CHAPTER 5

INTER-POPULATION COMPARISONS OF CRANIOFACIAL MORPHOLOGY BASED ON 3D COMPUTED TOMOGRAPHY

5.1 Introduction

Numerous studies in the past have stressed the need to develop norms for different human populations, sexes and ages. This is due to the observed differences in craniofacial form among human populations (Altemus, 1960; Drummond, 1968; Nanda and Nanda, 1969; Kowalski *et al.*, 1975b; Harris *et al.*, 1977), between the sexes (Riolo *et al.*, 1974; Bhatia and Leighton, 1993) and across different ages (Riolo *et al.*, 1974; Broadbent *et al.*, 1975; Bishara, 1981). Clearly, there will be greater validity when comparing an individual to referent data matched for their specific population, sex and age.

Normative references for a number of craniofacial variables have been established for Malaysian Malays, for each sex and at different age intervals in Chapter 3. It has also been demonstrated in Chapter 4 that some differences exist between the sexes and between right and left sides for certain variables within the Malay population.

Having established these normative data and noted differences within the Malay population, it was decided to investigate any differences between the collected data and those from other populations. This chapter will then focus in what differences, if any, there are between the craniofacial data derived from Malaysian Malays with data published for two Caucasian populations (Riolo *et al.*, 1974; Broadbent *et al.*, 1975).

5.2 Race or Ethnicity

Race has been defined as a taxonomic group of people who are believed to belong to the same genetic stock; usually this arises as a consequence of geographical isolation. Researchers who have attempted to define or classify humans into racial groups have not been able to find a satisfactory definition or classification (Richardson, 1980). Generally, they have concluded that there are three major racial groups, i.e. Asians, Blacks and Whites; and possibly a separate group of Australoids in the South Pacific. In physical anthropology, mankind have been classified into three major groups of Negroid, Caucasoid and Mongoloid based on physical characteristics, such as skin colour, hair form, head form and body proportions (Montagu, 1960). However, many biologists have expressed doubt that there are important genetic differences between different races of human beings. Furthermore, Richardson (1980) has questioned whether more than one race exists for humans, preferring instead to refer to ethnic groups that are separated by cultural, climatic and geographical boundaries. Ethnicity refers to people of the same nationality who share a distinctive culture and traditions (Macmillan School Dictionary, 2004). People of the same ethnicity, possess a common bond, such as geographical location, a culture or language, or are historically related.

It is now well accepted that employing a single standard for craniofacial structures is not appropriate when making diagnostic and treatment planning decisions for patients from diverse ethnic backgrounds. Early craniofacial analyses and major longitudinal growth studies were based mainly on people of European ancestry but most investigators have noted that there are significant differences between diverse ethnic groups. As a result, a large number of cephalometric references have been developed for different ethnic groups (Altemus, 1960; Riolo *et al.*, 1974; Broadbent *et al.*, 1975; el-Batouti *et al.*, 1994; Johannsdottir *et al.*, 1999).

5.3 Differences between human populations

Differences in craniofacial morphology within and between populations of different backgrounds result from complex interactions between genetic and environmental factors that exert their influence during formation and growth of the skull. Differences in the facial skeleton are more complex due to the effects of masticatory function (Kasai *et al.*, 1993). Australian Aboriginals were observed to have bigger bizygomatic and bigonial breadths than Japanese due to relatively greater muscularity and more powerful musculature (Kasai *et al.*, 1993). Given the environment that the Australian Aboriginals lived in, being hunter-gatherers living under harsh conditions, their teeth were used as tools for the manufacture of cultural items, for food preparation, and for eating a high fibre diet and with added abrasives (Barrett, 1976). This was associated with larger facial dimensions and smaller cranial vault dimensions. On the other hand, the Japanese live in a lifestyle that is less demanding in terms of mastication and they have more advanced food processing technology. They tend to display larger cranial and smaller facial and dental dimensions than Australian Aboriginals (Kasai *et al.*, 1993).

Differences of craniofacial form among different populations have also been identified as a result of studies of head form. The form of the head is determined using the cephalic index which is calculated as head breadth/ head length x 100. Head forms can be divided into three different shapes: dolichocephalic (long-headed); mesocephalic (intermediate); and brachycephalic.(braod-headed). Asians (Mongoloids) tend to have brachycephalic head shapes whereas Caucasians tend to have dolichocephalic heads.

Enlow (1990) reported that variations in head form are related to variations in the shape of the brain. The shape of the brain regulates the structure of the cranial base underneath it, which in turn corresponds to variations in the structure of the face. The cranial base serves as a bridge and template upon which the face is attached, and establishes correspondingly many variations in the form of the face (D'Aloisio and Pangrazio-Kulbersh, 1992). This is because the midface can be as wide as the floor of the cranium but it cannot be wider because there is nothing it can attach to. The cranial base in North American Blacks were observed not only to be shorter than that of Whites but differences were also noted in the relationships between cranial base dimensions with other facial measurements (D'Aloisio and Pangrazio-Kulbersh, 1992).

The brachycephalic head form in Asians gives rise to a broad but less protrusive face. The upper part of the ethmomaxillary region does not expand anteriorly as much as in the dolichocephalic head. This gives rise to a more bulbous and upright forehead, lesser protrusion of the glabella and eyebrow ridges and a thinner frontal sinus. The frontal sinus also tends to be thinner due to the lesser degree of separation between the inner and outer tables of the forehead. The face appears wider, flatter and less protrusive and it makes the cheekbones prominent and squared in appearance because the remainder of the upper and middle face is not as protrusive. The face also seems quite shallow in comparison to the deep and bolder contours of the dolichocephalic head. The eye balls tend to be more exophthalmic because of shorter anterior cranial fossa. The chin appears prominent and the mandible quite full. There is a tendency for a forward rotation of the entire mandible, with the brachycephalic head form being associated with a greater tendency for a class III malocclusion and a prognathic mandible (Enlow, 1990).

The nasal structure for all types of head forms is designed so that equivalent airway capacity is achieved. The wider nasal chambers and nasopharyx in brachycephalic head shapes give rise to a shorter nose vertically with a more rounded tip. The shorter nose in turn gives rise to shorter midfacial features which in turn establish a number of facial features that belong to a broad face type as mentioned before. Additionally, this is also associated with a lower interorbital region of the nasal bridge, flatter nose and less marked supraorbital protrusion. These observations of the nasal structures were also noted by Moate and Darendeliler (2002) in a Chinese ethnic group. In contrast, long-headed people tend to have long narrow and more protrusive faces and a much higher bridge and root of the nose (Enlow, 1990).

Brachycephalic head forms are often associated with more closed, upright cranial base flexure which influences a correspondingly wider, flatter, more upright face. Together with the rounder, horizontally shorter brain and shorter anterior cranial fossa, they establish a wider but anteroposteriorly shorter upper and midfacial region (Enlow, 1990). Anteroposterior facial dimensions were found to be smaller in a Japanese sample compared with a European-American sample (Miyajima *et al.*, 1996). Chinese were demonstrated to have a shorter anterior cranial base, a more protrusive maxillary and mandibular alveolar base, less prominent nose and less obtuse nasolabial angle than Caucasians (Moate and Darendeliler, 2002).

On the other hand, a few studies have reported only low correlations between cranial base angulation and maxillary and mandibular lengths (Varjanne and Koski, 1982; D'Aloisio and Pangrazio-Kulbersh, 1992). The whole upper and midfacial region is also placed less protrusively because of the more upright middle cranial fossa. The middle cranial fossa and therefore the pharyngeal region are also horizontally shorter in brachycephalic head. This further decreases the relative extent of the upper and midfacial protrusion. The more closed cranial base flexure also give rise to a more protrusive lower jaw with a greater tendency for a straighter or even concave facial profile. The lower jaw looks prominent in appearance. Moreover, the more upright nature of the cranial base produces the tendency for a more erect head posture, in contrast to the more slumped posture in many individuals with dolichocephalic head forms (Enlow, 1990). The broad but anteroposteriorly shorter anterior cranial fossa in brachycephalic heads sets up a wider but shorter palate and maxillary arch. The palate is therefore a proportionate projection of the anterior cranial fossa and the apical base of maxillary dental arch is established by the boundary of the palate (Enlow, 1990).

Marked dissimilarity in different ethnic groups can also be observed in the patterns of tooth sizes. Australian Aboriginals and Melanesians have been reported to show large teeth while the Filipinos, Indians and Yeminites have small teeth. Australian Whites and Taiwan Aboriginals have intermediate tooth size (Hanihara, 1967). Moreover, the Mongoloid group are characterised by relatively large lateral incisor teeth compared with their centrals. American blacks were reported not only to have significantly larger tooth crown dimensions than American whites (Richardson and Malhotra, 1975; Harris and Rathbun, 1989) but also larger arch size and arch form that was squarer and less tapered in the canine-premolar region (Burris and Harris, 2000). Another study revealed that Japanese adults tended to have more dental protrusion with more acute nasolabial angles and a greater tendency toward bilabial protrusion than European-Americans (Miyajima *et al.*, 1996).

Tooth size may be a manifestation of functional demand on the teeth and these demands can vary with local adaptations. Australian Aboriginals tend to have large teeth associated with the harsh conditions in which they live, i.e. by being hunter-gatherers, using their teeth as tools for the manufacture of cultural items and for food preparation and eating a high fibre diets (Barrett, 1976). On the other hand, the Japanese who have a less demanding diet and have more advanced food processing technology have been shown to have relatively smaller teeth (Kasai *et al.*, 1993).

Expression of certain dental traits may be observed more frequently in one population compared with another. For instance, Mongoloid ethnic groups were noted to have high frequencies of shovel-shape or shovelling of incisor teeth, cusp 6 and 7, and protostylids. On the other hand, Caucasians were observed to have low frequencies of shovelling, cusp 6 and 7, and protostylids, but high frequencies of Carabelli trait and bilateral counter-winging of central incisors (Mayhall *et al.*, 1982).

Richardson (1980) suggested that the dimensions of the face closer to the alveolar and dental areas show greatest differences among ethnic groups. This opinion is supported by

Dibbets and Nolte (2002) who found that American Blacks have larger lower face height, larger mandibular corpus length and larger sella to gnathion dimensions than three other white populations. This is not surprising as the function of mastication, which is influenced by the diet adopted by different population groups, may influence the dimensions of the facial structures as observed by marked differences particularly in the maxillary and mandibular regions between Australian Aboriginals and Japanese populations (Kasai *et al.*, 1993).

Using lateral cephalometry, Nubian children were shown to have a higher degree of bimaxillary protrusion, and smaller SNA and SNB angles, than American Caucasian children (Kowalski *et al.*, 1975a). North Mexican and Iowa boys did not display significant differences in cephalometric comparisons but measurements for the North Mexican girls showed a relatively more protrusive mandible than the Iowa females (Bishara and Fernandez, 1985). Australian Aboriginal boys have more marked alveolar development and forward migration of the dentition compared to Danish boys leading to their characteristic adult facial morphology (Bjork *et al.*, 1984). These growth changes were also associated with dimensional changes in dental arch width and length. Dental arch forms were also compared between Caucasians and Japanese in another study (Nojima *et al.*, 2001). Even though different ethnic groups may exhibit characteristic craniofacial morphologies, there is considerable variability within each group so that there are ranges of differing sizes and shapes of craniofacial variables and these tend to overlap between populations.

Craniofacial data for the Malay ethnic group are still limited. There have been a few studies of craniofacial morphology involving Malays in Indonesia and Singapore performed utilising cephalometric analyses (Lew, 1994; Munandar and Snow, 1995). Cephalometric findings for Chinese and Malays are quite similar but differences exist between Chinese and Indians and Malays and Indians (Lew, 1994).

With respect to the preceding description of differences in craniofacial morphology in different populations, comparisons of craniofacial morphology of Malaysian Malays with other populations are scarce. There is also no information about whether there are differences between the sexes or how craniofacial dimensions change with increasing age. Additionally, no research has been performed using CT scans to produce 3D craniofacial normative reference data for Malays. When this study was commenced there were very few reports of differences in craniofacial morphology between ethnic groups utilising 3D-CT.

Therefore, the aims of this section of the thesis were to utilise 3D-CT:

- To quantify the differences of craniofacial morphology of Malaysian Malays with well-known published data for two Caucasians populations.
- To observe whether population differences changed with age.

5.4 Materials and Methods

The methods of data collection have already been outlined in Chapter 2.

5.4.1 Data Collection

The sources of patients selected for this study, breakdown by age categories and sexes, are detailed in Section 2.5.

5.4.2 CT Protocol

Axial scans were obtained with a GE Lightspeed Plus CT Scanner System at the Department of Radiology, Hospital Universiti Sains Malaysia. The protocol used is detailed in Section 2.6.3.

5.4.3 Craniofacial Variables

For the purpose of comparison, a few selected variables from the Malay craniofacial data were compared with data from the Longitudinal Growth Study at the University of Michigan and from the Bolton-Brush Growth Study at the Case Western Reserve University

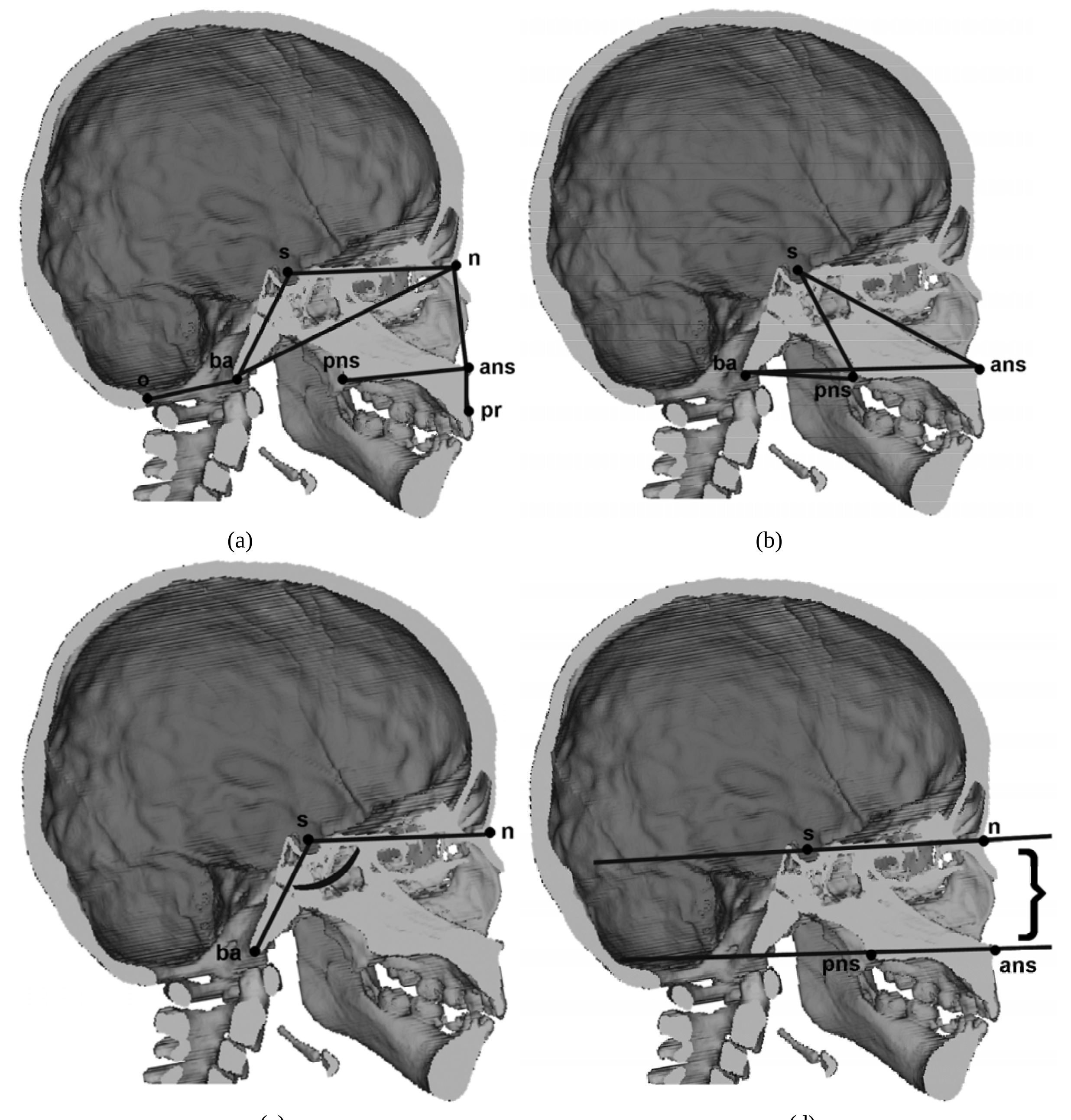
(Riolo *et al.*, 1974; Broadbent *et al.*, 1975). It would have been more appropriate to apply the comparison to 3D data from other populations, but there is still lack of published 3D data. However, both sets of cephalometric data are widely used for a variety of purposes and they have been available for a long time.

The author checked carefully that the variables to be compared had been determined using the same definition. That is, all three studies measured the same lengths or angles. As an example, the same landmarks, *sella* and *nasion*, were used to determine cranial base length. Secondly, only midline measurements could be compared. Bilateral structures, for example mandibular body length between point *gonion* and *gnathion* are essentially flat structures on the lateral cephalometric films, whereas 3D-CT enables values for left and right sides to be recorded. Finally, measurements derived from the lateral cephalometric films have an associated magnification factor. Therefore, this magnification had to be corrected to obtain the real value of the measurements before any comparisons could be made.

From the Michigan study, 11 linear variables and 2 angular variables were used for comparison and only 4 comparable linear variables were identified from the Bolton-Brush data. The variables for comparison are displayed in Figures 5.1 (a) to (d).

The Michigan study contains longitudinal data that spans the ages from 6 years to 16 years. Variables were compared at the age of 6 and 16 years to represent comparisons during childhood and adulthood. Age 16 years was chosen to represent adulthood as the Michigan data did not contain values beyond this age. Comparisons were made separately for males and females.

The Bolton-Brush study recorded longitudinal data from age 1 year to 18 years. Comparisons were made at 1 year, during childhood at 6 years and finally at age 18 years, separately for males and females. Age 18 years was selected for comparison in the Bolton-Brush study to represent the age of adulthood in contrast to the Michigan study where adult comparisons were made at the age of 16 years.



(a) (b)

(c) (d)

Figure 5.1 Craniofacial variables for inter-population comparisons are overlaid on 3D-CT reconstructions of the skull. Linear variables are displayed in (a) and (b) and angular variables are displayed in (c) and (d).

5.4.4 Magnification Corrections

The magnification factor for the Michigan study was 12.7%, therefore all linear measurements in the tables from this study had to be corrected using this magnification value. Angular variables were not corrected because their values were not affected by magnification. The formula used to correct for the magnification to obtain the real value was as follows:

$$\begin{aligned} \text{MagnificationValue} &= \text{RealValue} + (\text{RealValue} \times 12.7/100) \\ &= \text{RealValue} + (\text{RealValue} \times 0.127) \\ &= \text{RealValue}\ (1 + 0.127\ ) \\ &= \text{RealValue}\ (1.127) \end{aligned}$$

$$\text{Therefore} \qquad \text{RealValue} = \text{MagnificationValue}/1.127$$

The Bolton-Brush study had different magnification factors at different ages. The magnification value at age 1 year was 5.2%, at age 6 years was 5.4% and at age 18 years was 5.9%. The above formula, using specific magnification adjustments, was used to calculate the real value.

5.4.5 Statistical Analysis

Comparisons were made of mean values for each variable at the selected ages. Unpaired t-tests were employed to test whether significant differences existed between the mean values of variables from the Malays and the Michigan study, and between Malays and the Bolton-Brush study. On some occasions, sample sizes were very small in the Malay data for a specified age period. In these cases, z scores were used to determine the probability that individual values could have come from the population with which they were being compared. The z scores were calculated when the sample size was less than three and each score is presented in the tables. For variables with z-score, each z-score value is presented in the tables.

5.4.6 Errors of the Method and Data Cleaning

The methods for determining errors in landmark determination and anthropometric variables derived from these landmarks are outlined in Section 2.8.4. Systematic errors in landmark location were tested using Hotelling's T^2 statistic. For anthropometric variables, Student's paired t-tests were used to detect systematic errors (i.e. to ascertain whether the mean difference between repeated measures deviated significantly from zero) and Dahlberg's (1940) method of double determination was used to quantify the magnitude of random errors.

Data cleaning process was performed and has already been explained in detail in Section 3.6.7.

5.5 Results

The results of comparisons between the Malay and Michigan data are presented in Tables 5.1 and 5.2, and results for comparisons between the Malay and Bolton-Brush data are displayed in Tables 5.3 to 5.5. The tables are presented for different ages and contain sample sizes, means, standard deviations and either *p*- or z-score values separately for males and females. For variables with z-scores, each z-score value is presented in the tables. Statistically significant differences between the two sexes are marked with (*) as significant at $p<0.05$ and (#) as significant at $p<0.01$. Results are also displayed graphically in Figures 5.2 to 5.14, showing differences between the three samples.

Differences in size between the Malays and Caucasians in the Michigan study were observed for a few cranial base measurements in both males and females at age 6 years. The z-score values for measurements where no t-tests were performed, i.e. for palatal measurement *pns-ans*, cranial base measurement *s-n* and interregional measurement *ba-ans*, revealed that the Malay measurements tended to be smaller than those in the Michigan study. However, these z-scores values were still greater than -3. Differences in size between the Malay and Michigan data at 6 years of age were most notable for cranial base length *ba-n* and foramen magnum length *ba-o* measurements in males (significant at $p<0.01$). The Michigan value was larger than that in Malays for cranial base length, but foramen magnum length was found to be larger in Malays at this age. For females, the two groups showed significant differences in the cranial base variable *s-n* and foramen magnum length *ba-o*. The variable, *s-*

n, was found to be shorter in Malay girls while the variable, *ba-o*, was found to be longer in Malays. None of the angular variables was found to differ statistically between the samples, for either males and females, at this age.

At 16 years of age, more differences could be observed between the two populations for males, whereas girls showed quite similar trends (Table 5.2). Significant differences between samples were found for the palatal variable, *pns-ans,* maxillary alveolar variable, *ans-pr*, cranial base variables, *s-n*, *ba-n,* and inter regional variables, *s-ans*, *ba-pns* and *ba-ans* for males, with the Malay measurements always being a few millimeters smaller than those of the Michigan study. Females showed significant differences for variables, *s-n* and *ba-n,* with the Malay measurements again being smaller than those reported in the Michigan study. Angular variables did not show significant differences between the two populations at this age.

The palatal length variable *pns-ans* showed significant differences ($p<0.01$) between the Malay and Bolton-Brush data at all ages under comparison for both males and females (Tables 5.3-5.5). The other maxillary variable did not show any significant differences. Anterior cranial base length *s-n* revealed a statistically significant difference between the two groups at age 1 year and at age 18 years for both sexes. Differences were not statistically significant at age 6 years. Posterior cranial base length did not reveal a significant difference between the two populations at any of the ages.

Graphical presentations of the data for the three populations revealed that the shape of the growth curves were more or less similar for the three groups for most linear variables. The shapes of the growth curves were quite different for maxillary alveolar height (*ans-pr*) and foramen magnum length (*ba-o*) between the Malays and the Michigan studies. The mean lines for variables that showed significant differences with the Michigan and Bolton-Brush data were placed higher than the Malay mean lines in the graphs. Moreover, with the exception to anterior cranial base length (*s-n*), the mean lines for the Michigan and Bolton-Brush data almost coincided with each other. Foramen magnum length displayed significant differences in size at age 6 years, and there were also differences in the shape of the graphs between the Malays and the Michigan data. The graphs of angular variables revealed different shapes between the Malays and Michigan data.

Table 5.1 Comparison of selected linear and angular variables between Michigan and Malay studies for males and females at age 6 years.

Variable name	Male								Female							
	Michigan			Malay			*p*	z-score	Michigan			Malay			*p*	z-score
	N	Mean	SD	N	Mean	SD			N	Mean	SD	N	Mean	SD		
pns-ans	37	44.5	1.95	1	39.8			-2.43	24	43.4	2.04	4	41.2	2.94	0.07	
n-ans	37	40.7	2.48	1	36.9			-1.54	25	40.7	2.75	3	40.1	1.70	0.71	
ans-pr	37	16.3	1.95	1	14.1			-1.14	25	15.4	2.57	4	14.3	1.84	0.39	
s-n	37	64.5	2.48	1	58.3			-2.50	25	62.4	2.40	5	59.2	2.12	0.01^{*}	
ba-s	37	36.1	2.66	2	37.3			0.45	25	35.1	2.75	3	37.7	2.75	0.05	
					34.8			-0.49								
ba-n	37	91.7	3.28	3	85.2	2.08	$<0.01^{\#}$		25	89.0	3.99	4	86.3	1.89	0.20	
ba-o	37	32.4	3.19	3	35.6	0.26	$<0.01^{\#}$		25	30.4	2.93	4	33.9	2.25	0.04^{*}	
s-pns	37	40.8	2.66	1	39.1			-0.64	25	38.7	2.40	3	37.8	3.23	0.58	
s-ans	37	74.5	3.55		N/A				25	72.0	2.84	3	68.4	4.11	0.06	
ba-pns	37	41.9	2.48	2	37.3			-1.84	24	39.5	3.02	3	38.0	2.01	0.43	
					38.6			-1.32								
ba-ans	37	86.2	3.64	1	77.0			-2.54	25	83.0	3.64	3	79.2	2.07	0.10	
ba-s-n	37	129.3	5.00	2	131.8			0.50	25	129.6	5.00	3	128.0	8.99	0.63	
					130.9			0.32								
s-n/ans-pns	37	5.2	2.40		N/A				24	7.0	2.60	3	7.3	2.25	0.85	

* significant at $p<0.05$ $^{\#}$ significant at $p<0.01$

Table 5.2 Comparison of selected linear and angular variables between Michigan and Malay studies for males and females at age 16 years.

Variable name	Male								Female							
	Michigan			Malay			*p*	z-score	Michigan			Malay			*p*	z-score
	N	Mean	SD	N	Mean	SD			N	Mean	SD	N	Mean	SD		
pns-ans	23	54.7	3.28	6	50.5	2.48	$0.01^{\#}$		9	50.6	3.90	3	47.6	0.76	0.06	
n-ans	23	53.0	3.46	6	51.5	2.37	0.34		9	49.4	1.86	3	49.6	2.79	0.90	
ans-pr	23	18.1	2.57	6	15.1	2.12	0.01^{*}		9	16.1	2.40	2	14.0			-0.82
													12.0			-1.57
s-n	23	73.9	3.37	6	67.0	2.05	$0.00^{\#}$		9	68.2	3.46	5	63.5	1.41	0.01^{*}	
ba-s	23	43.8	3.37	6	44.1	3.37	0.85		9	40.2	2.75	5	41.4	2.12	0.41	
ba-n	23	106.8	3.73	6	98.9	1.94	$0.00^{\#}$		9	99.4	4.26	5	94.4	2.60	0.04^{*}	
ba-o	23	34.4	3.02	6	34.4	2.91	1.00		9	33.0	2.84	5	31.5	3.08	0.38	
s-pns	23	49.4	3.46	6	47.4	2.47	0.19		9	45.3	2.66	4	45.1	4.97	0.89	
s-ans	23	88.9	4.79	6	83.4	2.31	0.01^{*}		9	82.4	5.15	4	78.8	4.39	0.24	
ba-pns	23	46.3	3.02	6	41.6	1.90	$0.00^{\#}$		9	44.1	3.99	4	42.1	2.57	0.34	
ba-ans	23	100.6	4.53	6	91.9	3.42	$0.00^{\#}$		9	94.2	6.92	4	88.3	3.23	0.13	
ba-s-n	23	128.9	5.90	6	124.7	5.41	0.12		9	131.1	4.10	5	127.2	5.93	0.17	
s-n/ans-pns	23	7.0	3.00	6	7.9	2.52	0.51		9	8.0	2.20	4	8.3	4.17	0.90	

* significant at $p<0.05$ $^{\#}$ significant at $p<0.01$

Table 5.3 Comparison of selected linear variables between Bolton-Brush and Malay studies for males and females at age 1 year.

Variable name	Male								Female							
	Bolton-Brush			Malay			*p*	z-score	Bolton-Brush			Malay			*p*	z-score
	N	Mean	SD	N	Mean	SD			N	Mean	SD	N	Mean	SD		
pns-ans	8	37.1	1.58	5	34.3	1.56	0.01[#]		16	36.8	1.44	4	32.4	2.21	0.00[#]	
n-ans	8	30.9	1.14	5	30.6	1.93	0.72		16	29.1	1.27	4	29.9	1.84	0.31	
s-n	8	53.5	1.88	8	49.3	3.88	0.01[*]		16	51.7	2.09	5	47.3	2.57	0.00[#]	
ba-s	8	29.8	1.68	6	29.3	1.97	0.60		16	28.4	2.19	5	28.0	3.35	0.80	

[*] significant at p<0.05 [#] significant at p<0.01

Table 5.4 Comparison of selected linear variables between Bolton-Brush and Malay studies for males and females at age 6 year.

Variable name	Male								Female							
	Bolton-Brush			Malay			*p*	z-score	Bolton-Brush			Malay			*p*	z-score
	N	Mean	SD	N	Mean	SD			N	Mean	SD	N	Mean	SD		
pns-ans	16	44.7	1.53	1	39.8			-3.20	16	44.4	1.71	4	41.2	2.94	0.01[#]	
n-ans	16	40.8	1.89	1	36.9			-2.05	16	39.8	1.99	3	40.1	1.71	0.84	
s-n	16	62.6	2.39	1	58.3			-1.81	16	60.2	1.66	5	59.2	2.12	0.33	
ba-s	16	36.4	2.10	2	37.3			0.41	16	36.4	2.05	3	37.9	2.75	0.30	
					34.8			-0.78								

[*] significant at p<0.05 [#] significant at p<0.01

Table 5.5 Comparison of selected linear variables between Bolton-Brush and Malay studies for males and females at age 18 year.

Variable name	Male								Female							
	Bolton-Brush			Malay			*p*	z-score	Bolton-Brush			Malay			*p*	z-score
	N	Mean	SD	N	Mean	SD			N	Mean	SD	N	Mean	SD		
pns-ans	16	55.2	1.90	5	48.8	5.09	0.00[#]		16	52.1	2.54	5	48.2	1.84	0.01[#]	
n-ans	16	53.8	2.41	4	52.9	2.74	0.50		16	48.7	1.98	4	50.4	1.75	0.15	
s-n	16	71.2	2.38	5	64.2	1.65	0.00[#]		16	66.2	2.80	6	63.0	1.49	0.02[*]	
ba-s	16	45.4	3.09	7	45.8	3.57	0.80		16	42.4	2.62	6	41.8	1.37	0.60	

[*] significant at p<0.05 [#] significant at p<0.01

Figure 5.2 Palatal length (*pns-ans*) from Malay, Michigan and Bolton-Brush studies plotted on the same graph for males and females.

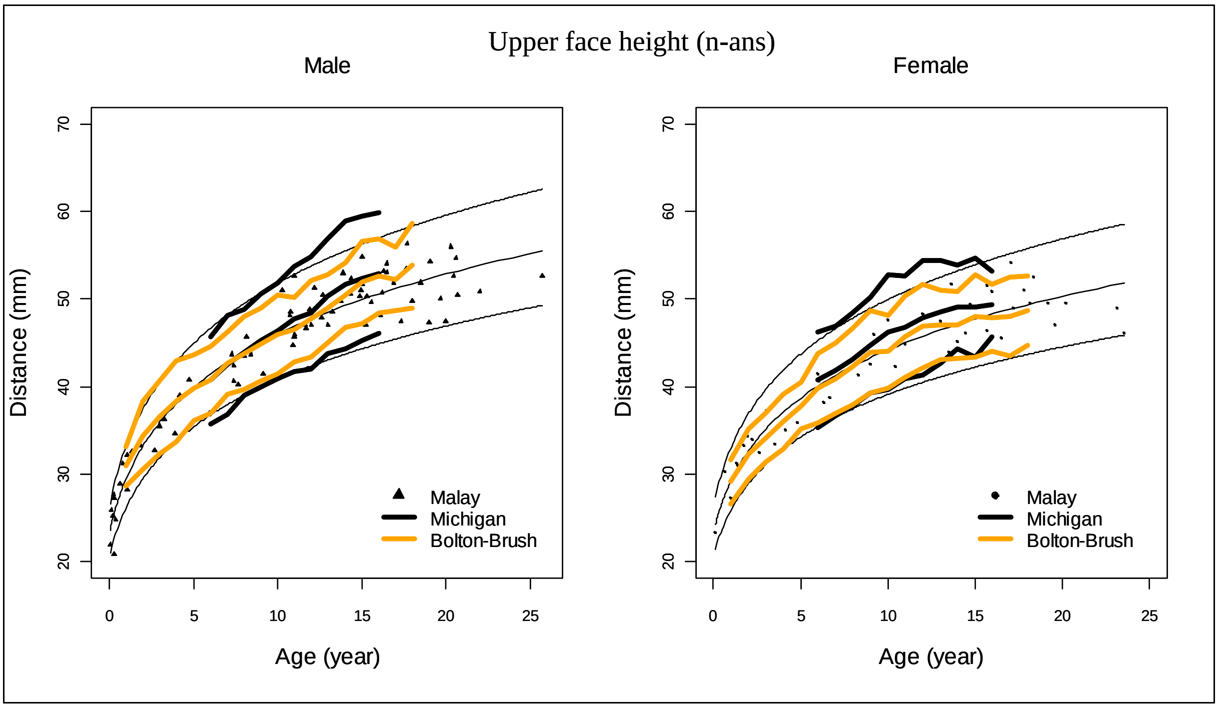


Figure 5.3 Upper face height (*n-ans*) from Malay, Michigan and Bolton-Brush studies plotted on the same graph for males and females.

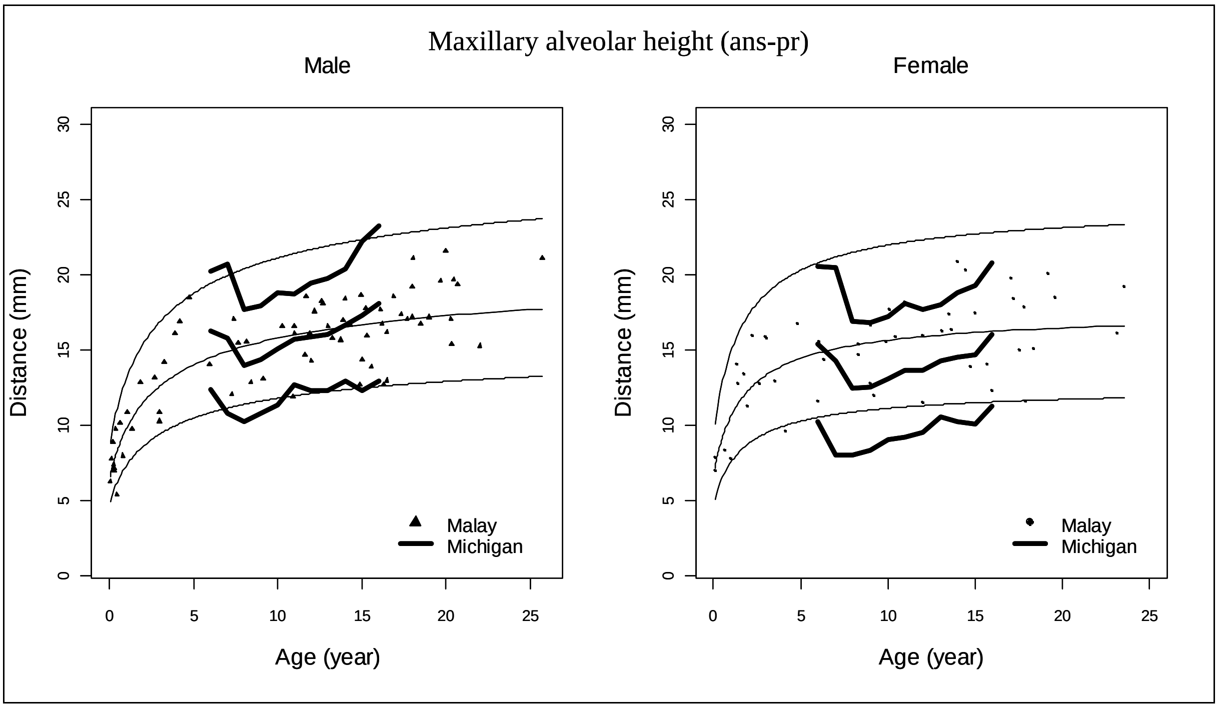


Figure 5.4 Maxillary alveolar height (*ans-pr*) from Malay and Michigan studies plotted on the same graph for males and females.

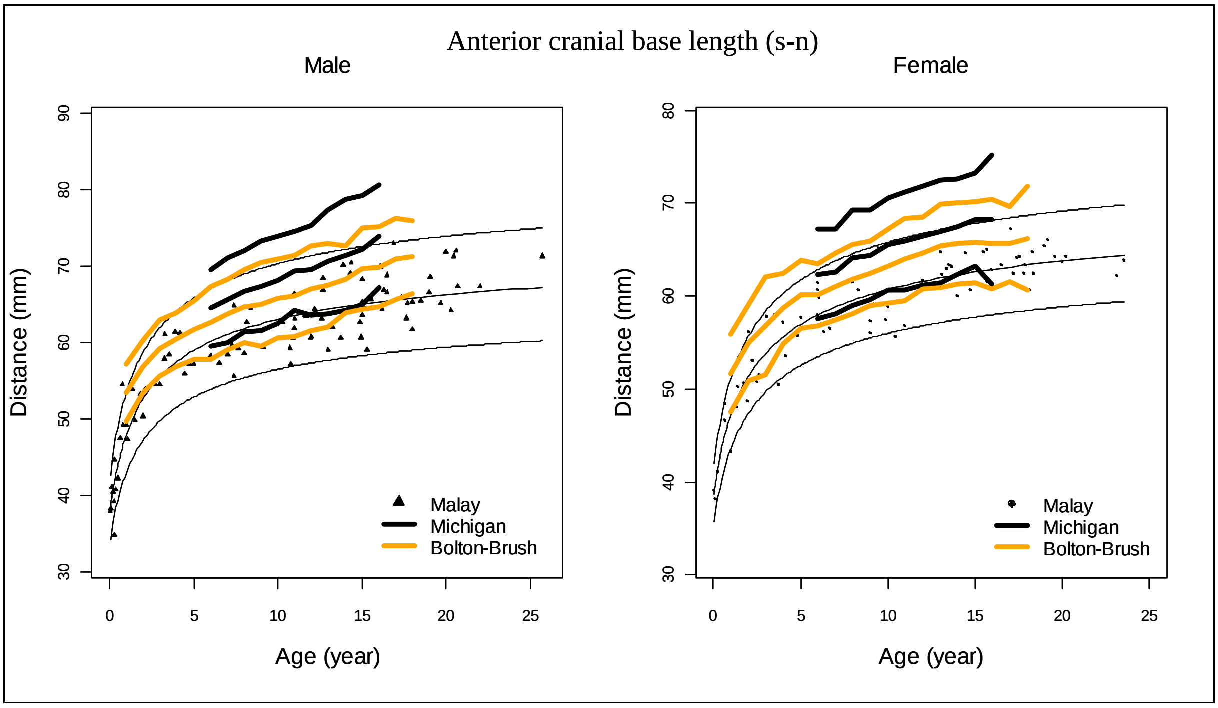


Figure 5.5 Anterior cranial base length (*s-n*) from Malay, Michigan and Bolton-Brush studies plotted on the same graph for males and females.

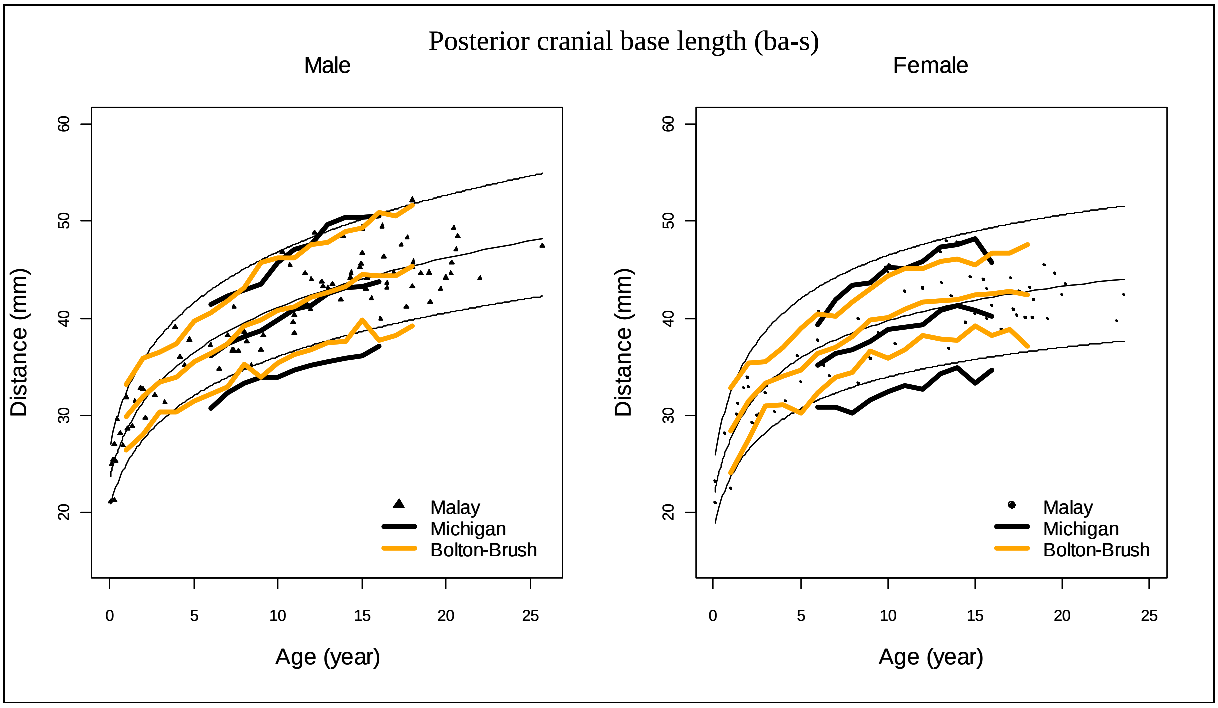


Figure 5.6 Posterior cranial base length (*ba-s*) from Malay, Michigan and Bolton-Brush studies plotted on the same graph for males and females.

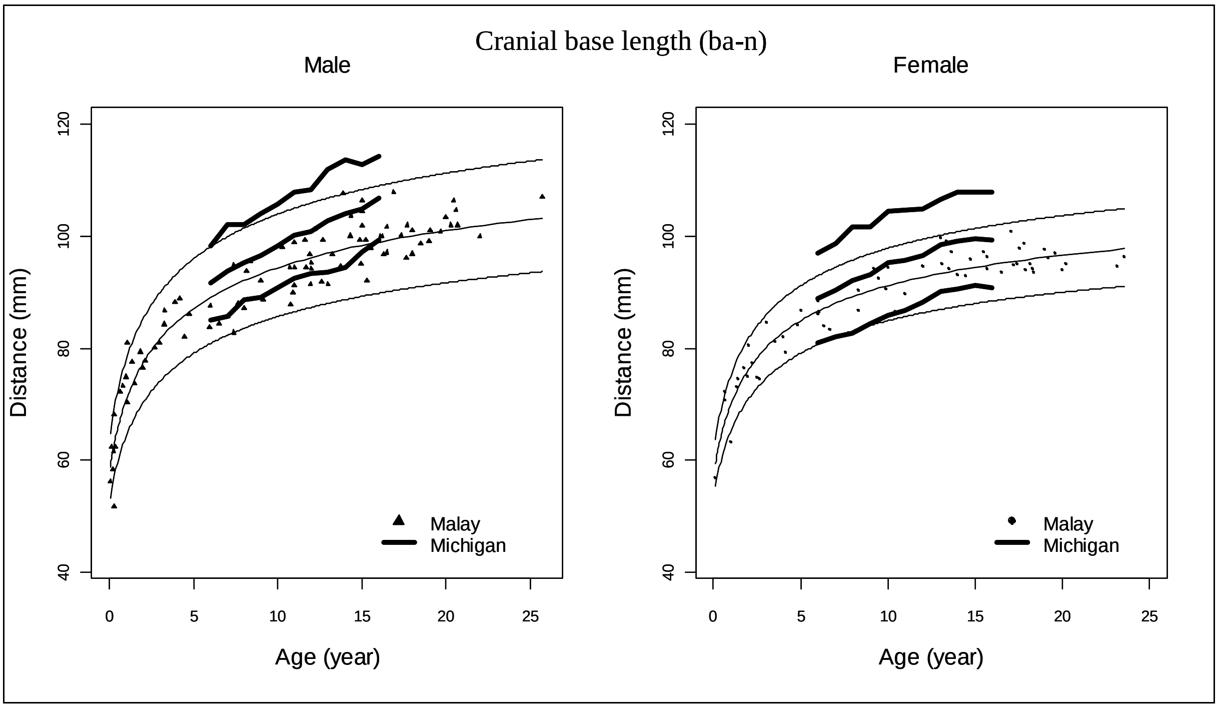


Figure 5.7 Cranial base length (*ba-n*) from Malay and Michigan studies plotted on the same graph for males and females.

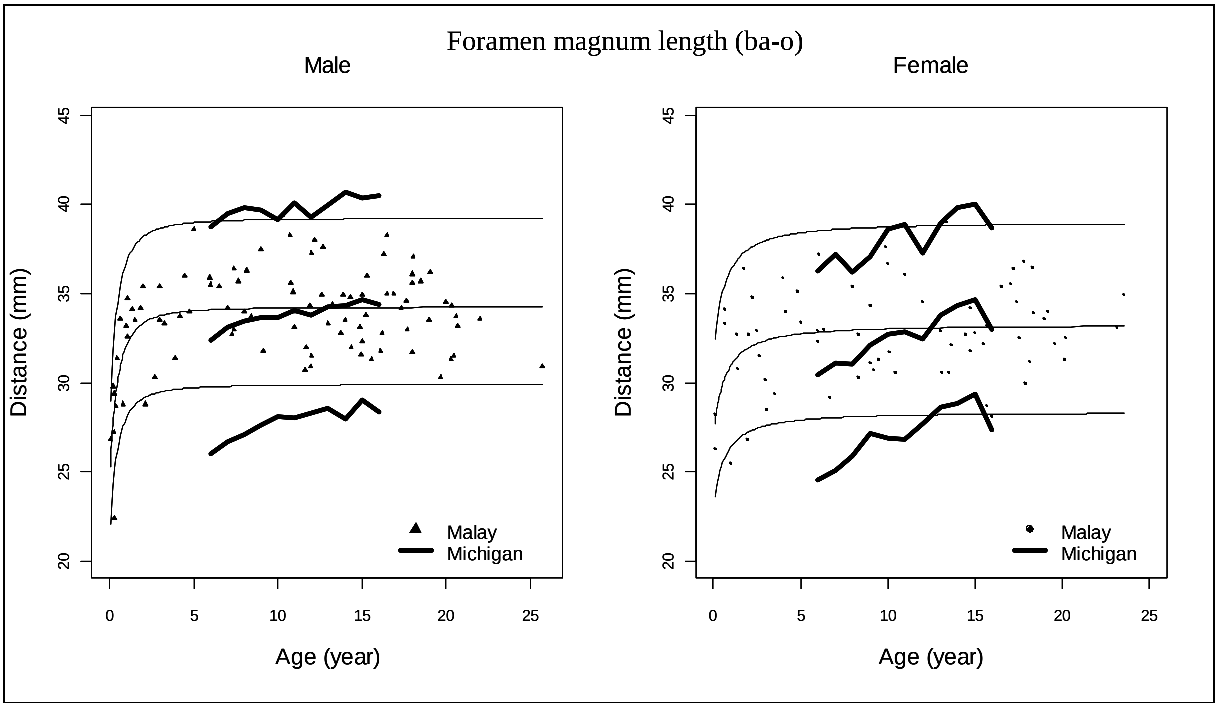


Figure 5.8 Foramen magnum length (*ba-o*) from Malay and Michigan studies plotted on the same graph for males and females.

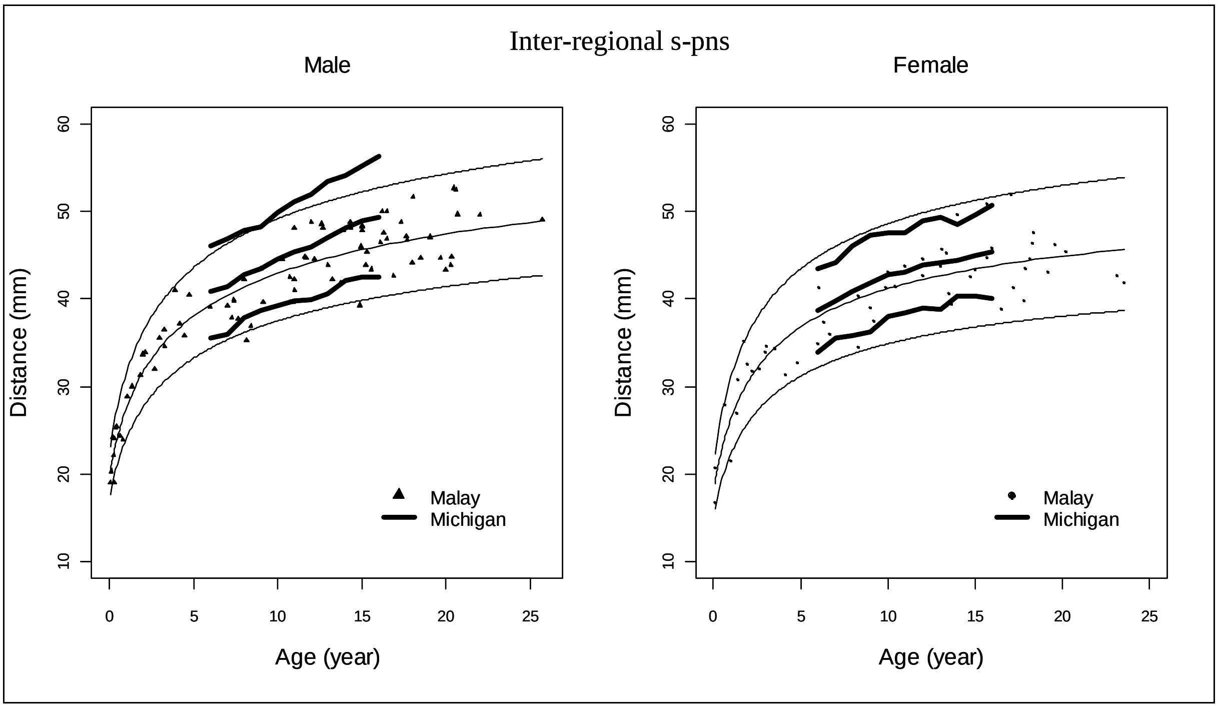


Figure 5.9 Inter-regional length (*s-pns*) from Malay and Michigan studies plotted on the same graph for males and females.

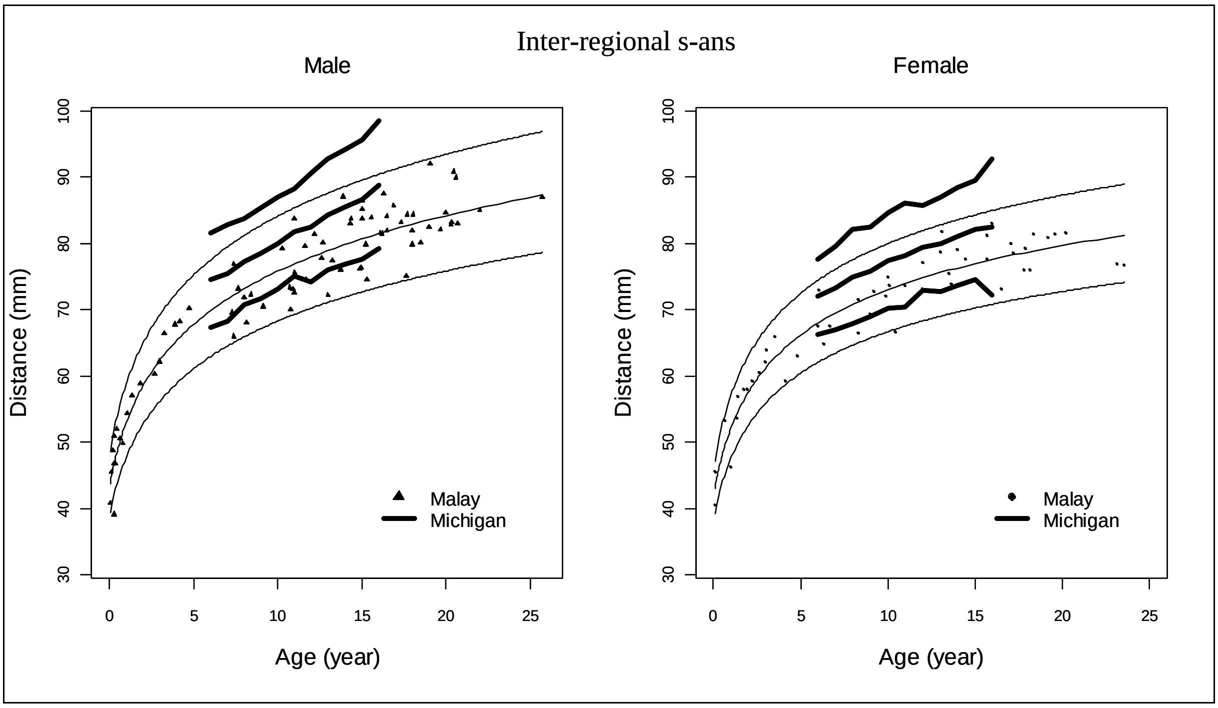


Figure 5.10 Inter-regional length (*s-ans*) from Malay and Michigan studies plotted on the same graph for males and females.

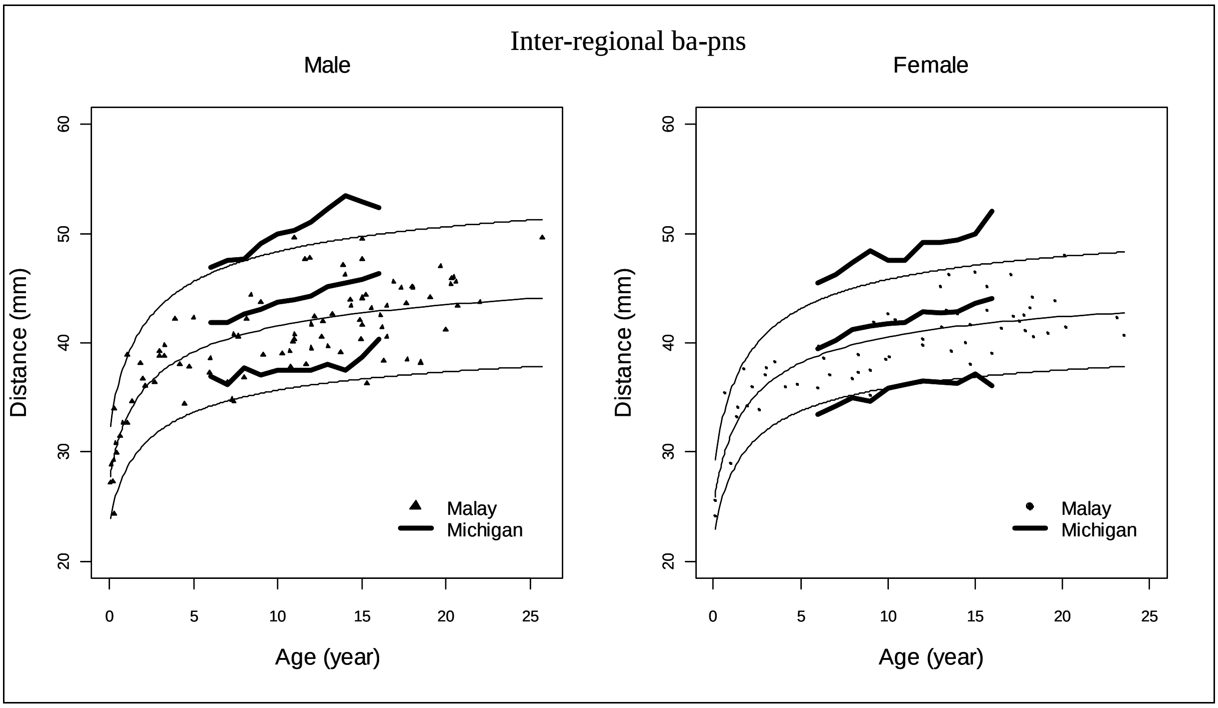


Figure 5.11 Inter-regional length (*ba-pns*) from Malay and Michigan studies plotted on the same graph for males and females.

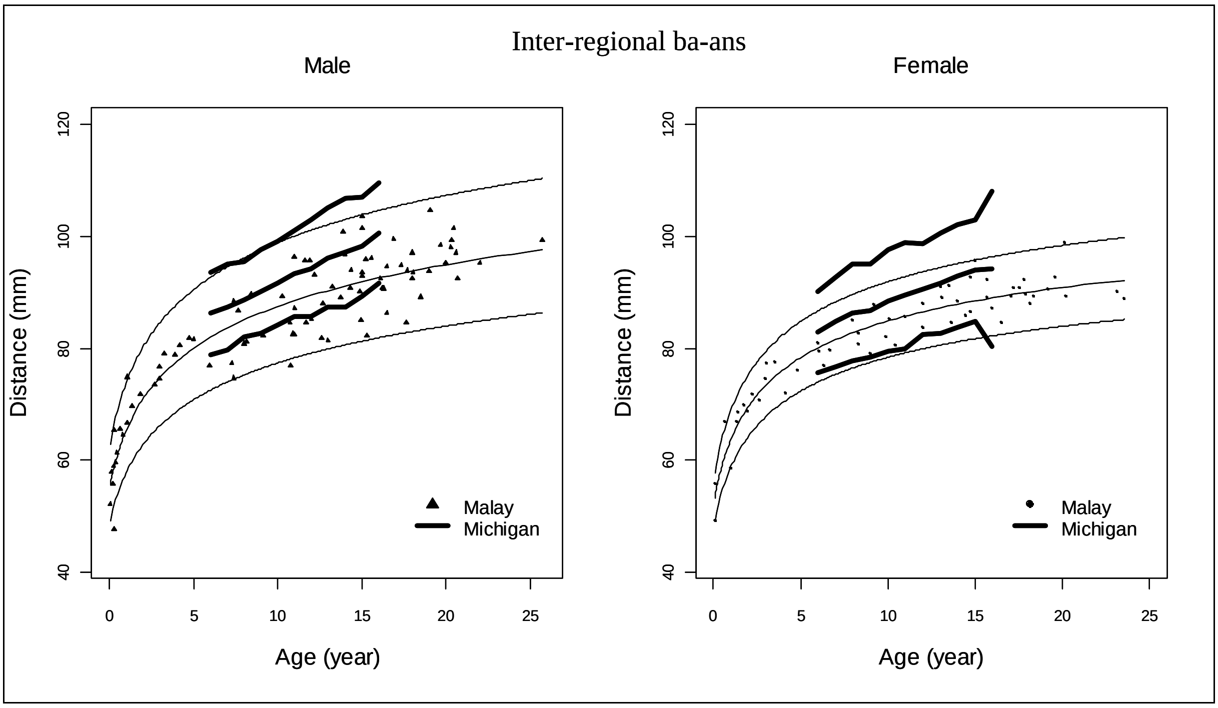


Figure 5.12 Inter-regional length (*ba-ans*) from Malay and Michigan studies plotted on the same graph for males and females.

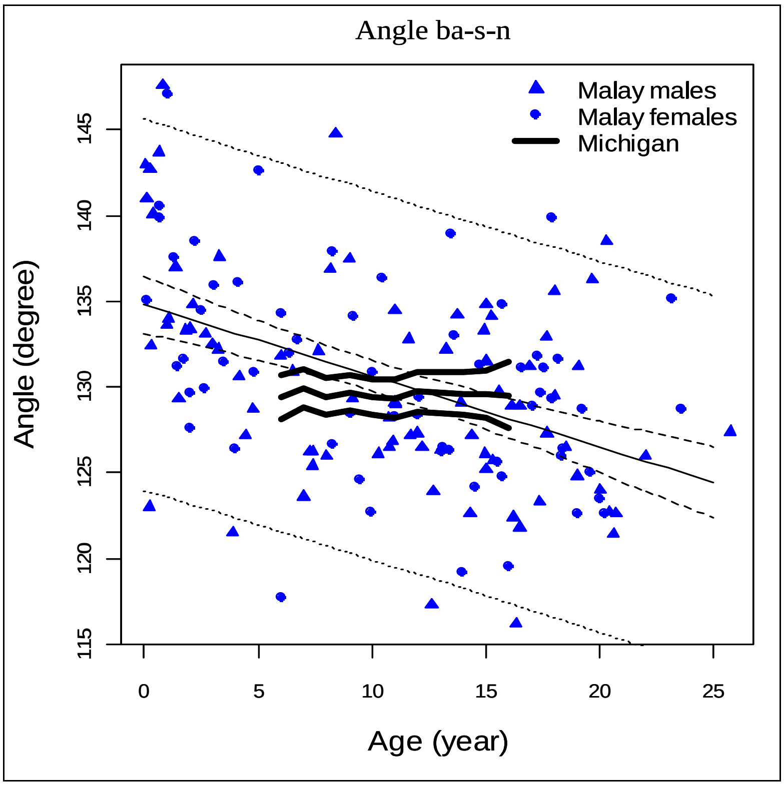


Figure 5.13 Angle *ba-s-n* from Malay and Michigan studies plotted on one graph with measurements for males and females combined.

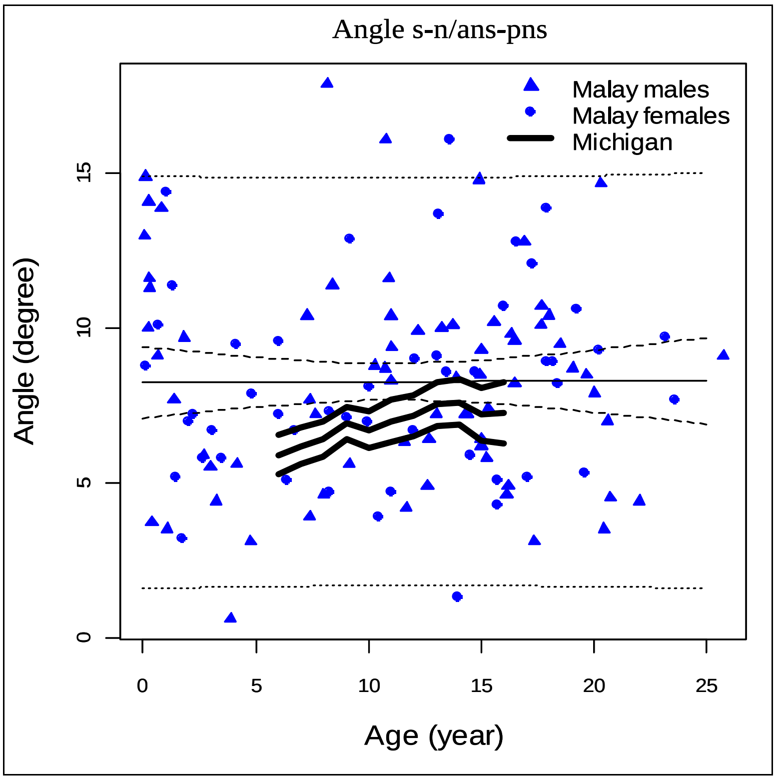


Figure 5.14 Angle *s-n/ans-pns* from Malay and Michigan studies plotted on one graph with measurements for males and females combined.

5.6 Discussion

At the age of 6 years, Malays were shown to have significantly smaller dimensions for some linear cranial base variables than those for Caucasians derived from the Michigan study. An exception to this was the measurement of foramen magnum length, where the Malays displayed bigger values on average. Other measurements did not show statistically significant differences but were consistently smaller in Malays. These variables may have been associated with statistically significant differences too, if larger sample sizes had been available for comparisons. For some variables, z-scores were utilised instead of a t-test for comparisons. This was performed for variables where the sample size was very small. The use of z-scores provided some indication of differences between the two populations.

At the adolescent age of 16 years, more differences in size were revealed between the Malay and Michigan studies, with Caucasians tending to have larger measurements. Males exhibited more differences than girls at this age. Anterior cranial base and cranial base lengths were found to be significantly different between the two studies for both males and females, with the Malays having smaller values. Malay males also manifested smaller measurements for palatal length, maxillary alveolar height, sella-ans length and basion-ans and basion-pns lengths.

Comparisons between the Malays and the Bolton-Brush data could only be performed for four linear variables. Palatal length measurement showed the individuals in the Bolton-Brush study had larger values on average than the Malays in both sexes during infancy, at 6 years of age and at 18 years of age. Differences in size were established quite early in life. Another variable that showed a significant difference between the samples was anterior cranial base length, with Malays having smaller values during infancy and adulthood. Differences were not significant at 6 years of age but the Malays tended to have smaller values. Again these differences may have been statistically significant if larger sample sizes had been available.

Differences in cranial base measurements have also been noted in other population comparisons, namely, North American Blacks having shorter cranial bases than whites (D'Aloisio and Pangrazio-Kulbersh, 1992). Anterior cranial base were also found to be shorter in Chinese compared with Caucasians at all ages under investigation (Moate and Darendeliler, 2002). Furthermore, palatal length measurements were demonstrated to be different in comparisons involving four populations (Dibbets and Nolte, 2002). Enlow (1990) has suggested that a shorter anterior cranial base and fossa sets up a wider but shorter palate and maxillary arch. The finding of shorter anterior cranial base and palatal length in this study suggests that the morphology of these structures is closely related.

Plotting data for the populations under comparison was very useful to see changes with age. Moreover, similarities and differences in the shape of the graphs of different populations could also be viewed. Many variables showed similar patterns in all three of the populations. However, differences in the shape of the growth curves were observed for maxillary alveolar height, foramen magnum length, cranial base angle and angle s-n/ans-pns. The plots revealed that the mean values for measurements of Caucasians derived from Michigan and Bolton-Brush studies almost coincided, suggesting that the two populations were similar. This is not surprising as the two studies were performed on children and young adults of European descent.

None of the angular measurements showed statistically significant differences at any ages. However, the graphs revealed some differences in trends across age groups. Again, these differences may have been significant if sample sizes had been larger (i.e. power was an issue). Cranial base angle for the Malays tended to have lower values, indicating that the Malays may have a tendency toward a more closed cranial base angle than Caucasians. Asians, who tend to have brachycephalic head forms, have been observed to have more closed cranial base flexure (Enlow, 1990). A difference in cranial base flexure was also found in American Blacks when compared to whites (D'Aloisio and Pangrazio-Kulbersh, 1992).

Although 3D-CT enables identification of hundreds of landmarks and measurement of many variables, only a few variables could be compared between the Malays and the Michigan data, and even fewer comparisons could be made between the Malays and Bolton-Brush data. The reason for this was that measurements were limited to those in the midsagittal plane because the Caucasian studies were based on lateral cephalometry. Moreover, only measurements using the same landmarks and the same definitions in both studies were used. This further decreased the number of possible comparisons. However, the comparisons gave some indication of differences in craniofacial morphology between the Malays and other populations. More elaborate comparisons could be carried out in the future. Moreover, other differences, well known for Asians, such as a broad type face and low nasal bridge could not be compared quantitatively in this study using the current method. This is because the selected

Caucasian data did not contain this information. Comparisons with other 3D data would be beneficial in the future.

Comparisons of cephalometric data from different sources have been performed commonly in the past (Phipps *et al.*, 1988; Miyajima *et al.*, 1996; Burris and Harris, 2000; Dibbets and Nolte, 2002). However, craniofacial structures are enlarged uniquely in each study as the result of differences in cephalostat specifications. These data are then associated with differing magnification factors. It is important that linear measures from different studies are corrected to natural size. Only then can meaningful comparisons be made (Dibbets and Nolte, 2002). Thus, the author ensured that the data derived from the Michigan and Bolton-Brush studies were corrected for magnification before comparisons were made.

Other craniofacial studies involving Malay have been performed by Lew (1994) and Munandar and Snow (1995). Cephalometric comparisons revealed that the Chinese and Malays shared many similarities in the lateral facial skeleton. These included more prognathic mandibles, more proclined upper and lower incisors, and more protrusive upper and lower lips. Some subtle differences were observed between the Malays and Chinese, with the Malays having higher cants of the occlusal and mandibular planes in relation to the cranial base. This study also revealed more differences were manifested between the Chinese and Indians and between the Malays and Indians. The Indians tended to have straighter facial profiles due to less protrusive jaws and teeth in the maxilla and mandible. The results were not surprisings as the Chinese and Malay ethnic groups were classified to be in the classical and Indo-Malays Mongoloid groups respectively, whereas the Indians were categorised in the Indo-Dravidian division of the Caucasoid group. Furthermore, Munandar and Snow (1995) reported that Indonesian Malays possessed a relatively protrusive dental pattern with some mandibular posterior rotation which is consistent with other published descriptions of Oriental (Asians) people.

The findings of the present study support observations of other researchers that there are ethnic differences in craniofacial form. The results support the opinion that a single standard of craniofacial normative reference data is not appropriate for application to diverse racial and ethnic groups. This also emphasizes the need to treat patients from different ethnic groups using norms peculiar to their own group. Clinicians should anticipate these differences when treating patients from different ethnic backgrounds.

5.7 Conclusion

Some differences in craniofacial morphology were noted between Malays and Caucasians. This emphasises the need to have different normative reference data for different ethnic groups. It is no longer appropriate to compare a patient with craniofacial abnormalities from a different ethnic background to reference data derived for Caucasians, as has been practised before. The findings presented in this chapter have placed an emphasis on the need to treat patients from different ethnic backgrounds using normative references developed for their own population.

CHAPTER 6

GENERAL DISCUSSION AND CONCLUSION

6.1 Introduction

There have been many studies of craniofacial morphology in human populations and their scope has been broad. Previous studies have reported normative values for a number of craniofacial variables (Riolo *et al.*, 1974; Broadbent *et al.*, 1975; Bhatia and Leighton, 1993), investigated growth changes of different craniofacial regions (Farkas *et al.*, 1992a, 1992b; Farkas *et al.*, 1992c, 1992d), assessed the degree of sexual dimorphism (Johannsdottir *et al.*, 1998; Ferrario *et al.*, 2000; Axelsson *et al.*, 2003), described the nature and extent of asymmetry (Woo, 1931; Shah and Joshi, 1978; Winning *et al.*, 1999), compared normal craniofacial structures with various abnormal conditions (Richtsmeier, 1987; Proudman, 1995; Prasad *et al.*, 2000; Quintanilla *et al.*, 2002), compared normal craniofacial structures between different human populations (D'Aloisio and Pangrazio-Kulbersh, 1992; Kasai *et al.*, 1993; Moate and Darendeliler, 2002) and explored the relationship of different craniofacial regions to each other and to dental occlusion (Richards, 1985; Nanda and Ghosh, 1995; Rothstein and Yoon-Tarlie, 2000). The intent of these studies has been to improve managements of patients affected with various forms of craniofacial abnormalities.

Numerous studies have stressed the need to develop norms for different ethnic groups, sexes and ages. This is important because there are differences in craniofacial form between different human populations (Altemus, 1960; Drummond, 1968; Nanda and Nanda, 1969; Kowalski *et al.*, 1975b; Harris *et al.*, 1977), between the sexes (Riolo *et al.*, 1974; Bhatia and

Leighton, 1993) and across different ages (Riolo *et al.*, 1974; Broadbent *et al.*, 1975; Bishara, 1981). Clearly, studies will have greater validity if individuals are compared to referent data matched for their own particular ethnic group, sex and age.

Most normative craniofacial data have been generated for people of European ancestry. As far as the Malaysian Malay ethnic group is concerned, no published craniofacial norms are available. The closest Malay craniofacial data that have been available until the present study were supplied by Lew (1994) and Munandar and Snow (1995). In Lew's study, the craniofacial data for Malay adults were generated from people living in Singapore. Moreover, the study performed by Munandar and Snow (1995) for Indonesian Malays may not be applicable to Malaysian Malays because of different geographical and cultural background. The data in their study were collected in Jakarta, the capital of Indonesia, which is very urban and may include people from all over Indonesia which is comprised of thousands of islands that vary in environmental status and cultural practices.

Previous craniofacial studies have been carried out utilising many methods. Some of the methods have included craniometry (De Villiers, 1968; Howells, 1989), soft tissue anthropometry (Farkas and Munro, 1987) and cephalometirc radiography (Riolo *et al.*, 1974; Broadbent *et al.*, 1975; Bhatia and Leighton, 1993). These studies were associated with several limitations. For instance, cephalometric radiographs were accompanied with limitations such as superimposition of structures, difficulty identifying landmarks and poor visualization of 3D structures (Ahlqvist *et al.*, 1986; Houston *et al.*, 1986; Kamoen *et al.*, 2001).

It has only been relatively recently that 3D analytic techniques have enabled a detailed assessment of the skeletal structures. More recently, the advent of three-dimensional computerised tomography (CT) technology (Cormack, 1979; Hounsfield, 1980), has provided a new tool for medical investigation and has become an important method for management of craniofacial patients. Because of this, there is a need for having CT craniofacial reference data so that abnormalities can be compared to base line data, leading to more accurate diagnosis and treatment planning for these patients. CT technology is further enhanced with the capability of three dimensional reconstructions from the axial slice data (Herman and Liu, 1977) and is then supplemented with computer software such as PERSONA for measuring purposes.

Thus, in this study, the author collected CT records from a normal Malay population. It is the first extensive set of 3D-CT craniofacial data to provide a three dimensional description of the craniofacial morphology and growth changes in normal Malaysian Malays based on subjects ranged form birth to adulthood.

Subjects in this study were patients needing CT investigations for certain medical conditions. However, careful selection was made so that individuals with conditions that affected their craniofacial growth and development were excluded from the study. Therefore, the sample collected is close to representing the “normal” Malay population. It is appropriate to refer to the data collected as “reference data” because all suitable subjects were included in the study during the data collection period.

The author performed a cross-sectional rather than a longitudinal study for this project. Some of the reasons for this included the fact that cross-sectional references are more representative of a “normal” population and enable comparisons of individuals with abnormalities. A cross-sectional approach was also selected because it would have been unethical to expose subjects unnecessarily to extra radiation by obtaining more than one CT scan. Nevertheless, it is acknowledged that longitudinal studies are particularly useful for determining the rate of growth and following individual subjects.

3D-CT reconstructions have proven to be very beneficial in allowing better opportunities to evaluate craniofacial structures. By using 3D-CT approaches, variables can now be defined that describe the size and shape of individual bones and regions. The particular advantage offered by this study is that sophisticated software enabled accurate and reproducible location of landmarks from which variables could be derived, thereby offering advantages over conventional radiographs. This has allowed views that are not possible with a conventional approach, particularly of the cranial base and orbital regions. Other structures that are difficult to view with conventional radiographs include the hyoid bone, cervical spine, nasopharynx and spheno-occipital synchondrosis. Although these regions are not described in this thesis, it is intended to examine them in detail in future investigations. Statistical analyses enabled comparisons to be made and helped to clarify associations between structures. Multivariate analyses and morphometric analyses are now possible with sophisticated computer software and, again, it is planned to pursue these areas further in the future.

The descriptions of the craniofacial morphology and growth changes in different regions of the skull and face for the Malaysian Malays, which have not been detailed before, are possibly the most important contributions of this thesis. In addition to developing the normative references, the author also studied differences between males and females, differences between left and right measurements, and differences between the Malay data and those of two Caucasian populations.

6.2 3D-CT Analysis of Craniofacial Morphology in Malaysian Malays

After detailed analysis of the data collected for this study, several findings were noted as follows:

6.2.1 New Normative Reference Data for Malaysian Malays

As far as the author is aware, this is the first 3D-CT study to generate comprehensive reference data for craniofacial measurements in Malays. Indeed, normative craniofacial data for Malays in two dimensions are still lacking. The data collected from this study are best referred to as ‘references’ instead of ‘standards’ due to the nature of selecting the subjects into the study.

The references have been presented in tables at selected age categories that span from birth to adulthood. The references were also presented in graphical form as scatter plots of variables against age so that trend of growth changes across age groups could be viewed graphically for each variable. The presentations of craniofacial ‘standards’ in tables and graphs have also been documented in many other studies (Riolo *et al.*, 1974; Broadbent *et al.*, 1975; Bhatia and Leighton, 1993). Often these ‘standards’ of growth have been presented separately for males and females due to significant differences observed between the two sexes (Riolo *et al.*, 1974; Costaras *et al.*, 1982; Farkas *et al.*, 1992a, 1992b, 1992c, 1992d; el-Batouti *et al.*, 1994; Johannsdottir *et al.*, 1999; Axelsson *et al.*, 2003). In this study, a large number of subjects was included and all parameters relating to measurements were standardised as much as possible. Differences in size and growth trends between males and females within their age categories were observed. Therefore, results have been presented separately for males and females in the tables and graphs.

The reference normative data in this study were obtained cross-sectionally. Some of the reasons for this included the fact that cross-sectional standards are more representative of a “normal” population and enable comparisons of individuals with abnormalities. A cross-sectional approach was also selected because it would have been unethical to expose subjects unnecessarily to extra radiation by obtaining more than one CT scan. Nevertheless, it is acknowledged that longitudinal studies are particularly useful for determining the rate of growth and following individual subjects.

Additionally, descriptive statistics, such as mean values and standard deviations as well as minimum and maximum values, were presented and summarised in the form of graphs and tables. Moreover, following Farkas *et al.* (1992), results are also presented as percentages of the mean values of the measurement in question at age 0 to 1 year and 3 to 5 years in relation to final adult values. These calculations give the magnitude of how much of the adult value has been attained at these respective ages.

6.2.2 Growth Changes of Different Craniofacial Regions

The craniofacial skeleton is made up of numerous constituent parts, with each region capable of having individual variations. Linear craniofacial variables were selected based on craniofacial regions which were categorised into cranial vault, cranial base and face. The face was further divided into orbital, maxillary, nasal, zygomatic and mandibular regions. Several inter-regional as well as angular variables were also included in the study.

Generally, measurement variables in all regions studied showed a rapid phase of growth in the first year of life and then significant growth up to the fifth year of life. This is apparent from the tables as the biggest size differences were noted during the first year. The graphs also gave an indication of periods of rapid growth during this time by exhibiting steep slopes.

Skeletal craniofacial structures demonstrated differential growth pattern as each region of the craniofacial complex studied displayed a unique growth pattern. Generally, the neurocranium was observed to develop earlier, faster and to much greater extent than the facial complex. It was confirmed that the cranium grew rapidly in the first year of life. Growth slowed down in the later years and was almost complete by 5 years of age. The cranial vault approached adult size early in life, as has been documented in other studies (Waitzman *et al.*, 1992; Farkas *et al.*, 1992a). Most cranial vault and some cranial base variables achieved adult size by the age of 5 years. The measurements collected indicate that by five years of age, the cranial structures had reached more than 90 percent of their eventual adult size. Growth of the cranial vault is a combination of sutural growth between the edges of the bones, deposition of bone on the external surface and resorption on the inner surface of the individual bones and outward displacement of the bones caused by the expanding brain (Sperber, 1989).

A number of cranial base variables displayed evidence of growth well into adulthood as shown by the graphs that displayed a gradual increase in size after a period of rapid growth during the first three years. This was especially true for measurements involving the spheno-occipital synchondrosis.

The spheno-occipital synchondrosis is the most important and most active contributor to growth of the cranial base, persisting into early adulthood (Ford, 1958; Stramrud, 1959; Thilander and Ingervall, 1973; Melsen, 1974). This structure remains open until adolescence and becomes the site for bone deposition that is responsible for growth of the cranial base and related structures that attach to the cranial base (Coben, 1998). Bone is added at the sutures producing growth anteroposteriorly and laterally. Remodelling of the cranial base takes place to accommodate the lobes of the developing brain and the pituitary gland (Sperber, 1989). The prolonged growth period also allows for continued posterior expansion of the maxilla to accommodate future erupting molars and provides space for the growing nasopharynx.

The author has commenced a project dealing with the timing of closure of the spheno-occipital synchondrosis (SOS) and whether differences exist between males and females. Initial findings have revealed that the SOS closes a few years earlier in females compared to males in Malaysian Malays which is in agreement with other previous studies. Previous studies that concentrated upon growth and closure of the SOS by examining human autopsy specimens (Ford, 1958; Thilander and Ingervall, 1973; Melsen, 1972) have shown that the spheno-occipital synchondrosis starts to fuse, beginning on its cerebral surface, at 12 –13 years of age in girls and 14-15 of age in boys; with ossification of the external aspect complete by around 20 years of age. Further assessment of growth changes in the SOS is planned for the future.

Orbital structures manifested differential growth patterns in which more growth was observed in lateral directions than vertically, as has also been reported in a previous study

(Enlow *et al.*, 1982). Measurements of orbital heights and lengths revealed that growth was almost complete in these dimensions by age five years but not for width measurements. However, the width measurement in the central part of the face showed little change from birth to adulthood.

At age five years, transverse dimensions for nasal, maxillary and mandibular regions had attained a greater percentage of adult size than corresponding vertical dimensions. In other words, these structures appeared to grow more vertically than horizontally, a finding also supported by other researchers (Farkas *et al.*, 1992b, 1992d; Snodell *et al.*, 1993). .

Utilizing the more complex methods of least squares and principal components of variation, differential craniofacial growth patterns have been observed (Buschang *et al.*, 1983). These researchers have reported that neurocranial traits show the least amount of growth whereas mandibular traits grow the most. The remaining facial traits show intermediate patterns of relative growth. Another study observed that transverse development of the jaws is also characterised by differential growth between the maxilla and mandible (Huertas and Ghafari, 2001).

The chondrocranium and encapsulated fat pads situated between it and the posterosuperior surface of the maxillae act as a base against which facial growth takes place (Sperber, 1989). The growth of craniofacial regions observed in this study is associated with the growth and development of other structures that also act as forces to promote growth of the facial skeleton. These factors include the growth of the eyeballs, enlargement of the orbital cavities, development of the nasal septum, enlargement of the nasal cavities, development and eruption of teeth of the deciduous and later the permanent dentitions, and development of the dental alveolar arches (Enlow, 1990). In infants and children, the face is vertically short because the nasal region is still small, the dentition has not yet fully established and the jaw bones have not yet grown to the vertical extent that will later support the teeth and the enlarging masticatory muscles and airways (Enlow, 1990).

Additional important findings noted in this study were the occurrence of increased size differences between certain age groups. This event may correspond to timing of mid-growth and adolescent growth spurts. These findings are consistent with many other studies (Farkas *et al.*, 1992a, 1992b, 1992c, 1992d; Snodell *et al.*, 1993; Johannsdottir *et al.*, 1999; Axelsson *et al.*, 2003).

The cranial base angle showed a tendency to decrease with age. Other studies (Thilander *et al.*, 1982; Axelsson *et al.*, 2003) reported that this angle only experiences minor changes in females but decreases in males over time. Nasal angle values tended to increase with age which was expected as the nasal bone becomes more prominent in adults. Cephalic indices were found to be in the ranges of 82.0 to 86.0 for males and 84.0 to 87.0 for females, indicating that Malays fall into the brachycephalic to hyperbrachycephalic category of head form.

The graphical presentations showed that many variables kept on increasing in size until adulthood. This is in contrast to a few other studies that observed growth levelling off by the age of 17 years (Savara and Singh, 1968; Bjork and Skieller, 1974; Costaras *et al.*, 1982; Waitzman *et al.*, 1992; Snodell *et al.*, 1993). The difference in results may be due to the study designs used, i.e. longitudinal versus cross-sectional. However, in the studies referred to above measurements were only collected up to age 17 years with no information available beyond that age. In the present study, measurements were obtained of subjects up to age 25 years and some variables were found to show increases in size until adulthood, albeit at a slower rate.

In the present study, relationships of structures and growth between different craniofacial regions were not explored in detail as this requires quite complicated statistical analyses to be carried out. The relationship of one craniofacial region with another has been documented in a few studies (Dhopatkar *et al.*, 2002; Klocke *et al.*, 2002; Tanabe *et al.*, 2002; Hayashi, 2003). Furthermore, directions of growth of different craniofacial structures were not determined as this also needs specialised methods. The facial skeleton was found to grow in a downward and slightly forward direction, emerging from beneath the neurocranium according to Sperber (1989).

6.2.3 Sexual Dimorphism of Craniofacial Structures

Investigation of sexual dimorphism of the collected craniofacial data for Malaysian Malays revealed differences between the sexes to varying degrees for different regions and at different age categories. The number of variables that showed significant size differences increased from infancy to adulthood. During infancy only a few linear variables were found to differ significantly in size between the sexes. At later ages of 5 to 10 years, more linear variables were found to differ between the sexes. Sexual dimorphism was not evident for most facial and cranial features at this stage but the number of variables showing significant differences was a little greater compared to infants. The lack of significant size differences between the sexes in infancy and childhood was probably due to the relatively small number of subjects available for comparison. This meant that the power of the statistical tests for making comparisons between the sexes was low. Variables were presumably beginning to show some size differences at these early stages that would become more obvious in adulthood.

Indeed, during adulthood, sex differences in size of the craniofacial structures became more obvious as indicated by a larger number of variables that showed significant differences between males and females. These differences were distributed across all of the craniofacial regions, including orbital, maxillary, zygomatic, mandibular, inter-regional, cranial base and cranial vault regions.

The findings in this study were in agreement with a few other studies that found similar patterns of increase in the number of variables that showed differences between males and females at older ages relative to younger ages (Snodell *et al.*, 1993; Cortella *et al.*, 1997; Huertas and Ghafari, 2001). On the other hand, in an established study of children of

European origin, Riolo *et al.* (1974) demonstrated significant differences in craniofacial dimensions between the sexes for most variables as early as 6 years of age. In another study of 6-year-old Icelandic children (Johannsdottir *et al.*, 1999), it was shown that males consistently showed larger values for most linear craniofacial variables.

Another interesting finding in this study was the trend in sex differences over time. The statistical analyses may not have revealed many significant differences but there was a trend for linear dimensions in males to be consistently larger than those in females during infancy. This indicates that there is a tendency for males to be slightly larger in craniofacial structures than females in infancy. During childhood, the males still tended to be larger in craniofacial structures than females but the magnitude of the sexual dimorphism was lower than during infancy. Females were even larger than males for some variables. This suggests that growth of some female craniofacial structures was more advanced than in males during this time. This could correspond with periods of acceleration of growth in females. Many studies support the notion that females grow more than males during childhood and reach maturity earlier than males (Farkas *et al.*, 1992b, 1992c, 1992d; el-Batouti *et al.*, 1994; Bishara, 2000). During the adult stage, males showed a consistent trend of having larger values than females for most variables.

Qualitative descriptions of differences between males and females in craniofacial structures have included reports from Enlow (1990) who observed that during infancy boys and girls look alike and often cannot be distinguished from their facial appearances only. The sex-related facial features begin to become more apparent during childhood. Male skeletal features are beginning to become more angular and robust whereas the females are more rounded. Then, in adulthood, marked differences between males and females are evident as adult males tend to display prominent supraorbital ridges and frontal areas continuous with the nose. Nasal apertures tend to be wider and longer, the chin squarer and the gonial angle shows marked eversion and strong muscle markings in males. Furthermore, the zygomatic arches are thicker and the teeth are bigger in males than in females. The female face looks softer, with the zygomatic area being quite prominent giving the appearance of high cheek bone. The forehead is more rounded in female with lack of prominent supraorbital ridge.

There was no clear pattern of differences between the sexes for angular variables despite the description of shape differences noted earlier. Indices showed no statistically significant differences in the first two stages and, at adulthood, only one orbital index showed a statistically significant difference between the sexes which could have been a sampling effect. However, the failure to discover more significant differences, particularly during adulthood, could once again be due to the relatively small number of subjects for comparison. More importantly, the failure to detect shape differences between the sexes may be due to the use of simple linear and angular dimensions alone that may not be sufficient to detect subtle differences. The angular variables selected in this study were unable to detect these sorts of differences. Shape analyses need to be carried out using more sophisticated tools to be able to distinguish differences between males and females.

During infancy and childhood stages, age was found to be a statistically significant factor for the majority of variables in all regions. This indicated that the subjects were still growing during these times and that minor differences in age could affect the size of dimensions. In contrast, during adulthood age was found to be a statistically significant factor for only a few variables suggesting that most had completed their growth.

The use of 3D-CT in this study has enabled more detailed analysis of sex differences for selected cranial base structures. The cranial base region has been reported to be larger in males than in females (Axelsson *et al.*, 2003). The author initially attempted to describe qualitatively any differences between males and females in the cranial base but this was a difficult task. The cranial base is, in fact, a very complex region and because we are not very familiar with viewing it directly, there are yet to be developed clear ways of expressing differences between the sexes.

Moreover, patterns of differential magnitudes of sexual dimorphism for different craniofacial regions were observed in the Malay sample, and trends across ages were also noted. The mandibular, nasal, maxillary and zygomatic regions and inter-regional variables all showed high magnitudes of dimorphism during infancy and adulthood. The cranial vault, cranial base and orbital variables revealed moderate dimorphism during infancy and adulthood. Most variables in all regions showed relatively low magnitudes of dimorphism during childhood.

The findings from this investigation emphasise the need for clinicians to take sex differences in craniofacial structures into consideration when treatment needs are being considered. These findings support the requirement for different normative data to be established for males and females at different age groups when considering linear measurements. Angular measurements and indices did not show differences at all ages, suggesting the need for more sophisticated analyses to quantify the relatively subtle shape differences between the sexes.

6.2.4 Nature and Extent of Craniofacial Asymmetry

A small degree of directional asymmetry was noted in the craniofacial structures of this sample of normal Malaysian Malays. These asymmetries were observed in all of the craniofacial regions investigated for more variables than would be expected purely due to chance. Cranial base, total face length and mandibular measurements showed mainly right side predominance. Cranial vault, orbital, maxillary and nasal measurements revealed evidence of asymmetry but with about the same number of dimensions showing right and left side dominance.

Cranial vault and orbital variables showed low asymmetry magnitudes with all variables while the zygomatic, face and mandibular regions demonstrated low to moderate asymmetry percentages. Cranial base and maxillary and nasal regions contained a mixture of variables that displayed low and moderate range of asymmetry magnitudes and a few variables that manifested quite high asymmetry values.

The asymmetry indices of a few variables revealed significant age and sex effects. Age changes in asymmetry, particularly for the mandible, may be due to alterations in masticatory function. It is possible that the change of asymmetry from one side to the other may be associated with changing side preference during mastication or a change in the direction of the masticatory pattern which occurred when children move from primary to permanent dentition (Gibbs *et al.*, 1982). One study has shown that the side of facial predominance was a function of age (Melnik, 1992), with a bigger left side of the face at 6 years of age which developed into a bigger right side with growth. In another study, asymmetries of craniofacial regions were presented in foetuses and infants, indicating that asymmetry occurs before the establishment of masticatory function (Rossi *et al.*, 2003).

Additionally, these findings also confirm a lack of sexual dimorphism in asymmetry for the majority of variables, with the ones that showed significant differences between the sexes possibly occurring due to chance.

In agreement with this study, overall facial structures have been reported previously to be larger on the right side (Shah and Joshi, 1978), and the right maxilla, frontal and parietal bones were larger than the left in another study (Woo, 1931). The later study also stated that the overall right side of the face was bigger due to greater development of the right side of the brain. Asymmetries in the cranial and craniofacial structures are influenced by asymmetry in brain structures (Pirttiniemi, 1998). Bilateral variation in brain development occurs during growth, as the brain is normally asymmetric both anatomically and functionally. This in turn gives rise to asymmetric neurocranial structures and the cranial base follows changes in the neural tissues (Pirttiniemi, 1998). In their three-dimensional evaluation of facial asymmetry, Ferrario *et al.* (1995) observed that, on average, the right side of the face was larger than the left. They also found that there was no sex difference in the manifestation of asymmetry. A slight tendency toward larger right-sided structures was also noted in a study of subjects with aesthetically pleasing faces (Peck *et al.*, 1991).

In contrast to the present study, Vig and Hewitt (1975) observed that the cranial base and maxillary regions were significantly larger on the left side in their radiographic investigation. They also found that the mandibular and dento-alveolar regions exhibited a greater degree of asymmetry. These findings were in agreement with another asymmetry study (Chebib and Chamma, 1981).

As has been reported, some craniofacial measurements showed a dominance on one side and others on the other side of the same skull. This condition may be related to the growth processes of craniofacial structures that reflect interrelationships between the various regions as they seek a functional equilibrium. Therefore, asymmetry in the cranial base region may be transferred to other regions on the same side or it may be compensated for and generate a contralateral asymmetry.

It is difficult to compare results from the present study with others because the methods, the measurements, and the sample characteristics (age, sex and race) are very different. Most differences may be methodological in nature, as investigators use different methods and measurements. Comparisons can only be made on a very general basis. Moreover, errors of measurements must be taken into consideration. This is especially crucial when postero-anterior and submento-vertex radiographs or photographic two-dimensional projections are used because errors of projection and errors of landmark identification can occur. The three-dimensional technique adopted in this study allowed direct identification of landmarks on the 3D-CTs and enabled calculation of the asymmetry of undistorted measurements.

It is important to stress that the author only concentrated on the directional component of asymmetry in this study. The author was aware of the fluctuating component of asymmetry but did not attempt to quantify this component for this thesis. Differentiations of fluctuating asymmetry need different approaches and more statistical power, and Livshits and Kobyliansky (1991) have given a comprehensive description of fluctuating asymmetry and its analysis. Results for directional asymmetry in this analysis may be compounded by inherent fluctuating asymmetry.

This observation supports previous suggestions that asymmetry in craniofacial regions is influenced by cranial base asymmetry which in turn is influenced by asymmetrical brain structures. Moreover, the mandible connects directly to the cranial base through the condyles at the glenoid fossa of temporal bone. So, it is not surprising that the mandible followed the asymmetry pattern displayed by the cranial base which, in this study, was found to be larger on the right for most variables. Moreover, the mandible being the farthest from the brain and also the movable part of the face, revealed greater asymmetry than other parts of the face. Together with an influence from the cranial base, functional effects of mastication may add to an already asymmetric mandible.

Additionally, the larger the asymmetry, the more attention needs to be given by the clinician because structures may approach a pathological condition. What determines whether a degree of asymmetry has reached a pathological level is not easy to decide, and clinical parameters relative to aesthetics and function must be taken into consideration. One of the objectives of the current study was to provide normative asymmetry reference values so that pathological conditions can be compared to them and the extent of deviation from normal determined.

Asymmetry of the craniofacial complex can be of concern to the treating clinicians as symmetry is usually taken into consideration in the assessment of patients undergoing surgical and orthodontic procedures. Normally, the goal is to achieve a symmetrical and harmonious face. Additionally, 3D-CT has become a new established method of research into craniofacial asymmetry (Katsumata *et al.*, 2005; Kwon *et al.*, 2006).

6.2.5 Differences in Craniofacial Morphology between Different Populations

Comparison of several selected craniofacial variables between the Malays and Caucasians demonstrated significant differences for a few variables as early as infancy. Other measurements that did not show statistically significant differences revealed that the Malays tended to have smaller measurements. These differences may have been statistically significant if larger sample sizes were available for comparisons. At older ages, more variables revealed statistically significant differences, with Malay craniofacial measurements smaller than those for the Caucasians. In particular, cranial base and palatal length variables showed consistently smaller measurements in Malays as compared to the Caucasians.

Differences in cranial base measurements have also been noted in other population comparisons, namely North American Blacks, who have a shorter cranial base than that of Whites (D'Aloisio and Pangrazio-Kulbersh, 1992). The anterior cranial base was also found to be shorter in Chinese compared with Caucasians at all ages under investigation (Moate and Darendeliler, 2002). Palatal length measurements were also demonstrated to be different in comparisons involving four populations (Dibbets and Nolte, 2002). Enlow (1990) has suggested that a shorter anterior cranial base and fossa sets up a wider but shorter palate and maxillary arch. The finding of a shorter anterior cranial base and palatal length in this study suggests that the morphology of these structures is closely related.

Enlow (1990) has suggested that differences of craniofacial form among different ethnic groups reflected different head forms. Asians (Mongoloids) tend to have brachycephalic head shape whereas Caucasians tend to have dolichocephalic heads. Variations in head form are related to variations in the shape of the brain. The shape of the brain regulates the structure of the cranial base underneath it which in turn corresponds to the variations in the structure of the face. The cranial base serves as a bridge and template upon which the face is attached and establishes correspondingly many variations in the form of the face (D'Aloisio and Pangrazio-Kulbersh, 1992).

Although 3D-CT enables identification of hundreds of measurements, in this study only a few variables were comparable between the Malays and Michigan data, and even fewer numbers of comparisons could be made between the Malays and Bolton-Brush data. The reason for this is that comparisons needed to be limited to measurements in the midsagittal plane because the Caucasian studies were based on lateral cephalometry. Moreover, only measurements that used the same landmarks and definitions of variables could be used. This further decreased the number of comparisons. However, the comparisons give some indication of differences between the Malays and the other populations. More elaborate comparisons could be carried out in the future. Moreover, other differences well known for Asians, such as broad face and low nasal bridge, cannot be compared quantitatively in this study by the use of the current method. This is because the selected Caucasians data did not contain this information. Comparisons to other 3D data would be beneficial at some stage in the future.

These findings support the observation of ethnic differences in craniofacial form observed in earlier studies. The results demonstrate that there are intrinsic ethnic differences and support the opinion that a single standard of craniofacial normative reference data is not appropriate for application to diverse groups. This also emphasizes the need to treat patients from different ethnic groups using norms specific to their own group. Clinicians should anticipate these differences when treating patients from different backgrounds. This study has emphasised the need and has supported the demand to have different normative reference data for different ethnic groups.

6.2.6 Application of Craniofacial Data

The reference data collected and the growth information gained in this study are useful in many ways. Most importantly they provide clinicians, including orthodontists and craniofacial surgeons, with normative values of measurements that can be used in diagnosis, treatment planning and post-operative care of patients with craniofacial abnormalities. Management of these patients usually includes analysis of the head, face and dentition for evaluation of the disorder and for optimising treatment outcomes.

As structures from different regions of the craniofacial complex experience differential growth patterns, clinicians need to take this information into consideration in deciding the timing of surgical intervention. The timing of reconstruction should be based on the residual growth expected. Additionally, the confirmation of sexual dimorphism and asymmetry in the craniofacial structures provided by this study reinforces the need for clinicians to take this information into account when planning treatment for their patients. The findings of differences between the Malay and Caucasian craniofacial variables demonstrate that there are intrinsic ethnic differences and emphasize the need to treat patients from different ethnic groups using norms specific to their own group. The data generated in this study will also provide references for following up growth changes post surgery in patients with abnormal craniofacial conditions.

3D-CT technology allows stereolithographic biomodelling to generate solid replicas of craniofacial anatomical structures (D'Urso *et al.*, 1998; Dolz *et al.*, 2000). This provides a further aid to the surgeon in preoperative planning, as the complexity of craniofacial anatomy combined with variation of the structures makes surgery a difficult task. This technology is commonly applied in the field of maxillofacial reconstructive surgery (Anderl *et al.*, 1994; Sailer *et al.*, 1998). Normative reference data are invaluable at preoperative planning so that the treating clinician can calculate the preferred osteotomy movements to be achieved at operation to produce a balanced cranial and facial form.

6.2.7 Summary of Findings

The craniofacial structures not only display differential growth patterns in various regions but varying degrees of sexual dimorphism and asymmetry. The growth of the brain, which is rapid right after birth, leads to a large percentage of adult size being achieved at an early age by cranial vault variables and some cranial base variables. Generally, the neurocranium was observed to develop earlier, faster and to a much greater extent than the facial complex.

The function and shape of the brain is asymmetric and this influences the growth of the cranial base (Pirttiniemi, 1998). An asymmetrical cranial base in turn gives rise to asymmetrical facial components attached to it. Differences in head form have been reported to be associated with different ethnic groups (Enlow, 1990). Indeed, differences in head form influence the cranial base structures which in turn give rise to differences in facial structures among ethnic groups. The observed differences may be due to the genetic factors but may also be influenced by different environmental and geographical factors that exert their influence during formation and growth of the skull. Differences in the facial skeleton are more complex due to the effects of masticatory function. Caucasians in America and Malays in Kelantan are very different in terms of geographical location, climate, cultural behaviour, life-style and possibly diet; therefore some differences in craniofacial form would be anticipated between these two ethnic groups.

Differences in size between males and females have been proposed to be influenced by lung capacity which in turn is associated with body size (Enlow, 1990). Males tend to have larger airways and nasal chambers and these influence other related differences of craniofacial structures between the sexes.

The variables that were included in this study have been shown to display differential growth patterns but also to be associated with sexual dimorphism and asymmetry. Differences between ethnic groups were also noted in relation to selected craniofacial variables. Many genes and growth factors have been reported to determine the shape of the craniofacial skeletal as they induce bone formation at genetically designated sites (Sperber, 2001). Although the basic shape and size of bones may be genetically determined, extrinsic functional or environmental factors would seem to become important determinants of final form.

Overall, the 3D analysis has provided extensive information of craniofacial structures not available with other conventional radiographic methods.

6.3 Limitations of the Study

One of the limitations of this study is the relatively small sample size in the selected age categories. Although the overall number of subjects was quite large, their ages ranged from birth to adulthood. The age categories needed to be selected to ensure a reasonable number of subjects were included in each selected age category but small enough to capture important events such as the mid- and adolescent growth spurts. However, the small number of subjects limited the statistical power of the analysis and hence, caution must be used when drawing inferences or conclusions from the data.

Also, while numerous craniofacial landmarks were measured, not all of them were analysed due to time constraints. The selection of the variables that were studied was based on craniofacial regions, namely the cranial vault, cranial base and facial regions. 3D imaging makes possible the analysis of hundreds of more variables from other regions including the hyoid bone, nasopharynx, cervical vertebrae, cranial sutures and fontanelles and more detailed analysis of the cranial base and spheno-occipital synchondrosis. It is the intent of the author to carry out further research into these areas in the future.

For measurements involving very small structures such as the width of separation of the spheno-occipital synchondrosis, higher resolution of the 3D-CT reconstructions will be needed. The author has attempted to locate landmarks to define this dimension but was unable to do so reliably with the current resolution of 3D-CT reconstruction. The author needs to devise a way of producing higher resolution of 3D-CT reconstructions using the available data. The current resolution used in this study is sufficient for determination of other landmarks with minimal relocation error as proved in the error analysis for this study. From the error study, location of landmarks for the current 3D-CT reconstructions is both accurate and reproducible.

Another limitation of this study is that it is cross-sectional, not longitudinal. This cross-sectional approach was selected for a few reasons: firstly, due to the time constraints associated with my PhD candidature; secondly, cross-sectional standards are thought to be more representative of a “normal” population than longitudinal studies (Tanner, 1962; Cameron, 2002); and thirdly, it would have been unethical to expose subjects unnecessarily to extra radiation by obtaining more than one CT scan if longitudinal approach was to be performed. This means that changes over time in individual subjects cannot be assessed and knowledge of growth rates cannot be drawn. However, cross-sectional studies can assess trends and provide valid representations of growth patterns.

This study also only provides linear and angular measurements from different craniofacial regions for use in the analysis of growth changes of different craniofacial variables, sexual dimorphism, asymmetry and differences with other groups. This study did not take into consideration the relationship of variables from different craniofacial regions and the direction of growth of different craniofacial regions. The later information can be derived utilising specialised methods and statistical analysis. Moreover, shape differences which were not sufficient with the use of angular variables and indices may be apparent with the use of more sophisticated morphometric analyses.

6.4 Future Studies

The present investigation has opened the way for further studies into the quantification and analysis of normal craniofacial morphology in Malaysian Malays in three dimensions. Several avenues of future research have been suggested by the findings reported here, including the use of more sophisticated morphometric shape analyses.

Geometric morphometric study was undertaken by Vioarsdottir *et al.* (2002) who examined interpopulation variations in the facial skeleton of ten human populations. Singh *et al.* (2004) have recently undertaken a comprehensive longitudinal craniofacial growth study of orofacial clefts involving morphometric analysis. Other studies have also applied geometric morphometric analysis in the description of shape changes in their investigations (Bookstein, 1983; Netherway *et al.*, 2006). Some preliminary investigation utilising morphometric analysis has been done for the mandible and was presented at the annual conference of International Association for Dental Research in 2003. The abstract for this presentation is presented in Appendix III.

It is planned to extend the area of study to include other craniofacial regions such as the hyoid bone, nasopharynx, cervical vertebrae, cranial sutures and fontanelles, paranasal sinus volume, temporomandibular joint. More detailed analyses of the cranial base, including cranial base foramina and fissures and spheno-occipital synchondrosis, are also planned. Some preliminary work has been conducted on the timing of closure of the spheno-occipital synchondrosis and cranial fontanelles. It is hoped that, with time, increasing numbers of patients will be added to the current sample, thereby allowing the use of more sophisticated methods of analysis.

It is also planned to explore the topic of fluctuating asymmetry in normal Malaysian Malays and its association with developmental homeostasis.

The availability of 3D imaging technology has enabled ambitious projects, such as computer-assisted surgical and orthodontic planning and simulation through the generation of computer software, that allow virtual simulation of the treatment proposed utilising the normative reference developed in this study. This idea has been brought forward in many studies and can be realised with the advancement of computer technology available nowadays (Lo *et al.*, 1994; Lo and Chen, 2003).

Additionally, CT materials collected by the author have been and currently are being used by some undergraduate and postgraduate students in the School of Dentistry at the University of Adelaide in their research projects. These include investigations of volumetric analysis of the paranasal sinuses of individuals with cleft lip and palate, and analysis of nasal bone morphology in infants with cleft lip and palate where the materials from this study serve as normal references. Other projects underway include investigations of certain aspect of cranial base morphology and more detailed analysis of craniofacial asymmetry undertaken by postgraduate students at the School of Dental Sciences, Universiti Sains Malaysia.

6.5 General Conclusion

From the findings of the present study of Malay Malaysians it can be concluded that differential growth patterns existed for different craniofacial regions with each region demonstrating a unique pattern of growth. The craniofacial structures also displayed varying degrees of sexual dimorphism and asymmetry. Moreover, craniofacial structures demonstrated ethnic differences as observed from the comparisons of the Malay data with data from two Caucasian studies. These findings support the requirement for different normative data to be established for different ethnic groups, sexes and age categories.

Clinicians need to take this information into consideration in deciding the timing of surgical interventions. During management of patients with craniofacial abnormalities, important treatment goals include producing a balance of cranial and facial form and improving the quality of life of patients. Additionally, the confirmation of sexual dimorphism and asymmetry in the craniofacial structures provided by this study reinforces the need for clinicians to take this information into account when planning treatment for their patients. Moreover, the findings of differences between the Malay and Caucasian craniofacial data demonstrate that there are intrinsic ethnic differences and that patients from different ethnic groups need to be compared with norms specific to their own group. The data presented also provide references for follow up of growth post-surgically in patients with abnormal craniofacial conditions.