CHAPTER 2

GENERAL MATERIALS AND METHODS

2.1 Introduction

This chapter presents the methodology behind the acquisition of the CT data used in the study. Essential processes are described, including collecting CT records to the stage where the data could be analysed. As this was a prospective cross-sectional study, an extended time was spent in collecting records (nearly 12 months), to ensure that sufficient numbers of subjects could be gathered. The CT records were then subjected to a series of procedures before landmark data could be acquired and qualitative analyses performed. Careful attention was given to ensuring that the landmark data were accurate by performing a landmark identification procedure on two separate occasions. Measurements of selected variables were then made based on the landmark data and used for investigations in subsequent sections of this thesis. CT data in 2D views and 3D reconstructions were also used for qualitative analysis. Finally, overviews of the statistical analyses used in this study are presented.

2.2 Planning Stage

During the preliminary stages of the study, frequent meetings were held with supervisors to discuss important issues, such as the scope of the project, what data should be collected and the methods of data collection. Specific topics relating to craniofacial morphology were also identified broadly at this stage. It was clear that CT data would be collected, but our initial plans to collect considerable additional records from each subject, including height and weight measurements, dental examinations and dental models, proved to be rather ambitious.

The most crucial issue at this initial stage was to determine whether the CT scans obtained in Malaysia would be compatible with the software used at the ACFU. Two sets of trial data were sent from Malaysia and it was confirmed that they could be read and analysed.

A research proposal was produced which was then used to obtain ethical approval from the Universiti Sains Malaysia (USM). Ethical approval was secured in August 2001, document number: USM/PPSP®/Ethics Com./2001[62.3(1)], Appendix I.

As this research was supported strongly by the Dean of the Dental School, Universiti Sains Malaysia, he nominated a few personnel to assist in record collection. The initial plan involved making a short trip to the Universiti Sains Malaysia Hospital (HUSM) to train the identified personnel in record collection. A set of flow charts containing instructions for each person was constructed.

2.3 Trip to Universiti Sains Malaysia, Kota Bharu

The trip to Malaysia from Adelaide was made in the middle of September 2001. Meetings were held with the key individuals who were to be involved in the study. They included the Head of the Radiology Department who was also a co-supervisor for this project, the Dean of the Dental School, a research officer, a senior radiographer and a dentist. At this stage, the Dean appointed the dentist to assist me and to be trained in record collection. Letters explaining the research were sent to relevant Heads of Departments at the Hospital and to the Hospital Director prior to commencing record collection. The radiology staff were made aware of the project to gain their cooperation. The radiology staff involved in the CT Unit were briefed about the project and about the specific protocols that were required for scanning. Auxiliary staff at the dental clinics were also informed of the project.

Announcements and brief information regarding the project were placed in the CT Unit and also in the dental clinics.

2.4 Data Collection

The CT Unit is run by medical officers, radiographers and nurses. They work on a rostered basis, i.e. they are also allocated to other radiology units. The roles of medical officers include preparation of patients should they need contrast medium for a scan and production of radiology reports. Radiographers are the ones who handle the machine and actually obtain the scans and, together with medical officers, decide on the protocols to use for scanning. The nurses provide assistance to the medical officers.

The details of all patients needing scans are entered into an appointment book. They can both be in- and out-patients and may be referred for various types of body scans. Suitable patients for this study who required head scans were interviewed prior to CT scanning either in the waiting room of the Radiology Department or in the ward. There were also urgent cases of patients needing CT scans of the head, due to various acute conditions, who were referred from the wards and from Accident and Emergency Departments.

Generally, cooperation was obtained to accommodate the specific protocol that we required for the study, which involved a longer processing time once the scanning had been completed. Having the Head of Radiology Department as a supervisor ensured that there was access to CT data and that radiology reports and patient medical records were received. It also tended to make data collection less difficult.

Some difficulties occurred during the data collection period, mainly attrition of subjects due to lack of cooperation from certain medical officers. Subjects lost from the study were mostly those who required scans as urgent cases. Urgent head scans formed 40% of the total subjects in this study. The medical officers were contacted by other departments when they required CT scans for their patients but the author was seldom contacted when such cases occurred. There was a need for the author’s presence at the CT Unit to maximise the number of subjects who could be enrolled. Some subjects were also lost due to time spent taking dental records and impressions at the dental school.

We later realised that there was no-one at the hospital who could really concentrate on this study. The identified personnel were unable to focus on this research due to other responsibilities. This change of event influenced the decision for me to stay in Malaysia for 10 months for the purpose of record collection. This was very important for the success of the project.

Carrying out clinical examinations and obtaining dental impressions had to be discontinued at a later stage for several reasons. There were not many subjects for whom it was possible to obtain dental impressions because they were ill and often intubated. It was not possible to obtain impressions from most children due to a lack of cooperation. The most important reason for discontinuing the collection of these records was that CT patients tended to be lost during the time spent obtaining dental information and impressions. The appointed dentist was not always available at the time when dental impressions were needed and these procedures needed to be carried out by the author. This proved to be too difficult and so it was decided to stop trying to obtain these extra records.

Height and weight could be measured accurately only for conscious subjects who were able to stand. For infants and unconscious patients, supine length was measured with a measuring tape. Weights could be obtained for infants as they could be easily placed on a baby scale but could not be recorded for unconscious and immobile older children and young adults.

2.5 Materials

2.5.1 Sampling Method

In making statistical inferences about data, a crucial question is how representative of the population is the actual sample chosen. When measurements are being made on groups of human subjects the question of possible bias in the selection procedures has to be carefully assessed before it can be concluded that a sample is representative of the larger population.

It was not possible to randomly select Malay subjects from the population. It was also not possible to randomly select CT records of Malays specified by sex and age, since only individuals with certain medical conditions were indicated for CT investigations. Ideally, it would be best to obtain CT scans from normal individuals, but the radiation dose involved in acquiring CT scans would be a major issue. There needs to be a medical and diagnostic reason for performing a CT investigation. This limited the potential source for normal population data to those patients with conditions that did not affect the craniofacial skeleton. Therefore, in this study, the subjects were patients who were undergoing CT scanning investigations for problems other than those known to cause abnormalities in craniofacial growth and morphology. Hence, the subjects in this study were patients with conditions significant enough to justify the taking of CT scans but for whom the conditions did not cause abnormalities in craniofacial growth and morphology. The patients and their medical conditions are listed in Table 2.1.

2.5.2 Subjects

CT scans were obtained of Malaysian Malay subjects between 2001 and 2002. All scans were performed at the Radiology Department, HUSM, located in Kota Bharu, Malaysia. Patients and/or parents were interviewed prior to scanning. Explanations were given regarding the project and a written consent form was signed when they agreed to participate.

Table 2.1 Distribution of subjects and their medical conditions displayed according to craniofacial regions.

Region	**Medical conditions**	**N (%)**
Brain and meninges	Infections	20 (9.8)
	Hydrocephalus 2º to infections	7(3.4)
	Encephalocoele	2(0.9)
	Meningocoele	1(0.5)
	Haemorrhage or haematoma 2º to trauma	51(24.9)
	Tumour	6(2.9)
	Headache	8(3.9)
	Fever with fits	6(2.9)
	Normal brain	17(8.3)
Cranial and facial bones	Osteoma	1(0.5)
	Fractures 2º to trauma	23(11.2)
Soft tissue	Benign cystic lesion	6(2.9)
	Other soft tissue lesion	4(2.0)
Eyes	Leukokoria	1(0.5)
	Retinoblastoma	4(2.0)
	Trauma	3(1.5)
	Reduced vision	1(0.5)
Sinus	Sinusitis	16(7.8)
Ear	Otitis media	1(0.5)
Parotid	Parotid abscess	1(0.5)
Neck	Retropharyngeal abscess	1(0.5)
	Foreign object	1(0.5)
TMJ	TMJ Problem	2(0.9)
Others	Others	9(4.4)
Not available	Not available	13(6.3)
Total		**205(100)**

Once consent was obtained, a sticker was placed on the patient’s radiology request form so that the specific protocol for this study could be followed during scanning. Height and weight measurements were normally taken while patients were waiting to be scanned. Dental records and impressions were obtained only from patients who were able to go to the dental clinic, after CT scanning.

Records were also gathered from the existing CT database in the Radiology Department, provided that the quality of the CT after reconstruction was acceptable. This was due to insufficient numbers of subjects who could be collected from a prospective approach alone. Reasons for the lack of suitable subjects included the limited time period available for record collection, consent refusal from some parents, and the need to only select normal subjects from patients presenting for CT scans. In this study, 205 subjects were selected comprising 115 males and 93 females with an age range between 0 to 25 years of age. The distribution of subjects according to age interval and sex is displayed in Table 2.2.

From the CT records that were selected, not all were complete head scans. Some of them were partial scans that covered most of the head and face. However, these partial scans were included because valuable information could still be extracted from them and also because this improved the sample sizes in each of the age categories.

2.6 Method

2.6.1 Equipment, the CT Scanner

High resolution helical scans were obtained with a General Electric (GE) LightSpeed Plus CT Scanner System (General Electric Company, Medical System Group, Wisconsin, USA) housed at the Department of Radiology, Hospital Universiti Sains Malaysia. The protocols practised at the Australian Craniofacial Unit (ACFU), Women and Children's Hospital, Adelaide served as the guidelines for the scanning procedure.

This CT scanner offers exceptional quality images at four times faster than traditional axial scanning. The faster rate of producing images also significantly reduced patients' exposure to radiation.

Table 2.2 Number of subjects in different age intervals and average ages (±SD) within each category.

Age interval (year)	N			Mean ± SD	
	M	**F**	**Total**	**M**	**F**
0-1	15	8	23	0.4 ± 0.29	0.4 ± 0.35
1-3	11	11	22	2.1 ± 0.76	2.0 ± 0.58
3-5	10	7	17	4.1 ± 0.69	4.0 ± 0.69
5-10	17	22	39	7.5 ± 1.10	7.8 ± 1.55
10-12	13	8	21	11.3 ± 0.59	11.2 ± 0.76
12-14	10	10	20	13.2 ± 0.66	13.2 ± 0.61
14-16	11	9	20	15.0 ± 0.37	15.2 ± 0.52
16-18	12	7	19	17.1 ± 0.76	17.3 ± 0.48
18-25	13	11	24	20.3 ± 1.93	20.0 ± 1.83
Total	**112**	**93**	**205**	**9.9 ± 6.72**	**9.9 ± 6.37**

2.6.2 Accuracy of Computerised Tomography data

Fundamental to the accuracy and reproducibility of the 3D landmark determinations used in this project is the precision of the axial slice data. The manufacturer of the CT scanner used in this study claims sub-millimeter accuracy for axial slices (GE Brochure, 1983). Abbott (1988) designed an acrylic test object containing metal markers to examine this claim, comparing measurements of the markers from the CT scanner to those of a travelling microscope (Travelling Microscope Cam Metric Ltd., Cambridge, England). She found an accuracy of 0.91 mm at the 95% confidence level, thereby supporting the manufacturer's claim.

2.6.3 Computed Tomography Protocols

2.6.3.1 Head Alignment and Immobilisation

Patients were placed in the supine position during the scanning procedure with the head symmetrically positioned within the head holder and the Frankfort plane (line joining superior margin of external auditory meatus and infraorbital margin) perpendicular to the floor (Figure 2.1). During scanning, the patient's head needed to stay still within the head holder. To achieve this, the head was strapped to the head holder to help ensure immobility. Sedation or general anaesthesia was required for young children and for patients whose cooperation could not be obtained to ensure that no movement occurred during the scanning procedure.

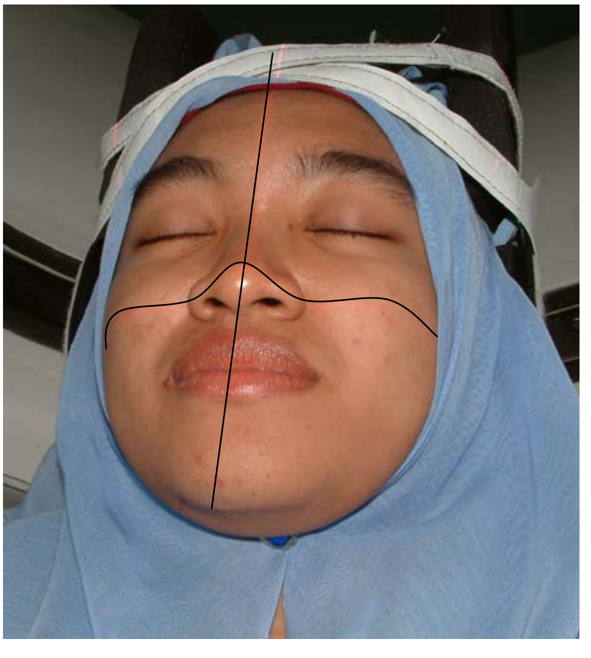

Figure 2.1 The patient is positioned according to specified protocols prior to scanning with laser beam guidance for standardisation and a head strap is put in place to prevent movement during scanning.

2.6.3.2 Scanning Procedure

Tube Voltage and Current

The tube voltage and current used were as follows:

Birth to 1 year: 100KV, 120mA;

1 year to 3 years: 100KV, 150mA;

Greater than 3 years: 120KV, 150mA.

These could be adjusted further according to patient's weight.

Field of view

The patient's head needed to be within the field of view. This was achieved by taking a pilot x-ray of the head and the field of view was adjusted to include the whole head. To ensure the top of the head and the chin were included, the scan range contained one slice past the top of the head and one slice past the bottom of chin.

Resolution

High resolution scans were achieved in this study, consistent with the patient and dose considerations. In this study the resolution was at 1.25mm thickness and 1.25mm spacing. Some of the partial scans mentioned earlier were at a lower resolution of 3.75mm thickness and spacing.

2.6.4 CT Data Transfer

Once the scans were acquired they were saved in a CT database that could be accessed on-line with an Advantage workstation. The Dental School at USM purchased the same workstation and placed it in the Otolaryngology Department, HUSM (Figure 2.2). It was useful to have a remote workstation similar to those used at the radiology department so that access could be gained easily. The one in the Radiology Department was constantly occupied by their medical officers who were interpreting scans to produce reports. It proved to be very convenient because considerable time needed to be spent looking through the database and copying information onto CDs.

Figure 2.2 The radiographer played a major role in obtaining the CT scans, image processing and data storage. An additional remote Advantage computer workstation proved to be very useful for copying data to CDROM

The CT data were copied on media for transfer to the ACFU and also for digital storage. CDROM is the preferable medium for transfer to an independent workstation as most Windows PCs, Macintosh computers and Unix workstation have built-in CDROM drives. CDROM disks are also cheap, permanent and easy to transport. Other media such as digital audiotape (DAT) and magneto-optical disk (MOD) may also be used, provided that prior arrangements have been made between the sender and receiver to ensure compatibility. However, the latter media were not used in this study because they tend to become mouldy due to high humidity in Malaysia and cannot be used to store data permanently.

The data format for transfer was DICOM 3. To ensure that the decoded orientation was correct, images of axial slices were clearly marked to indicate the patient's left and right sides.

2.6.5 3D-CT Reconstruction

The data were processed using this off-line technique, with the information stored on CDROMs being transferred to a Silicon Graphics Octane workstation (Silicon Graphics Corporation, Mountain View, California, USA). The slice data were extracted using information supplied by the CT scanner manufacturers and software developed by the ACFU. The PERSONA software package developed by the research team at ACFU, Women's and Children's Hospital, Adelaide (Abbott *et al.*, 1990) was used for 3D reconstruction of the images. The reconstructions were run on a Silicon Graphics computer workstation with Unix computer language.

The data were then processed to produce the necessary reformats and 3D-CT reconstructions required for the landmark determination.

Reproduction of CT images can be influenced by many factors (Koehler *et al.*, 1979; Baxter and Sorenson, 1981; Christiansen *et al.*, 1986). These factors include the resolution of the data (slice thickness) and the threshold that the skulls were rendered to produce the best reproduction. In this study, high resolution data comprised 80% of the data. The rest included partial neurological scans of the head at 3.75mm thickness.

The threshold level determines the minimum density of material to be included in a 3D-CT reconstruction. The CT scan needed to be reconstructed at a threshold value that distinguished bone from soft tissue and air, to enable the osseous contours of a living subject to be extracted from the CT data. The threshold of 151 Hounsfield Units was used to render the 3D-CT reconstruction of skulls of infants and children and a value of 176 Hounsfield Units for adults. These levels were maintained to ensure standardisation of the data.

Along with the Silicon Graphics Octane workstation, a Microsoft® Windows® PC was used to process the statistical data derived from the CT scans.

CT data that were saved onto CDROM were still in raw or slice format. A series of steps needed to be undertaken to produce the 3D reconstructions. The first step involved copying the data from the CDROM into the ACFU data recognition and conversion system through a series of computer instructions. The DICOM 3 format was converted into a data format readable by PERSONA software at the end of this procedure.

This was then followed by another series of steps for the generation of 3D images. These were as follows:

i) The reformatted data slices produced from the earlier procedure were put through a program called ‘clip’. The purpose of this procedure was to remove radiopaque objects that may hinder viewing of bone. The objects usually removed were the head holder, face mask and intubation tube. This procedure can be easy but often it took longer in subjects wearing a face mask or when intubated. The file size was reduced after this procedure (Figure 2.3).

ii) The ‘clipped’ data were then interrogated to produce files for 3D reconstruction.

iii) A program called ‘render’ was applied to the data to produce 3D images. The 3D images routinely rendered were the cranial base view (x-axis), the external skeletal view (z-axis) and the left and right sagittal views (z-axis sagittal-L and z-axis sagittal R). Additional images were generated at the time of landmark determination, with the mandible and the top of the head below the level of the roof of orbit removed, to assist viewing of the external cranial base region, superior aspect of the maxilla and the orbital floor. The rendering process took about one to two hours per subject (Figure 2.4).

After these procedures, the data were ready for landmarks identifications which were then used to generate the desired measurements for analysis.

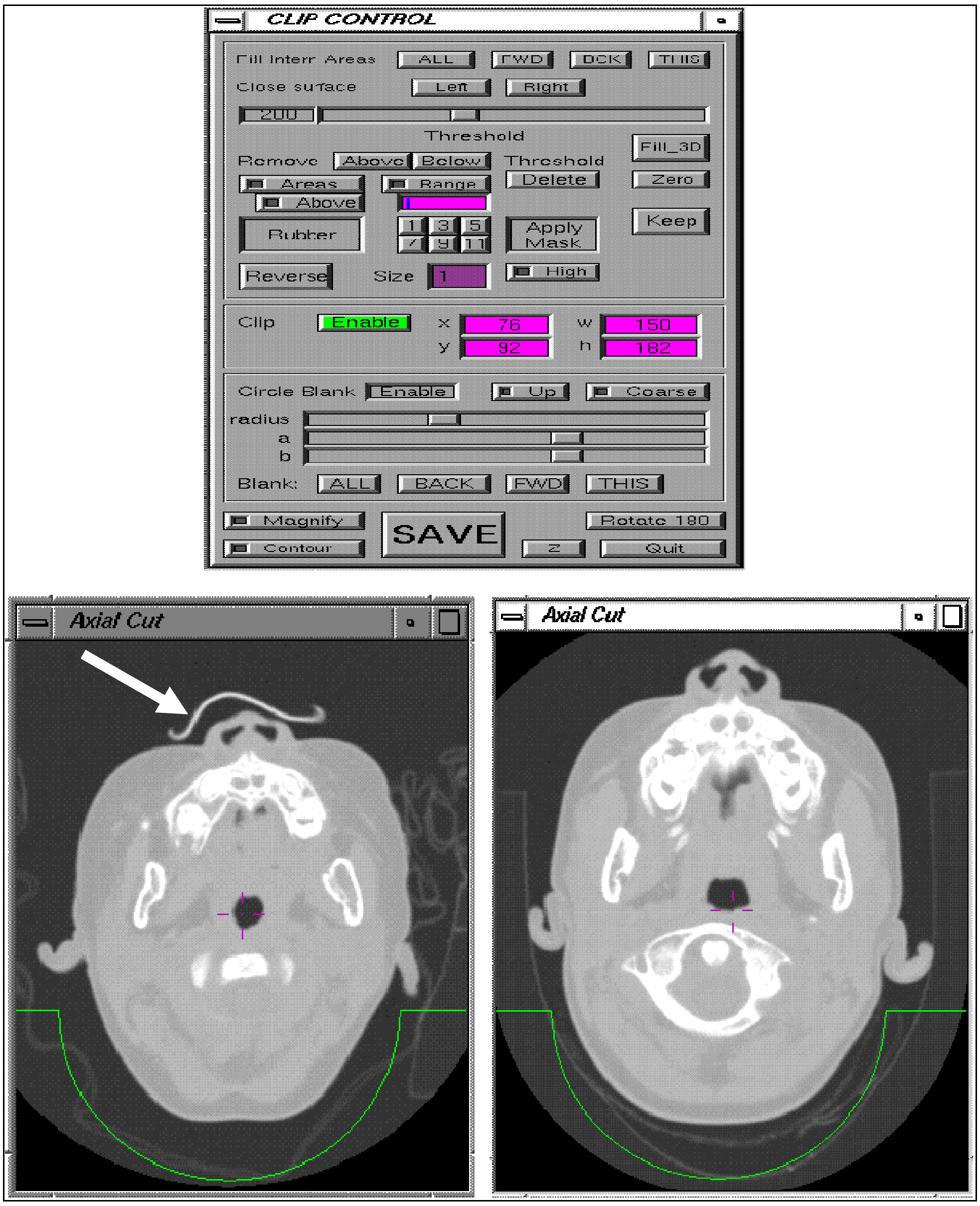

Figure 2.3 A ‘clipping’ procedure was applied to remove objects such as the head holder, face mask or intubation tube that may obscure viewing of reconstructed images. (a) Before and (b) after removal of the face mask (arrow) in this subject using the ‘clipping’ procedure.

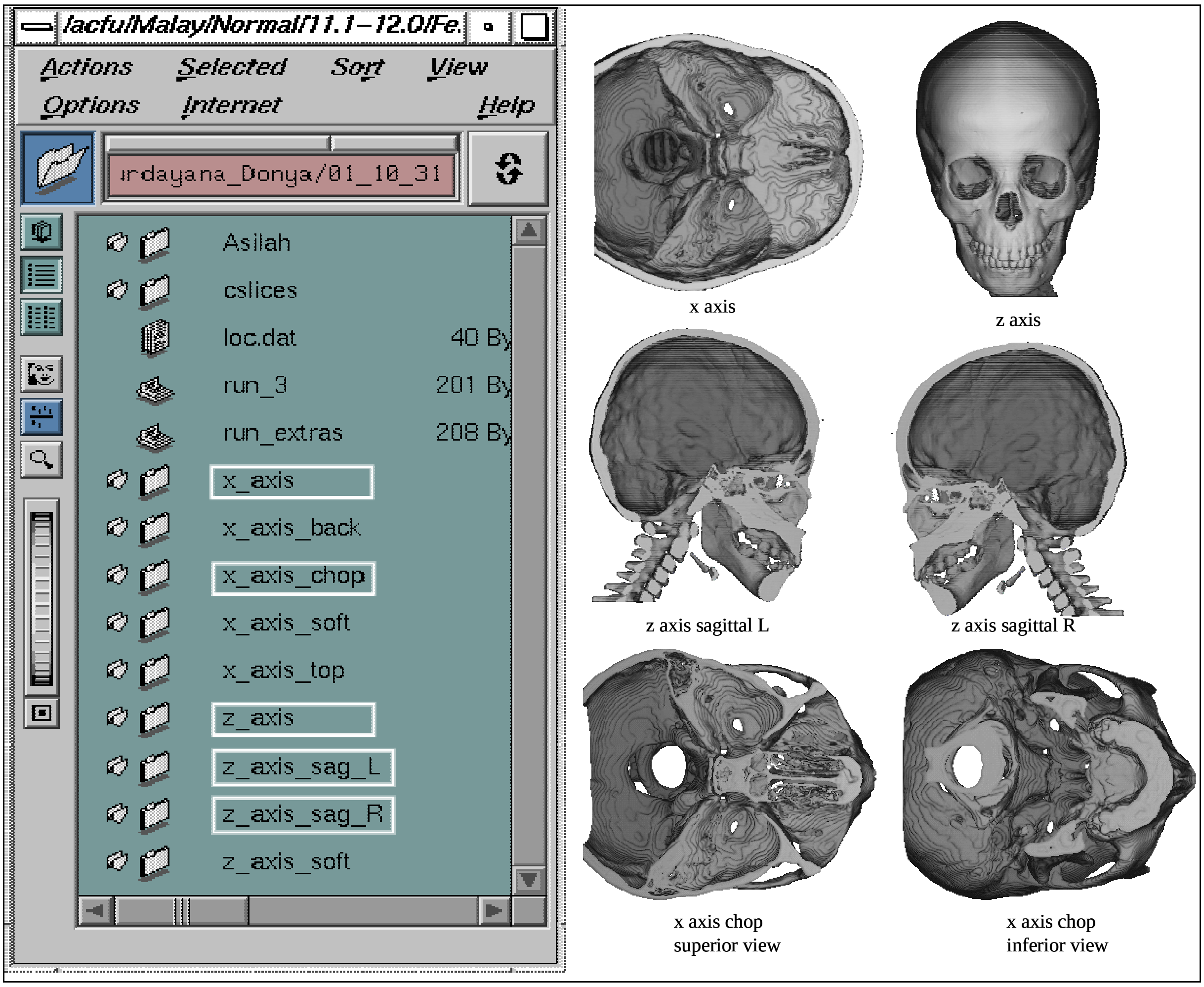

Figure 2.4 The clipped CT data in slice format were rendered to produce 3D images. The usual 3D images rendered are those outlined. X axis chop was usually performed at the stage of landmark determination. The other file directories contained instructions for rendering if required.

2.6.6 PERSONA 3D Medical Imaging and Analysis Software

PERSONA software (Maptek Pty Ltd, Adelaide, Australia) enabled simultaneous visualisation of the CT craniofacial data in both 2D and 3D. The package allowed the display of CT data in two-dimensions as axial (Z axis), coronal (Y axis), and sagittal (X axis) windows (Figure 2.5). Three-dimensional reconstructions of the skull with rotations about the Z axis in 6° steps were also available. A second 3D reconstruction with the top axial slices omitted and rotation in the X axis enabled visualisation of the internal cranial base. These facilities were assisted by the use of a magnification window which increased viewing landmark location. Three-dimensional stereoscopic images could also be viewed directly on the monitor with stereo glasses.

Additional 3D images (Figure 2.4) provided further assistance for landmark location. These images assisted in confirmation of landmark location and enabled identification of all landmarks in all 3 planes. Each landmark was recorded by the program as a coordinate in 3D following selection of the defined site.

2.6.7 Landmark Determination

Following 3D reconstruction of the CT images, identification of landmarks was performed directly and manually on the Silicon Graphic computer using PERSONA software and adhering to landmark definitions. Up to 115 osseous landmarks were identified for each subject.

First, all appropriate windows needed for landmark identification were opened and arranged on the computer screen (Figure 2.5). These included the axial, coronal and sagittal orthogonal slices through the CT data; two 3D-CT reconstructions reformatted from the slice data; and a "magnify" window around the screen cursor position or the "active" marker position that indicated the current position of the selected landmarks.

These facilities were further assisted by stereo mode views of each rotation axis of the 3D reconstructions. The stereo mode functioned by alternating the left and right eye views of the image on the screen and needed to be viewed with a pair of stereo glasses. This worked by activating the liquid crystal shutters of the stereo glasses.

The location of a specific landmark, for example *nasion* (Figure 2.5), was achieved by placing the active marker in the 3D reconstructions and in the orthogonal slices. Initially the landmark was located on one of the 3D reconstructions. The landmark was rotated to another image of 3D reconstruction and was adjusted in each orthogonal slice to ensure accurate identification. The magnify window assisted in magnifying the area of interest and further improved the accuracy of landmark identifications. Often additional 3D reconstructions (Figure 2.4) were utilised to provide further assistance with location of landmarks, particularly in the orbital floor and external cranial base regions.

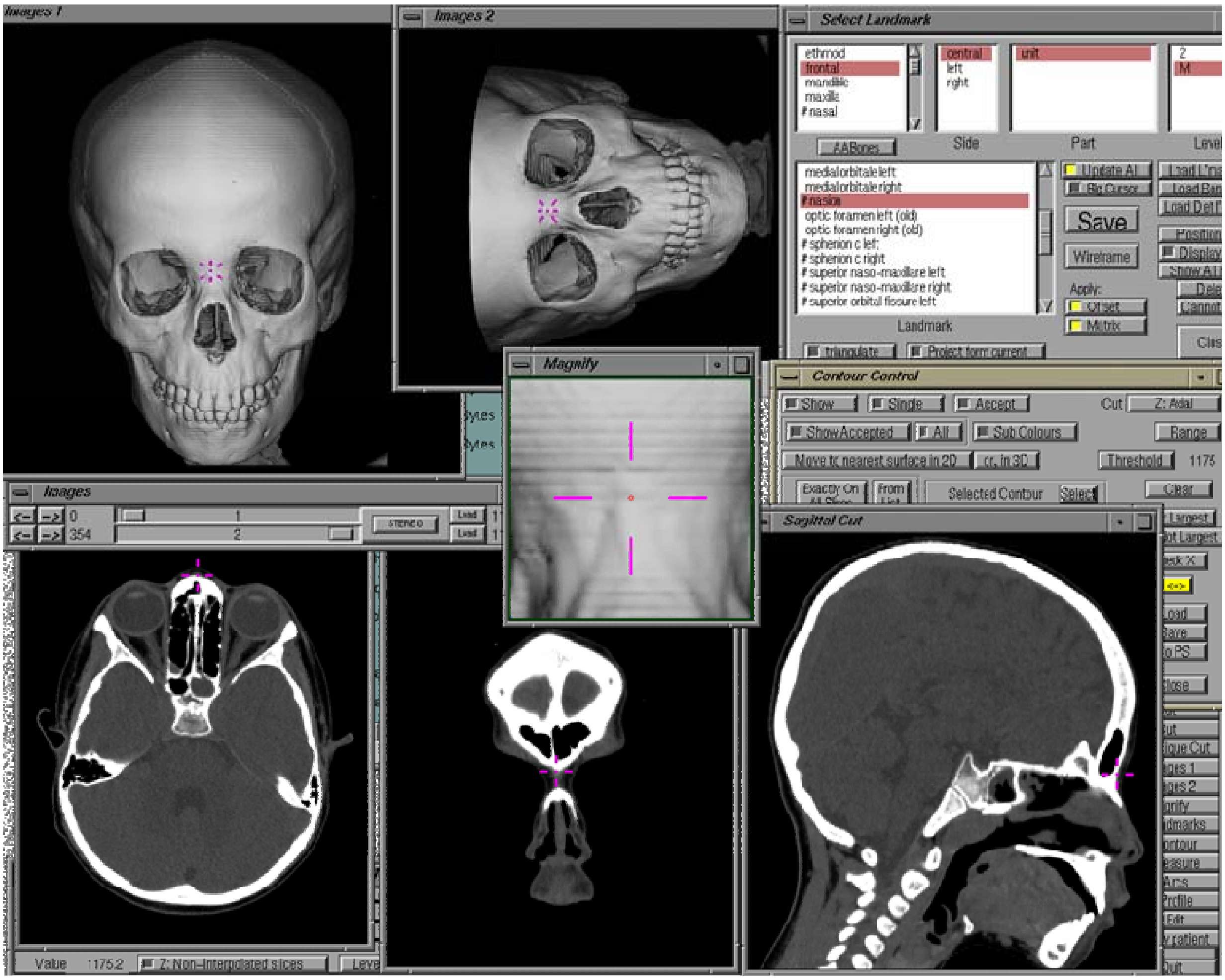

Figure 2.5 Example of a computer screen containing all the windows needed for landmark identification.

It was important to use the orthogonal slices for the refinement of landmark coordinate positions to minimize threshold difficulties. Osseous landmarks were moved to the nearest bony threshold value. The 3D coordinate position of the identified landmark was then saved as the specified landmark in a scrollable browser menu containing a number of anatomical regions. The landmark was saved as a 3D coordinate position in an appropriate file that was available for construction of measurements of distances and angles of bones constituting various regions of the cranium and face. Landmarks could be reselected if modification needed to be made at any stage.

A wire-frame model could be viewed or superimposed over the 3D-CT reconstructions for further validation of the landmark position. Separate bones could be selected from a *Wire Selection* menu to view their outlines (Figure 2.6). Additionally, the wire-frame function provided a method of checking for major error in identification of landmarks. Obvious errors occasionally occurred that were detectable by viewing the wire-frame, e.g. errors in saving a landmark into landmark files or sometimes mistaking left and right landmarks. This step formed part of the procedure for detecting errors of the method. The wire-frames also served to aid visualisation and segmentation of landmarks into anatomical regions.

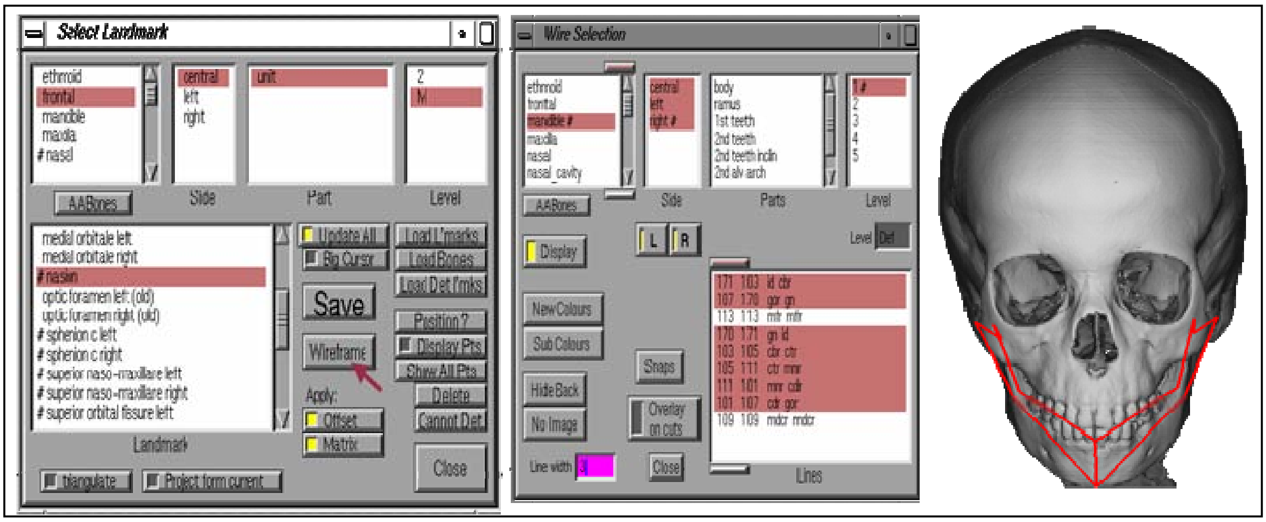

Figure 2.6 The outline of a bone could be viewed and superimposed on the bone by selecting the appropriate command in the program. In this example, the outline for the mandible has been selected. Wire-frames provided an aid to visualisation of separate anatomical regions and formed a part of the procedure for checking errors in placement of the landmarks.

2.6.8 Definition of Anatomical Units

Anatomic craniofacial landmarks are defined as biologically meaningful loci that can be unambiguously defined and repeatedly located on a biologic structure. The most basic requirement of a landmark is that it can be easily identified and located to a high degree of accuracy and precision (Howells, 1989). Landmarks need to be reproducible and the more defined and locatable a position, the more reproducible they tend to be. In this study, the landmark data were chosen so that they could adequately define various anatomic regions of the craniofacial skeleton. Classes of anatomic landmarks include foramina, the intersection of sutures and bony processes.

Using the detailed 3D-CT reconstructions, it was possible to visualise key anatomical landmarks for each of the anatomical regions. The key landmarks enabled true dimensions of the bony regions to be identified and recorded in three dimensions. The ACFU has defined over 500 key anatomical landmarks that comprehensively describe all individual bony components of the craniofacial skeleton. From this extensive selection, 115 landmarks were chosen in this study.

The craniofacial complex was categorised into separate regions consisting of various craniofacial bones. These regions included:

i) Cranial base:- sphenoid, basi-occipital, temporal and its synchondroses

ii) Calvarial bones:- frontal, temporal, parietal and occipital

iii) Facial bones:- mandible, maxilla, vomer, zygoma, nasal and palatine

iv) Cavities:- orbital and nasal

Included in the 3D landmark file are standard 2D cephalometric points. However, these landmarks could be located at all points of the craniofacial complex. None suffer from the problems of differential enlargement, distortion or superimposition inherent in 2D cephalometry. All areas could be visualised directly.

A complete list of the landmarks used in this work is presented in Appendix II.

2.6.9 Measurements

In this study, linear and angular measurements made up the majority of the data. This approach gave basic information about the dimensions of the bones under investigation. 3D coordinate landmarks were saved into a file that could be accessed for various measurements. A measurement program, using C and C++ computer programming, was written that utilised the landmark data. This was used to specify the measurements that were required from the landmark data.

The method of calculation of distances and angles and the choice of measurements is described in the following section.

2.6.9.1 Methods of Measurement of Distances and Angles

As all landmarks were recorded as 3D coordinate data, the measurement of distances and angles was possible. Calculations were made by determining the distance d_{ij}, between 2 landmarks whose positions are specified by the vectors $\mathbf{x}_i = (x_i, y_i, z_i)$ and $\mathbf{x}_j = (x_j, y_j, z_j)$. The distance, d_{ij}, is the magnitude of the vector difference between the points: $d_{ij} = | \mathbf{x}_i - \mathbf{x}_j |$; that is $d_{ij} = \sqrt{} [(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2]$

The angle, q, between 2 vectors defined by 3 landmarks $\mathbf{x}_i$, $\mathbf{x}_j$, $\mathbf{x}_k$ is calculated from the dot product of difference vectors (that is, the vectors $(\mathbf{x}_i - \mathbf{x}_j)$ and $(\mathbf{x}_k - \mathbf{x}_j)$):

$$\cos(q) = \frac{(\mathbf{x}_i-\mathbf{x}_j)\ |\mathbf{x}_k-\mathbf{x}_j|}{|\mathbf{x}_i-\mathbf{x}_j|\ |\mathbf{x}_k-\mathbf{x}_j|}$$

Similarly the angle, q, between two vectors, specified by the landmarks $\mathbf{x}_i$, $\mathbf{x}_j$, $\mathbf{x}_k$, and $\mathbf{x}_l$, (that is the vectors ($\mathbf{x}_j$- $\mathbf{x}_i$) and ($\mathbf{x}_l$ - $\mathbf{x}_k$)) is given by

$$\cos(q) = \frac{(\mathbf{x}_j-\mathbf{x}_i)\ (\mathbf{x}_l-\mathbf{x}_k)}{|\mathbf{x}_j-\mathbf{x}_i|\ |\mathbf{x}_l-\mathbf{x}_k|}$$

2.6.9.2 Measurement of Distances, Dimensions and Angles

The measurements were chosen mainly to define the shape of the face and skull by means of a consistent and coherent set of measurements distributed across all regions. In addition to this, there were several underlying reasons influencing the selection and modification of measurements used in this study. These reasons are as follows:

Relevance

The measurements used in this study were chosen to provide informative knowledge of the anatomical region under investigation. Linear and angular measurements, as well as indices, were included. Size information was adequately contained in the linear measurements, whereas angular measurements and indices gave shape information.

Coverage

A broad range of measurements was chosen to cover many different aspects of shape variation. Measurements related to the cranial vault, cranial base and face. Some important measurements were omitted on some CT scans due to incompleteness of the CT data, and due to localised abnormalities of structures, e.g. fractures.

Redefinition of points

Most landmark definitions were derived from cephalometry and craniometry, where measurements were taken from a bone or the junction of bones on adult specimens.

Modifications were needed for some measurements when performed on infant skulls, e.g. for landmarks relating to junctions of bones where the sutures had not yet closed, for instance bregma, asterion and lambda.

Measurements could be divided into 3 groups:

(i) Distances - representing the measurement between adjacent landmarks which specifically formed the outline of a cranial bone. Not many distances measurements were chosen in this study.

(ii) Dimensions - representing measurements between landmarks which did not follow the outline of the cranial bone but represented overall bony size (maximum width, length etc.) These formed the majority of measurements used in the study.

(iii) Angles - representing the shape of an anatomical unit. Interpretation was made difficult by the 3D nature of the study. Angles were measured by two methods - between three points or between the projected bisection of 2 lines (four points).

(iv) Indices - representing the ratio of one measurement over another. Ratios also gave some information about the shape of an anatomical unit.

From the purpose of this study, a number of variables were chosen to be analysed. These variables represented regions of the face, cranial base and cranial vault. The face can be further categorised into separate major structures i.e. the orbit, maxilla, zygoma and mandible. All regions were represented by width or distance, height and length measurements. There were also a few variables that showed inter-regional dimensions. Additionally, a few angular variables and indices were identified.

The linear variables, angles and indices are represented diagrammatically in Figures 2.7 to 2.21 and are defined in the legends to the figures.