Acta of Bioengineering and Biomechanics
Vol. 6, No. 1, 2004

Stereolitography – the choice for medical modelling

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Rapid development of manufacturing technology allows producing complex, physical 3D models based on a very accurate medical data. The aim of Rapid Prototyping (RP) is to reproduce most exactly "3D reality" within a solid, physical model. This paper presents the meaning of medical modelling, the process of manufacturing with the selected RP method (stereolitography), advantages of medical modelling to doctors and patients. It also reviews briefly the most common Rapid Prototyping methods.

Key words: stereolitography, medical modelling, Rapid Prototyping methods

1. Introduction

The term *medical model* stands for a physical reproduction of tissues, models of prostheses, implants and the other auxiliary equipment useful for planning and performing surgical treatments, for training and improving medical attendance and rehabilitation [11]. Medical models are created with Rapid Prototyping (RP) techniques. In terms of technological application, Rapid Prototyping refers to fabrication of prototype model, based on a three-dimensional digital data prepared in a CAD software. The RP technology enables manufacturing realistic physical models in each scale and form using various materials and colours. Compared to the traditional labor techniques, creating new models with RP is much less time-consuming.

Medical modelling is more and more commonly used to facilitate the doctor's work. It is employed both in diagnostics and in the planning of complicated operations. It is also used for designing implants, bone transplants, external prosthetic appliances, specialized surgical instruments and dental patterns. This method also serves as a form of training. An actual model of an object under examination facilitates the diagnosis of the problem and simplifies the study of the shape, location and size of an anatomic structure. For better understanding of the problem, the models or their fragments can be coloured. In some cases, sterilized models are used as tools during operations or are applied as means of visualizing a planned procedure.

RP has been applied in such fields of medicine as traumatology, cranial and craniofacial surgery, maxillofacial surgery, prosthetics, orthodontics and orthopaedics. The examples of uses of that technology are the following: cranial and craniofacial reconstructions, the treatment of bone and joint deformities, pelvis damage, vertebral injuries, innate and degenerative vertebra diseases and limb malformations.

The process of medical data preparation is more complicated than CAD design of technological data. It starts with data acquisition, processing, 2D imaging, 3D reconstruction, STL (Standard Triangulation Language) file creation, and is finished with the physical model building. Each of these phases has exerted a significant impact on the final result and the possibility of its application. Requirements for medical models are also different [1]. They are specific, depending on particular application and customer's requirements. They are mostly used in a medical diagnostics and treatment, not in a series production, which utilizes industrial models. New medical model is created for each particular case.

2. The process of medical model fabrication

2.1. The method

The input data, as the CT images (DICOM files), after digital processing are interpreted as 3D STL model. Then, after selection of proper adjustment parameters of RP machine, it is reproduced as a set of contours (layers) and control instructions. The RP machine creates a solidified model, which after post-processing phase is ready for use. The next part of the paper presents particular phases of the model creation with RP based on stereolitography as an example.

2.2. Data acquisition

The determination of three-dimensional data-points of the diagnosed (scanned) object is the first phase. The data can be obtained from the diagnostic equipment like CT, MRI, USG etc. As far as bone structures are concerned, computer tomography (CT) (figure 1) is most often employed, while magnetic resonance (MRI) is used for soft tissues.

The images of tissues of human body are collected by means of: the (CT) computer spiral tomography (osseous tissues) and the (MRI) magnetic resonance (soft tissues). Images retrieved from other apparatuses can also be used, however they must be cross-sections of 3D objects. The body under examination is being scanned layer by layer. As in CT, the data from MRI consist of series of images as cross-sections of the tissues examined. The MRI method is based on magnetic properties of nuclei of hydrogen atoms (protons), which are main elements of such soft tissues as muscles, blood or brain tissues. This requires, like CT, reconstruction of cross-sections to ob-

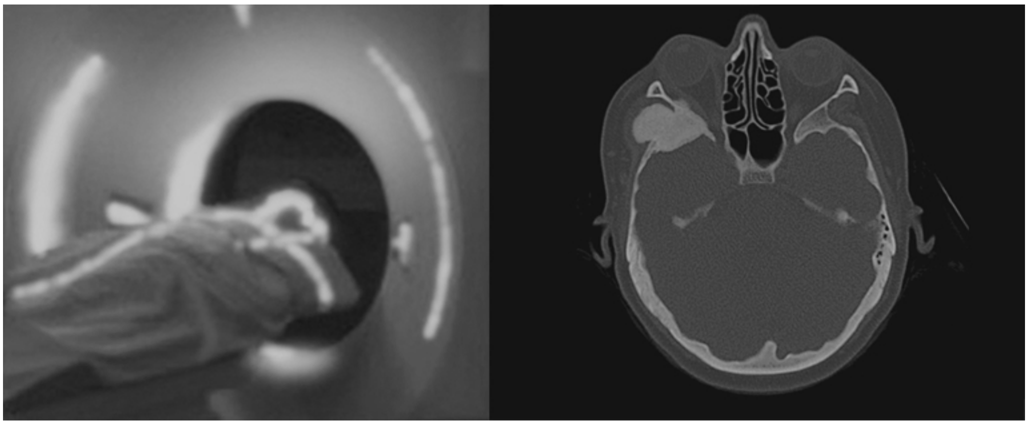

Fig. 1. Computer tomography (Materialise NV)

tain the 3D image of the object examined. Major issues in data acquisition are the so-called artifacts being distortion of an image occurring with the significant differences of density of the object examined (e.g. metallic parts). That problem was described more thoroughly in [3].

2.3. Data processing

The first phase of the data processing is preselection of all individual 2D images (cross-sections) and matching coordinates in order to make up the set of data files. Now, tissue parameters which are to be modelled must be isolated from all other entities. This phase is being conducted by a radiologist, who corrects the errors caused by artifacts. Then images are subjected to filtration and region of interest (ROI) classification based on Housfield scale or Grey Value scale and finally to segmentation. In the next phase, the 2D data are translated into 3D wireframe model in STL format. During this phase all useless elements are being removed from the model, these are: distortions, tissues not associated with an object of study, etc. This form of the data presentation makes the decision of necessary medical treatments, planning of activities, location of surgical implants, modelling of osseous grafts and their attachment easier. All these stages can be performed with Mimics program (Materialise NV) (figure 2). Virtual selection of appropriate support elements and location of the whole entity on the work platform are preceded by evaluation of correctness of the model surface. This job can be done with Magics (Materialise NV) or Lightyear (3D Systems) programs. Such a 3D project is ready to build (figure 3). The last phase of the data processing is the translation of the 3D image into the series of planar contours in the format recognized by the RP machine described in detail in [10], [11].

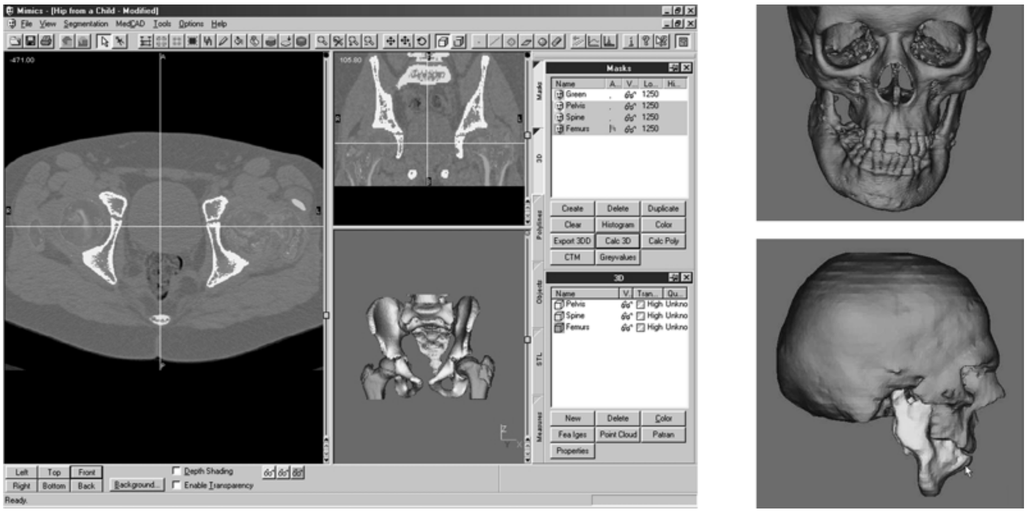

Fig. 2. CT data processing with Mimics (Materialise NV)

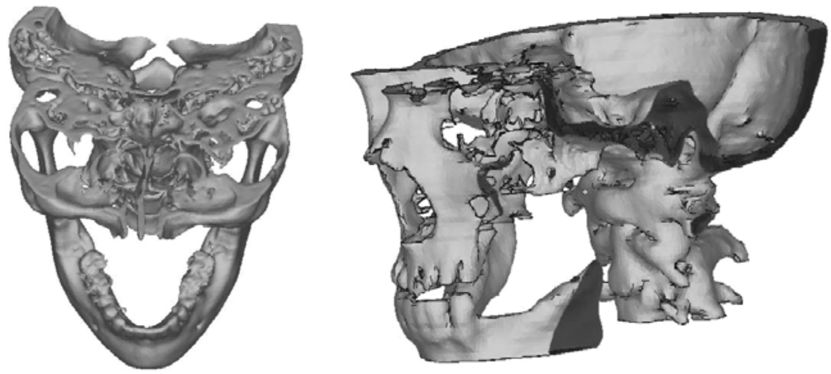

Fig. 3. A skull model visualization (STL) rendered with Mimics (Materialise NV)

2.4. Fabrication of the model and finishing

The project stored as a sequence of instructions is being transmitted to the SLA-250 machine (3D Systems) (figure 4). After completion (laser treatment) and removal from liquid resin (figure 5), the model is being rinsed with acetone and introduced into UV furnace for final hardening (figure 6). Depending on the application of the model, the finishing phase can be different. Some models may require polishing and the other additional treatments. The final phase is the sterilization or the disinfection – this specially refers to models intended for medical applications that come into contact with tissues. Low toxicity of acrylic resin enables one to use units made of this material as surgical instruments and models of bone implants and transplants. The

Renshape YC-9300R-SS is a biocompatible (FDA approved) resin. It can be sterilized and kept in contact with a patient for up to 24 hours, but it is not implantable [11].

Fig. 4. The SLA-250 (3D Systems), Rzeszów University of Technology

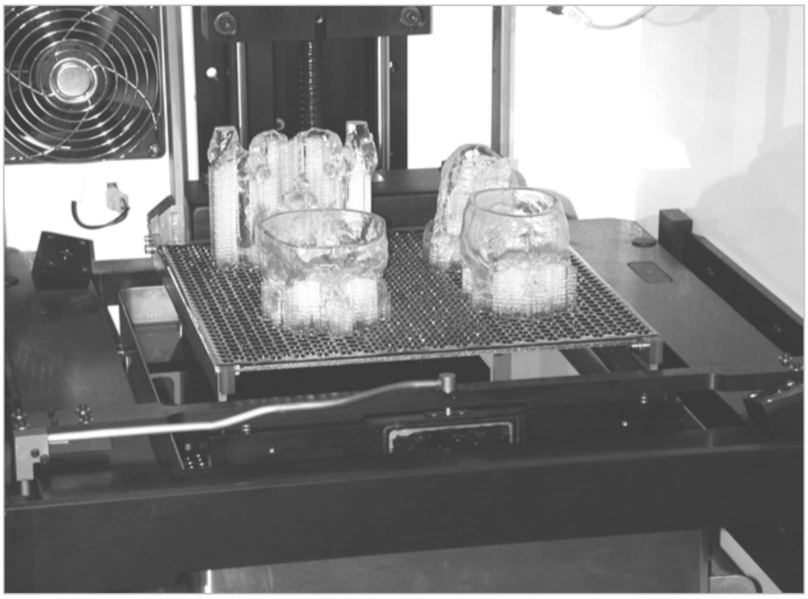

Fig. 5. The medical models manufacturing with SLA-250,
Rzeszów University of Technology

Fig. 6. Model hardening in UV furnace, Rzeszów University of Technology

3. Principles of the most common Rapid Prototyping methods

3.1. Stereolithography (SL)

SL is the most commonly used method, also in medical applications. It was worked out and launched in 1987 by the company of 3D Systems Inc [10]. The building of an object consists in irradiating consecutively layer by layer a photosensitive resin with a laser beam. The area of irradiation is determined by the cross-sections of the object,

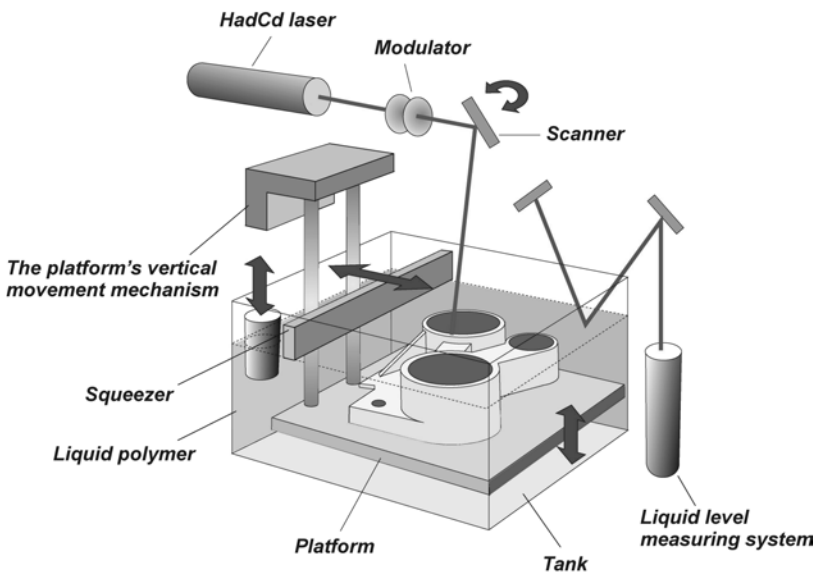

Fig. 7. The principle of operation of SLA-250 machine

e.g. a patient's bone structure obtained by means a computer tomography. The principle of machine operation in the SL method is shown in (figure 7). The final stage is the irradiation in a UV furnace that ensures complete curing of the material [6].

The size and structure of the machine, the technology of the model construction (liquid resins) as well as the model cleaning and curing in a UV furnace make the machine not suitable for a work in the hospital environment.

3.2. Solid Ground Curing (SGC)

This method is also based on building a model made of a photohardened resin, but instead of a laser beam, an ultraviolet radiation is used for curing. To determine the required curing layer, a mask put on a glass plate (a profile of the model cross-section) is used. In order to irradiate each successive layer, a new mask is applied after the old one has been removed. Unhardened resin is sucked off and replaced by liquid wax. The wax is cooled and after passing to the solid state it is ready for surface treatment. After each exposure to irradiation, the whole surface is milled to provide an appropriate thickness of layer, an appropriate vertical dimension and to increase the roughness of the surface of solidified polymer. That allows better adhesion of the next layer. The wax as the temporary support of the model is removed after the process has been finished. The advantage of this method is high rate of the model building, while the disadvantages are as follows: the noise made by a working miller, large overall dimensions of the machine and a complicated manufacturing process [7], [8].

3.3. Fused Deposition Modelling (FDM)

In this method, models are built by putting on consecutive layers of semi-fluid thermoplastic material fed by thermic heads equipped with replaceable nozzles. The material is fed in the form of fibre unrolled from a spool. It is melted in the heads and through nozzles placed in layers. The layer congeals quickly forming the base for the next layers [7], [13]. The advantage of the method described, contrary to SLA, is the possibility of placing the machine in a hospital environment. FDM is a small-size appliance not troublesome in use.

The machine, Medmodeller, based on the FDM technology is meant to be used in a hospital. It was certified by the FDA [11]. FDM enables one to use different materials such as thermoplastic materials and moulding wax (for casting) as well as medical materials, including coloured ones (ABS). The kind of material selected depends only on the method of sterilization and the purpose of the model construction.

3.4. Selective Laser Sintering (SLS)

The SLS method enables one to form an object by curing the selected areas of fusible powder thin layers with a laser. The rate of model construction is comparable to SLA (it can be even higher, depending on the degree of model complication). The quality of surface making and the precision of details are not poorer than the same features of models built with SLA. Theoretically, any thermoplastic material which is suitably powdered can be employed, e.g. powdered metals, low-melting alloys, ceramic materials, etc. Those most frequently utilized are: polyamides (PA), polystyrene (PS), polycarbonate (PC), metallic powders and powders coated with another material [8].

In medical practice, a nylon derivative has been allowed. However, the models made of this material should be sterilized before being used. The above-mentioned technology is especially suitable for orthopaedic use. The models are rather not transparent, their surfaces are granular, and the minimal wall thickness is 1 mm.

3.5. Laminated Object Manufacturing (LOM)

The above-mentioned method consists in constructing a model by means of cutting sheets of material with a laser beam and gluing such materials as foils, paper plastics, cloth, composites, metals, etc., layer by layer. Beside the model profile, the laser cuts out a larger area of the sheet to provide better stabilization of the layer. The allowance in the form of blocks is removed after the model has been made. The model is suitable for further mechanical postprocessing. This method is especially useful for constructing large-size models and casting moulds, for example, in orthopaedics.

3.6. Selective Adhesive Hot Press (SAHP)

The method is fundamentally similar to LOM. The sheets are glued under strictly determined pressure and at a definite temperature, which significantly influences the model's accuracy. The material that sets individual layers is spread or overprinted selectively only if required in the cross-section. After gluing and press-moulding, the allowance is cut off with a cutting instrument. The minimal wall thickness, as in the LOM method, is 1–1.5 mm.

3.7. 3D Printing (3DP)

3D Printing is a technology in which a head prints thin layers of a material one after another spreading the layer of a binding agent on the layer of loose powder. The drops of the binding agent set the grains of the powder. The method of binding agent spreading is similar to the method of spreading ink by an ink printer. After all the layers have been put on, the model is cured in a furnace. The machine is small-sized. It is characterized by great precision and it is suitable for making small models, especially casting moulds. Its obvious advantage lies in a low cost of object making. The types of machines used are Model Maker manufactured by Sanders and Z402 produced by Z Corporation [12].

3.8. Model-Maker 3D Plotting (MM3DP)

This method of model making is similar to plotting or printing a two-dimensional drawing. The difference consists in adding a third dimension in this case. Two piezo-electric nozzles put a material on each layer as if the layer was a mere sheet of paper. After solidification, the layer forms the base for the next one and the process starts from the beginning. Each layer is milled to improve accuracy. Thermoplastic materials and low-melting metals are utilized. The advantages offered by that method are high quality of the surface, dimensional precision and separation. A long time of model making constitutes the method disadvantage. The types of machines used are Sanders Model Maker II, MM 6 PRO. The model minimal wall thickness is 0.1 mm [7].

3.9. Multi-Jet Modelling (MJM)

This method is similar to MM3DP. The difference consists in the construction of the dosing system. Instead of two nozzles (MM3DP) there is, like in an ink printer, a head with 96 nozzles feeding a thermoplastic material. The type of the machine used is Actua 2100 produced by 3D Systems.

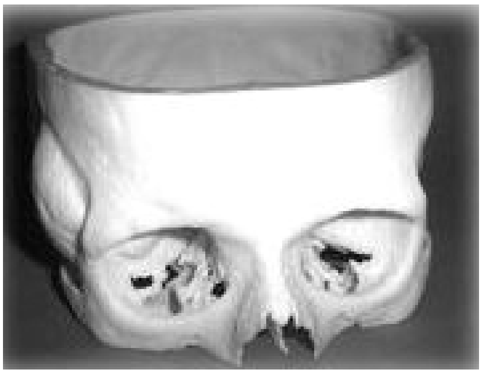

Fig. 8. A medical model made with MJM

3.10. High-Speed Milling (HSM)

Contrary to the methods described previously, in this one a model is formed by removing layers of a material. The model is made by milling a planned shape of the initial material. The process of treatment enables one to acquire complicated shapes in relatively short time due to digital control. The advantages of the method lie in low air pollution and high accuracy of surface imitation. The disadvantages are large overall dimensions of the machines and a complicated manufacturing process conditioned by numerous technological parameters [9]. The instruments produced and tools can be used in surgery, orthopaedics, etc. [11].

4. Criteria of method selection

The selection of a RP method depends on such standard conditions as the time and the costs of a physical model construction. Yet, in medical applications, those are less important. More significant seem such features as the dimension accuracy, the type and characteristics of the materials used, their biocompatibility and the type of sterilization. Ecological aspect and the possibility of using the machines in the hospital environment are also very important [2].

5. Conclusions

Medical modelling is beneficient for both doctors and patients. Its purpose is to reduce the discomfort to a patient, to decrease the recovery time, to reduce a risk of being a part of a surgical treatment or complications, etc. Medical modelling allows visualization of the problem (present injuries, deformations, disease), better planning the treatment, taking the method of treatment (simulation) and manufacturing of such equipment as devices, implants, osseous grafts, prostheses, etc., which are helpful in a medical attendance [1], [2], [4].

Benefits to a doctor are as follows:

– better communication between doctor-specialist and patient,

– better visualization of anatomical features, e.g., tumours,

– possibility of simulating complex surgical operations: the particular phases of the operation can be trained earlier on the model in order to reduce the probability of unexpected events,

– reconstruction of tissues, their supports can be precisely fitted into a model before operation; time of the operation itself is also reduced,

– possibility of producing and fitting prototypes of the implants into a model before operation; implants can be made of titanium or of the other biocompatible material based on the model.

Benefits to a patient:

– better understanding of an intent of the doctor and meaning of the planned treatment,

– speeding-up the treatment, reducing the operation time, reducing risk, discomfort to a patient and the rehabilitation time,

– earlier diagnosis of complex cases, in which model can, for example, indicate a necessity of additional treatment.

Advantages of the stereolitography method against the other RP methods:

– very reliable technology,

– ensures high quality of medical models,

– accessibility of SLA machines; it is the most popular RP method (70% of the world RP market),

– low toxicity of acrylic resin YC-9300R-SS,

– biocompatible (FDA approved) resin,

– models can be sterilized,

– transparency of the resin,

– quick model producing,

– possibility of colour marking of selected portions of reproduced tissues.

Acknowledgements

We would like to thank M.D., Ph.D. A. Urbanik – the Department of Radiology, Cracow University Hospital, for the access to resources, material and great help with writing this paper. The models for evaluation of the method were preprocessed with Mimics 7.2 and Magics 8.0 programs (Materialise N.V.) from 01.11.02 to 01.01.03. The great help provided by Mr. Maarten De Vleeschouwer (Materialise N.V.) is also very appreciated.

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