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Application of rapid prototyping techniques for modelling of anatomical structures in medical training and education

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Rapid prototyping has become an innovative method of fast and cost-effective production of three-dimensional models for manufacturing. Wide access to advanced medical imaging methods allows application of this technique for medical training purposes. This paper presents the feasibility of rapid prototyping technologies: stereolithography, selective laser sintering, fused deposition modelling, and three-dimensional printing for medical education. Rapid prototyping techniques are a promising method for improvement of anatomical education in medical students but also a valuable source of training tools for medical specialists. (Folia Morphol 2011; 70, 1: 1–4)

Key words: rapid prototyping, three-dimensional modelling, medical education

INTRODUCTION

Anatomy courses form an important part of medical schools' curricula. The use of cadaveric dissections is a core part of each anatomy course. However, the development of audio-visual resources, anatomical models, and the introduction of new technology can be an important supplement to the course. As access to cadaveric dissections is sometimes limited, which is an obstacle to understanding anatomy or medical procedures, the introduction and development new computer techniques and software enable the visualization and creation of virtual and real anatomical models which give students the opportunity to learn anatomy in detail and train for medical procedures as many times as necessary. Rapid prototyping techniques (RPT) offer new possibilities both in medicine and in medical education. Actually, a number of technologies available in RPT give opportunities to hold and visualize many organs as well as to practice medical procedures

TECHNIQUES

Four leading technologies are used for rapid prototyping (RP): stereolithography, selective laser sintering (SLS), fused deposition modelling (FDM), and three-dimensional (3D) printing [3].

The history of RP [12] goes back to the 1970s, when Herbert Voelcker developed algorithms that described 3D objects for the purposes of solid modelling. These methods were used for the development of 3D modelling. In the 1980s Carl Deckard devised a new method which created models layer by layer by fusing metal powder with laser light, patented in 1986, as 'Method and apparatus for producing parts by selective sintering', US patent 4,863,538 [1].

Selective laser sintering is a technique that uses computer-aided design or other 3D data sources.

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Based on 3D digital descriptions of the model, a high-power CO_2 laser fuses particles of a powder layer, and then the next layer of powder is placed on the previous one. The process is repeated until the model is created. A great advantage of SLS is the wide range of materials which can be applied, including polymers and metals. Depending on the material, the model obtains desirable properties such as high mechanical strength or temperature resistance up to 170°C. The layer thickness of the powder is approximately 0.1–0.15 mm.

Charles Hull is referred to as the 'father of rapid prototyping', who coined the term 'stereolithography' in 1986, in his U.S. Patent 4,575,330, for 'Apparatus for the Production of Three-Dimensional Objects by Stereolithography' [12]. Stereolithography is the most widely used technology, based on the application of a UV laser which solidifies a liquid photopolymeric resin. Typical layer thickness ranges between 0.03 and 0.25 mm; however, limited materials choice is a major drawback.

At the beginning of the 1990s FDM and three-dimensional printing were invented. In the FDM technique, unlike in other processes, the object is printed in an open space, with no support of an unused material, which would serve as support for more complicated structures. The most frequently used material in FDM prototyping is acrylonitrile butadiene styrene (ABS); however, other materials are also utilized, including polycarbonate, polyphenylsulphone, and elastomers [3]. Typical layer thickness for the FDM process ranges from 0.178 to 0.356 mm (Fig. 1) [9].

Three-dimensional printing is a fast and low cost technology of RP. Digitally prepared 3D objects are sent to the 3D printer like in an ordinary ink-jet desktop printer. The concept of printing is similar to that of a regular printer; however, consecutive solid thin layers of powder are placed on one another and liquid binder is spread through the inkjet printer nozzles in predefined locations. The excess powder serves as a support for the printed model and may be used for printing another model. The 3D printer can use various materials: high-performance composites are used to produce tough, strong, coloured, and best resolution models; elastomeric materials which give rubber-like properties or casting material which enables the creation of metal prototypes. 3D printers are characterised by their excellent speed: a hand-held part is produced within two hours [9], reaching a layer thickness of 0.076–0.254 mm. This technology is the only one that allows full, 24-bit colour printing of prototypes [16].

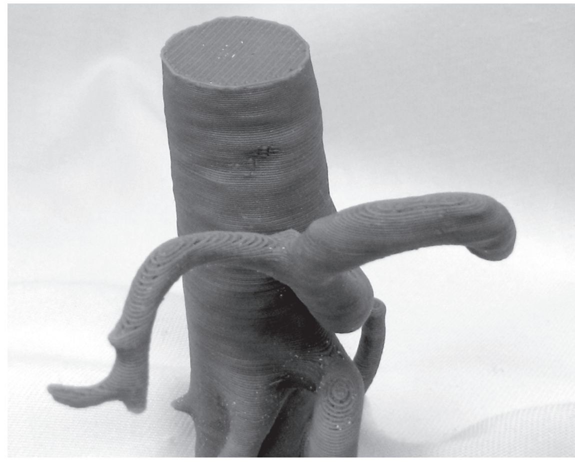

Figure 1. Abdominal aorta — a model produced by fused deposition modelling technique; 0.25 mm layer thickness produces a visible stepping effect in structures perpendicular to the Z-axis.

All these techniques are valuable tools in designing prototypes, e.g. in the electronics industry, the toy manufacturing industry, architecture, and many others. In medicine, rapid prototyping technology is progressively finding more applications due to the development and availability of imaging techniques like computed tomography (CT), magnetic resonance imaging, and ultrasound scanning [11, 13]. All these techniques produce fast, precise, and functional models within several hours, which can be used to practice medical procedures. The variety of devices and materials allow the wide application of rapid prototyping techniques in medical training and education.

MEDICAL TRAINING AND EDUCATION

The use of the SLS method for the creation of temporal bones for surgical training has been described [13]. The special powder comprised of polyamide nylon with the addition of glass beads gives the final product similar properties to those of real models. Due to its properties, the created temporal bone could be shaved with a burr in the same fashion as real bone, which gives additional applications of the model. Detailed structures such as suprameatal spine (Henle's spine) and tympanomastoid suture, as well as malleus and incus, can be reproduced; however, stapes reconstruction has not been possible. According to the authors, the model allows easy understanding of both surgical and anatomical relations from the surgeon's viewpoint and serves as a good educational tool for middle-ear surgery.

Proper understanding of anatomical relations is crucial for otolaryngological training. The application of rapid prototyping techniques as part of anatomical electronic phantom for mastoidectomy was presented by Grunert et al. [4]. A skull produced by a 3D printer based on CT scans was used. Structures of special anatomical consideration, such as facial nerves, sigmoid sinus, and semi-circular canals, were simulated by electrically conductible material and fibre optics. The evaluation of the system was performed by means of a questionnaire. The results were optimistic; the system was rated by the surgeons at +1.2 (evaluation range from –2 [not at all] to +2 [very good]).

Rapid prototyping technique can also be a helpful tool in understanding and treating heart disease [8]. Physical models of a patient's organs based on computed tomography angiography as a source image were used as a guide to find the best solution to remove congenital or acquired defects in four patients with the following conditions: congenital muscular ventricular septal defect, fenestral atrial septal defect with large atrial septal aneurysm, and prosthetic mitral valvae with perivalvular leak, as well as thoracic aortic pseudoaneurysm. In conclusion, the authors state that in all cases, the physical models allow surgeons to predict difficulties and adverse events before operating.

Rapid prototyping technique can be also applied in undergraduate dental education [2]. Using mechanical computer-aided design systems and stereolithography machines, a geometric model of a teaching cube with tooth cavities was constructed. The authors conclude that the advantages of stereolithography are due to the capability of building complex geometrical accuracy and good surface finish. In this presented case of a teaching cube (2.54 cm^3), the production time is usually thirty minutes and the cost is about $20 each. Using this system, it is easy to create teaching blocks with a variety of type and number of cavities, their sizes, and their positions. These models are used in preclinical dental education for the development of student's visual recognition skills and fine eye-hand coordination. The authors found that the students could grasp the concepts of different types of cavity preparation more easily with this model in their hands during exercises and they could start to communicate and express themselves in terms of evaluations of the cavity preparations at an earlier time in the preclinical technique.

Jirman et al. [6] presented a case of a patient after polytrauma that caused frontal bone destruction (7 × 3 × 2 cm). The CT scans of the traumatized skull were used to prepare a 3D print. The obtained model served as an individualized premodel for the ultra high molecular weight polyethylene (UHMWPE) model that replaced the missing frontal bone. The authors stress that success in this type of reconstructive surgery also depends on the precision and accuracy of the individual replaced model.

Taylor et al. [14] performed a study in which 3D models obtained by 3D printing technique were created to analyse a representation of eye trauma and to develop a prevention model by analysing different anatomical and anthropological features on different entity subjects.

Another use of 3D rapid medical prototyping was presented in the study by Mavili et al. [10]. The authors assessed the usage and value of 3D models prepared on the basis of CT scans in orthognathic surgery. They stress the usefulness of 3D anatomical models to evaluate the accuracy of the surgery. Similar results were obtained by Jacobs et al. [5], who created a 3D rapid prototyping heart model for patients with complex heart disease and altered geometry of the atria or ventricles. The individual models obtained were used to plan the resection of aneurysms or ventricular tumours before cardiac surgery. According to the authors, this method facilitated the procedure due to better planning and orientation of anatomical conditions based on individual patients.

Cardiovascular anomalies were presented in the study by Vranicar et al. [15] in which 3D models of blood vessels were analysed for better preoperative planning. The authors also mention the use of the models for parents' and students' education. Kalejs et al. [7], in their study, presented a rapid prototyping method of printing 3D models that could be utilized for the assessment of stents in human aortic roots in in-vitro conditions.

The authors' experience with 3D printing shows a wide range of applications of the technique. Our medical education program was enriched by models created by 3D printer. We created several models concentrating mostly on vascular structures and skull elements. The 3D printing process, where the unused powder serves as a support for the printed structure, allows formation of sophisticated structures, which is of high importance for modelling of blood vessels while preserving their lumen. After elaboration of CT scans of the abdominal aorta, a model of the aorta and its branches was prepared (Fig. 2). The obtained images were digitally processed and sent to an .stl file and then printed as 3D models. As the created model presented in vivo conditions, the anatomical conditions from the model were compared with dissected structures on cadavers. A model of the celiac trunk could be used for anatomical interventional cardiology workshops. Figure 3 shows the printed model of the branches of the abdominal aorta, which may be used for in-

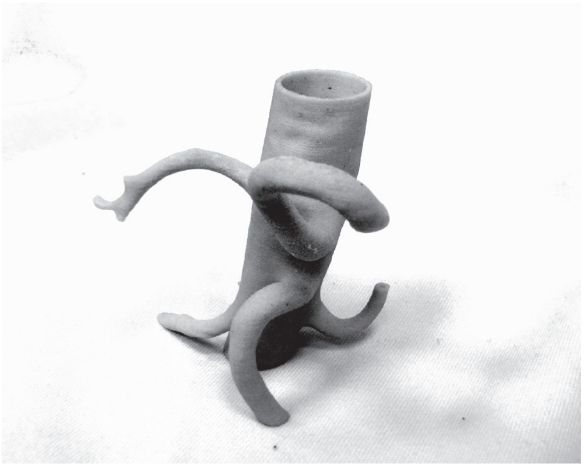

Figure 2. Three-dimensional printing allows detailed visualization of the produced model, with 0.1 mm layer thickness.

Figure 3. Preserved lumen of blood vessels in model produced with 3-dimensional printing technique allows simulation of anatomical relations important for intravascular procedures.

travascular procedure training. Additionally, the presented elaborated images were utilized as computer models in presentations and lectures.

CONCLUSIONS

In our opinion, the presented method of preparing anatomical models is a valuable educational supplement for standard cadaveric dissection. The possibility of printing models with congenital disorders and other pathologies creates a unique occasion to combine and introduce clinical anatomy into the standard course, and this remains in accordance with modern teaching trends.

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