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REVIEW ARTICLE

3D printing based on imaging data: review of medical applications

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Abstract
Purpose Generation of graspable three-dimensional objects applied for surgical planning, prosthetics and related applications using 3D printing or rapid prototyping is summarized and evaluated.
Materials and methods Graspable 3D objects overcome the limitations of 3D visualizations which can only be displayed on flat screens. 3D objects can be produced based on CT or MRI volumetric medical images. Using dedicated post-processing algorithms, a spatial model can be extracted from image data sets and exported to machine-readable data. That spatial model data is utilized by special printers for generating the final rapid prototype model.
Results Patient–clinician interaction, surgical training, medical research and education may require graspable 3D objects. The limitations of rapid prototyping include cost and complexity, as well as the need for specialized equipment and consumables such as photoresist resins.
Conclusions Medical application of rapid prototyping is feasible for specialized surgical planning and prosthetics applications and has significant potential for development of new medical applications.

Keywords Rapid prototyping · Patient care · Prostheses and implants · Medical education · Computer-assisted image processing

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Introduction

Medical imaging has evolved dramatically in the past few decades. With the evolution of Multidetector Computed Tomography (MDCT) and Magnetic Resonance Imaging (MRI), radiological diagnosis has become less invasive and more informative [1,2]. High-resolution three-dimensional image data can be acquired within a single breath-hold. Image processing plays a very critical role in diagnostic imaging [3,4]. 3D visualization, multiplanar reformation and image navigation help radiology to be pivotal for many clinical disciplines [5]. Today's image guided surgeries illustrate how radiology has become integrated in a therapeutic team together with different surgical specialists. However, we are limited by the use of flat screens for the visualization of three-dimensional imaging data. An emerging technique, referred to as 3D printing or rapid prototyping, overcomes this limitation by producing graspable three-dimensional objects [6]. This article illustrates the technique of generating 3D objects based on radiological image data and reviews its applications in the medical field as well as its limitations.

Generation of 3D objects

Source data acquired with any imaging modality typically is visualized in two dimensions. With post-processing tools and algorithms, it is possible to produce multiplanar reformations and three-dimensional views of the anatomy. The process chain involved from image acquisition to production of a three-dimensional rapid prototype model consists of the following three steps and will be discussed in detail in the next sections: "Image acquisition", "Image post-processing" and "3D printing".

Image acquisition

Image acquisition is a very important step in generation of 3D objects as the quality of the object depends on the quality of the data. Today, clinical image acquisition can be done at ultra-high spatial resolution (400–600 microns) with good quality contrast. Slice thickness of less than 1 mm and isotropic voxels are important parameters to be accounted for minimizing the partial volume effect during post-processing [7]. Although MDCT and MRI are equally good imaging modalities for data acquisition, MDCT is widely applied for rapid prototyping because image post-processing is less complex for MDCT data.

Cone Beam Computed Tomography (CBCT), Positron Emission Tomography (PET), Single Photon Emission Computed Tomography (SPECT) and Ultrasonography (US) are other non-invasive imaging modalities that can be used for data acquisition. Without regard to imaging modality, acquired data is saved in the common DICOM format (Digital Imaging and Communications in Medicine).

Image post-processing

Dedicated high performance workstations equipped with post-processing tools are used for processing the DICOM images generated during acquisition. The 3D post-processing tools common in practice include segmentation tools often based on simple region growing as well as visualization tools such as surface/volume rendering, maximal/minimal intensity projection and multiplanar reformation. A wide area of application lies in the surgical field, vascular surgery, orthopedic surgery, pediatric surgery, where these tools are routinely used in clinic practice for planning and executing surgery [5,8]. Additionally, advanced post-processing algorithms have been proposed, e.g., for low resolution or non-enhanced images [9].

The contours of a segmented region of interest can be computationally transformed into a 3D triangle mesh [10], i.e., the shape of a part is approximated using triangular facets. Obviously, tiny triangular facets produce a smoother surface, but increase the size of the data. The mesh data may be further processed using CAD (Computer-Aided Design) software. This may include automatic mesh optimization or manual modifications of the geometry. Finally, the data is sent to the 3D printing machine for production, where the STL (Surface Tesselation Language) file format is commonly used.

3D printing

3D printing is a methodology using three-dimensional CAD data sets for producing 3D haptic physical model. It is also referred to as rapid prototyping, solid free form, computer automated or layered manufacturing depending on the kind of production method used. The principle of rapid prototyping is to use 3D computer models for the reconstruction of a 3D physical model by the addition of material layers [11]. With additive fabrication, the machine reads in data from a CAD drawing and lays down successive layers of liquid, powder, or the sheet material, and in this way builds up the model from a series of cross sections (Fig. 1). These layers, which correspond to the virtual cross section from the CAD model joined together, create the final shape. The primary advantage of additive fabrication is its ability to create almost any complex shape or geometric feature.

The word rapid has to be taken rather relatively: construction of a model with contemporary methods can take from several hours to days, whereas additive systems for rapid prototyping can typically produce models in few hours. The eventual construction time depends on the specific method used, as well as the size and complexity of the model.

Rapid prototyping includes a number of established manufacturing techniques and a multitude of experimental technologies either in development or used by small groups of individuals. Each technique has its own limitations and applications in producing prototype models. Established rapid prototyping techniques are summarized in Table 1. Stereolithography (SLA) uses photopolymers that can be cured by UV laser (systems e.g., by 3D Systems, Rock Hill, SC, USA). Selective Laser Sintering (SLS) is based on small particles of thermoplastic, metal, ceramic or glass powders that are fused by a high power laser (systems e.g., by EOS GmbH, Munich, Germany). Materials include polymers such as nylon, glass-filled nylon or polystyrene, or metals such as steel, stainless steel alloys, bronze alloys or titanium. Fused Deposition Modeling (FDM) works by extruding small beads of fused thermoplastic materials or eutectic metals that immediately bond to the layer below (systems e.g., by Stratasys Inc., Eden Prairie, MN, USA). Laminated Object Manufacturing (LOM) uses layers of paper or plastic films that are glued together and shaped by a laser cutter (systems e.g., by Cubic Technologies, Torrance, CA, USA). Inkjet printing techniques are based on different kinds of fine powders such as plaster or starch (systems e.g., by Z Corporation, Burlington, MA, USA). After a layer of the powder has been

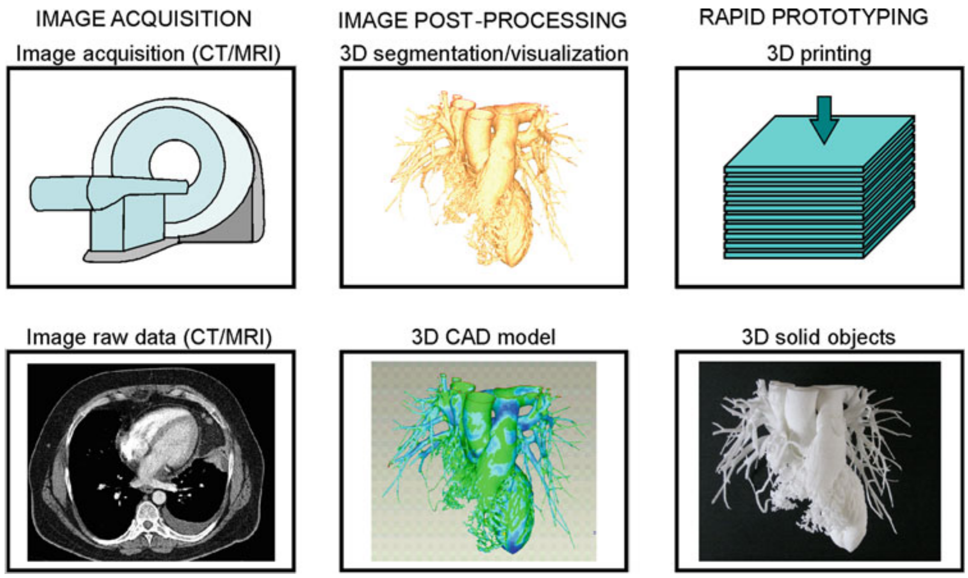

Fig. 1 The process chain involved from image acquisition to production of a rapid prototype model consists of three major steps: image acquisition, image post-processing and rapid prototyping. Images are acquired using CT or MRI. Image raw data can then be transferred to a dedicated image post-processing workstation. On the workstation, 3D segmentation and visualization are performed and a Computer-Aided Design (CAD) model of the segmented structures can be generated. Such data can then be used by rapid prototyping machines to create the 3D solid object by the addition of material layers

Table 1 Overview of established rapid prototyping techniques used in the medical arena

	Accuracy	Cost	Advantages	Disadvantages
Stereolithography (SLA)	+++	$$	Large part size	Moderate strength
Selective Laser Sintering (SLS)	++	$$$	Large part size, variety of materials, good strength	High cost, powdery surface
Fused Deposition Modeling (FDM)	++	$	Low cost, good strength	Low speed
Laminated Object Manufacturing (LOM)	+	$	Low cost, large part size	Limited materials
Inkjet printing techniques	+	$	Low cost, high speed, multimaterial capability	Moderate strength

The characteristics can vary depending on the specific printing system used

dispended by a piston, the parts of this layer belonging to the 3D object are bonded by an adhesive liquid deposited by another piston. Inkjet printing techniques can also be used to generate a 3D scaffold with different types of tissue by printing living cells and biomaterials simultaneously [12,13].

Some fabrication techniques use two materials in the course of constructing parts. The first material is the part material and the second is the support material (to support overhanging features during construction), the support material is later removed by heating or dissolved with a solvent or water. This is not required in techniques where a powder bed provides the support such as in SLS and inkjet printing techniques. Depending on the fabrication technique it is also possible to combine materials of different elasticity or color in one model. This can be useful to create more realistic models for educational or research purposes, or for naturally looking prostheses.

Medical applications of 3D objects

Rapid prototyping has been recently introduced in health care application when compared to its long-standing use in the manufacturing industries. In the last decades, rapid prototyping has been used in a variety of medical applications including individual patient care, research and as an educational and training tool.

Individual patient care

Surgical planning

Rapid prototyping has recently been introduced into the surgical arena as a tool for better understanding of complex underlying anomaly. This can improve and facilitate the diagnostic quality and help in pre-surgical planning. Its application and benefit in craniofacial and maxillofacial surgery [14–20] has been proven. First studies in pelvic surgery [21,22], neurosurgery (Fig. 2) [23,24], spine surgery [25], cardiovascular surgery [26,27] and visceral surgery [28] demonstrated a significant improvement in diagnosis and treatment due to better 3D appreciation of pathological structure, increased accuracy and possibility of pre-planning. Simulating all complicated surgical steps in advance [17] using prototype models can help to foresee intra-operative complications. This may result in reduced operating time and hence allowing a cost-effective use of operating rooms [29]. Moreover, rapid prototyping is a helpful tool in radiotherapy

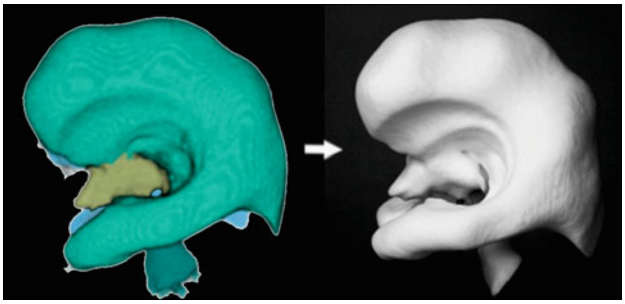

Fig. 2 MRT image data set of the ventricular system of a child with Dandy–Walker malformation was transferred to a dedicated workstation. The software on the workstation provided a 3D visualization and segmentation. The exported segmentation could be used by a rapid prototyping printer to create a 3D print of the 3D ventricular system. Such a print offers the unique possibility of a truly 3D appreciation and palpation of the complex ventricular morphology. Both 3D visualization and 3D print can help the parents and clinicians to understand the exact nature of child's anatomical abnormalities

planning [30,31] and generating individual radiation shields [32].

Implant and tissue designing

The rapid prototyping technique is also serving in medical prosthesis and implant designing. The potential of the rapid prototyping technique lies within the possibility of customized prostheses. Standard sized bone implants are commercially available solving the requirement in most surgical procedures and for many of the patients, but might not be used in all the cases. Reasons emphasizing the need of customized implants are (1) patients outside the standard range with respect to implant size- or disease-specific special requirements, (2) improved surgical outcome because of individual fitting and adequate match with individual anatomical needs.

The rapid prototyping technique has been applied in reconstruction for various anatomical structures especially in facial surgery like customized prostheses were successfully used for mandible [15,33] and dental restoration [34]. Hip [35], femoral [36], hemi-knee joint reconstruction [37,38] are other surgical areas potentially benefiting from the prototyping technique. Biocompatible materials include metals, ceramics and polymers. Bioceramics such as hydroxyapatite currently are the preferred material for bone reconstruction [39]. The biodegradable polymer polycaprolactone may be used for bone and cartilage repair [11]. Metals like titanium can be used particularly in load-bearing areas, e.g., for hip reconstruction.

The rapid prototyping technique is beneficial not only for bone reconstructions but also for replacing soft tissues, as rapid prototyping can be applied on a variety of materials. Individual auricular prostheses [40,41] probably provide the most vivid impression on the potential usefulness of this technique. In patients with anotia, a mirrored scan of the contralateral auricle is used for producing a flesh-like rapid prototyping ear model. Application of rapid prototyping in creating tissue scaffolds for cellular growth is also widely explored [12,13]. Future applications may include generation of whole artificial organs adapted to the individual patient anatomy and needs. However, further research and development are needed until functional and viable tissues can be produced and applied in clinical practice.

Medical research

Rapid prototyping opens new opportunities for scientific research activities. Research with phantoms produced by rapid prototyping can help to elucidate physiological processes that are not yet fully understood (Fig. 3) [42,43] along with a better understanding of complex pathologies [27,42, 44]. The latter are characterized by either a complex morphology or functional consequences. Complex morphologies may be better depicted on 3D solid models in hand rather than on 2D or 3D visualizations tools [27]. Hemodynamics can be investigated, e.g., by velocity-encoded MRI or by optical flow measurements in transparent models [45]. Compliant models can be manufactured using materials such as silicon or polyurethane to mimic the elastic properties of vessels [26,46]. Physiological and pathophysiological processes as well as post-operative hemodynamics can be assessed with patient-based phantoms simulating in vivo conditions and compared to computational fluid dynamics [42,47]. This may give new insights into hemodynamic or aerodynamic aspects of cardiovascular or airway diseases [48].

Medical education and training

Surgical procedures require a thorough knowledge of human anatomy and topographical relations of various anatomical structures. This comprehensive knowledge is traditionally taught by the preparation of human cadavers in the preclinical studies of medical school and then put into vivid practice and intensified during real surgery. However, gaining greater experience and expertise in the special area of interest before operating the patient is desirable. 2D or 3D visualizations on a computer screen can be insufficient for obtaining an intuitive understanding of complex anatomical details [27,49]. Rapid prototyping objects enhance 3D learning especially in challenging anatomical and pathological conditions (Fig. 4). Furthermore, the possibility of training surgical procedures in general as well as patient-specific procedures in very complex cases improves the surgeon's abilities and results [50]. Rapid prototyping models allow for intensive training of young surgeons, e.g., for endovascular stent implantation simulating in vivo conditions and real tissues without any risk of patient complications [26,46,51,52]. After being

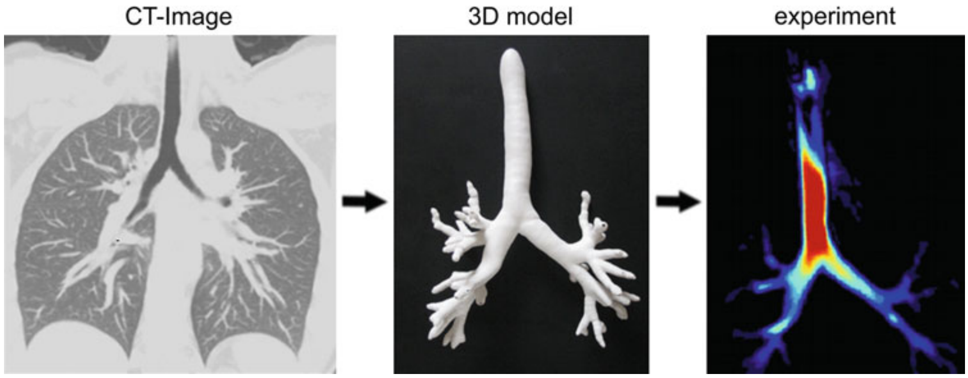

Fig. 3 Rapid prototyping can be used in medical research for creating 3D models of living organs. In this work, a CT image data set of the bronchial tree was processed for rapid prototyping. A 3D model of the human trachea and bronchial tree was produced. The model was then used as a flow phantom for gas flow experiments with hyperpolarised helium (3He) MRI to study the flow pattern through trachea and bronchial tree

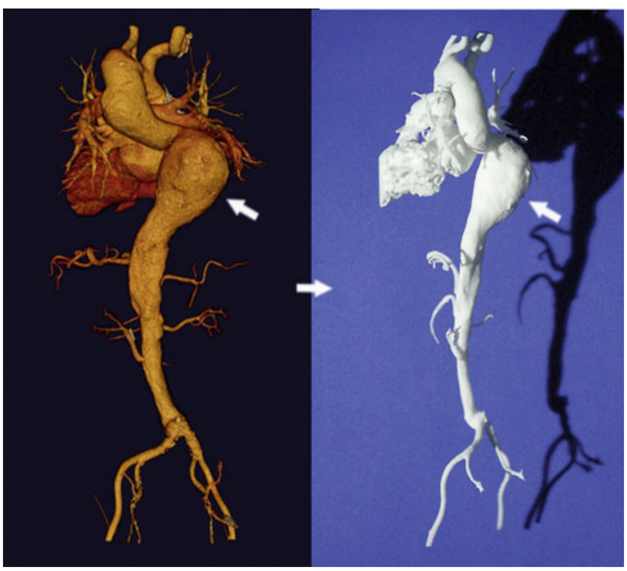

Fig. 4 3D visualization and 3D rapid prototyping of the aorta in a patient with thoracic aortic aneurysm (*arrow*). 3D models are helpful in demonstrating complex pathologies. Vascular surgeons may find models useful for evaluation of the best treatment strategy as well as for training. Individual patient care can benefit from rapid prototyping by providing a graspable model, thus helping the patient to understand the pathology and to give informed consent for surgical interventions

adequately trained on models, surgeons feel more confident while going to the operating room for actual surgery. Besides, the pre-operative simulation of a specific and complex surgery provides a unique opportunity to employ surgical steps in order to determine the best operating strategy [17], again increasing the surgeon's confidence during the operation.

Discussion

Diverse applications of rapid prototyping have been emerging throughout the last decade. It is regarded as one of the most promising techniques to be associated with medical imaging. Although medical application of rapid prototyping is still in an early phase its potential has already been demonstrated in several studies [18,21,29].

The process chain from imaging to 3D prototype modeling is a multidisciplinary field involving knowledge ranging from acquisition of imaging data, image post-processing and manufacturing of the prototype models by various techniques. Radiologists play a pivotal role in this process chain connecting engineering to health care. Nevertheless, the process chain runs smoothly with close association and collaboration of radiologists, clinicians, computer scientists and material scientists together. Recent work demonstrated that the whole workflow can be integrated into clinical routine [53].

The application of rapid prototyping in surgery is valuable for diagnosis, treatment planning and intra-operative surgical navigation especially for complex cases where 2D images or 3D virtual visualization are insufficient to provide a complete understanding of the pathology [15–23,25–28]. Besides, rapid prototyping models are helpful for training surgeons while simulating surgical procedures in a very realistic manner [17]. However, the benefit of 3D objects compared to 3D visualization regarding better 3D appreciation is still unclear. Furthermore, 3D objects usually do not adequately simulate human tissue and surrounding structures.

On the one hand, customized implant and prosthetics are one of the other widely explored areas for application of rapid prototyping [33–38,40,41]. Also, 3D prototype models may be beneficial for the communication between clinicians and patients for demonstrating required treatment and consenting for the procedure. On the other hand, commercially available implants are suitable for most patients.

Medical research has already benefited from rapid prototyping providing a new vision into physiological and pathological processes [42,43]. Efforts have been made on the development of artificial organs and tissues using rapid prototyping [11,44,54]. However, application of artificial tissues is very limited so far, and the issue still is in an early stage of research.

The medical school teaching of normal human anatomy by use of cadavers does not reflect the variations encountered in a clinical scenario. Medical imaging is getting its way in anatomical class rooms giving a good idea of normal anatomical and pathological variations to medical students. Thus, rapid prototyping can serve as the medium to bring the anatomical variations from clinics into the preclinical studies in order to improve the understanding of anatomy. The available number of models at university or hospital is very limited by costs though [55]. And individual 3D models only represent one individual anatomy. Furthermore, 3D objects are often fragile. Thus, its real hands-on use in large student classes does not seem reasonable.

Limitations

A number of limitations have already been discussed. There are further limitations of rapid prototyping that apply to rapid prototyping in general. Nevertheless, at least some of those limitations might be overcome by future technological developments.

To begin with, rapid prototyping can only be applied to structure not exceeding certain dimension as 3D printers are not able to produce extremely large, e.g., whole body, models. The limitation is currently overcome by producing a miniature version of large structure by post-processing or by dividing the whole model into smaller parts which can be combined after printing.

The major limitation of rapid prototyping lies within time and cost spent in generation of 3D objects. At present, a widespread use of rapid prototyping for surgical planning or individual implant design does not seem to be justified because standard planning procedures or standard implants are sufficient. However, in complicated cases, additional costs of rapid prototyping may be compensated by reduced operating times and higher success rate of the surgical procedure. The time needed for producing a 3D object also limits its use in surgery to elective cases and makes it unsuitable for emergency cases.

Conclusions

Rapid prototyping is an emerging technique with a variety of medical applications such as surgical planning and training, implant design, biomedical research and medical education. Due to its current limitations, rapid prototyping is not used in everyday clinical practice yet. However, with respect to the enormous potential of the technique, the near future promises growing utilization and development of new applications in the fields of individual patient care, as well as academic and research activities.

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