Computer-Aided Reconstruction of Traumatic Fronto-Orbital Osseous Defects: Aesthetic Considerations

Lun-Jou Lo, MD; Yu-Ray Chen, MD; Ching-Shiow Tseng[1], PhD; Ming-Yih Lee[2], PhD

Background: In addition to functional goals, a satisfactory aesthetic outcome is important for reconstruction of fronto-orbital osseous defects. The purpose of this study is to report on a method for presurgical fabrication of custom implants using 3-dimensional (3-D) imaging data and computer-assisted manufacturing techniques.

Methods: Preoperative 3-D computed tomography data were processed and displayed for evaluation of defects. Implants were created by a computer-aided design/computer-aided manufacturing (CAD/CAM) program. A rapid prototyping system was applied for production of the physical models. Rehearsal of surgery was performed using the implants and skull models. Negative castings were created and were used during the operations to prepare the surgical implant utilizing methyl methacrylate. Traumatic fronto-orbital defects in 4 patients were reconstructed using this method. The follow-up period ranged from 29 to 55 months.

Results: Results showed that the custom implants perfectly fit the defects during the operation. Symmetry and normal fronto-orbital contours were achieved. There were no peri- or postoperative complications. All patients were satisfied with the results.

Conclusions: Computer-aided presurgical simulation and fabrication of implants is a reliable and effective method for the reconstruction of traumatic fronto-orbital defects, with reduced anesthesia time and improved aesthetic outcomes.
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Key words: **fronto-orbital defect, computer-aided reconstruction, custom implant, rapid prototyping models.**

Reconstructive surgeons may deal with skull defects resulting from congenital anomalies, trauma, infections, and resection of tumors. The reconstruction becomes difficult if the defect is large and located in the fronto-orbital region, which is an area requiring aesthetic considerations. For successful reconstruction of such a defect, good preoperative evaluation, ideal surgical planning and preparation, and accurate restoration of the anatomical contours are mandatory for a satisfactory outcome. Conventionally, such reconstructions have been achieved with autografts or alloplastic materials applied using the surgeon's clinical experience, with occasional inconsistent results. The combination of

From the Craniofacial Center, the Department of Plastic and Reconstruction Surgery, Chang Gung Memorial Hospital, Chang Gung University, Taoyuan; [1]Department of Mechanical Engineering, National Central University; [2]Graduate Institute of Mechanical Engineering, Chang Gung University, Taoyuan, Taiwan.
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Address for reprints: Dr. Lun-Jou Lo, Department of Plastic and Reconstruction Surgery, Chang Gung Memorial Hospital. 5, Fushing Street, Gueishan Shiang, Taoyuan, Taiwan 333, R.O.C. Tel.: 886-3-3281200 ext.2855; Fax: 886-3-3285818;
E-mail: lunjoulo@cgmh.org.tw

technological advances in 3-dimensional (3-D) computed tomography (CT), computer-aided design/computer-aided manufacturing (CAD/CAM) systems, and rapid prototyping offer another option for preoperative evaluation and preparation of custom implants. This study reports our experience in using these methods for reconstruction of traumatic fronto-orbital defects in a series of patients.

METHODS

The patients in this series had traumatic injuries, with initial management performed elsewhere. They were referred to the Craniofacial Center, Department of Plastic and Reconstructive Surgery, Chang Gung Memorial Hospital, Taoyuan, Taiwan for reconstruction of the skull defects (Table 1). The neurological status and overall condition of the patients were good. CT scanning was performed using a standard craniofacial protocol.(1) The entire head of the patients was scanned using a spiral CT scanner at an axial plane from below the chin to above the top of the head, and the thickness was set to between 1 and 3 mm. The CT data were transferred, reformatted into cubic voxel units, and reconstructed for display as 2- and 3-D images. A threshold technique was used to control the CT densities for inspection of the craniofacial structures and the osseous defect. The skull was rotated for evaluation and measurement of the defect. Simulation of the surgery for producing the implant image object was performed.(2,3) The imaging procedures were performed on IBM-compatible personal computers running Analyze™ software (Biomedical Imaging Resource, Mayo Foundation, Rochester, MN, USA).(4-6)

The CT data were transferred to another computer system using CAD/CAM interface software, where the reconstructive implant was created (Fig. 1). Production of the implant image was facilitated by a mirror-imaging function, using the uninjured contralateral anatomy as a template. For the patient (case 2) with an orbital wall defect, the image of the orbital wall was manipulated so that the implant was constructed thicker in this area for stability of the solid implant. For the portion of the defect that crossed the midline, (case 1) where the mirror-imaging function could not be used, the surface and thickness of the implant image were adjusted to best fit the neighboring osseous structures to create a smooth and normal anatomic appearance. Revisions were made when necessary. The custom implant together with the skull images were examined from various views until a satisfactory result was achieved. The image data were then transferred in a stereolithography (STL) format and read by a rapid prototyping machine to produce skull models and customized implants.(3) Rehearsal of surgery was performed using the physical skull and implant models. If the result was acceptable, negative castings of the custom implant were produced. The outer and inner parts of the negative castings were made from the contour of the physical implant model, using silicone (cases 1 and 2) or dental alginate materials (case 3), or were produced from the CAD/CAM system (case 4).(3) Castings were sterilized and used intraoperatively to mold the methyl methacrylate into the appropriate shape as it solidified. Scalp incisions were made with the assistance of a neurosurgeon, and the skull defect was dissected and exposed.

Case presentations

Case 1

This 21-year-old man was in a motor vehicle accident on February 5, 1998. At presentation in the emergency room, he had a large laceration over the left frontal area and his consciousness was blunted.

Table 1. Characteristics of Patients with Traumatic Skull Defects Receiving Reconstruction

Case no.	1	2	3	4
Gender	male	male	male	male
Age at reconstruction (yr)	21	21	28	8
Location of defect	left fronto-orbital	left fronto-orbital	left fronto- parieto-temporal	left fronto- parieto-temporal
Dimensions of defect (cm)	6×4	12×6	12×8	13×11
Follow-up period (mon)	55	44	40	29
Complications	none	none	none	none

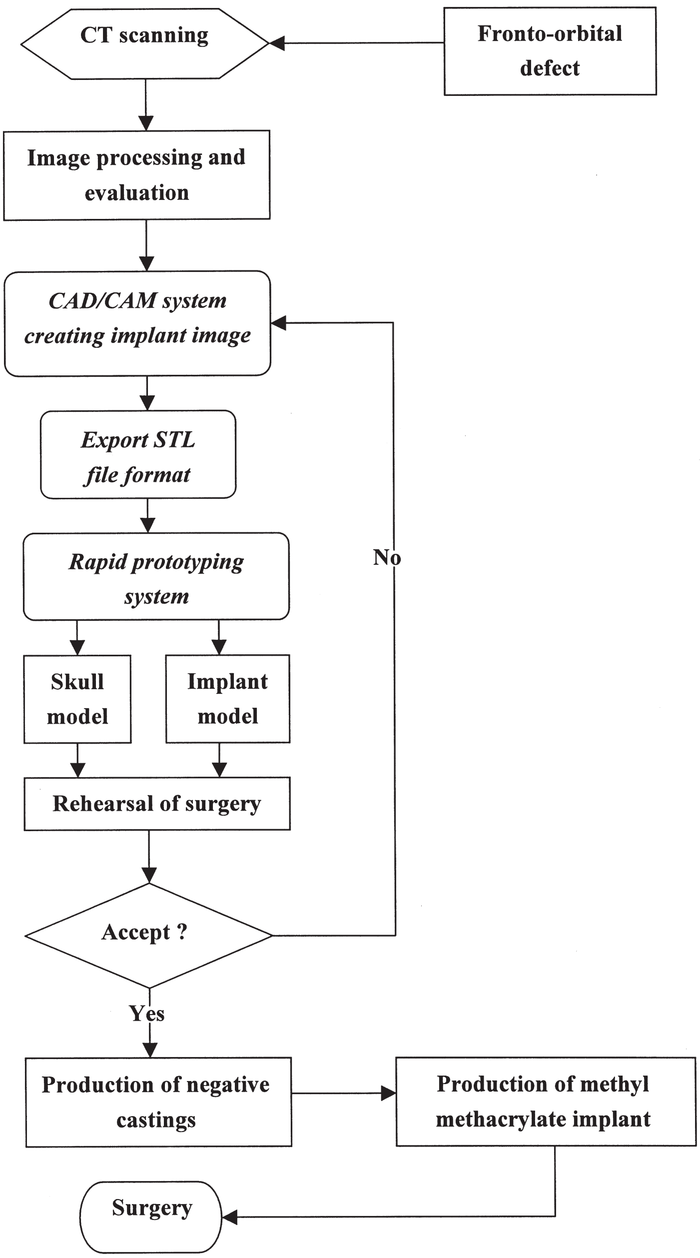

Fig. 1 Flow chart for the production of custom implants for patients with traumatic fronto-orbital defects.

Physical examination and CT scans demonstrated left fronto-orbital compound depression fractures, frontal intracranial hemorrhage, a naso-ethmoid fracture, and maxillary fractures. Evacuation of the intracranial hematoma and repair of dural tears were urgently accomplished. Contaminated frontal and orbital bone segments were debrided. His neurological condition gradually improved. On post-injury day 12, he underwent open reduction of the maxillary fractures.

He was referred for treatment 4 months later, requesting surgical reconstruction of his craniofacial deformities. Examination revealed ptosis and optic neuropathy of the left eye, as well as anosmia. Deformities included depression of the left fronto-orbital area, nasal dorsum, and enophthalmos. CT reconstructions demonstrated these defects. The skull defect was 6×4 cm and crossed the midline. Image processing was performed and models were created. During surgery, there was no communication with the frontal sinus, and the implant was fixed to the defect. Rib bone grafts were harvested for correction of the depressed nasal dorsum and enophthalmos. He subsequently received a levator resection operation for ptosis, and another operation for fat grafting and scar revision for a residual soft tissue deformity.

Case 2

This 19-year-old man had a motorcycle accident with left fronto-orbital injury. He was transferred to our neurosurgical emergency unit 3 days after initial management at another hospital. Examination revealed a long sutured laceration and depression over the left frontal region, redness and swelling over the left eye, and a fracture of the left scapula. A CT scan revealed intracranial hemorrhage over the left frontal lobe and comminuted fronto-orbital fractures. There were optic neuropathy and 3rd cranial nerve palsy on the left. He was initially treated conservatively. He returned 6 weeks later with a left frontal brain abscess. The abscess was drained, with a partial left frontal lobectomy and debridement of devitalized frontal and supraorbital bone segments. He had occasional seizures after the injury. A subsequent CT scan showed the defects over the left frontal area, supraorbital rim, and superior orbital wall (Fig. 2). The defect was 12×6 cm.

Models and castings were produced with an extension for reconstruction of the superior orbital wall. During surgery, the defect was exposed and was found to communicate with the frontal sinus. The mucosal lining of the frontal sinus was excised. The methyl methacrylate implant was created to cover the defect. A slit was made at the junction of the implant and the frontal sinus for passage of a frontalis muscle flap, which was raised for obliteration and separation of the sinus from the reconstructive implant. Three months later, he underwent nasal dorsum augmentation with a silicone prosthesis and left eyelid fat graft injection.

Case 3

This 28-year-old man was referred for reconstruction of a large left fronto-temporal osseous defect following a motor vehicle accident 6 years previously. He had sustained cranial injuries and had received several cranial operations at another hospital including a craniotomy, treatment for infection involving debridement of the cranial bone, metallic plate coverage of the defect, treatment for recurrent infection, and removal of the plate. His post-traumatic seizure disorder required medical therapy. A CT scan showed the osseous defect over the left frontal and temporal regions. Image processing and model production were undertaken per the protocol. The skull contour was satisfactory following reconstruction. His seizures persisted, but were less frequent. He had temporal hollowing out due to soft tissue atrophy, but he rejected suggestions for correction.

Case 4

This 8-year-old boy was referred with sequelae of cranial injuries following a motor vehicle accident, following a 4-month course at another hospital. Previous operations included a craniotomy for removal of intracranial hematoma, a ventriculoperitoneal shunt, a second craniotomy for debridement of infected bone, and shunt revisions. His level of consciousness was normal, but he had seizures, left hemiplegia, and aphasia. After a protracted course, he was referred for reconstruction of his left fronto-temporal osseous defect, which measured 13×11 cm. His postoperative course was uneventful.

RESULTS

Intraoperatively, dissection and exposure of the osseous defects were facilitated by on-site inspection of the facsimile skull model. No unexpected deformities or untoward injuries were encountered during the surgery. The methyl methacrylate implants fit the skull defects well, and consequently, few adjustments were needed. Rigid fixation of the implants was achieved using miniplates and screws, with plates and screws placed under the hair-bearing scalp where possible. The surgical procedures were uneventful, and the anesthesia time was reduced as compared to our cranioplasties using conventional

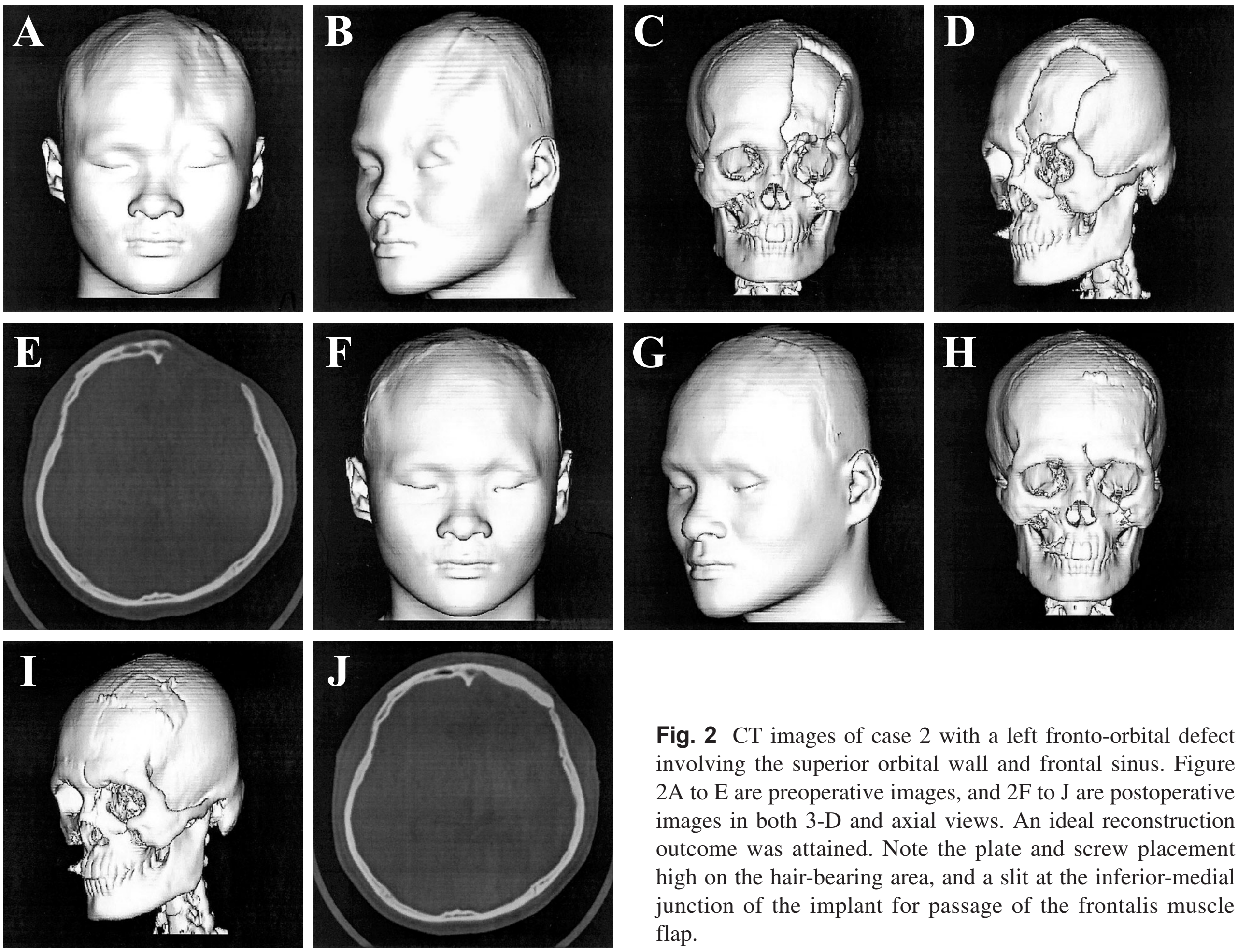

Fig. 2 CT images of case 2 with a left fronto-orbital defect involving the superior orbital wall and frontal sinus. Figure 2A to E are preoperative images, and 2F to J are postoperative images in both 3-D and axial views. An ideal reconstruction outcome was attained. Note the plate and screw placement high on the hair-bearing area, and a slit at the inferior-medial junction of the implant for passage of the frontalis muscle flap.

methods. The patients were followed-up for 29 to 55 months, with an average of 42 months. Symmetry and normal fronto-orbital contours were achieved. Three-dimensional CT and axial views showed satisfactory results (Fig. 2A-J). There were no complications. All patients were satisfied with the results.

DISCUSSION

Reconstruction of traumatic fronto-orbital osseous defects is important both for protecting the underlying brain and for aesthetic appearances. A major patient concern is an abnormal appearance, which can cause psychosocial impacts. The protective purpose is especially important in the presence of seizure disorders, as occurred in 3 of our patients. Traditional methods for reconstructing skull defects involve harvesting bone grafts or using alloplastic materials, shaping these materials, and fixing them to the defect. It is difficult to shape an identical or ideal contour for the missing part, particularly if the defect is large or located in an aesthetically important area such as the fronto-orbital region. To achieve good results, substantial training and experience are requisite and longer anesthesia times are required; yet results are not consistently satisfactory.

Cranioplasty can be traced back to antiquity, with available evidence suggesting that bone substitutes were used for repairing skull defects.[7] Autografts, metals, and plastics have been used.

Methyl methacrylate was introduced and proven to be safe and reliable, and is currently a common alloplastic material for cranioplasty. Regardless of the surgical methods or materials chosen, accurate restoration of osseous contour defects is mandatory. Clinical attempts to improve the aesthetic results of cranioplasty have been reported.[8-11] Custom implants have been prefabricated using a positive impression fashioned directly on the patient.[12] Life-size 3-D solid skull models have been produced from patients' CT data, and were used to select optimal bone graft donor sites,[13,14] or used as a guide to fabricate implants.[15-17] Computer technology is employed for CT data processing, and to facilitate the design and generation of individual alloplastic implants.[3,18-21]

The development and advancement of 3-D CT imaging has been very helpful for evaluating skull deformities and surgical planning. Using an interactive program, 3-D CT images can be manipulated, and osseous objects can be created to simulate the surgical procedures.[2,3] The computer simulation system provides the advantage of unlimited trials. Quantitative measurements are conveniently performed on the images, with validated accuracy.[22,23] The simulations are helpful for the design and manufacture of implants. CAD/CAM systems, commonly used in mechanical engineering, have been successfully explored for biomedical applications.[3,19,20,24,25] One was used in this study for CT data processing, design of custom implants, and the export of data to a rapid prototyping machine for the manufacture of the solid models. The rapid prototyping technology is a well-developed method for production of 3-D physical models from 3-D computerized digital data for various industries, including medicine.[25-28] A high-quality 3-D model is automatically produced without the need for manual revisions. It has become a useful tool for reverse engineering in clinical applications.

A main concern of using computer-aided methods as in this study involves the time and cost consumed in the preoperative preparation. This has gradually become less of a concern with advancement of technologies, and it seems to be well rewarded by reductions in operative times and better aesthetic results. The use of methyl methacrylate in this study should be discussed. In this series, patients had large defects, 3 had a history of prior infection, and 1 had involvement of the frontal sinus. These are circumstances for which it has been advised against using methyl methacrylate cranioplasty.[29] However, in an analysis of risk factors, the choice of reconstructive material was found to have no significant correlation with the occurrence of complications.[30] Clinical cases have also been reported to confirm the safety of the use of alloplastic implants for large fronto-orbital defects with or without a history of prior infection,[11,15,19-21,31] as was observed in our study. Guidelines for prevention of complications with these procedures include anatomical restoration of the defect, rigid fixation, partitioning of the frontal sinus, and provision of adequate overlying soft tissue coverage.

A difficult situation which was not seen among our cases can arise when there is a very large defect, leaving little remaining skull for reference in the computer-aided design. In such cases, a gender- and size-matched normative skull image/model can be used as a guide for designing the implant. Creation of "average" models of anatomy is also helpful for this kind of difficult reconstruction.[32-34] In summary, traumatic fronto-orbital defects in 4 patients were reconstructed by computer-aided methods, and satisfactory results were obtained. The combined use of 3-D CT imaging, CAD/CAM, and rapid prototyping technologies is not new. Yet they are becoming more-convenient, user-friendly, and readily available tools for those who are in need of fronto-orbital reconstruction.

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REFERENCES

1. Lo LJ, Chen YR. 3-dimensional CT imaging in craniofacial surgery: morphological study and clinical applications. Chang Gung Med J 2003;26:1-11.
2. Lo LJ, Marsh JL, Vannier MW, Patel VV. Craniofacial computer assisted surgical planning and simulation. Clin Plast Surg 1994;21:501-16.

3. Lee MY, Chang CC, Lin CC, Lo LJ, Chen YR. 3D image reconstruction and rapid prototyping models in custom implant design for patient with cranial defect. IEEE Eng Med Biol 2002;21:38-44.
4. Robb RA, Barillot C. Interactive display and analysis of 3-D medical images. IEEE Trans Med Imaging 1989;8: 217-26.
5. Robb RA, Hanson, DP, Karwoski RA, Larson AG, Workman EL Stacy MC. ANALYZE: a comprehensive, operator-interactive software package for multidimensional medical image display and analysis. Comput Med Imag Graph 1989;13:433-54.
6. Robb RA. The Biomedical Imaging Resource at Mayo Clinic. Guest Editorial. IEEE Trans Med Imaging 2001;20:854-67.
7. Sanan A, Haines SJ. Repairing holes in the head: a history of cranioplasty. Neurosurgery 1997;40:588-603.
8. Cooper PR, Schechter B, Jacobs GB, Rubin RC, Wille RL. A pre-formed methyl methacrylate cranioplasty. Surg Neurol 1977;8:219-21.
9. Cabbabe EB, Shively RE, Malik P. Cranioplasty for traumatic deformities of the frontoorbital area. Ann Plast Surg 1984;13:175-84.
10. van Gool AV. Preformed polymethylmethacrylate cranioplasties: report of 45 cases. J Maxillofac Surg 1985;13:2-8.
11. Replogle RE, Lanzino G, Francel P, Henson S, Lin K, Jane JA. Acrylic cranioplasty using miniplate struts. Neurosurgery 1996;39:747-9.
12. Epker BN, Stella JP. Reconstruction of frontal and frontalnasal deformities with prefabricated custom implants. J Oral Maxillofac Surg 1989;47:1272-6.
13. Sailer HF, Haers PE, Zollikofer CP, Warnke T, Carls FR, Stucki P. The value of stereolithographic models for preoperative diagnosis of craniofacial deformities and planning of surgical corrections. Int J Oral Maxillofac Surg 1998;27:327-33.
14. Santler G, Karcher H, Ruda C. Indications and limitations of three-dimensional models in cranio-maxillofacial surgery. J Craniomaxillofac Surg 1998;26:11-6.
15. Joffe JM, McDermott PJ, Linney AD, Mosse CA, Harris M. Computer-generated titanium cranioplasty: report of a new technique for repairing skull defects. Br J Neurosurg 1992;6:343-50.
16. Binder WJ, Kaye A. Reconstruction of posttraumatic and congenital facial deformities with three-dimensional computer-assisted custom-designed implants. Plast Reconstr Surg 1994;94:775-85.
17. Tanaka Y, Matsumoto K, Song S, Tajima S, Ohmura T. Reconstruction of a cranial bone defect with hydroxyapatite and free flap transfer. J Craniofac Surg 1997;8:141-5.
18. Toth BA, Ellis DS, Stewart WB. Computer-designed prostheses for orbitocranial reconstruction. Plast Reconstr Surg 1988;81:315-22.
19. Eufinger H, Wehmoller M, Harders A, Heuser L. Prefabricated prostheses for the reconstruction of skull defects. Int J Oral Maxillofac Surg 1995;24:104-10.
20. Eufinger H, Wehmoller M, Machtens E, Heuser L, Harders A, Kruse D. Reconstruction of craniofacial bone defects with individual alloplastic implants based on CAD/CAM-manipulated CT-data. J Craniomaxillofac Surg 1995;23:175-81.
21. Eppley BL, Kilgo M, Coleman JJ 3rd. Cranial reconstruction with computer-generated hard-tissue replacement patient-matched implants: indications, surgical technique, and long-term follow-up. Plast Reconstr Surg 2002;109: 864-71.
22. Patel VV, Vannier MW, Marsh JL, Lo LJ. Assessing craniofacial surgical simulation. IEEE Computer Graphics 1996;16:46-54.
23. Lo LJ, Lin WY, Wong HF, Lu KT, Chen YR. Quantitative measurement on 3-dimensional computed tomography: an experimental validation using phantom objects. Chang Gung Med J 2000;23:354-9.
24. Wehmoller M, Eufinger H, Kruse D, Mabberg W. CAD by processing of computed tomography data and CAM of individually designed prostheses. Int J Oral Maxillofac Surg 1995;24:90-7.
25. Chua CK, Chou SM, Ng WS, Chow K Y, Lee S T, Aung S C, Seah C S. An integrated experimental approach to link a laser digitiser, a CAD/CAM system and a rapid prototyping system for biomedical applications. Int J Adv Manuf Technol 1998;14:110-5.
26. Zollikofer CPE, Ponce de Leon MS. Tools for rapid prototyping in the biosciences. IEEE Comput Graphics 1995;15:48-55.
27. Chua CK, Chou SM, Lin SC, Eu KH, Lew KF. Rapid prototyping assisted surgery planning. Int J Adv Manuf Technol 1998;14:624-30.
28. D'Urso PS, Earwaker WJ, Barker TM, Redmond MJ, Thompson RG, Effeney DJ, Tomlinson FH. Custom cranioplasty using stereolithography and acrylic. Br J Plast Surg 2000;53:200-4.
29. Blum KS, Schneider SJ, Rosenthal AD. Methyl methacrylate cranioplasty in children: long-term results. Pediatr Neurosurg 1997;26:33-5.
30. Manson PN, Crawley WA, Hoopes JE. Frontal cranioplasty: risk factors and choice of cranial vault reconstructive material. Plast Reconstr Surg 1986;77:888-904.
31. Yamamoto Y, Mendel E, Raffel C. Acrylic cranioplasty with alginate molding: technical note. Neurosurgery 1997; 41:305-6.
32. Cutting C, Dean D, Bookstein FL, Haddad B, Khorramabadi D, Zonneveld FW, McCarthy JG. A three-dimensional smooth surface analysis of untreated Crouzon's syndrome in the adult. J Craniofac Surg 1995; 6:444-53.
33. Dean D, Bookstein FL, Koneru S, Lee JH, Kamath J,

Cutting CB, Hans M, Goldberg J. Average African American three-dimensional computed tomography skull images: the potential clinical importance of ethnicity and sex. J Craniofac Surg 1998;9:348-58.
34. Brief J, Hassfeld S, Dauber S, Pernozzoli A, Munchenberg J, Redlich T, Walz M, Krempien R, Weisser H, Poeckler C, Raczkowsky J, Burgert O, Salb T, Kotrikova B, Rembold U, Worn H, Dillmann R, Muhling J. 3D norm data: the first step towards semiautomatic virtual craniofacial surgery. Comput Aided Surg 2000;5:353-8.

創傷性額眶骨缺損的電腦輔助重建：一個美觀的考量

羅綸洲 陳昱瑞 曾清秀[1] 李明義[2]

背 景：額眶骨缺損的重建，除了達到改善功能的目標，也要能獲得滿意的外觀。這項研究是報告應用三度影像資料和電腦輔助性製造技術，以製造個別的植入物，重建缺損。

方 法：術前的三度電腦斷層資料經重整及顯像，做爲缺損部份的評估，植入物的製造則是藉由電腦輔助設計 / 電腦輔助製造的軟體程式來達成，實物模型則是利用快速成型系統來做成，做出來的植入物及頭骨模型則用來做手術演練。下一步則是製作負模，以便在手術中用人工骨水泥做出缺損的植入物。利用這種方法，我們重建了四個病人的創傷性額眶骨缺損，追蹤的時間從29至55個月之久。

結 果：所有的病例顯示這種方法製成的植入物能完美的符合缺損的形狀大小，達到額眶骨對稱正常的外觀，沒有發生手術中、手術後的併發症，所有的病人都滿意手術的結果。

結 論：以這種應用電腦輔助來製造植入物，來重建額眶部的創傷性缺損，是一個可靠而有效的方法，進而減少麻醉時間，達到滿意的外觀。
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關鍵字：額眶骨缺損，電腦輔助重建，個別植入物，快速成型模型。

長庚紀念醫院 台北院區 整形外科；[1]中央大學 機械工程學系；[2]長庚大學 機械工程研究所
受文日期：民國92年9月22日；接受刊載：民國92年12月26日。
索取抽印本處：羅綸洲醫師，長庚紀念醫院 整形外科。桃園縣333龜山鄉復興街5號。Tel.: (03)3281200轉2855; Fax: (03)3285818; E-mail: lunjoulo@cgmh.org.tw