CHAPTER 1

AN INTRODUCTION TO THE STUDY OF HUMAN CRANIOFACIAL GROWTH AND MORPHOLOGY

1.1 Background to the Present Investigation

Many studies leading to the construction of ‘normative’ reference data for dental and craniofacial features have been carried out using a variety of methods. The intent of these investigations has been to provide clinicians, often orthodontists and craniofacial surgeons, with normative values of measurements that are of some use in disease 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 disease and for improvement of clinical treatments. Many conditions are treated over several years, from infancy until adulthood when patients are no longer growing. Therefore, it is important for clinicians to be able to recognise the nature and extent of normal variation of craniofacial structures and also the growth changes that may occur over time, before investigating these changes in patients with craniofacial abnormalities.

Important treatment goals include producing a balanced cranial and facial form to approximate that of unaffected people and also improving the quality of life of patients. Indeed, comparison of measurements of these patients to well-characterised referent data has been reported to facilitate diagnosis and overall patient management (Carr *et al.*, 1992; Waitzman *et al.*, 1992; Posnick *et al.*, 1995).

So-called ‘normative’ reference data are influenced by many factors that may affect their applicability. Steiner (1959) has stated that his normative data of dentofacial measurements should only be used as a starting point and that they must be modified by other factors such as age, sex, race, growth potential and individual variations within the groups.

Previous investigations have shown that there are differences in craniofacial form among racial groups (Altemus, 1960; Drummond, 1968; Nanda and Nanda, 1969; Kowalski *et al.*, 1975; Harris *et al.*, 1977). Moreover, differences between sexes (Riolo *et al.*, 1974; Bhatia and Leighton, 1993; el-Batouti *et al.*, 1994) and across different ages (Riolo *et al.*, 1974; Broadbent *et al.*, 1975; Bishara, 1981) have also been documented. Therefore, there is a need to develop norms for different racial groups, sexes and ages. This necessity rests on the fact that there will be greater validity if an individual is compared to referent data matched for their specific racial group, sex and age.

Normative data have been generated using many methods, such as craniometry, soft tissue anthropometry and cephalometric radiography. With the advent of three-dimensional computerised tomography (CT) (Cormack, 1979; Hounsfield, 1980), this technology has provided new tools for disease investigation and CT has become an important method for management of craniofacial patients. However, there is then a need to have normative referent CT data against which data relating to the craniofacial morphology of patients with various abnormalities can be compared.

This research project was initiated to provide a three-dimensional description of craniofacial morphology and growth changes in a large convenience sample of Malaysian Malays. For the Malay population, craniofacial data, even in 2-dimensions, are still lacking. The 3D data reported in this thesis will provide, for the first time, comprehensive normative reference material for Malaysian Malays. These data will be useful for many purposes, but most importantly they are intended to be used for comparison with data derived from individuals with craniofacial abnormalities, either congenital or acquired, to assist in diagnosis and treatment planning.

1.2 Methods of Investigating the Craniofacial Morphology

Observations of craniofacial form have been recorded for many centuries and many early studies of craniofacial morphology and growth were aimed at describing patterns of normative variation (Finlay, 1980). Understanding the nature and extent of normal variation of craniofacial structures, including growth changes, is necessary in order to investigate changes of morphology and growth in patients with craniofacial abnormalities.

Normative references for craniofacial morphology have been developed mainly by using a few well-known methods, including craniometry, anthropometry and cephalometric radiography. There are many other methods such as photography, and laser surface scanning, as well as modifications and improvements to the above methods. Brief descriptions of these methods are given in the following sections.

1.2.1 Craniometry

Craniometry is a branch of physical anthropology dealing with the study and measurement of dry skulls after removal of the soft tissues. One of the earliest craniometric references was produced by Martin (1914). Subsequently, craniometric references for different tribal groups in South Africa were reported based on a large number of skeletal specimens (De Villiers, 1968). More recently, Howells (1989) constructed a comprehensive summary of measurements from skeletal material derived from various geographical regions of the world.

1.2.2 Soft Tissue Anthropometry

Anthropometric data have been obtained directly on living subjects using many kinds of callipers, either traditional or more recently digital ones. The most widely known anthropometric references have been provided by Farkas and Munro (1987) who obtained measurements from a large number of subjects and constructed normative reference measurements of the head and face for North Americans (Western European Caucasian descendants) at yearly intervals from age 6 to 18 years.

1.2.3 Cephalometric Radiography

Since the advent of cephalometric radiography (Broadbent, 1931; Hofrath, 1931), this method has been widely used as a descriptive, analytical and diagnostic tool, particularly in orthodontics and in research. It has been employed to study craniofacial morphology of the same subjects throughout their growth periods. Cephalometric radiography has offered very useful insights to orthodontists and surgeons about how growth processes may influence treatment for patients.

From 1931 onwards, there has been a considerable amount of work published that has investigated the utility and validity of cephalometric radiography analyses. Most of cephalometric radiography is based on the use of lateral cephalograms, where landmarks and measurements lie in the mid-sagittal plane. Many studies have produced standards for craniofacial variables outlining changes in two-dimensions (Riolo *et al.*, 1974; Broadbent *et al.*, 1975; Bhatia and Leighton, 1993). Landmarks are identified on the film or tracings, and a selection of linear and angular measurements is derived to produce standards at different ages. Summary statistics have usually been presented in tabular and graphical forms. This has recently been supplemented by computer-aided technologies that now enable rapid assessment and comparison of craniofacial anatomy.

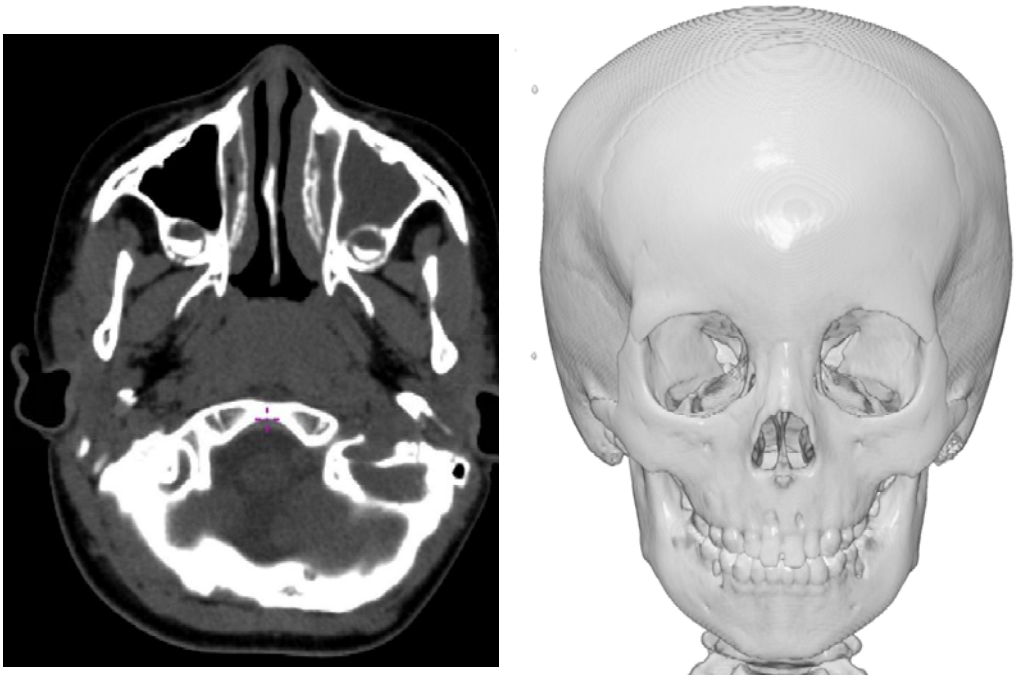
However, several disadvantages of radiographic cephalometry have been documented (Ahlqvist *et al.*, 1986; Houston *et al.*, 1986; Kamoen *et al.*, 2001). The data are only 2-dimensional, and images may be distorted due to the projection of three-dimensional objects into two dimensions. There are also the effects of differential enlargement. Analysis of such data is limited and often inaccurate when attempting to describe a complex three-dimensional structure like the skull. Many of the three dimensional craniofacial features are unable to be identified in detail on traditional cephalograms. These records are also associated with greater measurement errors due to the nature of the images.

1.2.4 Computerised Tomography

With the advent of three-dimensional computerised tomography, the whole craniofacial complex can be comprehensively imaged and therefore accurately analysed. Computerised tomography (CT) was pioneered by Cormack and Hounsfield in the 1960s and 70s, for which they were awarded the Nobel Prize in Medicine (Cormack, 1979; Hounsfield, 1980). This technology has provided new tools for medical investigation and has become one of the most widely used imaging methods today. CT provides the capability of visualising tissues of interest in sequential layers without the problem of superimposed structures interfering with visualisation or distortion of these tissues. CT is now well established and has advanced to the stage where more sophisticated CT scanners are in use.

An important step forward in CT technology came with the introduction by Herman and Liu (1977) of three-dimensional reconstructions from axial slice data (Figure 1.1). This eliminated the need for the clinician to attempt mental assimilation of three-dimensional images from two dimensional data (either cephalograms or axial CT scans). Often this would be inaccurate or even impossible.

Abbott (1988) established the reliability and accuracy of this reconstruction technique. It has the ability to comprehensively quantify the whole craniofacial complex (both normal and abnormal) in three dimensions. This technique was then applied to quantify craniofacial morphology in Crouzon and Apert conditions by Proudman (1995) and Holten (1996).



(a) **(b)**

Figure 1.1 Three-dimensional reconstruction of the craniofacial skeleton (b) from axial CT slices (a).

In both studies, 3D normative references were needed as the basis for comparisons with abnormal subjects. Experimental references derived from a limited number of living subjects and dry skulls were constructed for this purpose. Normative references were needed in order to characterise abnormal structures and to quantify the magnitude of deviation from normal. Referent data from CT scans were produced by Waitzman *et al.* (1992), but only two-dimensional images were used and only a small part of the craniofacial region was selected. The information gathered was lacking in terms of the number of landmarks used and the images generated were still unable to give an exact picture of the craniofacial bones. At present, 3D normative standards for craniofacial variables derived from large samples are still lacking.

1.3 The Malaysian Malays

Malaysia consists of different ethnic groups with different cultures and languages. The total population of Malaysia was 23.27 million in the census carried out in the year 2000 with the Bumiputeras comprising 65.1% of the total population. The Chinese and Indians form 26% and 7.7% respectively. The Bumiputeras are the natives of Malaysia, who comprise Malays, Serani, Baba Cina, the indigenous people of East Malaysia, and the Orang Asli, with the Malays being the majority.

(http://www.statistics.gov.my/english/census/pressdemo.htm).

The Malays are people who originated from assimilation between Proto-Malays and Chinese during the Chao Dynasty, Indians from Bengal and Decca, and also Arabs and Thailanders.

(http://www.magickriver.net/ethnocide.htm).

In Kelantan, where the data for this study were collected, the Bumiputeras make up 95% of the total population of nearly 1.3 million people in the census carried out in the year 2000.

(http://www.undp.org.my/uploads/files/KelantanHumanDevelopment.pdf).

The genetic makeup of the Malays, whose ancestors were from different geographical areas, may influence morphology and size of the craniofacial structures. Within this Malay ethnicity, much variation can be viewed from the bony structure of the head and face to the colour of the skin. The majority of Malays have similar features to the description by Enlow (1990) of the Oriental head and face, with brachycephalic/short head form, wide face, low nasal bridge, flat and short nose, and short midface and upright forehead (Figure 1.2). The eyes may look wide-set because the nasal bridge is low. The mandibular corpus tends to be shorter relative to the maxillary arch, that contributing to a tendency towards bimaxillary protrusion (Enlow, 1990). Despite these trends, more dolicocephalic, angular, long, and thin-nosed individuals also exist in this group.

Figure 1.2 Frontal and lateral views of a Malay male in his early twenties.

1.4 Overview of Normal Embryonic Craniofacial Development

1.4.1 Development of the Face

The development of the face is well described and illustrated (Figure 1.3) in terms of its formation and the fusion of various processes or prominences (Sperber, 1989). This occurs mainly between the 4th and 8th weeks, when the face develops a human appearance. The stomatodeum becomes surrounded by five processes that are formed by proliferations of mesenchyme. These are the single frontonasal processes and the paired maxillary and mandibular processes.

The frontonasal processes form the site of the future forehead. On its inferolateral surface two thickenings appear, the nasal placodes from which nasal pits will form as elevations develop laterally and medially. These elevations are the lateral nasal and medial nasal processes. The medial nasal processes merge and give rise to the tip of the nose, the middle portion of the upper lip, the anterior portion of the maxilla and the primary palate.

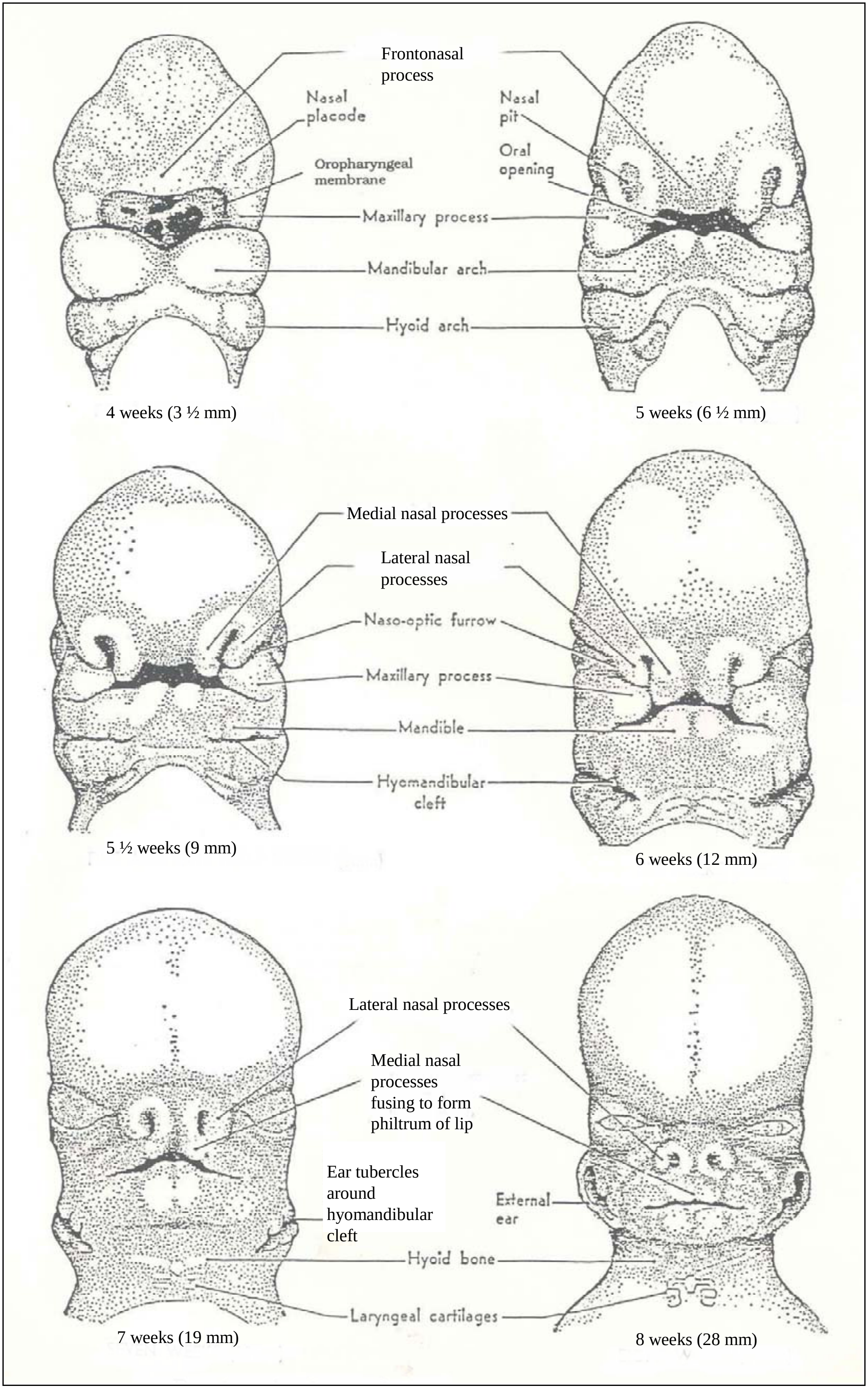


Figure 1.3 Some important steps in the formation of the face (After William Patten, from Morris, "Human Anatomy," McGraw-Hill Book Company, New York in Lecture notes, Development of the Head and Neck, Department of Anatomy and Structural Biology, University of Otago, 1993).

The maxillary processes develop at the dorsal end of the mandibular arch. They grow forwards beneath the developing eye and fuse with the lateral nasal processes. The maxillary processes continue anteromedially to fuse with the medial nasal processes and form the upper lip. The nasal pits then become separated from the stomatodeum.

The mandibular processes merge in the midline to form the lower jaw and lip. The maxillary and mandibular processes of each side merge to form the cheeks and define the size of the openings of the mouth. The primitive jaws develop a labiogingival groove between the developing lips and alveoli for the developing teeth. The facial bones develop by intramembranous ossification from centres in the embryonic facial processes. Ossification centres for most of the bones appear by the 8th weeks (Figure 1.4).

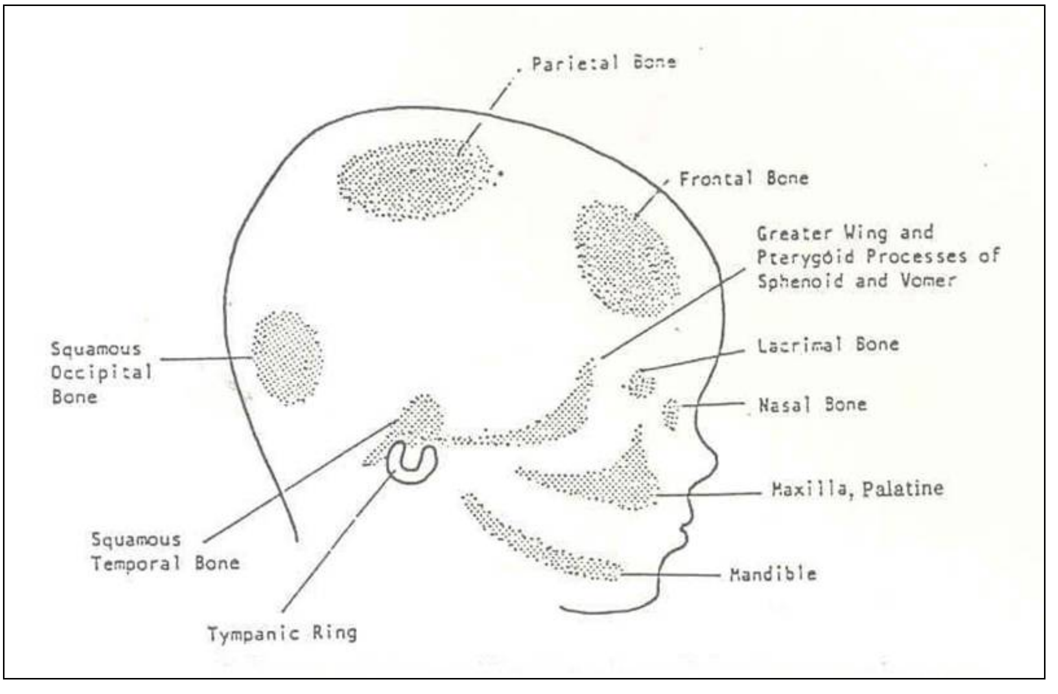


Figure 1.4 Drawings of the ossification centres for most bones of the head and face (Lecture notes, Development of the Head and Neck, Department of Anatomy and Structural Biology, University of Otago, 1993).

1.4.2 Development of the Skull and Cranial Base

The main developmental regions of the head can be classified into cranial vault (neurocranium), cranial base (chondrocranium) and facial skeleton (viscerocranium) (Figure 1.5). The bones of the cranial vault and of the facial skeleton ossify via intramembranous ossification and the bones of the cranial base ossify via endochondral ossification.

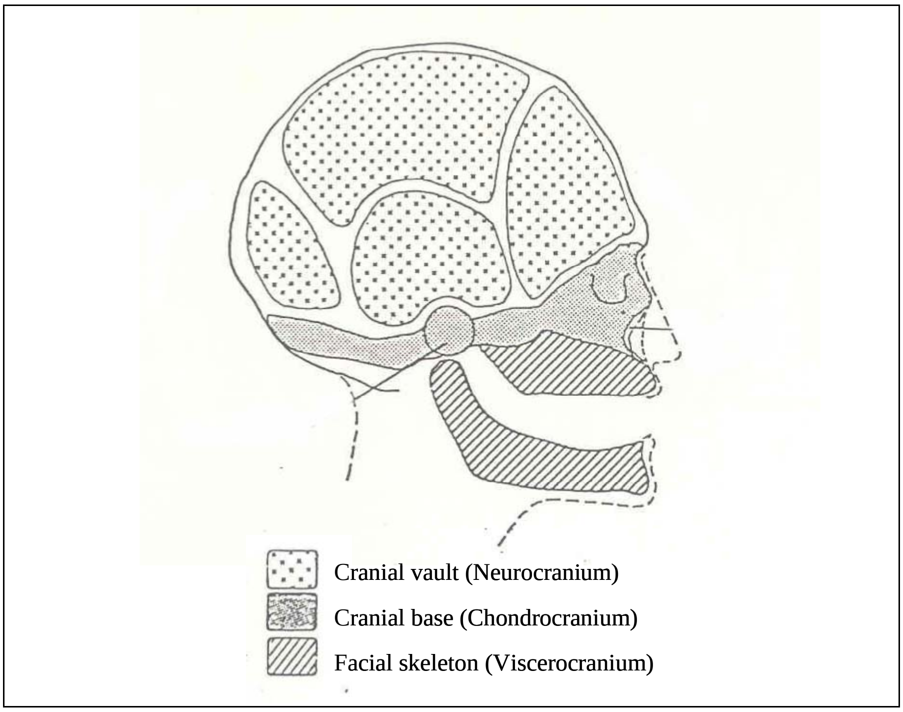


Figure 1.5 The main developmental divisions of the head and face (Lecture notes, Development of the Head and Neck, Department of Anatomy and Structural Biology, University of Otago, 1993).

The cranial vault forms ossification centres that develop in the mesenchymal capsule surrounding the brain (Figure 1.4). These centres appear in the 7th and 8th weeks and ossification continues until birth. At birth the bones of the cranial vault are widely spaced by sutures and fontanelles.

During the 3rd and 4th weeks, a concentration of mesenchyme forms a floor for the developing brain. This is closely related to the end of the notochord and the occipital somites and anterior to these structures. Centres of chondrification appear in the mesenchymal during the 7th week and form the cartilages of the embryonic cranial base. All cartilages unite to form a basal plate for the support of the developing brain. The plate is perforated by foramina for the passage of nerves, blood vessels and the spinal cord. Centres of ossification appear within the cartilage of the cranial base commencing in the 3^{rd} month.

During the embryonic and fetal periods the cranial base becomes flexed in the region of the pituitary fossa and spheno-occipital junction. This brings the developing face to its position beneath the cranium. Other changes resulting from the cranial base flexion are a flexion of the brain stem, an enlargement in the capacity of the cranial cavity and a change in direction of the foramen magnum and the exit of the spinal cord to vertically downwards.

1.5 Overview of Normal Postnatal Craniofacial Growth

1.5.1 Postnatal Growth of the Facial Skeleton

The facial skeleton grows in a downwards and slightly forwards direction, emerging from beneath the neurocranium (Figure 1.6). 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. Growth occurs by formation of new bone at sutures and surface apposition of bone and remodelling. Sutural growth is most active up to the age of 4 years, after which adjustments are made by apposition and remodelling.

The growth and development of other structures 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, to name a few.

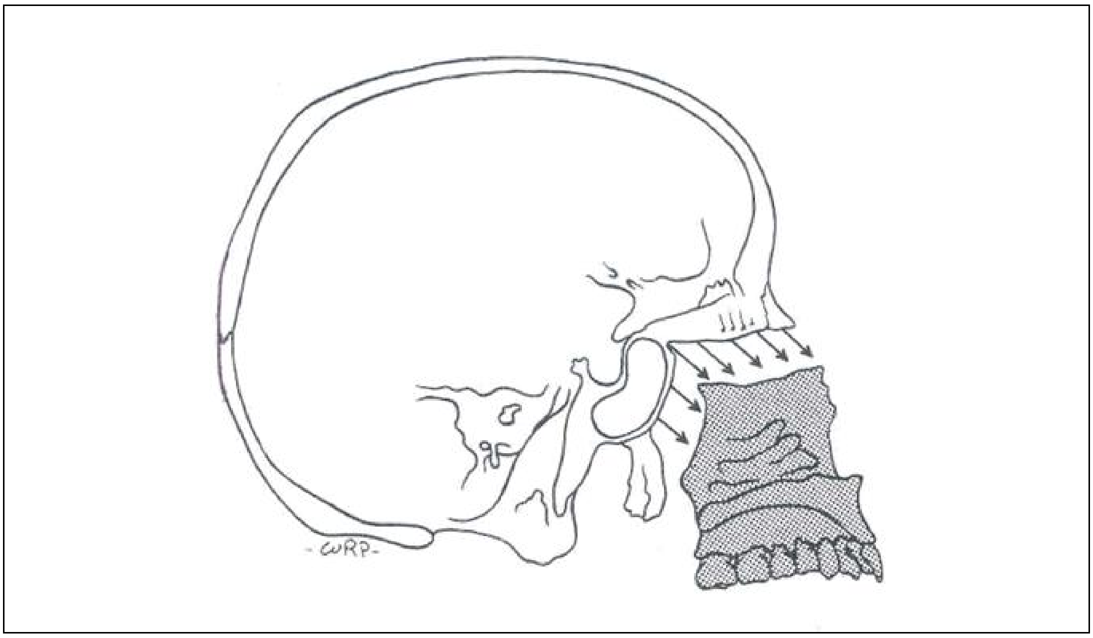


Figure 1.6 Growth of the facial skeleton in downwards and forwards direction in relation to the cranium as shown by arrows (Enlow, 1990).

1.5.2 Postnatal Growth of the Skull and Cranial Base

Growth of the calvarial bones 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. The wide sutures then become fibrous joints and the fontanelles close with the anterior fontanelle closing last during the second year.

Growth of the cranial base takes place as a result of growth of cartilage remnants that continue to be present between bones and parts of individual bones and the growing brain displacing the bones at their suture lines. These cartilaginous sutures are called synchondroses. Bone is added at the sutures producing growth anteroposteriorly and laterally. The spheno-occipital synchondrosis is the most important and most active contributor to growth of the cranial base. It remains active until mid-adolescence with ossification completed about 20 years of age. Remodelling of the cranial base takes place to accommodate the lobes of the developing brain and the pituitary gland (Enlow, 1990).

In addition to the complexities of growth of the interconnected and related parts of the craniofacial complex, variation occurs between different individuals even within the same population. Even more variations are anticipated between individuals from different groups of diverse geographical and ethnic groups. Investigations of postnatal growth changes in Malays from birth to early adulthood have still not been well documented. It is anticipated that growth changes may not vary so much from what is already known in other populations. However, some differing trends may be noted.

Additional information that the author wants to explore in this thesis includes the differences in craniofacial morphology between males and females, asymmetrical expression of features in both sexes, and whether craniofacial data for Malays are different from published data for Caucasian populations that have been widely used. More detailed discussion of these topics will take place in the subsequent chapters.

1.6 Aims of this Study

The main aims of this study are to use CT imaging and computer technology to produce new 3D reference data for selected craniofacial variables in Malaysian Malays and to study growth changes in different craniofacial regions.

The specific areas of investigation include:

1. Construction of craniofacial growth references (in tabular and graphical formats) for Malaysian Malays;

2. Quantitative analysis of growth changes in the craniofacial complex using linear and angular measurements derived from landmark data;

3. Comparison of measurement differences between males and females;

4. Quantitative analysis of the nature and extent of directional asymmetry of selected craniofacial regions;
5. Comparisons of selected variables with published data from other ethnic groups.

1.7 Significance of this Study

It is hoped that findings from this research will be valuable to many disciplines. Most importantly this research has been initiated to fill a void in the availability of normative referent data and growth changes for Malays. These data should be of value in surgery and orthodontics during management of patients with abnormal craniofacial conditions. Others who should also benefit from these data and the results of the associated analyses include medico-legal experts and forensic scientists for whom this new information will complement other data that are already available. In addition, these referent data will provide an important resource for craniofacial researchers in the future.

It is intended that the data obtained as part of this thesis will be placed in a data bank and thus be made accessible for future use. This should enrich the training of clinicians who will be able to use these data to demonstrate morphologic variations that they may encounter. In particular, this study will have major significance for the management of patients in Malaysia at the Centre for Craniofacial Sciences, Hospital Universiti Sains Malaysia, Kota Bharu, Kelantan.

1.8 Structure of the Thesis

This is the first 3D CT study of craniofacial growth changes in Malaysian Malays and it provides the first comprehensive 3D normative craniofacial referent data for Malays from birth to young adulthood. The thesis contains a general methodology used, and chapters discussing the generation of normative reference data and growth changes in Malays, a description of the differences between males and females, an analysis of craniofacial asymmetry and a comparison between Malay data with those published for two Caucasian populations (Riolo *et al.*, 1974, Broadbent *et al*., 1975).