7.10 Evaluation of Ventricular Function Parameters

K.-U. Jürgens, R. Fischbach

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7.10.1 Introduction

The accurate and reproducible determination of left ventricular myocardial function is fundamental to the diagnosis, disease stratification, treatment planning, and estimation of prognosis of patients with ischemic and non-ischemic cardiomyopathy (Schocken 1992, White 1987). Analysis of left ventricular myocardial function includes the determination of global and regional function parameters. Global cardiac function is represented by the ejection fraction, stroke volume, and cardiac output, which are derived from diastolic and systolic left ventricular volume measurements. Regional function parameters include myocardial wall thickness and systolic wall thickening; these provide more detailed information on the functional state and viability of ischemic and non-ischemic myocardial segments. Analysis of ventricular volume and secondary function parameters are clinically useful to:

- Determine the magnitude of dysfunction and the level of compensation, e.g., in patients with clinically manifest coronary heart disease or dilative and hypertrophic cardiomyopathy
- Measure the response to a therapy, e.g., revascularization or medical treatment
- Assess a patient's risk for future cardiac events and prognosis for survival

The assessment of ventricular function may provide information for the initial diagnosis of coronary heart disease in symptomatic patients, although left ventricular function does not sensitively reflect the severity of coronary artery stenosis, since contraction remains normal until coronary blood flow is reduced below a critical threshold. The relationship between the severity of coronary artery stenosis and ventricular function in the ischemic region is therefore nonlinear and ventricular function decreases exponentially once blood flow falls below resting levels. Since regional or global ventricular dysfunction may also result from cardiomyopathy or valvular disease, left ventricular dysfunction is not specific to coronary heart disease or acute myocardial infarction, since unstable angina may also depress ventricular function.

Multi-slice CT of the heart is being increasingly used to assess coronary artery and cardiac morphology. Image reconstruction in multi-slice CTA has been optimized for coronary artery visualization, but with ECG-gated spiral acquisition, image data are available for any phase of the cardiac cycle (Ohnesorge 2000). Thus, retrospective image reconstruction in specific heart phases can be used to determine end-systolic and end-diastolic ventricular volumes as well as myocardial wall thickness. This section will discuss the potential of multi-slice CT in the assessment of ventricular function with regard to accuracy, limitations, and clinical applications.

7.10.2 Determination of Cardiac Function Parameters with Multi-slice CT

7.10.2.1 Calculation of Ventricular Volume

The ventricular volume changes throughout the cardiac cycle (Fig. 7.72). The mechanical cycle starts with an isovolumetric contraction at the end of ventricular filling. The increase in ventricular pressure results in the ejection of blood into the systemic and pulmonary circulation. This is followed by isovolumetric ventricular relaxation and then by the ventricular filling period. Ventricular volume changes are similar in the right and the left chambers of the heart. Left ventricular volume can be measured using the following approaches:

- The *area-length method* uses a vertical or horizontal long-axis view (Fig. 7.73a). It has been developed to allow for ventricular volume measurements with catheter coronary angiography based on a limited number of available projections. The ventricular area (A) and the length from apex to the mitral valve plane (*L*) are used to calculate the left ventricular volume (*V*) according to the formula:

$$V = \frac{8}{3} \times \frac{A^2}{\pi \cdot L}$$

- The *Simpson's method* employs contiguous *short-axis* image sections of the left ventricle (Fig. 7.73b). It was developed for MR ventricular volume measurements that produce short-axis images in a single image sequence. The cross-sectional images have a certain section thickness (*S*) and are adjacent one to another. The left ventricular volume (*V*) is calculated by adding all cross-sectional areas (*A*) multiplied with the section thickness (*S*) as:

$$V = \sum A_N \times S$$

- A threshold-based direct volume measurement is achieved using a segmentation technique in imaging modalities that depict density or signal-intensity differences between the myocardium and cardiac chambers. The signal difference can be produced by contrast-enhanced blood in the cardiac chambers. The sum of all contiguous voxels exceeding a predefined attenuation threshold represents the total chamber volume.

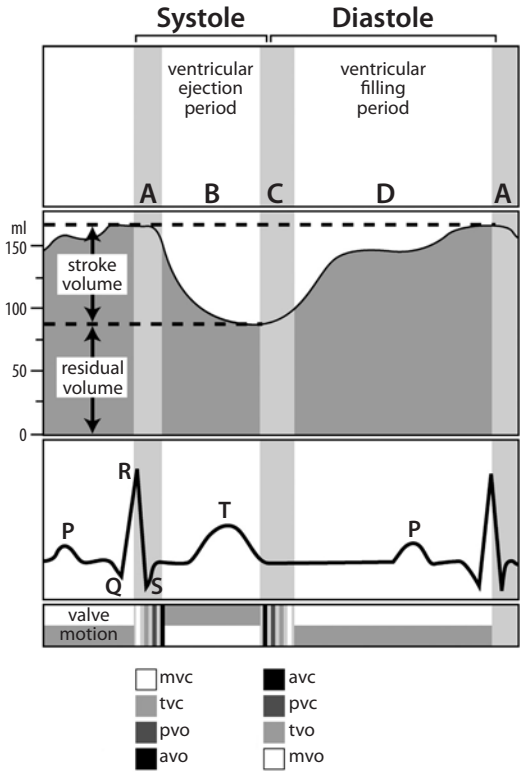


Fig. 7.72. The electrical and mechanical events during the cardiac cycle: left ventricular volume curve, electrocardiogram, and valvular events are depicted. *A* Isovolumetric contraction phase, *B* ventricular ejection period, *C* isovolumetric relaxation phase, *D* ventricular filling period. mV/mV Mitral valve closing/opening, Tec/to tricuspid valve closing/opening, pro/PVC pulmonary valve opening/closing, Ave/Ave aortic valve opening/closing

The Simpson's method and direct volumetry do not rely on geometric assumptions and thus are preferred over the area-length method for accurate ventricular volume determination with multi-slice CT. Short axis MPRs can be generated from a multi-slice CT axial image data set in different phases of the cardiac cycle and can then be used as input for the Simpson's method. However, as multi-slice CT produces thin-slice volumetric data, voxel-based methods for direct volumetry are well-suited for CT-based calculations of ventricular volume.

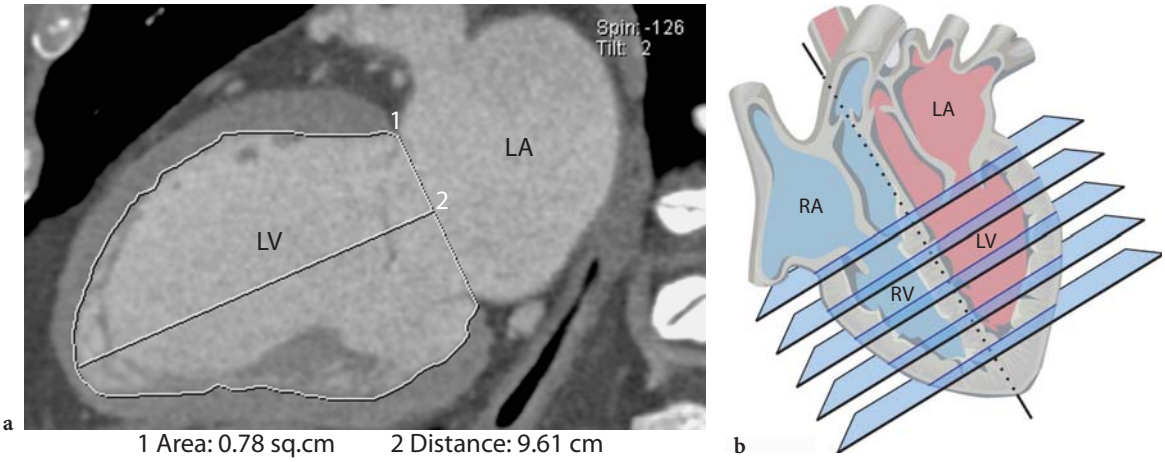


Fig. 7.73. a Area-length method for determination of left ventricular volume. Left ventricular dimension and area are measured on a vertical long-axis reformation. **b** Simpson's method for left ventricular volume measurement. A series of short-axis images is used for area measurement. Every cross-sectional area is multiplied with the section thickness to give the ventricular volume. *RA* Right atrium, *RV* right ventricle, *LA* left atrium, *LV* left ventricle

7.10.2.2 Calculation of Ejection Fraction, Stroke Volume, and Cardiac Output

The normal ventricle ejects about two-thirds of its end-diastolic volume during systolic contraction. The ventricular ejection fraction (EF) describes the relative change of ventricular volume from end-diastolic volume (EDV) to end-systolic volume (ESV) and reflects global ventricular function. EF is calculated according to:

$$EF = \frac{(EDV - ESV)}{EDV} \times 100\%$$

The stroke-volume (SV) is the absolute change in ventricular volume [SV (ml) = EDV–ESV]. Cardiac output (CO) is the SV multiplied by the heart rate, which means the pumped blood volume per minute [CO (ml/min) = SV × heart rate].

7.10.2.3 Assessment of Regional Function

Systolic contraction results in a significant reduction of ventricular volume and a thickening of the ventricular myocardial wall. The thickness of the left ventricular myocardial wall is between 6 and 8 mm in diastole and between 10 and 14 mm in systole. Normal wall thickening of the left ventricular myocardium during systole is approximately 5 mm. Systolic contraction requires functional muscle tissue and an adequate regional blood supply. Scar tissue does not contract and thus does not show systolic wall thickening. The reduction of regional coronary blood flow below a critical threshold also prevents normal contraction. Due to the coronary flow reserve, only high-grade lesions will reduce coronary blood flow below this critical level at rest. Coronary blood flow increases significantly under physical stress, such that flow-obstructing lesions become symptomatic, resulting in regional hypoperfusion and thus impaired ventricular contraction. Stress imaging techniques, using exercise or drugs that induce vasodilatation to cause regional hypoperfusion, make use of this fact to diagnose obstructive coronary artery disease based on the occurrence of impaired wall motion under stress.

Stress imaging requires serial measurements, which are easily achieved with cine magnetic resonance imaging (CMR) and ultrasound but represent a major limitation for CT due to the need for repeated contrast injections and radiation exposure. Despite these limitations, CT can still reveal basic information on regional wall function at rest. Systolic and diastolic image reconstructions depict changes in

wall thickness, and multi-phase reconstructions even allow analysis of ventricular wall motion over the cardiac cycle.

Wall motion abnormalities can be qualitatively assessed (Fig. 7.74). An area with impaired contraction or wall thickening is called hypokinetic; a paradoxical outward motion during systolic contraction is called dyskinesis. In accordance with other cross-sectional cardiac imaging modalities, the segment model of the American Heart Association should be used to describe the exact location of abnormal motion (Cerqueira 2002).

7.10.3 Data Acquisition and Image Reconstruction

Since information on virtually any cardiac phase is contained in an ECG-gated multi-slice CT spiral data set, images from end-systolic and end-diastolic phases can be retrospectively produced using ECG gating without the need for additional radiation exposure or administration of contrast material. From the reconstructed axial CT images, quantitative information on ventricular volume changes throughout the cardiac cycle can be derived.

Pure ventricular function analysis is not the focus of multi-slice CT, since other non-invasive imaging modalities, which do not require ionizing radiation or administration of potentially nephrotoxic contrast media, are available. In most cases, functional assessment will be carried out complementary to coronary CTA, and the imaging protocols are the same. While coronary CTA aims for selective enhancement of the coronary arteries and left ventricle, homogenous contrast enhancement in all cardiac chambers is crucial for the reliable detection of cardiac contours, especially if right ventricular parameters are to be assessed. A biphasic injection of contrast agent with a second phase at reduced flow or – if a double-head injector is available – at 50% contrast-agent concentration and constant flow volume will produce adequate right ventricular opacification without artifacts from excessive contrast density in the right atrium or ventricle. Some multi-slice CT scanners provide prospective tube-current modulation with coronary artery scan protocols. As tube current is reduced during the systolic phase, image noise increases significantly. Since cardiac function studies do not need high-resolution images and make use if thicker section thickness, tube-current modulation should not prevent the assessment of cardiac function. However, published reports have not included tube-current modulation with their imaging protocols.

For global functional assessment, only a systolic and a diastolic phase is needed. To identify the proper image reconstruction windows, a single axial image is reconstructed every 5% of the RR-interval at a representative mid-ventricular level. The appropriate reconstruction windows for the systolic and diastolic phases are visually identified as the images showing the minimum and maximum ventricular diameter and checked against the ECG. The systolic phase is usually found at 25% of the RR-interval and the end-diastolic phase at around 85% (Juergens 2004).

This approach to determine the systolic and diastolic phases is vulnerable to criticism, since the

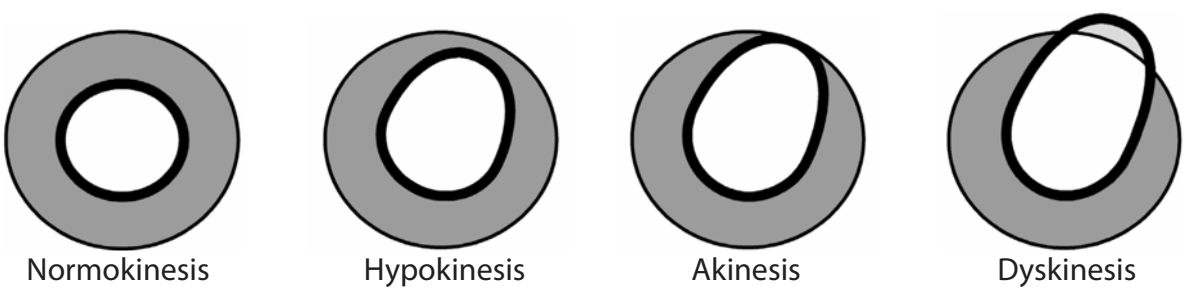


Fig. 7.74. Qualitative assessment of regional left ventricular (LV) wall motion. Regular LV wall motion is classified as normokinesis. Disturbances of LV wall motion are graded into hypokinesis (reduced regional systolic wall thickening), akinesis (absent regional systolic wall thickening), and dyskinesis (outward movement of the LV wall segment during systolic contraction)

transverse plane does not visualize the left ventricle in its appropriate anatomical axis. However, possible systematic errors should be minimal if the reference plane is chosen properly, i.e., at a level showing the anterior and posterior leaflets of the mitral valve and the anterior papillary muscle. The alternative would be to produce axial image sets every 5–10% of the cardiac cycle and visually determine the maximum and minimum ventricular volume from short-axis reformations. This method produces enormous amounts of unnecessary axial images and is very time-consuming due to the reconstruction time and extensive post-processing tasks involved. With the advanced raw-data reconstruction algorithms provided by some manufacturers, short-axis images can be directly produced from the acquired raw data (Fig. 7.75). This approach reduces the number of images created for the assessment of cardiac function and allows integrating global as well as regional function analyses seamlessly into a coronary CT study.

If direct reconstruction of short- and long-axis MPRs is not available, the same views can be generated manually with a few post-processing steps that are based on the axial images. A vertical long-axis view is produced along a line from the apex of the left ventricle to the middle of the mitral valve. Based on this long-axis view, a stack of secondary reformations in an orientation perpendicular to the vertical long axis and parallel to the mitral valve plane is created to encompass the entire left ventricle. The same approach is possible based on a horizontal long-axis reformation. The section thickness for the short-axis images is usually set to 8 mm, in analogy to CMR protocols.

7.10.4 Image Analysis

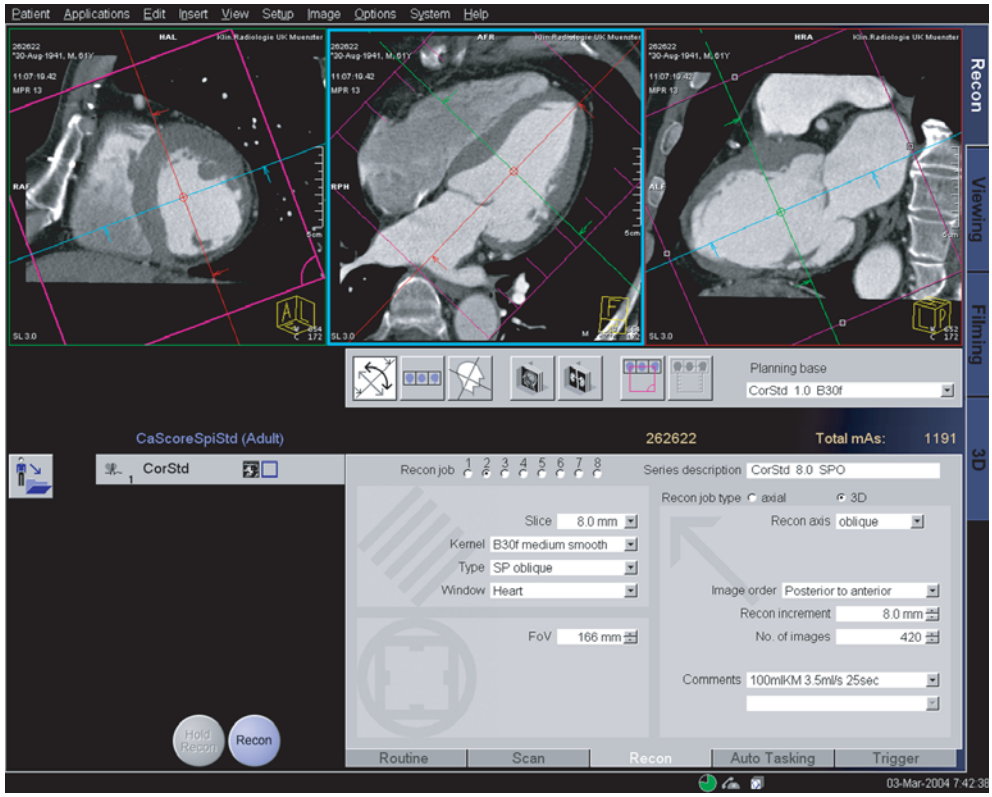
Diastolic and systolic left ventricular volumes can be calculated using standard software for distance and area measurements with the area-length method or Simpson's method. Software packages adapted from validated CMR analysis tools that semi-automatically measure ventricular volume and wall thickness are commercially available and help to speed up analysis and reporting. For the analysis of global function, only the endocardial borders of the left or right ventricle are needed. Endocardial contours are either automatically detected by the software or manually traced on systolic and diastolic short-axis images. The most basal slice lies just forward of the atrioventricular ring and should display the myocardium in at least 50% of its perimeter. The most apical slice is the last image showing a contrast-opacified lumen. By convention, the papillary muscles are included in the ventricular lumen. The analysis time is 10–15 min.

Endocardial and epicardial contours are required to assess wall thickness and systolic wall thickening, and to estimate cardiac mass. If regional wall motion is to be displayed, at least eight to ten heart phases are needed. Images from corresponding slice positions can be viewed in a cine loop to visually assess motion abnormalities. The analysis software will provide quantitative information on ventricular volume and wall thickness over time as well as volumes normalized to body surface area, which enables comparison to normal values (Table 7.13).

7.10.5 Limitations

Imaging of the moving heart requires a modality with a high temporal resolution in order to achieve artifact-free display of myocardial contraction over the cardiac function cycle and determination of peak systolic contraction. Usually, multi-slice cardiac CT reconstruction algorithms used for coronary artery visualization achieve a temporal resolution that is equivalent to the time for a 180° rotation and thus to half of the system rotation time. Two-segment reconstruction algorithms have also been introduced; these provide a temporal resolution that is one-fourth the rotation time at certain heart rates.

Thus, 250-ms temporal resolution using one segment and down to 125-ms temporal resolution using two segments were reached by the first 4-slice systems, with 500-ms rotation time. The newest 16-slice CT scanners provide rotation time down to 370 ms, and the latest 64-slice CT scanners even down to to 330 ms, thus improving temporal resolution even further. With rotation times of 400 ms or less and the use of up to two segments for image reconstruction, the assessment of global cardiac function with



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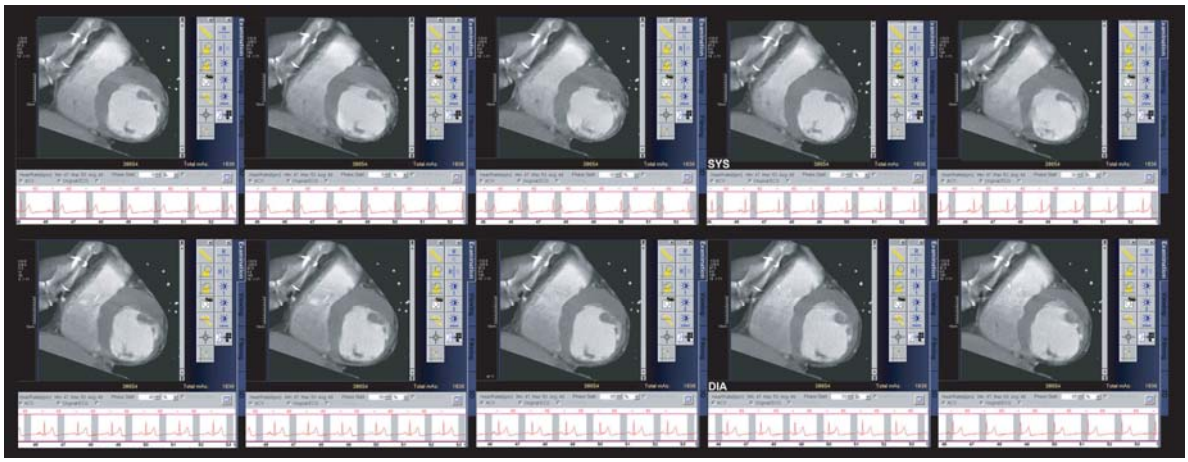

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Fig. 7.75a,b. Direct generation of short-axis images from a multi-slice CT data set. **a** The appropriate orientation is interactively defined and a series of short-axis images is produced without the need to generate primary axial reformations. **b** Direct reconstruction of short-axis MPRs from mid-ventricular level images allows for easy identification of maximum contraction and maximum dilatation. Systolic and diastolic image series are then used for ventricular volume measurement

Table 7.13a. Global left ventricular (*LV*) and right ventricular (*RV*) function parameters adapted from cine magnetic resonance imaging data in healthy volunteers. *EDV* End-diastolic volume, *ESV* end-systolic volume, *EF* ejection fraction, *BSA* base area (from Sandstede 2000, Alfakih 2003)

	Males	Females
Left ventricle		
LV-EDV (ml)	102–235	96–174
LV-EDV/BSA (ml/m^2)	53–112	56–99
LV-ESV (ml)	29–93	27–71
LV-ESV/BSA (ml/m^2)	15–45	14–40
LV-EF (%)	55–73	54–74
LV mass (g)	85–181	37–67
LV mass/BSA (g/m^2)	46–83	–
Right ventricle		
RV-EDV (ml)	111–243	83–178
RV-EDV/BSA (ml/m^2)	111–243	48–103
RV-ESV (ml)	47–111	32–72
RV-ESV/BSA (ml/m^2)	25–53	18–42
RV-EF (%)	48–63	50–70

Table 7.13b. Regional LV function parameters adapted from CMR data in healthy volunteers (from Sandstede 2000, Alfakih 2003). *EDWT* End-diastolic wall thickness, *ESWT* end-systolic wall thickness, *SWT* systolic wall thickness, *SWTH* systolic wall thickening

	Males	Females
Left ventricle		
EDWT (mm)	7.6 ± 1.4	6.3 ± 1.0
ESWT (mm)	13.2 ± 1.8	12.2 ± 1.6
SWT (mm)	5.5 ± 0.8	5.8 ± 1.2
SWTH (%)	75 ± 16	96 ± 24

multi-slice CT is feasible. Multi-segment reconstruction algorithms using up to four segments have been developed to increase the temporal resolution for better assessment of regional function parameters. Using four segments and a rotation time of 370 ms, a temporal resolution of less than 50 ms can be realized. However, clinical experience with these image reconstruction algorithms is still limited.

Despite a pronounced improvement in temporal resolution, multi-segment algorithms suffer from several limitations. The spiral pitch has to be reduced to prevent degradation of the slice-sensitivity profile, which in turn adversely affects endocardial contour definition (Juergens 2005). A low pitch increases the scan time and, consequently, the radiation dose. Furthermore, optimal temporal resolution is only reached for a very specific heart rate, but heart rate only rarely remains constant for the duration of the entire scan.

7.10.6 Clinical Considerations

7.10.6.1 Measurement of Left Ventricular Function

Determination of global left ventricular function has a high clinical impact, since it is the strongest determinant of pump failure and death due to myocardial infarction (Shah 1986). Different non-invasive imaging modalities allow assessment of ventricular function and will eventually determine the potential role of multi-slice CT in this setting. Trans-thoracic echocardiography is a widely available, relatively inexpensive, and mobile modality for cardiac imaging. However, image acquisition is acoustically window and operator-dependent. The accuracy of quantitative left ventricular function measurement is hampered due to geometric assumptions of left ventricular shape, especially in remodeled hearts with complex and irregular shape changes.

Radionuclide ventriculography is commonly used to measure left ventricular EF, but it is hampered by its limited temporal and spatial resolution as well as the prolonged preparation and examination times (Lethimonnier 1999). Gated-perfusion single-photon emission computed tomography (SPECT) allows three-dimensional assessment of cardiac function and is especially useful when perfusion needs to be assessed. However, diagnostic accuracy is limited in small and large ventricles because of the technique's restricted spatial resolution. Furthermore, definition of ventricular borders in ventricular segments with circumscribed thinning after infarction can be difficult, due to very low

emission from these areas. The need for repeated radionuclide injections in sequential studies may also be problematic since radiation exposure cannot be neglected. The dose equivalent for myocardium and a blood-pool marker is about 8×10^{-1} mSv per 100 MBq with ^{99m}Tc-Tetrofosmin; 750–900 MBq ^{99m}Tc-Tetrofosmin are commonly used for first-pass radionuclide ventriculography.

EBCT has long been used successfully to measure cardiac function and mass; however, such systems are costly and the limited number of scanners available restricts access to this modality. Scanning is commonly done with prospective ECG synchronization in a sequential technique and thus suffers from the well-known limitations of this approach.

Currently, CMR is the gold standard for determining cardiac function. Its well-evaluated, documented advantages include the lack of radiation exposure, the avoidance of contrast-medium injection, and the excellent temporal resolution. Furthermore, short-axis images are easily produced and secondary reformations are not needed. There are few limitations and contraindications; for example, CMR is rather susceptible to irregular or changing heart rates and cannot be performed in patients with implanted pacemakers or defibrillators.

Due to the availability of the many competing imaging modalities, radiation exposure and the need for iodinated contrast material injection will prevent multi-slice CT from becoming a first-line modality for pure cardiac function evaluation. Still, the many advantages of multi-slice CT are apparent: (1) It does not rely on geometric assumptions when measuring cardiac chamber volumes and direct voxel-based volumetry can be applied; (2) it has an outstanding spatial resolution, data acquisition is quickly performed in a single breath-hold, and cardiac implants do not represent a contraindication; (3) cardiac function data are contained in any coronary artery CT study. Since multi-slice CT is becoming an accepted tool for coronary artery visualization, the combination of coronary artery imaging and global left ventricular function determination as a one-step procedure constitutes a promising approach to obtaining a conclusive cardiac assessment. At present, normal values for cardiac chamber volumes and global function, as determined from multi-slice CT, have not been published. Therefore, quantitative multi-slice CT data have to be referenced to normal values established by CMR or echocardiography. A synopsis of global and regional parameters of ventricular function determined by CMR is given in Table 7.13.

7.10.6.2 Accuracy and Reproducibility of Left Ventricular Volume and Function Measurement

Several studies have been published on the evaluation of left ventricular volume and function determination by multi-slice CT. End-diastolic and end-systolic volumes as well as left ventricular EF determined by multi-slice CT showed good agreement with respective measurements from cineventriculography, echocardiography, and CMR in patients with suspected or manifest coronary heart disease (Table 7.14). All authors reported a slight overestimation of left ventricular end-systolic volumes by multi-slice CT compared to CMR, resulting in a systematic underestimation of left ventricular EF of 1–7% (Juergens 2004a, Mahnken 2003, Grude 2003). The most likely explanation of this observation is the lower temporal resolution achieved by multi-slice CT systems compared to CMR. A temporal resolution of 30–50 ms per image is required to accurately capture the maximum systolic contraction, especially in patients with higher heart rates. The multi-slice CT scanners that have been used for referenced clinical studies had a fastest rotation time of 500 ms (4-slice CT) and 420 ms (16-slice CT) and image reconstruction was done using single-segment and 2-segment reconstruction. Thus, the temporal resolution provided was between 125 and 250 ms for 4-slice CT and between 105 and 210 ms for 16-slice CT. Due to the limited temporal resolution, end-systolic volumes were usually overestimated and thus EF was underestimated. Due to the faster rotation times of the newer 16-slice and recent 64-slice CT scanners, the improved temporal resolution will result in even better agreement between multi-slice CT and CMR measurements.

At present, the assessment of left ventricular function from multi-slice CT coronary angiography data sets has not entered clinical routine. Experience with multi-slice CT and cardiac function assessment has

Table 7.14. Comparison of LV-EDV and LV-ESV determined from multi-slice CT of the heart. Results are compared to cine-ventriculography (CVG), 2D-echocardiography (2D-Echo), and CMR using turbo-gradient echo (TGrE) and steady-state free precession (SSFP) cine sequences

Author	N	Modality compared to MSCT	LV-EDV	LV-ESV	LV-EF	LV-EF: MSCT vs. other modality (%)
Juergens 2002	22	CVG	–	–	0.80	–11.5 ± 5.7
Hundt 2002[a]	30	CVG	0.72	0.88	0.76	–13.7 ± 11
Heuschmid 2003[a]	25	CVG	0.59	0.82	0.88	–17 ± 9
Boehm 2004[a]	20	CVG	–	–	0.83	–4.7 ± 7.1
Dirksen 2002[a]	15	2D-echo	–	–	0.93	–1.3 ± 4.5
Grude 2003[a]	28	TGrE-CMR	0.92	0.90	0.90	–7.9 ± 5.6
Mahnken 2003[a]	16	SSFP-CMR	0.99	0.99	0.98	–0.9 ± 3.6
Juergens 2004a[b]	30	SSFP-CMR	0.93	0.94	0.89	–0.25 ± 4.9
Coche 2004[a]	14	SSFP-CMR	0.84	0.90	0.98	–
Juergens 2004b[b]	29	SSFP-CMR	0.95	0.96	0.95	–2.1 ± 4.8

[a]CT data were acquired using 4-slice CT technology.
[b]CT data were acquired using 16-slice CT technology.

been limited by the small patient numbers reported to date and by the rather homogenous patient populations (Juergens 2004a, Juergens 2002, Heuschmid 2003, Mahnken 2003, Grude 2004, Boehm 2004). Most reports describe patients with coronary heart disease and normal ranges of left ventricular size, configuration, and function. Since multi-slice CT is a true volumetric modality, enlarged or grossly deformed hearts should not influence the accuracy of the measurements. A recent study demonstrated that global cardiac function parameters were accurately determined by 16-slice CT in patients with left ventricular dysfunction or left ventricular dilatation (Juergens 2004b). Thinned left ventricular wall segments and reduced or absent systolic wall thickening after myocardial infarction was clearly delineated (Figs. 7.76, 7.77).

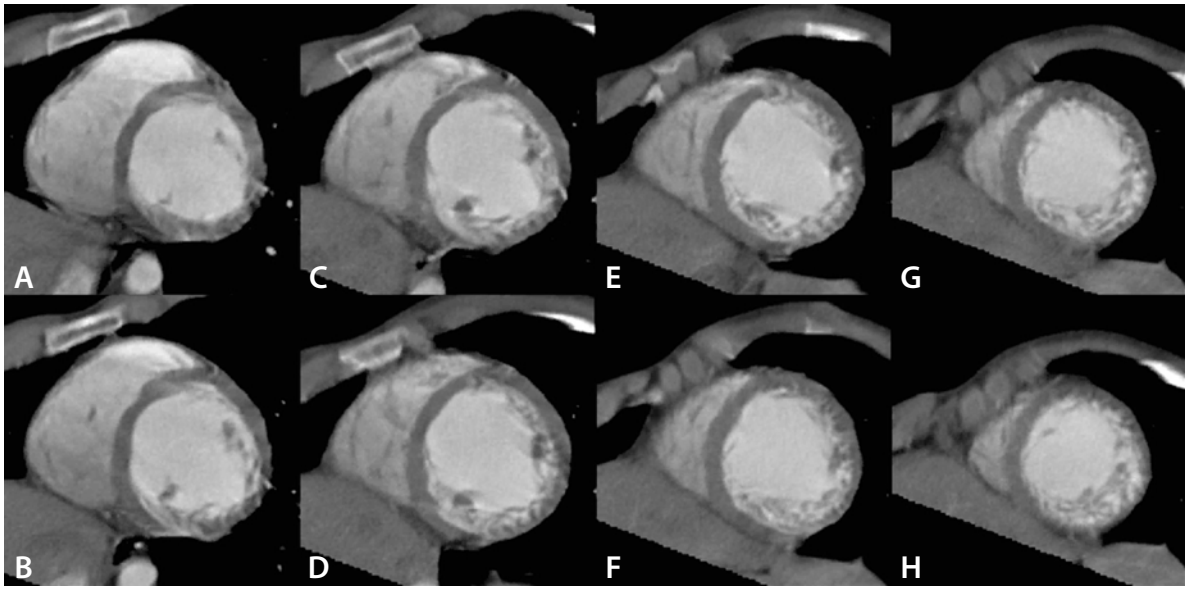
Only a few studies have used multi-slice CT to focus on the detection and quantification of regional myocardial dysfunction (Dirksen 2002, Mahnken 2003). Areas of impaired motion were identified with good reliability compared to echocardiography and CMR, but a definitive role for multi-slice CT needs to be further defined once improved post-processing tools and scanners with improved temporal resolution become widely available.

Reproducibility of global function parameters seems acceptable based on the available reports. The inter-observer variability was 2–11% for left ventricular end-diastolic volume and 6–9% for end-systolic volume. The corresponding values for CMR are 2–6%.

7.10.6.3 Myocardial Viability

The determination of left ventricular myocardial damage and its consecutive dysfunction is important with regard to the clinical management of patients with coronary heart disease, especially if viable myocardium can be detected and myocardial revascularization might lead to improvement in left ventricular function and patient survival. The "late enhancement" phenomenon, initially described for CT of the heart, has become the cornerstone for detection of myocardial scar tissue and assessment of myocardial viability with CMR. Recently the technique has been re-transferred to multi-slice CT to investigate myocardial viability (Koyama 2004).

Initial observations made in a study comparing the myocardial enhancement patterns seen with CT



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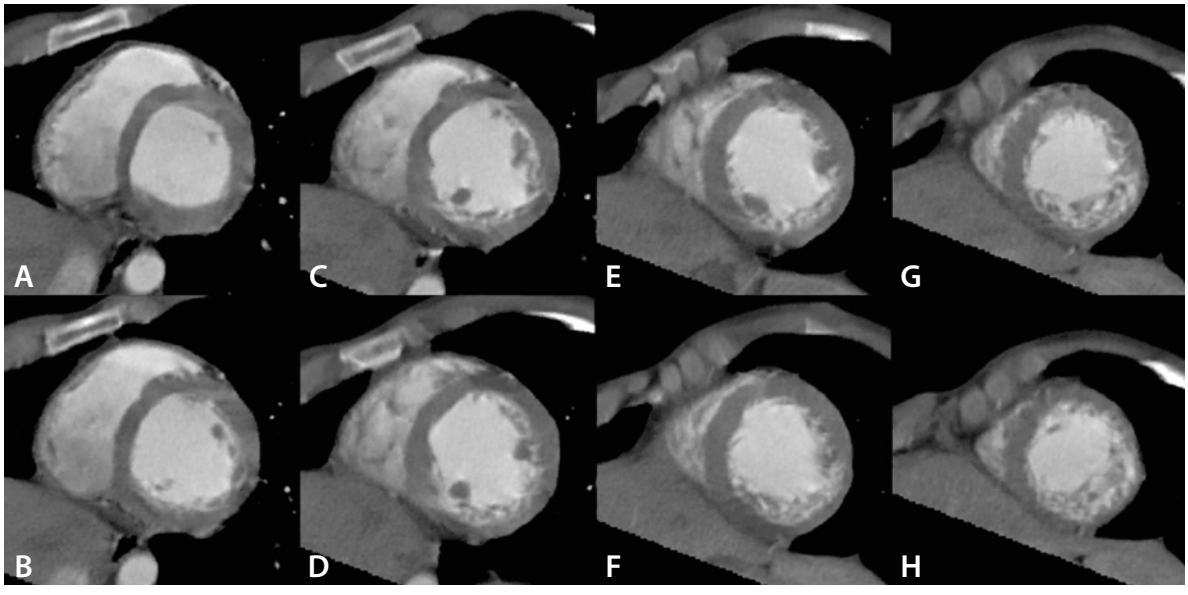

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Fig. 7.76a,b. 16-slice CT study from a 29-year-old man suffering from dilatative cardiomyopathy. Short-axis diastolic (**a**) and systolic (**b**) image reconstructions each from eight contiguous levels (A–H) of the left ventricle illustrate its heavily dilated cavity (end-diastolic volume: 357.8 ml) and global hypokinesis (left ventricular ejection fraction: 22.1%)

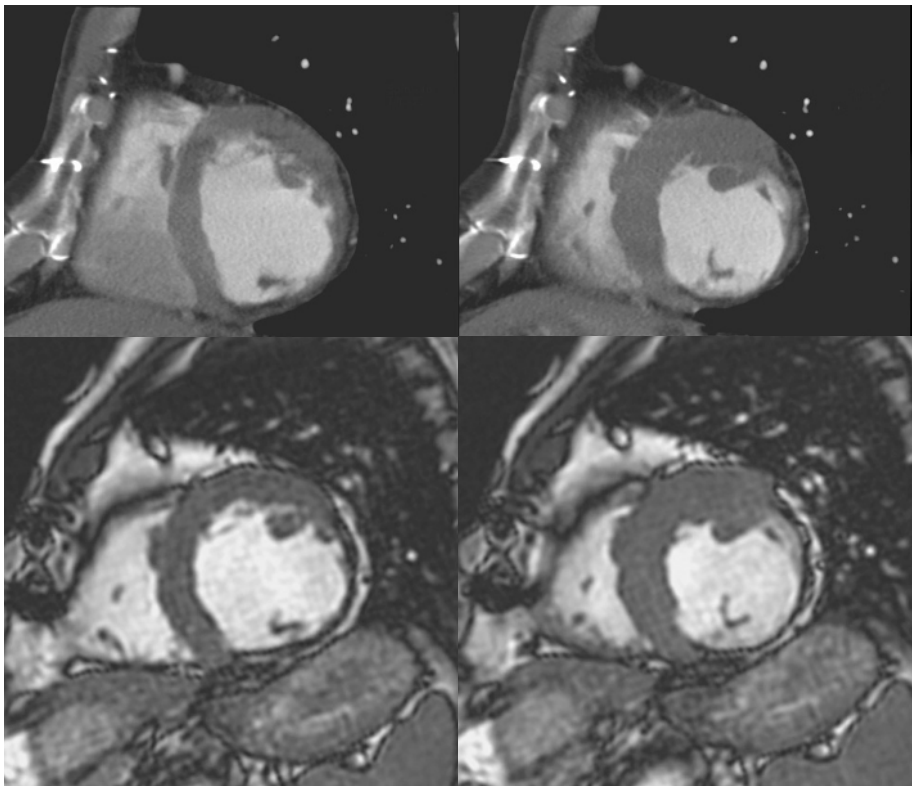

Fig. 7.77. 16-slice CT study from a 64-year-old male patient with 2-vessel coronary artery disease who underwent bypass surgery. Diastolic (left column) and systolic (right column) short-axis reformations from 16-slice CT (upper row) and cine magnetic resonance imaging (CMR, lower row) studies demonstrate reduced left ventricular diastolic myocardial wall thickness and absent systolic wall thickening in the lateral and inferior myocardium. calculation of the left ventricular ejection fraction (LVEF) with 16-slice CT and CMR correspond well (LV-EF by 16-slice CT = 60.6%, LV-EF by CMR = 61.7%)

those of dual isotope SPECT showed that the extent of an early myocardial enhancement deficit could predict subsequent myocardial wall thickness and wall motion recovery in patients after successful revascularization (Koyama 2002).

7.10.6.4 Right Ventricular Disease

Even though published reports on ventricular function determination have focused on the left ventricle, multi-slice CT seems to also be a promising modality for the diagnosis of right ventricular diseases. The excellent spatial resolution is advantageous for the depiction of the rather thin right ventricular myocardium, and CT does not suffer from acoustic window or signal intensity limitations. Right ventricular shape can be well-depicted if an appropriate contrast-injection protocol is used (see above).

Right ventricular enlargement has been reported to be a prognostic factor and a predictor of early death in patients with acute pulmonary embolism (Quiroz 2004, Schoepf 2004). Even though conventional multi-slice chest CTA protocols were used in these studies, the application of ECG-gated protocols may help to eliminate underestimation or overestimation of right ventricular enlargement in future clinical use.

Fatty replacement of the right ventricular myocardium is easily depicted with CT and is an important finding in arrhythmogenic right ventricular cardiomyopathy (ARVC). ARVC is a genetic cardiomyopathy characterized by right ventricular enlargement, hypertrophied trabeculations, abundant epicardial fat, and fibro-fatty replacement of right ventricular musculature, all of which lead to ventricular arrhythmia and right ventricular failure. Exclusion or confirmation of ARVC is especially important in young adults presenting with clinical symptoms that may vary from occasional palpitations to syncope or even to sudden cardiac death. At present, only preliminary data on the detection of morphologic and functional pathologies in ARVC with multi-slice CT have been published (Bomma 2003). While the ability to detect regional abnormalities of right ventricular wall motion needs to be further investigated, multi-slice CT offers a large potential to initially diagnose right ventricular abnormalities and to follow patients with ARVC after implantation of a defibrillator.

7.10.7 Summary and Outlook

Although the assessment of cardiac function with multi-slice CT has not entered clinical routine, several studies using 4-and 16-slice CT scanners have shown that the determination of cardiac chamber volumes and, consequently, global cardiac function parameters is feasible, and the results are in good agreement with established imaging modalities as cine ventriculography, echocardiography, and the gold-standard CMR. The limited temporal resolution of 4-slice CT scanners and first generation 16-slice CT scanners results in an overestimation of end-systolic volume and an underestimation of EF compared to CMR. However, the faster rotation speeds of the newer 16-slice and the latest 64-slice CT scanners, with rotation times down to 330 ms, combined with multi-segment reconstruction algorithms are expected to provide significantly better end-systolic image quality (Fig. 7.78) and even better agreement of global cardiac function parameters measured by CMR. Newly developed cardiac post-processing tools enable a true volumetric segmentation of the contrast-enhanced cardiac chambers based on the thin-slice data sets (Fig. 7.79). Reconstruction of short-axis MPRs as input for Simpson's calculation will no longer be required. These new semi-automated tools can provide a comprehensive analysis of global cardiac function parameters in 2–3 min. Consequently, the clinical applicability of global left ventricular functional assessment with multi-slice CT will substantially increase. Nonetheless, careful development of standardized quantification methods and successful evaluation in relation to the gold-standard modalities will be required.

Regional function analysis, such as regional wall motion and wall thickening, is possible with 16-slice CT for patients at rest. The further improvement in temporal resolution provided by 64-slice CT scanners in combination with multi-segment reconstruction is a prerequisite for obtaining agreement with the results of CMR analyses and for carrying out imaging studies of patients under physical stress.

Due to the radiation exposure and the need to inject iodinated contrast material, multi-slice CT may be the first-line modality for cardiac function evaluation only in a select group of patients, such as those with contra-indications for CMR. However, as cardiac function data are contained in any coronary artery CT study and since multi-slice CT is becoming an accepted tool for coronary artery visualization, the combination of coronary artery imaging and global left ventricular function determination as a one-step procedure constitutes a promising approach to a conclusive cardiac assessment.

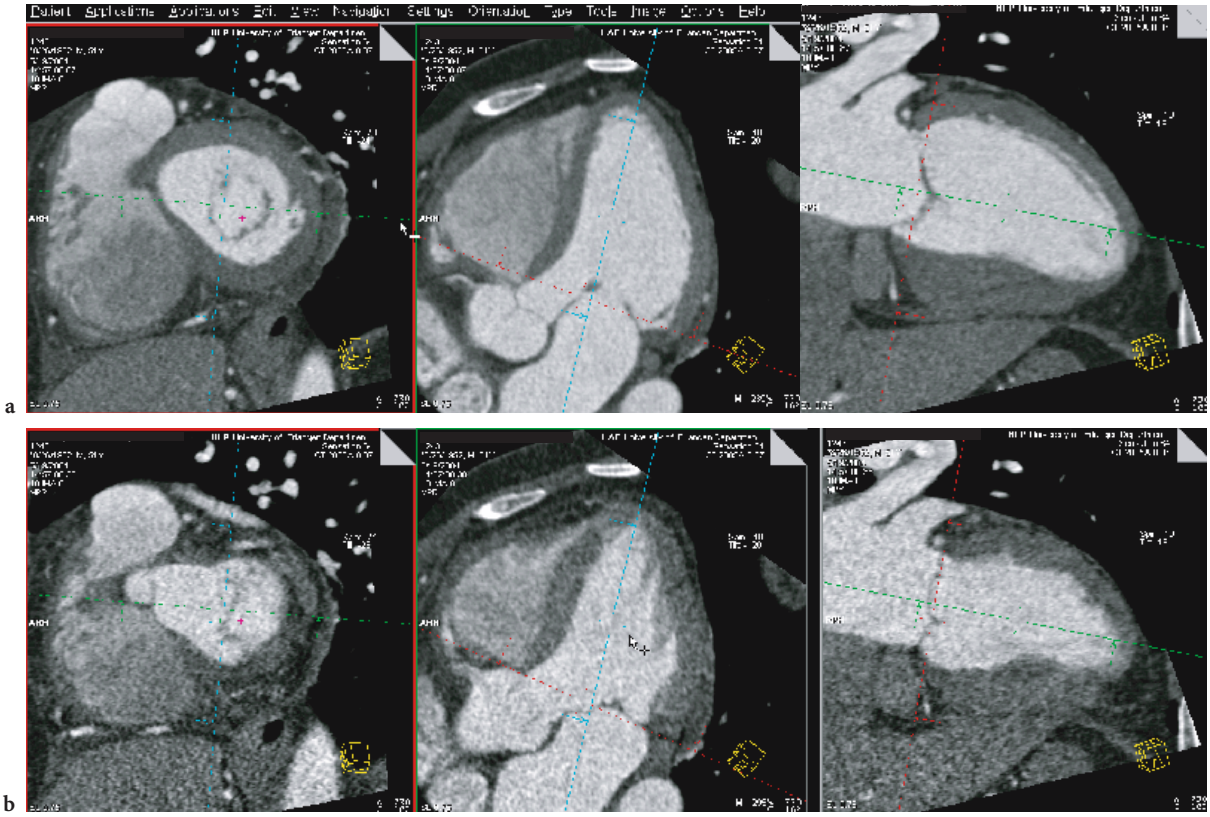

Fig. 7.78a,b. A patient with a normal EF of 59% was examined with 64-slice CT, 330-ms rotation time, and ECG-pulsed acquisition. Due to the high temporal resolution, the images in end-diastole (**a**) and in end-systole (**b**) are virtually free of motion artifacts. ECG pulsing causes the relatively high image noise in systolic reconstruction. However, the use of ECG pulsing does not compromise cardiac function evaluation since noisier axial slices or MPRs with thicker slices are acceptable as input for segmentation of the chambers and for ventricular analysis

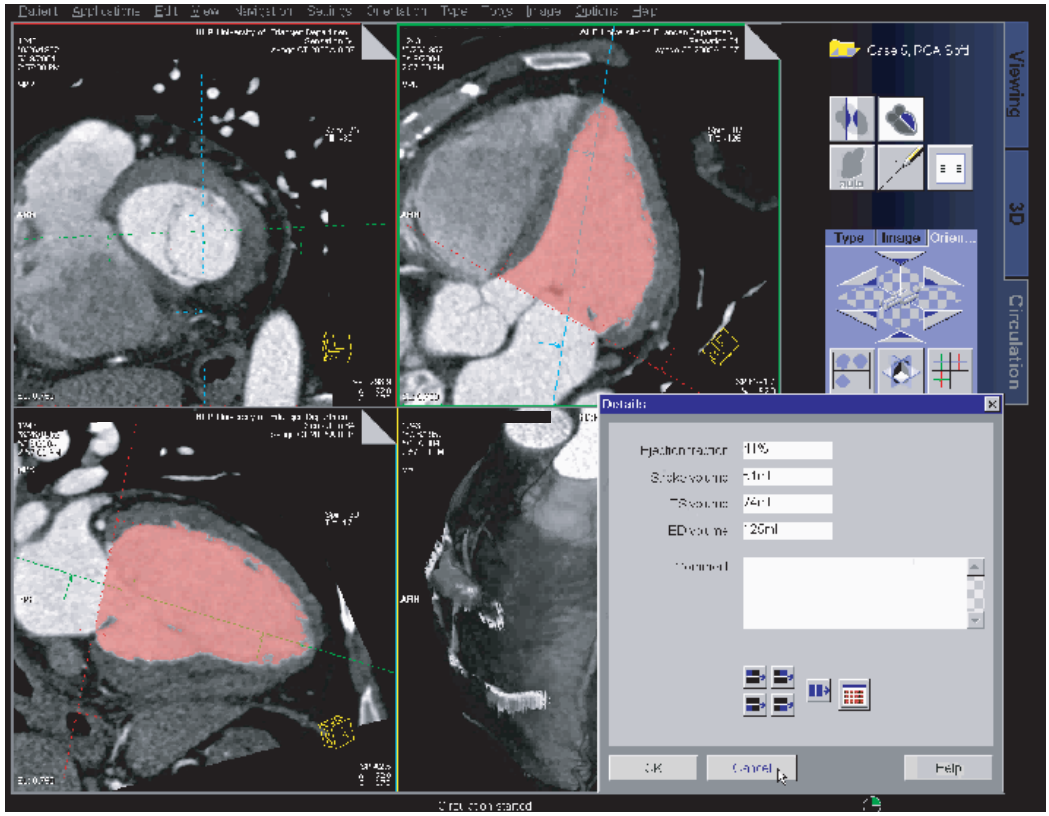

Fig. 7.79. New evaluation platform for semi-automated cardiac function assessment illustrated with a 64-slice cardiac CT data set. Ventricular volumes are calculated with a threshold- and voxel-based segmentation of the contrast-enhanced blood within the ventricle. Start-plane and end-plane of the segmentation are positioned in the plane of the mitral valve and at the apex of the heart. The thresholds were selected such that the papillary muscles are not included in the volume calculation

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