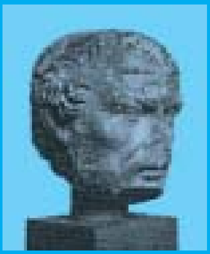
Phidias
RAPID PROTOTYPING IN MEDICINE



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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Anatomical Accuracy in Medical 3D Modeling

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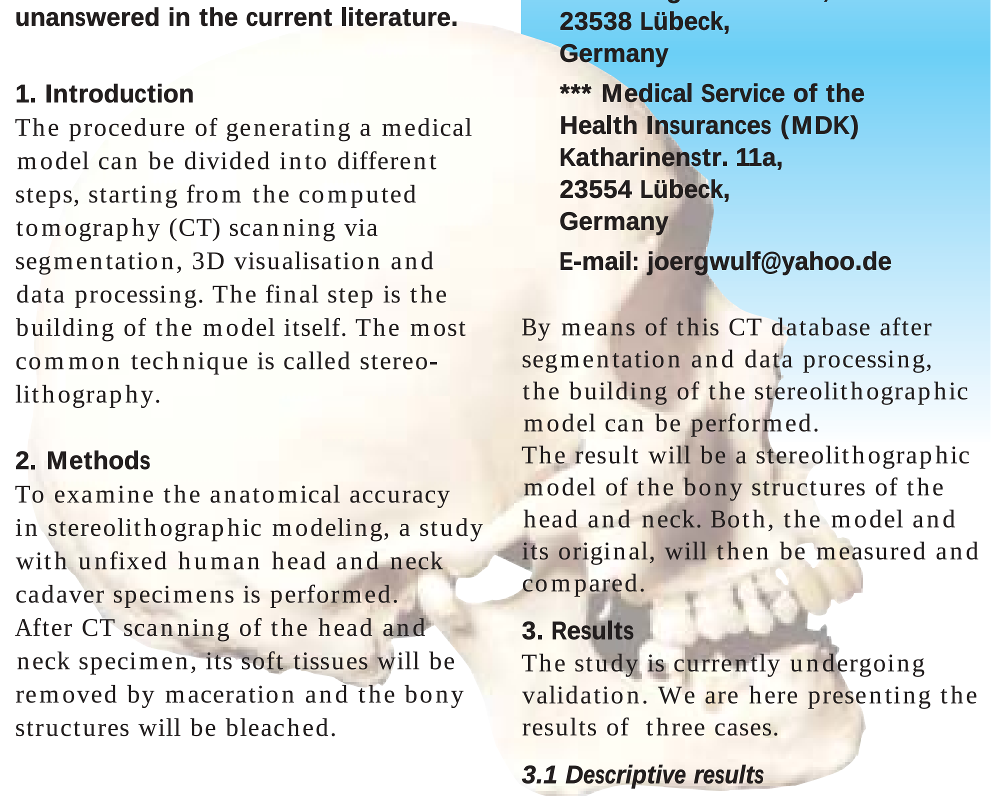
In complex surgery, medical modeling has become an accepted tool for diagnosis, simulation and the planning of surgical interventions [1]. However, the question concerning the accuracy of the model, i.e. the equivalence between the model itself on the one hand and the original anatomical situation on the other hand, remains unanswered in the current literature.



1. Introduction

The procedure of generating a medical model can be divided into different steps, starting from the computed tomography (CT) scanning via segmentation, 3D visualisation and data processing. The final step is the building of the model itself. The most common technique is called stereolithography.

2. Methods

To examine the anatomical accuracy in stereolithographic modeling, a study with unfixed human head and neck cadaver specimens is performed. After CT scanning of the head and neck specimen, its soft tissues will be removed by maceration and the bony structures will be bleached.

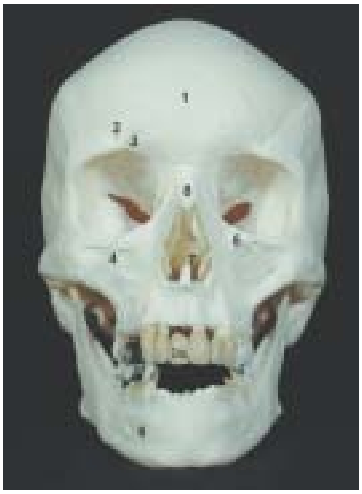
By means of this CT database after segmentation and data processing, the building of the stereolithographic model can be performed.
The result will be a stereolithographic model of the bony structures of the head and neck. Both, the model and its original, will then be measured and compared.

3. Results

The study is currently undergoing validation. We are here presenting the results of three cases.

3.1 Descriptive results

1 Os frontale
2 Foramen supraorbitale
3 Incisura frontalis
4 Foramen infraorbitale
5 Margo infraorbitalis
6 Foramen mentale
7 Septum nasi
8 Os nasale
9a Prosthetic reconstruction
9b Artifacts caused by prosthetic reconstruction



Bony skull, frontal view

Model of skull, frontal view

Continued on page 2 ▶

Continued from the front page

3.2 Morphometric results

Base of bony skull

Model, base of skull

1	Fossa incisiva
2	Processus palatinus maxillae
3	Spina nasalis posterior
4	Arcus zygomaticus
5	Foramen ovale
6	Foramen lacerum
7	Canalis caroticus
8	Foramen stylomastoideum
9	Crista occipitalis externa
10	Processus styloideus

4. Conclusion

The aim of this study is to provide and to evaluate a database on the anatomical accuracy of stereolithographic modeling, taking into account the overall procedure from CT scanning and segmantation to model building.

In addition to morphometric techniques used in physical anthropology, electronic measurement methods will be applied in our further investigation.

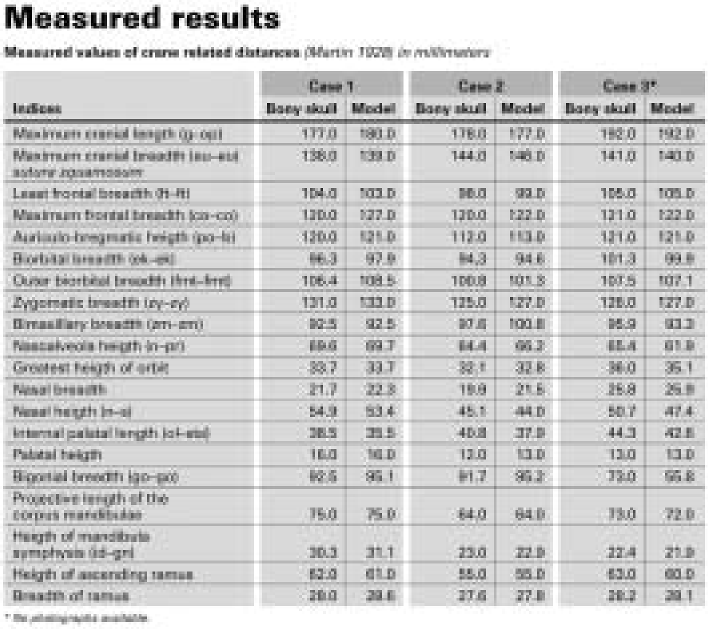
5. Acknowledgements

Model building:
Materialise N.V.,
Technologielaan 15,
3001 Leuven, Belgium

Morphometric measurement in co-operation with:
Anthropologische
Staatssammlung München
(Anthropological State Collection)/
University of Munich (LMU),
Karolinenplatz 2a,
80333 München, Germany

Reference

[1] Ericksson DM, et al., An opinion survey of reported benefits from the use of stereolithographic models. J Oral Maxillofac Surg 1999 Sept; 57(9):1040-3

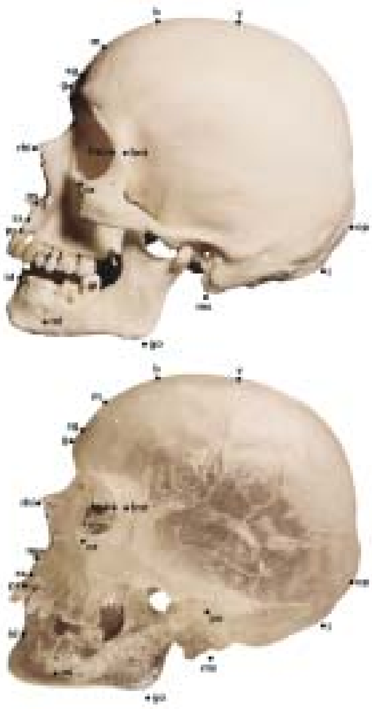


Measured results

Measured values of crane related distances *(Martin 1928) in millimeters*

	Case 1		Case 2		Case 3*	
Indices	**Bony skull**	**Model**	**Bony skull**	**Model**	**Bony skull**	**Model**
Maximum cranial length (g-op)	177.0	180.0	178.0	177.0	192.0	192.0
Maximum cranial breadth (eu-eu) sutura squamosum	138.0	139.0	144.0	146.0	141.0	140.0
Least frontal breadth (ft-ft)	104.0	103.0	98.0	99.0	105.0	105.0
Maximum frontal breadth (co-co)	120.0	127.0	120.0	122.0	121.0	122.0
Auriculo-bregmatic heigth (po-b)	120.0	121.0	112.0	113.0	121.0	121.0
Biorbital breadth (ek-ek)	96.3	97.9	94.3	94.6	101.3	99.8
Outer biorbital breadth (fmt-fmt)	106.4	108.5	100.8	101.3	107.5	107.1
Zygomatic breadth (zy-zy)	131.0	133.0	125.0	127.0	128.0	127.0
Bimaxillary breadth (zm-zm)	92.5	92.5	97.6	100.8	95.9	93.3
Nasoalveola heigth (n-pr)	69.6	69.7	64.4	66.2	65.4	61.8
Greatest heigth of orbit	33.7	33.7	32.1	32.8	36.0	35.1
Nasal breadth	21.7	22.3	19.9	21.5	25.8	25.8
Nasal heigth (n-ns)	54.3	53.4	45.1	44.0	50.7	47.4
Internal palatal length (ol-sta)	38.5	35.5	40.8	37.9	44.3	42.8
Palatal heigth	16.0	16.0	13.0	13.0	13.0	13.0
Bigonial breadth (go-go)	92.6	95.1	91.7	95.2	73.0	65.8
Projective length of the corpus mandibulae	75.0	75.0	64.0	64.0	73.0	72.0
Heigth of mandibula symphysis (id-gn)	30.3	31.1	23.0	22.9	22.4	21.9
Heigth of ascending ramus	62.0	61.0	55.0	55.0	63.0	60.0
Breadth of ramus	28.0	28.6	27.6	27.8	28.2	28.1

* No photographs available



Selection of landmarks used in craniometry

v	Vertex	**id**	Infradentale	**fmt**	Frontomalare temporale
b	Bregma	**pr**	Prostion	**fmo**	Frontomalare orbitale
m	Methopion	**ss**	Subspinale	**po**	Porion
sg	Supraglabellare	**ns**	Nasospinale	**fmo**	Frontomalare orbitale
g	Glabella	**ms**	Mastoideale		
rhi	Rhinion	**i**	Inion		
go	Gonion	**op**	Opisthocranion		
ml	Mentale	**or**	Orbita		

The use of Rapid Prototyping in Vascular Flow Phantoms

A PRELIMINARY REPORT

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There is a need for anthropomorphic flow phantoms to allow in vitro investigation of flow in arteries. Models of human vasculature have previously been constructed using casts of post-mortem arteries [1] or using mathematical approximations [2]. Models of aortic aneurysms have been built from CT images using rapid prototyping techniques [3], but the size of the model is much greater. In this project, angiography images from CT and MR images are being used to construct realistic models of carotid and femoral arteries from which flow phantoms are generated using a lost core technique.

Input data

Since the anatomical areas of interest are branches such as the carotid or femoral bifurcations, it is desirable that high quality angiography images without artifacts are used for the models. MR angiography without contrast suffers from artifacts and, although models can be generated from the images, it requires expert knowledge to edit out flow voids. MR angiography with contrast allows more accurate delineation of the vessel contours but still suffers from artifacts, particularly when there is a tight stenosis. Multi-slice CT angiography is potentially the most accurate although bright areas associated with calcification may need to be edited. Because no multi-slice CT scanner is available in Edinburgh, some multi-slice CT images used in this project have been supplied from a Phidias network partner in Erlangen (courtesy of Prof. W. Kalender, Institute of Medical Physics).

Continued on page 4 ▶

From the project manager's desk

*Phidias
Network
Administration
Wim Versluys*

The Phidias project is coming to an end and we have accomplished a lot already, ranging from this newsletter to a lot of local workshops. I would like to ask everybody who still wants to organize something to do this on time, as the end of March is the deadline for all network activities.

These last six months we've seen the final phases of the project started, we have already seen the results of the validation study based on the questionnaires that have been send and it shows clear indications of the advantages of the use of medical modeling done by Rapid Prototyping techniques. I would like to stress though that the study has not finished yet, so please keep on filling in those questionnaires and send them to MDK, at the latest by the beginning of March.

The accuracy study is also in its final stages and already shows some interesting results. Gustav, the phantom on which this study is based, is travelling all over Europe to be scanned in with different types of scanners. Gustav has already been build with several Rapid Prototyping techniques, which were shown at CAS2001 in Nuremberg. The results of this study will feature in the last Phidias newsletter.

In my last paragraph, I would like to thank Niels Moos from DTI, Danish Technology Institute, for his work on all the published newsletters. He is retiring in January and I wish him all the best. I still hope to see him at the final Phidias workshop, which will be held in Leuven, Belgium, on March the 23rd.

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The use of Rapid Prototyping in Vascular Flow Phantoms

A PRELIMINARY REPORT

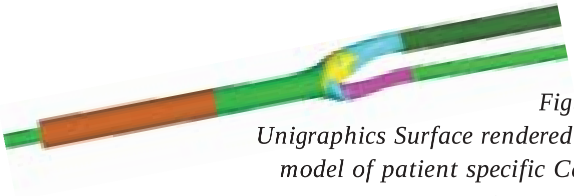

Figure 1: Unigraphics Surface rendered CAD model of patient specific Carotid artery geometry

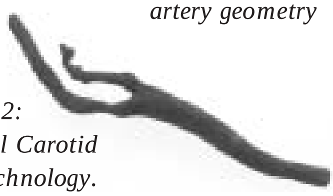

Figure 2: Fused Deposition Model of Diseased Patient Specific Carotid Artery showing Stenosed Internal Carotid Artery branch. Stair Stepping is evident in the model due to the poor z-axis resolution of the technology.

Software

Segmentation of the images has been made using either custom software or the Materialise Mimics software. It is important to generate smooth surface data from the images. One method that has been attempted is to filter and interpolate the original image data before generating an STL file using the Marching Cubes algorithm. However smoother models can be generated by fitting Nurbs surfaces to the data. Mimics has an option in MedCAD to fit Nurbs surfaces, but branches caused problems for this software. To overcome this, a series of polynomial Nurbs curves are fitted to the segmentation data and are exported as iges curves (cross-platform data) to EDS Unigraphics modelling software, an industrial CAD/CAM platform.

The free form surface deformation option in Unigraphics allows interactive manipulation of surfaces, and using techniques such as partitioning the model into smaller sections, a smoothed Nurbs surface including the branch can be generated. The resulting surface can then be extended to suitable terminating connectors before manufacture of the model (see fig 1).

Manufacture

The size of the artery branches is at the limit of rapid prototyping technology. A significant factor in the production of the models is the resolution of the particular chosen technology in the x, y, and z axes. Fused Deposition Modelling (FDM) cannot reproduce the in vivo size of the arteries accurately even with the smallest step size (see fig 2) although the manufacture of a model scaled up by a factor of three has been recently reported [4].

Figure 3: (From Bottom) Manually hand polished Stereolithography model of arterial geometry shown in figure 1. Low Melting Point alloy cast of Stereolithography model for investment casting process. Flow Phantom in clear silicone (with alloy still present) for PIV measurements.

Stereolithography (SLA) was chosen because it was the most accurate technology available and due to the ease of removal of ‘stair-stepping’ (an effect of layered manufacturing) and the high surface quality that can be produced from manual polishing techniques. This is important to minimise turbulent flow along the walls of the flow phantoms.

Using techniques similar to those used for models of blood vessel anastomoses [5], an inverse model is manufactured from the stereolithography model to produce a mould. A low-melting-point alloy is then poured into the mould, and a reproduction of the model obtained in the alloy. This can then be used as the lost core for the next stage of the process, which we are currently investigating – the manufacture of the flow phantom in either ultrasound compatible tissue mimicking material or clear silicone for PIV flow measurement (fig 3).

Other models are planned to reproduce a range of stenoses in the carotid and femoral bifurcations from contrast MRA and multi-slice CTA images. ■

[1] Gailloud P., Muster M., Piotin M. et al "In vitro models of intracranial arteriovenous fistulas for the evaluation of new endovascular treatment materials" Am J. Neuroradiology 1999; 20:291-295

[2] Smith R.F., Rutt B.K, Holdsworth D.W. "Anthropomorphic carotid bifurcation phantom for MRI applications" JMRI 1999;10:533-544

[3] *http://www.comp.leeds.ac.uk/comir/research/wellcomeAAA/aaa.htm*

[4] Yedavalli R.F., Loth F. et al "Construction of a physical model of the human carotid artery based upon in vivo magnetic resonance images" ASME J. Biomech Eng. 2001;123: 372-376

[5] Chong C.K., Rowe C.S., Sivanesan S., Rattray A., Black R.A, Shortland A.P, How T.V "Computer aided design and fabrication of models for in vitro studies of vascular fluid dynamics" Proceedings Inst Mech Eng Part H- J. Eng Med 1999;213(H1):1-4

Acknowledgement.
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Analysis of data collected in the Phidias Validation Study

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Background

The aim of this multicentric European study is to determine data concerning the application of stereolithographic models, especially in craniomaxillofacial surgery.

Therefore a questionnaire based survey is performed assessing case-related variables taking into account diagnosis, indication and benefits of stereolithographic models with regard to different steps of surgical procedure: preoperative planning and intraoperative application and overall outcome after surgical intervention.

The validation study started in september 1999. Questionnaires were mailed to 38 partners of the Phidias-Network. The study is co-ordinated by Medical Service of the Health Insurances (MDK) Schleswig-Holstein, Germany. Partners were asked to distribute questionnaire among surgeons who apply stereolithographic models. Until october 2001 a number of 172 questionnaires could be transferred into the database of the study.

Results

Diagnosis that related to application of stereolithography (according to ICD-9)

Neoplasma.

- Mal. neoplasma of gum: N = 12
- Mal. neoplasma of floor and mouth: N = 8
- Mal. neoplasma of bone and articular cartilage N = 9
- Benign neoplasma of bone and articular cartilage N = 4

Congenital

- Congenital anomalies of head and neck N = 8
- Certain congenital muskuloskeletal deformities N = 17
- Other congenital muskuloskeletal deformities N = 9

Trauma

- Fractures of face bones N = 18
- Late effects of musculosceletal and connective tissue injuries N = 8

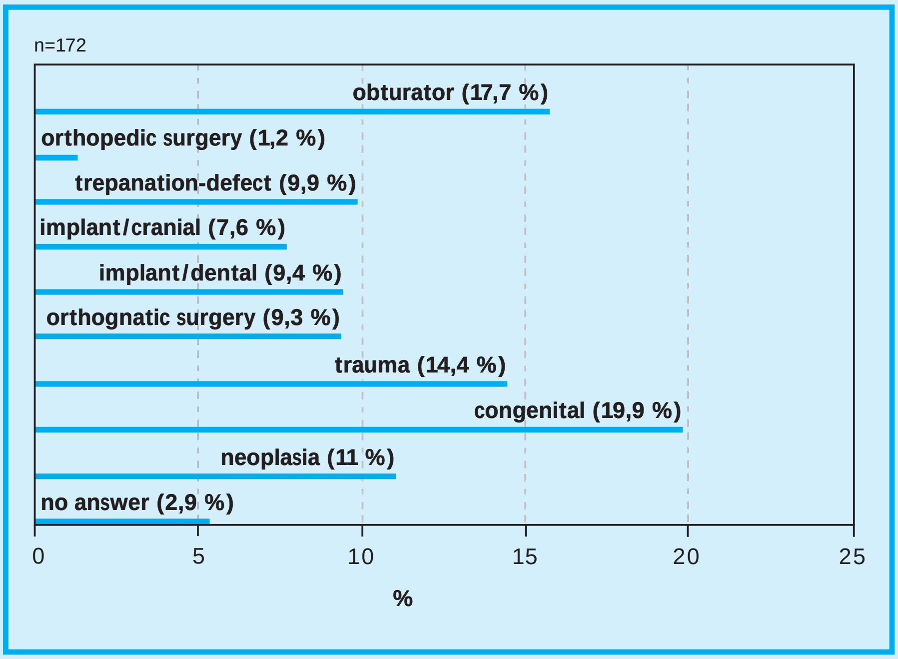
Dentofacial anomolies

- Dentofacial anomalies including malocclusion N = 30
- Other diseases of and conditions of teeth and supporting structures N = 18

Other diseases or unknown N = 31

The study population consists of 45 % female and 55 % male patients. The reported diagnosis that related to application of the model can be divided into 5 main groups:

1.) 19,2 % neoplasia
2.) 20,0 % congenital
3.) 15,0 % trauma
4.) 28,9 % dentofacial anomalies
5.) 16,9 % other diseases/unknown



Indication/clinical problem for the necessarity of a surgical planning model (figure 1)

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Distraction Osteogenesis and

– in a patient with a Goldenhar syndrome using STL techniques

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Introduction

Hemifacial microsomia is a syndrome in which an underdevelopment exists of one side of the face compared to the other side.

In some children, only an ear deformity is evident while in others, the ear is normal and only the jaw is affected. In more severe cases, all the structures of the first and second branchial arches can be involved.

The ear, skin and underlying facial tissues such as muscles, nerves and bony structures are deficient or underdeveloped.

When the eye and the spine are involved the term Goldenhar Syndrome is used (1).

Hemifacial microsomia is the second most frequent facial anomaly, after lip and palate clefts. Studies indicated that the incidence in birth is estimated between 1 in 3500 and 1 in 5642 live births.

A recent study was initiated in October 1995 in response to Gulf war veterans about a possible excess of Goldenhar Syndrome among their infants. The study showed a rate of 14.7 per 100,000 compared to a rate of 4.8 per 100,000 of Goldenhar cases. The statistical precision of these results however, proved to be rather low.

Case Report

An eight-year-old boy was presented at the department of Cranio and Maxillofacial Surgery of the University Hospital Maastricht. The child showed a severe underdevelopment of the left side of his face (figure 1).

The left zygomatic arch, the left ear and the left hemimandible were deficient.

A broad maxillary cleft with dental agenesis was observed (figure 2).

FIG. 1

FIG. 2

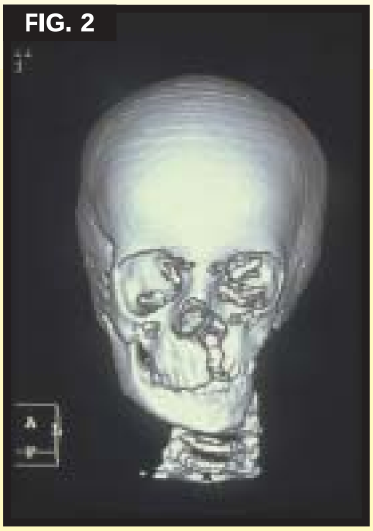


FIG. 3

FIG. 4

The child was known with a scoliosis and finally a tetralogy of Fallot.

Because of the variety of symptoms, the anomaly could be diagnosed as Goldenhar Syndrome.

Distraction Osteogenesis

The complexity of this case made it necessary to study the surgical options for the necessary corrections.

A stereolithographic (STL) medical model of the affected skull had been made.

The objective of the first intervention was the correction of the position of the left Orbito-Maxillary

Mandibular Reconstruction

FIG. 5

Complex (OMC) by distraction osteogenesis and thus the narrowing of the cleft.

Using the STL model, a precise planning of the osteotomy at a Lefort III level of the left Orbito-Maxillary Complex had been possible (figure 3).

The vector of the movement of this bony complex had been precised also by a rehearsal operation on the STL model.

A Riediger Midface Distractor, a device that allows distraction osteogenesis over a distance of maximal 20 mm, would be used. This Distractor had been especially developped for indications for midfacial advancements at a Lefort III level.

The intervention had been carried out according to the planning. The distraction vector was guided intra-orally by an orthodontic appliance.

The distance of distraction turned out to be 12,5 mm (figure 4). The postoperative result showed a more favourable position of the OMC. A dramatic narrowing of the cleft had been observed.

Mandibular Reconstruction

The next phase of the treatment existed out of the hemimandibular reconstruction. A new STL model had been build for study of the design for the reconstruction of this mandibular deficiency. The model could also been used for a wax up for missing of the left mandible (figure 5).

The final design showed Titanium tray made for carrying slurry of TCP Tri-calcium-phosphate granulates (Curasan) and bonechips mixed with PRP.

The intervention had been combined with removing of the Riediger Midface Distractor.

A short intervention was undertaken for the fixation of the custom-made Titanium hemimandible reconstruction with Titanium screws. The tray was filled up with TCP/ Bone mixture as planned.

Discussion

Complex cases such as patients with Goldenhar Syndroms are much better understood using a STL model. Both the preoperative planning and the vector-planning for the distraction osteogenesis have been made easier.

The mandibular reconstruction would never been possible without the making of a STL model (figure 6).

In both interventions, there had been a considerable reduction in operation time.

References

1. Complex Craniofacial Problems.
Churchill Livingstone ©
Edited by Craig Dufresne
Section 3: 15.
So and Dufresne 295-319

FIG. 6A

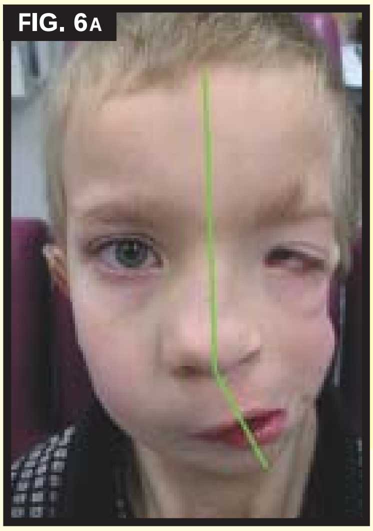
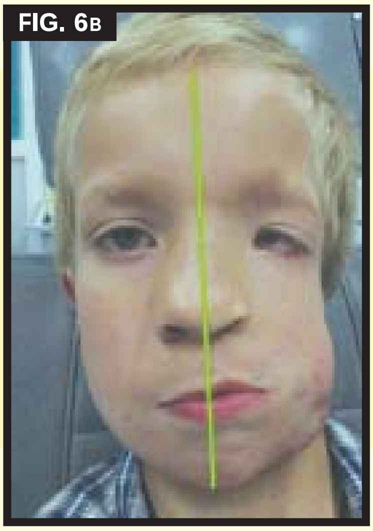


FIG. 6B



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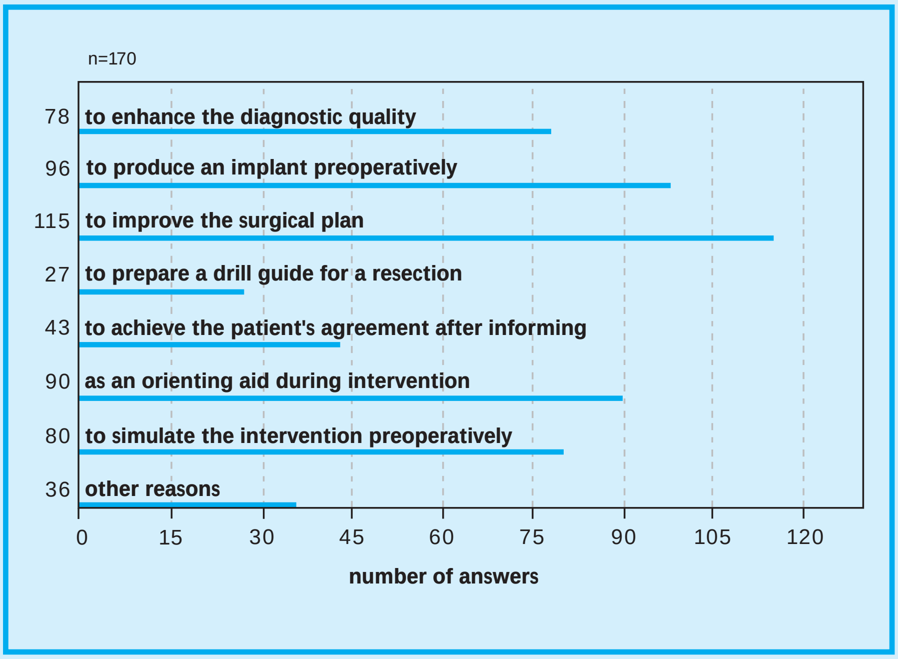
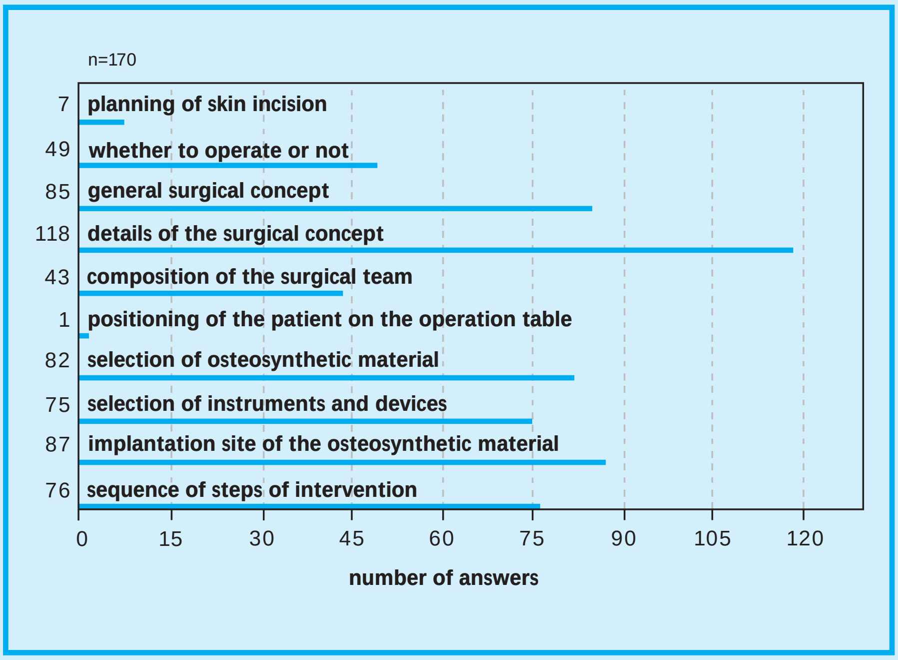
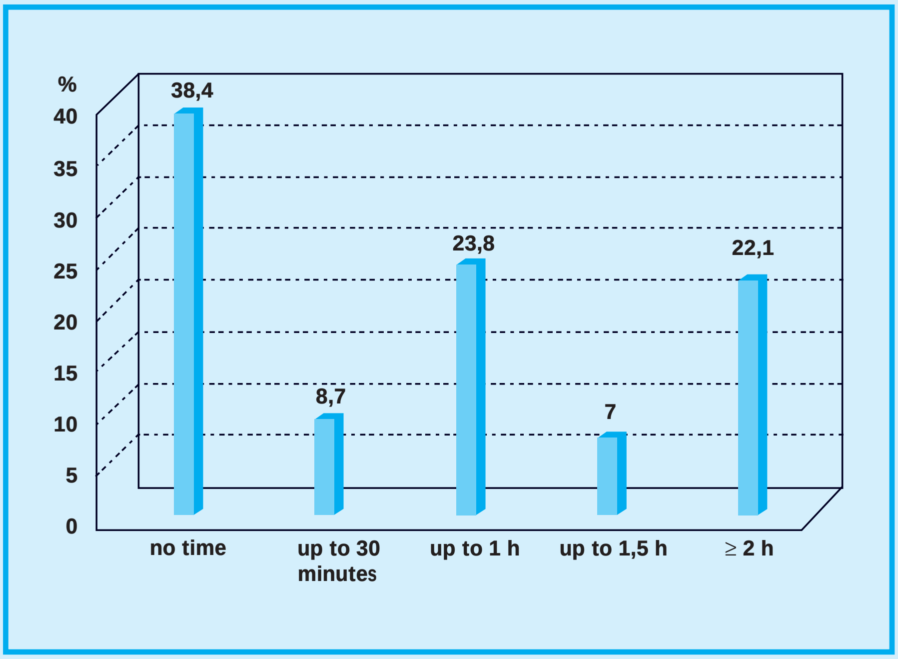
Analysis of data collected in the Phidias Validation Study



There were different reasons reported by the surgeons, why a medical model was applied (figure 2)



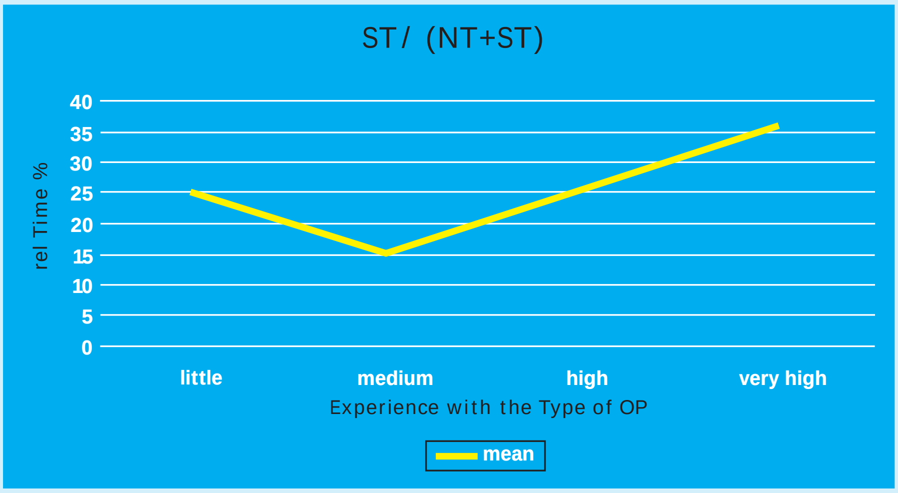
In the following topics the preoperative application lead to a change of decision (figure 3)



Saved operation-time (figure 4)

Due to the use of the model in 22,1 % of all cases surgeons reported a decrease of saved op-time that was 2 hours or more.

In addition, time was reduced up to 1.5 hours in 7 % and more than 25 % of the surgeons reported a reducement between 30 minutes and 1 hour.



Saved op-time - Surgeons´ experience (figure 5)

The time saving effect increased with surgeons´ experience, i.e. the number of similar operation in his career. This effect was less high if surgeon has an average experience in using planning models

Discussion

The validation of a prediction model of the outcome after surgical interventions, where medical models were applied, depends on the realationship and interactions of several predictable items that have to be investigated. Thus, it is needed to analyse clinical conditions to enable us to provide comprehensible and evidence-based information regarding strategies to optimize and to improve outcome of surgical procedures.

Flexible Tubular Replicas for Simulation of Endovascular Repair

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Introduction

Traditional open repair of abdominal aortic aneurysm (AAA) requires a large abdominal incision, post-operative intensive care and carries a mortality of 5-13 %. The need for the large incision and intensive care can be removed by using keyhole surgical techniques in which a graft is deployed into the lumen of the aneurysm from a small incision in the groin [1].

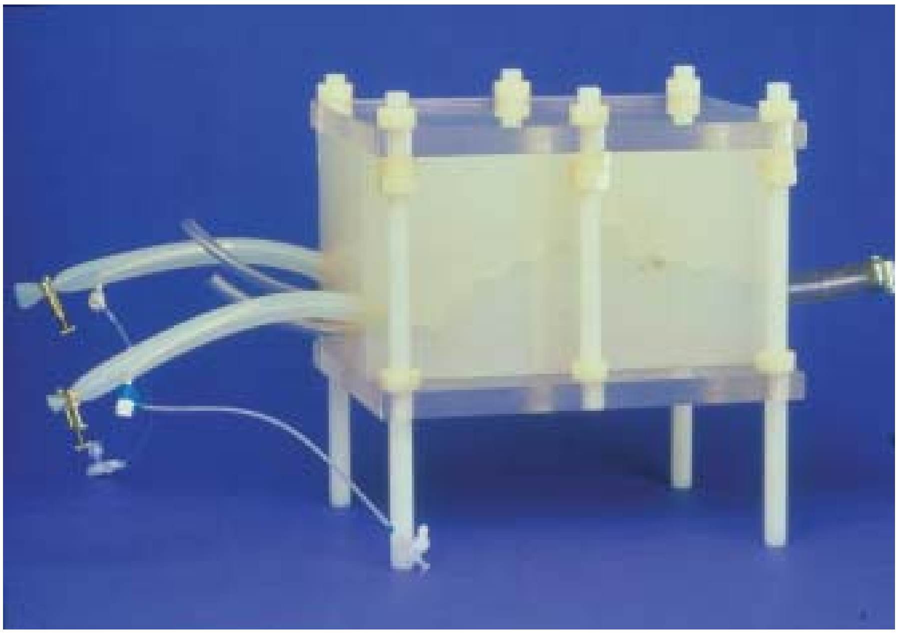
As with all surgical approaches, there is a learning curve to be climbed by a surgeon before he or she becomes proficient in the procedure. Training in endovascular surgery has been achieved in the past under guidance from someone skilled in the operation, or by practising on animal models. Neither is satisfactory. Firstly there are relatively few experienced surgeons, and secondly, the many disadvantages of animal models include their failure to replicate the variable anatomy of diseased human arteries, in particular tortuosity of the iliac arteries which determines the endovascular route to the aneurysm.

Published recommendations [3] have emphasised the need for formal training for surgeons before they are declared competent to perform the procedure.

We have developed a method of manufacturing an accurate, flexible life-size model of the AAA and the major aortic branches. A series of replicas has been produced that reflect the different patterns of aneurysmal disease, in particular angulation of the neck of the aneurysm and tortuosity of the iliac arteries. Each replica can be used as the focus of a bench-top training rig in order to duplicate the stages of deployment of an endovascular device. The replicas are radiolucent, to allow imaging using the standard x-ray method during stent deployment and can be reused.

Figure 1. Four examples of completed replicas; they represent a range of typical anatomical configurations

Figure 2. The style of flow rig used to perfuse a replica at arterial pressure and provide a realistic sensation when working with the vessel replicas



Data processing

Contrast enhanced spiral computed tomography (CT) data from ten individuals, chosen to represent a range of vascular geometry and tortuosity, were used. The lumen of the aorta, common iliac vessels and renal arteries were interactively segmented from the CT data using Analyze™ (AnalyzeDirect.com). The surface cloud of points thus generated was converted into a smoothed surface representation, suitable for rapid prototyping (STL), using the software package geomagic Wrap® (Raindrop Inc). These data represented the inner surface of the replica.

# of Abdominal Aortic Aneurysms

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Making the tubular replica

1. Create a hollow rapid prototyping model in low density polystyrene. The wall thickness should be approximately 1.5 mm; the outer surface of this model represents the luminal wall.
2. Seal the surface of the polystyrene model
3. Dip the polystyrene model in latex solution to create a layer of approximately 2 mm in thickness
4. Crush the polystyrene core to a powder and remove

Four of the completed replicas are shown in Figure 1.

The replicas in use

The model was connected into a flow rig (Figure 2) and then perfused at arterial pressure. It was possible to practice, under fluoroscopic control, all the stages of stent deployment, from insertion of the catheter through one of the iliac vessels (Figure 3) to checking the deployed stent for leaks (Figure 4).

Conclusion

Rapid prototyping has previously been used as an aid to stent graft planning, particularly in aortic aneurysms of complex morphology [2,4]. Solid replicas were used, because until recently it has not been possible to manufacture a model from flexible material directly by rapid prototyping.

In order to produce replicas for training, we have developed a cost-effective manufacturing method that combines the anatomical replication possible using rapid prototyping with the versatility of other manufacturing techniques.

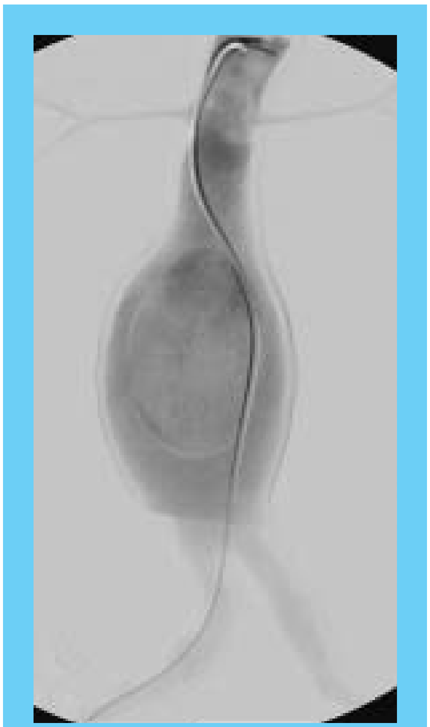

Figure 3. Angiographic image of one of the replicas, perfused with contrast agent, in the flow rig

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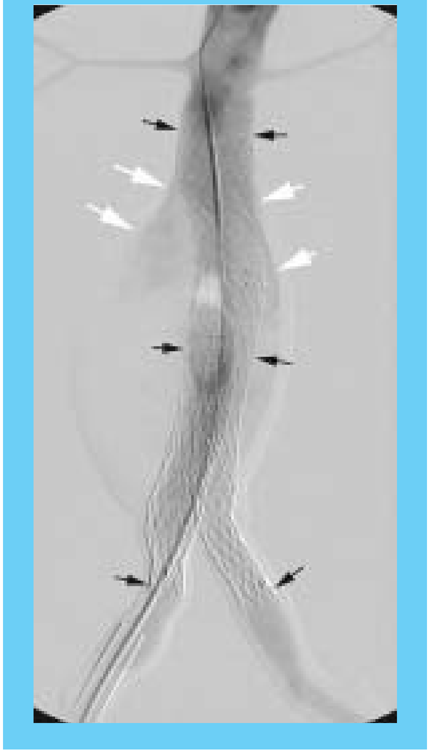

Figure 4. Angiographic image of a replica containing a deployed stent. The white arrows indicate areas where the contrast medium has leaked between the vessel wall and the stent, indicating that the seal is poor. This occurs if the diameter of the stent is too small.

BELFAST WORKSHOP

Medical Applications of Rapid Prototyping

Dr Elizabeth Berry, University of Leeds, Leeds, United Kingdom

A UK Phidias Workshop on Medical Applications of Rapid Prototyping took place in Belfast on 14 September 2001, as a satellite meeting alongside the European Congress of Medical Physics and Clinical Engineering.

The workshop, which was sponsored by the Phidias Network, was jointly organised by John Winder (Northern Ireland Medical Physics Agency) and Elizabeth Berry (University of Leeds). Fifty-five participants attended the event, including the companies Image Diagnostic Technology Ltd, Laser Prototypes Europe Ltd, Materialise NV and the Northern Ireland Technology Centre.

Models were brought for discussions and there was a poster presenting the latest results from the Phidias questionnaire-based survey. Following an introductory talk by Wim Versluys of Materialise, the morning was devoted to Craniofacial, Maxillofacial and Neurosurgical applications. Comprehensive overviews were provided by visiting speakers Dr Jan Karel Th. Haex (University Hospital, Maastricht) and Mr Ninian Peckitt (Doncaster Royal Infirmary and ComputerGen Implants), and Belfast surgeons Mr Peter Ramsay-Baggs and Mr Steve Cooke reported their experiences of using rapid prototyping.

In the afternoon, the emphasis shifted to novel applications. We learned about a phantom for assessing CT imaging in endovascular stent grafting from Dr Zhonghua Sun (University of Ulster), modelling of the nasal airways from Dr Neil Bailie (Queen's University of Belfast) and test objects and spinal drilling guides from Dr Elizabeth Berry (University of Leeds).

The programme was closed by a report on the state-of-the-art, and a look to the future, from John Winder (Northern Ireland Medical Physics Agency), who finished by encouraging delegates to sample a Guinness in Belfast before returning home.

Wim Versluys (Materialise) and Dr Jan Haex (University Hospital, Maastricht) prepare their presentations at the Belfast Workshop

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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.

The newsletter is published two times per year and is circulated to 3000 medical practitioners throughout Europe.

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