Michael W. Vannier, M.D.
Jeffrey L. Marsh, M.D.
James O. Warren, B.S.A.E.

Three Dimensional CT Reconstruction Images for Craniofacial Surgical Planning and Evaluation[1]

Three dimensional reconstruction images of bony and soft tissue surfaces have improved understanding of complex facial deformities. Applied to CT studies of complex craniofacial abnormalities, this method has delineated abnormal facial soft tissue and bony morphology, facilitated surgical planning, and improved quantitative postoperative evaluation. Advanced computer-aided aircraft design techniques were adapted and applied to craniofacial surgical procedure-planning and evaluation using surface contours obtained from CT scans.

Index terms: Computed tomography, image processing • Head, abnormalities • (Midface, special technique, 24.12 • Midface, congenital anomaly, 24.14) • Surface imaging

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THE preoperative radiologic evaluation of complex craniofacial anomalies has traditionally been accomplished with cephalometric skull radiography. Craniofacial surgery is capable of habilitating individuals who have major deformities of the head, based on the premise that surgical correction of aberrant skeletal anatomy is fundamental to normalization of soft tissue features and functions. Planning and evaluation of craniofacial operations is dependent on radiological imaging for defining the underlying bony structures and their relationship to overlying soft tissue. Traditionally this planning has been accomplished using manually derived acetate tracings of cephalometric skull radiographs in the AP and lateral projections.

The availability of state-of-the-art CT scanners has altered our approach to the analysis of complex craniofacial anomalies. We routinely obtain a set of equal-spaced, nonoverlapping, high resolution CT scans of the face with narrow collimation pre- and postoperatively. Reformatting in the sagittal, coronal, and oblique planar orientations is used to demonstrate aberrant anatomy and to facilitate surgical planning and evaluation.

Complex structural anomalies encountered by the surgeon are not completely explained by planar reconstructions. The surgeon has had to imagine the three dimensional character of each patient's skull abnormality based on a sequence of two dimensional images (CT axial scans and reformatted planar views) supplied by the radiologist.

Earlier work on three dimensional reconstructions from CT scans has been reported by others (1–7). These methods may be more complex and time consuming when using ordinary CT scanners than needed to achieve wide clinical acceptance. Three dimensional edge detection (5) or encoding and display from a three dimensional geometrical model derived from the original CT scans (1–3) have been employed. These steps imply a computational burden that is greater than practical for routine use on an ordinary CT scanner. Storage requirements may exceed reasonable limits for three dimensional reconstructions with acceptable resolution.

We have developed computer methods (8–15) that reconstruct three dimensional bone and soft tissue surfaces given a high resolution CT scan series of the facial skeleton. These methods, implemented as a series of computer programs, are efficient in both computation time and storage requirements and can be added with modest effort to virtually any modern CT scanner. We have applied these programs to scans from more than 300 patients with congenital and acquired craniofacial abnormalities. The surface reconstructions of bone and soft tissue contours have been helpful in an understanding and interpretation of these abnormalities.

MATERIALS AND METHODS

High resolution CT scans of facial structures were obtained using

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[1] From the Mallinckrodt Institute of Radiology (M.W.V.) and the Cleft Palate and Craniofacial Deformities Institute, St. Louis Children's Hospital (J.L.M.), Washington University School of Medicine, and the McDonnell Aircraft Company (J.O.W.), St. Louis, Missouri. Received July 19, 1983; accepted Aug. 19. Presented at the Sixty-eighth Scientific Assembly and Annual Meeting of the Radiological Society of North America, Chicago, Illinois, Nov. 28–Dec. 3, 1982. cp

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See also the paper by Totty and Vannier (pp 173–177) in this issue.

unmodified commercially available units (Siemens Somatom 2 or Somatom DR3). Each study consisted of between 30 and 100 nonoverlapping sections obtained at 2-mm intervals with 2-mm collimation. A 256 X 256 reconstruction matrix was used. To delineate the facial structures better, often only the frontal half of the subject's skull was included in the original transverse transaxial CT images. Young subjects were lightly sedated during scanning to minimize motion and improve the registration of the scan sequence. Most of the patients studied were outpatients.

The original CT scans were archived to floppy discs, and surface reconstructions were obtained subsequently using the CT scanner or after transfer to an independent CT scan-viewing console (Siemens Evaluscope B or RC). The image data was ultimately copied to a moderate capacity (28 Mbyte) cartridge disk unit[2] (Model RK07) integrated in the viewing console. Routine planar reconstructions in the sagittal, coronal, and oblique orientations were obtained as needed.

Computer programs for three dimensional surface reconstruction from sequences of high resolution CT scans were designed and implemented. These programs were written in Fortran and assembler languages to operate on a minicomputer[2] (Model PDP-11/34A) incorporated in the CT viewing console. These programs operate without modification on the CT scanners (Siemens Somatom 2 and Somatom DR 3). The programs accept the original transaxial high resolution CT scan sequence as input and produce a set of three dimensional surface-reconstruction images as output. More than 50 views are output, including soft tissue and bony surfaces in the frontal, rear, lateral, oblique, top, and bottom projections. Any view from any projection may be obtained, but we routinely produce only those views that have clinical significance.

The surface reconstruction computer program reads each of the original high resolution CT scans in order from the cartridge disc and loads the image into the 256 X 256 pixel display memory of the evaluation console (or CT scanner). Since the scans were obtained with the patient supine, in passing from the top of each image to the bottom, air, skin, facial bones, and finally intracranial contents are encountered.

Each column of the image is read in sequence from left to right. The soft tissue contour is extracted by comparing each value of CT density in the column from top to bottom of the image with a preset threshold that represents the CT attenuation that distinguishes air from soft tissue (typically −100 CT units in our scanners). The column index where an air to soft tissue transition occurs was used to form the soft tissue contour for each CT scan section. This index value is scaled and output to the cartridge disc as a line in the reconstructed soft tissue three dimensional surface image.

Each column of the CT scan section is then examined from top to bottom in comparison with a bone threshold (+175 CT units typically). The soft tissue to bone density transition detected in this manner forms the bone contour in the frontal projection. This bone contour vector was written to a separate file on the cartridge disc. During the contour extraction process, the frontal contours were displayed on the evaluation console TV monitor as a quality control measure. Each succeeding CT scan was read from the disc, loaded into the display memory, bone and soft tissue contours were extracted, and results were written to the cartridge disc to complete the surface reconstructions.

To facilitate surface reconstruction file handling, the three dimensional images were written on the cartridge disc in the same format as the original CT scans. These three dimensional surface reconstructions could be viewed and manipulated in the same manner as any CT scan. The relationship between pairs of soft tissue and bone reconstructed images was maintained, and superimpositions or comparisons of soft tissue thicknesses could be directly computed. The gray scale values in the surface reconstructions represent actual distances, and within the geometrical resolution of the CT scanner they can be used for rectilinear measurements.

Extracted contours were replicated several times in the output file so the vertical sample interval was equal to the horizontal interval to obtain geometrically accurate surface images. For example, when the pixel size in the raw CT scans was 0.5 mm^2, four replicas of each detected contour were copied to produce the correct vertical spacing given 2-mm nonoverlapping section thickness. Using a 256 X 256 pixel matrix, this means that up to 64 sequential CT sections could be included in each surface reconstruction. The replication of contours produces undesirable effects with a coarse "digital" appearance that was particularly pronounced at obliquely oriented edges, such as the lateral orbital margins. Smoothing programs were developed to reduce this effect based on local averaging or median filtering. A specialized nonlinear digital filter was adapted to this application (9).

The contour extraction and surface reconstruction process is computationally efficient since minimal computer operations are needed. The reconstruction process speed is primarily determined by the time needed for cartridge disc input and output operations. Typically, the programs require approximately 10 minutes to produce four different surface views from 40 raw CT scans. This process is clinically practical, even in a busy radiology department since the reconstructed views can be obtained in the time between the completion of the patient's CT examination and commencement of the next patient's examination, using the CT scanner that collected the original scans, and it requires no operator intervention. Operationally, the process is comparable to sagittal, coronal, or oblique planar reformatting in terms of computation time. The three dimensional surface reconstruction process is somewhat simpler since preselected views are automatically generated.

Contour extraction at other than soft tissue-air or soft tissue-bone interfaces requires an image-segmentation scheme (16) that is more sophisticated than the simple thresholding or level sectioning described above. This sophistication has been achieved using adjunctive procedures that require increased interaction and increase the overall computational and storage requirements.

The images output by this software are copied to film in life-size format. Calibration of the CT scanner and film recorder[3] (Model Video Imager multiformat camera) was performed to facilitate production of life-size hardcopy images.

RESULTS

The surface reconstruction procedures described above have been in routine use at the Mallinckrodt Institute of Radiology for more than 28 months. These procedures, developed to aid in the analysis of craniofacial deformities, are exemplified by analysis of representative cases.

CASE REPORTS

CASE I: A 3-month-old girl with Apert syndrome (acrocephalopolysyndactaly) was examined for management of the associated craniofacial deformities. High resolution axial CT scanning was performed. The patient was sedated and scanned with her head in extension lying in the lateral decubitus position to prevent interference

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[2] Digital Equipment Corporation, Maynard, Massachusetts.

[3] Matrix Instruments, Incorporated, Northvale, New Jersey.

with her airway. Soft tissue and osseous reconstructions were obtained, demonstrating the diminutive anterior cranial fossa, midline bony ridge corresponding to a metopic synostosis, and maxillary hypoplasia.

The infant uneventfully underwent extended bicoronal and metopic craniectomies with supralateral orbital advancements to release the synostoses, enlarge the anterior cranial fossa, and provide superior globe protection. Postoperative surface images (Fig. 1) demonstrate the osteotomies, ostectomies, and altered cranial anatomy. The bird's eye osseous surface images were produced life size preoperatively to plan the frontal bone advancement and later to evaluate the postoperative result.

CASE II: A 19-year-old man sustained a blow to the left cheek. A trimalar fracture was diagnosed from findings on plain radiographs. A high resolution CT scan was obtained, consisting of 31, 2-mm sections. The osseous surface reconstruction (Fig. 2) demonstrated the fracture to be within the body of the zygoma with torque of the fragments. The degree of lateral antral wall destruction and comminution within the left maxillary antrum was unappreciated on the original radiographs.

CASE III: This 4-year-old girl with nasofrontal encephalocoele was examined preoperatively. A high resolution CT scan was obtained, and the image data reformatted (Fig. 3) into the component three dimensional bony, skin, and cerebral surfaces. By exploiting the registration of the surface images in the frontal and lateral projections, it was possible to overlay the skin surface and underlying bone and cerebral structures to define their relationship accurately preoperatively.

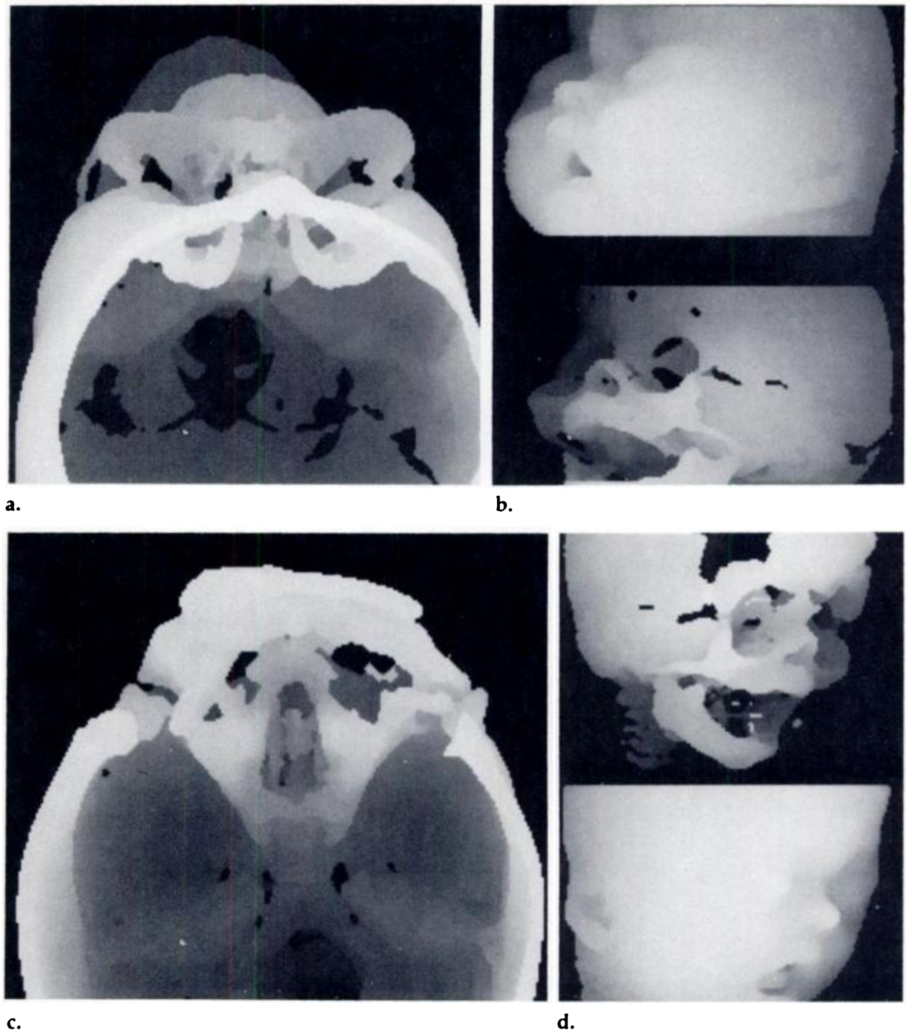
CASE IV: This 12-year-old boy with Tessier type 4-10 clefts (17) was evaluated pre- and postoperatively. The left globe was deviated anteriorly and inferolaterally in comparison with the normal right side. Surgical cranioplasty was performed on two occasions in early childhood with placement of a methylmethacrylate plate and tantalum mesh over the left frontal encephalocoele defect. The upper and lower lid colobomata were repaired as well, but the asymmetric hypertelorism was not.

In the preoperative surface reconstructions (Fig. 4) the soft tissue protuberance over the large frontal cleft is seen. The postoperative reconstructions (Fig. 4f) show mesial and superior movement of the bony orbit to restore facial symmetry.

INTERACTIVE COMPUTER-AIDED DESIGN

Advanced military aircraft production uses computer-aided technology to permit examination of alternative solutions to design problems. Three dimensional analysis of aircraft fuselage surfaces is analogous to the diagnostic evaluation of bony and soft tissue facial surfaces.

Figure 1. Case I.



Infant with Apert syndrome. Pre- and postoperative reconstructions from high resolution CT scans.

- **a.** Preoperative evaluation. Top view in bird's eye projection shows small anterior cranial fossa. The patient's head is in extension and the hypoplastic maxilla can be seen anteriorly.
- **b.** Preoperative evaluation. Frontal left oblique projection of soft tissue and bony surfaces demonstrates the prominent midline forehead bony ridge, unroofed orbits, and small maxillae bilaterally.
- **c.** Postoperative evaluation. Top view of the intracranial skull base shows the enlargement of the anterior cranial fossa created by surgical frontal bone advancement. The extended coronal osteotomies are seen anterolaterally, and osteotomies through the orbital roofs are demonstrated bilaterally.
- **d.** Postoperative evaluation. Frontal right oblique projection of soft tissue and bony surfaces shows the results of frontal bone advancement and orbital translocations with enlargement of the anterior cranial fossa and bicornal defects after release of synostoses.

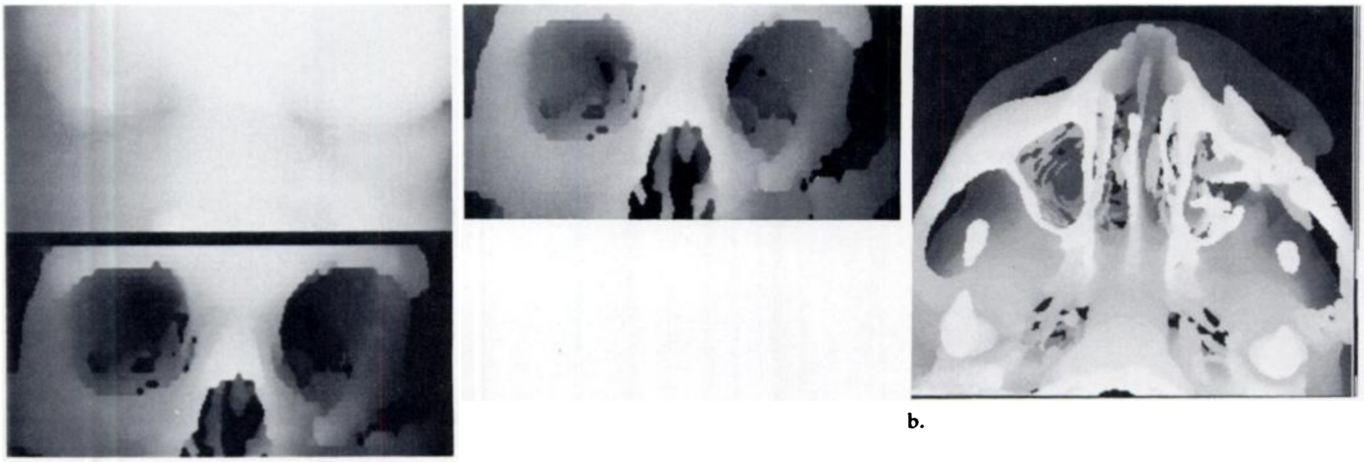
Using a sophisticated computer-aided design system, computer-aided design and drafting (CADD) or UNIGRAPHICS (McDonnell Douglas Automation Company), operating on an advanced three dimensional display console (Picture System 2, Evans and Sutherland Computer Corp., Salt Lake City, Utah), we have developed a methodology for the planning and evaluation of craniofacial surgical procedures. The system is the same as that used for the design of advanced military aircraft.

After extracting frontal soft tissue and bone contours from the original CT scans using level slicing, the corresponding point data was curve fit using cubic splines (18).

The three dimensional surface geometry of frontal bony contours was encoded in fewer than 2,500 coordinates using 40 CT scans as input for a patient with asymmetric hypertelorism (CASE IV). Soft tissue contours were separately entered in the system using the same technique. These contours were rotated to show the plane or top view using the interactive capabilities of this system. The inferolateral displacement of the left orbit is seen in the frontal views. The left frontal bone cleft is clearly demonstrated.

The major advantages of the CADD

Figure 2. Case II.



a.

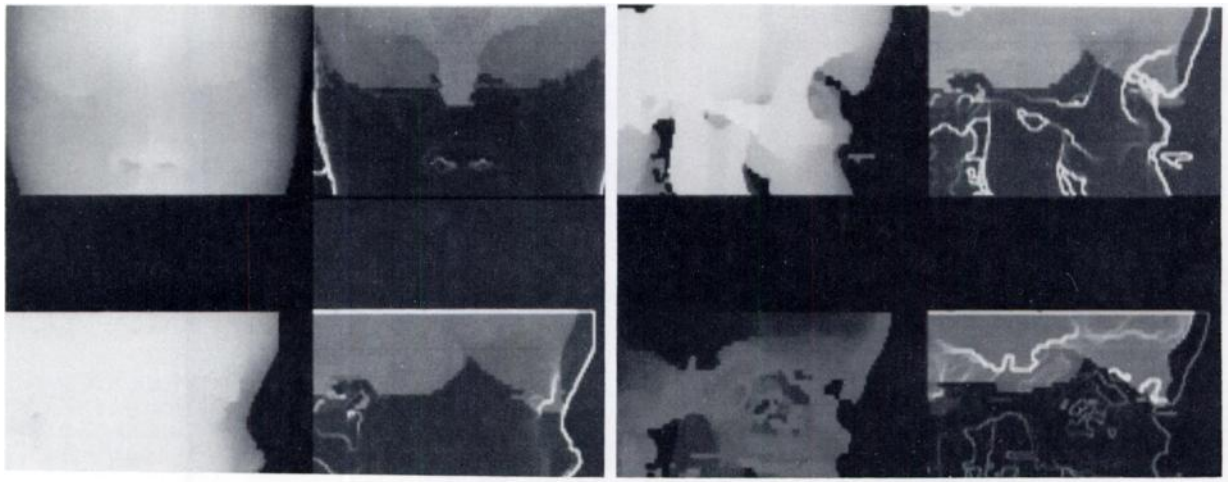
b.

Traumatic injury to the midface in a young man. Surface reconstructions from CT scans provide information on the extent of facial fractures and degree of comminution.

a. Frontal view of soft tissue and bony surfaces shows the trimalar fracture with extension into the anterior wall of the left maxillary antrum.

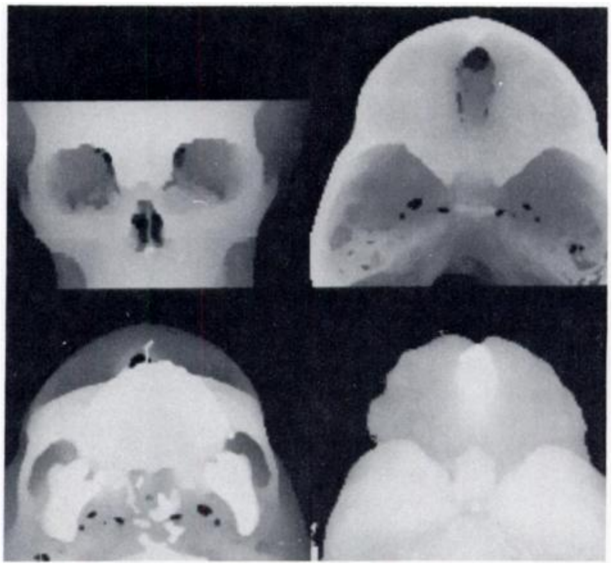
b. Bottom view shows angulation of the left zygomatic arch and small fracture fragments within the maxillary antrum.

Figure 3. Case III.



a.

b.



c.

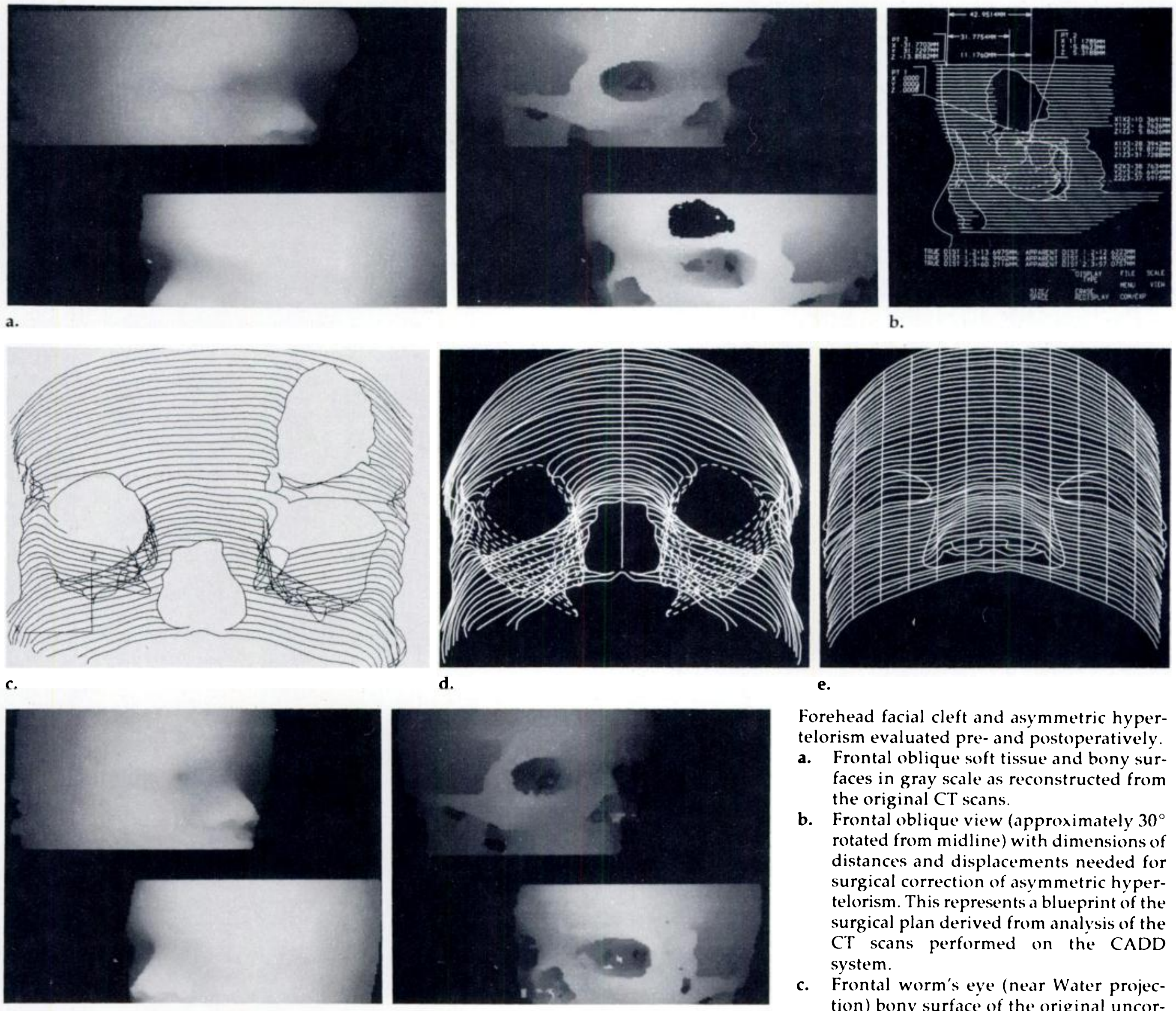
Nasofrontal encephalocoele in a young child. Preoperative evaluation by comparison of skin, brain, and skull surfaces with computed overlays.

a. Skin surface (left) and superimposition of brain surface (right) with skin contours show brain tissue in midline extending inferiorly from frontal lobes. Frontal (top) and lateral (bottom) views are shown.

b. Skull surface (top) in the right lateral projection, and bony contours (bottom) of the left midsagittal surface. Superimposition of the brain surface (right) and contours derived from the skull demonstrate the relationship of the midline bony defect and meningoencephalocoele.

c. The skull defect responsible for the nasofrontal encephalocoele is seen in the interorbital region on the frontal views (top left), at the anterior margin of the cribiform plate on the top intracranial skull base view (top right), and just anterior to the midpoint of the maxillary alveolus on the bottom view of the extracranial skull base view (bottom left). The base of the brain viewed from below (bottom right) corresponds to the extracranial skull base view (bottom left). The sellar contents are seen between the temporal lobes. An abnormal appendage from the frontal lobes is seen in the midline anteriorly (bottom right image).

Figure 4. Case IV.



Forehead facial cleft and asymmetric hypertelorism evaluated pre- and postoperatively.

a. Frontal oblique soft tissue and bony surfaces in gray scale as reconstructed from the original CT scans.

b. Frontal oblique view (approximately 30° rotated from midline) with dimensions of distances and displacements needed for surgical correction of asymmetric hypertelorism. This represents a blueprint of the surgical plan derived from analysis of the CT scans performed on the CADD system.

c. Frontal worm's eye (near Water projection) bony surface of the original uncorrected skull deformity. The left frontal bone cleft and deviated left orbit are shown.

d. Frontal worm's eye bony and soft tissue surfaces of simulated surgical outcome created by reflecting the normal (patient's right) side about the midline using the CADD system.

e. Frontal worm's eye bony surface of simulated surgical outcome.

f. Frontal oblique soft tissue and bony surfaces derived from CT scans obtained one year postoperatively. The frontal cranial defect has been closed with split cranium, and the left orbit has been translocated surgically to restore symmetry with the normal right side.

system approach to craniofacial surgical planning and evaluation include interactive display, quantitation of linear, surface, and volumetric measurements, and ability to move image components independently. The soft tissue and bony contours may be overlaid to study their relationship with the face by displaying them simultaneously.

A most effective means of planning an orbital translocation procedure is demonstrated in this example of asymmetric hypertelorism. The right orbit and its contents are normal while the left orbit is displaced inferiorly, anteriorly, and laterally. By measuring these displacements in three dimensions, the surgeon can execute the orbital translocation with improved precision.

By convention, we assign the X direction to be horizontal, in the mediolateral orientation. The Y direction refers to anterior-posterior, and the Z direction to superior-inferior. Thus the X-Y plane corresponds to the plane of section. The Z axis is perpendicular to the plane of section and corresponds to the direction of table motion in CT scanning.

Computer-aided design and drafting provided measurements used in planning an orbital translocation. A plane of symmetry was chosen in the midsagittal region and an arbitrary reference point selected above the nasion in the midfrontal region. The normal right orbit was converted from solid to dashed-line type for ease of display. The delineation of the normal orbit was then reflected about the midsagittal plane of symmetry. Measurements of the X, Y, and Z displacements were made with reference to this arbitrary fixed point. These dimensions are given in the oblique frontal view (Fig. 4b). The most useful measurements are the X, Y, and Z differences between the normal transposed and abnormal dislocated orbit. These measurements serve to define the required translocation procedure needed to realign the left orbit to normalcy. The required superior, medial, and posterior displacements were shown to be 0.59 cm, 1.04 cm, and 0.68 cm, respectively. This corresponded to a displacement of the orbit by 13.7 mm in three dimensional space.

DISCUSSION

Craniofacial surgical procedures have traditionally been planned and evaluated radiographically using cephalometric AP and lateral views of the skull. With the availability of high resolution CT scanners, reformatted (sagittal, coronal, and oblique) images obtained from contiguous sections through the facial structures have found application.

The two dimensional nature of both methods is a significant limitation when applied to the analysis of three dimensional aberrant anatomy. CT scans and reformatted planar images contain information on anatomic abnormalities, but their form of presentation may create difficulties in interpretation for the radiologist, and especially when communicating the results to the surgeon.

Mentally reconstructing a patient's facial appearance from a sequence of CT scans may be a formidable task for observers skilled and experienced in reading CT scans. The radiologist or surgeon can better plan and evaluate complex procedures for correction of three dimensional bony anomalies with a means to characterize facial anatomy fully. This tool, three dimensional surface reconstruction of bony and soft tissue structures, is realized by computer processing of a CT scan sequence.

We have developed such a tool and recognize several additional practical benefits. There is no geometric error due to magnification effects (inherent in cephalometric skull radiography) in these surface images. The true character of bilaterally asymmetric malformations may be appreciated, since overlap of structures is not encountered. The surface images allow the surgeon to precisely visualize the abnormality to be corrected at operation. Life-size surface images may be produced to permit accurate dimensional measurement required for surgical planning. Finally, using interactive digital graphic systems, the surface images can be altered to simulate the surgical outcome. These images are helpful for instructing physicians, and even patients themselves, in pathologic anatomy and craniofacial surgical procedures.

CONCLUSION

A new method for reconstruction of a three dimensional surface from a sequence of high resolution CT scans has been developed. This algorithm, realized as a set of computer programs that can operate on a CT scanner or evaluation console, is both efficient and easy to implement. No operator intervention is required.

The CT data have also been used to generate surface images on an industrial computer-aided design system. This allows the generation of industrial blueprint diagrams for application to craniofacial surgery.

These methods have been used to assist in the management of over 300 patients with congenital or acquired craniofacial deformities by extracting important anatomic details from a sequence of high resolution CT scans. These surface reconstructions have aided the surgeon in comprehending the primary deformity, facilitated surgical planning, and clarified postoperative results.

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References

1. Udupa JK. Display of 3D information in discrete 3D scenes produced by computerized tomography. Proceedings of IEEE 1983; 71:420-431.
2. Bloch P, Udupa JK. Application of computerized tomography to radiation therapy and surgical planning. Proceedings of IEEE 1983; 71:351-355.
3. Herman GT, Reynolds TA, Udupa JK. Computer techniques for the representation of three-dimensional data on a two-dimensional display. Proceedings SPIE 1983; 367:3-14.
4. Herman GT. Image Reconstruction from Projections. New York: Academic Press 1980:260-276.
5. Artzy E, Frieder G, Herman GT. The theory, design, implementation and evaluation of a three-dimensional surface detection algorithm. Comput Graph Image Proc 1981; 15:1-24.
6. Hemmy DC, David DJ, Herman GT. Three dimensional reconstruction of craniofacial deformity using computed tomography. University of Pennsylvania Department of Radiology, Medical Image Processing Group, Technical Report MIPG-81, April 1983.
7. Latamore GB. Creating 3-D models for medical research. Comput Graphics World 1983; 7:31-38.
8. Vannier MW, Marsh JL, Gado MH, Totty WG, Gilula LA, Evens RG. Clinical applications of 3-dimensional surface reconstruction from CT scans. Electromedica 1983, in press.
9. Vannier MW, Marsh JL, Warren JO. Three dimensional computer graphics for craniofacial surgical planning and evaluation. Comput Graphics 1983; 17:263-273.
10. Vannier MW, Marsh JL, Warren JO, Barbier J. Three dimensional computer aided design of craniofacial surgical procedures. Diagn Imaging 1983; 5:36-43.
11. Marsh JL, Vannier MW. The "third" dimension in craniofacial surgery. Plast Reconstr Surg 1983; 71:759-767.
12. Vannier MW, Gado MH, Marsh JL. Three dimensional display of intracranial soft tissue structures. Am J Neuroradiol 1983; 4: 520-521.
13. Vannier MW, Marsh JL, Warren JO, Barbier J. Three dimensional CAD for craniofacial surgery. Electronic Imaging 1983; 2:48-54.
14. Totty WG, Vannier MW. Complex musculoskeletal anatomy: analysis using three dimensional surface reconstruction. Radiology 1983; 150:173-177.
15. Marsh JL, Vannier MW. Surface reconstruction from CT scans. Surgery 1983; 94: 159-165.
16. Fu KS, Mui JK. A survey on image segmentation. Pattern Recog 1981; 13:65-77.
17. Kawamoto H. The kaleidoscope world of rare craniofacial clefts: Tessier classification. Clin Plast Surg 1976; 3:529-572.
18. Rogers DF, Adams JA. Mathematical Elements for Computer Graphics. New York: McGraw Hill 1976:119-124.

Michael W. Vannier, M.D.
Mallinckrodt Institute of Radiology
510 South Kingshighway
St. Louis, Missouri 63110