Phidias
RAPID PROTOTYPING IN MEDICINE

The Greek sculptor Phidias – fourth century BC – is known for the technical and artistic quality of his representation of the human being, full of dignity and nobility. His conserved masterpiece, the friese of the Parthenon, is still today a great symbol of European culture. The medical models resulting this project should contribute to make disabled, injured or ill persons resemblant again to the ideal human beings of Phidias.

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Preoperative stereolithographic model planning in craniomaxillofacial surgery

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Introduction

Stereolithography has become a well-known technique in the rapid prototyping sector. In preoperative model planning and surgery simulation, this technique has been used in the field of craniofacial surgery, tumour surgery, reconstructive surgery, orthognathic surgery, preprosthetic surgery and dental implants (Lambrecht, 1989; Kärcher, 1992; Millesi et al., 1994; Ono et al., 1994; Wolf et al., 1994; Bill et al., 1995; Kermer et al., 1998). The method was improved at our department in 1991 and 359 skull models have been produced since by LASERFORM MODELLBAU GMBH.

The technique of colour stereolithography was developed very recently. This technique allows the selective colouring of structures in the three dimensional (3D) solid model.
The 3D information of a solid model combined with the extra information from the selective colouring of certain anatomical structures both combine as an ultimate diagnostic and preoperative planning tool. This paper outlines the possibilities and the advantages in the clinical application of stereolithography.

Clinical application

Traumatology
3D model reconstruction was performed in several patients suffering from acute maxillofacial trauma. In late primary repair, when open reduction and internal fixation had to wait for a decrease in facial swelling or cerebral oedema, computer-aided surgery has proven to be useful in terms of facilitating anatomical reduction, minimizing surgical approaches, and saving operating time (Kermer et al., 1998). Due to surgery simulation it was possible to adjust prefabricated mini- or microplates in the patient as in the preoperative planning. The configuration and bending of the plates also acted as a device for the anatomical reduction of the fragments. However, in cases of comminution with very small fragments, surgery simulation with complete reduction on the 3D model is not advisable. In such cases the 3D model is only useful for planning the reduction of the buttresses. Exact reduction of small fragments is only possible in the patient itself by

Fig. 1. Coloured 3D model demonstrating an osteosarcoma of the ethmoid bone.

maintenance of the occlusion, but not in the 3D model.

Tumour surgery
Preoperative model planning by colour stereolithography is useful in ablative surgery of the maxilla and the ethmoid bone (Fig. 1).
The colouring of the tumour clarifies its relation to surrounding structures such as the paranasal sinuses, the orbit, the infratemporal fossa and

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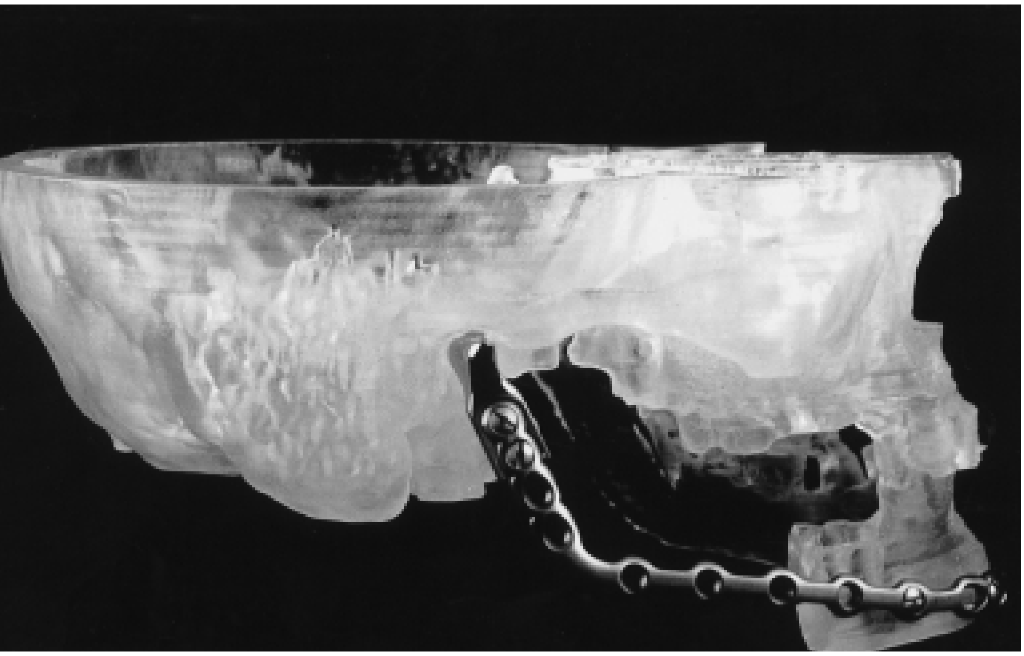

Fig. 2. Surgery simulation: resection of the right mandible including the condyle and positioning of a reconstruction plate. The length and shape of the bone graft can be estimated.

the cranial base, and illustrates eventual extension in the adjacent tissue. The main advantages of this technique are visualisation of the problem, planning of the surgical approach and determination of extent of the resection in areas of complex anatomy.

Reconstructive surgery

Surgery simulation is helpful in primary reconstruction of maxillofacial defects caused by ablative surgery to determine the donor area, such as, the scapular bone, the fibula or the iliac crest. Positioning of the graft can be studied, thus reconstructing different bony structures as the mandible, the orbital floor, the zygoma or the hard palate. In model surgery the length and shape of the graft can be estimated, and plates can be prefabricated to hold the future bone graft (Fig. 2).

Trauma, cranial bone tumours and external decompression are the main reasons for cranial defects. The main indication for reconstruction of these defects are cosmetic reasons and protection of intracranial structures. At the clinic in Vienna large cranial defects are covered by carbonic implants prefabricated on the 3D model. These precise fitting implants facilitate surgery thus saving operating time.

Craniofacial surgery

Craniosynostoses is the term that designates premature fusion of one or more sutures in either the cranial vault or cranial base (Fig. 3). The disparity between intracranial volume and brain volume may increase intracranial pressure. The goals of surgery of the newborn with a craniosynostosis are twofold: 1. Decompression of the intracranial space (to reduce intracranial pressure, to prevent visual problems, and to permit normal mental development) and 2. Achievement of satisfactory craniofacial form. The different methods of osteotomy for cranial vault remodeling can be simulated on the 3D model. The introduction of stereolithography for cranioplasty of newborns and infants has reduced operating time significantly.

Discussion

Stereolithographic skull models have proven to be very useful for preoperative model planning and surgery simulation. The compact structure allows cutting with a saw, drilling with burrs and the fixation of screws. A further advantage is the reproduction of closed cavities, and the transparent structure makes the course of intraosseous canals visible, as well as intraosseous tumour expansion.

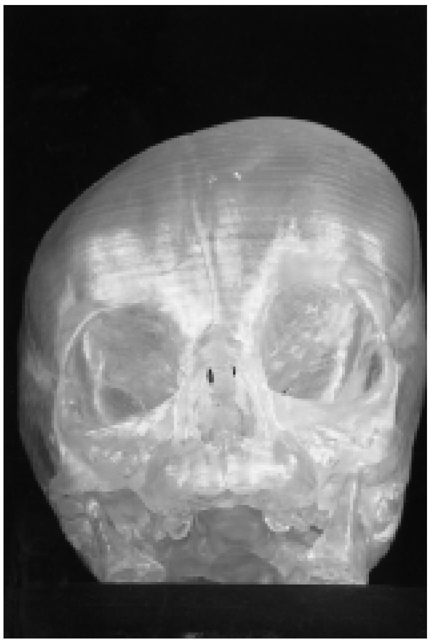

Fig. 3. 3D model of an infant with craniosynostosis.

The processing time (from CT to the complete model around 36 hours) was no disadvantage in our patients. However, stereolithographic skull models are expensive and thus are not indicated or necessary in every patient.

To summarize, in our hands the indicators for preoperative model planning and computer aided surgery turned out to be:

1. *late primary repair of complex craniomaxillofacial fractures*
2. *complex ablative surgery of the maxilla, the paranasal sinuses and the cranial base*
3. *maxillary reconstruction*
4. *primary mandibular reconstruction when tumour expansion has led to an extensive osteodestruction*
5. *secondary mandibular reconstruction in case of displaced resection stumps*
6. *cranioplasty*

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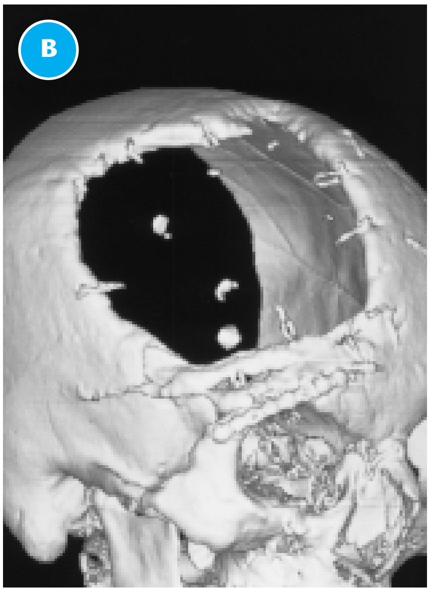
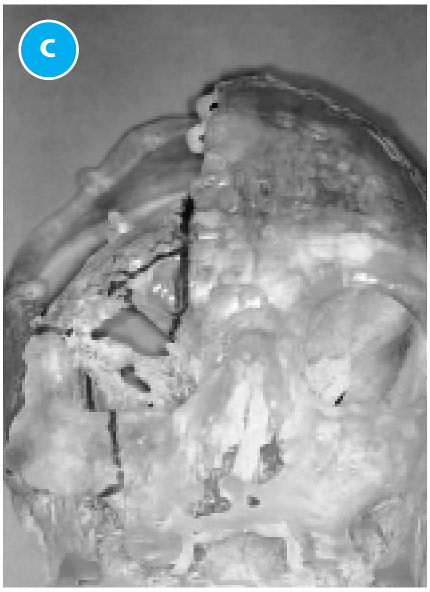
Indications to the use of solid models for planning of craniomaxillofacial surgery

3D reconstruction and visualisation of CT data were introduced in clinical use in the 80's. These methods provided great advantages over traditional radiological techniques and planar CT in the diagnosis and surgical planning in cranio-maxillo-facial malformations and are surely now routine techniques in most centers (Marsh e Vannier, 1983; Altobelli et al., 1993). The possibilities of visualisation of anatomical structures have further evolved in the following years thanks to the joining of medical 3D to rapid prototyping techniques, that now allow the production of solid copies of the patient's bones and soft tissues (Brix e Lambrecht, 1987; Bianchi e Ramieri, 1996).





Up to now these techniques have been extensively used in cranio-maxillo-facial as well as in dental surgery, for a wide range of investigations, like in craniofacial malformations, posttraumatic deformities, tumour reconstruction, orthognatic surgery, implant surgery. However, these technologies are expensive and time consuming. Their use must be therefore critically evaluated with regard to accuracy, informative value, cost and benefits in terms of improved diagnosis and better surgery.

At the University Hospital in Turin (Italy), 3D technologies have been used since 1993. Raw data are obtained from contiguous 1mm thick axial CT scans on a Siemens Somatom HiQS (Siemens, Erlangen, Germany) scanner, Gantry tilt = 0°. Anatomical structures are identified by means of gray level thresholding and are then elaborated for 3D visualisation by use of commercial softwares (Materialise N.V., Leuven, Belgium). Solid models are constructed either by use of stereolytography (3D System Corp., Valencia, CA, USA; EOS GmbH, München, D; Materialise NV, B); or SLS (Selective Laser Sintering, DTM Inc, Austin Tx, USA).

Case 1:
Post-traumatic cranial defect with orbital dystopia requiring cranioplasty and orbital osteotomies.
In (A) clinical presentation, in (B) visual 3D reconstruction of the skull, in (C) stereolithographic model with osteotomies simulation, reproducing the cranial bone defect to be grafted.

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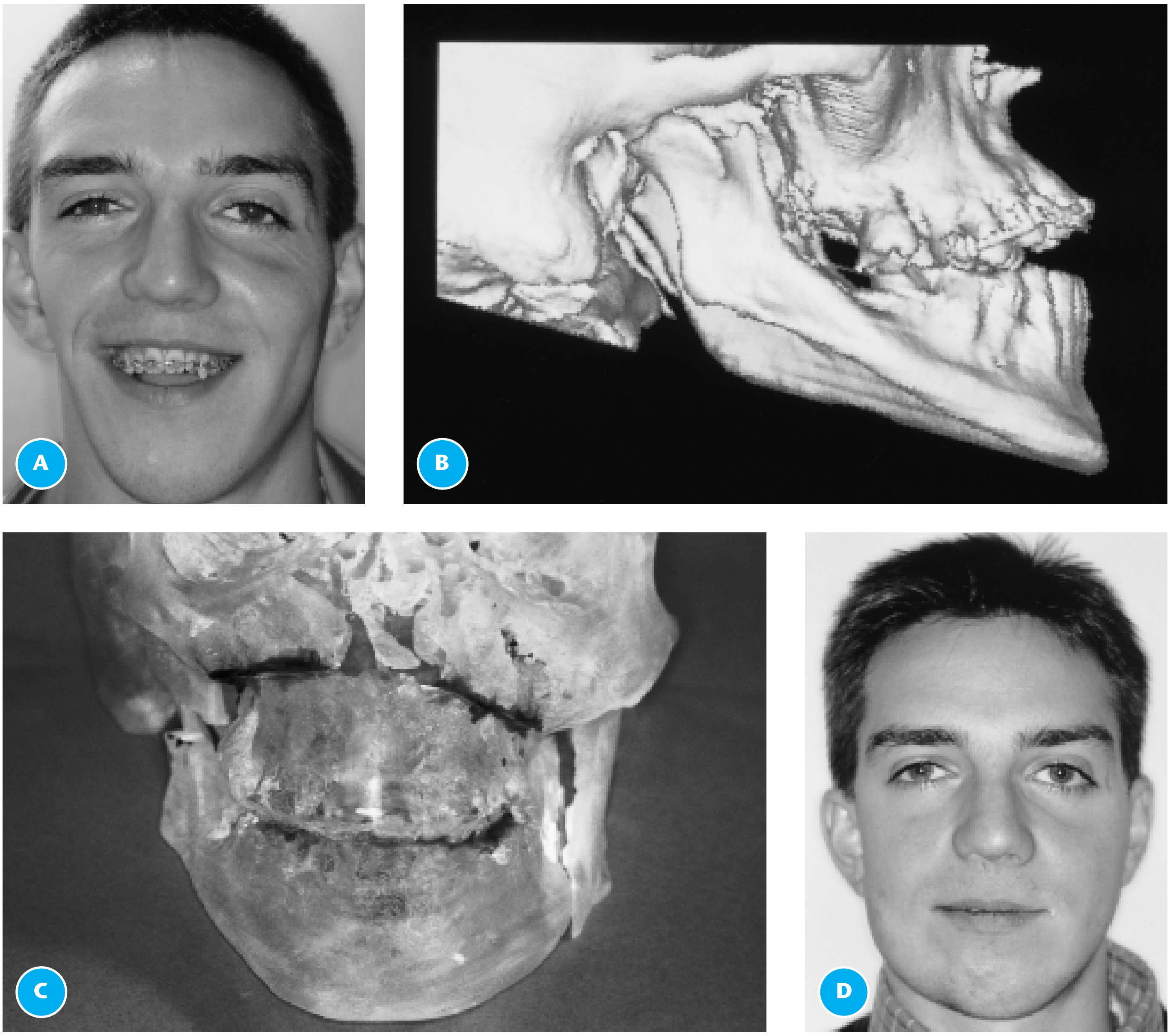
Cases have been classified with regard to the pathology and surgical intervention. The quality and fidelity of anatomical reproduction, the presence of artefacts, as well as the informative value for diagnosis and surgical planning have been assessed on the basis of the subjective surgeons' experience.

On the basis of our clinical practice, both 3D visual reconstructions and RP models usually result accurate with regard to anatomic detail reproductions at least in the limits required for surgical applications. The defect that is commonly observed in maxillofacial applications is a poor reproduction of dental elements.



Case 2: Congenital facial asymmetry. In (A) clinical aspects, in (B) lateral view of the facial bones, in (C) osteotomies planning and simulation on a stereolithographic model, in (D) postoperative result.

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3D models may also present over- or under-contours in the reproduction of maxillofacial bones. In general the dimensional errors are within acceptable values; however, major artefacts may be observed in the presence of hyperdense structures (i.e. dental fillings and osteosynthetic devices) or decalcified bones (atrophic jaws). Dental filling materials are the major source of artefacts, while titanium plates and screws do not usually affect the data. However, when investigating operated complex trauma cases, the presence of multiple plates, screws and wires may generate some problem as well. False bony defects may be generated on the contrary in the study of the very thin bones typical of the orbito-ethmoidal region or of the decalcified edentulous jaws in old patients.

Concerning the informative value of these techniques, our experience suggests to separate visual 3D from RP models, and the diagnostic use from surgical planning. We believe that a diagnostic improvement over planar techniques has been offered by visual 3D-CT in unusual malformations (Lambrecht e Brix, 1990), especially in asymmetric patients, and in complex post-traumatic corrections, mainly in those involving the orbital region, while a limited advantage is obtained in the study of acute trauma cases, which then do not justify normally the increased cost and time required for these exams. Similarly, no substantial diagnostic benefit is obtained with regard to benign jaw pathologies or tumors. Our opinion concerning 3D models is rather different: they probably do not offer the clinician relevant diagnostics contribute, but they may be very useful in the surgical planning of virtually any maxillofacial operation.

In fact, RP models allow the direct simulation of osteotomies and grafts, the measurement of bone movements, the preoperative construction of templates and surgical prostheses. This, in our experience, strongly contributes to reduce intraoperative time, increase accuracy and minimize complications and surgeon's stress (Bill et al., 1995).

Thus, considering their cost, we see indications in secondary corrections of craniofacial trauma, tumour reconstruction, malformations and also in some preprosthetic-implant procedures. Finally, our clinical practice suggests a high informative value of 3D techniques for teaching, patient information and documentation of unusual cases.

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PATHOLOGY	DIAGNOSTIC UTILITY		SURGICAL PLANNING UTILITY		ARTIFACTS	
	3D	RP	3D	RP	3D	RP
Acute trauma	-	-	+	-	-	-
Trauma (late corrections)	+++	++	+++	++++	+++	+++
Reconstructive surgery	+	+	++	+++	-	-
Malformations	+++	++	++++	++++	-	-
Preprosthetic-implant surgery	-	+	++	++	+++	+++
Benign lesions	+	-	+	-	-	-

Subjective surgeon's evaluation of the utility of visual 3D and RP models in either diagnosis or surgical planning, and presence of artifacts. (- absent, + occasional, ++ limited, +++ high, ++++ very high)

Use of a template for custom cranioplasty

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There are several techniques available for custom cranioplasty to cover a defect in the skull. The use of a pre-formed polymethylmethacrylate (PMMA) implant with a stereolithography model has been described in a previous *Phidias Newsletter* [1]. Titanium sheet is used for cranioplasty in a number of centres in the UK, because it is considered to be stronger and more durable than PMMA. The titanium implant is manufactured by moulding a custom shape to fill the hole in a model, and then using a hydraulic press to shape the titanium over the mould cast in dental stone [2]. Mirror imaging techniques can also be used to design a mould from the contra-lateral side of the skull [3] [4]. An example of a large titanium plate designed using a stereolithography model is shown in figure 1.

For cases such as tumours involving bone where the skull is resected during the operation, use of a model can allow the surgeon to define the limits of the cut before the operation. An implant can be designed for the required shape to fill the hole on the model, but there is still a need to transfer the cutting plane to the patient. In a recent case in Edinburgh of meningioma involving bone, a stereolithography model was manufactured from an STL file designed from spiral CT images (3 mm slice thickness reconstructed at 1 mm intervals) using a custom sub-pixel contouring algorithm followed by triangulation using Nuages software [5]. The surgeon outlined what he considered to be the limit of the tumour on the model, and the model was then cut along the specified line (figure 2). A wax shape was created to fill the resulting hole in the model, and used to design the mould for the titanium implant.

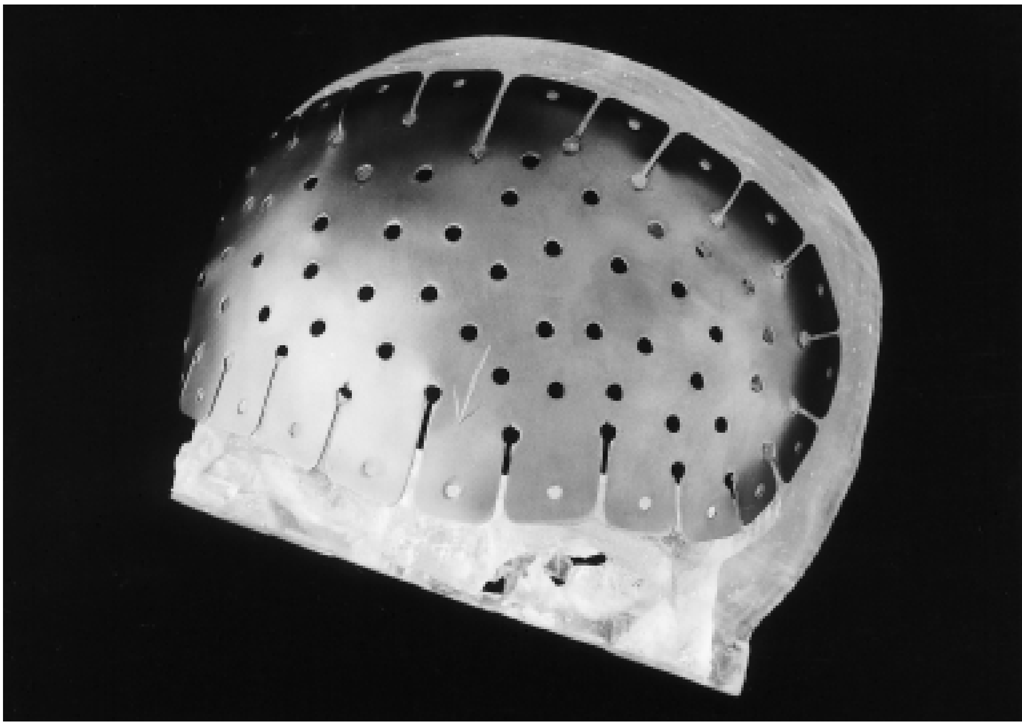

Figure 1

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A PMMA template was then shaped on the model along the edge of the specified cutting plane, and this was subsequently used to transfer the cutting plane from the model to the patient (figure 3).

Figure 2

The surgeon found that the template could be positioned to fit the skull of the patient and, by resecting the bone to the limit defined by the template, he was then able to fit the custom titanium implant to cover the hole. An additional advantage of the titanium sheet method over the pre-formed PMMA design in this case is that the implant does not need to be the exact size of the hole, since a small degree of overlap and the lugs to fix the implant to the skull allow some tolerance in cutting the hole.

It is worth noting that the transparency of the stereolithography model aided definition of the limit of bone thickening in this case, but the limit of the tumour in bone is still a matter of clinical judgement. If the tumour can be defined more accurately by MRI, it is technically feasible to combine tumour segmentation from MRI with bone from CT in a colour stereolithography model to increase the confidence of defining a cutting plane before the operation. However the most important factor in determining the use of rapid prototyping in routine custom cranioplasty is the development of procedures and technologies to reduce the cost of manufacture.

Figure 3

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NEXT ISSUES THEME?

Because of the strong potential of RPT-based templates we have decided to focus on this topic in the December issue of the Phidias Newsletter.

DEADLINE for contributions is WEEK NO 38

The aim of the **Phidias Newsletter** is to inform the vast majority of medical practitioners throughout Europe on the significant influence of Rapid Prototyping on the effectiveness of medical practice. This target will be reached via descriptions of selected cases where Rapid Prototyping has been taken into use.

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