Image Processing Methods for an Exact Reproduction of Unique Waxed Heart Specimens

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Summary. Precise knowledge of cardiac anatomy forms the basis for diagnosis and treatment of congenital heart disease. Only a few centers worldwide have access to specialized pathology collections of hearts with congenital malformations. Rare specimens cannot be replaced after loss or damage. To preserve, reproduce, and publish the unique specimens of the Cardiac Registry, Children's Hospital Boston, for worldwide teaching and research purposes, we have developed the image processing methods described in this paper. The challenge is to preserve all relevant details unaltered in the reproduced models.

1 Introduction

Congenital heart defects are one of the most common congenital defects in children and often have a complex anatomic structure. Precise knowledge of cardiac anatomy forms the basis for diagnosis and treatment of congenital heart disease [1]. Static images in books are very limited for the demonstration of complex three-dimensional (3D) relationships. Virtual 3D models, which can be rotated and cut in any plane are much more sufficient for this purpose. However, the perfect teaching and research tool would be a highly accurate reproduction of the original heart. Only anatomic specimens provide the best possible way to learn and understand the special relations and dimensions of cardiac malformations. For example, inserting probes into the specimens help to clarify the connections between different cavities.

Continued use of the specimens lead inevitably to their gradual degeneration. Rare specimens cannot be replaced after loss or damage. As many congenital heart defects can be surgically corrected nowadays, many specimens of the Cardiac Registry are unique, since this collection was established as cardiac surgery was in a very early stage. Additionally, only a few centers worldwide have access to specialized pathology collections.

A method for an exact reproduction of unique specimens is therefore desirable. Conventional methods do not yield the accuracy required to show all details of the essential pathology.

2 Material and Methods

A unique collection of waxed heart specimens with congenital heart defects is available at the Cardiac Registry of the Children's Hospital, Harvard Medical School, Boston. In contrast to formalin fixed specimens, waxed hearts keep their original shape and therefore 3D dimensions are easier to appreciate. Twelve of the 70 specimens were reproduced with our method.

The hearts were digitized by high-resolution spiral computer tomography (0.5 mm slices with 0.2-0.3 mm overlap, in-plane resolution < 0.25 mm) with a Siemens Volume Zoom 4 scanner. The specimens were placed on a flat Plexiglas® plate, which can be more easily removed from the data than the curved CT table.

For reproduction, we use stereo-lithographic rapid prototyping techniques, for which a surface representation of the model has to be generated. The conversion of the voxel-data into a surface requires the selection of a threshold and must preserve the size, thickness and topology of the heart specimen. A single threshold yields unsatisfactory results because of the high degree of accuracy necessary to show all relevant details of the congenital malformation. In the following, we describe the steps of our reproduction scheme in further detail.

2.1 Removing the Plexiglas® Plate

Since it is practically impossible to place the Plexiglas® plate exactly horizontally on the CT table, the first step to its removal is to determine its position and normal. We use a least-squares fit to the plate outside the area where the heart actually touches it. Simply defining all voxels below the detected plate as background would yield a flat surface of the model in the parts of the heart that were in the immediate vicinity of the plate. Therefore, we calculate the mean value of the plate in the respective distance from its top outside the area, where the heart lay, and subtract it along the whole plane. The subtraction procedure is performed for all voxels inside and below the plate (Figure 1).

2.2 Optimal Threshold Calculation and Conversion in Surface Representation

The conversion of voxel data into a surface representation, e.g. by means of the Marching Cubes algorithm [2], requires the definition of a threshold. Manual threshold selection yields optically similar visualizations for a wide range of threshold values. Lower thresholds seem to be better at the first glance, since thin structures like heart valves tend to have lower houndsfield-unit values due to partial volume effects. Lowering the threshold naturally increases the thickness of all other parts of the model, e.g. of the vessel walls (Figures 2a and 2b, solid arrows). The solid volume of the model varies up to 30% depending on the chosen threshold. When lowering the threshold, small vessels are closed completely due to this effect before all valves appear, especially in small heart specimens. Closing of vessels that are not closed in the original specimen dramatically changes the type of pathology and is therefore unacceptable.

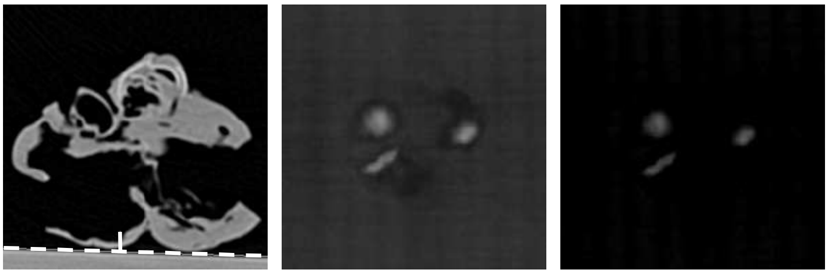

Fig. 1. (a) Original slice with detected plate. Reconstructed slices along the top of the plane (b) before and (c) after subtraction.

We applied the method of Wiemker and Pekar [3] for an automatic detection of the optimal threshold. The method allows for the calculation of the total absolute gradient value on the surface generated by the selection of a threshold for all possible threshold values in a single path through the volume. Using a similar technique, the resulting surface area for all possible threshold values can also be computed in a single path. Thus, the mean absolute gradient on the surface for all possible threshold values can be calculated. The threshold that yields the maximal mean absolute gradient is selected for the surface generation.

For validation if this actually provides a result with correct thickness, our software allows to measure the thickness of structures in the 3D visualization. The user clicks on the structure of interest and the thickness is calculated along the viewing ray. If the surface of the structure is not perpendicular to the ray, a local least-squares fit of the surface can provide the new direction of measurement. These virtual measurements as well as real measurements on a rapid-prototyping model both confirmed the plausibility of the selected threshold.

The conversion of the voxel-data into the surface representation is performed using vtk (Kitware, Inc., New York, USA). For large specimens, a simplification of the generated surface mesh is necessary to comply with the specifications of rapid-prototyping machines, which can only handle data of up to approx. 80 MB (in binary STL format). Mesh simplification and visualization of the simplification error as a color-coded surface rendering is also done by the application of vtk.

2.3 Interactive Local Threshold Adaptation

The threshold value selected as described in the previous section yields correct thickness of those parts of the model that are not seriously affected by partial volume effects (thus, the larger parts), but, since it is rather high, substantial parts of the valves tend to vanish and some of the visible parts of the valves may be not connected to the main part of the model.

These problems can be more precisely analyzed and corrected in two-dimensional slices than in 3D reconstructions. Therefore, the mesh is cut with two-dimensional slices and the resulting contours – color coded according to a connected component analysis – are displayed as overlays on top of the voxel data, see Figure 2c. In the figure, the voxel data is shown with a lower threshold than the one used for the mesh generation, so that the valve (arrow) is now completely visible.

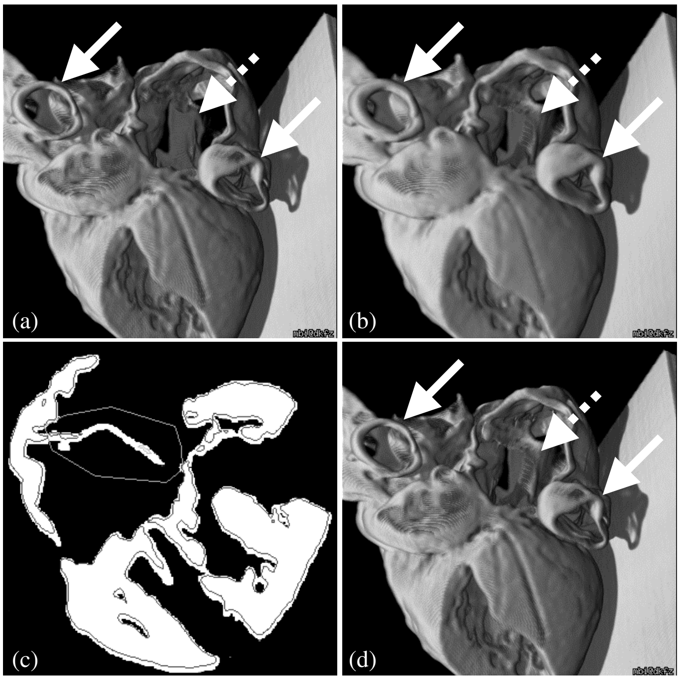

Fig. 2. (a), (b) Visualizations of unchanged data set with (a) the calculated optimal threshold and (b) a lower threshold. (c) Interactive definition of area for local adaptation of threshold. (d) Result after adaptation. Arrows: see text.

Our software allows using locally a different (lower) threshold to make the valves visible in the visualization and the reproduced models. A rough delineation of the area, where the lower threshold should be applied, is sufficient, as the polygon in Figure 2c.

Figure 2d shows that with this technique the valve (dashed arrow) is now present and the thickness of the vessels and other structures are preserved (solid arrow); compare with Figures 2a,b.

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