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New Imaging-based Tools for the Assessment of Ventricular Function in Ischemic Heart Diseases

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ABSTRACT

Ischemic heart disease morbidity and mortality are closely related to global and regional left ventricular function. The evaluation of left ventricular global function is a relevant part in the evolution of ischemic heart disease because it plays a significant role in prognosis prediction and patient management after revascularization. Regional function is also a critical part of the evolution, offering a possible and reliable mode for the assessment of myocardial disease. Currently several techniques for the evaluation of left ventricular parameters and function are in use. In this review we will discuss and compare currently available methods for the evaluation of global and regional left ventricular function such as 2D and 3D echocardiography, 3D speckle-tracking echocardiography, multi-slice computed tomography, and cardiac magnetic resonance imaging.

Keywords: ischemic heart disease, echocardiography, 3D speckle-tracking echocardiography, multi-slice computed tomography, cardiac magnetic resonance imaging

Ischemic heart disease is the leading cause of death around the world. The morbidity and mortality rates are closely associated to regional and global left ventricular function in these patients.[1,2]

The evaluation of global left ventricular (LV) function with noninvasive imaging tools has an important role in the therapeutic management and prognosis of patients with ischemic cardiac diseases. Several parameters have been proposed as illustrative for global left ventricular function such as volumes, ejection fraction, dimensions, end-diastolic pressure, contractility, and deformation parameters. Global systolic function is most often evaluated by measuring the difference in the end-diastolic and end-systolic volumes, determined in one, two and three dimensions, divided by the adequate end-diastolic volume.[3] Echocardiography is the most frequently used noninvasive technique for the analysis of LV parameters and function because of its accessibility, portability, and widely validated scale.

LV regional function has the benefit of offering a feasible and valid mode for the evaluation of myocardial disease. Regional function parameters can give a prognostic value regarding common LV efficiency parameters.[4,5] Imaging-based tools like 2D and 3D echocardiography, 3D speckle-tracking echocardiography, multi-detector computed tomography and cardiac magnetic resonance are constantly evolving. The aim of this review is to provide an overview regarding the usefulness of these imaging tools for the assessment of ventricular function in ischemic heart disease.

ECHOCARDIOGRAPHY FOR THE EVALUATION OF LV FUNCTION

2D and 3D echocardiography

Transthoracic echocardiography (TTE) is the most commonly used noninvasive cardiac imaging method for assessing the global and regional function of the left ventricle.[4] Global LV function can be evaluated on the basis of LV dimensions, volumes, or ejection fraction (EF). Several studies evaluated the reliability of 3D TTE measurements of LV volumes and EF, using cardiovascular magnetic resonance (CMR) as a reference. Most studies showed that 3D TTE slightly underestimates both end-diastolic and end-systolic volumes.[6,7] Evaluating the regional function using 3D TTE has important benefits because, unlike 2D TTE, it can illustrate all ventricular walls in a single echocardiographic loop. For these reasons, 3D TTE is well adaptable to discover the location and extension of segmental wall motion abnormalities. The determination of regional LV volumes by 3D TTE shows a good correlation with CMR data.[8,9] Thorstensen *et al.* have shown in their study that wall motion score index by 3D TTE presents a significant correlation with the extent of delayed gadolinium enhancement by CMR.[10]

3D speckle-tracking echocardiography

3D speckle-tracking echocardiography represents an innovative technique used for the quantitative estimation of LV volumes and function, and regional wall motility disturbances with superior accuracy and reproducibility. 3D speckle-tracking echocardiography (3D-STE) provides information on the motility of the myocardium by tracking speckle echoes that are uniformly spread in the myocardial muscle and are moving with myocardial movement. Helle-Valle *et al.* showed that regional left ventricular rotation and torsion can be precisely evaluated by 3D-STE; hence, it is a new method for quantifying LV contractility.[11] Thebault *et al.* established, in another study, that 3D-STE offers a rapid strategy for measuring global LV mechanical asynchronism in subjects undergoing cardiac resynchronization.[12] While this method has numerous benefits, it also has some restrictions such as its dependence on image quality or a relatively low temporal resolution.[13]

CARDIAC COMPUTED TOMOGRAPHY IN THE ASSESSMENT OF LV FUNCTION

Cardiac computed tomography is an accepted tool for the evaluation of ischemic heart disease and global cardiac function. The analysis of LV function after an acute coronary syndrome has treatment and prognostic implications.[14,15] This technique is especially useful in subjects with severe claustrophobia or implanted devices such as cerebral vascular clips, because these devices can cause large image artifacts on CMR.[16] Currently accessible multidetector computed tomography (MDCT) and dual-source computed tomography (DSCT) scanners offer a high spatial and temporal resolution with faster gantry rotation, enabling the 3D reconstruction of the heart.[17]

Several studies were performed comparing global function parameters determined by MDCT with other investigation techniques results. Sarwar *et al.* compared the LV global analysis of contrast-enhanced 64-slice MDCT with CMR in ST-elevation myocardial infarction following primary PCI treatment. MDCT had demonstrated a good correlation with CMR for the estimation of EF and LV volumes including end-systolic volume (ESV) and end-diastolic volume (EDV). The mean deviation between MDCT and CMR values were 3 ml for ESV, −0,2 ml for EDV and 1% for EF.[18] The use of DSCT for the determination of ventricular volumes and EF in comparison to CMR showed similarly good results: EDV was underestimated by 3.7 ml, while ESV and EF were overestimated by 2.6 ml and 3.8%, respectively.[19] In another publication by Greupner *et al.*, MDCT was compared with CMR, 2D echocardiography, and 3D echocardiography for the analysis of LV global function after coronary angiography. The study showed comparable limits of agreement for both MDCT and 2D echocardiography in the evaluation of EF vs. CMR. MDCT also showed better agreement for stroke volume than 2D or 3D echocardiography and CMR, while EDV and ESV were significantly underestimated by 2D and 3D echocardiography, but not by MDCT.[20]

The utility of MDCT in the assessment of regional function has not been proven yet. The limitations of MDCT in the evaluation of LV regional function are the low temporal resolution and the absence of markers for identifying myocardial strain. A study using a floating axis system, which means a different LV geometric center in end-systolic and end-diastolic images, showed that regional EF assessed by MDCT is comparable to single-photon emission computed tomography (SPECT) for predicting ischemia; moreover, it is a better predictor of significant lesions compared to SPECT.[21]

CARDIAC MAGNETIC RESONANCE IMAGING IN LV FUNCTION ASSESSMENT

Cardiac magnetic resonance imaging is the gold standard method for evaluating the global function of the left ventricle.[22] The most frequently used quantification technique for LV volumetric analysis is ECG-gated, segmental balanced steady-state free precession cinegraphic imaging, which gives excellent blood-tissue differentiation without any contrast.[23,24] LV volumes are evaluated by applying the Simpson rule, using a series of short-acting images obtained with a slice thickness of 6–8 mm. Although the absolute and indexed LV volumes, as well as the absolute and indexed myocardial mass are important quantitative indices, left ventricle EF is the most frequently reported measurement when assessing systolic function. The accuracy and reproducibility of the quantification of LV systolic function by CMR was analyzed in multiple studies.

Bellenger *et al.* demonstrated a wide range of agreement between EF assessment with Simpson's technique using echocardiography and CMR in patients with ischemic heart disease (IHD) and systolic heart failure.[25] Gardner *et al.* evaluated 47 patients with recent infarction analyzing the EF and LV volumes with the use of echocardiography and CMR. Modest correlations were found for LV volumes, but significant differences were discovered in absolute volumes and EF between the two methods.[26] Gruszczynska *et al.* found similar results when evaluating 67 patients with IHD by CMR and transthoracic echocardiography. Significant differences were noted between the techniques, with LV volume underestimation by echocardiography.[27] Recent data evidenced better correlations between 3D echocardiography and CMR for the quantification of EF, with similar values between the two methods (50% ± 14% vs. 50% ± 16%).[28]

Regarding the data collected on the clinical utility of global function evaluation with EF as a marker, it is relatively insensitive to the early manifestations of ischemic heart disease. A good example is non-transmural myocardial infarction or small transmural infarctions, which do not reduce LVEF significantly. Quantifying regional function using quantitative imaging parameters such as myocardial velocities and strain has shown promising results in the occurrence of LV dysfunction with normal EF.[29]

To understand regional function better, it is necessary to understand the myocardial structure and muscle fiber orientation. The LV has three different fiber orientations with circumferential, oblique and longitudinal layers, arranged in two helical geometries.[30] These orientations are essential for the development of the shearing and torsion mechanics of the LV.[31] The right-handed helix in the subendocardium contributes to the longitudinal mechanism, while the left-handed helix in the subendocardium mostly generates the circumferential mechanism.[30] Myocardial strain refers to a change in the length of the myocardium compared to its original length and is an extensively studied marker for the assessment of regional dysfunction.[32] The attenuation of subendocardial function is reflected by abnormalities in the longitudinal strain, while the mid-myocardial and epicardial attenuation is reflected by circumferential and radial strain. In early IHD, subendocardial modifications appear first, and abnormalities in longitudinal strain can predict early myocardial dysfunction, before global dysfunction occurs.[32]

Various CMR techniques are available for the assessment of regional LV function such as myocardial thickening, balanced steady-state free precession imaging (bSSFP), tissue phase mapping (TPM), myocardial tagging, displacement encoding with stimulated echoes (DENSE), strain encoding (SENC), and feature-tracking MRI (FT-MRI).[29]

The bSSFP technique is most commonly used for the quantitative or qualitative segmental analysis of the wall motion, which is more sensitive than global function in IHD. The image recording in bSSFP can be segmented or ECG-triggered real-time cine. Both of these two methods can be used in the evaluation of qualitative regional function, however real-time cine images are not adequate for the quantitative assessment of function. Qualitatively the segmental wall motility is categorized as normal, hypokinetic, akinetic, or dyskinetic. The quantitative interpretation can be performed by measuring regional myocardium thickening between the diastole and systole from the epicardial and endocardial contours.[30]

Myocardial tagging is probably the most studied CMR method for regional function analysis. Tagging consists in a preparatory pulse, which generates grids or parallel lines on the myocardium over the cardiac cycle at the start of the R wave. The advantage of tagging over other techniques is represented by the intuitive, visually appealing images. Grid tagging is preferred over line tagging because it allows analysis of the perpendicular components of myocardial deformation. Tags can be qualitatively interpreted visually, but quantitative tag evaluation is laborious and time-consuming.[33]

TPM uses a bipolar gradient to encode velocity vector fields into the phase.[34] This method proposes a higher spatial resolution of functional information compared to the tagging method. Regional function is assessed by using myocardial velocities. Studies have demonstrated altered myocardial velocities in patients with IHD. Long axis velocities were reduced in patients with IHD and were further reduced in subjects with infarction. The radial velocities were significantly reduced in subjects with myocardial infarctions.[35,36]

DENSE is a phase-based method that encodes tissue velocity into image phase in three directions. Due to T1 recovery, the encoding does not last for an entire cardiac cycle, limiting the interpretation of diastolic tissue displacement. DENSE has an inherently low signal-to-noise ratio.[30,37] This technique has been shown to be useful in the assessment of subjects with acute myocardial infarction and ventricular dyssynchrony.[38]

SENC is a relatively new method in which the tag planes are oriented parallel to the imaging plane.[34] Because of the orientation, the circumferential strain is measured on a long axis plane and the longitudinal strain on a short axis plane.[37] In this technique, tag fading with T1 recovery is limited to late diastolic function evaluation. SENCE strain rate reserves, at full dobutamine stress, reveal the presence of a significant coronary artery stenosis.[39] The strain rate reserve at intermediate dobutamine stress, when evaluating regional wall motion abnormalities, has an increased diagnostic accuracy for significant CAD. Similarly, peak systolic circumferential and longitudinal strains are useful for identifying chronic myocardial infarctions and identifying myocardial scar transmurality.[40]

FT-CMR is a newer optical flow technique analogue to STE, which allows the quantification of myocardial motion such as strain, strain rate, displacement, and tissue velocities.[41] This imaging method is not limited to tracking the blood myocardium junction, it can also be used to track midmyocardium features. Currently, the use of FT-CMR for segmental strain assessment is not supported due to its inherent strain heterogeneity.[30] The clinical utility of FT-CMR has been evaluated in a limited number of studies. Schuster *et al.* demonstrated valuable results on the quantification strategy for reversible myocardium dysfunction with low dose dobutamine stress in subjects with IHD.[42] The results showed that the assessment of regional function using FT-CMR seems to be useful in analyzing viability and ischemia in patients with IHD.

CONCLUSION

The assessment of global cardiac function is a basic step in evaluating left ventricular performance. Ejection fraction and LV volumes have an important role in guiding the clinical decision and providing a main prognostic value. Advanced techniques such as 3D echocardiography, MDCT, and CMR, allow a more precise analysis of the EF and LV volumes. The assessment of regional function is a feasible approach for the subclinical identification of myocardial disease and gives incremental prognostic value. The previously listed techniques are quickly evolving as noninvasive methods that extend our knowledge about the remarkable sides of myocardial fiber architecture. Cardiac magnetic resonance offers possibilities for acquiring the best parameters for left ventricular regional function such as torsion, twisting, shearing, strain, and strain rate. These parameters are of great aid in the management of ischemic heart disease by offering sensitive subclinical signs of the disease progression.

CONFLICT OF INTEREST

Nothing to declare.

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REFERENCES

1. Murray CJ, Lopez AD. Alternativevisions of thefuture: projecting mortality and disability, 1990–2020. Boston: Harvard University Press; 1996. p. 325-395.
2. White HD, Norris RM, Brown MA, Brandt PW, Whitlock RM, Wild CJ. Left ventricular end-systolic volume as the major determinant of survival after recovery from myocardial infarction. *Circulation*. 1987;76:44-51.
3. Thomas JD, Popovic ZB. Assessment of left ventricular function by cardiac ultrasound. *J Am Coll Cardiol*. 2006;48:2012-2025.
4. Wong M, Johnson G, Shabetai R, et al. Echocardiographic variables as prognostic indicators and therapeutic monitors in chronic congestive heart failure. Veterans Affairs cooperative studies V-HeFT I and II. V-HeFT VA Cooperative Studies Group. *Circulation*. 1993;87:Vi65-Vi70.
5. Lang RM, Bierig M, Devereux RB, et al. Recommendations for chamber quantification: a report from the American Society of Echocardiography's Guidelines and Standards Committee and the Chamber Quantification Writing Group, developed in conjunction with the European Association of Echocardiography, a branch of the European Society of Cardiology. *Journal of the American Society of Echocardiography*. 2005;18:1440-1463.

6. Qi X, Cogar B, Hsiung MC, et al. Live/real time three-dimensional transthoracic echocardiographic assessment of left ventricular volumes, ejection fraction, and mass compared with magnetic resonance imaging. *Echocardiography*. 2007;24:166-173.
7. Chukwu EO, Barasch E, Mihalatos DG, et al. Relative importance of errors in left ventricular quantitation by two-dimensional echocardiography: insights from three-dimensional echocardiography and cardiac magnetic resonance imaging. *J Am Soc Echocardiogr*. 2008;21:990-997.
8. Corsi C, Lang RM, Veronesi F, et al. Volumetric quantification of global and regional left ventricular function from real-time three-dimensional echocardiographic images. *Circulation*. 2005;112:1161-1170.
9. Nesser HJ, Sugeng L, Corsi C, et al. Volumetric analysis of left ventricular function with real-time three-dimensional echocardiography: validation by magnetic resonance and clinical utility testing. *Heart*. 2007;93:572-578.
10. Thorstensen A, Dalen H, Hala P, et al. Three-dimensional echocardiography in the evaluation of global and regional function in patients with recent myocardial infarction: a comparison with magnetic resonance imaging. *Echocardiography*. 2013;30:682-692.
11. Helle-Valle T, Crosby J, Edvardsen T, et al. New noninvasive method for assessment of left ventricular rotation: speckle tracking echocardiography. *Circulation*. 2005;112:3149-3156.
12. Thebault C, Donal E, Bernard A, et al. Real-time three-dimensional speckle tracking echocardiography: a novel technique to quantify global left ventricular mechanical dyssynchrony. *Eur J Echocardiogr*. 2011;12:26-32.
13. Kleijn SA, Aly MF, Terwee CB, van Rossum AC, Kamp O. Reliability of left ventricular volumes and function measurements using three-dimensional speckle tracking echocardiography. *Eur Heart J Cardiovasc Imaging*. 2012;13:159-168.
14. Bauters C, Deneve M, Tricot O, Meurice T, Lamblin N, Investigators C. Prognosis of patients with stable coronary artery disease (from the CORONOR study). *Am J Cardiol*. 2014;113:1142e1145.
15. Lewis EF, Moye LA, Rouleau JL, et al. Study C. Predictors of late development of heart failure in stable survivors of myocardial infarction: the CARE study. *J Am Coll Cardiol*. 2003;42:1446-1453.
16. Mahnken AH, Gunther RW, Krombach GA. The basics of left ventricular functional analysis with MRI and MSCT. *Rofo*. 2004;176:1365-1379.
17. van Ooijen PM, de Jonge GJ, OudkerkM. Informatics in radiology: postprocessing pitfalls in using CT for automatic and semiautomatic determination of global left ventricular function. *Radiographics*. 2012;32:589-599.
18. Sarwar A, Shapiro MD, Nasir K, et al. Evaluating global and regional left ventricular function in patients with reperfused acute myocardial infarction by 64-slice multidetector CT: a comparison to magnetic resonance imaging. *Journal of Cardiovascular Computed Tomography*. 2009;3:170-177.
19. Busch S, Johnson TR, Wintersperger BJ, et al. Quantitative assessment of left ventricular function with dual-source CT in comparison to cardiac magnetic resonance imaging: initial findings. *Eur Radiol*. 2008;18:570-575.
20. Greupner J, Zimmermann E, Grohmann A, et al. Head-to-head comparison of left ventricular function assessment with 64-row computed tomography, biplane left cineventriculography, and both 2- and 3-dimensional transthoracic echocardiography: comparison with magnetic resonance imaging as the reference standard. *J Am Coll Cardiol*. 2012;59:1897-1907.
21. Farsalinos KE, Daraban AM, Unlu S, Thomas JD, Badano LP, Voigt JU. Head-to-head comparison of global longitudinal strain measurements among nine different vendors: the EACVI/ASE Inter-Vendor Comparison Study. *Journal of the American Society of Echocardiography*. 2015;28:1171-1181.
22. Kaandorp TA, Bax JJ, Bleeker SE, et al. Relation between regional and global systolic function in patients with ischemic cardiomyopathy after betablocker therapy or revascularization. *J Cardiovasc Magn Reson*. 2010;12:7
23. Carr JC, Simonetti O, Bundy J, et al. Cine MR angiography of the heart with segmented true fast imaging with steady-state precession. *Radiology*. 2001;219:828-834.
24. Scharf M, Brem MH, Wilhelm M, et al. Atrial and ventricular functional and structural adaptations of the heart in elite triathletes assessed with cardiac MR imaging. *Radiology*. 2010;257:71-79.
25. Bellenger NG, Burgess MI, Ray SG, et al. Comparison of left ventricular ejection fraction and volumes in heart failure by echocardiography, radionuclide ventriculography and cardiovascular magnetic resonance; are they interchangeable? *Eur Heart J*. 2000;21:1387-1396.
26. Gardner BI, Bingham SE, Allen MR, et al. Cardiac magnetic resonance versus transthoracic echocardiography for the assessment of cardiac volumes and regional function after myocardial infarction: an intrasubject comparison using simultaneous intrasubject recordings. *Cardiovasc Ultrasound*. 2009;7:38.
27. Gruszczynska K, Krzych LJ, Golba KS, et al. Statistical agreement of left ventricle measurements using cardiac magnetic resonance and 2D echocardiography in ischemic heart failure. *Med Sci Monit*. 2012;18:MT19-MT25.
28. Pouleur AC, le Polain de Waroux JB, Pasquet A, et al. Assessment of left ventricular mass and volumes by three-dimensional echocardiography in patients with or without wall motion abnormalities: comparison against cine magnetic resonance imaging. *Heart*. 2008;94:1050-1057.
29. Collins JD. Global and Regional Function Assessment of Ischemic Heart Disease with Cardiac MR Imaging. *Radiol Clin North Am*. 2015;53:369-395.
30. Chen JL, Liu W, Zhang H, et al. Regional ventricular wall thickening reflects changes in cardiac fiber and sheet structure during contraction: quantification with diffusion tensor MRI. *Am J Physiol Heart Circ Physiol*. 2005;289:H1898-H1907.
31. Mor-Avi V, Lang RM, Badano LP, et al. Current and evolving echocardiographic techniques for the quantitative evaluation of cardiac mechanics: ASE/ EAE consensus statement on methodology and indications endorsed by the Japanese Society of Echocardiography. *J Am Soc Echocardiogr*. 2011;24:277-313.
32. Bansal M, Sengupta PP. Longitudinal and circumferential strain in patients with regional LV dysfunction. *Curr Cardiol Rep*. 2013;15:339.
33. Osman NF, Sampath S, Atalar E, et al. Imaging longitudinal cardiac strain on short-axis images using strain-encoded MRI. *Magn Reson Med*. 2001;46:324-334.
34. Markl M, Schneider B, Hennig J, et al. Cardiac phase contrast gradient echo MRI: measurement of myocardial wall motion in healthy volunteers and patients. *Int J Cardiovasc Imaging*. 1999;15:441-452.
35. Karwatowski SP, Mohiaddin RH, Yang GZ, et al. Regional myocardial velocity imaged by magnetic resonance in patients with ischaemic heart disease. *Br Heart J*. 1994;72:332-338.
36. Schneider B, Markl M, Geiges C, et al. Cardiac phase contrast gradient echo MRI: characterization of abnormal left ventricular wall motion in patients with ischemic heart disease. *J Comput Assist Tomogr*. 2001;25:550-557.
37. Simpson RM, Keegan J, Firmin DN. MR assessment of regional myocardial mechanics. *J Magn Reson Imaging*. 2013;37:576-599.
38. Aletras AH, Ingkanisorn WP, Mancini C, et al. DENSE with SENSE. *J Magn Reson*. 2005;176:99-106.
39. Korosoglou G, Lossnitzer D, Schellberg D, et al. Strain-encoded cardiac MRI as an adjunct for dobutamine stress testing: incremental value to conventional wall motion analysis. *Circulation*. 2009;2:132-140.
40. Oyama-Manabe N, Ishimori N, Sugimori H, et al. Identification and further differentiation of subendocardial and transmural myocardial infarction by fast strain-encoded (SENC) magnetic resonance imaging at 3.0 Tesla. *Eur Radiol*. 2011;21:2362-2368.
41. Hor KN, Baumann R, Pedrizzetti G, et al. Magnetic resonance derived myocardial strain assessment using feature tracking. *J Vis Exp*. 2011;pii:2356.
42. Schuster A, Paul M, Bettencourt N, et al. Cardiovascular magnetic resonance myocardial feature tracking for quantitative viability assessment in ischemic cardiomyopathy. *Int J Cardiol*. 2013;166:413-420.