Three-dimensional medical imaging with computed tomography (CT) data for clinical study of craniofacial morphology was started and gradually popularized at early 1980.(1-5) Special technological requirements, methodology, or software were needed to avoid artifacts and to produce a useful result for the 3-dimensional imaging.(2,6) Although details of the surface images at the primary stage were not ideal, they were found to be useful in the diagnosis, treatment planning, and longitudinal follow-up for the patients with congenital and acquired craniofacial deformities.(4,7,8) 3-dimensional image reforma-
tion, production, and modification for clinical needs have been continuing. With the advancement of computer hardware and software, 3-dimensional medical imaging has become more user-friendly, convenient, and with better resolution and user-inter-
action. Several kinds of medical imaging data could be reconstructed for 3-dimensional display, including CT, magnetic resonance imaging, ultrasonography, laser scanning, and microscopic imaging. In particular, the 3-dimensional CT imaging has been developed, improved, and widely used. The 3-dimension-
al images are not only beautiful pictures, but also contain scientific significance that is helpful for medical research and clinical applications.

CT Data Acquisition, Processing, Display, and Manipulation

Patients were scanned in the radiology department and the CT data were initially processed in a computer workstation at the department, creating contiguous 1 to 3 mm image slices of Digital Review Article

Three-Dimensional Computed Tomography Imaging in Craniofacial Surgery: Morphological Study and Clinical Applications

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Three-dimensional craniofacial CT imaging has been developed and progressed during the past two decades. The advancement of the hardware and software has made the imaging study more convenient, user friendly, and affordable. Processing and analysis of the imaging data are readily performed on personal computers. Accuracy of the 3-dimensional measurement has been validated. Collaborative study can be achieved with other departments or disciplines, such as orthopedic, otolaryngologic, and dental departments, as well as mechanical engineering department. All the data should be adequately archived as medical imaging data bank for later use. The data can be transferred for production of rapid prototyping models to enhance clinical application. Inter-center sharing of imaging data can be done through common image format. Comprehensive morphological study and clinical information may help to improve or refine treatment planning, which in turn yield better treatment outcome.


Key words: 3-dimensional CT, craniofacial surgery, medical imaging.
Imaging and Communications in Medicine (DICOM) format. Currently the spiral CT scanner has been used with faster speed during data acquisition. The thinner the slices, the better the image resolution, but with longer processing time and larger digital data space requirement. With the Chang Gung Craniofacial Protocol, the whole head of a patient was scanned at an axial plane from below the chin to above the head top, and the thickness of the slices was set between 1 and 3 mm. The raw data were sent through intranet to the medical imaging laboratory for further processing. In the laboratory, the equipments include personal computers or mini-computer workstations, software programs for working with the digital image data, and the storage devices. Since the equipments for the laboratory do not take up much space, the imaging laboratory can be located in any place that is convenient for the clinicians and researchers. Communication of the digital data among the computers has become expedient through the network.

To process the data, the unused parts of the volume data were removed to decrease the file space. The image data were reformatted and the voxel, the unit of the 3-dimensional image, was set according to the limitations of the computer hardware and software, as well as the required resolution for study purpose. For the head of a patient at the age of 3 months to one year, a 3-dimensional image file ranges from 20 to 40 megabytes at a voxel size of 0.6×0.6×0.6 mm. After the data reformation, display of the images was performed in 2-dimensional or 3-dimensional modes for analysis. Both raw data and 3-dimensional volume data are archived. Experiences have showed that with the advancement of computer hardware and software, the resolution and display of a same set of medical imaging data have become more improved than those on previous imaging facilities. The image data can also be sent to milling, stereolithography, or modern rapid prototyping machines for 3-dimensional model manufacturing, and to computer aided design/computer aided manufacturing (CAD/CAM) program for further manipulation or analysis.

Display of the 3-dimensional volume data is an important function in the medical imaging study. Modern imaging program has made it interactive and user-friendly that the researchers and clinicians can view the medical images in several modes of multiple 2-dimensional or 3-dimensional views.

![Fig. 1](image.jpg) A patient’s CT data with 3-dimensional reconstruction and demonstration of simultaneous 2-dimensional axial, coronal, and sagittal views. The image display was processed in a computer running the Analyze program (Biomedical Imaging Resource, Mayo Foundation, Minnesota, USA)
Special modes of display of the 3-dimensional volume rendering images were created for better clinical evaluation or research purposes (Fig. 2). Because each craniofacial tissue has its own range of "density" on CT images, thresholding technique can be employed for differential display of the craniofacial structures. Using this technique, the soft tissue can be removed to show the craniofacial skeleton, the muscle of mastication can be distinguished from the surrounding tissues and then segmented, the orbital cavity can be defined and the eyeball can be separated, the intracranial content and the CSF can be segmented, etc. (Fig. 3) Segmentation of the craniofacial tissues and definition of the segmented tissues as

![Fig. 2](image)

**Fig. 2** The radial image from 3-dimensional CT data of a patient presented with prominent mandibular angles. Photos showed (A) preoperative and (B) postoperative views.

![Fig. 3](image)

**Fig. 3** Brain and cerebrospinal fluid extracted from the 3-dimensional CT image data of a patient. The skull and extra-cranial soft tissues were removed. The brain and fluid were segmented through their different CT densities. The upper row showed the brain tissue without the cerebrospinal fluid, the middle row showed the fluid, and the bottom row showed the combination of the brain and fluid.
different objects are imperative procedures in medical imaging study. The task of segmentation is accomplished by automatic, semi-automatic, or manual tracing. The defined objects can be selectively displayed and quantitated by 3-dimensional linear, angular, area, and volume measurements.

According to the need, the image data can be made into slides, hardcopy, or movie for the purposes of presentation, clinical use, research, and education. Current archiving devices include compact disks, magnetic-optical disks, and magnetic tapes. The compact disks have developed to be the best and popular storage tool, in that it is easy to handle, cheap, long duration, and less room needed.

Validation of 3-dimensional CT Imaging

Three-dimensional CT imaging is accurate on the 3-dimensional structure without distortion of its spatial form, shape and size. The spatial relationship and the measurement on the 3-dimensional CT images have been validated using phantom studies. Digital and physical phantoms have been used to compare the differences of the landmark localization and the measurements between the physical measurement and the computer measurement. An earlier validation test for accuracy of the skull surface landmarks by Hildebolt and Vannier showed that 3-dimensional measurements were equivalent in quality to caliper measurements for craniometric studies, but were easier to obtain. At a later study in 1990, Hildebolt et al, found that 3-dimensional CT measurement techniques were superior to those in which measurements were obtained directly from the original CT slices. However, they also discovered that the 3-dimensional CT methods must be significantly improved before measurements based on these techniques could be used in studies that required a high degree of precision. Currently the resolution of the 3-dimensional CT display has been greatly improved for better landmark localization and object definition. Cavalcanti et al, using cadaver heads and spiral CT, showed that the accuracy for 3-dimensional CT was higher than 2-dimensional CT images, and reported that measurement of the skull and facial bone landmarks by 3-dimensional reconstruction is quantitatively accurate for surgical planning and treatment evaluation of craniofacial fractures. Using phantom tests, Lo et al obtained the differences between the physical and 3-dimensional CT measures from 0 to 2.57% on linear, area, and volume measurement. These validation studies demonstrate that the 3-dimensional imaging is accurate and convenient, and that the 3-dimensional measurement is equal or superior to the conventional measurement methods.

Clinical Applications

Use of the 3-dimensional CT imaging in the craniofacial area has been extensive. It has been used for evaluation of the craniofacial deformity, preoperative planning, surgical simulation, postoperative evaluation, and longitudinal follow-up for outcome assessment (Fig. 4). These were the primary applications of 3-dimensional CT imaging. Offutt et al explored the graphics processing techniques for diagnostic evaluation of patients with craniofacial disorders. Ono et al used 3-dimensional CT images for evaluation of facial deformity associated with cleft lip/palate and hemifacial microsomia. They developed 3-dimensional CT measurement system and the wire frame model for detailed analysis of the skeletal deformities. Today, 3-dimensional CT images have been extensively used for evaluation of the craniofacial dysmorphology. In the same imaging environment, the 3-dimensional images were conveniently used for preoperative measurement and simulation of surgery. Through the CT data, 3-dimensional models were produced for evaluation of the craniofacial deformity, surgical planning, and simulation of craniofacial surgery.

Surgical Simulation

After evaluation of the craniofacial deformity, treatment planning and surgical simulation could be performed. Because manipulation of the 3-dimensional data has become readily available and user friendly, interactive computer-based simulation is gaining acceptance. An assessment of the craniofacial surgical simulation was performed using multiple phantoms and fresh cadaver heads to verify the accuracy of the movement of osseous segments. This study characterized the accuracy of 3-dimensional CT-based measurement, defined a criterion standard for evaluation of surgical simulation, defined criteria for pairwise comparison of 3-dimensional craniofacial images, simulated surgical correction of selected congenital and acquired craniofacial deformities.
deformities, and applied the comparison criteria to surgical simulations. After the validation, the simulation cannot only be used in pre-operative surgical planning, but also as a post-operative descriptor of surgical and traumatic physical changes.\(^{10}\) Validated image comparison methods can also show discrepancy of surgical outcome to surgical plan, thus allowing evaluation of surgical technique. Altobelli et al integrated the cephalometric and anthropometric databases with 3-dimensional CT reconstructions to quantitate the skeletal deformity and to assist in the design of the surgical procedure.\(^{31}\) Interactive techniques were applied to simulate osteotomies by segmenting the image bony structures and to move the segments in three dimensions. The measurements from the computer graphic simulation were used intraoperatively to establish the correct positions of the skeletal movements.\(^{31,38,39}\) Programs have been developed to perform surgery on 3-dimensional images, also called virtual surgery. For application of simulation craniofacial or otosurgical procedure, a cutting tool ("virtual scalpel") and drill-like tool were created for simulation surgery.\(^{40}\)

Life-sized skull models have been produced for evaluation and simulation of surgery. The biomodelling was reported as an intuitive, user-friendly technology that facilitated diagnosis, operative planning and communication between colleagues and patients.\(^{10}\) While the reported limitations of the technology were the manufacturing time and cost, they should not be an impediment with current rapid prototyping technology. Imai et al reported reduction of both blood loss and operating time from the use of 3-dimensional models for fronto-orbital advancement and LeFort III advancement.\(^{17}\) We have applied and compared both 3-dimensional CT imaging and facsimile models for craniofacial surgical simulation.\(^{42}\) The results found that the digital imaging method had the advantages of multiple trials and convenience of quantitative measurement, but the operator needed computer training and the method was virtual reality in nature. The physical models, on the other hand, had the benefits of its reality, for education purpose, and preoperative fabrication of plates and implants. The disadvantages associated with the physical models were its one simulation per model, more expense, and the need of a storage room.

**Morphological Studies**

By thresholding technique and object definition methods, specific tissues can be isolated for evalu-
tion and measurement, i.e., skin, bone, muscle, eyeball, brain, cerebrospinal fluid, etc. Accuracy of the 3-dimensional imaging and 3-dimensional measurement has been validated. The 3-dimensional imaging morphological study is comparable to an in vivo study that is difficult or impossible using conventional methods. For some diseases such as hemifacial microsomia, the lateral cephalometric radiographs are of limited value because of superimposition of normal and abnormal bony structures. Acquisition of landmark positions for the study of the craniofacial complex in three dimensions was encouraged using 3-dimensional CT reconstructions.

David et al examined a complete series of facial clefts studied with 3-dimensional CT, and found that the analysis supported some, but contradicted other, hypotheses and speculations presented by Tessier. Marsh and Vannier reported that 3-dimensional CT reconstructions not only assisted clinical management of craniofacial deformities, but also useful in the study of unique anomalies, the definition of group characteristics for dysmorphic heads, the differentiation of similar phenotypes, and the documentation of the effects of cranial surgery on craniofacial growth. These findings should assist the formulation and evaluation of hypotheses regarding mechanisms of congenital malformation and deformation.

Three-dimensional CT images were used to evaluate the calvaria and cranial base in Apert and Crouzon syndromes. The results showed that the two diseases were different in cranial development and their dysmorphology was age-dependent. Based on the findings, Kreiborg et al suggested that cartilage abnormalities, especially in the anterior cranial base, play a primary role in cranial development in the Apert syndrome from early intrauterine life. Cutting et al compared untreated adult Crouzon disease to normal skulls, and 3-dimensional images of an average normal and an average Crouzon skull were illustrated. Evaluation of the cranial base dysmorphology with quantitative measurement could be performed to differentiate the etiologies of plagiocephaly.

Mandible as an individual bone was extracted for quantitative study in patients at young age. It was not appropriate to use conventional cephalometry in patients at young age, because of the lack of cooperation from patients taking the X-ray and the overlapping landmarks in cephalometric radiographs.

In a study to determine the normal physiologic timing of the closure of the metopic suture in non-craniosynostotic patients, a series of patients' 3-dimensional CT images were evaluated. The results showed that normal or physiologic closure of the metopic suture occurred much earlier than what had been previously described, and normal fusion was found between 3 and 9 months of age. An interesting research was carried out by Neumann et al, in which CT examinations were performed on 26 aborted normal fetuses between 10 and 25 weeks gestational age. The 3-dimensional CT images allowed sensitive identification of the cranial ossification centers and accurate evaluation of the bone topography, which was helpful in the evaluation of prenatal cranial development. CT data of infants with deformational plagiocephaly and other subjects were used to determine the intracranial volume. The results were compared with the old Lichtenberg's normal population, in which skull X-rays were used to determine the intracranial volume. Although both sets of the data were aimed to represent normal population, some significant differences were found between the two methods.

Definition of the soft tissues such as eyeballs, muscle, and nerve could be performed on 3-dimensional CT data because of different image densities in the CT scans. The eyeballs were defined as special objects for study of its relationship with the orbital cavity for the purposes of surgical simulation, evaluation of the craniofacial deformity, and assessment of the surgical outcome. The muscles of mastication were segmented in order to evaluate their relationship with the attached mandible in hemifacial microsomia. The course of the inferior alveolar nerve within the mandible was recently investigated. The nerve is important for morphological study in that it should be protected from injury during mandibular osteotomy, and its uncertain existence in the affected mandible of hemifacial microsomia.

In imaging study, the nerve was indirectly identified and isolated from the intra-osseous canal and displayed with 3-dimensional skeletal structures.

**Interdisciplinary Collaboration**

Interdisciplinary collaboration has been emphasized to improve the treatment outcome. Eppley reported the use of 3-dimensional CT scans to produce an anatomical model, and on the model the pre-
dicted amount of bone tumor excision was performed. The defect in the model was then used to create an alloplastic implant for reconstruction and surgical placement. Unlike a computer generated mandibular model was created for the purpose of harvesting iliac bone graft or producing titanium implant for restoration of a large bony defect. We have reported the use of 3-dimensional image reconstruction and rapid prototyping models in custom implant design for patients with fronto-orbital defect. The technique has improved surgical outcome by reducing operating time and increase aesthetic results. The treatment involved mechanical engineering and medical imaging technique, in addition to plastic surgery discipline. A study of measuring palatal surface on the dental cast models was achieved by CT scanning the models and performing 3-dimensional image reconstruction. The palatal surface was then defined and measured with accuracy from the 3-dimensional CT images. The digital data could be considered to replace the physical dental casts, because of its high resolution and reproducibility using the rapid prototyping technique. Storage and manipulation of the digital dental casts are more convenient than those of the physical casts. In another study, anthropologists obtained 3-dimensional landmark coordinate data from the CT scans and used Euclidean Distance Matrix Analysis to study the morphology and possible pathogenesis of sagittal synostosis.

**Summary**

The development and advancement of the 3-dimensional medical imaging depend on the progress of the computer hardware and software. The progress has made the imaging study more convenient, user friendly, and affordable. Processing a larger imaging file is accomplished in a shorter time and with a better resolution. Image analysis is performed using the methods and functions built in the software program for research purposes or obtaining clinical information. Collaborative study can be achieved with other departments or disciplines, such as orthopedic, otolaryngologic, and dental departments, as well as mechanical engineering department. All the data should be adequately archived as imaging data bank for possible later use. The data can be transferred for production of rapid prototyping model to enhance clinical application. Inter-center sharing of imaging data can be done through common image format. Because of the low incidence for many craniofacial anomalies, cooperation and share of the CT data for research purpose is necessary. One of such examples was the collaborative 3-dimensional morphological analysis of isolated metopic synostosis between The Johns Hopkins Medical Institutions and The Children's Hospital in St. Louis. Comprehensive morphological study and clinical information may help to improve or refine treatment planning, which in turn yield better treatment outcome (Fig. 5).

**Fig. 5** Diagram showing the summary of development in 3-dimensional medical imaging.
As 3-dimensional CT imaging is more popularly and extensively used, 3-dimensional norm data should be established. This can be achieved by collecting CT data from patients without pathologies\(^{(9,10)}\). The norm data should be classified by race, age, and sex. Based on appropriate statistical and imaging methods, an age- and sex-matched "average" model of the anatomy can be created. The norm data and the average model can be used for clinical evaluation of patients and planning craniofacial surgical interventions.

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顱顏外科三度電腦斷層影像：形態學研究和臨床應用

羅綸洲  陳昱瑞

顱顔三度電腦斷層影像在過去二十年來持續地發展及進步，因爲軟體和硬體的改善，促使影像研究更為方便普及。影像資料的處理和分析可以在個人電腦上執行，三度測量的準度已經試驗證實，也可以和骨科、耳鼻喉科、牙科、及機械工程學科進行跨領域的合作研究。影像資料應該妥善的處理保存在影像資料庫，以供日後需要時使用。影像資料也可以輸出製作快速成型模型，以加強臨床應用。影像資料也可以與其他的影像中心分享，達成學術合作。這些深入的形態研究所得的臨床資訊，將有助於治療計劃的改善，獲得更好的治療成果。（長庚醫誌 2003;26:1-11）

關鍵字：三度電腦斷層影像，顱顔外科，醫學影像。