Journal of Cardiovascular Magnetic Resonance (2005) **7**, 769–774

ISSN: 1097-6647 print / 1532-429X online
DOI: 10.1080/10976640500295433

VENTRICULAR FUNCTION

Modified RV short axis series—a new method for cardiac MRI measurement of right ventricular volumes

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Purpose. The current standard image orientation employed in the MRI assessment of right ventricular volumes uses a series of short axis cine acquisitions located with respect to a horizontal long axis view with the first slice placed across the atrio-ventricular valve plane at end diastole. Inherent inaccuracies are encountered with the use of this image orientation due to difficulty in defining the tricuspid valve and the border between atrium and ventricle on the resultant images. Our experience indicates that because the tricuspid valve is usually not in-plane in the slice the atrio-ventricular margin is difficult to distinguish. This leads to inaccuracies in measurements at the base of the RV and miscalculation of the RV volume. The purpose of this study was to assess an alternative method of image orientation aimed at increasing the accuracy of RV volume measurements using current commercially available CMRI sequences. This technique, the modified RV short axis series, is oriented to the outflow tract of the right ventricle. *Method.* We undertook a prospective study of 50 post cardiac transplant patients. A series of LV short axis multi-slice cine acquisition FIESTA images was acquired using the current standard technique. From this data set, LV and RV stroke volumes were derived on an Advantage Windows workstation using planimetry of the endocardial and epicardial borders in end systole and end diastole. Our new technique involved obtaining a set of multi-slice cine acquisition FIESTA images in a plane perpendicular to a line from the centre of the pulmonary valve to the apex of the RV. Planimetry of the RV was then performed and a stroke volume calculated using the same method of analysis. RV stroke volumes obtained from both techniques were compared with LV stroke volumes. Three operators independently derived RV data sets. *Results.* On the images acquired with the new technique, the tricuspid valve was easier to define leading to more accurate and reproducible planimetry of ventricular borders. RV stroke volumes calculated from the new method showed better agreement with LV stroke volumes than with the current method. These results were consistent across the three operators. *Conclusions.* This new method improves visualisation of the tricuspid valve and makes analysis easier and less prone to operator error than the current standard technique for MRI assessment of RV volumes.

Key Words: Cardiac MRI; Right ventricular volume; Right ventricular function; Steady state free precession imaging (SSFP); FIESTA

1. Introduction

With the improved accuracy and reproducibility afforded by the advent of fast imaging techniques, CMRI has become the gold standard for the quantitative assessment of cardiac function and its use in both the clinical and research fields is now commonplace (1–5). The use of CMRI evaluation of the right ventricle in a host of disease processes is becoming routine (6–8). It is well known that the complex shape of the right ventricle renders geometric modelling inaccurate (9) and that the superiority of MRI over other techniques for ventricular assessment lies in its unique ability to image the entire ventricle and to apply Simpson's rule without the need for geometric assumptions (2, 8). However, difficulties with MRI assessment of RV volumes remain and improvements in reproducibility of measurements are still required (10).

In vitro assessment of four different image orientations showed no significant differences between measured and true RV volumes (5). This is not the case in vivo where cardiac and diaphragmatic motion are significant sources of error in ventricular volumetric analysis (11). While the axial plane is often recommended and used for RV volume analysis (7, 8, 11) many studies use the current standard image orientation employed for LV analysis (6, 10, 12). This technique uses a series of short axis cine acquisitions located with respect to a four-chamber (horizontal long axis) view with the first slice placed across the atrio-ventricular valve plane at end diastole and covering both ventricles through to the apex (10, 13). This method has gained widespread acceptance in the clinical setting, most likely for reasons of time efficiency, as it enables the use of a single imaging series for the analysis of both ventricles. However, inherent sources of error are encountered when using this image set for RV analysis. Difficulties arise

Received 6 November 2004; accepted 6 July 2005.
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when attempting to separate the ventricles from the atria. For the left ventricle, this potential source of error is minimized by the implementation of a number of practical measures (13). However, these methods do not work as well when using the same image data set for RV analysis. The use of this image orientation does not account for the fact that the tricuspid valve lies in a different plane and orientation to the mitral valve. Our experience indicates that RV analysis from this image data set is problematic as the tricuspid valve is usually not in the plane of the slice and the right atrio-ventricular margin is difficult to distinguish. This leads to inaccuracies in measurements at the base of the right ventricle and miscalculations of the RV volume. Accurate identification of the tricuspid valve position is important as the cross-sectional area of the base of the ventricle is large and the potential for error is significant. We developed an alternative plane of image orientation for the right ventricle to improve visualisation of the tricuspid valve thereby increasing the accuracy of RV volumetric analysis by CMRI.

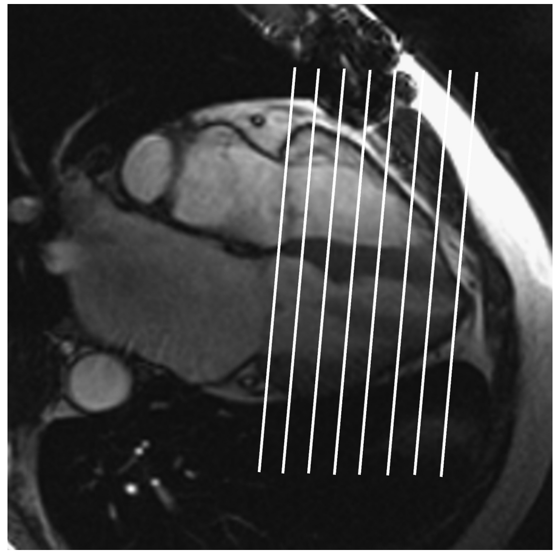

Figure 1. Scan prescription for LV short axis series with the first slice placed across the atrioventricular valve plane at end diastole and the series of slices covering both ventricles through to the apex of the heart (Lines represent the center of the imaging slice).

2. Methods

2.1. *Patients*

Fifty post-cardiac transplant patients underwent MRI following informed consent. The study was approved by the Prince Charles Hospital Health Service District Human Research Ethics Committee.

2.2. *MR imaging*

MR imaging was performed on a 1.5 Tesla GE Signa Twin-speed system (GE Medical Systems, Milwaukee, WI, USA) with a 4-element cardiac phased array coil. Cine MR images were acquired using a steady state free precession (SSFP) acquisition with the following parameters: TE 1.5 ms, TR 3.4 ms, flip angle 45°, receiver bandwidth ± 125 kHz, FOV 35 cm, slice thickness 8 mm, slice gap 2 mm, acquisition matrix 224 × 224, number of averages = 1. ECG gating with k-space segmentation of 16 views per segment was used. Twenty cardiac phases per slice location were reconstructed. All images were acquired at end expiration. Respiratory bellows were used to ensure compliance with breathing instructions.

The following imaging series were obtained:

1. Axial–prescribed through mid-ventricular level using a 3-plane localiser.
2. LV vertical long axis–located with respect to the axial series in a plane through the mitral valve and the apex of the left ventricle.
3. Four-chamber (horizontal long axis) view–located with respect to the LV vertical long axis series in a plane through the mitral valve and the apex of the left ventricle.
4. LV Short axis series through both ventricles–located with respect to the four-chamber view using the technique described by Lorenz (13), whereby the most basal slice is placed across the atrioventricular valve plane at end diastole (Fig. 1).
5. RV long axis series–located with respect to the four-chamber view with slices placed parallel to the interventricular septum to intersect the pulmonary valve and the apex of the RV.
6. Modified RV short axis series–located with respect to the RV long axis series using a plane perpendicular to a line from the centre of the pulmonary valve to the apex of the RV, with the first slice placed across the pulmonary valve at end diastole (Fig. 2).

(Since completing this study, GE Medical Systems has implemented software which allows the use of multiple image orientations as localizers. The method for prescription of the modified RV short axis series using this software is given in the Appendix.)

2.3. *MR image review and analysis*

A radiologist experienced in cardiovascular MRI assessed the long axis and four-chamber views for any evidence of valvular disease. Physiologically, in a normal heart, the left and right cardiac outputs are equal. Therefore, patients with valvular disease were excluded, leaving a total of 34 subjects in the study. Ventricular stroke volumes were derived with MASS software (MEDis Medical Imaging Systems, Leiden, NL) on an Advantage Windows workstation (GE Medical Systems, Milwaukee, WI, USA) using the standard technique of tracing the contours of the ventricular borders with a trackball cursor (planimetry) and then applying Simpson's rule. The images with the largest and smallest ventricular

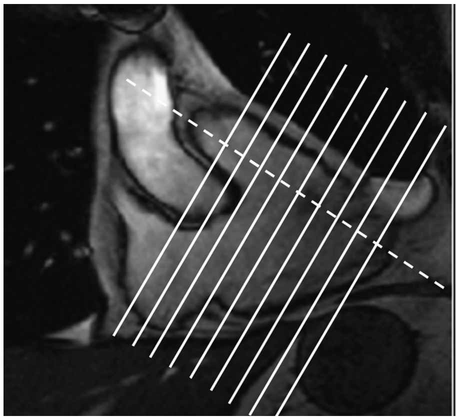

Figure 2. Scan prescription for the modified RV short axis with the first slice placed across the pulmonary valve at end diastole (Lines represent the centre of the imaging slice).

volumes were selected as the end-diastolic and end-systolic images respectively. RV endocardial borders in end diastole and end systole were used to determine RV stroke volumes from the LV short axis series images and from the modified RV short axis series images (Fig. 3). For the purposes of this paper, RV stroke volumes calculated from the LV short axis series are designated RV1, and those from the modified RV short axis series, RV2. Planimetry of left ventricular endocardial and epicardial borders in end diastole and end systole was used to determine LV stroke volumes from the LV short axis series images. Papillary muscles were included in the ventricular volume. Three operators, blinded from all other results, independently derived RV data sets. LV data sets were determined by consensus of the three operators.

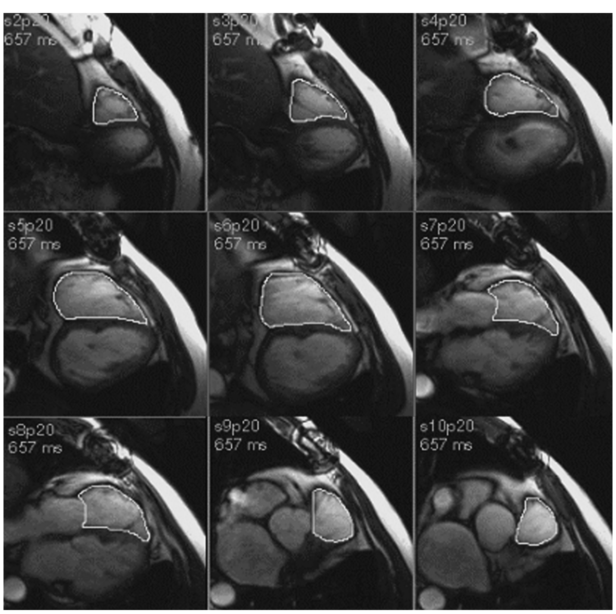

Figure 3. The modified RV short axis series image set in diastole showing manual planimetry of RV endocardial borders.

2.4. *Statistical analysis*

The calculated LV stroke volume was assumed to represent the true stroke volume of both ventricles. The calculated RV stroke volume from each technique was compared with this standard by examining the difference "RV value-LV value" in each case. The two calculated values of RV stroke volume were also compared with one another by direct comparison of the respective differences. Initially, a paired *t*-test was used to compare the two RV values; the results of this test were also confirmed using an ANOVA test with "RV-LV" as the response variable and operators and estimation techniques as the two factors. The two calculated values of RV stroke volume were compared against the LV "standard" by using *t*-tests of each difference (RV-LV) against an assumed mean difference of zero. The variabilities of the two techniques were also compared by using tests for equality (homogeneity) of variance.

3. Results

The modified RV short axis series is essentially aligned to the outflow of the right ventricle. With this slice orientation, the

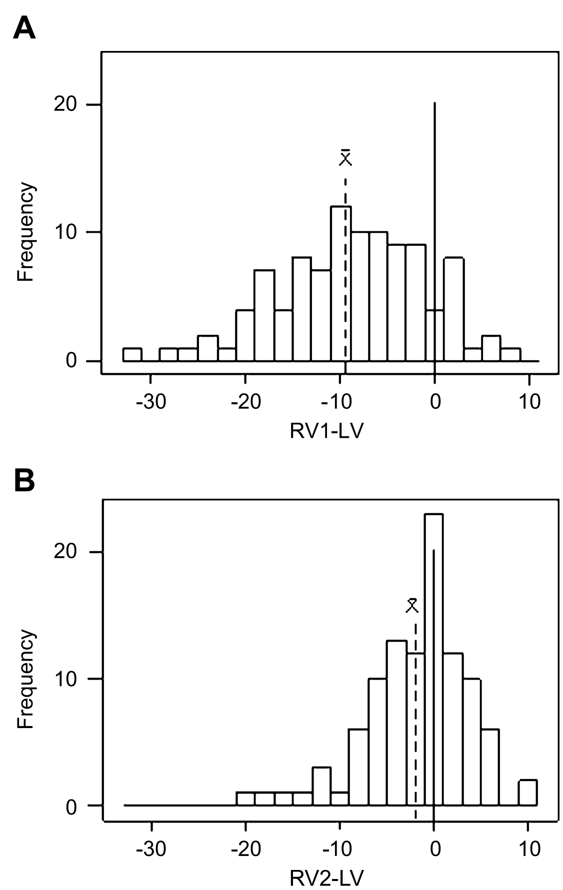

Figure 4. Histograms of RV value-LV value for LV short axis series (A) and modified RV short axis series (B) with sample average ($\overline{X}$) superimposed in each case.

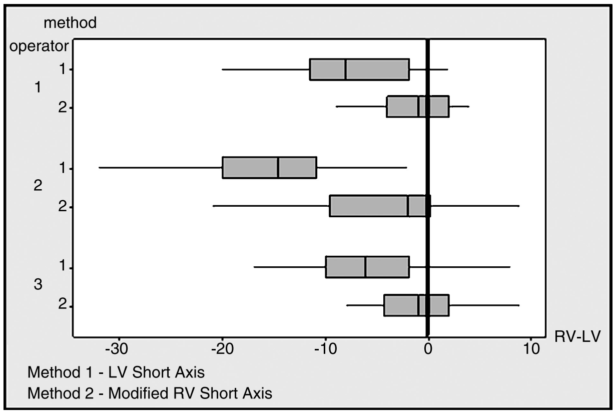

Figure 5. Boxplots of the differences "RV value-LV value" for various combinations of operator and method.

tricuspid valve is transected. The LV short axis series is aligned to the inflow of the RV; therefore, the tricuspid valve is in the plane of the slice. For this reason, the tricuspid valve is more easily visualized on the modified RV short axis images than on the LV short axis images, leading to more accurate and reproducible planimetry of ventricular borders. RV stroke volumes calculated from this new method show better agreement with LV stroke volumes. (The mean difference (± 2 SD) was −2.2 mL ± 11 mL for the modified RV short axis (RV2) compared with −9.3 mL ± 16 mL for those derived from the LV short axis (RV1)) (Fig. 4). While both methods showed a tendency to undercalculate the stroke volume, the modified RV short axis was significantly less biased to underestimation ($p = 0.000$). Corresponding to this result, the proportion of cases underestimated by the new method was around 65%, compared to 87% for the existing method. The existence of an average difference between techniques was consistent across the three independent operators: for all operators the calculated values of RV stroke volume from the new method (modified RV short axis) were significantly closer on average to the LV standard than those calculated from the existing method (LV short axis). In addition, the spread of values and the standard deviation of the discrepancies RV-LV were less in each case when using the new method (Fig. 5). (Although the reduction of standard deviation was not significant for every operator individually, it was highly significant ($p = .000$) when the results from all operators were analysed together).

4. Discussion

4.1. *Use of post cardiac transplant patients*

This study was conducted as an adjunct to a larger study of post cardiac transplant patients. Although the orientation of the heart in the thorax may vary with post cardiac transplantations compared to non transplant patients, the techniques used were orientated to the ventricles and not to the thorax and should therefore be independent of this variation. As the right and left ventricles in post transplant hearts are morphologically normal, the results should be directly applicable to non-transplant patients.

Mild degrees of tricuspid regurgitation were common in this study group. The authors recognize that quantification of tricuspid regurgitation is difficult from examination of a series of steady-state free precession images of the right ventricle and that inclusion of patients with significant tricuspid regurgitation could introduce an error between right and left ventricular stroke volumes. However, this error should apply equally to the volumes measured by both techniques and should not affect comparison of these two techniques. In order to minimize systematic error due to tricuspid regurgitation, it was felt appropriate to exclude those patients with obvious tricuspid regurgitation evident on the steady-state free precession images.

4.2. *Comparison of LV short axis and modified RV short axis series*

The current standard method for RV analysis uses the same image set as for LV analysis. The disadvantage with using this method for RV volumetric assessment is that it is difficult to determine the border between the right atrium and right ventricle with this image set. While LV volumetric assessment is still subject to some limitations, the use of some practical features facilitates differentiation between the left atrium and ventricle. With the first slices placed across the atrio-ventricular valve plane at end diastole, through-plane descent of the mitral valve in systole is accommodated for by excluding the most basal slice from volumetric analysis at end systole (2). The slice orientation and position of this technique favors the mitral valve and therefore does not work as reliably for the basal part of the right ventricle. The septal insertion of the tricuspid valve tends to be slightly apical of that of the mitral valve, and the two valves may be oriented slightly differently. The tricuspid valve may move further with systolic contraction, rotating slightly relative to the mitral valve. Also, whereas the left ventricle has a thick muscular wall, the wall of the right ventricle is thin which makes it difficult to see whether a basal slice lies in the atrium or ventricle.

In a study of the reproducibility of RV volumes derived using the short axis series, difficulty in separating the right atrium and the right ventricle was cited as a reason for the relatively large degree of inter-observer subjectivity reported (10). By using an image orientation which improves differentiation of atrium and ventricle, we found that results were consistent across three operators with calculated RV volumes significantly closer on average to the LV standard than those calculated from the LV short axis series. The image orientation of the modified RV short axis series also provides more accurate identification of the tricuspid valve position throughout the cardiac cycle by including it in the margin rather than in the plane of the basal slices. This helps to minimize errors due to rotation and descent of the tricuspid valve towards the right ventricular apex with ventricular systole. Any errors due to the fixed image orientation in relation to RV contraction are limited to beneath the pulmonary valve and at the right ventricular apex where the cross-sectional area of the ventricle is small.

4.3. *Comparison of modified RV short axis series with axial series*

The use of an axial slice orientation has been reported as a more suitable image orientation for volume analysis of the right ventricle than a short axis series aligned to the ventricular inflow tract as the tricuspid valve is imaged in profile and is better demarcated (11). The image orientation of the modified RV short axis series provides the same advantage. Alfakih et al. (14) reported partial volume effects encountered on the inferior wall of the right ventricle when using the axial plane caused difficulty in identifying the blood/myocardial boundary. This has been previously cited as the reason for using the short axis series for quantitative assessment of the right ventricle (13) as the slice orientation transects the inferior wall of the right ventricle at an angle. Similarly, the slice orientation of the modified RV short axis transects the inferior wall (Fig. 2) and provides improved identification of the blood/myocardial boundary compared with an axial plane. Although this study did not compare the new technique with an axial series, it is reasonable to assume that a slice plane oriented to the heart rather than the thorax is a more reproducible technique for longitudinal studies.

Therefore, we believe that this new technique has advantages over both the LV short axis series and the axial series for the volumetric assessment of the right ventricle.

5. Conclusions

RV function is assuming greater importance in the clinical management of cardiac patients. Accurate reproducible quantification of RV function will expand treatment strategies and potentially assist in achieving the ultimate goal of improving patient management. This study was designed to offer a simple method of improving RV volume measurements using current, commercially available CMRI sequences and analysis software. RV volume analysis remains imperfect. It is likely that thinner slices and improved edge detection techniques combined with better volumetric acquisitions will continue to improve RV volume calculations in the future. Within the current limitations, the modified RV short axis series improves visualization of the tricuspid valve and makes analysis easier and less prone to operator error. Serial RV assessments could be undertaken with greater confidence in diagnostic accuracy and reproducibility with this technique.

Appendix

Alternative method of prescription for modified RV short axis series where multiple image orientation localizers are allowed:

1. Axial oblique–prescribed at the level of the main pulmonary artery (MPA) using a 3-plane localiser and angled to the artery on the sagittal localiser.
2. Sagittal oblique MPA–located with respect to the axial oblique series in a plane along the MPA and RVOT. This view provides good visualization of the pulmonary valve.
3. Coronal oblique MPA–located with respect to the sagittal oblique series in a plane along the MPA and RVOT, perpendicular to the pulmonary valve.
4. RV long axis series–as previously described.
5. Modified RV short axis series–prescribed on the sagittal oblique series using a plane parallel to the pulmonary valve with the first slice placed across the pulmonary valve at end diastole. Position of first slice is cross-referenced on coronal oblique series and the angle of slice with respect to the pulmonary valve is adjusted, if necessary. Series is cross-referenced to RV long axis series to ensure complete coverage of the right ventricle.

Acknowledgments

The authors would like to thank Dr. David Leggett, Dr. Andrew Galbraith and the staff of the Prince Charles Hospital Cardiovascular MRI Research Centre for their assistance in the planning, implementation and facilitation of this study.

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