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Ventricular Volume and Mass by CMR*

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INTRODUCTION

Cardiovascular magnetic resonance (CMR) is an ideal technique for investigating the cardiovascular system, because it has excellent high resolution differentiation of myocardium from blood pool and lung, and is free from x-rays and noninvasive. This combined with high levels of accuracy,^[1–4] and reproducibility,^[5–9] has made it very popular in the research arena for the assessment of ventricular volumes and mass. Ethical committees approve such scans with little hesitation, and small patient numbers are needed to prove hypotheses such as the effect of a new drug on remodeling.^[10,11] CMR is now considered the gold standard for such measurements.^[12]

The techniques for applying CMR to the problem of assessing ventricular size and mass (volumetry) have been developed over many years, and earlier methods have been discarded because they compromised quality for speed, something which is not necessary in the fast scanning environment we enjoy in modern times. Thus, single or multislice spin echo techniques in the transaxial plane,^[13]

or single and dual long axis cine techniques adopting geometric assumptions,^[14] will not be considered further. The technique that has won widespread acceptance is the short axis multislice (multiple 2D or 3D) cine acquisition, where both ventricles are sampled from the atrioventricular ring to the apex, with subsequent planimetry of the endocardial and epicardial borders of the ventricles to derive the required volume and mass parameters. The volumes obtained by this method are independent of geometric assumptions, which is a major advantage over 1D and 2D echocardiographic techniques. In this article describing this technique, the agreed nomenclature and display of planes of the heart is used as agreed by jointly published guidelines.^[15,16]

CMR SEQUENCES

In order to achieve full 3D coverage of the ventricle using conventional free-breathing gradient-echo cine sequences, a total scanning time of 30 min or more is

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required, but on modern scanners with fast imaging, a single cine can be acquired in just one breath-hold of 8 sec, allowing the whole stack of images to be acquired in 5–10 min. This also has the considerable additional advantage of reducing breathing and movement artifact. The reproducibility of breath-hold techniques is similar to conventional cines.^[17–19] In patients unable to hold their breath consistently, or who are orthopneic, solutions using the same sequence combined with navigator echo imaging have been shown to be successful, during free-breathing.^[20] The most modern scanners with ultrafast capability can acquire the complete 3D ventricular data set in a single breath-hold,^[21] whilst a 3D solution using an intravascular contrast agent has also been reported.^[22] Real-time acquisition is also now possible, but the definition of its accuracy and reproducibility is at an early stage.^[23,24] Advances in acquisition sequences have also started to play an important role with the use of steady-state free precession (SSFP) sequences, with the magnetization driven to steady state, which makes the cines independent of inflow enhancement, which greatly improves the blood to myocardium contrast especially in the long axis planes.^[25] These sequences (True-FISP, FIESTA, Balanced FFE for Siemens, GE, and Philips scanners, respectively) run at their best with ultrafast gradients, as a very short TR is required to reduce the sensitivity of the sequence to movement artifact. It can also be run in real-time.^[26] True-FISP cine imaging is greatly superior to fast low angle shot (FLASH) imaging and should become the gold standard acquisition technique for volume and mass studies.

In addition to the left ventricle (LV), it is important to remember the right ventricle (RV), as its function is also known to be an important determinant of prognosis, both in coronary artery disease,^[27] heart failure,^[28] and

pulmonary disease.^[29] Global RV function is difficult to assess adequately by echocardiography, while radio-nuclide ventriculography suffers from projection of overlapping structures, unless research techniques such as first pass techniques with ultra-short half-life isotopes are used. Such problems are not experienced by CMR, and RV function and mass are well characterized.^[30,31] Like the LV, RV function measured by CMR is very reproducible.^[32]

Normal values for FLASH volumetry are shown in Tables 1 and 2 which are adjusted for body surface area and shown by gender. It should be noted that the normal values depend on the population under test, and age or race corrected values are not available. In addition, adjustment of the values to body surface area is not without its problems,^[33] and true FISP volumes are slightly different to those derived by FLASH.^[25] Therefore, clinical judgment regarding the boundaries of normality is required and the results of one acquisition technique can only be compared with the results of another with care.

A PRACTICAL GUIDE TO CMR VOLUMETRY

The following protocol is designed to be as efficient as possible in gaining the volumetric data from the ventricles of the heart. Figure 1 illustrates the sequence of cines used to achieve imaging in the long axis of the LV, and thereby the true short axis. A coronal pilot is first taken and used to acquire a transaxial cine which shows both the mitral valve and the apex of the LV. By taking a plane through the center of the mitral valve ring (halfway between the back end of the septum and the back end of

Table 1

Normal Values in Adults for Volumes and Mass of the LV (FLASH Technique)

Parameter	Males		Females	
	Absolute	Normalized to BSA	Absolute	Normalized to BSA
LVEDV	136 ± 30 (77–195) mL	69 ± 11 (47–92) mL/m ²	96 ± 23 (52–141) mL	61 ± 10 (41–81) mL/m ²
LVESV	45 ± 14 (19–72) mL	23 ± 5 (13–33) mL/m ²	32 ± 9 (13–51) mL	21 ± 5 (11–31) mL/m ²
LVSV	92 ± 21 (51–133) mL	47 ± 8 (32–62) mL/m ²	65 ± 16 (33–97) mL	41 ± 8 (26–56) mL/m ²
LVEF	67 ± 5 (56–78)%	—	67 ± 5 (56–78)%	—
LVM	178 ± 31 (118–238) g	91 ± 11 (70–113) g/m ²	125 ± 26 (75–175) g	79 ± 8 (63–95) g/m ²

BSA, body surface area; EDV, end-diastolic volume; ESV, end-systolic volume; SV, stroke volume; EF, ejection fraction; M, mass including papillary muscles. Values are quoted as mean ± 1 standard deviation, with the 95% confidence interval for the normal range in brackets. Data adapted from Ref. [9].

Table 2
Normal Values for Volumes and Mass of the RV (FLASH Technique)

Parameter	Males		Females	
	Absolute	Normalized to BSA	Absolute	Normalized to BSA
RVEDV	157 ± 35 (88–227) mL	80 ± 13 (55–105) mL/m ²	106 ± 24 (58–154) mL	67 ± 10 (48–87) mL/m ²
RVESV	63 ± 20 (23–103) mL	32 ± 8 (16–48) mL/m ²	40 ± 14 (12–68) mL	26 ± 6 (20–32) mL/m ²
RVSV	95 ± 22 (52–138) mL	48 ± 8 (32–64) mL/m ²	66 ± 16 (35–98) mL	42 ± 8 (27–57) mL/m ²
RVEF	60 ± 7 (47–74)%	—	63 ± 8 (47–80)%	—
RVM	50 ± 10 (30–70) g	26 ± 5 (16–36) g/m ²	40 ± 8 (24–55) g	25 ± 4 (18–33) g/m ²

BSA, body surface area; EDV, end-diastolic volume; ESV, end-systolic volume; SV, stroke volume; EF, ejection fraction; M, mass of the RV free wall. Values are quoted as mean ± 1 standard deviation, with the 95% confidence interval for the normal range in brackets. Data adapted from Ref. [9].

the lateral wall) and the tip of the apex, the vertical long axis cine (VLA) is acquired. This VLA is used to plan the horizontal long axis cine (HLA), by again using a plane through the center of the mitral valve (halfway

between the back of the anterior and inferior walls) and the tip of the apex. It should be noted that it is common to find centers describing planes which are parallel to the septum for the VLA, and parallel to the inferior wall for

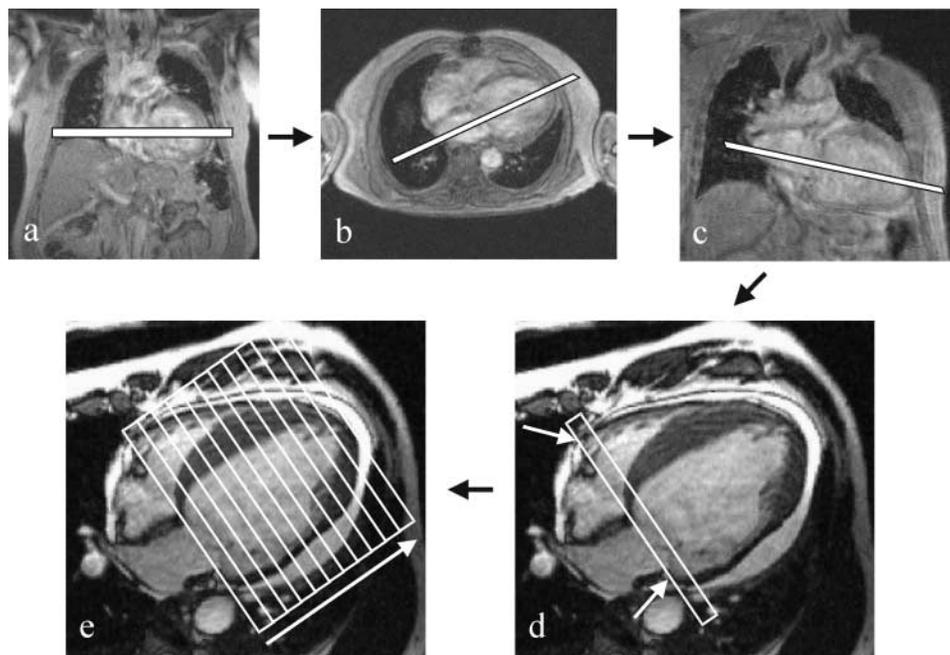


Figure 1. Illustration of the piloting used to achieve efficient ventricular volumetry. A coronal pilot (a) is first acquired, and used to pilot the end-expiratory breath-hold transaxial cine (b). The vertical long axis (c) is obtained from the end-diastolic transaxial image and subsequently the horizontal long axis (d), upon which a single basal short axis slice is carefully positioned parallel to the plane of the atrioventricular ring at the back of the ventricles, with the two anchor points being the extreme rear of the right and left ventricular myocardium (arrowed). Note that the LV septum cannot be used to guide placement of this key slice because it may be foreshortened by the aortic outflow tract. Subsequently the entire stack of short axis cines are acquired moving towards the apex (e) and the volumes enclosed are unequivocally ventricular at the end-diastolic time point. The HLA and VLA cines are important as they will be used in future 3D analysis software to solve the issue of how many slices contain end-systolic volume following atrioventricular ring descent in systole. Both RV and LV can be analyzed using this technique, as biventricular coverage is complete.

the HLA, but these are not correct, as they are likely to lead to the long axis plane *not* passing through the center of the basal ring of the LV, and it also may lead to an offset from the tip of the apex which is also undesirable. This can lead to problems planning the short axis cuts to adequately cover the full extent of LV and RV, and in addition, it reduces the reproducibility of the short axis plane positioning for repeated studies. Finally, the short axis slices are placed on the HLA to encompass the heart.

In order to achieve the most reliable results, which are the most reproducible, attention to detail is required. First, all the cines should be acquired if possible using a breath-hold cine sequence, and this includes the short axis and the VLA and HLA cines. Second, when using breath-hold techniques, it is more reproducible to ask the patient to hold their breath at end-expiration, rather than elsewhere in the respiratory cycle, and this applies to all the cines.^[34] Third, the first short axis plane should be placed at the base of the heart covering the most basal portion of the LV and RV just forward of the atrioventricular ring (Fig. 1d), and it should be placed on the end-diastolic HLA image. Finally, further short axis planes should then be planned to move apically from this plane until the apex is encompassed (Fig. 1e).

Whilst it possible to acquire the VLA and HLA as single pilot images instead of cines, there is little practical merit in this, as the time for two breath-hold cines is small, and the contraction pattern in these two planes is very useful during qualitative assessment of ventricular function. In future with the development of 3D post-processing software solutions for analyzing the cines, these long axis cines will become mandatory. It is also worth noting that in the future, full 3D analysis of atria as well as ventricles may be simple and practical with automated analysis, in which case cines encompassing the entire heart would be acquired.

TECHNICAL TIPS

- The average FLASH breath-hold required to acquire 16 phases with a phase encoded grouping (PEG) of six is approximately 15–20 sec. While this does not constitute a problem for most patients, those with orthopnea may find this difficult. By increasing the PEG, the breath-hold time can be reduced. A compromise is reached, however, as less phases will be captured with a higher PEG. Less than 11 phases will give inadequate information on wall motion and may not cover end-systole precisely. Decreasing the field of view will also

reduce the breath-hold time but may result in some wrap around occurring at the edges of the image. If this remains remote from the heart it may be considered an acceptable compromise. The PEG size and the number of phases acquired are related through the repeat time (TR) of the sequence. Modern CMR scanners with faster gradients allow a shorter TR and echo time (TE) which improves this compromise, and as scanners improve, such compromises should become a problem of the past. Typically, best results are seen with the time between cine phases being 50 msec or less, and this yields a cine with approximately 16 frames in clinical practice. This is not always achievable with older scanners with breath-holding. With true FISP sequences, the breath-hold is now approximately 8 sec, and these problems are not apparent.

- Analysis of the short axis slices is relatively straightforward (Fig. 2) providing the quality of the images is reasonable (mainly dependent on accurate ECG gating and good breath-holding). The main source of error is in separating the ventricles from the atria. Identifying this basal slice is made more difficult by the through-plane descent of the atrio-ventricular ring in systole, which is usually about 1 cm. This makes the placement of the first, most basal short axis slice very important. By ensuring that this basal slice is carefully positioned on the end-diastolic, end-expiratory breath-hold HLA image just forward of the atrioventricular ring, the first short axis cine will by definition contain end-diastolic volume and mass within both ventricles. However, at end-systole, the basal slice will include only atrium due to descent of the AV ring, and in general, the systolic area in the basal cine is not included in the analysis of the systolic volume so that one less image is analyzed at end-systole than at end-diastole (Fig. 2). In general, the next slice down contains both end-diastolic and end-systolic volume. An alternative approach to this rigorous approach is to over-sample with short axis slices into the atrium and attempt to retrospectively differentiate ventricle from atrium based on the degree of descent of the AV ring in the long axis images, and whether the chamber dilates or contracts in systole. In general, it is preferable not to over-sample but to ensure the first basal slice is acquired correctly, as this leads to a reproducible approach, is more time efficient for both acquisition and analysis, and because

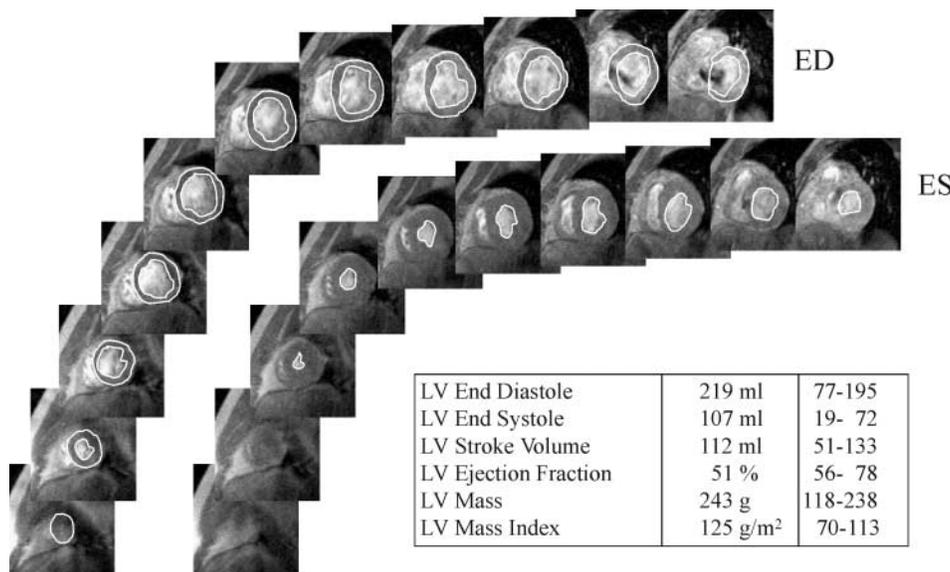


Figure 2. The end-diastolic (ED) and end-systolic (ES) slices from multiple contiguous short axis cines that encompass the LV, from base to apex, in a patient with ventricular dilatation and hypertrophy from chronic aortic regurgitation. The epicardial and endocardial borders are traced and the summation values shown with the normal male values shown in the right-hand column. Note that there is one more image at end-diastole (11) than at end-systole (10) reflecting the need to allow for the systolic descent of the atrioventricular ring, as described in the text. Note also the ingress of the LV outflow tract in the most basal end-diastolic image, where there is no ventricular mass, and the open ends of the LV myocardial horseshoe are joined together in order to form the appropriate volume. In this patient, there is significant ventricular dilatation, and dysfunction with hypertrophy.

oversampling relies more heavily on good image quality to differentiate atrium from ventricle.

- Papillary muscles and endocardial trabeculae should be excluded from the LV volume and included in the LV mass. Although there is no clear consensus at present, LV mass is usually taken from the end-diastolic images. There is unpublished data (B. Cowan, personal communication) showing that LV mass by CMR varies by a small amount from end-diastole to end-systole, and this may be due to expulsion of intramyocardial blood into the venous system. The reproducibility of LV diastolic volumes is in general better than at end-systole because the volumes are larger, and this is probably as good a reason as any for working from the end-diastolic images to determine mass, but in addition, following the routine above, there may be doubt as to whether LV mass is present in the most basal LV slice at end-systole, if its quality is less than ideal, but by definition, LV mass is always present at end-diastole in the most basal slice.
- A slice thickness of 8 mm at 1.5T provides adequate spatial resolution without overly increasing the number of slices, and thereby the

analysis time. It also limits partial volume effects. A 2 mm slice gap is commonly used to allow easy calculation of volumes, as the center of each slice is then 1 cm apart. There are no formal studies to aid the choice of slice thickness, but 8 mm is a reasonable consensus. Some centers prefer thinner slices, but it is important to maintain signal to noise and image quality. 3D imaging may eventually allow more partitions with thinner slices.

- For the very best interstudy reproducibility for follow-up studies and drug trials, it is necessary to go the extra mile in the analysis, and always have the first set of cines with the regions of interest (ROIs) on screen alongside the follow-up cines during the analysis. At least a print out on paper of the first study and the ROIs used for analysis is required for comparison. For this reason, we routinely print out the diastolic and systolic ROIs in a systematic way for every patient on whom volumes are analyzed.
- It should be noted that this field is still being defined, and as new approaches are being generated regularly, these recommendations may change in the future. In particular, as mentioned above, it is

highly likely that automated post-processing of the cines will become the norm in the near future, but with a 3D analytical approach to fully take into account the motion in systole of the atrioventricular ring, by incorporating VLA and HLA cines to define accurately the mitral valve position at each phase in the cardiac cycle. In my opinion, none of the 2D automatic approaches currently on the market in 2002 fully address this issue with a complete solution, although they clearly can save time and effort in drawing the ROIs, and are a useful aid. A fully robust 3D solution for the post-processing is the holy grail of this field, but there is every reason to be optimistic that it will soon be solved.

CONCLUSIONS

Ventricular volumetry by CMR is a very valuable tool in modern cardiology, because it is safe, fast, accurate, and more reproducible than edw^[35–37]. The simple procedures espoused above are efficient in obtaining the necessary cines, and with the trueFISP technique the image quality is excellent in a high majority of cases. Good quality volumetry should be a staple technique for all centers performing CMR and has application in nearly all pathologies because of the link of increased volumes, and mass, with adverse prognosis.

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