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Abstract: The cardiac flow volumes through the mitral valve orifice were measured using a Gaussian control surface based, Doppler angle independent method on real-time three-dimensional digital Doppler data from 13 children. Our flow volume measurements correlated and agreed well with the ascending aorta flow volumes measured by PVC MRI and stroke volumes obtained from MRI left ventrical volumetric measurements.

* Manuscript

Real-time three-dimensional digital Doppler method based on Gaussian control surface for measurement of flow volumes

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Abstract. The cardiac flow volumes through the mitral valve orifice were measured using a Gaussian control surface based, Doppler angle independent method on real-time three-dimensional digital Doppler data from 13 children. Our flow volume measurements correlated and agreed well with the ascending aorta flow volumes measured by PVC MRI and stroke volumes obtained from MRI left ventrical volumetric measurements.

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1. Introduction

Accurate and reproducible measurement of cardiac flow volumes has important implications for clinical medicine and cardiovascular research but has not been achieved with conventional ultrasound Doppler methods. Several three-dimensional (3D) Doppler techniques were developed but currently available three-dimensional flow volume measurement methods have their limitations such as Doppler angle dependency [1,2], geometric shape assumption requirements [1,2], and over-simplified theoretical model [3,4]. A method based on Gaussian control surface was reported and validated in animal models and in vivo studies [5,6,7]. This control surface method eliminated those limitations existed in other 3D methods but the accuracy was limited by low quality of the 3D data that was acquired by reconstructing 30 rotational long axis slices.

The latest real-time three-dimensional digital Doppler (RT 3DDD) technique implemented in Philips Sonos 7500 ultrasound system equipped with X4 matrix transducer (Philips, Andover, MA) produced 3D volumetric flow velocity measurement and superior image quality. Because cardiac ultrasound is non-invasive, inexpensive and portable to the bedside, if proven accurate and reproducible, RT 3DDD may become the modality of choice for intracardiac flow measurement in patients with congenital and acquired heart diseases.

The purpose of this study was to validate the feasibility of a RT 3DDD method that is independent of the angle of incidence and utilizes the 3D velocity profiles at the mitral

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valve orifices as a non-invasive clinical and research tool for measurement of cardiac flow volumes. The potential of achieving semi-automatic flow volume measurement was also explored.

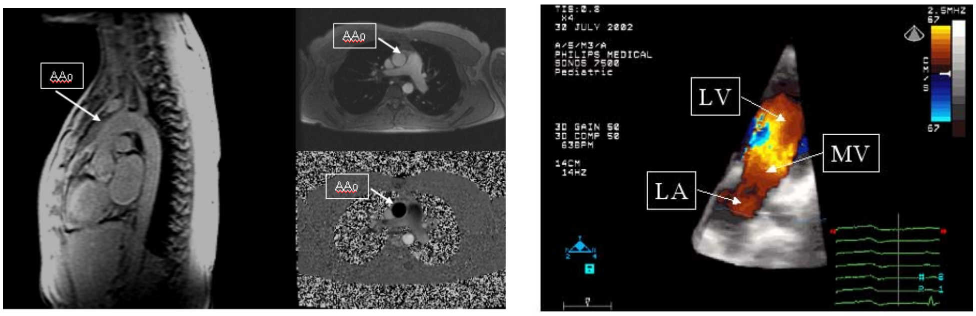
2. Material and methods

2.1 Study population

This study was approved by the Institutional Review Board at the University of Iowa. A total of 13 children with ages ranging from 6 to 13 years (mean age 10.46±2.5 years, 8 male and 5 female) were enrolled after obtaining written informed consent and assent. 12 subjects were healthy and one was found unexpectedly to have a moderate sized secundum atrial septal defect. All subjects were included in our feasibility study.

2.2 Data Acquisition

The 3D Doppler and MRI studies were performed consecutively on the same day for each subject after heart rates and blood pressures were obtained before each study. MRI study was performed using a GE CV/i 1.5T scanner with a torso coil. 2D cine phase contrast images were acquired in a plane perpendicular to the long axis of the ascending aorta (VENC=150cm/s, 256×160 matrix, 20 degree flip angle, 32 kHz bandwidth, 6 views/segment and 20 cardiac phases). Short axis 2D Fiesta images of the left ventricle were also acquired (8 mm slice thickness, 224×160 matrix, 40 degree flip angle, 125 kHz bandwidth, 12-16 views/segment and 20 cardiac phases). The location of ascending aorta cross section plane, sample magnitude and phase images are shown in Fig. 1A.



A **B**

Fig. 1. A: PVC MRI sample images. Left, ascending aorta cross section location shown on long axis slice. Top right, cross section magnitude image. Bottom right, cross section phase image. B: RT 3DDD sample rendered 3D flow profile.

A Philips Sonos 7500 ultrasound system equipped with X4 matrix transducer was used to acquire the 3D Doppler velocity data through the mitral valve orifice from an apical window (12-19 frames per cardiac cycle, 80×80×208 array for each frame). Acquisition was performed in left recumbent position with breath holding in EKG triggering mode. Fig. 1B shows a sample rendered 3D flow profile. Four subvolumes of 3D flow profile were compiled and time-aligned to create the larger volume shown.

2.3 MRI Data Analyses

MRI data were analyzed on off-line workstation (GE Advantage Windows) using vendor-provided software. The boundary of the ascending aorta was manually traced on each magnitude image and then fine tuned on the corresponding phase image. The instantaneous flow rate was calculated by integration of flow velocity on the aortic cross section. Flow rate curve was generated by linear interpolation of measured instantaneous flow rates with respect to time. Net forward flow per cardiac cycle was quantified by flow rate integration with respect to time.

The endocardial border of left ventricle was manually traced on contiguous 2D Fiesta sequence short axis slices in end-systole and end-diastole. Left ventricular stroke volume (LVSV) was calculated as the difference between end-systolic and end-diastolic LV volumes. LV volume was calculated as summation of measured slice areas multiplied by slice thickness.

2.4 RT 3DDD Data Analyses

Based on the Gaussian control surface theorem from fluid mechanics [8], a spherical control surface centered at the transducer with adjustable radius was placed at the mitral valve orifice. The measured velocity components on this control surface are along the directions of ultrasound beams and normal to the control surface. By surface integration of flow velocities inside the mitral valve orifice on the control surface, the instantaneous flow rate was calculated. Therefore, the effect of Doppler angle on flow rate accuracy was removed. Flow rate curve was generated by cubic interpolation of measured instantaneous flow rates with respect to time. The flow volume was calculated in the same way as that of PVC MRI.

Fig. 2 shows different views in a diastolic data with gray scale images in Figs. 2A and 2C, color Doppler images in Figs. 2B and 2D. Figs. 2A and 2B show the long axis views with locations of control surfaces. The control surface was projected onto the short axis for viewing and segmentation purposes. Figs. 2B and 2D show the projected control surfaces. For each frame, the control surface was manually placed at a location where the mitral valve can be identified on both projected control surface gray scale and color Doppler images.

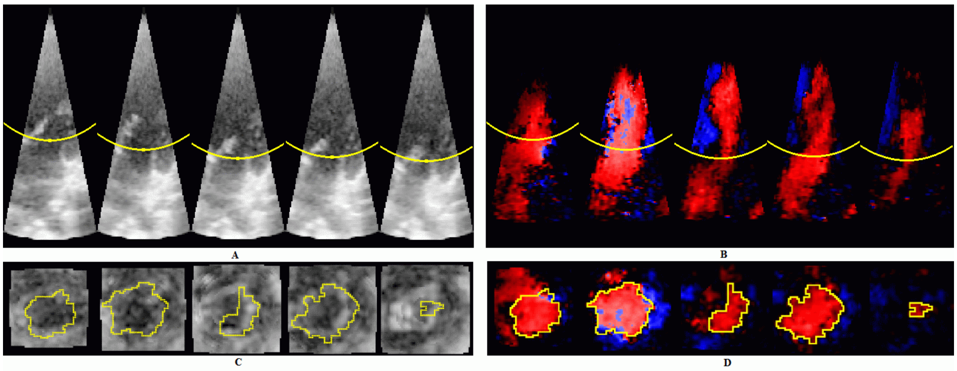


Fig. 2. Different views of diastole. A: Long axis gray scale images with control surface locations. B: Long axis color Doppler images with control surface locations. C: Projected control surface gray scale images with identified flow region. D: Projected control surface color Doppler images with identified flow region.

On each of the projected control surface color Doppler images, the flow region, defined as the region inside the mitral valve orifice with visible flow velocity, was segmented using a semi-automatic method. First, a very low threshold was used to remove background noise. Second, several candidate regions were automatically identified using binary distance transform [9] followed by watershed [10]. Then the operator manually selected several candidate regions to create the flow region. Fig. 3 shows the automatically identified candidate regions on the left and selected flow region from candidates on the right. The flow region selection results of one data set are shown in Fig. 2C and 2D. The flow region can also be manually traced by operator.

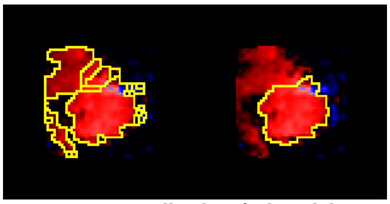


Fig. 3. Automatically identified candidate regions and flow region identified from candidate regions.

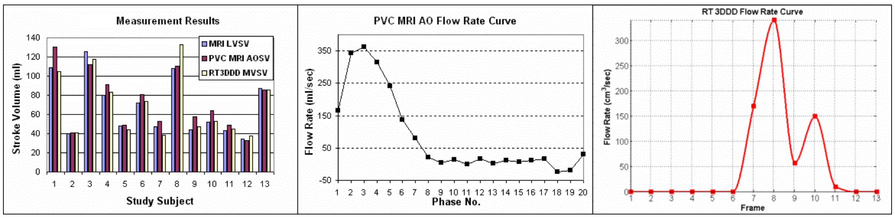
Based on the fact that the cardiac flow through mitral valve orifice is directed uniformly from the left atrium to the left ventricle. The aliased velocities inside the flow region were automatically identified and unwrapped.

3. Results

There were no statistically significant differences in the heart rate, systolic and diastolic blood pressures before 3D Doppler and MRI studies (paired t-test: two tails, $p > 0.05$).

In 234 out of all 260 frames of RT 3DDD data from 13 study subjects (multiple data sets available for some subjects), the flow regions were successfully segmented using our semi-automatic method. In the remaining 26 frames, which happened between the Epeak an A-peak of diastole, manual tracing produced better segmentation results than semi-automatic method but the difference reflected in flow volumes was less than 2.5%.

If multiple data sets were acquired for a subjects, the measurement on the data set with a better 3D image quality was used. Fig. 4A shows all measurement results by MRI, PVC MRI and RT 3DDD. The flow rate curves of PVC MRI at the ascending aorta and RT 3DDD through mitral valve of subject 12 are shown in Fig. 4B and Fig. 4C.



A B C

Fig. 4. A: Measurement results of MRI, PVC MRI and RT 3DDD. B: Flow rate curve of PVC MRI at the ascending aorta. C: Flow rate curve of RT 3DDD through mitral valve orifice.

To validate the accuracy of measurement of flow volume by PVC MRI, stroke volume (SV) by PVC MRI at the ascending aorta (AOV) was compared with the SV by LV volumetric measurement (LVSV) using Pearson and Bland-Altman analyses. The SV measured by the two methods correlated well (Pearson test: $r = 0.96$, $y = 0.96\ x + 7.66$ ml, SEE = 9.17 ml, $p < 0.05$) and agreed well (Bland-Altman: mean difference = 5.08 ml, STD = 8.50 ml). The results are shown in Fig. 5A.

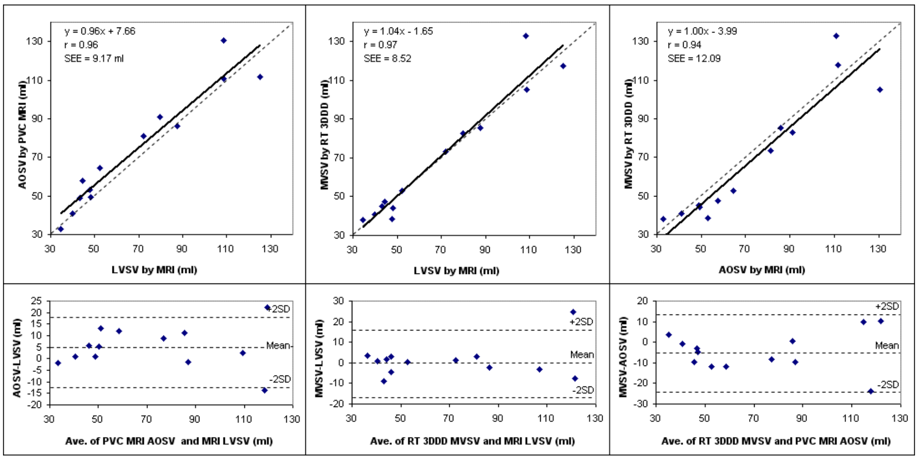


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Fig. 5. Comparison results (top: Pearson test, bottom: Bland-Altman) of different flow volume measurement methods. A: PVC MRI AOSV vs. MRI LVSV. B: RT 3DDD SV vs. PVC MRI AOSV. C: RT 3DDD SV vs. MRI LVSV.

The SV measured at the mitral valve orifice (MVSV) by the RT 3DDD method was compared with the SV at the ascending aorta by PVC MRI and SV by LV volumetric measurement by MRI. The SV measured by the RT 3DDD method correlated well and agreed well with both the SV by LV volumetric measurement by MRI (Pearson test: r = 0.97, y = 1.04 x - 1.65 ml, SEE = 8.52 ml, $p < 0.05$. Bland-Altman: Mean difference = 0.93 ml, STD = 8.23 ml) and the SV measured at the ascending aorta by PVC MRI (Pearson test: r = 0.94, y = 1.00 x – 3.99 ml, SEE = 12.09 ml, $p < 0.05$. Bland-Altman: mean difference -4.61 ml, STD = 9.44 ml). The results are shown in Fig. 5B and Fig. 5C.

4. Discussion

This study demonstrated that the measurement of cardiac flow volumes through the mitral valve by our RT 3DDD method is feasible. The flow volume measurements correlated and agreed well with the flow volumes measured at the ascending aorta by PVC MRI and SV by LV volumetric measurement by MRI.

The simple semi-automatic flow region segmentation algorithm performed well for 90% of the data frames acquired and it relieved the operator from time-consuming manual border tracing. Identifying diastolic frames, selecting control surface locations, and selecting flow regions from candidate regions all require expert knowledge and interaction. The accuracy of measurement is affected by those operator dependent factors. In the future, automated segmentation of mitral valve orifice on gray scale images will be explored to minimize human interactions in control surface location selection and flow region segmentation.

Acknowledgements

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References

[1] Tsujino H, Jones M, Shiota T, et al. Real-time three-dimensional color Doppler echocardiography for characterizing the spatial velocity distribution and quantifying the peak flow rate in the left ventricular outflow tract. Ultrasound Med Biol. 2001;27(1):69-74.
[2] Shiota T, Jones M, Aida S, et al. Validation of the accuracy of both right and left ventricular outflow volume determinations and semiautomated calculation of shunt volumes through atrial septal defects by digital color Doppler flow mapping in a chronic animal model. J Am Coll Cardiol. 1999;34(2):587-593.
[3] Berg S, Torp H, Martens D, et al. Dynamic three-dimensional freehand echocardiography using raw digital ultrasound data. Ultrasound Med Biol. 1999;25(5):745-753.
[4] Ishii M, Hashino K, Eto G, et al. Three-dimensional reconstruction of color Doppler-imaged vena contracta and flow convergence region. Circulation. 2001;103(5):664-9.
[5] Mori Y, Rusk RA, Jones M, Li XN, Irvine T, Zetts AD, Sahn DJ. A new dynamic three-dimensional digital color Doppler method for quantification of pulmonary regurgitation: validation study in an animal model. J Am Coll Cardiol. 2002;40(6):1179-1185.
[6] Rusk RA, Li XN, Mori Y, et al. Direct quantification of tansmitral flow volume with dynamic 3-dimensinonal digital color Doppler: a validation study in an animal study. J Am Soc Echocardiogr 2002;15(1): 55-62.
[7] Mehwald PS, Rusk RA, Mori Y, et al. A validation study of aortic stroke volume using dynamic 4-dimensional color Doppler: an in vivo study. J Am Soc Echocardiogr. 2002;15(10): 1045-1050.
[8] Plapp JE. Engineering Fluid Mechanics. Englewood Cliffs, NJ: Prentice-Hall, 1968:591¨C4.
[9] Breu H, Gil J, Kirkpatrick D, Werman M. Linear time Euclidean distance transform algorithms. IEEE Trans on Pattern Analysis and Machine Intelligence. 1995;17(5):529-33.
[10] Vincent L, Soille P. Watersheds in digital spaces: An efficient algorithm based on immersion simulations. IEEE Trans of Pattern Analysis and Machine Intelligence. 1991;13(6):583-98.

Figure

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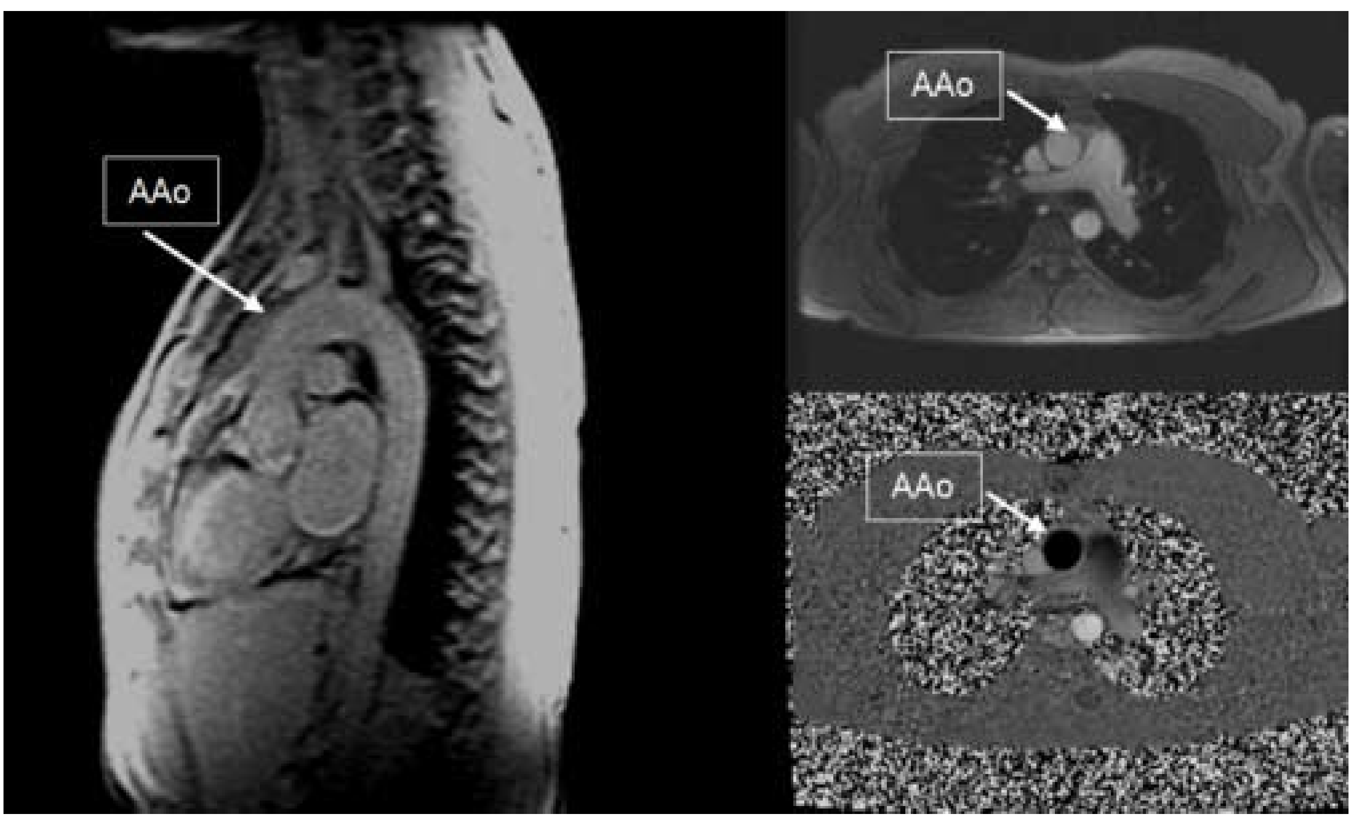

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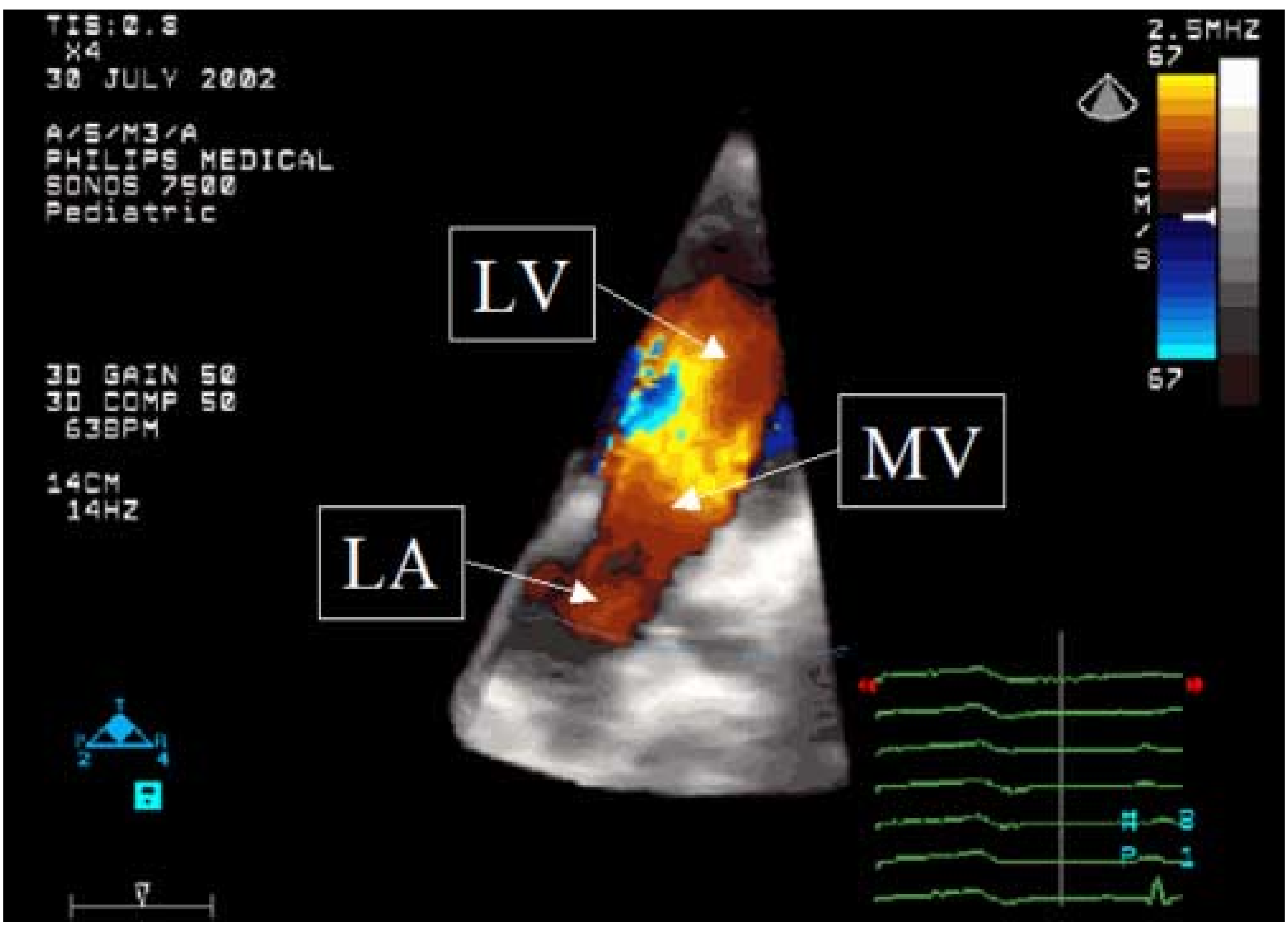

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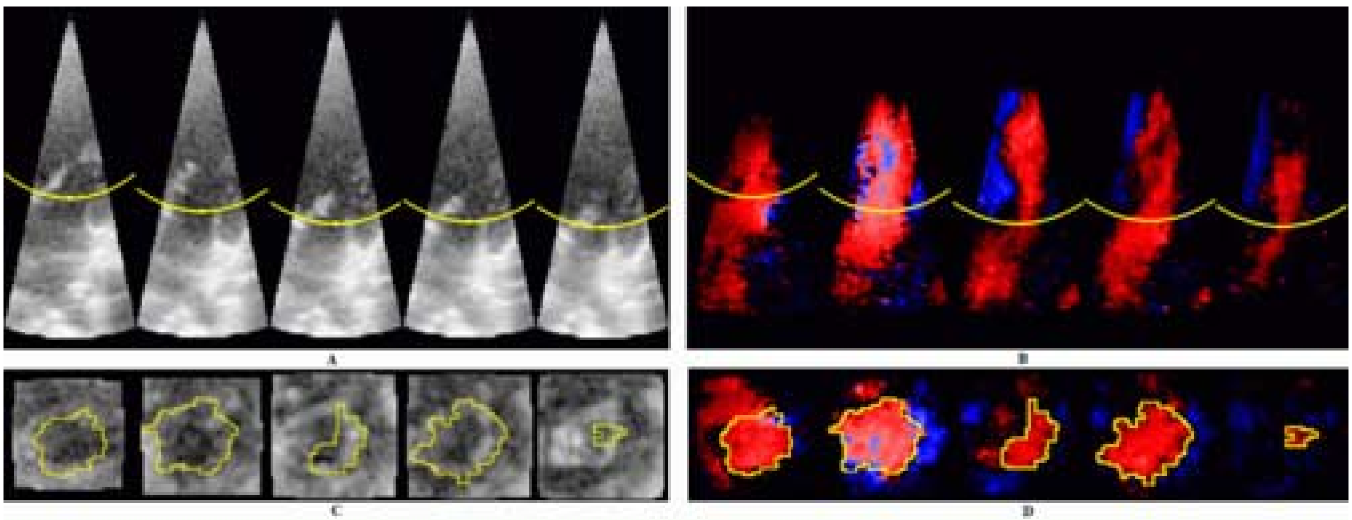

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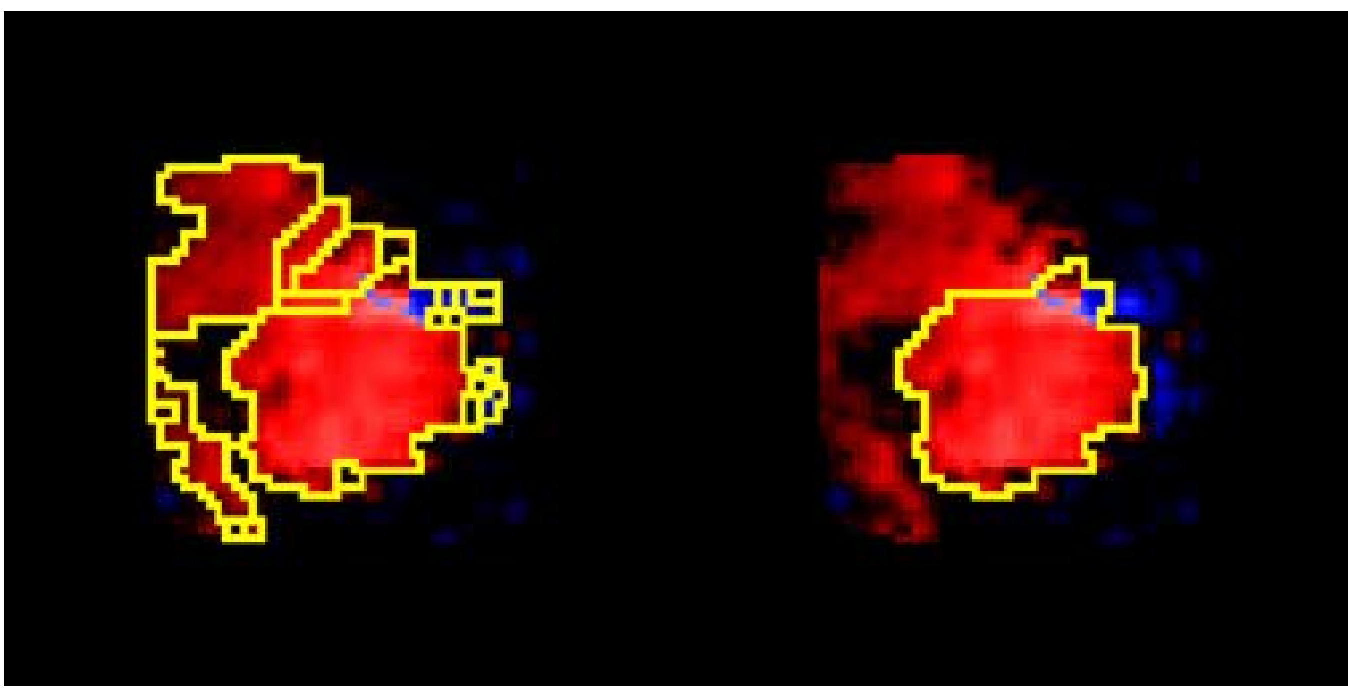

Figure4

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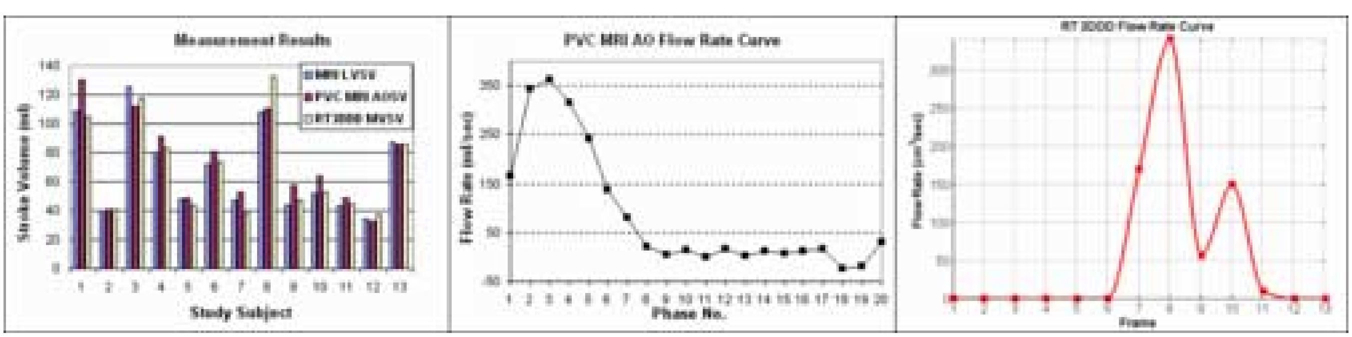

Figure5

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