CMR Assessment of Global Ventricular Function and Mass: Greater Efficiency and Diagnostic Accuracy with Argus 4D VF and Inline VF

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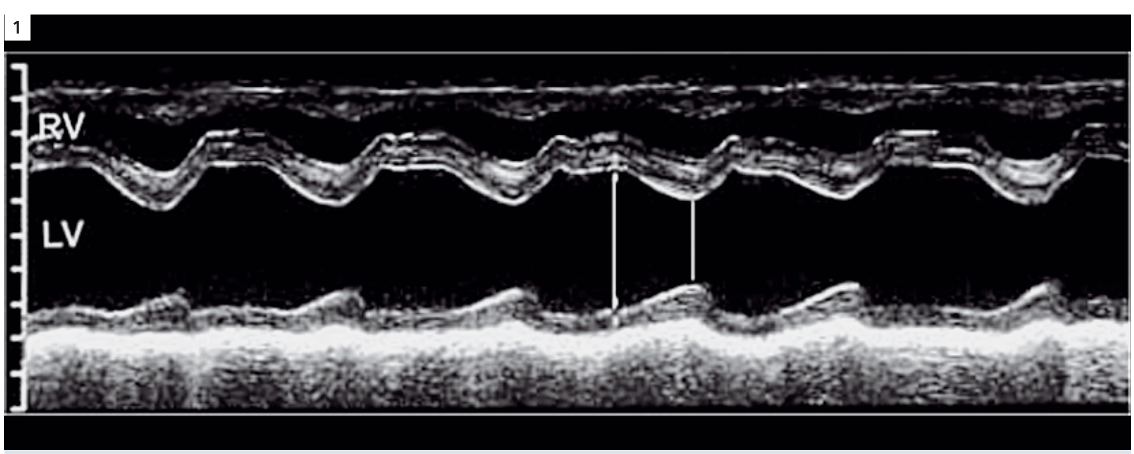
CMR is considered the gold standard for accurate assessment of left and right ventricular function.

Both cardiac volumes and ejection fraction have important prognostic and therapeutic implications in cardiology, hence the accuracy of the data can significantly affect the appropriateness of certain diagnostic or therapeutic approaches in an individual patient, e.g. when considering the implantation of an Implantable Cardioverter Defibrillator (ICD) in a heart failure patient with an ejection fraction (EF) below 35%.
As a widely available and validated method, transthoracic echocardiography is used most frequently for left ventricular function assessment. But in today's medicine, multiple diagnostic tools are available for ventricular function (VF) assessment including nuclear techniques, CT and CMR. However, ejection fraction and volume measurements by these techniques are not completely interchangeable due to the different type of data entered into analysis. Normal values for CMR assessed ventricular function and mass are shown in tables 1A–C. In echocardiography there are various approaches for LV EF assessment:

M-mode echo with Teichholz correction (Fig. 1):

End-diastolic volume = $[7/(2,4+EDD)] \times EDD^3$
End-systolic volume = $[7/(2,4+ESD)] \times ESD^3$

(EDD = end-diastolic diameter,
ESD = end-systolic diameter)



1 M-mode echocardiogram of the left ventricle. The long line shows the end-diastolic position; the short line shows the end-systolic position. The length of the lines reflects the LV diameter at end-diastole (EDD) and end-systole (ESD), respectively and can be used for LV function assessment.

Table 1A: CMR Assessed Left Ventricular (LV) Function Indexed by Body Surface Area (BSA)

Parameter	Mean ± SD		p
	Men	Women	
LVEDVI (mL/m^2)	73.9 ± 14.7	64.5 ± 10.8	< 0.0001
LVESVI (mL/m^2)	24.5 ± 8.8	18.2 ± 5.1	< 0.0001
LVSVI (mL/m^2)	49.4 ± 9.9	46.3 ± 8.4	0.1457
LVEFI (%/m^2)	35.5 ± 5.9	42.9 ± 5.6	< 0.0001
LVMI (g/m^2)	85.1 ± 15.2	66.9 ± 10.9	< 0.0001
CI (mL/min/m^2)	2.9 ± 0.6	2.9 ± 0.6	< 0.1675

Table 1B: CMR Assessed Left Ventricular (LV) Volumes and Mass

Parameter	Mean ± SD		p
	Men	Women	
LVEDV (mL)	142.2 ± 34.0	109.2 ± 22.5	< 0.0001
LVESV (mL)	47.4 ± 19.4	30.9 ± 9.5	< 0.0001
LVSV (mL)	94.8 ± 21.3	78.2 ± 17.0	< 0.0001
LVEF (%)	67.2 ± 7.2	71.8 ± 5.6	< 0.0001
LV mass (g)	163.8 ± 35.8	113.6 ± 24.2	< 0.0001
CO (mL/min)	5.6 ± 1.2	4.9 ± 1.1	< 0.0001

Table 1C: CMR Assessed Left Ventricular (LV) Function by Ethnicity

Parameter	White	p			AA	p		Hispanics	p	Asian
	(mean ± SD)	AA	Hispanics	Asian	(mean ± SD)	Hispanics	Asian	(mean ± SD)	Asian	(mean ± SD)
LVEDV (mL)	148.0 ± 30.5	NS	NS	< 0.05	153.6 ± 30.9	NS	< 0.05	147.3 ± 26.7	< 0.05	116.5 ± 18.4
LVESV (mL)	50.1 ± 14.7	NS	NS	< 0.05	54.9 ± 16.5	NS	< 0.05	50.3 ± 13.6	< 0.05	36.5 ± 7.0
LVSV (mL)	97.9 ± 21.4	NS	NS	< 0.05	98.7 ± 20.9	NS	< 0.05	97.1 ± 18.2	< 0.05	80.0 ± 14.9
LVEF (%)	66.3 ± 6.4	NS	NS	NS	64.5 ± 6.9	NS	< 0.05	66.2 ± 6.2	NS	68.5 ± 4.4
LV mass (g)	170.0 ± 32.1	NS	NS	< 0.05	181.6 ± 35.8	< 0.05	< 0.05	163.8 ± 25.7	< 0.05	129.1 ± 20.0
CO (L/m^2)	5.7 ± 1.4	NS	NS	< 0.05	5.81 ± 30.9	NS	< 0.05	5.7 ± 1.1	< 0.05	4.8 ± 1.0
LVEDVI (mL/m^2)	74.5 ± 14.0	NS	NS	< 0.05	74.8 ± 12.1	NS	< 0.05	77.4 ± 13.0	< 0.05	68.3 ± 7.4
LVESVI (mL/m^2)	25.2 ± 7.1	NS	NS	< 0.05	26.7 ± 7.4	NS	< 0.05	26.4 ± 7.1	< 0.05	21.4 ± 3.4
LVSVI (mL/m^2)	49.3 ± 10.1	NS	NS	NS	48.1 ± 8.5	NS	NS	51.0 ± 8.8	NS	46.9 ± 6.7
LVMI (g/m^2)	85.6 ± 14.7	NS	NS	< 0.05	38.8 ± 16.8	NS	< 0.05	85.9 ± 11.3	< 0.05	75.7 ± 8.2
CI (L/min/m^2)	2.9 ± 0.6	NS	NS	NS	2.8 ± 0.6	NS	NS	3.0 ± 0.6	NS	2.8 ± 0.5

Table 1A–C: Normal values for MRI-assessed left ventricular function indexed by BSA **(A)**, for left ventricular volumes and mass by gender **(B)**, and left ventricular function by ethnicity **(C)**. Note – White = white Americans, AA = Africans, Asia = Asian-Americans, NS = not statistically significant, ESVI = end-systolic volume index, EDV = end-diastolic volume, ESV = end-systolic volume, SV = stroke volume, EF = ejection fraction, CO = cardiac output, EDVI = end-diastolic volume index, ESVI = end-systolic volume index, SVI = stroke volume index, MI = mass index, CI = cardiac index. P values based on on Dunnett's two-tailed t test, with the Asian-American group used as the control group
[Source: Cardiovascular Function in Multi-Ethnic Study of Atherosclerosis (MESA): Normal Values by Age, Sex, and Ethnicity. Natori S, Lai S, Finn P et al. AJR 2006;186:S357–S365.]

Single-plane area-length method (Fig. 2):

$$V = \pi/6 \times LD^2$$

(L = length of the ventricle,
D = diameter of the ventricle)

Biplane modified Simpson rule (BSR, Fig. 3A, B):

$$V=(\pi/4) \times (LVL/n) \sum_{i=1}^{n} DiX \times DiY$$

(V = volume,
LVL = length of LV,
n = number of slices,
DiX = diameter in plane X and slice *i*,
DiY = diameter in plane Y and slice *i*)

LV mass can be calculated in echocardiography by the corrected ASE simplified cubed equation:

$$LVM\ (grams) = 0.8\ [1.05\ [(LVID + IVST + PWT)^3 - (LVID)^3]]$$

(LVID = left ventricular internal dimension,
IVST = interventricular septum thickness,
and PWT = posterior wall thickness, 1.05 g/ml is the specific mass of myocardial tissue)
Due to the geometric assumptions in all of these techniques with regard to the left ventricular shape, the accuracy of LV EF assessment using 2D

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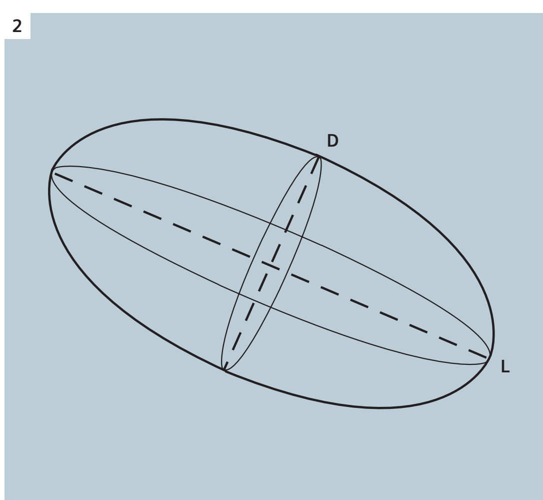
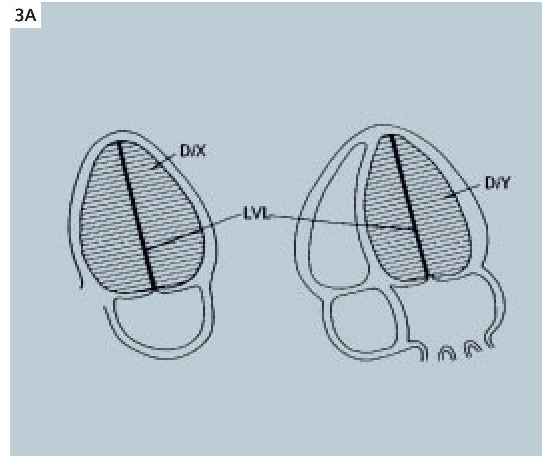


2 The ellipsoid model is used to make geometric assumptions for the left ventricular function calculation according to the single-plane area-length method (D = diameter of LV, L = length of LV).

3A



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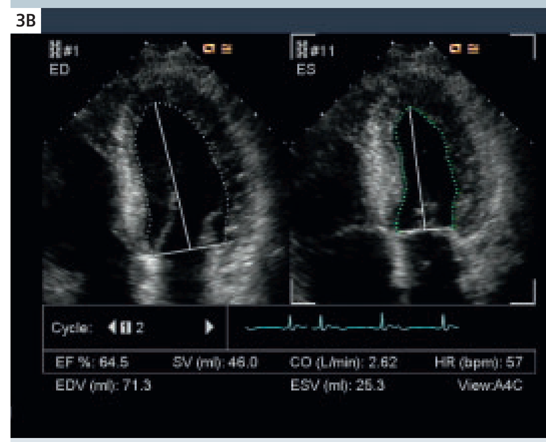


3 Illustration of the application of the biplane modified Simpson rule for LV function analysis to 2- and 4-chamber view images in echocardiography **(A)**. Endocardial contours are needed to be drawn in end-diastole and end-systole to calculate volume data for both phases **(B)**. (V = volume, LVL = length of LV, n = number of slices, DiX = diameter in plane X and slice i, DiY = diameter in plane Y and slice i).

echo is low, especially in patients with regional left ventricular wall motion abnormalities (Kuroda T et al., Echocardiography, 1994).
Although 3D echocardiography shows much higher correlation to CMR it has not yet replaced 2D VF assessment in cardiology (Table 2, Krenning BJ et al. Cardiovasc. Ultrasound, 2003 and Qi X et al., Echocardiography, 2007). Cardiovascular magnetic resonance is the preferred technique for volume and ejection fraction estimation in heart failure patients, because of its 3D approach for non-symmetric ventricles and superior image quality (Bellenger NG et al., Eur Heart J, 2000) which leads also to less user dependency and higher reproducibility. Due to the difficulties in appropriate

Table 2: Volume and function measurement by 3D Echo reconstruction in comparison with CMR

Author/ref.	Object	N	r.	SE	Mean Diff. ± SD
Gopal et al.	LV-EDV	15	0.92	7ml	
	LV-ESV	–	0.81	4ml	
Iwase et al.	LV-EDV	30	0.93	–	-17 ± 23ml
	LV-ESV	–	0.96	–	-4 ± 18ml
	LV-EF	–	0.85	–	-2 ± 6%
Buck et al.	LV-EDV	23	0.97	14.7ml	-10.7 ± 14.5ml
	LV-ESV	–	0.97	12.4ml	-3.4 ± 12.9ml
	LV-EF	–	0.74	5.6%	-2.5 ± 6.7%
Altmann et al.	LV-EDV	12	0.98	8.7ml	-14.2 ± 8.3ml
	LV-ESV	–	0.98	5.6ml	-3.4 ± 5.5ml
	LV-EF	–	0.85	5.3%	-4.4 ± 5.3%
Nosir et al.	LV-EDV	46	0.98	–	-1.4 ± 13.5ml
	LV-ESV	–	0.98	–	-1.5 ± 10.5ml
	LV-EF	–	0.98	–	0.2 ± 2.5%
Kim et al.	LV-EDV	18	–	–	6.4 ± 20ml
	LV-ESV	–	–	–	0.0 ± 13.3ml
	LV-EF	–	–	–	1.4 ± 3.5%
Kim et al.	LV-EDV	10	–	–	-3.1 ± 4.9ml
	LV-ESV	–	–	–	-1.4 ± 2.2ml
	LV-EF	–	–	–	0.5 ± 1.8%
Poutanen et al.	LV-EDV	0.80	–	–	4.0 ± 19.6ml
	LV-ESV	0.88	–	–	0.4 ± 13.0ml
	LV-EF	0.20	–	–	1.7 ± 15.1%
Mannaerts et al.	LV-EDV	17	0.74	–	-13.5 ± 13.5%
	LV-ESV	–	0.88	–	-17.7 ± 23.9%
	LV-EF	–	0.89	–	-1.8 ± 5.8%
Krenning et al.	LV-EDV	15	0.98	13.4ml	-22.7 ± 13.6ml
	LV-ESV	–	0.99	8.7ml	-12.6 ± 9.9ml
	LV-EF	–	0,97		

Table 2: Volume and function measurement by 3D Echo (reconstruction) in comparison with CMR. (N = number of subjects; LV = left ventricle; r = correlation coefficient; SE = standard error or regression; Diff. = difference; SD = standard deviation; EDV = end-diastolic volume; ESV = end-systolic volume; EF = ejection fraction). *[Mod. from: Krenning BJ, Voormolen MM, Roelandt JRTC. Assessment of left ventricular function by three-dimensional echocardiography. Cardiovasc Ultrasound. 2003;1:12].*

Argus Function® allows for a comprehensive evaluation of right and left ventricular function.

With the new Argus 4D VF, LV EF analysis can be performed in less than a minute.

visualization of the right ventricle in transthoracic echocardiography this holds true even more for the assessment of right ventricular function.
MRI is considered also as the ideal method for the determination of LV mass for the same reasons, although transthoracic echo with second harmonic imaging and contrast echocardiographic techniques or 3D echo showed comparable accuracy (Bezante GP et al., Heart, 2005 & Mooney MG et al. Int J Card Imaging, 2000). However, most of the echocardiographic formulas overestimate LV mass, when compared to CMR (Scharhag et al. Z Kardiol, 2003).

CMR for quantification of ventricular function and mass

There are several ways for the acquisition of MR images for LV/RV function and mass assessment. TrueFISP (SSFP) sequences provide high spatial resolution and a high contrast between the dark myocardium and the bright blood-pool and therefore are preferred for this purpose: a stack of short-axis cine images (with a slice thickness of 8–12 mm) by which both ventricles can be covered without a gap in 1–2 breathholds.
Preferably, retrospectively ECG-gated sequences should be used to cover the whole R-R interval. Nevertheless, prospectively gated sequences can also be used, without losing accuracy. In a 2-breathhold acquisition, usually 4–6 slices with a gap of 100% from slice to slice are acquired during the first breathhold. Ideally, the acquisition can be planned on 4-chamber and 2-chamber plane. The most basal slice should cover the mitral valve plane in diastole and the stack should be parallel to the mitral valve plane in both orientations. For the second acquisition, the complete stack is shifted with the “gap filling +/-” functionality towards the apex. Using this 2-breathhold approach, a high spatial and temporal resolution can be ensured. The use of integrated Parallel Imaging Techniques – iPAT (e.g. GRAPPA) – can help to accelerate the acquisition or to increase the resolution even further, so that a single breathhold approach can be applied routinely.

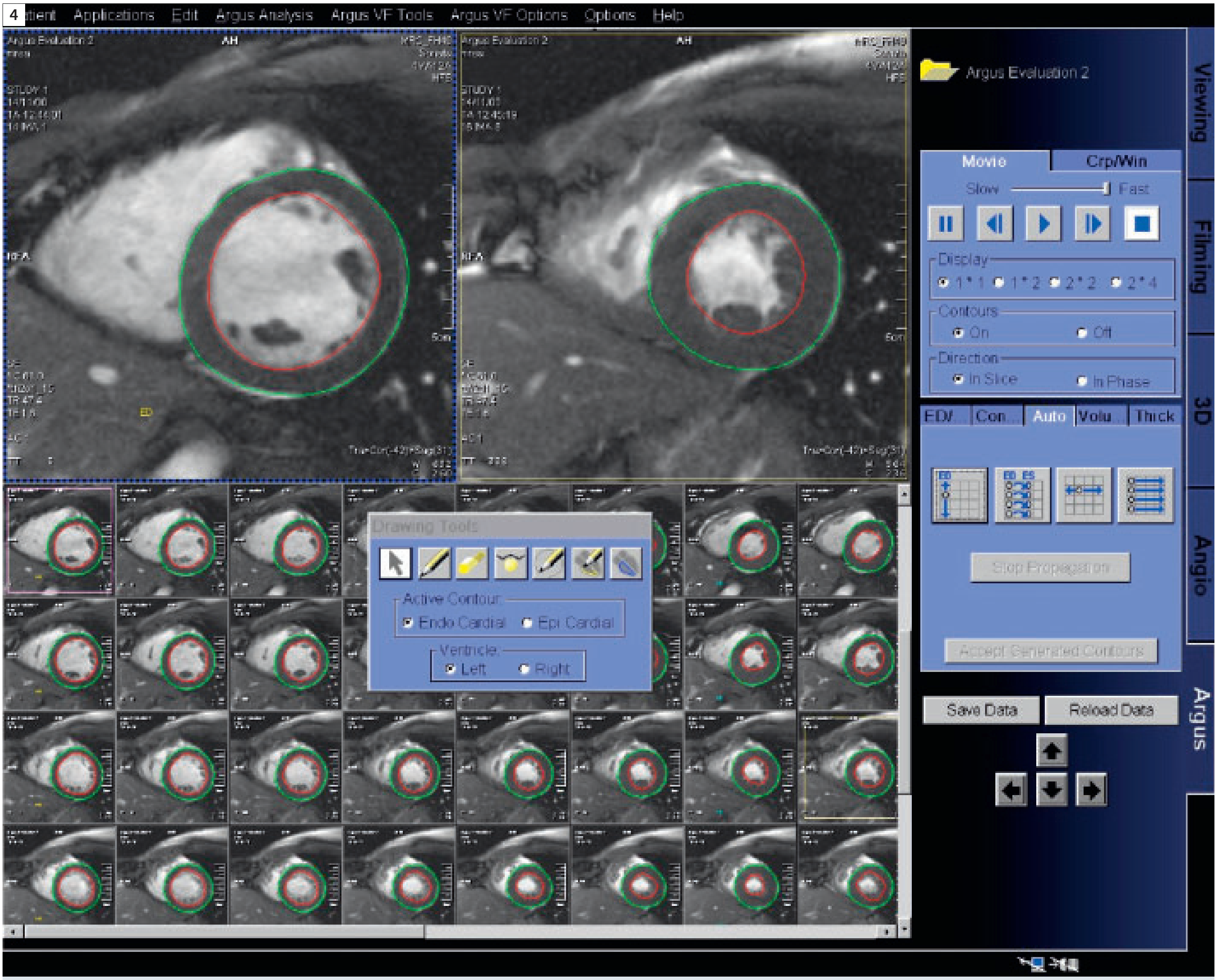
Tools for ventricular function and mass assessment

In cardiovascular MRI, Argus Function® has been used as a comprehensive tool for ventricular function and mass assessment by Siemens users for many years with continuous improvements in the functionalities over time.
The workflow is simple: When loading the acquired images into Argus Function, the images get sorted vertically according to the slice position, from base to apex, and horizontally according to the point in the cardiac cycle from the beginning of the systole to the end-diastole (Fig. 4). After zooming in on the region-of-interest (LV/RV), the endocardial and epicardial contours of LV and RV can be drawn manually or rather semi- or fully automatically on the first image. The contours can be propagated horizontally and vertically to the rest of the images for a fast analysis. Contour changes, e.g. for in- or excluding papillary muscles, can be applied manually with various tools.
The resulting section provides the typical volumetric and functional data for LV and RV including parameters such as EDV, ESV, SV, CO and filling rates. The calculation is done using the modified Simpson’s rule. When both endo- and epicardial contours are drawn, ventricular mass and regional wall thickening can be calculated. Argus Function provides tabular and graphical, color-coded display of the results in parameter maps (e.g., in parameterized bull’s-eye plots with a sector based model) or graphs (e.g., volume-time curve). The customizable layout of the Movie Viewer allows for single movie display or a simultaneous display of up to 8 movies, which is helpful especially in the setting of dobutamine stress MRI. AVI files can be generated and exported easily. Contrast and brightness windowing of the images can be done at any time during the analysis.
All results including the graphs and summary tables can be integrated in a DICOM structured report and stored to database. Data can be exported as ASCII files when needed.

New tools for LV function and mass assessment using CMR

Argus 4D VF®

In left ventricular analysis, the correct selection of the basal slice is of importance for highly accurate measurement of volume data. Siemens’ new tool for LV function analysis, Argus 4D VF, enables the user to identify the mitral valve insertion points in end-diastole and end-systole on long-axis planes and automatically adapts the basal border of the LV cavity in every single phase of the cardiac cycle. With Argus 4D VF there is neither missing ventric-



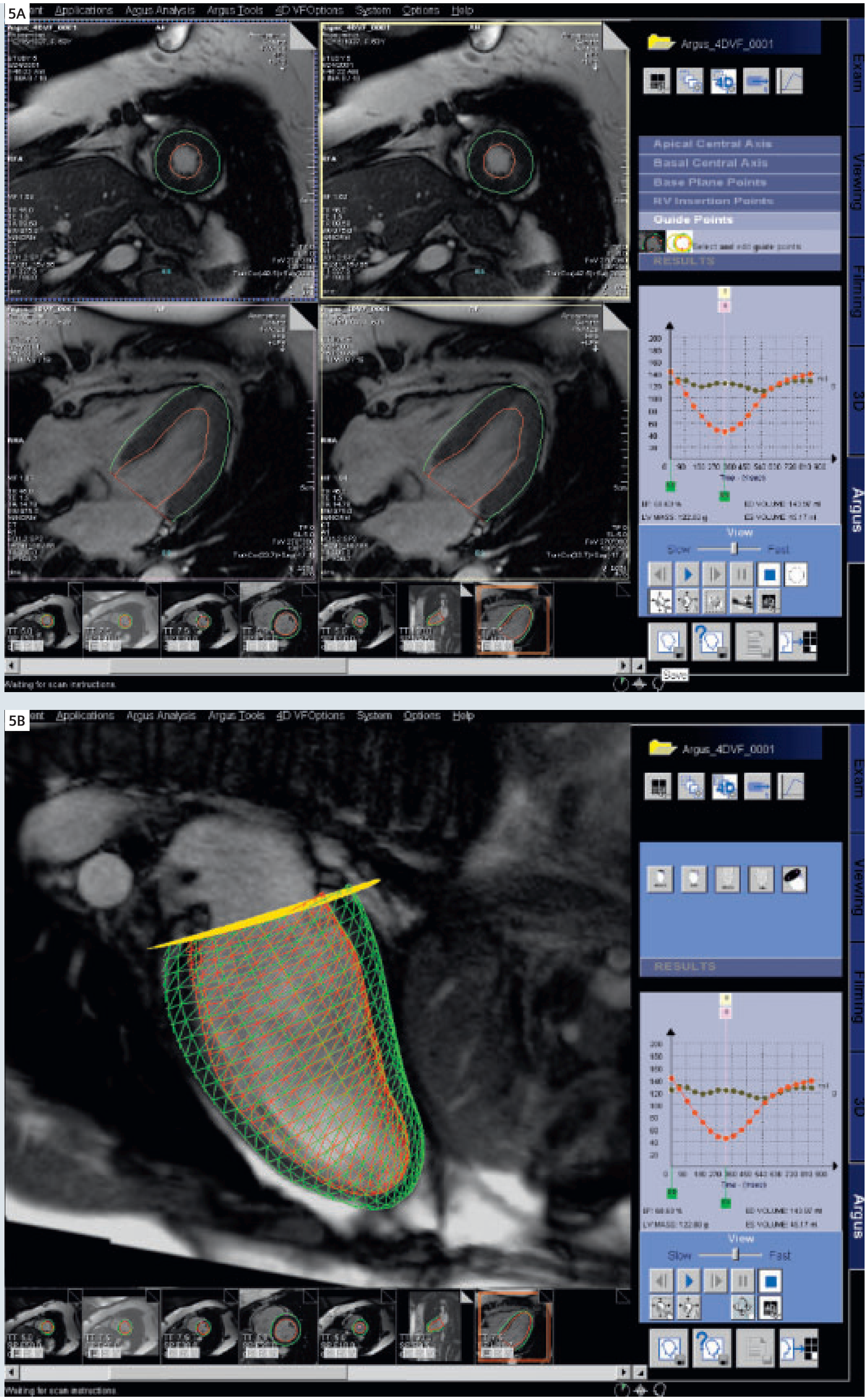
4 User interface of Argus Function®. Contours are drawn initially on one or more slices and then propagated to other slices and phases automatically. Argus Function allows for volume, function and mass analysis for both LV and RV.

ular volume nor additional atrial volume deteriorating the accuracy of the LV volumetric analysis anymore.

Beyond providing higher accuracy, the tool's main advantage is its speed: Using Argus 4D VF, a typical LV function and mass analysis can be done in less than a minute. The reason for this is a new approach: Instead of contour tracing, a heart model-based algorithm enables the user to limit the input to a few mouse clicks with a guided workflow to identify the following anatomical landmarks:

- Center of the LV apex on a apical short-axis cine
- Center of the LV base on a basal short-axis cine
- Mitral valve insertion points on a 2- and/or 4-chamber plane in diastole and systole

The model-based algorithm provides within a few seconds the appropriate endo- and epicardial contours on all slices and phases as well as a summary table including various data for volume, function and mass. A volume-time curve and the key parameters are also integrated into the main window which allows to see parameter changes immediately



5 The user interface of the new Argus 4DVF®. After loading short- and long-axis images, a guided workflow ensures a fast calculation of the contours by use of a heart-model based algorithm and the automatic assessment of LV function **(A)**. Advanced volume rendering options are available for a time-resolved (4D) visualization **(B)**.

when changes are done on contours (e.g. for papillary muscle inclusion/exclusion, Fig. 5A). A comprehensive visualisation task-card provides various 4D volume visualization options (solid/mesh, endocardium only/epicardium only etc.) with or without spatial integration of the respective 2D cine MR images (Fig. 5B).

Inline VF®

Especially in a high-throughput setting, instead of the necessity of using post-processing tools, one might expect to have the most relevant data available right after a scan – without any user interaction. With another tool, Inline VF, Siemens introduced the first fully automatic LV function assessment tool implemented on the MR acquisition workplace. Inline VF is integrated directly into the acquisition sequence (Fig. 6), enabling the calculation of functional data already during image acquisition. The heart is localized on the short-axis CMR images automatically with the support of a motion compensation algorithm; endo- and epicardial contours are detected and shown on the inline display with no user interaction (Fig. 7A, B). Subsequently the parameters of LV function are generated and shown on the display without additional mouse clicks (Fig. 7C). The images can be loaded and modified in Argus Function, when needed. Inline VF is embedded in *syngo* BEAT, thus can be used with each triggered 2D cine sequence (GRE or TrueFISP contrast, segmented or real-time acquisition, cartesian or radial sampling scheme).

CMR is the gold standard for functional cardiac diagnostics; the new tools further lead to an efficient workflow and will help to increase the utilization of CMR in clinical routine.

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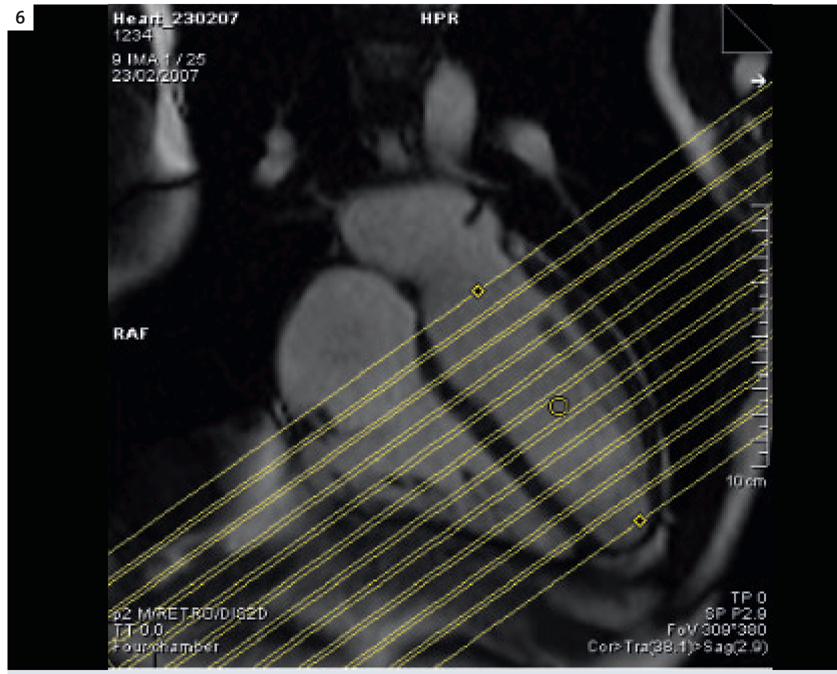
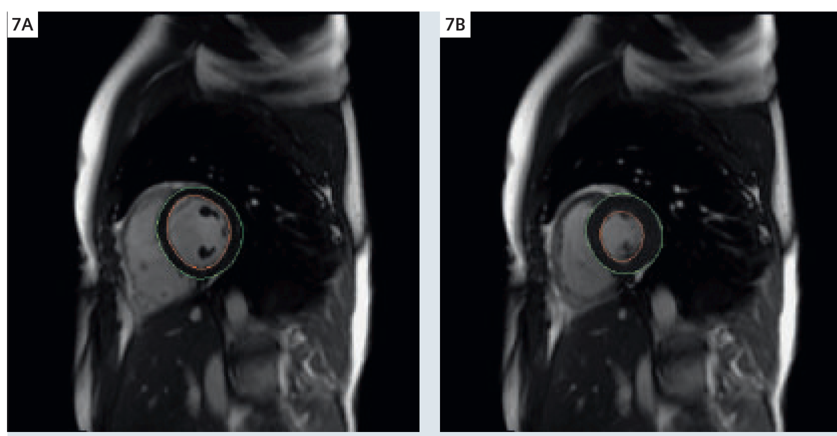


6 Planning of short-axis slices on a 4-chamber view using Inline VF®. The most basal slice is positioned on the mitral valve plane in end-diastole. An automatic algorithm moves the most basal slice for calculation purposes in end-systole to the next slide when necessary, to avoid left atrial volume affecting the volumetric analysis.

7A 7B



7C

7 Inline VF® automatically locates the heart and detects endo- and epicardial contours in all cardiac slices and phases **(A, B)**. Parameters of left ventricular function (e.g., EDV, ESV, EF, SV etc.) are shown on the inline display right after scan **(C)**.