9	0.5	7.9	9.6
	22	19	6.6	1.2	3.6	8.3
	23	19	7.7	0.5	7.0	8.8
	24	19	7.3	0.4	6.8	8.4
	25	19	7.2	0.3	6.6	7.8
	26	20	11.2	0.5	10.2	12.6
	31	25	5.7	0.6	4.7	6.9
	32	25	6.4	0.4	5.8	7.2
	33	25	7	0.3	6.3	7.5
	34	25	7	0.5	6.1	8.1
	35	24	7.4	0.5	6.1	8.3
	36	25	11.5	0.5	10.7	12.7
	41	25	5.5	0.5	4.7	6.4
	42	25	6.3	0.4	5.7	7.4
	43	25	6.7	0.5	5.8	7.4
	44	25	7.2	0.6	6.1	8.7
	45	24	7.5	0.6	6.0	8.9
	46	25	11.5	0.6	10.5	12.9

6.3.3 Sex Comparisons

F-tests were carried out to determine whether there were any significant sex differences in variances for each variable. These were calculated by dividing the square of the larger male or female standard deviation by the smaller one (Table 11). It is expected that one in twenty of the F or T tests will be significant due purely to chance.

Table 11 : Summary of male and female descriptive statistics comparison

	MALE			**FEMALE**				
Tooth	**N**	**Mean**	**Sd**	**N**	**Mean**	**Sd**	**F Test**	**T Test**
11	20	8.9	0.6	20	8.9	0.6	0.72	0.68
12	21	7.3	0.6	21	7.3	0.7	0.65	0.57
13	21	7.9	0.7	20	7.8	0.4	0.01	0.2
14	21	7.4	0.7	21	7.4	0.6	0.38	0.97
15	18	7.1	0.5	20	7.2	0.5	0.92	0.67
16	21	11.4	0.5	21	11.4	0.7	0.28	0.82
21	21	8.9	0.7	19	8.9	0.5	0.16	0.73
22	21	6.9	0.8	19	6.6	1.2	0.1	0.06
23	21	7.9	0.6	19	7.7	0.5	0.57	0.12
24	20	7.4	0.5	19	7.3	0.4	0.77	0.99
25	17	7.2	0.4	19	7.2	0.3	0.32	0.55
26	21	11.2	0.6	20	11.2	0.5	0.32	0.68
31	24	5.7	0.5	25	5.7	0.6	0.39	0.96
32	24	6.4	0.4	25	6.4	0.4	0.49	0.45
33	23	7.1	0.6	25	7.0	0.3	0.00	0.19
34	22	7.1	0.6	25	7.0	0.5	0.79	0.44
35	20	7.4	0.6	24	7.4	0.5	0.38	1
36	24	11.5	0.7	25	11.5	0.5	0.18	0.52
41	24	5.4	0.4	25	5.5	0.5	0.82	0.16
42	24	6.4	0.3	25	6.3	0.4	0.3	0.6
43	23	6.9	0.6	25	6.7	0.5	0.44	0.08
44	22	7.3	0.6	25	7.2	0.6	0.87	0.14
45	21	7.4	0.6	24	7.5	0.6	0.92	0.49
46	24	11.5	0.6	25	11.5	0.6	0.79	0.68

Significant f tests at the $p<0.05$ level are shaded in yellow

The t and F values illustrate no statistically significant differences between males and females except for the mesio-distal width of tooth 13. Table 12 below defines the male versus female delta values, the gross difference between each male and female variable.

Table 12: Male vs Female Delta values

	MALE			FEMALE			
Tooth	**N**	**Mean**	**sd**	**n**	**Mean**	**sd**	***M-F Delta***
11	20	8.9	0.6	20	8.9	0.6	*0*
12	21	7.3	0.6	21	7.3	0.7	*0.1*
13	21	7.9	0.7	20	7.8	0.4	*0.1*
14	21	7.4	0.7	21	7.4	0.6	*0*
15	18	7.1	0.5	20	7.2	0.5	*0*
16	21	11.4	0.5	21	11.4	0.7	*0*
21	21	8.9	0.7	19	8.9	0.5	*0*
22	21	6.9	0.8	19	6.6	1.2	*0.3*
23	21	7.9	0.6	19	7.7	0.5	*0.2*
24	20	7.4	0.5	19	7.3	0.4	*0*
25	17	7.2	0.4	19	7.2	0.3	*0*
26	21	11.2	0.6	20	11.2	0.5	*0*
31	24	5.7	0.5	25	5.7	0.6	*0*
32	24	6.4	0.4	25	6.4	0.4	*0.1*
33	23	7.1	0.6	25	7	0.3	*0.1*
34	22	7.1	0.6	25	7	0.5	*0*
35	20	7.4	0.6	24	7.4	0.5	*0*
36	24	11.5	0.7	25	11.5	0.5	*0*
41	24	5.4	0.4	25	5.5	0.5	*0*
42	24	6.4	0.3	25	6.3	0.4	*0.3*
43	23	6.9	0.6	25	6.7	0.5	*0.2*
44	22	7.3	0.6	25	7.2	0.6	*0*
45	21	7.4	0.6	24	7.5	0.6	*0*
46	24	11.5	0.6	25	11.5	0.6	*0*

Both males and females exhibited a similar pattern of tooth size (Figure 23)

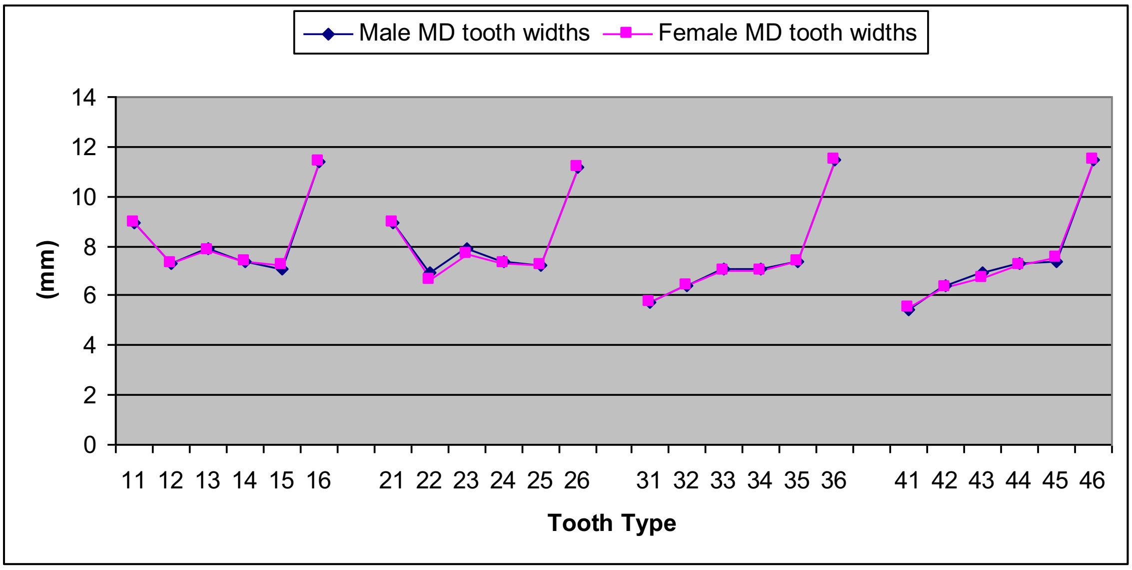


Figure 23: Male and Female MD tooth widths showing little difference in size.

As the results showed little or no significant differences between male and female mesio-distal crown widths, the sample was pooled for the following tests (Figure 24 & 25).

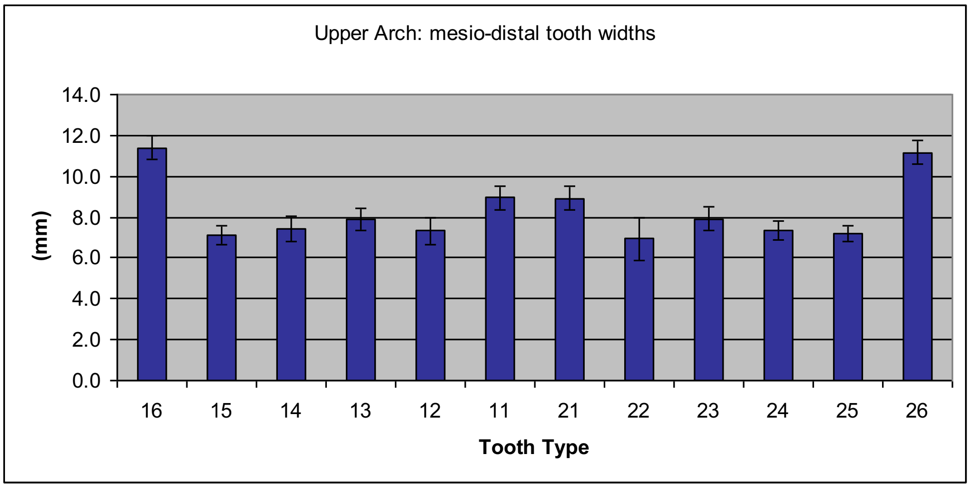


Figure 24 : Summary graph of the upper arch mesio-distal tooth widths for the pooled sample.

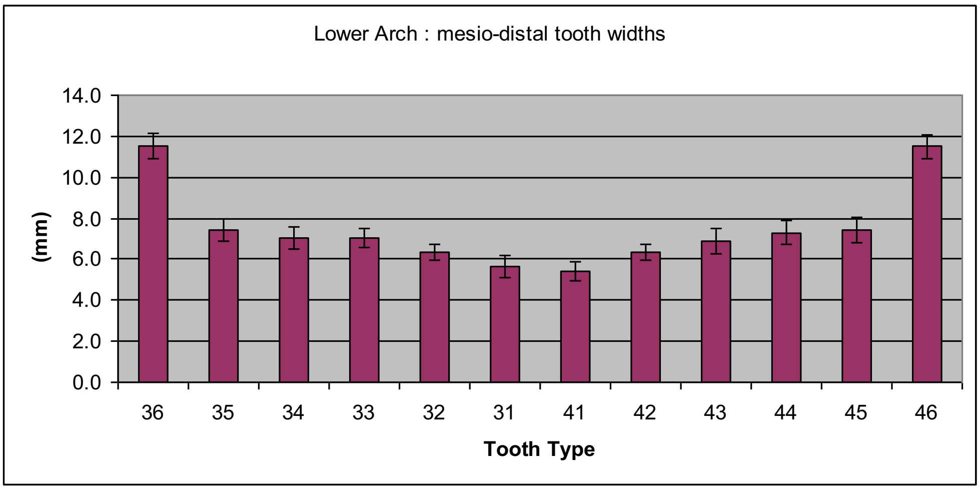


Figure 25: Summary graph of the lower arch mesio-distal tooth widths for the pooled sample.

6.3.4 Right versus Left comparisons

Paired t tests were used to determine whether significant differences were present between antimeric pairs of teeth at T2 for upper (Table 13) and lower (Table 14) arches.

Table 13: Comparing MD widths of the teeth on the Right versus Left sides in the upper arch.

Tooth	n	Mean (R)	SD (R)	Mean (L)	SD (L)	t-test
6	36	11.4	0.5	11.2	0.5	0.01
5	30	7.1	0.4	7.2	0.4	0.53
4	34	7.4	0.5	7.4	0.6	0.07
3	35	7.9	0.5	7.9	0.6	0.71
2	35	7.3	0.6	6.9	0.6	0.00
1	32	8.9	0.6	8.9	0.6	0.68

Table 14: Comparing MD widths of the teeth on the Right versus Left sides in the lower arch.

Tooth	n	Mean (R)	SD (R)	Mean (L)	SD (L)	t-test
6	42	11.5	0.6	11.5	0.6	0.79
5	38	7.4	0.6	7.4	1	0.48
4	41	7.3	0.5	7.1	0.6	0.03
3	43	6.9	0.6	7.1	0.4	0.01
2	44	6.4	0.5	6.4	0.4	0.94
1	44	5.4	0.6	5.7	0.6	0.00

At T2

The t test values comparing right versus left changes at age 12 illustrate that overall the differences between mean values obtained for corresponding right and left teeth were small; 0mm to 0.4 mm in the upper arch and -0.2mm to 0mm in the lower arch.

6.3.5 Arch Length

Arch length at age 8 (T1) was not calculated for two reasons:

1. The primary aim for this particular part of the analysis was to observe changes in arch length associated with changes in mesio-distal widths of individual permanent teeth in the arch therefore study models with unerupted or primary teeth were not used.

2. The high number of missing permanent teeth and or primary teeth at T1 (age 8) resulted in an inadequate sample number for some teeth types.

The mesio-distal widths of all teeth (central incisor to first molar) in each arch were summed to calculate arch length. The average values for upper and lower arches at T2 and T3 are displayed in Tables 14 and 15 and Figure 26.

The t-test showed no significant differences in arch length between T2 and T3. This indicates that the arch length remained relatively unchanged.

The mean values indicate a slight increase in arch length in the upper arch (mean delta value = 0.86mm) and decrease in the lower arch (mean delta value = 0.03mm), which are not significant. Looking at the range of the values, the large variation in minimum and maximum values is noted.

Delta values for this summed variable are reported in the last row of Table 15 and 16. Every individual in the sample with paired data has a delta value and the mean delta value is the mean change of all the delta values. The standard deviation of delta is calculated in a similar manner. Thus a standard deviation (of the delta) as large as noted in this study for both upper and lower arch lengths illustrates large individual variability that makes it impossible to infer any systematic effect of change.

Figure 26 visually demonstrates the lack of change in arch length from T2 to T3.

Table 15 Upper arch length (mm)

	Arch Length (mm) - Upper					
	N	Mean	sd	Min	Max	**t-test**
Age 12	32	99.94	4.98	91.35	115.43	
Age 15+	36	100.9	4.68	92.48	113.08	
						0.17
Delta	*26*	*-0.86*	*3.09*	*-8.47*	*3.65*	

Significant values at the p<0.05 level are highlighted

Table 16: Lower arch length (mm)

	Arch Length (mm) - Lower					
	N	Mean	sd	Min	Max	**t-test**
Age 12	44	89.97	4.04	80.38	89.97	
Age 15+	41	89.65	3.55	79.18	96.39	
						0.92
Delta	*38*	*0.03*	*2.1*	*-4.29*	*3.63*	

Significant values at the p<0.05 level are highlighted

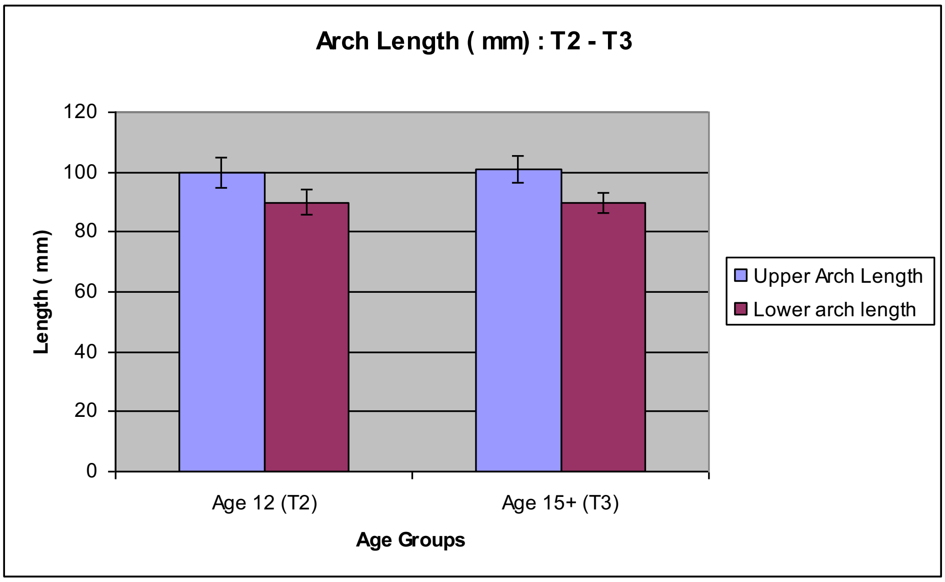


Figure 26 Arch length: upper and lower arches (mm)

6.3.6 Arch Dimensions

Digitised maxillary and mandibular centroids were used to calculate the intercanine distance (the distance between the centroid of right canine to the centroid of left canine), the intermolar distance (the distance between the centroid of the right first molar to the centroid of the left first molar) and the dental arch depth (the perpendicular distance measured from the midpoint of the most labial points of the central incisors to a line joining the distal midpoints of the first molars).

Descriptive statistics are outlined in Table 17 for all arch dimensions investigated. Delta values for the difference between upper and lower arch dimensions were also calculated and t tests carried out to determine any significant differences.

Table17: Descriptive statistics for Upper and Lower arch dimensions.

		UPPER ICW				LOWER ICW			Upper versus Lower		
	Age	**N**	**Mean**	**SD**	**Age**	**N**	**Mean**	**SD**	**Delta value**	**t test**	
T1	**8**	39	33.5	2.0	**8**	40	26.1	1.7	7.4	0.00	**ICW**
T2	**12**	40	35.3	2.7	**12**	49	27.1	1.4	8.3	0.00	
T3	**15+**	39	35.8	1.8	**15+**	44	27.6	1.4	8.2	0.00	
		UPPER IMW				**LOWER IMW**					
	Age	**N**	**Mean**	**SD**	**Age**	**N**	**Mean**	**SD**			
T1	**8**	40	48.4	2.0	**8**	43	42.2	1.6	6.2	0.00	**IMW**
T2	**12**	41	50.0	2.4	**12**	49	43.6	2.2	6.4	0.00	
T3	**15+**	39	51.5	2.4	**15+**	43	44.3	2.1	7.2	0.00	
		UPPER AD				**LOWER AD**					
	Age	**N**	**Mean**	**SD**	**Age**	**N**	**Mean**	**SD**			
T1	**8**	40	34.3	2.2	**8**	42	30.5	1.4	3.8	0.00	**AD**
T2	**12**	41	33.7	2.2	**12**	49	29.2	1.8	4.5	0.00	
T3	**15+**	39	32.7	1.9	**15+**	43	28.2	1.5	4.5	0.00	

Significant values at the $p<0.05$ level are highlighted

The t tests comparing upper versus lower for all arch dimensions revealed significant differences between upper and lower arches for intercanine, intermolar and arch depth. Figures 27, 28 and 29 illustrate that the upper arch dimensions were consistently larger than the lower arch dimensions.

6.3.6.1 Intercanine Width

The results show there was an increase in intercanine width from age 8 to age 12 years after which the changes plateau at age 15. As observed, upper intercanine width was greater than the lower.

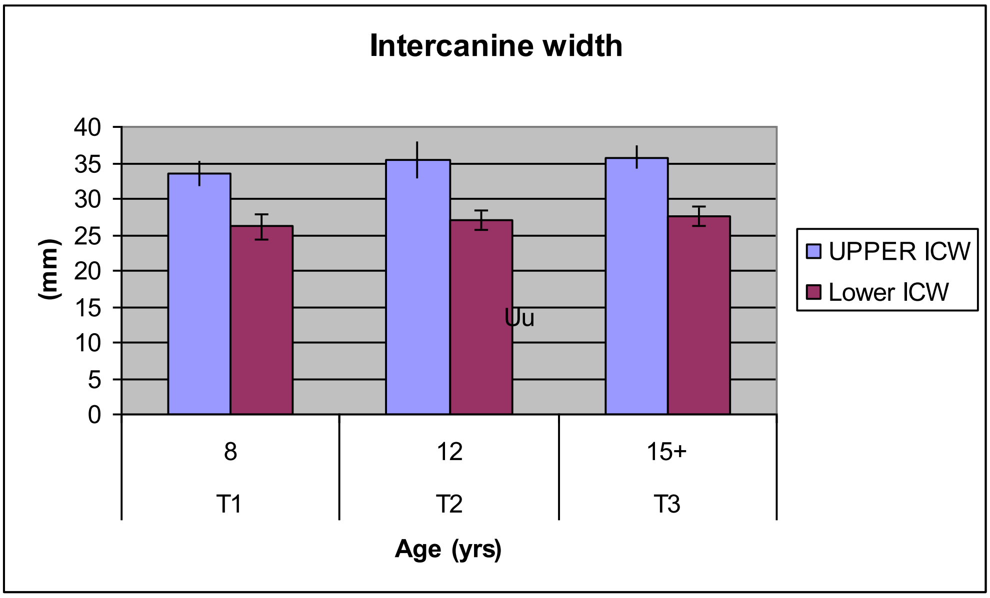


Figure 27: Upper and Lower Intercanine Widths (ICW)

6.3.6.2 Intermolar Width

Again, intermolar width was greater in the upper arch than in the lower arch. The results demonstrate an increase in both upper and lower intermolar widths with time. Patterns of change for both arches were similar.

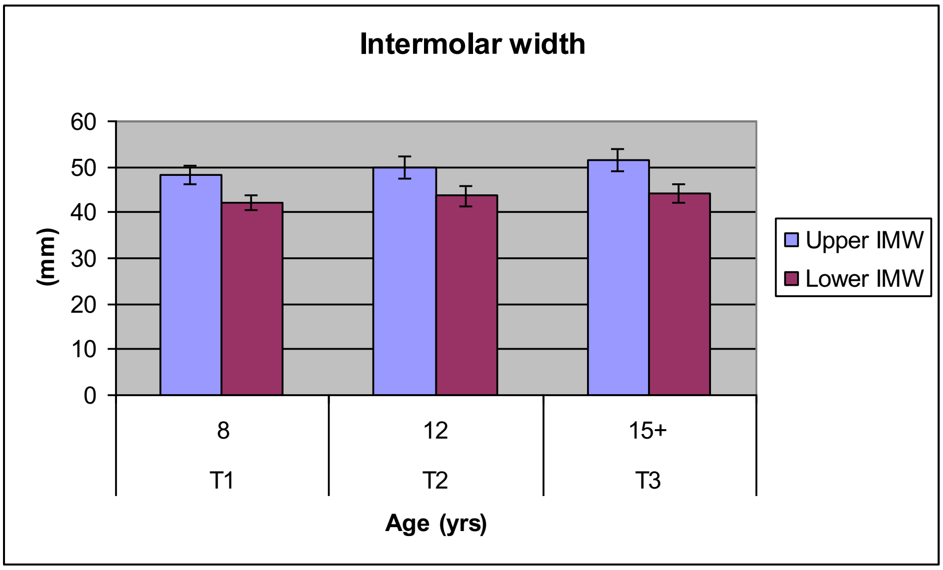


Figure 28: Upper and Lower Intermolar Widths (IMW)

6.3.6.3 Arch Depth

Arch depth was greater in the upper arch compared to the lower. The chart below (Figure 29) illustrates a decrease in arch depth from age 8 to age 12 and age 15+. The trends were similar for both arches.

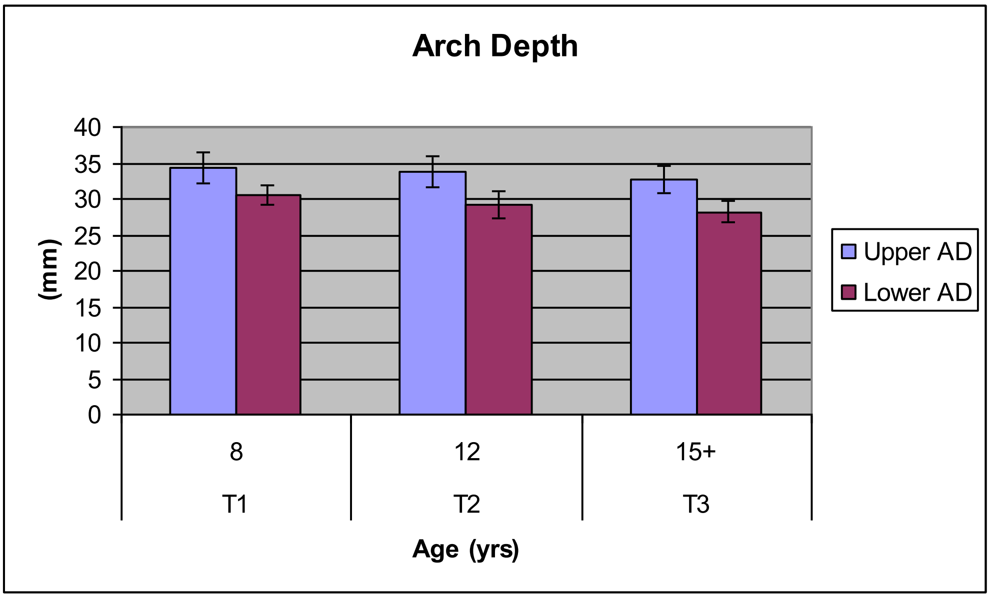


Figure 29: Upper and Lower Arch Depths (AD)

6.3.7 Comparison of Arch dimension changes with time

Delta values were calculated using paired data sets for each variable (Table 17). T-tests were carried out to demonstrate any significant changes in arch dimension with time. The results are illustrated in Table 21 below.

The t tests show that from T1 (Age 8) to T2 (Age 12) all arch dimensions except the upper arch depth showed significant differences (Table 17). Within the variables showing significant differences, upper intermolar width, upper intercanine width, lower intercanine width and lower intermolar width all displayed an increase in size with time. This is in agreement with the trend noted in the pooled sample.

From T2 to T3, all variables except the upper intercanine width showed significant differences (Table 17). From these, the upper intermolar width and lower intermolar and intercanine width showed a trend to increase in size from T2 to T3. Upper and lower arch depth appeared to be decreasing in size.

From T1-T3, all variables as expected showed significant differences in dimensional change with time (Table 17). All width measurements displayed increase with time while both upper and lower arch depths displayed a decrease from T1 – T3.

Table 18:Delta values comparing changes in arch dimensions from T1 to T2, T2 to T3 and T1 to T3.

	T1 vs. T2					
	UPPER			LOWER		
	IMW	ICW	AD	IMW	ICW	AD
N	33	31	33	43	40	42
Max	1.8	2.7	4.4	2.4	6.2	4.4
Min	-5.2	-10.8	-4.0	-5.8	-4.2	-2.4
Mean	1.6	2.0	-0.5	1.4	1.0	-1.3
SD	1.7	2.6	1.8	1.8	1.8	1.4
t-test	0.00	0.00	0.14	0.00	0.00	0.00
	T2 vs. T3					
		UPPER		LOWER		
	IMW	ICW	AD	IMW	ICW	AD
N	36	35	36	43	44	43
Max	3.9	9.2	5.5	3.3	1.4	4.1
Min	-5.1	-3.1	-1.8	-5.0	-3.1	-0.8
Mean	1.3	0.3	-1.1	0.8	0.6	-1.0
SD	2.1	2.7	1.7	1.7	0.9	1.0
t-test	0.00	0.45	0.00	0.00	0.00	0.00
	T1 vs. T3					
		UPPER		LOWER		
	IMW	ICW	AD	IMW	ICW	AD
N	31	30	31	37	35	36
Max	1.0	1.2	5.9	4.0	5.5	4.8
Min	-6.8	-6.4	-3.2	-7.2	-4.4	-0.5
Mean	3.1	2.3	-1.6	2.4	1.4	-2.4
SD	2.1	1.6	1.7	2.1	1.8	1.3
t-test	0.00	0.00	0.00	0.00	0.00	0.00

Significant values at the $p<0.05$ level are highlighted

-ve signs indicate values that have reduced in magnitude.

6.3.8 Arch Dimension- Sex Comparisons (Figure 29)

F tests were carried out to determine whether there were any significant sex differences in variances for each variable (Table 19). T tests were done to investigate any significant differences in mean values between male and female arch dimensions (Table 18).

All arch width and depth measurements were greater in male subjects but only lower arch depth showed any statistically significant difference.

Table 13: Summary of male and female descriptive staitistics comparison (Age 12).

At T2		**MALE**			**FEMALE**			
	N	**Mean**	**SD**	**N**	**Mean**	**SD**	***F Test***	***T Test***
UICW	20	35.3	2.3	20	35.1	3.2	0.16	0.6
UIMW	20	50	2.4	21	49.4	2.4	0.92	0.1
UAD	20	33.7	2.2	21	33.2	2.2	0.9	0.16
LICW	24	27.1	1.3	25	27.1	1.5	0.5	0.96
LIMW	24	43.6	2.3	25	43.2	2	0.55	0.17
LAD	24	29.2	2	25	28.6	1.5	0.17	0.02

Significant values at the p<0.05 level are highlighted

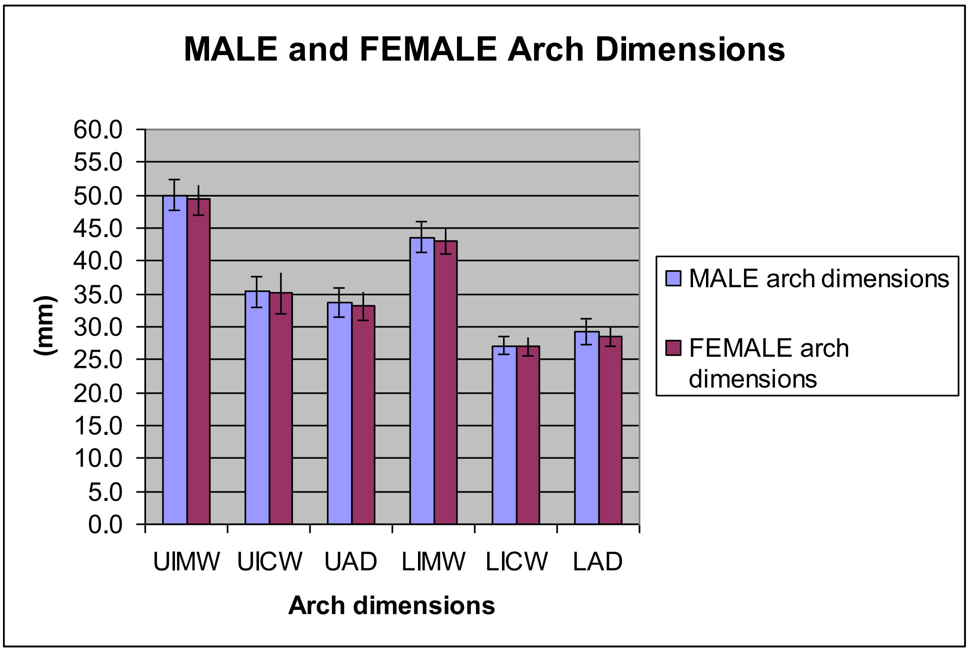


Figure30: A comparison of Male and Female Arch dimensions

6.3.7 Descriptive Statistics – Mesio-distal tooth widths (3D method)

The mesio-distal widths of all teeth, from centrals to first molars in the 5 individuals in our subsample were reanalyzed using the Minolta surface scanner and Rapidform software as described in sections 7.4.4 to 7.4.7. Descriptive statistics for the above at age 12 (T2) are outlined in Table 20.

Table20: Descriptive statistics for subsample (at age 12) for mesio-distal tooth widths measured using the 3D system (mm).

		3D System			
Tooth	**N**	**Mean**	**SD**	**Min**	**Max**
11	**5**	8.5	0.58	7.8	9.0
12	**5**	7.5	0.54	6.9	8.2
13	**5**	7.5	0.46	6.9	8.2
14	**5**	6.4	0.54	5.7	7.1
15	**5**	7.2	1.21	6.2	9.3
16	**5**	10.9	0.43	10.5	11.5
21	**5**	8.6	0.48	8	9.3
22	**5**	7.1	0.18	6.8	7.2
23	**5**	7.3	0.45	6.7	7.9
24	**5**	6.8	0.32	6.4	7.1
25	**5**	6.3	0.64	5.5	7.2
26	**5**	10.2	0.66	10.4	12.0
31	**5**	5.6	0.29	5.2	5.8
32	**5**	6.3	0.50	5.5	6.8
33	**5**	6.9	0.48	6.4	7.5
34	**5**	6.8	0.52	6.2	7.6
35	**5**	7.0	0.58	6.1	7.7
36	**5**	11.4	0.62	10.4	11.9
41	**5**	5.6	0.27	5.1	5.8
42	**5**	6.1	0.79	5.2	7.4
43	**5**	6.8	0.87	6	8.2
44	**5**	7.0	0.54	6.3	7.6
45	**5**	6.9	0.42	6.3	7.5
46	**5**	11.5	0.42	11.1	11.9

6.3.8 Comparison of results for subsample - 2D versus 3D

T-tests were used to look for significant differences between measurements carried out on the same five individuals using the two methods. The results are tabulated in Table 21 below. The results show that only 3 out of the 24 teeth compared showed significant differences:

- Upper left central incisor
- Upper left second premolar
- Lower left first premolar

This demonstrates that the two systems are broadly comparable in their measurement reliability. The variables showing significant differences are likely to be an effect of sampling error.

It is apparent that whilst the two systems are comparable there is a systematic difference in that the 2D method consistently measures tooth size larger than the 3D method. This difference, whilst not statistically significant, is relevant and is visually illustrated in Figure 31.

Table 21: Comparison of measurements (mm) obtained for 5 subjects analysed using both 2D and 3D systems.

	2D System		3D System		2D vs. 3D
Tooth	**Mean**	**SD**	**Mean**	**SD**	**t-test**
11	8.9	0.45	8.5	0.58	0.09
12	7.8	0.32	7.5	0.54	0.22
13	6.0	0.76	7.5	0.46	0.06
14	7.2	0.74	6.4	0.54	0.08
15	7.2	0.27	7.2	1.21	0.99
16	11.2	0.46	10.9	0.43	0.41
21	9.1	0.49	8.6	0.48	0.02
22	7.8	0.65	7.1	0.18	0.08
23	8.0	0.38	7.3	0.45	0.11
24	7.3	0.29	6.8	0.32	0.1
25	7.0	0.24	6.3	0.64	0.02
26	11.2	0.74	10.2	0.66	0.47
31	5.6	0.24	5.6	0.29	0.75
32	6.4	0.36	6.3	0.5	0.67
33	7.2	0.15	6.9	0.48	0.45
34	7.2	0.5	6.8	0.52	0.03
35	7.4	0.09	7.1	0.58	0.13
36	11.7	0.93	11.4	0.62	0.09
41	5.4	0.06	5.6	0.27	0.58
42	6.5	0.07	6.1	0.79	0.27
43	7.1	0.33	6.8	0.87	0.45
44	7.4	0.64	7.0	0.54	0.34
45	7.3	0.23	6.9	0.42	0.06
46	11.6	0.41	11.5	0.42	0.39

Significant values at the $p<0.05$ level are highlighted

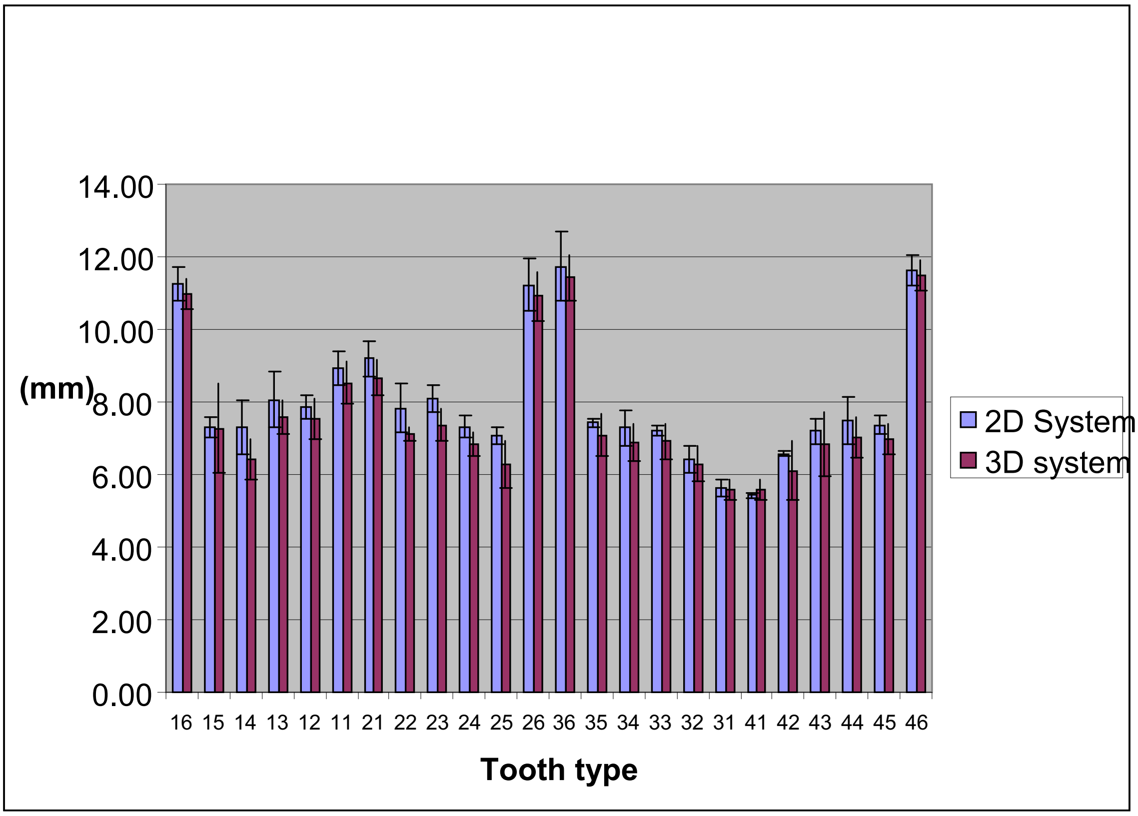


Figure 31: A comparison of mesio-distal tooth widths measured using 2D and 3D images.

The bar chart above (Figure 31) illustrates the close approximation of the measurements obtained by the two methods. The 2D system appears to consistently measure teeth larger than the 3D system. The range of the error bars explain the lack of statistical significance with this finding. This is consistent with results from the study by Santoro et al [83].

6.3.9 Comparison of 2D and 3D methods : the Bland Altman Test

Bland Altman visual plots were constructed to assess the agreement between the two sets of observations for the same five subjects for each tooth type (Figures 32 - 37). When interpreting the Bland Altman plots, the closer the mean difference is to zero the closer the two systems are in measuring the same variable. The tighter the spread of data about the mean difference, the more comparable are the systems. The Bland Altman limits are demarcated by the red lines while the black lines mark a 1mm boundary. When comparing two methods, a range of difference within 1mm of the mean difference can be considered to be clinically acceptable.

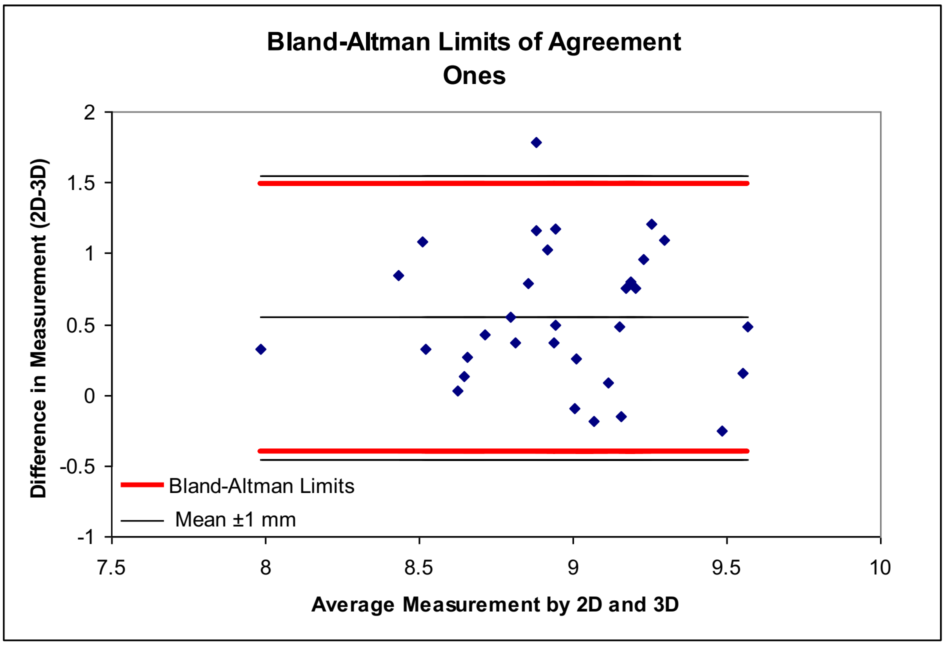


Figure 32:Bland Altman chart of the 2D system versus 3D system measurements for the central incisors.

Limits of Agreement, Centrals

Mean Difference	SD Difference	Mean-1.96*SD	Mean-1.96*SD
0.54	0.48	-0.39	1.49

97% measurements within range Mean ± 2 sd.

97 % measurements fall within 1mm range

Agreement suggested

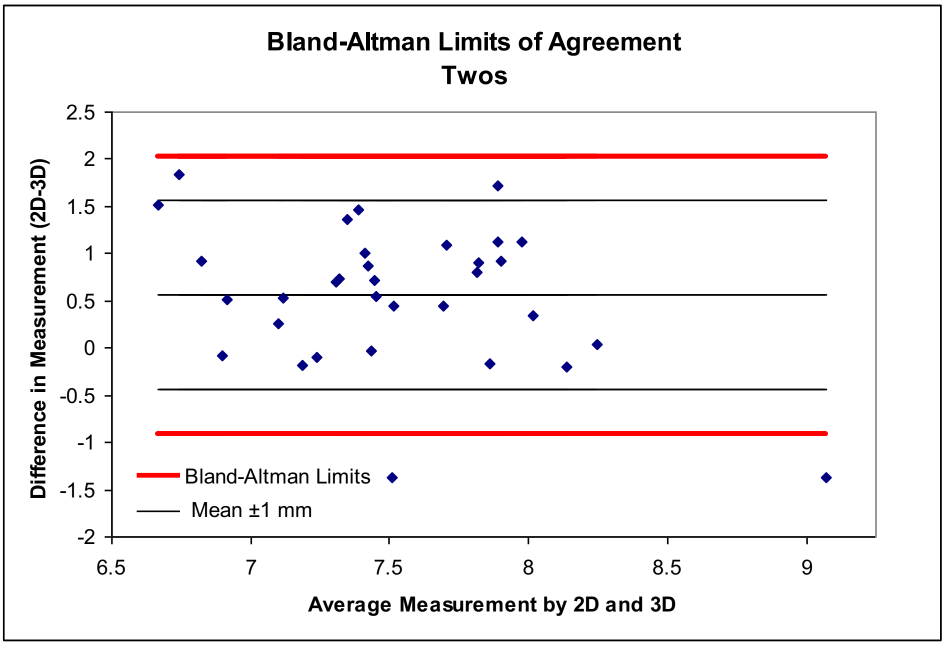


Figure 33: Figure :Bland Altman chart of the 2D system versus 3D system measurements for the lateral incisors

Limits of Agreement, Laterals

Mean Difference	SD Difference	Mean-1.96*SD	Mean-1.96*SD
0.55	0.74	-0.90	2.02

94% measurements within range Mean ± 2 SD.

86 % measurements fall within 1mm range

Agreement not suggested

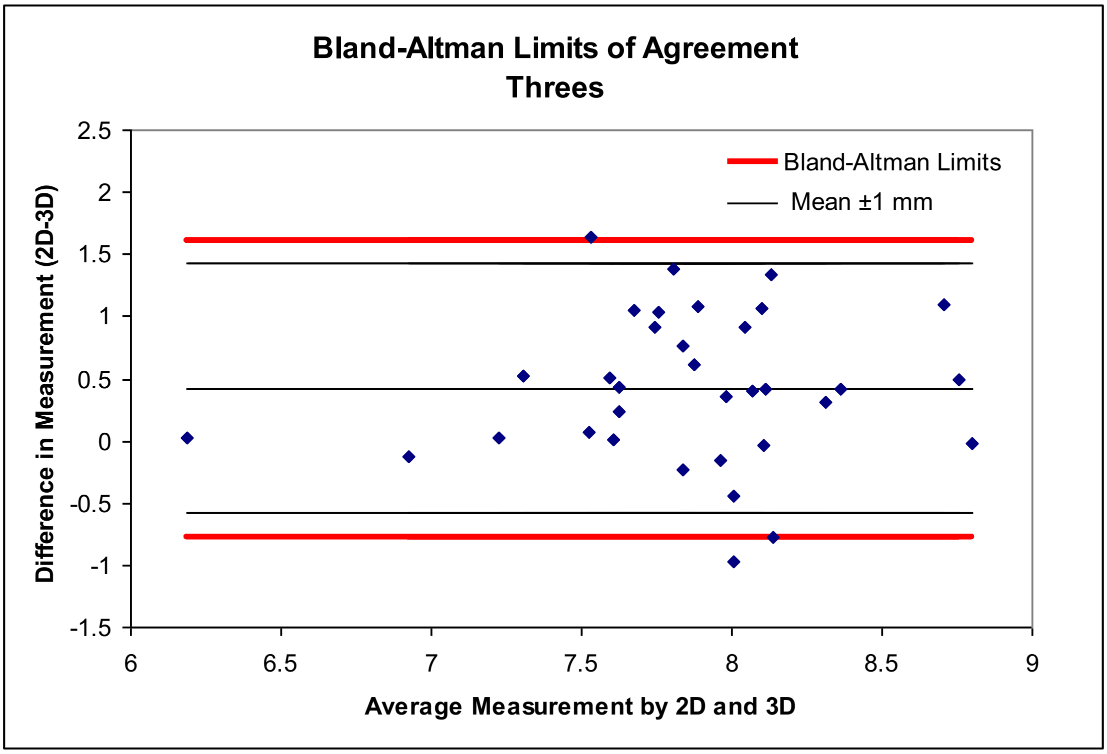


Figure 34: Bland Altman chart of the 2D system versus 3D system measurements for the canines.

Limits of Agreement, Canines

Mean Difference	SD Difference	Mean-1.96*SD	Mean-1.96*SD
0.42	0.60	-0.77	1.61

97% measurements within range Mean ± 2 SD.

91 % measurements fall within 1mm range

Agreement suggested

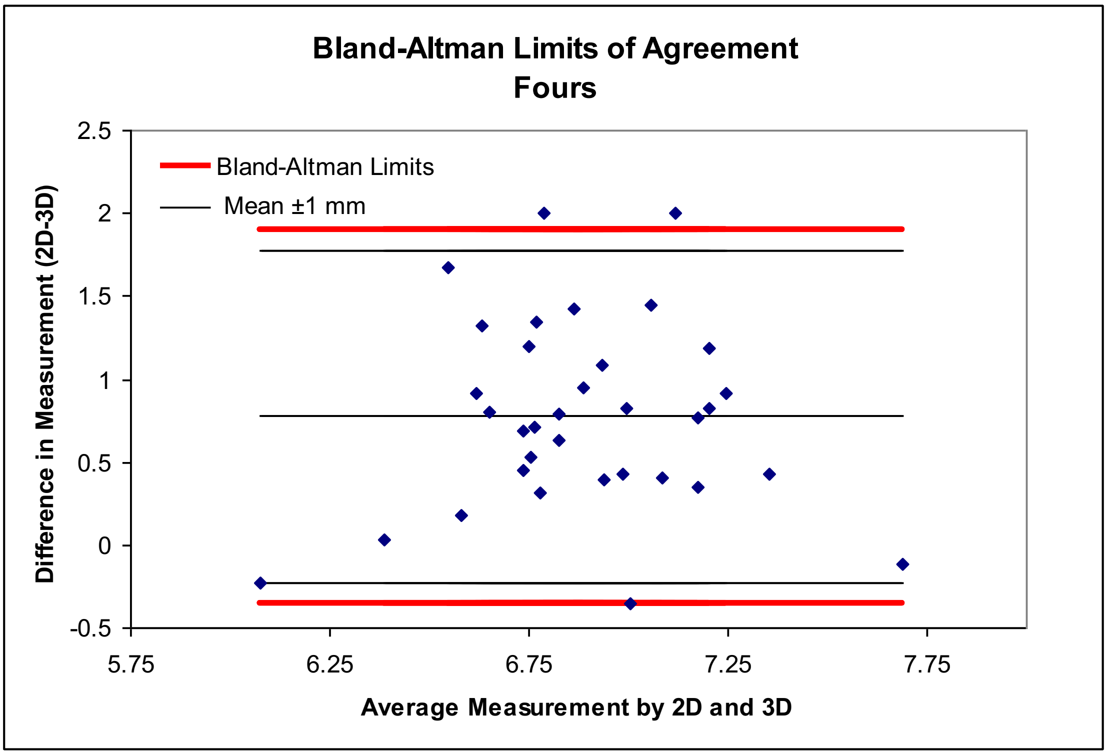


Figure 35: Bland Altman chart of the 2D system versus 3D system measurements for the first Premolars.

Limits of Agreement, First premolars

Mean Difference	SD Difference	Mean-1.96*SD	Mean-1.96*SD
0.77	0.57	-0.35	1.90

94% measurements within range Mean ± 2 SD.

88 % measurements fall within 1mm range

Agreement not suggested

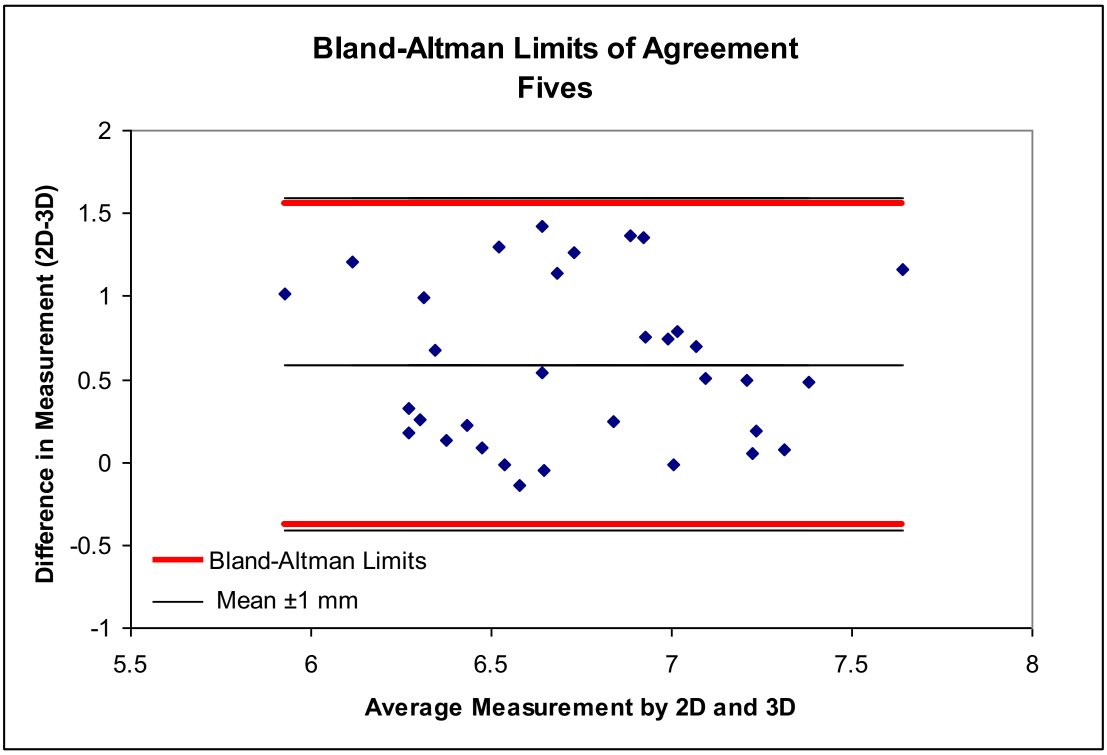


Figure 36: Bland Altman chart of the 2D system versus 3D system measurements for the second premolars.

Limits of Agreement, second premolars

Mean Difference	SD Difference	Mean-1.96*SD	Mean-1.96*SD
0.58	0.49	-0.37	1.55

100% measurements within range Mean ± 2 SD.

100 % measurements fall within 1mm range

Agreement suggested

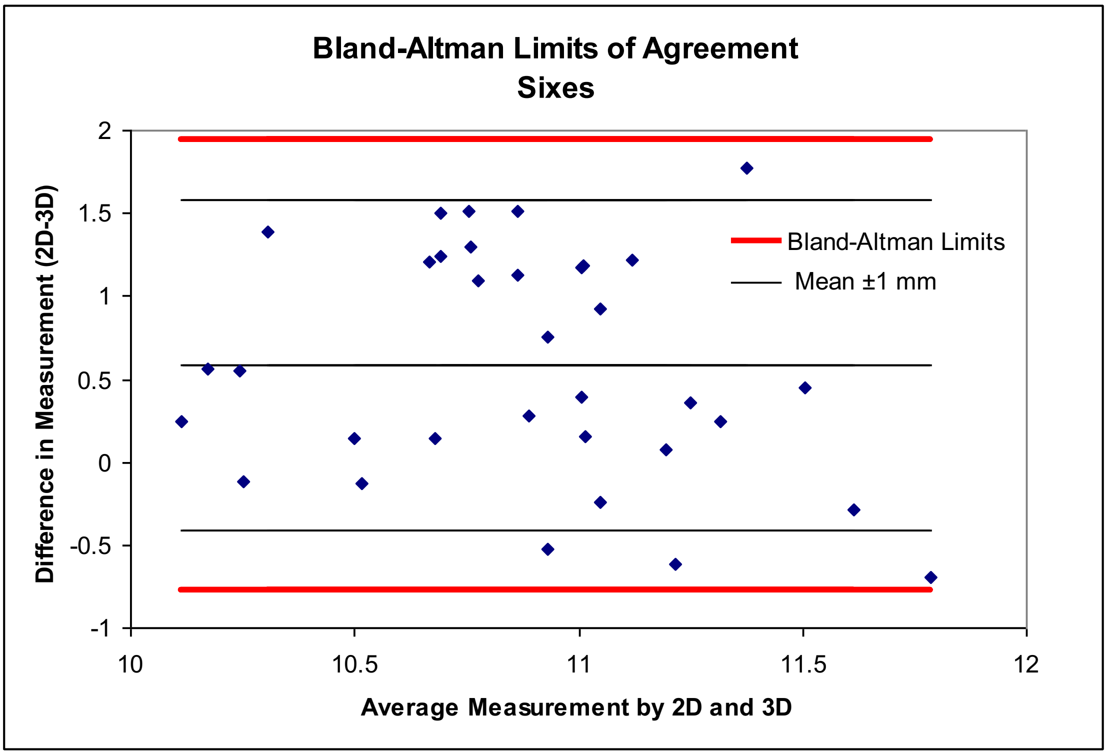


Figure 37: Bland Altman chart of the 2D system versus 3D system measurements for the first molars.

Limits of Agreement, first molars

Mean Difference	SD Difference	Mean-1.96*SD	Mean-1.96*SD
0.58	0.69	-0.76	1.93

100% measurements within range Mean ± 2 SD.

87 % measurements fall within 1mm range

Agreement suggested

The Bland Altman Limits demonstrate that for the centrals, cuspids, second bicuspids and first molars 95% measurements fell within the range of mean ± 2 sd. There is, therefore, agreement between the two methods.
Figures 25 and 27 illustrate that 94% of measurements fall within the Bland Altman limits of agreement for the lateral incisors and first bicuspids or conversely that only 6 percent of the difference between paired observations fall outside the Bland Altman limits of Mean +/- 2 standard deviations.

The overall picture gained from the Bland Altman test Is that there is a range of 0.42-0.77 in mean difference between all the measurements. As the photographic system was compared against the 3D system, the results indicate that the measurements taken from the 2 dimensional photographic method are systematically slightly larger than those measurements obtained from the virtual models scanned by the Minolta Vivid Scanner. This is in agreement with the t-test comparisons carried out in Section 8.3.8 (Table 20, Figure 31). Santoro et al [83] reported similar findings from their study comparing measurements made on digital and plaster models.

7. Discussion

There were several limitations to the study and they will be discussed in sections 7.1.1 – 7.1.5.

7.1.1 Limitations of the sample

It would have been of great interest and value to continue the investigation by following up the subjects at later age groups but we were limited by the age range of the available sample. Barrett[22] reported that one of the limitations of the original study of the Yuendumu population was that the number of subjects available for study relatively was small. He also found, that due to temporary or permanent migration, subjects were not always available for repeat examinations thus, the restricted numbers of longitudinal data sets for us to study.

7.1.2 Method of measurement

The Yuendumu sample is housed in the Murray Barrett Laboratory at the University of Adelaide. While permission was obtained to study the dental casts from that sample, limitations were placed on how it could be done. The author was not permitted to carry out any direct measurements on the casts as there was concern of further damage and loss of surface structure. As direct caliper measurements could not be carried out, alternate means of measuring the teeth had to be utilized.

7.1.3 Loss of surface detail

The Yuendumu casts have been widely and thoroughly studied for over 50 years. The scars of that use emerge as loss of detail and damage to the casts that can lead to misinformation regarding actual lengths and widths of the teeth or the dental arch. The author attempted to select cases where there were no or little obvious damage to the casts but this was not always possible as the number of subjects who met all inclusion criteria was limited.

7.1.4 Limitations of 2D images of study models

Two-dimensional representation of a 3D object poses a multitude of problems when trying to measure and calculate variables such a crown width, arch length and levels of attrition. It is difficult to accurately identify landmarks in tipped and tilted teeth as the image cannot be manipulated or rotated.

7.1.5 Limitations of 3D images of study models

The first limitation to the 3D system in this study was the location of the scanner and analysis software in Singapore. This limited the size of the subsample and the amount of time that could be spent exploring and retesting the system.

Most studies comparing measurements of teeth done on 3D versus 2D images have reported a tendency for the 3D method to measure smaller than the 2 D method [83]. Some possible reasons for this observation could be due to the lack of clarity of interproximal contact areas on digital models. Selecting maximum mesial-distal crown widths can be difficult and while 3D images have the advantage of manipulation of image to better view landmarks, some degree of over-manipulation can occur leading to subjective errors in identifying points.

7.2 Error of the overall method

The present study employed a number of steps during which a small degree of error was anticipated. A number of factors contributed to the method error of the present study. The factors contributing to the method error in both the 2D and 3D systems will also be discussed.

The overall method as outlined from Section 5.4.2 to 5.5.2 included photographing the dental casts, duplication of the subset study models, digitization of the images, identification of the landmarks and measurement of the linear variables specifically, mesial-distal tooth widths and arch dimensions; inter-molar and inter-canine widths and arch depth.

Identifiable sources of errors were:

1. Accuracy of the digital image acquired using the 2D photographic system; in particular, the vertical location in space of the calibration scale and the orientation of the image.
2. During the duplication of the subset of models for testing of the 3D method.
3. Bias in selecting reference points whilst digitizing the image
4. Inconsistencies in locating reference points during measurement
5. Frank measurement errors

Because of the variability in tooth morphology, the magnitude of the measurement error of different teeth varies. Hunter and Priest [71] found that measurements on casts were on an average of 0.1 mm larger than those of the actual teeth. However, Lundstrom[20] recorded measurements of six anterior teeth by a direct method. He claimed that no significant differences were observed between the direct and indirect methods. This could be explained by the fact that Lundstrom[20] did not measure the posterior teeth which they found difficult to measure due to inaccessibility with a direct measurement system.

7.2.1 Photographic Technique - Error of method

All images of the sample were obtained using the same photographic set up and equipment at one location. All photographs were taken by the same individual and a standardized technique was used to fix the focal lengths, level the camera and level and position the dental casts. Appropriate lighting was used to decrease shadowing.

Much effort was made to flesh out any possible areas of error introduction during the photography process. The effect of varying the ruler height from the occlusal plane was tested by re-photographing a single lower dental study model in the precise manner that the original sample had been recorded. The ruler was maintained at occlusal height, that is, level with the incisal edges. The images were then retaken with the ruler height adjusted to 3cm below and 3cm above the occlusal plane. The images were digitized using the chipmunk software program as done for the original sample. Statistical tests were run to look at random and systematic error due to the ruler height variation. The random error due to landmark identification inaccuracy was found to be insignificant and small. The systematic error introduced by altering ruler height was found to be significant and ranged from -0.2mm to +0.2mm. This is a significant method error. An error of 0.2mm per tooth would significantly affect the total arch length as arch length in this study was defined as the sum of the mesial-distal widths of all the teeth from central incisor to distal margin of the first molar. Systematic error of this magnitude causes a considerable problem in interpreting our results by obscuring the effects of changes to the mesial-distal widths of the teeth and, therefore, the total arch length.

7.2.2 Error of the overall method – 2D method

Reproducibility or reliability is defined by Houston [97] as the closeness of successive measurements of the same object. The reproducibility of the measurement varies according to the quality of the records, the conditions under which they are measured, and the care and skill of the examiner.

The results in Tables 2 and 3 illustrate some statistically significant systematic errors associated with the following variables

1. Mesial-distal width of the lower left first premolar
2. Mesial-distal width of the lower left lateral incisor and
3. Mesial-distal width of the lower right central incisor.

On closer examination of the results, the t values for the three significant variables can be explained. Variables 1 and 2 displayed very small values of standard deviation and thus small values for standard error and large t values. Variable 2 displayed a t value very close to the critical t value.

Often in the absence of double blinding, bias can be introduced because a single operator is aware that they are performing the second series of measurements and thus may do so slightly differently from the first series. Systematic errors can also arise over a period of time if a single examiner's practice changes with experience. In this study, such bias was controlled by randomizing the order in which the dental casts/images were measured, preventing the examiner from measuring the casts in chronological sequence.

The systematic error observed in measuring mesial-distal widths of teeth in the present study using the primary method (2D images) ranged from 0.01 to 0.38mm at the most. This is a small error but could be argued that values closer to 0.3mm could be significant when looking at interproximal attrition but not necessarily clinically significant when investigating tooth widths. However, some variables showed statistically significant errors and the results for these variables should be considered with the degree of associated error in mind.

When performing double determinations of the same image/cast, errors associated with landmark identification should not be ignored [97]. This is often one of the largest contributors to random error either due to identification or imprecision in its definition. In this study, random error ranged from 0.01mm to 0.6mm.

Other factors that affect random errors include material differences of the dental casts, occlusal plane differences and the tip and tilt of teeth. The 3D sub-sample could have additional errors associated with the duplication process and again the identification of landmarks. The identification of proximal points is also affected by the sharpness and contrast of the images. Partially erupted teeth or tipped teeth make it challenging to mark accurately the most proximal points. The 3D system allowed more manipulation of the image to better visualize the interproximal areas.

7.2.4 Error of the overall method – 3 D method

40 casts from five male subjects from the original sample were duplicated, scanned using the Minolta vivid 900 and digitized with the Rapidform software package as outlined in section 5.4.4 to 5.4.7.

To determine the error associated with the above methods, 8 casts were selected at random and re-measured. Systematic errors were determined by calculating the mean difference, SD difference, paired *t*-test and p value for each variable. Random errors were determined by calculating Dalhberg values (Se) and error of variance (Evar) and Reliability (R).

The results in Tables 4 & 5 illustrate some statistically significant systematic errors associated with the mesio-distal width of the upper left central incisor and the lower left central incisor.

The systematic error observed in measuring mesial-distal widths of teeth using the 3D computer generated models was 0mm to 0.58mm. and the random error or Dahlberg values ranged from 0mm to 0.71mm. Again the avenues for random error are likely to originate from inaccuracies in landmark identification. It is also possible that the increased ability to manipulate (tip, rotate, tilt) the images to locate points (which most would consider an advantage), could also lead to inaccuracies in locating points due to over analyzing of the 3D image.

7.2.5 Summary of method error

The overall method errors for this study varied according to the system used. The 2D system displayed systematic errors in the range 0.01mm to 0.38mm. The random or stochastic error ranged from 0.01mm to 0.6mm. For the 3D computer generated study models the systematic error ranged between 0mm to 0.58mm and random error associated with this method ranged from 0mm to 0.71mm.

The results from this study indicate that the magnitude order of error for different teeth varied between the two methods used. Using the 2D method, the lower left first premolars were the least accurately measured. With the 3D method, the lower left central incisors were the least accurately measured.

7.3 Mesio-distal crown widths

The estimation of individual mesio-distal tooth widths posed a methodological problem. The tooth widths were sometimes obtained from contact points which may not coincide with the points of maximum mesial-distal convexity. Although, this was not a problem in the present study (as the authors were interested in reduction in interproximal contact areas due to attrition) true mesial-distal crown widths may not be well represented. Some individuals also showed a degree of malalignment of teeth (Please refer to Appendix 9.4: 2D images of sample).

The mesio-distal crown widths of permanent teeth at age 12 are summarized in Tables 9 and 10. Although few significant differences were noted between male and female tooth size, the delta values indicate that male teeth were, on average, larger than females.

Mesio-distal crown widths were found to be comparable to previous cross-sectional studies [20-22] of the Yuendumu sample (Table 22) The range of difference in mean dimensions between the two studies was 0.01 to 0.55mm, despite the difference in numbers of individuals in the samples.

Table 22: Mesial distal tooth widths of the Yuendumu sample reported from this study and compared against similar measurements from a study by Barrett et al [20]

M-D crown diameters of Yuendumu permanent teeth measured in this study						
	MALE				FEMALE	
Sd	**Mean**	**n**	**Tooth(Maxilla)**	**n**	**Mean**	**sd**
0.65	8.9	41	**1**	39	8.9	0.55
0.7	7.1	42	**2**	40	6.95	0.95
0.65	7.9	42	**3**	39	7.75	0.45
0.6	7.4	41	**4**	40	7.35	0.5
0.45	7.2	35	**5**	39	7.2	0.4
0.55	11.3	42	**6**	41	11.3	0.6
Sd	**Mean**	**n**	**Tooth(Mandible)**	**n**	**Mean**	**sd**
0.45	5.6	48	**1**	50	5.6	0.55
0.35	6.4	48	**2**	50	6.35	0.4
0.6	7	46	**3**	50	6.85	0.4
0.6	7.2	44	**4**	50	7.1	0.55
0.6	7.4	41	**5**	48	7.45	0.55
0.65	11.5	48	**6**	50	11.5	0.55
M-D crown diameters of Yuendumu permanent teeth measured by Barrett et al						
	MALE					FEMALE
Sd	**Mean**	**n**	**Tooth(Maxilla)**	**n**	**Mean**	**sd**
0.58	9.35	130	**1**	111	9	0.58
0.63	7.65	115	**2**	104	7.34	0.63
0.57	8.31	80	**3**	84	7.95	0.41
0.46	7.69	98	**4**	86	7.53	0.41
0.43	7.19	96	**5**	83	7.01	0.44
0.52	11.34	115	**6**	109	10.92	0.5

sd	Mean	n	Tooth(Mandible)	n	Mean	sd	
0.4	5.87	136	**1**	117	5.68	0.43	
0.42	6.6	130	**2**	112	6.36	0.41	
0.46	7.49	98	**3**	95	7.01	0.38	
0.54	7.49	95	**4**	85	7.36	0.41	
0.51	7.56	89	**5**	82	7.31	0.44	
0.61	12.04	119	**6**	101	11.62	0.55	

7.3.1 Sex Comparisons

Sex differences in tooth size have been observed in other population groups and the mandibular canine often shows the most marked difference [20 100]. The results of this study illustrate no statistically significant differences between males and females except for the mesial-distal width of tooth 13. This is somewhat surprising as the author expected more evidence of sexual dimorphism as reported by several investigators in the past [20 101 102 103]. Although no significant sex differences (except for tooth 13) were found, the delta values (Table 12: male vs female delta values) showed that on average, the male laterals and canines were larger than the corresponding female teeth.

Both males and females exhibited a similar pattern of tooth size (Figure 23) Richardson et al [102] found teeth of males to be larger than those of females for each type of tooth in both arches in American blacks. Singh and Goyal [103] found similar results from their study reporting on mesial-distal widths of teeth of North Indian children. Smith et al [104] in their study on incisor shapes and crowding found males to have slightly larger average teeth dimensions than females. Moorrees [105] looked at the mesial-distal widths of North American children and reported that males had wider teeth than females. Hashim and Murshid [100] conducted a study to establish mesial-distal tooth widths of permanent teeth in a Saudi population. They too found that the canines in both jaws exhibited significant differences between the sexes while the other teeth did not. Their finding relates more to the present study in that there were differences detected in the widths of the lateral incisor and canine teeth but no others. This is in contrasts with the previously mentioned studies, where all teeth types showed an increased size in males compared to females

As the results showed no significant differences between male and female crown widths, the data were pooled for further statistical analysis.

7.4.2 Right versus left sides

The t test values comparing right versus left at age 12 illustrated that the differences between mean values obtained for corresponding right and left teeth were small; 0mm to 0.4 mm in the upper arch and -0.2mm to 0mm in the lower arch. There were significant differences between right and left sides in upper first molars and lateral incisors both of which were found larger on the right side.

Hashim and Ghamdi [100] studied tooth width and arch dimensions and found similar results in mean values of the mesial-distal width of individual teeth on the right side in the upper jaw were relatively greater than those in the left side but not statistically significant. Otuyemi and Noar [106] found no statistically significant differences between left and right sides tooth widths in a Nigerian and British population. In the present study, the lower first premolar, canine and central incisors also demonstrated significant differences. The first premolars were found to be larger on the right side while both canines and central incisors were found to be larger on the left side.

Although we expected to see some values of significance due to chance, the occurrence of five out of twelve tests that were significant indicated some level of directional asymmetry. Ballard [68] studied asymmetry in tooth size by measuring 500 sets of casts. The mesial-distal diameters of each tooth on one side of the dental arch were compared to the corresponding tooth on the opposite side. Ninety per cent of the sample demonstrated a right-left discrepancy in mesial-distal width amounting to 0.25 mm or more [68].

As there was a statistically significant size difference between corresponding teeth on the right and left, it follows that right or left side teeth could not be pooled for further statistical investigation and were thus investigated separately.

7.4.3 Comparisons with other ethnic groups

Several studies have reported tooth size variation between and within different racial groups. Keene [107] [108] reported racial differences in tooth sizes among the American Negroes and their Caucasian counterparts in caries-free naval recruits. Turner and Richardson [109] also observed significant differences in mesial-distal tooth width in Kenyan and Irish populations. In another related study, Bishara et al [110] compared the mesial-distal and bucco-lingual crown dimensions of the permanent teeth in three populations from Egypt, Mexico and the United States and found statistically significant differences between the three populations. Oteyumi and Noar [106] compared the mesial-distal and bucco-lingual crown dimensions of the permanent teeth in modern Nigerian and British populations. They reported that mesial-distal crown diameters were consistently larger in the Nigerian sample and no left-right side differences were observed.

Other than ethnicity and gender, factors that can affect tooth size variability include hereditary factors [111], bilateral differences [68], environment and secular changes [112]. Townsend and Brown [111] attempted to quantify the relative contributions of genetic and environmental influences to the observed variability of permanent tooth size in a group of Australian Aboriginals. Their analysis suggested that about 64 percent of the total variability of permanent tooth size could be attributed to genetic factors, while a further 6 percent was due to common environment. Although the findings confirm a relatively strong genetic component, they emphasised the importance of non-genetic influences such as diet and environment in the determination of tooth size variability. Garn et al [112] suggested that maternal and fetal (or gestational) determinants of both deciduous and permanent tooth crown dimensions may account for as much as half of crown-size variability.

7.5 Arch Dimension and Length changes from age 8 to age 15+

The development of dental arch dimension involves dynamic processes marked by continual changes in the positions and alignment of teeth within the alveolar bone. The arch changes observed from age 8 to 15 years are discussed in the following paragraphs. The findings refer only to arch regions from the permanent first molar forwards. Differences in size and shape of dental arches between males and females showed that the male arches were larger than female arches at corresponding ages, although not significantly so. The finding that male arches are larger is consistent with findings by Barrett et al [22], Cheng [113]. An explanation of the sex differences in size of the dental arches could be the larger mesial-distal crown diameters of the teeth of males compared with females.

Arch changes between the late mixed dentition stage and the early permanent stage involved an increase in inter-canine width from age 8 to age 12 before plateauing at age 15 years. Inter-molar width demonstrated an increase in both arches from age 8 to age 15. Arch depth decreased with age. The results show that all maxillary arch dimensions were significantly larger than the mandibular dimensions. In most studies, maxillary or mandibular (or both) widths were larger in male than in female subjects [59]. However, Slaj et al [60] investigated longitudinal arch changes using dental casts of 30 children in the early and late mixed dentitions. They reported no width or depth variables indicating statistically significant sexual dimorphism.

These changes in size and shape of the arches are almost certainly the result of positional adjustments of the teeth after exfoliation of the deciduous molars and their replacement with permanent successors having tooth crowns narrower mesial-distally. The considerably greater size reduction in mandibular arches for males compared with females could be the result of relatively greater differences between the diameters of deciduous molars and their successors. This explanation is supported by the measurements of the mesial-distal crown diameters of teeth of Australian aborigines reported by Barrett, Brown and MacDonald [20] and Margetts and Brown [114].

Studies by Bishara et al [61], Slaj et al [60] and the Craniofacial Growth Series of the Michigan Growth Study [96] indicate that most arch width dimensions are established in the early mixed dentition. The minimal width changes that occur during the late mixed dentition are not a factor that should influence a treatment plan.

It is hypothesized that interproximal wear could possibly contribute to the reduction in dental arch size. Both Campbell [66] and Begg [4] in their investigations of skeletal material of Australian aborigines found that there was considerable reduction in dental arch perimeter of length due to wear. They pointed out that the marked tooth wear of Australian aborigines living under natural conditions arose from vigorous mastication of coarse, fibrous and gritty foods.

Relatively little tooth wear was found in the aborigines of the present study and thus total arch length was not found to decrease as had been expected in a group with an attritive dietary history. The reasons for this could be the different lifestyle experienced by our sample compared to aborigines living under native conditions. The Yuendumu population had mixed eating habits with some foods high in sugars and processed flour, whereas others were more traditional hunter-gatherer type foods. Also the developmental stages selected for investigation included fairly recently erupted teeth that were observed for a relatively short period of time. It is likely the age group examined might not be the most representative of the transitory aboriginals as the children tended to stay at the reserve and not all food was prepared using traditional methods.

It is worth noting that observation of the study models and the 2D images obtained of this sample quite clearly show some casts with visible tooth wear and some that are crowded. Future studies should consider differentiating subjects with crowded, spaced and maloccluded arches, to improve the quality of information obtained. It is also apparent we require far more accurate measuring systems and tools to account for these small but visible changes.

7.6 2D images versus 3D computer generated images

Previous studies have shown that the dimensional accuracy of laser scanned digital models is within 0.05mm [15,16 17].

Smith et al [91] have reported a high correlation between their 2D and 3D measurements. The mean differences between 2D and 3D measurements were found to be between 0.0mm and 0.6mm. They did qualify their results to state that if only mesial-distal widths were considered, the range would then only be 0 to 0.1mm closer to values reported by some investigators[16]. The range of mean differences between the 2D and 3D systems measured in this study ranged from 0.0mm to 0.58mm and was larger than previous studies.

The t tests comparing tooth size measurements for the subsample showed that the two systems were broadly comparable in their measurement reliability. Reliability here is defined as the closeness of successive measurements for the same object or variable [97].

What was noted was that the measurements obtained from the 2D images were consistently larger (an average of 0.5mm) than the measurements obtained using the 3D images. This difference was not statistically significant but is relevant in studies investigating tooth size. This finding is similar to studies by Santoro et al [83] who compared digital models obtained using the OrthoCAD system and plaster models. They found that the digital measurements were smaller than the manual measurements and the magnitude of these differences ranged from 0.16 mm to 0.49 mm [83].

Bland Altman[99] visual tests were used to assess agreement between two sets of observations for the same five individuals for each tooth type. The results indicated that there is an average of 0.5mm mean difference between measurements of the same tooth by the two methods. As observed from the t tests comparisons of the two methods, the 2D method is visualized as measuring larger at each instance.

The reasons for this difference in size could be related to the increased capabilities within the 3D system to magnify contact areas for more precise landmark selection and to manipulate the images so as to more accurately reveal tipped and tilted teeth. The 2D photographic system, while allowing a certain amount of enlargement of the whole image, is limited by its static two-dimensional properties. Digitising mesial and distal points in the 2D system was complicated or limited by the examiner's inability to maneuver the model to reach the most mesial or distal points. These points would not have been accurately marked if, for example, the first molars were only partially erupted or tipped in the occlusal plane. First molars often erupt just below the distal margin of the deciduous second molars. This led to difficulties landmarking the most mesial point which was often located just under the distal marginal ridge of the deciduous molar and could account for the instances where the tooth size seemed to increase with age.

Minor alterations in the vertical position of the scaling ruler in relation to the occlusal plane whilst photographing the 2D images, has been investigated and found to contribute significant errors; in the range of -0.2mm to 0.2mm. Thus any interpretation of the results from the 2D method should take into account this additional source of error.

When comparing digital models to plaster models, some researchers believe that digital models result in more valid measurements than plaster because there is no physical barrier of the caliper dictating placement of measurement points. But the 3D system also allows one to click the mouse pointer either within or on the outside surface of the teeth. As long as a careful measuring point is selected on the computer screen, it would be reasonable to believe that digital measurements are more valid than those made by calipers on plaster. Another contributing factor to the difference between plaster and emodel measurement might be the operator's learning curve in precisely measuring with the computer mouse on the screen. In this study as we are comparing 2D versus 3D images, both systems have similar issues relating to placement of the mouse pointer in the right spot and selecting a careful measuring point.

As discussed earlier, the differences in arch length between the two methods could be due to the ability to maneuver the computer generated 3D image and attempt to pinpoint contact areas more accurately. With the 2D images, although clarity was excellent, limitations were experienced by the 2 dimensional nature of the image that did not allow compensating for tipped teeth or tilted occlusal planes. With partially erupted teeth, the mesial end is often hidden by the margins of the primary teeth and without manually rotating the study model or a 3 dimensional method of manoeuvering the models, the full mesial-distal width of the teeth would not have been selected.

In comparing plaster models with computer-based models, Quimby et al [84] reported that measurements made from computer-based models were larger than those made on plaster casts, except for overbite and overjet. They found that the differences between measurements on the two model systems were less than 1 mm [84]. Quimby et al [84] hypothesised that the larger values for measurements made on the computer-based models may have several possible sources including the increased time that elapsed before the irreversible hydrocolloid impressions were poured in plaster, the process of producing the plaster casts by the manufacturer, the process of scanning and recording data points from the plaster model, the display and measurement algorithms of the manufacturer's proprietary software, and the examiners' lack of familiarity with the computer-based measurement of computer-based models. Depending on the orthodontist's training, abilities, and preferences, measuring on a computer screen can be more or less accurate than the traditional gauge-on-cast method [83].

Other factors could have introduced some inconsistency such as an incorrect angulation during the traditional model manipulation or rounding the digital measurements to the nearest 0.5 mm [83]. As long as the smaller tooth size is generalized and uniform, it is not a threat to the diagnostic capability of the digital method, because it does not affect proportional measurements (such as Bolton analysis). However, it is a problem for research studies such as this one that are investigating changes in mesial-distal crown dimensions and long term changes in arch length and crown width.

An additional difficulty with both 2D and 3D images displayed on a 2D computer screen is the closer the points are on adjacent teeth, the harder the task of distinguishing them.

7.6.1 Virtual models

Digital or virtual models present several unique challenges compared with plaster models. Firstly the 3D computer image is displayed on a 2D screen. Although in this study we did not look at occlusion or related factors, it has been found that observing crossbites, especially in the posterior can be difficult [86]. Stevens [86] compared digital models (emodels, GeoDigm, Chanhassen,Minn) and plaster models and noted that teeth can falsely appear in crossbite or appear to have positive overjet in the posterior segment when they really do not on the 3D images on the screen. Alternatively they will seem to have a positive overjet. They concluded that it appears to depend on the amount of zoom and rotation [86]. They also noted that details for midlines, occlusal anatomy, and wear facets and precise interdigitation are not as clear on the digital emodel [86]. It is possible that these functions will improve with future software improvements.

In this study, duplication of the original study models was carried out using silicone impression material and poured up using high grade diestone within an hour of removal of the silicone impression from the original cast. The accuracy study carried out to compare duplicate and original study models showed that the duplicates were near exact replicas of the original stone models with a range in mean difference in tooth size of only 0.09 to 0.16mm.

Several companies offer computer-based three-dimensional models. Impressions of the patient's occlusion, taken in the practitioner's office, are sent to the company. At the company, models are poured up and scanned to create data points representing the surface of the teeth and the supporting soft tissue. These data points are then sent by way of the Internet to the originating dentist's office and are available to the proprietary company- supplied software, which resides on the practitioner's computer. The software allows visualization of the models in three dimensions.

Although not applicable in this study, it is important to be aware of the potential for distortion in using alginate impressions. Coleman et al[115] found significant dimensional changes between dental models poured within 1 hour of the hydrocolloid impression compared with pouring 24 hours later. This 'error' would be translated into the digital image.

With 3D or 2D computer images the learning curve for the digitisation software is relatively steep but short-lived. As Stevens [86] noted, those more familiar with computers will probably experience a shorter learning curve with 3 dimensional imaging software and be able to achieve precise measurements without complications.

The two main difficulties incurred with the 3D method involved identifying the points used to measure the teeth and the loss of 3 dimensions by using 2D images of the 3D models. Perhaps marking the models before digitizing them would have prevented this variability. In his review, Houston[97] stated that perhaps the greatest source of random errors is difficulty in identifying a particular landmark or imprecision in its definition.

7.6.2 Advantages of Computer generated 3D study models

Three dimensional measurements using the contours of the crown enable more accurate information to be gathered as it will take into account the surface curvature and not just the straight distance between two points[91]. This ability to perform 3D measurements allows various new parameters to be calculated such as volume calculations, which may be very useful in studies investigating tooth wear.

Recent studies by Quimby et al [84] , Stevens et al [86], Ho et al [116] have found computer models are reasonably reliable and accurate. They can provide the clinician with adequate information to develop a treatment plan and thus eliminate the need for storing plaster casts. The true test of clinical significance would be to determine whether treatment plans produced with computer-based models differ significantly from treatment plans produced with plaster models. In turn, the results of the treatment from the two different sets of models would determine the true value of computer-based models. It is questionable whether the differences demonstrated in this and other investigations would lead to significantly different clinical results; however, those differences are likely to pose problems for use in research investigating tooth size, arch length changes and attrition.

It is the opinion of the author that the accuracy and reliability of the computer-based models is clinically acceptable, and it will be the relative convenience and total cost of the computer-based model that will determine its acceptance. Models can be viewed chair-side in seconds, and thousands can be stored in small portable hard drives and other compact storage devices. The model can be shared over a network within a university department, a practice or with another party without it ever leaving the practice or without the danger of the models being damaged by handling. This is of particular relevance to valuable historic samples. A copy of the model can be secured at a second site for minimal or no cost. From a practical point of view it must be noted that computer failure, software failure, or manufacturer insolvency can possibly mean that the models may become inaccessible for a time or forever [84].

It can be concluded that 3D computer generated models appear to be clinically viable but there remains doubt as to whether they are accurate and reproducible enough for research purposes. Further investigation will be required comparing the different 3-dimensional modalities with a gold standard in a research setting.

7.7 Future improvements to this study

1. Larger sample – this study was limited by the availability of the sample.
2. Longer observation time – we were limited by the availability of the sample.
3. Larger comparison study between 3D and a gold standard such as the coordinate measuring machine to investigate accuracy of the 3D system

4. Analysis of the different stone materials used in the original sample to assess any difference in expansion or shrinkage of material.
5. Calculate crowding of the arches and Investigate whether individuals expressing more wear show more or less levels of crowding.
6. More sophisticated statistical analysis to maximize use of all available data.

7.7.1 Further analysis of the data

Several issues were identified when analyzing the data of this study. The variation in sample numbers of different teeth at each time period is a common finding in studies that are retrospective in nature. Paired and unpaired t tests are sufficiently powerful to compare two means and investigate significant differences between measurements that are paired. This means that some data will be left out if all necessary data points are not present.

An improved statistical test to analyse the interaction of mesial-distal tooth widths with age, sex, arch and side would be to carry out a linear mixed model analysis. This system would allow us to model the change over time and include the entire sample even if there are one or two missing observations. The intercept can be allowed to vary indicating that within the sample, the starting point is not the same for all subjects. Change over time can also be allowed to vary, indicating that subjects are different in the rate of change over time. Plots can then be created over time to show the pattern of change.

Analysing total arch length can be difficult if there are missing data where teeth have not yet erupted or are missing. To overcome this problem, multiple imputations can be used to obtain estimates of the missing values before the analysis is carried out. The basic premise of multiple imputations is that when data are missing at random (which means that there is no relationship between the variables that show missing values and the fact that they are missing), we can use the information contained in the data that are present to replace the missing value with a plausible value. In our data, the assumption of missing at random appears plausible. Multiple imputations (MI) generate 10 complete sets of data. The analysis is performed for each generated data set and the results are combined for a final result. Utilising values derived from multiple imputation rather than simply replacing tooth size with one from the opposite side is considered of more value for analysis of the whole sample/population as certain versions of MI take into account details such as sex, age, gender, side and arch to impute the missing value and thus has more relevance when it comes to further analysis.

8. CONCLUSIONS

- Changes in arch dimensions with age in the Aboriginal sample were similar to those reported for other populations.
- No measurable change was detected in arch length over time.
- It was concluded that the 2D and 3D imaging methods would be suitable for clinical use but would require further refinement for research projects aimed at assessing minor changes in arch lengths associated with interproximal wear.

This investigation will add to the extensive data base of information relating to the Australian Aboriginal dentition that has been gathered over the last 50 years. It will provide more information on the dental and dental arch dimensions of the Yuendumu Aboriginals. The failure to find evidence of reduction in arch length (as measured by summing the mesiodistal widths of the teeth from first molar to first molar) is likely to be, firstly, a reflection of the westernization of the diet of the younger Aboriginal population in Yuendumu and secondly, demonstrates the inability and lack of precision of the current method in discerning minor changes in arch length.