Graph-cuts based Reconstructing Patient Specific Right Ventricle: First Human Study*

Liang Zhong[1,2], Min Wan[3], Yi Su[3], Soo Kng Teo[3], Chi Wan Lim[3], Xiaodan Zhao[1], Jun-Mei Zhang[1], Bo Yang Su[1], Ju Le Tan[1], and Ru San Tan[1,2]

***Abstract*— Right ventricular (RV) function is increasingly recognized to play an important role in the clinical status and long-term outcome in patients with congenital heart disease as well as ischemic cardiomyopathy with left ventricular dysfunction. However, quantification of RV characteristics and function are still challenging due to its complex morphology and its thin wall with coarse trabeculations. To assess RV functions quantitatively, establishing the patient-specific model from medical images is a prerequisite task. This study aims to develop a novel method for RV model reconstruction. Magnetic resonance images were acquired and preprocessed. Contours of right ventricle, right atrium and pulmonary artery were manually delineated at all slices and all time frames. The contour coordinates as well as the medical image specifications such as image pixel resolution and slick thickness were exported. The contours were transformed to the correct positions. Reorientation and matching were executed in between neighboring contours; extrapolation and interpolation were conducted upon all contours. After preprocessing, the more dense point set was reconstructed through a variational tool. A Delaunay-based tetrahedral mesh was generated on the region of interest. The weighted minimal surface model was used to describe RV surface. The graph-cuts technique, i.e., max-flow/min-cut algorithm, was applied to minimize the energy defined by the model. The reconstructed surface was extracted from the mesh according to the min-cut. Smoothing and remeshing were performed. The CPU time to reconstruct the model for one frame was approximately 2 minutes. In 10 consecutive subjects referred for cardiac MRI (80% female), right ventricular volumes were measured using our method against the commercial available CMRtools package. The results demonstrated that there was a significant correlation in end-diastolic and end-systolic volumes between our method and commercial software (r= 0.89 for end-diastolic volume and r=0.79 for end-systolic volume, both P<0.0001). The time to obtain right ventricular volumes was shorter using our method than commercial one. In conclusion, a new method for right ventricle reconstruction has been developed. We envisage that this automatic modeling tool could be used by radiographer and cardiologists to assess the RV function in diverse heart diseases.**

*Research supported by the Agency for Science, Technology and Research (A*STAR), SERC Biomedical Engineering Programme Grant 1211480003, the SingHealth Foundation (SHF/FG408/2009), (SHF/FG453P/2011) and (SHF/FG503P/2012), National Medical Research Council Grant (NMRC/EDG/1037/2011), Goh Cardiovascular Research Grant (Duke-NUS-GCR/2013/0009), and NHCS Centre Grant Seed Funding (NHCS-CGSF/2014/003).

[1]L. Zhong, et al. are with National Heart Centre Singapore, 5 Hospital Drive, 169609, Singapore. {zhong.liang, zhao.xiaodan, zhang.junmei, su.boyang,tan.ju.le, tan.ru.san}@nhcs.com.sg

[2]L. Zhong, et al. are with Duke-NUS Medical Graduate School, 169857, Singapore.

[3]M. Wan, et al. are with Institute of High Performance Computing, 1 Fusionopolis Way #16-16 Connexis, 138632, Singapore. wanm@ihpc.a-star.edu.sg

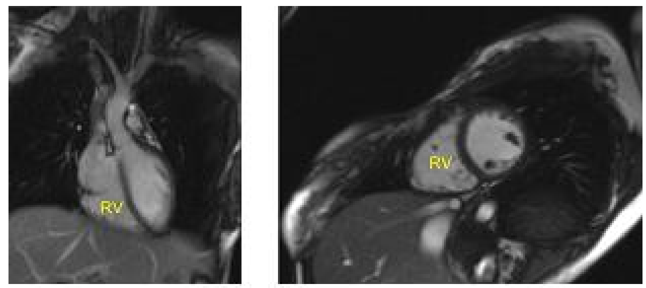


Fig. 1. Two dimensional view of right ventricle

I. INTRODUCTION

The importance of right ventricle (RV) in various physiological and pathological conditions has now been well recognized after four decades of neglect [1]. Being a predominant factor for the prognosis of pulmonary hypertension, myocardial infarction and left ventricular dysfunction [1], as well as the treatment of congenital heart diseases [4], the right ventricular morphology and function require a more quantitative assessment in clinical practice. The accurate and proper functional assessment is based on the correct and precise ventricular model.

Due to its complex geometry, the right ventricle poses a great challenge for patient-specific modeling from contours. Its normal anatomy is triangular from the long-axis view and crescent from short-axis view [2], which is also shown in the MR images (Fig. 1). According to Goor et al, [3], the whole right ventricle could be divided into three components: (a) the inlet portion with the tricuspid valvular apparatus (tricuspid valve, chordae tendineae and papillary muscles); (b) the trabeculated apical myocardium; (c) the outlet portion with the infundibulum or conus, which corresponds to the smooth myocardial outflow region.

The complex crescent shape renders some existing techniques used in left ventricle (LV) reconstruction ineffective. The old procedure used the centroids of all contours to extrapolate the apex, which was not reasonable in the RV since the centroids probably lie outside the contours. Our previous studies [4] used commercial software to reconstruct the models. The demand of an in-house reconstruction tool, which could take into account the right ventricle characteristics effectively, motivates this study.

In this study, we developed a novel method to reconstruct patient-specific right heart structure including the right ventricle, right atrium, and pulmonary artery. MR images were

978-1-4244-7929-0/14/$26.00 ©2014 IEEE

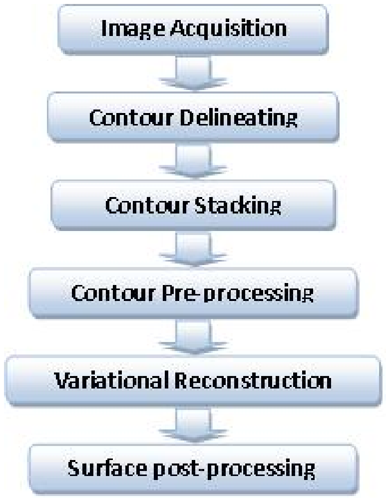


Fig. 2. Reconstruction Workflow

acquired and pre-processed. Contours indicating right ventricle or right atrium and pulmonary artery were delineated on short axis images by trained experts. Contour coordinates were transformed to the correct position according to the image specification. The classified contour data were re-oriented, matched, extrapolated, and interpolated. A variational reconstruction tool was applied and a delaunay-based tetrahedral mesh was generated in 3D space. The weighted minimal surface model [8] was used to describe the reconstruction. A mature minimization tool, the max-flow/min-cut algorithm [11] developed in combinatorial optimization theory, was utilized. The reconstruction result was extracted from the mesh according to the min-cut. Remeshing and smoothing were then performed to improve the surface mesh quality, which facilitates the downstream geometry analysis or simulation. The chart in Fig. 2 illustrates the workflow, which is described in detail in Section II. Section III presents and analyzes the results. Section IV concludes the article.

II. Methods

A. Contour Delineating and Stacking

Magnetic Resonance Imaging (MRI) was used as the medical imaging modality in this study due to its non-invasive and non-radiant advantages. After Cardiac MR images were acquired, contours were chosen and delineated on short-axis images. The following contour transformation from 2D image plane to 3D space (1) was extracted from the DICOM data (see Fig. 3).

$$\begin{bmatrix} P_x \\ P_y \\ P_z \\ 1 \end{bmatrix} = \begin{bmatrix} X_x\triangle i & Y_x\triangle j & 0 & S_x \\ X_y\triangle i & Y_y\triangle j & 0 & S_y \\ X_z\triangle i & Y_z\triangle j & 0 & S_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i \\ j \\ 0 \\ 1 \end{bmatrix} = M \begin{bmatrix} i \\ j \\ 0 \\ 1 \end{bmatrix}. \quad (1)$$

B. Contour Data Pre-processing

Three types of contours, i.e., RV, RA, and PA, were regrouped into two groups, RV-RA and RA-PA. The first two phases in Fig. 4 illustrates this step. The following pre-processing was then performed sequentially on each group of contours separately.

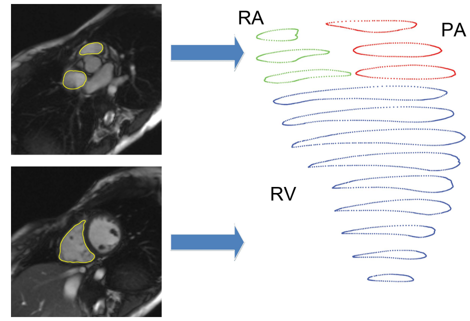


Fig. 3. Contours transformation

Contour re-orientation was first performed. All contours were re-oriented in the counterclockwise direction. This task is accomplished via checking the signed area of the region bounded by the polygon or constructing the constrained Delaunay triangulation of the polygon. Contour matching and interpolation were similar to previous studies [5]-[7], which are illustrated in Fig. 4. The extrapolation was aimed to add an apical patch for the truncated shape. Our previous study on LV used centroids of contours to derive (extrapolate) the apex. In the case of the RV, the crescent shape of all contours would cause the usage of centroids improper since the centroids will probably lie outside the contours. Instead, we firstly computed the medial axis of each contour. The medial axes were then applied in the extrapolation to estimate the right ventricle apex. The output is a more dense point set.

C. Variational Reconstruction

The weighted minimal surface model [8] was used to address the reconstruction problem. We adapted the model by adding an area regularization term.

$$E(S) = \sum_{S=\bigcup_i S_i} \int_{S_i} \big(d(x,P) + \alpha\big) ds. \quad (2)$$

To solve this problem, numerical methods [9] were applied. A Delaunay based tetrahedral mesh was generated in the 3D space. The energy functional was then discretized as in (3):

$$\begin{aligned} E(S) &= \int_S \big(d(x,P)+\alpha\big)ds \\ &= \sum_{i\neq j} \int_{K_i \bigcap K_j} \big(d(x,P)+\alpha\big)ds \\ &= \sum_{i\neq j} \big(d_{i,j}+\alpha\big) s_{i,j} \mathbf{1}_{\{l_i \neq l_j\}}. \end{aligned} \quad (3)$$

The reconstructed surface was approximated as a triangle mesh, i.e., the union of all triangles shared by two tetrahedral from different partitions. The mesh generation and constraints establishment steps are shown in Fig. 5. The discrete minimization problem is equivalent to a graph

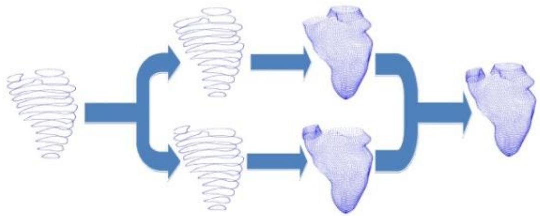
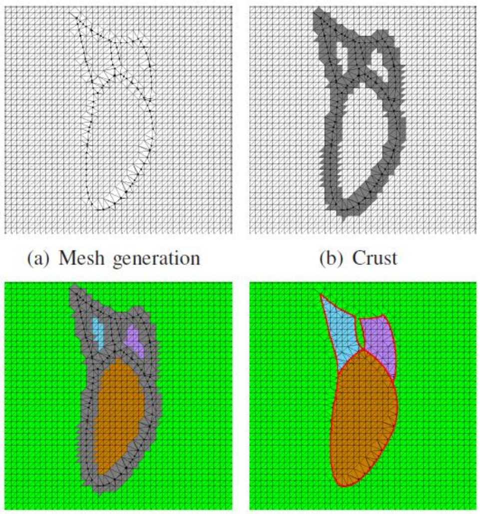


Fig. 4. Contour Data Pre-processing



(a) Mesh generation (b) Crust

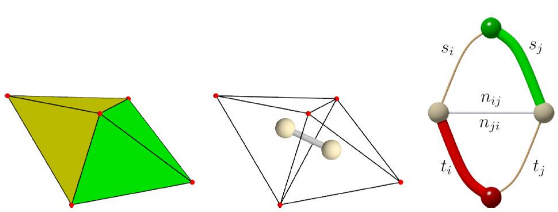
(c) Constraints establish (d) Segmentation

Fig. 5. Variational Reconstruction

problem. The equivalence has been well justified in [10]. The graph topology is the dual of the primal mesh as shown in Fig. 6. The edge weights are assigned according to (2). After applying the max-flow/min-cut algorithm in [10], the reconstructed surface could then be extracted from the mesh according to the min-cut, as shown in Fig. 5(d).

D. Smoothing and Remeshing

An improved Laplacian smoothing algorithm [11] is adopted in our method. The remeshing algorithm in [12] is used in our study. First, normalized edge lengths are computed based on geometric metric and mesh sizing function [13]. Edge splitting and contraction are conducted using the classic criterion. Meanwhile, edge flipping is also done in each iteration to improve the triangle mesh quality.



(a) Primal mesh (b) Dual graph (c) Edge weights

Fig. 6. Graph Construction

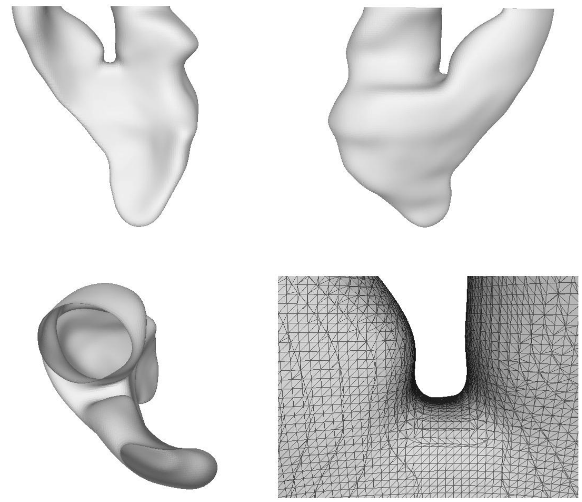


Fig. 7. Reconstructed models

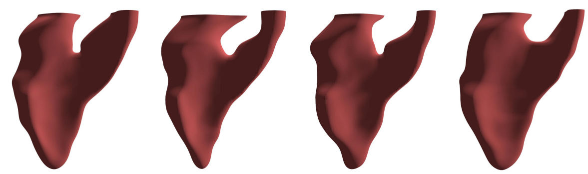


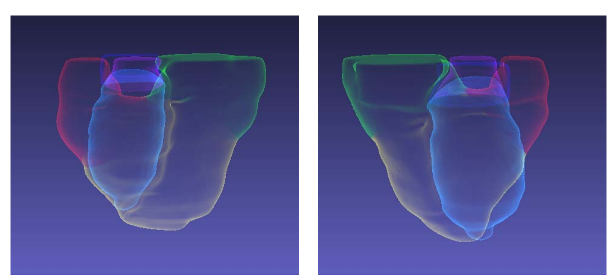
Fig. 8. Reconstructed models

III. RESULTS

The proposed method was experimented on ten subjects, whose characteristics are listed in Table I. The cine MR images were acquired on a 1.5T Siemens scanner with ECG gating. The slice thickness is 8mm. The pixel spacing is 1.46mm. The TR/TE/flip angle is 68ms/1ms/70^o.

In Fig. 7, views from several angles as well as a zoomed view are shown. In Fig. 8, selected frames of reconstructed model are shown: the first and the third of which are end-diastole and end-systole phases. In Fig. 9 and 10, a complete heart model is shown, including both ventricles and atria, aorta, and pulmonary artery. In Fig. 11, two statistics concerning the surface mesh quality are shown. The criterion for (a) is based on [14] and (b) is the triangle angle distribution.

From the experiment, we could observe an anatomically reasonable right cardiac structure, especially the RV-RA-PA



(a) (b)

Fig. 9. View of chambers and arteries separated

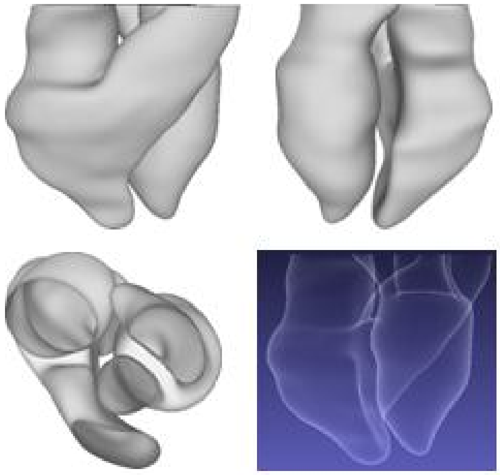


Fig. 10. Full heart model

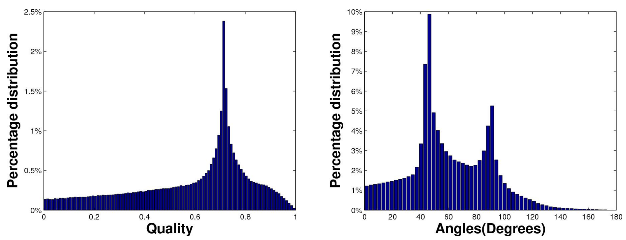


Fig. 11. Mesh quality statistics

junction region, which validates our proof of concept. The end-diastole and end-systole volumes were computed and compared with results from the CMRtools suite (Cardiovascular Solution, UK). The results demonstrated that there was a significant correlation in end-diastolic and end-systolic volumes between our method and commercial software (r= 0.89 for end-diastolic volume and r=0.79 for end-systolic volume, both P<0.0001). The time to obtain right ventricular volumes was shorter using our method than commercial one.

IV. CONCLUSIONS

Our proposed graph-cuts based method with automated model reconstruction is a practical alternative for modeling the right ventricle, as well as right atrium and pulmonary artery, and for obtaining right ventricular volumes in a time-efficient manner compared to the current clinical standard.

TABLE I
PATIENT STATISTICS

Patients	Gender	Age	bsa(m^2)	RR(ms)
Patient 1	F	29	1.3	805
Patient 2	F	45	1.2	800
Patient 3	F	21	1.3	850
Patient 4	F	54	1.3	1025
Patient 5	F	17	1.5	715
Patient 6	F	20	1.7	760
Patient 7	F	66	1.7	1040
Patient 8	M	23	2	680
Patient 9	M	27	1.6	1100
Patient 10	F	24	1.5	930

We envisage that this tool shall be used by radiographer and cardiologists to assess right ventricular function in patients with diverse heart disease.

ACKNOWLEDGMENT

This work was supported in part by research grants from the Agency for Science, Technology and Research (A*STAR), SERC Biomedical Engineering Programme Grant (121 148 0003), the SingHealth Foundation (SHF/FG408/2009), (SHF/FG453P/2011) and (SHF/FG503P/2012), National Medical Research Council Grant (NMRC/EDG/1037/2011), Goh Cardiovascular Research Grant (Duke-NUS-GCR/2013/0009), and NHCS Centre Grant Seed Funding (NHCS-CGSF/2014/003).

REFERENCES

[1] L.L. Mertens, and M.K. Friedberg, “Imaging the right ventriclecurrent state of the art,” Nature Reviews Cardiology, vol. 7, pp. 551?563, 2010.
[2] S. Ho, and P. Nihoyannopoulos, “Anatomy, echocardiography, and normal right ventricular dimensions,” Heart(suppl 1), pp. i2–i13, 1992.
[3] D.A. Goor, and C.W. Lillehei , Congenital malformations of the heart: embryology, anatomy, and operative considerations, Grune & Stratton New York, 1975.
[4] L. Zhong, “Right ventricular regional wall curvedness and area strain in patients with repaired tetralogy of Fallot,” American Journal of Physiology-Heart and Circulatory Physiology, vol. 302, pp. H1306–H1316, 2012.
[5] C.L. Bajaj, et al., “Arbitrary Topology Shape Reconstruction from Planar Cross Sections,” Graphical Models / graphical Models and Image Processing /computer Vision, Graphics, and Image Processing, vol. 58, pp. 524–543, 1996.
[6] J.-D. Boissonnat, “Shape reconstruction from planar cross sections,” Graphical Models /graphical Models and Image Processing /computer Vision, Graphics, and Image Processing, vol. 44, pp. 1–29, 1988.
[7] M. Wan, C. Lim, J.-M. Zhang, Y. Su, S.Y. Yeo, D. Wang, R.S. Tan, and L. Zhong, “Reconstructing Patient-Specific Cardiac Models from Contours Via Delaunay Triangulation and Graph-Cuts,” presented at the 2013 Int. Conf. Engineering in Medicine and Biology Society, Osaka, Japan
[8] H.K. Zhao, “Fast surface reconstruction using the level set method. Variational and Level Set Methods in Computer Vision,” Proceedings. IEEE Workshop on, IEEE, 2001.
[9] M. Wan, Y. Wang, and D. Wang, “Variational surface reconstruction based on delaunay triangulation and graph cut,” International journal for numerical methods in engineering, vol. 85, pp. 206?229, 2011.
[10] Y. Boykov and V. Kolmogorov, “An experimental comparison of min-cut/max-flow algorithms for energy minimization in vision,” Pattern Analysis and Machine Intelligence, IEEE Transactions on, vol. 26, pp. 1124?1137, 2004.
[11] J. Vollmer, et al., ”Improved Laplacian Smoothing of Noisy Surface Meshes,” Computer Graphics Forum, vol. 18, 131–138, 1999.
[12] D. Wang, et al., ”Enhanced remeshing from STL files with applications to surface grid generation.” Communications in Numerical Methods in Engineering, vol. 23, pp. 227–239, 2007.
[13] P.J., Frey, “About Surface Remeshing,” International Meshing Roundtable, pp. 123–136, 2000.
[14] P.J. Frey, and H. Borouchaki, ”Surface mesh quality evaluation,” International journal for numerical methods in engineering, vol. 45, pp. 101–118, 1999.