

Selective Laser Sintering: Application of a Rapid Prototyping Method in Craniomaxillofacial Reconstructive Surgery

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Abstract

Advances in technology have benefited the medical world in many ways and a new generation of computed tomography (CT) scanners and three-dimensional (3-D) model making rapid prototyping systems (RPS) have taken craniofacial surgical planning and management to new heights.

With the development of new rapid prototyping systems and the improvements in CT scan technology, such as the helical scanner, biomedical modelling has improved considerably and accurate 3-D models can now be fabricated to allow surgeons to visualise and physically handle a 3-D model on which simulation surgery can be performed. The principle behind this technology is to first acquire digital data (CT scan data) which is then imported to the RPS to fabricate fine layers or cuts of the model which are gradually built up to form the 3-D models. Either liquid resin or nylon powder or special paper may be used to make these models using the various RPS available today. Selective laser sintering (SLS), which employs a CO₂ laser beam to solidify special nylon powder and build up the model in layers is described in this case report, where a 23-year old Chinese female with panfacial fracture and a skull defect benefited from SLS biomodelling in the preoperative workup.

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Introduction

The value of computed tomography (CT) in craniofacial trauma is now well established with progress in imaging modalities. Three-dimensional (3-D) CT has changed the way craniofacial surgery is planned and its valuable contributions and limitations have been studied.^{1,2} Recent developments in CT scanning and rapid acquisition time in comparison to magnetic resonance imaging have consolidated the role of CT as a standard radiological method in maxillofacial surgery.³

The last decade saw the introduction of the spiral CT which enables more data capture within a shorter time,⁴ and also relates to higher resolution 3-D images rendered by using special imaging software tools. Whether using original CT scan data or magnetic resonance imaging (MRI) data, today's 3-D imaging software programmes can transform, edit and finally convert the files into .stl formats (machine files), which will instruct the rapid prototyping systems (RPS) to generate 3-D physical models. It only remains for the user to decide which appropriate type of rapid prototyping technique to em-

ploy. The model thus made is usually a very accurate replica and includes all the details of the underlying skull, which normally could be assessed only by viewing the two-dimensional (2-D) CT scan 'cuts' or by studying the hard copy of a 3-D image on the monitor or X-ray film.

A case report involving a craniofacial fracture with a resultant cranial defect due to road traffic accident is presented. Helical CT scan data was used to fabricate a model using the selective laser sintering (SLS) method of rapid prototyping.

Rapid Prototyping Techniques

Rapid prototyping (RP) relies on digital data from an imaging source, such as the CT scan data which has been converted into machine files, to fabricate a model, layer upon layer, building from the base layer to the top. Each layer is very thin and details such as small foramina or overhanging parts are faithfully reproduced. One of the earliest RP methods is the stereolithography apparatus (SLA) where liquid resin is solidified each layer at a time

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to build up the details of the model. Other RP systems use different materials to fabricate the physical models. Special sheets of paper, which are laminated in layers as a laser beam cuts out the details for each layer, are used in laminated object manufacturing (LOM) and special molten nylon material is injected through a fine nozzle to build up the layers in fused deposit modelling (FDM). Selective laser sintering uses fine nylon composite powder which is fused by CO₂ laser to build the model. A new system, the Solid Ground Curing machine (SGC) allows resin to be solidified by UV light passing through photo masks. All these new techniques have made the previous 3 or 5 axes milling machines outdated, in terms of the details that can be captured when making 3-D models.

Although SLA was first on the scene in RP techniques and most of the early skull models were made using this system,⁵⁻⁷ the more recent and newer methods have proved to be better in terms of the degree of toxicity, better look and feel and, most importantly, durability.

In recent years, SLS has been used more often to make biomodels of the skull to assist in the planning of complex craniofacial surgeries. The accuracy of the 3-D models from RP systems has been validated for both SLA and SLS models and have been found to be accurate.^{7,8}

Advantages of Using 3-D Biomodels

The use of 3-D biomodels can greatly facilitate the assessment and the surgical planning for craniofacial deformities such as craniosynostosis, Treacher-Collin's Syndrome, hemifacial microsomia and also in craniofacial injuries. The complex structure of the skull may sometimes make assessment for these deformities difficult and a physical model helps in the evaluation of these deformities and defects.

Even though 3-D CT images can be reformatted on the computer monitor or printed out on X-ray films, being able to physically handle a 3-D model and assess it as one would actually do on a real skull means a more detailed study can be carried out, especially for complex cases. The bony morphology and the abnormal features can be better perceived and the surgeon will find it easier to plan on the model, knowing fully well that he will be able to duplicate the same moves on the patient. Operations requiring the introduction of rigid fixation methods could be prepared in advance by selecting appropriate miniplates and bending them into shape on the biomodel to ensure a quick and smooth operation later. Unforeseen difficulties due to inadequate exposure during dissection can be eliminated, as all parts of the skull that requires correction would have been visible on the physical model. It is however not recommended for routine craniofacial surgical procedures because the cost and radiation exposure far outweighs

its usefulness as an aid to the surgery itself.

Material and Methods

The CT scans were acquired from the Department of Radiology, Singapore General Hospital, using a GE Helical Scanner with sections interval of 1.5 mm and the data files were transferred to the 3-D workstation using 4 mm digital data storage tapes. The latter part of the project was carried out at the Nanyang Polytechnic (GSI), and involved image processing on a Silicon Graphics workstation using MIMICS™ software to convert into a 3-D model for image manipulation. The finished product was exported as machine files in .stl formats which were then ported into the RP (Selective Laser Sintering) machine itself. Using this method, a special nylon composite in powdered form was sintered in the RP process to make the whole skull model (Fig. 1). The whole process of sintering took about 40 hours and would be shorter if only selective parts of the skull were made.

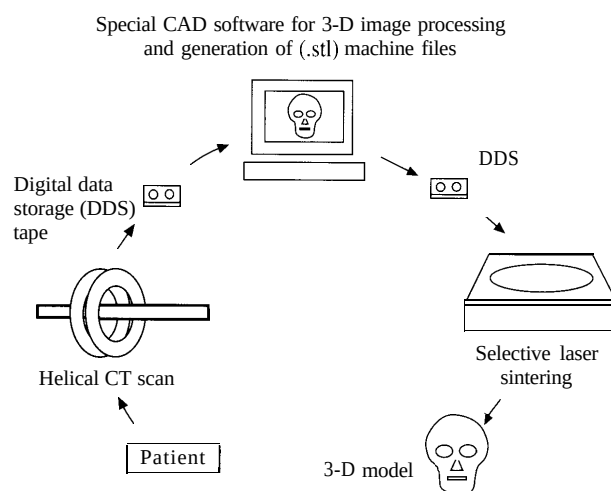


Fig. 1. The process of making a selective laser sinter skull model.

Case Study

The benefits of having a 3-D biomodel of the skull is demonstrated in the following case study of a patient involved in a road traffic accident and sustaining craniofacial injuries requiring soft tissue repair, reduction of panfacial fractures and a skull plate.

The patient, a 23-year-old Chinese female, who was a front seat passenger in a road traffic accident, suffered head injuries and panfacial fractures. She received emergency treatment of her head injuries, requiring a frontal craniotomy. Her facial fractures were not treated at that time due to her serious condition. The obvious bony injuries were, fractures of the right (R) zygomatic arch, R malar complex, R lateral and inferior orbital rim, R orbital floor, R lateral and medial orbital walls, anterior

and postero-lateral walls of the R maxillary antrum, nasal bone and subluxation of the R mandibular condyle. After the initial soft tissue repair, reconstructive surgery of facial bone defects was delayed until 3 months post-injury. She also had a fronto-temporal skull defect as the craniotomy bone fragment had become infected and had to be removed (Fig. 2).

The objective of making the 3-D models in this case was to have a physical 3-D model to assess the complex facial injuries and to plan the surgical reconstruction. The delay in primary correction of the panfacial numbers meant that the deformity resulting from the malunion would be more difficult to correct as the displaced bony fragments would have to be repositioned in all 3 dimensions during reconstruction.

The deformity caused by the malunited bone fragments had resulted in the right half of her face being flat with the right orbito-zygomatic complex being displaced lower than the other side. A preoperative assessment of the biomodel revealed the sites where the surgeon would need to make the cuts, the angle of cuts, the amount or

length of bone to be osteotomised and the reconstructive procedure. This helped in the repositioning of the inferior orbital rim, the malar complex, the naso-ethmoidal complex, and especially in rotating and realigning the lateral nasal bone to which the medial canthal ligament was still attached. Relocation of the medial canthal ligament is crucial in correcting the level of the eyeball.

In a later stage of management, the craniofacial surgeon, together with the neurosurgeon needed to reconstruct the wide skull defect in the right temporal region. The 3-D biomodel was used to design and fashion an acrylic (methylmethacrylate) skull plate in order to assess the shape and contour over the defect (Fig. 3). A titanium mesh (Timesh™), to be used in the actual surgery, was then shaped and trimmed while referring to the acrylic template, till a snug fit was achieved over the defect area (Fig. 4). This obviously saved a lot of time and the titanium mesh could be utilised efficiently as the pre-packed single sheet could be designed and moulded to cover the large defect. The metal sheet was not very malleable and proved to be difficult to shape. It would



Fig. 2. The biomodel of the skull showing the malunited panfacial fracture and a large craniotomy defect in the right temporal region.

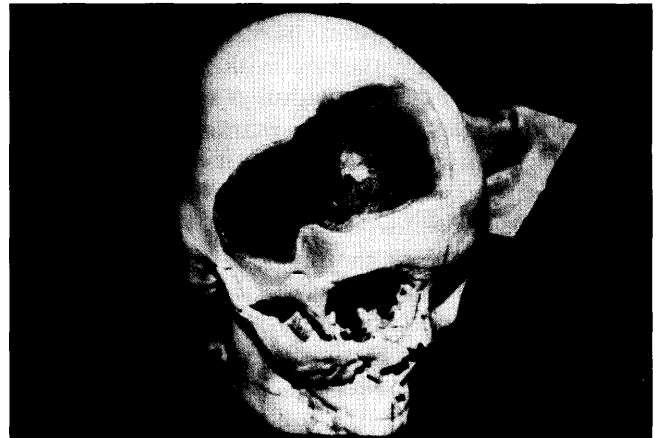


Fig. 3. An acrylic cranioplasty plate was designed and fabricated, using the biomodel as a template, to assure a close fit and a smooth and flush surface contour.

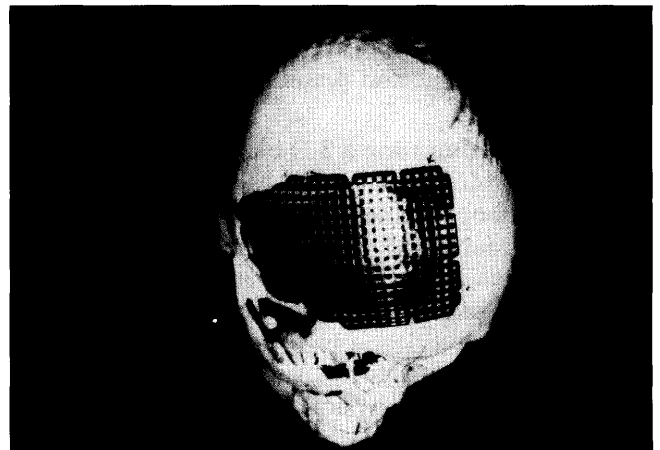


Fig. 4. A titanium mesh was used to cover the craniotomy defect, showing how the mesh was pre-designed and shaped to achieve a natural surface contour.

have been difficult to shape it properly intraoperatively to conform to the skull defect. Prefabrication on the skull model provides an ideal mesh, which needs only to be sterilised before being implanted.

Discussion

Radiological investigations have already been established as one of the most reliable methods and are commonly used in the management of craniomaxillofacial cases. The conventional 2-D sections from computed tomography could indicate underlying bony pathology and later, the 3-D CT imaging proved to be an even more useful improvement. The 3-D models were found to be accurate and reliable and contributed considerably in the diagnosis, management and planning of craniomaxillofacial surgery.

Further advances in technology in the last decade gave us 3-D physical models using either CT or MRI data sources. Early 3-D models were milled on 3 axis or 5 axis machines and later using rapid prototyping techniques which involved UV lasers and liquid resin to make stereolithographic models. This form of rapid prototyping gave us models which were far better than those previously milled by 5 axes machines, allowing the faithful reproduction of cavities and undercuts which were difficult to manufacture with the former technique.^{3,7} It was inevitable that other methods of rapid prototyping began to reach the market and soon there was a choice of at least 5 to 6 different methods of making the physical models. Selective laser sintering or SLS, using nylon composites powder which is solidified with a CO₂ laser, is one of the methods readily available locally; this method was employed for the case in this study as it produced a model which was much more durable than the SLA model and could withstand the rough handling and model dissection.

There are many CAD software programmes capable of reading the CT scan data and creating 3-D image files and the machines files which instruct the RP machines.⁵ Both the SLA and SLS models have been assessed and found to produce accurate replicas^{8,9} and can be used as a reliable diagnostic and planning tool in craniofacial surgery.

The cost of fabricating a 3-D biomodel may far outweigh its usefulness in many cases, but with each passing year and improvement in technology, this cost may become affordable and the service may be available on a routine basis in the future. Its usefulness in understanding and planning very complicated craniofacial deformities or injuries is well established and many surgeons have been able to visualise and plan surgical procedures using the physical model as a template and a guide. Even though the same case may have been managed without the help of such biomodels, the amount of time saved in the operating theatre by using the

physical models is significant. It helps the surgeon to plan and execute the surgery on the models as a means of a “practice” run, which diminishes the operating time.

The advantages of using the biomodels are therefore, the accurate 3-D reconstruction of complex anatomical structures, high precision and accuracy of the replicas and, for the assessment and planning of surgery. It refines the accuracy of diagnostic information, facilitates preoperative planning and surgical technique and reduces operating time. More accurate planning, using this method, improves postoperative results, decreases risks and shortens treatment time.^{8,10,11} The disadvantages are the radiation exposure, the production time and the costs involved in fabricating a model. This technique is certainly not recommended for emergency situations or on a routine basis for the above reasons.

Many other centres have come to use the biomodels for various indications. Oral surgeons and maxillofacial surgeons have used such biomodels in conjunction with their cephalometry, in carrying out orthodontic and surgical treatment planning.¹² Others have employed the use of models of both skull and soft tissue in the treatment plan for cleft lip and palate infants.¹³ Radiology and especially CT scans play a very important role in the management of maxillofacial trauma^{14,15} and it is now becoming more frequent for surgeons to request for a physical biomodel.

Our experience has shown us that even though the surgeon's skill and acumen contribute the major part in the surgical corrections, the presence of a 3-D physical model speeds up his decision-making and execution of ideas and he can anticipate problems and design operative steps in the planning stage. It is a valuable adjunct to the various investigative tools available nowadays and with greater advances in technology, it may be readily available to surgeons as a routine procedure in the future.

Conclusion

Selective laser sintering, one of the many rapid prototyping methods available to the surgeons locally, has been used in making biomodels of the skull as illustrated in this case report. The 3-D model proved to be a very accurate replica, which served the surgeon as a planning and assessment guide and greatly facilitated the surgical management of the case. The biomodel was also found useful for the neurosurgeon in the fabrication of a titanium cranioplasty for the skull defect. The biomodel can later serve as a physical model to be archived and studied in future. It will contribute to a library of rare craniofacial deformities.

Fabrication of biomodels is readily available today and its uses in the diagnosis and management of craniofacial disorders are many. There are many technical

institutes and private companies, which can provide the services to manufacture biomodels using different materials. When every effort is being made to improve the level and excellence of surgical management of craniofacial disorders, we should be aware of and be able to utilise locally available resources, which would help us attain this objective.

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