Multimodality Comparison of Quantitative Volumetric Analysis of the Right Ventricle

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Abstract

Real-time 3D echocardiography (RT3DE), cardiac magnetic resonance (CMR) and cardiac computed tomography (CCT) can quantify right ventricular (RV) volume and overcome the limitations 2D echocardiography that stem from the unique geometry of the right ventricle. We tested a new technique for volumetric analysis of the right ventricle designed for RT3DE, CMR and CCT (TomTec) on images obtained in RV-shaped phantoms and in 28 patients with a range of RV geometry who underwent RT3DE, CMR and CCT imaging on the same day. In-vitro measurements showed that: (1) volumetric analysis of CMR images yielded the most accurate measurements; (2) CCT measurements showed slight (4%) but consistent overestimation; (3) RT3DE measurements showed small underestimation, but considerably wider margins of error. In patients, both RT3DE and CCT measurements correlated highly with the CMR reference (r-values 0.79-0.89) and showed the same trends noted in-vitro. In conclusion, eliminating analysis-related inter-modality differences allowed fare comparisons and highlighted the unique limitations of each modality. Understanding these differences promises to aid in the functional assessment of the right ventricle.

1. Introduction

Accurate assessment of the right ventricle by 2D echocardiography remains difficult due to the unique geometry of this chamber. In contrast, 3DE does not require geometric modeling and thus has the potential of improved accuracy, and is advantageous over CCT and CMR imaging because of its portability, no need for ionizing radiation, and the ability to image patients with pacemakers and defibrillators. Most previous studies used disc summation (DS) with CMR, CCT and 3DE to calculate RV volumes [1-4]. This methodology is imperfect due to its inability to accurately determine RV boundaries in basal slices, since the tricuspid valve and the RV outflow tract are not in one plane. Consequently, alternative approaches have been sought after.

Most recently, new software was designed and tested for volumetric analysis of the right ventricle from RT3DE datasets, using a combination of views that allow the visualization of the tricuspid valve, RV outflow tract and apex in order to reconstruct RV endocardial surface and directly calculate RV volumes without geometric modeling [5,6]. Most prior studies compared RV volumes calculated from 3DE and CCT datasets to CMR as a reference, with all measurements obtained using the DS technique. However, no studies have compared all 3 modalities using the new volumetric approach.

This study was designed to allow such side-by-side multimodality comparison of RV volume calculations in separate in-vitro and in-vivo protocols by using the same volumetric analysis software with all 3 modalities to eliminate analysis-related differences as a potential source of error. The aims of the in-vitro study were: (i) to determine the accuracy of the volumetric approach, when applied to all 3 imaging modalities using RV-shaped phantoms; (ii) to determine whether the use of the volumetric and DS techniques within a single modality provide the same results. The human protocol was designed to determine in patients with a wide range of RV geometry to what extent RV volume measurements obtained with the 3 modalities are interchangeable, and to establish their respective reproducibility.

2. Methods

2.1. In-vitro protocol

The in-vitro protocol was performed in RV-shaped phantoms made from different materials suitable for imaging with different imaging modalities. We first compared side-by-side the accuracy of DS technique and

volumetric analysis using RV Analysis software (TomTec), applied to CMR images of 3 static RV-shaped plastic phantoms (Figure 1, top left) of different sizes.

These measurements were compared against the true volumes of the phantoms, which were determined by measuring the displaced volume of water when submerging each phantom in a water bath. Subsequently, to allow inter-modality comparisons of in-vitro accuracy between CMR and CCT, another set of three RV-shaped cement models were imaged using both MRI and CT scanners, and volumes calculated using the volumetric analysis were then compared to the true volumes. Finally, RT3DE images of an ejecting RV-shaped latex phantom were acquired and analyzed using the same software to obtain end-systolic and end-diastolic RV volumes (ESV, EDV), which were compared against the true volumes of the model chamber.

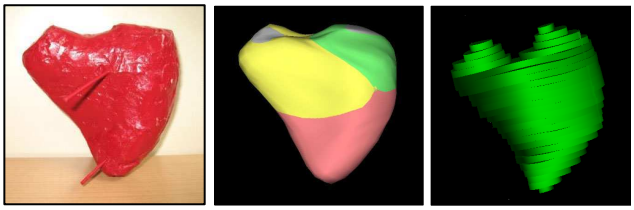

Figure 1. In vitro accuracy of volumetric analysis (top middle) and disk summation method (top right) applied to CMR images of an static RV-shaped phantom (top left).

2.2. Human study

Twenty-eight patients (age 53±18 years) were referred for clinically indicated CCT studies were scanned for transthoracic 2D acoustic windows that allowed adequate RV endocardial visualization prior to enrollment. In each patient, CMR, CCT and RT3DE images were acquired on the same day. CMR images were obtained using a 1.5T Sonata scanner (Siemens, MAGNETOM Sonata) with a phased-array cardiac coil. CCT images were obtained using a Toshiba 16-slice multi-detector scanner (Toshiba). Transthoracic RT3DE images were acquired from an apical window using a Philips iE33 ultrasound imaging system (Philips) equipped with a fully-sampled matrix array transducer (X3-1).

2.3. Image analysis

CMR volumes were initialized on originally acquired slices. In contrast, CCT and RT3DE datasets were first converted into Cartesian coordinates to allow standardized positioning of the cut-planes, including the short-axis, the four-chamber and the coronal views. Manual initialization of contours was performed, while making an effort to include the endocardial trabeculae in the RV cavity, in predetermined end-systolic and end-diastolic frames in the four-chamber and coronal views as well as one mid-RV short-axis slice. Following automated identification of RV boundaries throughout the cardiac cycle, manual corrections were performed when necessary. Then, the end-systolic RV cavity was displayed as a solid cast with a wire-frame representation of the end-diastolic cavity superimposed. ESV, EDV and ejection fraction (EF) were automatically calculated. Endocardial tracing and volume measurements for each imaging modality were performed by independent investigators experienced in the interpretation of cardiac images, who were blinded to the results of all prior measurements.

In 11 randomly selected patients, image analysis was repeated at least one month later by the same primary reader and by an additional investigator to determine the reproducibility of LV volume and EF measurements for each imaging modality.

2.4. Statistical analysis

In each in-vitro experiment, volumes measured from all images were compared against the actual volume by calculating the difference in percent of the actual volume. These values were averaged to estimate percent error for each imaging modality. Based on the results of the in-vitro studies, the results of volumetric analysis of CMR images were used as a reference standard for CCT and RT3DE measurements. Each comparison included linear regression and Bland-Altman analysis. The reproducibility of the CMR-, CCT- and RT3DE-derived measurements of EDV, ESV and EF was evaluated by calculating the intra- and inter-observer variability of each technique, which was defined as the absolute difference between the corresponding repeated measurements, expressed in percent of their mean. Variability values obtained for each index in each patient for each imaging modality were then averaged over the entire group of patients.

3. Results

In the phantom experiments, the DS method resulted in volumes that were consistently overestimated by approximately 20% compared to the true volumes. In contrast, volumetric analysis of the same images resulted in more accurate measurements, as reflected by percent error <1%. The use of volumetric analysis with CMR and CCT images obtained in another set of phantoms confirmed the accuracy of this analysis technique when applied to CMR images, and also demonstrated that when applied to CCT images, this technique resulted in volumes that were consistently overestimated by 4% compared to the true volumes. Volumetric analysis of RT3DE images of the ejecting RV phantom resulted in EDV and ESV that slightly underestimated the true

volumes, as reflected by percent errors of -6.3% and -1.7%. Of note, the standard deviations of the differences were of the order of magnitude 20%.

Based on the results of these three experiments that demonstrated that volumetric analysis of CMR images provided the most accurate in-vitro volume measurements, this methodology was used in the human protocol as the reference standard for CCT and RT3DE measurements.

While volumetric analysis of the right ventricle from CCT and CMR data was feasible in all patients, the feasibility of this analysis with RT3DE images was 92% due to poor image quality in 2/30 patients. The time required for image analysis of each data set was <5 min on personal computer. Manual corrections were necessary to optimize the position of the endocardial boundaries in all patients for all imaging modalities, but the required corrections were more extensive for RT3DE than CCT and CMR. Figure 2 shows an example of end-diastolic images obtained using all three imaging modalities in one patient, which are shown with the initialized RV boundaries superimposed, along with the resultant RV endocardial surfaces.

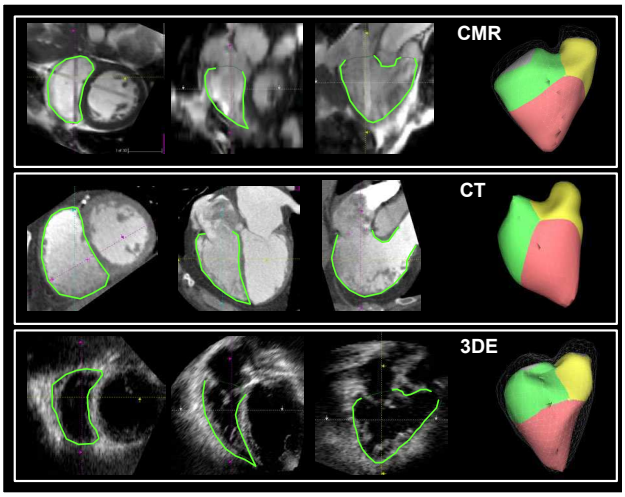

Figure 2. Volumetric analysis of CMR (top), CCT (middle) and RT3DE (bottom) images obtained in one patient. Shown from left to right: RV boundaries initialized in a mid-ventricular short-axis view, apical four-chamber view and coronal view, shown along with the resultant calculated RV endocardial 3D surfaces (right), with the solid cast representing end-systole and the wire frame representing end-diastole.

CMR measurements of ESV, EDV and EF in the remaining 28 patients were 131±54 ml, 205±73 ml and 40±11%, respectively. Figure 3 shows the results of the linear regression analyses between CCT and RT3DE measurements of RV volumes with the CMR reference values. Correlation coefficients were similar for both imaging modalities: 0.87, 0.85 and 0.79 for ESV, EDV and EF, respectively, for CCT, and 0.89, 0.87 and 0.87 for RT3DE. Bland-Altman showed that CCT overestimated ESV by 17ml and EDV by 23ml. In contrast, RT3DE underestimated ESV by 9ml and EDV by 14 ml. Both CCT and RT3DE underestimated EF by 2%. The limits of agreement with CMR reference were similar for both CCT and RT3DE measurements.

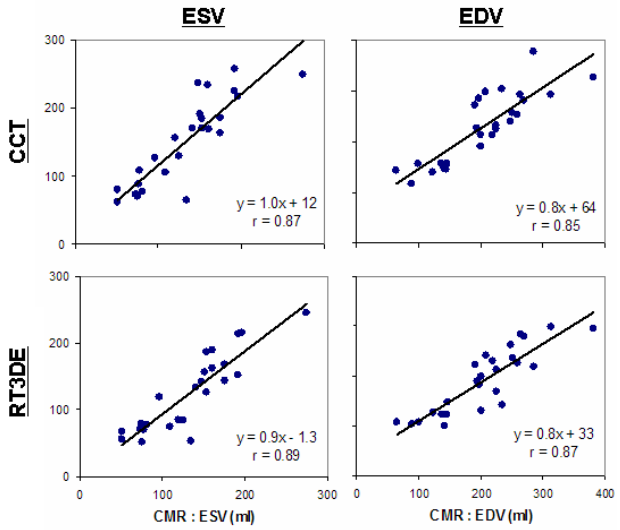

Figure 3. Results of linear regression analysis of end-systolic and end-diastolic RV volumes (ESV, EDV), calculated using volumetric analysis of CCT (top), and RT3DE (bottom) images against CMR reference values obtained in 28 patients.

Table 1 shows the results of the reproducibility analysis of RV volumes and EF for CMR, CCT and RT3DE images. For both EDV and ESV, both inter- and intra-observer variability were lowest for CCT-derived measurements. Interestingly, the variability levels of RT3DE measurements were lower than those of CMR values. Not surprisingly, for both EDV and ESV measured from all three imaging modalities, the inter-observer variability was higher than the intra-observer variability. Importantly, all variability values were below 15%. It is worthwhile noticing however, that in individual patients variability levels of all three imaging modalities exceeded the acceptable 10-15% levels.

		ESV	EDV	EF
Inter-observer	CMR	12 ± 7	13 ± 9	13 ± 13
	CCT	8 ± 4	4 ± 3	13 ± 9
	RT3DE	10 ± 9	7 ± 5	11 ± 11
Intra-observer	CMR	13 ± 8	12 ± 9	10 ± 8
	CCT	4 ± 4	4 ± 4	8 ± 6
	RT3DE	9 ± 10	5 ± 7	13 ± 8

Table 1. Inter- and intra-observer variability of volumetric analysis applied to CMR, CCT and RT3DE images obtained in a subset of 11 randomly selected patients.

4. Discussion and conclusions

This study was designed to test the recently developed volumetric analysis technique across the three most commonly used cardiac imaging modalities. Because there is no perfect "gold-standard" reference technique to measure RV volume in-vivo, we first used RV-shaped phantoms with known volumes to determine the accuracy of this volumetric analysis in conjunction with each of the three imaging modalities. Based on the results of these in-vitro studies, volumetric analysis of CMR images was used as the reference technique in the human protocol, wherein the same analysis technique was applied to CCT and RT3DE images.

The results of this protocol showed that in humans, both RT3DE and CCT measurements of RV volumes correlated highly with the CMR reference, with correlation coefficients similar to those recently reported [5]. We found that CCT measurements were overestimated by a higher percentage of the measured RV volumes compared to the phantoms. Similarly, RT3DE measurements in humans showed a larger percent of underestimation than that measured in-vitro. These differences can be probably attributed to the effects of endocardial trabeculae that did not exist in the phantoms, but are quite prominent in human right ventricles. This factor was found to play an important role in the inter-modality discordances in left ventricular volume measurements [7], and could certainly be expected to affect RV volume measurements even to a larger degree since the right ventricle is more heavily trabeculated than the left ventricle. This is because these measurements rely on the visualization of the endocardial boundary, which vary widely among modalities depending on their spatial resolution that determines the ability of each modality to differentiate trabeculae from the myocardium or blood pool [7].

It is likely that the higher spatial resolution in CCT contributed toward the higher reproducibility of CCT compared to RT3DE measurements. The reproducibility of CMR measurements in this study was lower than that of either CCT or RT3DE. This is probably because CMR is the only one of the three imaging modalities that is not truly three-dimensional, and that the 3D definition of the RV outflow tract for this modality depends on a single coronal view. Importantly, on the other hand, despite the wide margin of error in-vitro, the reproducibility of RT3DE-derived RV volume measurements was within clinically acceptable 15% range.

The limitations of this study include the relatively small number of phantoms and patients studied. However, building these phantoms is expensive, as is performing two additional imaging tests for research purposes on each patient.

In summary, this multi-modality study tested the newly developed approach of volumetric quantification of RV volume on CMR, CCT and RT3DE images. We found that this analysis overcomes many of the known hurdles that impeded accurate assessment of this geometrically complex chamber in the past, and can be used with all 3 imaging modalities. However, our results also showed that RV volume measurements are not interchangeable between modalities, and therefore serial evaluations should preferably be performed using the same modality.

References

[1] Alfakih K, Plein S, Thiele H, Jones T, Ridgway JP, Sivananthan MU. Normal human left and right ventricular dimensions for MRI as assessed by turbo gradient echo and steady-state free precession imaging sequences. J Magn Reson Imaging 2003;17:323-9

[2] Gopal AS, Chukwu EO, Iwuchukwu CJ, et al. Normal values of right ventricular size and function by real-time 3-dimensional echocardiography: comparison with cardiac magnetic resonance imaging. J Am Soc Echocardiogr 2007;20:445-55

[3] Raman SV, Shah M, McCarthy B, Garcia A, Ferketich AK. Multi-detector row cardiac computed tomography accurately quantifies right and left ventricular size and function compared with cardiac magnetic resonance. Am Heart J 2006;151:736-44

[4] Shiota T, Jones M, Chikada M, et al. Real-time three-dimensional echocardiography for determining right ventricular stroke volume in an animal model of chronic right ventricular volume overload. Circulation 1998;97:1897-900

[5] Niemann PS, Pinho L, Balbach T, et al. Anatomically oriented right ventricular volume measurements with dynamic three-dimensional echocardiography validated by 3-Tesla magnetic resonance imaging. J Am Coll Cardiol 2007;50:1668-76

[6] Tamborini G, Brusoni D, Torres Molina JE, et al. Feasibility of a new generation three-dimensional echocardiography for right ventricular volumetric and functional measurements. Am J Cardiol 2008;102:499-505

[7] Mor-Avi V, Jenkins C, Kuhl HP, et al. Real-time 3D echocardiographic quantification of left ventricular volumes: Multicenter study for validation with magnetic resonance imaging and investigation of sources of error. J Am Coll Cardiol Img 2008;1:413-23

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