Abstract

The aim of the study was to create an anatomical correct 3D rapid prototyping model (RPT) for patients with complex heart disease and altered geometry of the atria or ventricles to facilitate planning and execution of the surgical procedure. Based on computer tomography (CT) and magnetic resonance imaging (MRI) images, regions of interest were segmented using the Mimics 9.0 software (Materialise, Leuven, Belgium). The segmented regions were the target volume and structures at risk. After generating an STL-file (StereoLithography file) out of the patient’s data set, the 3D printer Z® 510 (4D Concepts, Gross-Gerau, Germany) created a 3D plaster model. The patient individual 3D printed RPT-models were used to plan the resection of a left ventricular aneurysm and right ventricular tumor. The surgeon was able to identify risk structures, assess the ideal resection lines and determine the residual shape after a reconstructive procedure (LV remodelling, infiltrating tumor resection). Using a 3D-print of the LV-aneurysm, reshaping of the left ventricle ensuring sufficient LV volume was easily accomplished. The use of the 3D rapid prototyping model (RPT-model) during resection of ventricular aneurysm and malignant cardiac tumors may facilitate the surgical procedure due to better planning and improved orientation.

Keywords: Imaging; Ventricular remodeling; Cardiac tumor; 3D print

1. Introduction

The use of imaging techniques for preoperative planning is helpful to improve the results of complex surgical interventions.

1.1. Congestive heart failure and ventricular aneurysm

In case of anterior myocardial infarction, the ventricular shape and volume changes [1] and there is loss of contraction of the anterior wall and septum. Ventricular dysfunction and eventually aneurysm formation may lead to congestive heart failure (CHF). Surgical methods for aneurysm resection and left ventricular reshaping vary from volume reduction only if a dyskinetic scar is present, to surgical repair of the postinfarction dyskinetic, dilated ventricle with simple excision and closure to Jatene’s septal excision technique [2]. In 1984, Dor et al. [3] suggested reduction of ventricular size by excluding the non-contracting segment with an intraventricular patch. If the residual volume is too small, the result will be catastrophic, resulting in the physiology of a restricted cardio-myopathy. If the residual chamber is too large, the benefit will be limited [4]. Beside the rest volume of the ventricle, the geometry is important. Ventricular volume should be reduced in its septal and anterior components without deforming the chamber. In normal hearts, myocardial fibers have a spiral direction from the base to the apex with two opposite layers and well-defined intersection angles [5]. When the spiral architecture is lost due to resection of the aneurysm especially at the apex, ventricular function is impaired and ejection fraction and stroke volume decrease. An elliptical ventricle decreases lateral force (stress) compared to a longitudinal one with a spherical rounded apex [6]. Standardized preshaped elliptical balloons (Chase Medical, Dallas, TX; The Blue Egg™, BioVentrix) have helped to size and configure the ventricle [7].

1.2. Cardiac tumors

Primary tumors of the heart are exceedingly rare. The angiosarcoma is the most common primary malignant tumor of the heart in adults with a uniformly dismal prognosis [8]. Besides echocardiography, magnetic resonance imaging and computed tomography are beneficial in the diagnostic work-up [9]. These imaging modalities are particularly helpful in defining the extent to which cardiac tumors infiltrate surrounding structures. Complete surgical resection is required for improved survival [10]. However, by its very location, radical complete resection is rarely possible. Optimal management strategies have not been defined.
because of the low incidence of this disease and the limited experience in the treatment of primary cardiac tumors.

A real anatomical 3D model consisting of the target area together with all structures at risk could potentially support the planning of the resection. Knowledge of the optimal resection volume is necessary to perform an organ preserving surgical intervention.

Information about the position of a target volume (aneurysm or tumor), and its relation to structures at risk (such as the left anterior descending artery which is in certain cases not visible due to an intramyocardial LAD or overlaying fat tissue, papillary muscles, ventricular wall, mitral and tricuspid valve) as well as functional information (kinetic, dyskinetic or non-contracting ventricular wall and elliptical shape of the ventricle) can be derived from standard imaging techniques and using 3D-reconstruction techniques but are usually displayed in two dimensions only. The aim of this paper is to describe the process of generating solid anatomical RPT of cardiac structures that could be used to facilitate preoperative planning.

2. Material and methods

2.1. Patients, data acquisition and segmentation

There were three patients included. One with a malignant tumor and two with ventricular aneurysm. The tumor patient was a 50-year-old female with a histological poor differentiated high grade sarcoma. She received a radical tumor resection, a mechanical tricuspid valve replacement and an epicardial pacemaker. The second patient was an 81-year-old female with a huge anteroseptal aneurysm. The patient had a myocardial infarction 9 months previously with a LAD occlusion and received at that time PCI and stent implantation. She had an ejection fraction of 27% and mild mitral valve regurgitation. Isolated left ventricular reshaping with aneurysm resection was performed. The third patient was a 50-year-old male with triple vessel disease, mitral valve regurgitation and an aneurysm of the anterior wall. The ejection fraction was 25%. He received bypass grafts, mitral valve repair, ICD implantation and left ventricular aneurysmectomy.

Chest-CT-datasets were acquired with the CT Siemens (Siemens BRILLIANCE 64 slice), with a reconstructed layer thickness of 0.5 mm up to 1.0 mm with a 512 × 512 matrix. The segmentation of the anatomical structures was based on the acquired CT data set using the software Mimics 9.0 (Materialise, Leuven, Belgium). The relevant anatomical structures (LAD, aneurysm with the functional and non-functional tissue, papillary muscles, mitral valve and tumor tissue) were segmented and a virtual 3D reconstructed model was created. Beside the quality of the printed resolution of the CT data set, we wanted to evaluate which reconstructed layer thickness is the most eligible, regarding time needed for segmentation and quality of target area and structures at risk. Accordingly, one CT data set with a layer thickness of 0.5 mm was segmented semi-automatically and manually, and a second CT data set with a layer thickness of 1.0 mm was segmented only manually.

Patients with a ventricular aneurysm received an additional Cardiac-MRI (Achieva 1.5 T from Philips). In these data sets with a reconstructed layer thickness of 10 mm, the contracting and non-contracting wall segments were determined and the kinetic rest volume of the LV was segmented. The objective of this RPT model was to create a template of the ideal post-reconstruction left ventricular volume, which would allow for an optimal surgical ventricular reconstruction (Fig. 1).

2.2. 3D rapid prototyping

After segmentation of the regions of interest, this model is triangulated and stored as an STL- (StereoLithography) file. STL is a file format that is used in StereoLithography CADsoftware and is an industry standard for rapid prototyping. STL files describe a raw unstructured triangulated surface by the unit normal and vertices of the triangles using a three-dimensional Cartesian coordinate system.

Subsequently the STL file is sent to the 3D-printer. The printing technology is similar to an inkjet printer. Instead of conventional ink, a mixture of fluid-binding substances and ink is applied. Every desired color can be obtained with a mixture of the three base colors – magenta, cyan, and yellow. Apart from the base colors an uncolored fluid binder can be used for uncolored anatomic structures. Thus, different anatomical structures can be represented with a special color for better recognition. The printer consists of a plaster powder piston and a building piston. A roller transports a 0.1 mm layer plaster powder from the material piston to the building piston. Then the print heads spray the binder on the segmented areas (regions of interest) in the building piston and the first layer is completed. To create a 3D model, this procedure has to be repeated layer by layer until the 3D model is finished. The unbound plaster powder which fills in the regions which were not segmented is removed with compressed air. After drying of the model, which takes approximately one hour, the manufacture process of the model is finished (Fig. 2).

The material used for 3D-printing is based on plaster. To achieve elastic material properties to create a deformable volume, optional starch can be used as base material. Subsequent to the drying process the model has to be deformed in order to break the inner structure. This leads to elastic material properties.

Fig. 1. Rapid prototyping model consisting of deformable volume (rest kinetic volume of the LV) based on starch material of a viable ventricular cavity.
ARTICLE IN PRESS


Fig. 2. 3D solid anatomical rapid prototyping models (RPT) show an inside view of patients individual cardiac structures with the aneurysm and the LV-residual-volume. The model was segmented manually out of a data set with a layer thickness of 0.5 mm.

Fig. 3. Rapid prototyping model shows a massive cardiac-tumor with infiltration to the right ventricular wall and the tricuspid valve.

Fig. 4. Rapid prototyping model shows an enlarged LV with an aneurysm. Segmentation was performed manually with a layer thickness of 1.0 mm.

3. Results

The comparison of the 3D heart model with the real open heart and the use of the model during the surgical procedure influenced preoperative planning and facilitated the operation. Due to the massive volume of the tumor and the infiltration to the tricuspid valve (Fig. 3), the access to the target was chosen through the right ventricle instead of access through the right atrium. A complete mass reduction of the histological poor differentiated sarcoma was achieved including the tricuspid valve, which had to be replaced. Due to enabling identification of risk structures like the right ventricular wall and the right ventricular outflow tract (RVOT), the surgeon was guided through the operation and could determine the malignant tissue (distinguish myocardium and malignant tissue). Afterwards a Cryoablation was done. Postoperatively the echocardiography showed properly the size of the right ventricle with no obstruction of the RVOT.

In two patients, the models were used for aneurysmectomy and LV reshaping (Fig. 4). Preoperative LVESV, measured by echocardiography, was 139.9 ml/m² and 125.0 ml/m². The surgeon could reshape the LV around the residual volume template (Fig. 1) and decrease the LVESV to 64.5 ml/m² and 58.3 ml/m² postoperatively. These residual volumes are in line with the current literature [11]. The postoperative images show a complete resection of the akinetic and dyskinetic target tissue and an elliptical ventricular geometry.

The time to segment the CT data set semi-automatically with a layer thickness of 0.5 mm took about 3 h compared to the segmentation performed manually with a layer thickness of 0.5 mm which took about 8 h. The segmentation performed manually with a layer thickness of 1.0 mm required 5 h.

Quality of resolution of the semi-automatically segmented CT data set and the coarsely layered thickness of 1.0 mm was unsurprisingly less. Regarding time needed for segmentation and quality of target area and structures at risk, only segmentation performed manually with a layer thickness of 0.5 mm showed acceptable results in terms of identifying all target areas and structures at risk.

4. Discussion

Performing an aneurysmectomy or Dor-plasty, visual inspection of the ventricle leads to identification of scarred and viable myocardium. Transmural palpation of contracting muscle delineates the junction of viable and non-viable tissue. An encircling suture at this junction excludes the scar from the ventricular cavity and creates a pursed opening. A Dacron patch is secured onto this opening and eliminates the akinetic or dyskinetic segment [12]. The identification of the scarred and viable tissue on the arrested or fibrillating heart is based on experience but misidentification can occur. In addition, creation of an elliptical ventricle is demanding. Standardized preshaped elliptical balloons (Chase Medical, Dallas, TX; The Blue Egg ™, BioVentrix) may help to size and configure the ventricle, but do not provide a patient’s individual solution. The 3D RPT method tries to support the transfer of 2D images into a 1:1 geometric model, which can be used intraoperatively. Once the viable ventricular cavity (rest kinetic volume of the LV) is printed out as a RPT model, the template can potentially be used for patient individual reshaping the left ventricle. This method converts a two-dimensional (2D) image into a three-dimensional (3D) struc-
ture. The advantage of a 3D model is particularly opponent when dealing with complex structures that have not been previously viewed [13–15]. When a person views a 2D image of a human face, for example, the viewer knows that the nose is in front of the ears and, therefore, gains some 3D perspective of the object. When viewing a 2D image of a rare complex cardiac structure such as an infiltrating tumor, however, the viewer has no preset 3D recognition. A 3D model would, therefore, be helpful when planning or performing an operation on such a complex structure. In terms of identifying all target areas and structures at risk, only the 3D models, segmented manually with a layer thickness of 0.5 mm provide a sufficient resolution. Regarding time for segmentation and the printing process, the whole procedure can be performed within one day in advance of surgery but at this stage is clearly too cumbersome as to be performed on a routine base.

5. Limitations

One limitation of this study is the small number of pathologies in this methodology paper. The second limitation is the lack of validation of the impact of the RPT models. This method may facilitate the surgical procedure due to enhanced orientation, but objective data that would allow determining any benefit on patient outcome are lacking.

6. Conclusion

The use of the 3D RPT-model during resection of ventricular aneurysm and malignant cardiac tumors facilitates the surgical procedure, due to enhanced preoperative planning and intraoperative orientation of risk structures and the target tissue, and may improve surgical outcome.

Acknowledgments

The authors wish to thank all the collaborators at the Medical Faculty at University of Leipzig and ICCAS. The Innovation Center of Computer Assisted Surgery (ICCAS) at the Faculty of Medicine at the University of Leipzig is funded by the German Federal Ministry for Education and Research (BMBF) and the Saxon Ministry of Science and Fine Arts (SMWK) in the scope of the initiative Unternehmen Region with the grant numbers 03 ZIK 031 and 03 ZIK 032.

References