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Review Article

Myocardial Strain: A Primer for Anesthesiologists

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ABSTRACT

Aim of review: This review is intended to provide a high-level summary of strain and its implications for anesthesiologists.

Methods: Pubmed search using the following keywords, 'strain' and 'perioperative', to identify literature from 1985 to 2016 was performed to summarize recent research on myocardial strain measurements, their perioperative implications and its association with clinical outcomes.

Recent findings: Evaluation of cardiac function improves risk assessment and guides anesthetic decisions. However, the most common echocardiographic measure of myocardial function, the left ventricular ejection fraction, has important limitations. Myocardial strain by the echocardiography performs a quantitative assessment of global and regional myocardial function and has become a useful tool for perioperative care of surgical patients. The strain could be used to diagnose myocardial ischemia, evaluate effects of valvular heart disease, coronary artery disease and follow up on cardiotoxicity.

Conclusion: As the echocardiography is becoming more available in operating rooms, anesthesiologists could perform myocardial strain measurements easily in the perioperative period to evaluate cardiac functions accurately, alter their hemodynamic management strategies accordingly and improve patient outcomes.

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The term 'strain' is used to describe local shortening, thickening and lengthening of the myocardium as a measure of regional left ventricular (LV) function in echocardiography. The term originates from the field of continuum mechanics and is used to describe a general 3D deformation of a small cube during a short time interval (Figure 1) (1). The myocardial strain is defined as the deformation of myocardium relative to its original length and is more closely linked to myocyte metabolism and contractility than left ventricular ejection fraction (LVEF) (2). As would be expected with ejection fraction, increasing pre-load is associated with increasing strain at all levels of wall stress, and increasing after-load is associated with a reduction of strain. Although LV cavity size close to the normal range has a limited impact on strain, the radial strain is increased and longitudinal strain is reduced in small left ventricles. In contrast, strain rate is thought to be less related to pre-load and after-load. Frequent heart rate, preload and after-load changes in the perioperative period should be taken into considerations when interpreting these data.

When considering the different echocardiographic modalities available to assess myocardial contractile function, it is necessary to make a distinction between myocardial wall motion and wall deformation (3-6). Displacement and velocity characterize wall motion while strain describes wall deformation. Over time a moving object will change its position (displacement) but does not necessarily undergo deformation if all its parts move with the same velocity. If, however, different parts of the object move with different velocities, the object will undergo deformation and change its shape. This means that wall motion measurements (displacement and velocity) cannot differentiate between active and passive of a myocardial segment, whereas deformation analyses (strain) allow discrimination between active and passive myocardial tissue movement (7).

How to Measure Myocardial Strain?

The LV wall motion is very complex and consists of four types of movements. The long axis of the LV is directed from the apex to the base; the radial axis is perpendicular to the epicardium, away from the cavity; and the circumferential axis is perpendicular to the radial and longitudinal directions and is oriented counterclockwise around the short-axis image (Figure 1) (7). For rotations, the apex rotates counterclockwise, and the base rotates first counterclockwise and then clockwise later in systole (8). These four types of deformation can all be evaluated by strain imaging: longitudinal, radial, circumferential, and rotational strains.

Strain can be estimated with echocardiography, cardiac magnetic resonance imaging (cMRI) or computed tomography (CT) (9). The cMRI is the standard reference modality for strain measurements due to its accuracy and reproducibility. The cMRI allows 3D assessment of regional strain, but needs longer time for analysis and is very complicated. Therefore, cMRI is only used at academic centers for research purposes (10). Cardiac computed tomography (CCT) is the newest and most rapidly growing modality for noninvasive imaging of the heart, which can assess the coronary arteries and provide functional information for both the left and right ventricles (11). However, neither the cMRI nor the CCT is suitable for use in the operating room.

Echocardiography with tissue Doppler imaging or speckle tracking technique is now widely available in the clinical setting. Myocardial strain measurement by echocardiography shows reasonable agreement with cMRI (9). Echocardiography has the advantages of portability, low risk, and comparatively high temporal resolution (12). For anesthesiologists, echocardiography has become an easily accessible tool for them during the perioperative period.

Two echocardiographic techniques/methods have been developed to assess LV deformation noninvasively, tissue Doppler imaging (TDI) and speckle- tracking echocardiography (13). Measurement of strain by using TDI is derived by integrating strain rate over time. Myocardial tissue velocities are measured at 2 points relative to the transducer (14, 15). Strain rate (SR) is estimated from the spatial velocity gradient described as $SR = (va-vb)/d$ where va, vb represents the difference in myocardial velocities at points a and b, and d represents the distance between these points (13). Since TDI is Doppler based, the calculation is very angle dependent and could introduce significant inaccuracy in the formula. Speckle-tracking echocardiography is a newer, non- Doppler, angle- independent technique for measurement of myocardial strain.

Speckle-tracking techniques assess myocardial movement and deformation by tracking "speckles" in echocardiographic images. A unique pattern or "fingerprint" of bright and dark pixels, or speckles, in standard B-mode (2D) echocardiographic images remains fairly consistent within a small region in the myocardium. These speckles, which are generated by reflected ultrasound from myocardial tissue, are tracked from one frame to another throughout the cardiac cycle. A software algorithm extracts displacement, velocity, strain rate, and strain within the defined myocardial segment (13). A bull's eye analysis of the left ventricle will be displayed with the strain of each segment labeled. The timing or synchronization of each of the 17 segments is provided by the graph for evaluation of LV contraction synchronization and could be used to

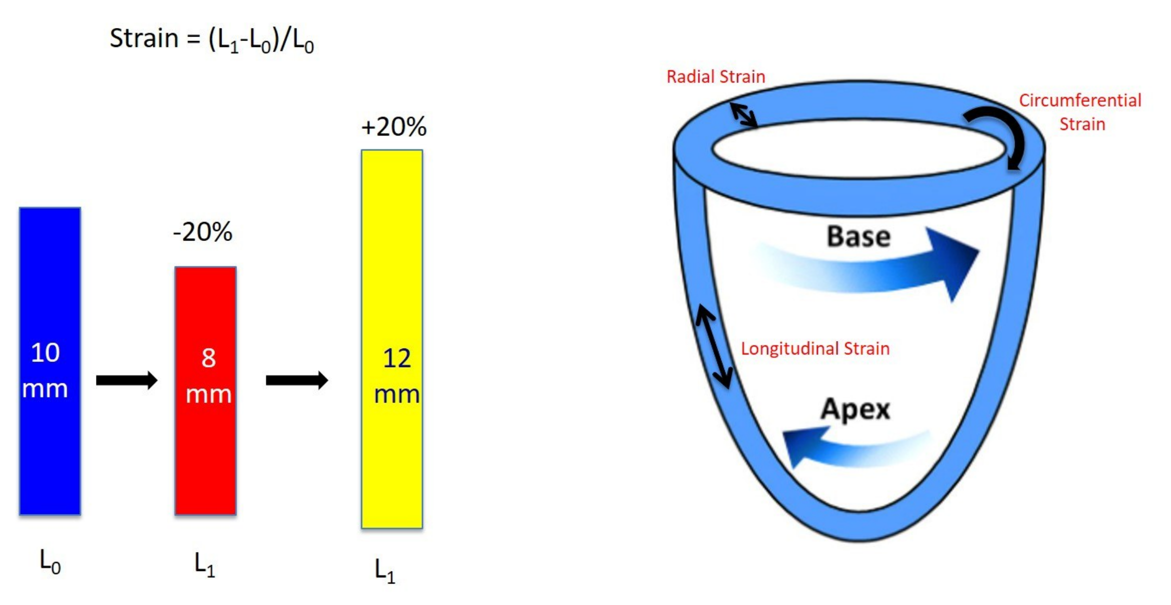


Figure 1. Definition of Strain and Three Different Strains of The Hearts: Longitudinal, Radial and Circumferential Strain.

guide resynchronization therapy (Figure 2).

Clinical Applications of Strain

Echocardiographic strain imaging enables more reliable and comprehensive assessment of myocardial function. The spectrum of potential clinical applications is very wide and includes differentiation between active and passive motions of myocardial segments, quantification of intraventricular dyssynchrony and evaluation of components of myocardial function, such as longitudinal myocardial shortening, which is not visually assessable. Strain and strain rate measurements are helpful in the selection of different therapies and follow- up evaluations of myocardial function after different medical and surgical treatment. The high sensitivity of strain and strain rate for early detection of myocardial dysfunction, assessment of myocardial viability, detection of acute allograft rejection after heart transplantation, and early detection of patients with transplant coronary artery disease has led to the recommendation for their routine clinical use. Strain and strain rate data has also been shown to provide important prognostic information (16).

Assess Left Ventricular Systolic Functions

The LVEF is one of the most important prognostic markers of patients with cardiovascular diseases (17). The introduction of echocardiographic contrast media and real-time three-dimensional echocardiography has improved the accuracy of echocardiographic assessment of LVEF. However, LVEF may not truly represent LV systolic function in specific cardiac diseases or when subtle LV systolic dysfunction is present (18). For example, a patient with a structurally normal heart may show a similar LVEF to that of a patient with severe mitral regurgitation or significant CAD, since LVEF reflects merely the change in LV volume but does not take into consideration ultra- structural changes, which may occur at the myocardial level and may impair LV systolic performance (19). Two- dimensional speckle tracking echocardiography enables assessment of myocardial strain, thereby providing detailed information on global and regional active LV deformation. Changes in the composition and geometry of the LV myocardium may lead to changes in LV deformation that may only be detected by strain, not by LVEF. Radial, cir-

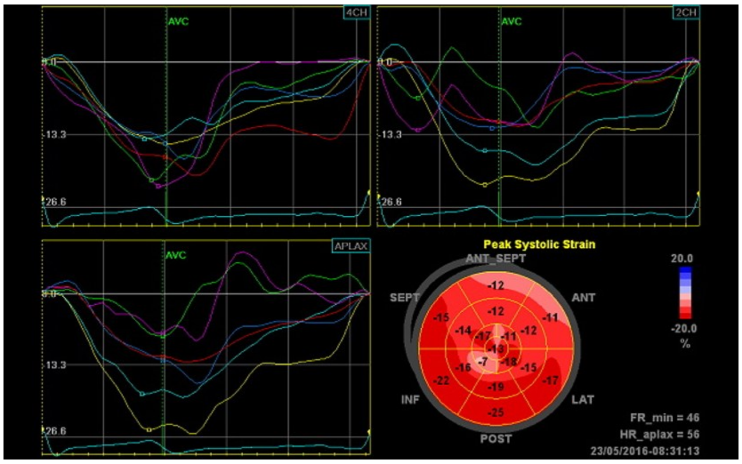


Figure 2. Strain Bull's Eye Display of 17 Left Ventricular Segments with Mild Anterior and Anteroseptal Hypokinesis.
Synchronization of Different Left Ventricular Segments is Displayed with Graphs Over Time.

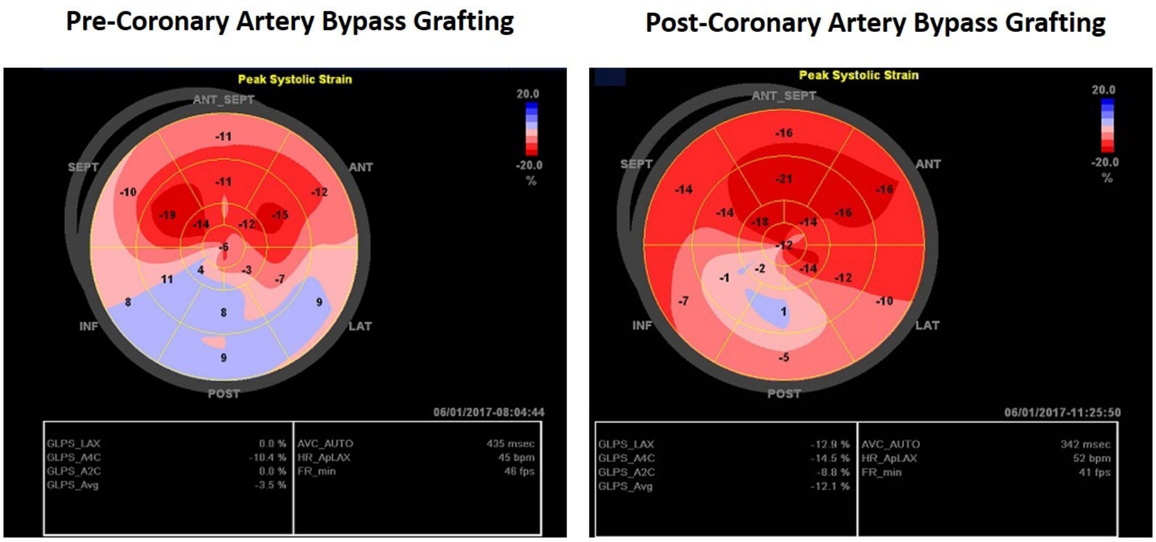
cumferential, and longitudinal strains are the three natural deformations that can be measured with 2D speckle tracking (20). There are several clinical scenarios where subtle LV systolic dysfunction is present despite preserved LVEF and can be characterized by 2D speckle tracking echocardiography (21).

The normative values of LV global longitudinal systolic strain (GLS) vary according to gender, age, and system used to acquire and analyze the data. As such, current recommendations do not provide universal normal values or lower limits of normal but, as a general guidance, the expected value of LV GLS in a healthy individual is around −20% (22). Conventionally, LV GLS is expressed as a negative value because it represents the shortening of the myocardium relative to the original length. The more negative the LV GLS is, the better the LV systolic function is. Therefore, any value of LV GLS less negative than − 20% could be considered pathological. Women show slightly more negative (better) LV GLS compared with men and it has been shown that LV GLS decreases (becomes less negative) with age (22). Leopoldo et al. studied the area strain and showed that overall mean area strain was -38.87 ± 5.89%. Mean values at the level of the basal, middle, and apical segments were -38.42% ± 7.58%, -38.74% ± 6.34%, and -43.18% ± 12.81%, respectively, in healthy people (23). The LV GLS has shown better reproducibility and to be more sensitive than LVEF in follow-up examinations. This is of particular importance in patients treated with chemotherapy (24). Unreliable measurements of LVEF may have important therapeutic and prognostic consequences. Several studies have shown that LV GLS may detect subtle changes in LV systolic dysfunction that is not detected when LVEF is measured (18, 25). Figure 3 showed strain analysis of the pre- and post-coronary artery bypass grafting (CABG) left ventricle in the same patient. Pre-analysis showed inferior and inferolateral wall dyskinesis, which improved to moderate hypokinesis after CABG. These subtle changes in LV systolic functions can be more accurately and automatically appreciated compared to visual analysis. Both the values of left ventricular GLS and GCS were increased significantly after cardiopulmonary bypass if the revascularization was successful (26).

Strain Imaging in Valvular Heart Diseases

The chronic effects of abnormal loading from valvular diseases on myocardial function may be difficult to detect by conventional means, but strain imaging may reveal important information. Delgado et al. demonstrated that patients with severe aortic stenosis and preserved LVEF exhibited decreased radial, circumferential, and longitudinal speckle tracking strain (27). In addition, significant improvement in these parameters was observed at long-term follow-up after aortic valve replacement, whereas LVEF remained unchanged. De Isla et al. reported that preoperative speckle tracking longitudinal strain at the level of the interventricular septum strongly predicted a postoperative LVEF decrease of > 10% in patients with chronic severe mitral regurgitation (28).

Tayyareci et al. demonstrated that longitudinal and circumferential strains were significantly decreased in asymptomatic patients with severe aortic regurgitation and normal LVEF compared to normal volunteers (29). These findings highlight that TDI of or 2D speckle tracking strain enables an early detection of subtle changes in



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AVC_AUTO 435 msec
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Figure 3. Strain Analysis Pre and Post CABG.
Pre-analysis showed inferior and inferolateral wall dyskinesis, which improved to moderate hypokinesis after CABG. CABG, Coronary Artery Bypass Grafting.

LV systolic function in patients with valvular heart diseases.

Strain Imaging in Coronary Artery Disease

Strain imaging may be applied to diagnose ischemia by showing a reduction in peak systolic strain, but equally important is the demonstration of systolic lengthening and post- systolic shortening which are characteristic features of ischemic dysfunction (30, 31). It has been suggested that the end-systolic strain should be used to measure systolic function as the peak strain was not as accurate (21). For example, in a patient with atypical symptoms, no chest pain and no ECG signs of ischemia, strain imaging showed moderately reduced systolic shortening and marked post-systolic shortening in the inferior wall. The patient was referred for angiography, which then revealed a subtotal stenosis of the right coronary artery and was successfully treated with the percutaneous coronary intervention (21). Another promising application of strain imaging is the identification of a relatively large subgroup of non ST- elevation myocardial infarction patients with total coronary occlusion (32). Lack of ST elevation in these patients reflects the limited sensitivity of electrocardiogram (ECG) in identifying patients with coronary occlusion (33). Interestingly, echocardiographic parameters of LV systolic function correlate with infarct size.

Global longitudinal strain and wall motion score index are both excellent parameters to identify patients with substantial myocardial infarction, who may benefit from urgent reperfusion therapy (32). To detect the coronary artery disease early and to perfuse the blocked coronary before the irreversible injury during the perioperative period is very important for anesthesiologists. When there is systolic hypokinesia or akinesia, post- systolic shortening measured by strain indicates viable myocardium (31). Even for the myocardial segment, which is entirely passive during the first few hours after coronary occlusion, the presence of deformation reflected by strain could imply potential recovery with reperfusion (34).

Strain Imaging to Detect Drug- Induced Cardiotoxicity

Myocardial toxic effects from chemotherapy have become a leading cause of morbidity and mortality in cancer survivors (21). When a reduction in LVEF during chemotherapy is established, it may be too late for treatment (37). Reduction in myocardial strain precedes significant change in LVEF (38). In a recent consensus document from the American Society of Echocardiography (ASE) and European Association of Cardiovascular Imaging (EACVI), a practical guide was given for how to apply strain imaging in the evaluation of adult patients who receive cancer therapy, and GLS by stress echocardiography was the recommended parameter for early detection of sub-clinical LV dysfunction (39).

A relative decrease in GLS by 15% compared with the baseline is likely to be of clinical significance, whereas a decrease 8% is not (39). Although anesthesiologists usually don't follow the toxic effect on the heart routinely, understanding the potential cardiac dysfunction from reading the echocardiographic reports or self- performing quick strain analysis will help the anesthesiologists to be prepared to manage hemodynamic instabilities in these patients.

Strain Imaging in Cardiomyopathy

For patients with hypertrophic cardiomyopathy, both hypertrophy and fibrosis contribute to regional impairment and then influence the myocardial strain (35). In Quarta's study, patients with cardiac amyloidosis were assessed. Despite a preserved LVEF, the longitudinal strain was severely impaired in cardiac amyloidosis. Reduced longitudinal strain and advanced New York Heart Association class were negative predictors of survival in patients with cardiomyopathy (36). Hypertrophic cardiomyopathy (HCM) is a genetic disease characterized by cardiac hypertrophy, myocyte disarray, interstitial fibrosis, and left ventricular dysfunction (40, 41). Strain imaging in obstructive HCM facilitates detection of subclinical systolic dysfunction in focal areas of pathological myocardial hypertrophy. There have been recent reports distinguishing fibrotic from nonfibrotic lesions in LV myocardium in patients with HCM and normal LV myocardium in healthy controls with regional peak longitudinal speckle- tracking strain (40). Yang et al. showed that patients with HCM had reduced myocardial Doppler strain at the ventricular septum compared with control patients. The midseptal longitudinal strain was markedly decreased, even reversed in patients with HCM (paradoxical longitudinal systolic expansion), which was directly related to the degree of septal hypertrophy. Myocardial Doppler imaging could offer a unique approach to quantify regional systolic dysfunction in these patients (42).

Strain Imaging to Evaluate the Right Heart

One of the newer applications of strain is the assessment of the right ventricular (RV) free wall (43). The ability to use an early, non- invasive method to assess for acute RV dysfunction in situations where submassive pulmonary embolism (PE) is suspected would enable earlier initiation of thrombolytic therapy (44).

Right ventricular (RV) dysfunction is a frequent consequence of pulmonary embolism (PE) and a marker of increased risk. However, current qualitative methods assessing RV function are imprecise. Elke et al. showed that regional RV longitudinal strain was altered in all regions except the apical septum in subjects with acute PE. Strain rates of PE subjects were significantly reduced in all segments of the RV free wall. Automated methods to assess strain and strain rate could be valuable in rapidly identifying RV dysfunction in the setting of acute PE and might assist in patient risk stratification and management (45). 2D RV strain with medical treatment has correlated with better survival in patients with pulmonary hypertension. 3D RV strain imaging has been shown to be of independent prognostic value in patients with pulmonary hypertension when compared with normal subjects (40).

Risk Assessment and Prognosis

Prognosis in cardiac disease is closely related to systolic function, which is commonly measured by LVEF. An increasing number of studies have suggested that GLS is superior to EF as a measure of LV function and as predictor mortality and cardiac events (46-48). No absolute values for GLS, that indicate high risk are established, but the absolute value of GLS $< 12\%$ represents severe systolic dysfunction and adverse prognosis (47, 48), and $< 15-16\%$ seems to represent the risk in patients with relatively preserved EF (48, 49).

How to Do a Practical Strain Analysis by Anesthesiologists?

With the advancement of technology in speckle tracking echocardiography, left ventricular longitudinal strain can be obtained with minutes on most machines by online analysis and is very practical for busy anesthesiologists in the perioperative period. Here are the steps.

1. Optimize 2D echocardiographic images settings.
2. Acquire midesophageal long axis, 4 chamber and 2 chamber views without ECG or motion artifacts.
3. Record time of aortic valve closure.
4. In midesophageal long axis view, track endocardial borders as prompted by the machine to identify the region of interest.
5. Review tracking results.
6. Adjust tracking if necessary.
7. Accept tracking when the tracing appears to reflect true ventricular deformation.
8. Review strain analysis results.
9. Repeat process for the 4 chamber and 2 chamber views
10. Select Bull's eye view to display all 17 segments' strain analysis.

Conclusions

Measurement of myocardial strain provides important quantitative information on global and regional myocardial function. It will be incorporated into clinical practice. As the echocardiography is becoming more available in operating rooms, anesthesiologists could perform myocardial strain measurements easily in the perioperative period to evaluate cardiac functions accurately, alter their hemodynamic management strategies accordingly and improve patient outcomes.

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References

1. Waldman LK, Fung YC, Covell JW. Transmural myocardial deformation in the canine left ventricle. Normal in vivo three-dimensional finite strains. *Circ Res* 1985;57(1):152-63.
2. Sengupta PP, Narula J. Cardiac strain as a universal biomarker: interpreting the sounds of uneasy heart muscle cells. *JACC Cardiovasc Imaging* 2014;7(5):534-6.
3. Heimdal A, Støylen A, Torp H, Skjaerpe T. Real-time strain rate imaging of the left ventricle by ultrasound. *J Am Soc Echocardiogr* 1998;11(11):1013-9.
4. Stoylen A, Heimdal A, Bjornstad K, Torp HG, Skjaerpe T. Strain Rate Imaging by Ultrasound in the Diagnosis of Regional Dysfunction of the Left Ventricle. *Echocardiography* 1999;16(4):321-9.
5. Veyrat C, Pellerin D, Larrazet F. Myocardial Doppler tissue imaging: past, present and future. *Arch Mal Coeur Vaiss* 1997;90(10):1391-402. (Article in French)
6. Urheim S, Edvardsen T, Torp H, Angelsen B, Smiseth OA. Myocardial strain by Doppler echocardiography. Validation of a new method to quantify regional myocardial function. *Circulation* 2000. 102(10):1158-64.
7. D'hooge J, Heimdal A, Jamal F, Kukulski T, Bijnens B, Rademakers F, et al. Regional strain and strain rate measurements by cardiac ultrasound: principles, implementation and limitations. *Eur J Echocardiogr* 2000;1(3):154-70.
8. Streeter DD Jr, Hanna WT. Engineering mechanics for successive states in canine left ventricular myocardium. II. Fiber angle and sarcomere length. *Circ Res* 1973;33(6):656-64.
9. Tee M, Noble JA, Bluemke DA. Imaging techniques for cardiac strain and deformation: comparison of echocardiography, cardiac magnetic resonance and cardiac computed tomography. *Expert Rev Cardiovasc Ther* 2013;11(2):221-31.
10. Shehata ML, Cheng S, Osman NF, Bluemke DA, Lima JA. Myocardial tissue tagging with cardiovascular magnetic resonance. *J Cardiovasc Magn Reson* 2009;11:55.
11. Achenbach S. Limiting radiation exposure in coronary CT angiography: much can be achieved with little extra effort. *Int J Cardiovasc Imaging* 2009;25(4):421-3.
12. Gorcsan J 3rd, Tanaka H. Echocardiographic assessment of myocardial strain. *J Am Coll Cardiol* 2011;58(14):1401-13.
13. Duncan AE, Alfirevic A, Sessler DI, Popovic ZB, Thomas JD. Perioperative assessment of myocardial deformation. *Anesth Analg* 2014;118(3):525-44.
14. Teske AJ, De Boeck BW, Melman PG, Sieswerda GT, Doevendans PA, Cramer MJ. Echocardiographic quantification of myocardial function using tissue deformation imaging, a guide to image acquisition and analysis using tissue Doppler and speckle tracking. *Cardiovasc Ultrasound* 2007;5:27.
15. Mor-Avi V, Lang RM, Badano LP, Belohlavek M, Cardim NM, Derumeaux G, 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. *Eur J Echocardiogr* 2011;12(3):167-205.
16. Dandel M, Hetzer R. Echocardiographic strain and strain rate imaging-- clinical applications. *Int J Cardiol* 2009;132(1):11-24.
17. Schou M, Torp-Pedersen C, Gustafsson F, Abdulla J, Kober L. Wall motion index, estimated glomerular filtration rate and mortality risk in patients with heart failure or myocardial infarction: a pooled analysis of 18,010 patients. *Eur J Heart Fail* 2008;10(7):682-8.
18. Armstrong GT, Joshi VM, Ness KK, Marwick TH, Zhang N, Srivastava D, et al. Comprehensive Echocardiographic Detection of Treatment- Related Cardiac Dysfunction in Adult Survivors of Childhood Cancer: Results From the St. Jude Lifetime Cohort Study. *J Am Coll Cardiol* 2015;65(23):2511-22.
19. Witkowski TG, Thomas JD, Debonnaire PJ, Delgado V, Hoke U, Ewe SH, et al. Global longitudinal strain predicts left ventricular dysfunction after mitral valve repair. *Eur Heart J Cardiovasc Imaging* 2013;14(1):69-76.
20. Voigt JU, Pedrizzetti G, Lysyansky P, Marwick TH, Houle H, Baumann R, et al. Definitions for a common standard for 2D speckle tracking echocardiography: consensus document of the EACVI/ASE/Industry Task Force to standardize deformation imaging. *J Am Soc Echocardiogr* 2015;28(2):183-93.
21. Smiseth OA, Torp H, Opdahl A, Haugaa KH, Urheim S. Myocardial strain imaging: how useful is it in clinical decision making. *Eur Heart J* 2016;37(15):1196-207.
22. Lang RM, Badano LP, Mor-Avi V, Afilalo J, Armstrong A, Ernande L, et al. Recommendations for cardiac chamber quantification by echocardiography in adults: an update from the American Society of Echocardiography and the European Association of Cardiovascular Imaging. *Eur Heart J Cardiovasc Imaging* 2015;16(3):233-70.
23. Pérez de Isla L, Millán M, Lennie V, Quezada M, Guinea J, Macaya C, et al. Area strain: normal values for a new parameter in healthy people. *Rev Esp Cardiol* 2011;64(12):1194-7. (Article in Spanish)
24. Zamorano JL, Lancellotti P, Rodriguez Muñoz D, Aboyans V, Asteggiano R, Galderisi M, et al. 2016 ESC Position Paper on cancer treatments and cardiovascular toxicity developed under the auspices of the ESC Committee for Practice Guidelines: The Task Force for cancer treatments and cardiovascular toxicity of the European Society of Cardiology (ESC). *Eur Heart J* 2016;37(36):2768-801.
25. Kang Y, Xu X, Cheng L, Li L, Sun M, Chen H, et

al. Two-dimensional speckle tracking echocardiography combined with high-sensitive cardiac troponin T in early detection and prediction of cardiotoxicity during epirubicine-based chemotherapy. *Eur J Heart Fail* 2014;16(3):300-8.

26. Lee CH, Yang MM, Ho AC, Chen CY, Huang CC, Lui PW, et al. Evaluation of the longitudinal contraction of the ventricle septum in patients undergoing off-pump coronary artery bypass graft surgery by strain rate imaging. *Acta Anaesthesiol Taiwan* 2006;44(1):11-8.

27. Delgado V, Tops LF, van Bommel RJ, van der Kley F, Marsan NA, Klautz RJ, et al. Strain analysis in patients with severe aortic stenosis and preserved left ventricular ejection fraction undergoing surgical valve replacement. *Eur Heart J* 2009;30(24):3037-47.

28. de Isla LP, de Agustin A, Rodrigo JL, Almeria C, del Carmen Manzano M, Rodríguez E, et al. Chronic mitral regurgitation: a pilot study to assess preoperative left ventricular contractile function using speckle-tracking echocardiography. *J Am Soc Echocardiogr* 2009;22(7):831-8.

29. Tayyareci Y, Yildirimturk O, Aytekin V, Demiroglu IC, Aytekin S. Subclinical left ventricular dysfunction in asymptomatic severe aortic regurgitation patients with normal ejection fraction: a combined tissue Doppler and velocity vector imaging study. *Echocardiography* 2010;27(3):260-8.