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EDITORIAL

Left atrial physiology and pathophysiology: Role of deformation imaging

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Abstract

The left atrium (LA) acts as a modulator of left ventricular (LV) filling. Although there is considerable evidence to support the use of LA maximum and minimum volumes for disease prediction, theoretical considerations and a growing body of literature suggest to focus on the quantification of the three basic LA functions: (1) Reservoir function: collection of pulmonary venous return during LV systole; (2) Conduit function: passage of blood to the left ventricle during early LV diastole; and (3) Contractile booster pump function (augmentation of ventricular filling during late LV diastole. Tremendous advances in our ability to non-invasively characterize all three elements of atrial function include speckle tracking echocardiography (STE), and more recently cardiovascular magnetic resonance myocardial feature tracking (CMR-FT). Corresponding imaging biomarkers are increasingly recognized to have incremental roles in determining prognosis and risk stratification in cardiac dysfunction of different origins. The current editorial introduces the role of STE and CMR-FT for the functional assessment of LA deformation as determined by strain and strain rate imaging and provides an outlook of how this exciting field may develop in the future.

Key words: Left atrium; Strain; Strain rate; Physiology; Pathophysiology; Cardiovascular magnetic resonance; Echocardiography; Feature tracking; Speckle tracking; Diastolic dysfunction

Core tip: Recent advances in speckle tracking echocardiography (STE) and cardiovascular magnetic resonance myocardial feature tracking (CMR-FT) allow a detailed quantification of left atrium (LA) dynamics in terms of strain and strain rate imaging. Corresponding imaging biomarkers are progressively found to have the potential to predict the outcome in a variety of cardiovascular disease states. The current editorial introduces the role of STE and CMR-FT for the functional assessment of LA deformation and provides an outlook of how this exciting field may evolve in the future.

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INTRODUCTION

Heart failure of different origins including ischemic aetiology remains a major determinant of mortality[1]. Left atrial (LA) enlargement has been shown to be a sensitive parameter for the prediction of adverse cardiac events[2,3]. The interplay between LA enlargement and atrial remodelling in the development of atrial fibrillation (AF) has been demonstrated[4,5]. However, the pure relation of LA pathology to its enlargement within different diseases may oversimplify cardiovascular physiology. It is important to note that the LA does not merely represent a stiff chamber, which passively transports blood from the pulmonary veins to the left ventricle (LV), but a more complex and active chamber. Its role should rather be described as a dynamic modulation of LV filling by functioning as a reservoir, conduit and contractile booster pump[6,7]. There have been tremendous advances in terms of our ability to characterize all three elements of atrial function using non-invasive imaging techniques[8]. Recent advances include LA deformation analysis using speckle tracking echocardiography (STE)[9,10] as well as cardiovascular magnetic resonance myocardial feature tracking (CMR-FT)[7,11]. Corresponding imaging biomarkers are progressively found to have the potential to predict the outcome in a variety of cardiovascular disease states[6]. The current editorial introduces the role of STE and CMR-FT for the quantification of LA dynamics as expressed by strain and strain rate (SR) imaging and provides an outlook of how this exciting field may evolve in the future.

LA DEFORMATION ANALYSIS

Besides conventional techniques to analyse LA functional parameters (*e.g.*, pulmonary venous velocity, LA phasic volumes, mitral valve inflow velocity or mitral annular velocity; recent advances in deformation analysis allow to quantify LA longitudinal strain and SR using STE or - more recently - CMR-FT[7,11] (Figure 1). Strain and SR represent the magnitude and rate of myocardial deformation (please see the review by Gorcsan and Tanaka for in depth explanation[12]). LA strain profiles result in three aspects of LA physiology: passive strain (ε_E, representing LA conduit function), active strain (ε_A, representing LA contractile booster pump function) and total strain (ε_S, representing atrial reservoir function)[7] (Figure 1 and Table 1). Correspondingly, three SR parameters can be quantified: peak positive strain rate (SR_S, representing LA reservoir function), peak early negative strain rate (SR_E, representing LA conduit function) and peak late negative strain rate (SR_A, representing LA contractile booster pump function)[7] (Figure 1 and Table 1). It is interesting to speculate on the physiological relevance of the three LA functional elements: LA reservoir function as a measure of LA compliance and LA active relaxation may represent a compensatory mechanism at early stages of congestive LV failure. Conversely, LA conduit function as a measure of LA compliance is already affected by early diastolic LV relaxation abnormalities with changes in LV stiffness and compliance. Lastly LA booster pump function representing LA contractility has impact on ventricular filling and cardiac output[13].

LA deformation quantification comprises challenges that are not present when dealing with ventricular strain and SR imaging. These include the insertion of pulmonary veins and the presence of the LA appendage, the thin LA wall and the variable LA geometry[7]. Notwithstanding these facts, 2D STE and CMR-FT have both shown good performance and reproducibility of LA deformation analysis[7,14]. However, using two-dimensional representations of 3D structures may oversimplify the complex LA anatomy. Through-plane motion or reduced STE imaging quality with poor imaging windows can affect LA deformation analysis and may be difficult to correct. Recent advances in STE provide three-dimensional imaging that eliminates the effects of through-plane motion in patients with sufficient imaging windows and may allow the comprehensive analysis of global and regional LA strain[15,16]. At the present time, similar developments for CMR-FT based on three-dimensional imaging have not yet been introduced.

STE

Two-dimensional STE makes use of offline software analysis using conventional gray scale B-mode images, which are typically acquired during a breath-hold. The frame rate is set between 50 and 70 frames/sec. Speckles can be described as acoustic markers distributed within the myocardium, which can be

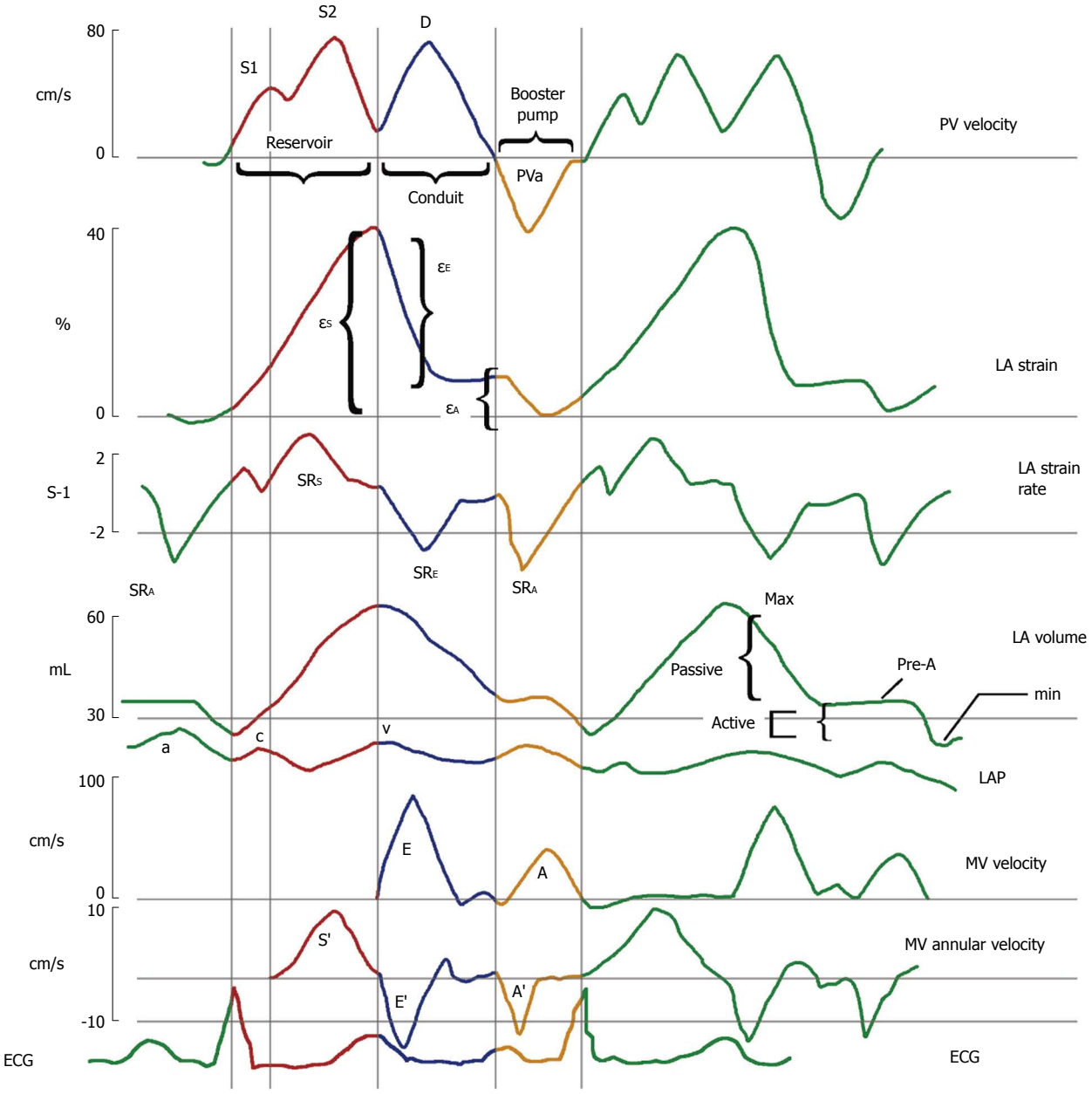

Figure 1 Left atrial physiology imaging using different methods. The figure displays pulmonary venous (PV) velocity, left atrial (LA) strain (ε), LA strain rate (SR), LA volume, left atrial pressure (LAP), and mitral spectral and tissue Doppler. Displayed are two cardiac cycles and the color-coded imaging of reservoir, conduit, and booster pump functions in red, blue, and yellow lines are shown within the first cardiac cycle, respectively. Reprinted from Journal of the American College of Cardiology, Vol 63, Brian D. Hoit, Left atrial size and function: role in prognosis, 493-505, 2014 with permission from Elsevier[6].

tracked from frame to frame[17]. This provides local myocardial displacement information, which can be utilized for the calculation of velocity, strain or SR. It is important to note that there is currently a lack of standardization for LA STE resulting in different approaches to calculate LA deformation indexes: LA strain and SR have been calculated by averaging values from a 15-segment model[18] (six equidistant segments in the apical 4-chamber view, six in the 2-chamber view and three in the 3-chamber view) or from a 12-segment model[14] (six equidistant segments in the 4-chamber view and six segments in the 2-chamber view). Usually, strain and SR indexes are averaged from a total of three consecutive cardiac cycles that provide stable electrocardiographic recording. Furthermore, it is important to understand that there are two different approaches to quantify LA strain with STE. Based on the reference point set at the onset of the P wave (corresponding to the beginning of the atrial cycle)[10,19] or set at the QRS-complex (corresponding to the beginning of the ventricular cycle)[14,20], different LA strain profiles are generated. The description above and the explanation in Figure 1 represent strain profiles acquired with the reference point set at the onset of the QRS-complex resulting in the acquisition of reservoir, conduit and booster pump

Table 1 Left atrial strain and strain rate indexes as determined by speckle tracking echocardiography and cardiovascular magnetic resonance myocardial feature tracking

LA function	Strain	Strain rate
Reservoir	ε_S	SR_S
Conduit	ε_E	SR_E
Booster pump	ε_A	SR_A

Nomenclature refers to the QRS complex set as the reference point and is therefore applicable to both peckle tracking echocardiography and cardiovascular magnetic resonance myocardial feature tracking. LA: Left atrial; ε: Strain; SR: Strain rate.

function[6]. In contrast, if the reference point is set at the onset of the P wave, LA strain profiles display early negative strain (representing LA booster pump function) followed by peak positive strain (representing LA conduit function) while their sum corresponds to LA reservoir function[6].

The wide availability and high temporal resolution of echocardiographic real time images are advantages of STE. However, due to the far-field location of the LA, the main drawback of STE is its dependency on high quality images that frequently cannot be guaranteed in patients with limited acoustic windows[14].

CMR-FT

CMR-FT allows tracking of tissue voxel motion directly from standard steady-state free precession (SSFP) cine CMR images and derivation of myocardial deformation (Figure 2) without the need for additional sequence acquisition as compared to myocardial MR Tagging[7]. Therefore, this technique appears particularly applicable from a clinical perspective and can be easily implemented into a running CMR laboratory. Although CMR-FT was initially validated for ventricular function analysis[21-27], its applicability has recently been extended to quantitative longitudinal LA strain and SR analysis[7]. Typically, LA endocardial borders are initially traced in the 2- and 4-chamber views at the minimum atrial volume after atrial contraction[7]. Subsequently, an automatic tracking algorithm is applied. According to STE, LA contours are divided into six segments[20] and subsequently averaged to global strain and SR indexes using a 12-segment model (six equidistant segments in the 4 and 2-chamber views). CMR-FT benefits from high quality CMR images allowing robust contouring of the thin LA myocardium. Furthermore, CMR includes the acquisition of standardised and highly reproducible imaging planes, which is particularly important in longitudinal studies with repeated measurements[28]. Future studies will need to address whether or not CMR-FT has better inter-study reproducibility than STE. On the other hand, low temporal resolution of CMR images might affect deformation analysis, *e.g.*, the ability to accurately quantify peak strain rates[7]. Future evaluations will have to compare STE and CMR-FT regarding the analysis of LA dynamics to determine whether or not results are interchangeable between modalities or one approach should be preferred over the other.

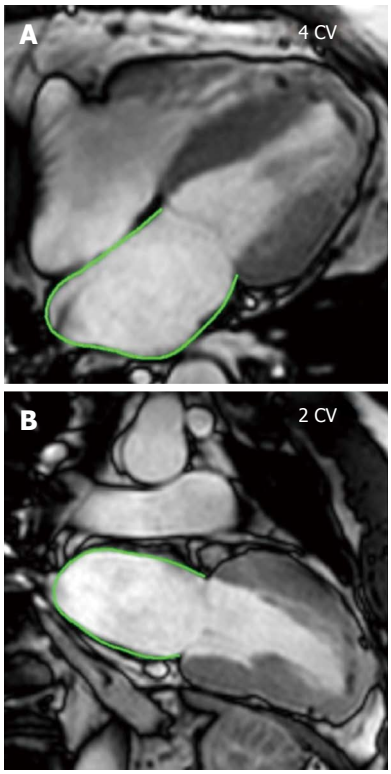

Figure 2 Cardiovascular magnetic resonance myocardial feature tracking of the left atrium in a patient with hypertrophic cardiomyopathy. Cardiovascular magnetic resonance myocardial feature tracking is performed in 4-chamber (A) and 2-chamber (B) views. Contours are based on 48 features, which are tracked throughout the cardiac cycle to generate longitudinal strain and strain rate profiles as displayed in Figure 1.

FUTURE POTENTIAL OF LA DEFORMATION QUANTIFICATION

A growing body of literature suggests to focus on the quantification of the three basic LA functions rather than on the LA volumes only: LA reservoir function has shown to closely correlate with LV filling pressures[29] and has demonstrated to be a sensitive biomarker for the prediction of adverse cardiac events independently of other measures of cardiac dysfunction in patients with heart failure[30]. Strong association between LA conduit function and recurrent atrial fibrillation after pulmonary vein isolation has been described[31]. Accordingly, there has been tremendous effort to study LA dynamics with STE. Mounting evidence suggests that impaired LA strain and SR dynamics have the potential to serve as imaging biomarkers for the prognosis and risk stratification or the decision to intervene in heart failure[32,33], hypertension[34], coronary artery disease[35], atrial fibrillation[36], valvular heart disease[20] and cardiomyopathies[37,38] (please see reviews by Hoit[6] and

Viera *et al*[17] for in depth information).

CMR-FT has been introduced more recently[7]. However, recent studies were able to demonstrate an association of impaired LA reservoir function and the development of heart failure in the general population[39]. Impaired reservoir function as determined by volumetric indexes, strain and SR measurements is also closely related to LV fibrosis[40]. With respect to previous reports on the relevance of LV fibrosis[41], LA reservoir function may also represent a promising target for risk stratification. Furthermore, initial experiences on patients with hypertrophic cardiomyopathy (HCM) and heart failure with preserved ejection fraction (HFpEF) demonstrate impaired LA reservoir and conduit function in HCM and HFpEF[7], when compared to healthy controls. In contrast, patients with HCM exhibit increased LA booster pump function while this is decreased in HFpEF[7]. Future studies will need to investigate whether or not this might refer to a potential compensatory mechanism in HCM, as opposed to a complete impairment of LA dynamics in HFpEF[7]. LA CMR-FT has not been applied to patients with atrial fibrillation yet. Deteriorated image quality, which is frequently present in patients with atrial fibrillation, might negatively impact on CMR-FT quality. It remains to be investigated whether or not CMR-FT is feasible in patients with atrial fibrillation using both, conventional ECG-gated SSFP sequences or real-time CMR techniques[42,43], which have demonstrated improved image quality in arrhythmic patients as compared to conventional ECG-gated techniques[44].

CONCLUSION

LA physiology and pathophysiology as quantified by STE and CMR-FT carry promising clinical and prognostic implications. Future studies will need to apply LA deformation imaging to support our understanding of heart failure development and risk stratification in valvular heart disease, atrial fibrillation, hypertension, coronary artery disease and different types of cardiomyopathy.

REFERENCES

1 **Murray CJ**, Lopez AD. Alternative projections of mortality and disability by cause 1990-2020: Global Burden of Disease Study. *Lancet* 1997; **349**: 1498-1504 [PMID: 9167458 DOI: 10.1016/S0140-6736(96)07492-2]

2 **Tsang TS**, Abhayaratna WP, Barnes ME, Miyasaka Y, Gersh BJ, Bailey KR, Cha SS, Seward JB. Prediction of cardiovascular outcomes with left atrial size: is volume superior to area or diameter? *J Am Coll Cardiol* 2006; **47**: 1018-1023 [PMID: 16516087 DOI: 10.1016/j.jacc.2005.08.077]

3 **Benjamin EJ**, D'Agostino RB, Belanger AJ, Wolf PA, Levy D. Left atrial size and the risk of stroke and death. The Framingham Heart Study. *Circulation* 1995; **92**: 835-841 [PMID: 7641364]

4 **Abhayaratna WP**, Seward JB, Appleton CP, Douglas PS, Oh JK, Tajik AJ, Tsang TS. Left atrial size: physiologic determinants and clinical applications. *J Am Coll Cardiol* 2006; **47**: 2357-2363 [PMID: 16781359 DOI: 10.1016/j.jacc.2006.02.048]

5 **Casaclang-Verzosa G**, Gersh BJ, Tsang TS. Structural and functional remodeling of the left atrium: clinical and therapeutic implications for atrial fibrillation. *J Am Coll Cardiol* 2008; **51**: 1-11 [PMID: 18174029 DOI: 10.1016/j.jacc.2007.09.026]

6 **Hoit BD**. Left atrial size and function: role in prognosis. *J Am Coll Cardiol* 2014; **63**: 493-505 [PMID: 24291276 DOI: 10.1016/j.jacc.2013.10.055]

7 **Kowallick JT**, Kutty S, Edelmann F, Chiribiri A, Villa A, Steinmetz M, Sohns JM, Staab W, Bettencourt N, Unterberg-Buchwald C, Hasenfuß G, Lotz J, Schuster A. Quantification of left atrial strain and strain rate using Cardiovascular Magnetic Resonance myocardial feature tracking: a feasibility study. *J Cardiovasc Magn Reson* 2014; **16**: 60 [PMID: 25196447 DOI: 10.1186/s12968-014-0060-6]

8 **Blume GG**, Mcleod CJ, Barnes ME, Seward JB, Pellikka PA, Bastiansen PM, Tsang TS. Left atrial function: physiology, assessment, and clinical implications. *Eur J Echocardiogr* 2011; **12**: 421-430 [PMID: 21565866 DOI: 10.1093/ejechocard/jeq175]

9 **Cameli M**, Lisi M, Righini FM, Mondillo S. Novel echocardiographic techniques to assess left atrial size, anatomy and function. *Cardiovasc Ultrasound* 2012; **10**: 4 [PMID: 22296702 DOI: 10.1186/1476-7120-10-4]

10 **Vianna-Pinton R**, Moreno CA, Baxter CM, Lee KS, Tsang TS, Appleton CP. Two-dimensional speckle-tracking echocardiography of the left atrium: feasibility and regional contraction and relaxation differences in normal subjects. *J Am Soc Echocardiogr* 2009; **22**: 299-305 [PMID: 19258177 DOI: 10.1016/j.echo.2008.12.017]

11 **Kowallick JT**, Edelmann F, Lotz J, Lamata P, Schuster A. Imaging Diastolic Dysfunction with Cardiovascular Magnetic Resonance. *J Cardiol Ther* 2014; **1**: 58-64 [DOI: 10.6051/j.issn.2309-6861.2014.01.20]

12 **Gorcsan J**, Tanaka H. Echocardiographic assessment of myocardial strain. *J Am Coll Cardiol* 2011; **58**: 1401-1413 [PMID: 21939821 DOI: 10.1016/j.jacc.2011.06.038]

13 **To AC**, Flamm SD, Marwick TH, Klein AL. Clinical utility of multimodality LA imaging: assessment of size, function, and structure. *JACC Cardiovasc Imaging* 2011; **4**: 788-798 [PMID: 21757171 DOI: 10.1016/j.jcmg.2011.02.018]

14 **Cameli M**, Caputo M, Mondillo S, Ballo P, Palmerini E, Lisi M, Marino E, Galderisi M. Feasibility and reference values of left atrial longitudinal strain imaging by two-dimensional speckle tracking. *Cardiovasc Ultrasound* 2009; **7**: 6 [PMID: 19200402 DOI: 10.1186/1476-7120-7-6]

15 **Mochizuki A**, Yuda S, Oi Y, Kawamukai M, Nishida J, Kouzu H, Muranaka A, Kokubu N, Shimoshige S, Hashimoto A, Tsuchihashi K, Watanabe N, Miura T. Assessment of left atrial deformation and synchrony by three-dimensional speckle-tracking echocardiography: comparative studies in healthy subjects and patients with atrial fibrillation. *J Am Soc Echocardiogr* 2013; **26**: 165-174 [PMID: 23140846 DOI: 10.1016/j.echo.2012.10.003]

16 **Chadaide S**, Domsik P, Kalapos A, Sághy L, Forster T, Nemes A. Three-dimensional speckle tracking echocardiography-derived left atrial strain parameters are reduced in patients with atrial fibrillation (results from the MAGYAR-path study). *Echocardiography* 2013; **30**: 1078-1083 [PMID: 23659362 DOI: 10.1111/echo.12218]

17 **Vieira MJ**, Teixeira R, Gonçalves L, Gersh BJ. Left atrial mechanics: echocardiographic assessment and clinical implications. *J Am Soc Echocardiogr* 2014; **27**: 463-478 [PMID: 24656882 DOI: 10.1016/j.echo.2014.01.021]

18 **Kutty S**, Padiyath A, Li L, Peng Q, Rangamani S, Schuster A, Danford DA. Functional maturation of left and right atrial systolic and diastolic performance in infants, children, and adolescents. *J Am Soc Echocardiogr* 2013; **26**: 398-409.e2 [PMID: 23337737 DOI: 10.1016/j.echo.2012.12.016]

19 **Saraiva RM**, Demirkol S, Buakhamsri A, Greenberg N, Popović ZB, Thomas JD, Klein AL. Left atrial strain measured by two-dimensional speckle tracking represents a new tool to evaluate left

atrial function. *J Am Soc Echocardiogr* 2010; **23**: 172-180 [PMID: 20152699 DOI: 10.1016/j.echo.2009.11.003]

20 **Ring L**, Rana BS, Wells FC, Kydd AC, Dutka DP. Atrial function as a guide to timing of intervention in mitral valve prolapse with mitral regurgitation. *JACC Cardiovasc Imaging* 2014; **7**: 225-232 [PMID: 24529886 DOI: 10.1016/j.jcmg.2013.12.009]

21 **Kowallick JT**, Lamata P, Hussain ST, Kutty S, Steinmetz M, Sohns JM, Fasshauer M, Staab W, Unterberg-Buchwald C, Bigalke B, Lotz J, Hasenfuß G, Schuster A. Quantification of left ventricular torsion and diastolic recoil using cardiovascular magnetic resonance myocardial feature tracking. *PLoS One* 2014; **9**: e109164 [PMID: 25285656 DOI: 10.1371/journal.pone.0109164]

22 **Morton G**, Schuster A, Jogiya R, Kutty S, Beerbaum P, Nagel E. Inter-study reproducibility of cardiovascular magnetic resonance myocardial feature tracking. *J Cardiovasc Magn Reson* 2012; **14**: 43 [PMID: 22721175 DOI: 10.1186/1532-429X-14-43]

23 **Onishi T**, Saha SK, Ludwig DR, Onishi T, Marek JJ, Cavalcante JL, Schelbert EB, Schwartzman D, Gorcsan J. Feature tracking measurement of dyssynchrony from cardiovascular magnetic resonance cine acquisitions: comparison with echocardiographic speckle tracking. *J Cardiovasc Magn Reson* 2013; **15**: 95 [PMID: 24134158 DOI: 10.1186/1532-429X-15-95]

24 **Padiyath A**, Gribben P, Abraham JR, Li L, Rangamani S, Schuster A, Danford DA, Pedrizzetti G, Kutty S. Echocardiography and cardiac magnetic resonance-based feature tracking in the assessment of myocardial mechanics in tetralogy of Fallot: an intermodality comparison. *Echocardiography* 2013; **30**: 203-210 [PMID: 23167248 DOI: 10.1111/echo.12016]

25 **Schuster A**, Kutty S, Padiyath A, Parish V, Gribben P, Danford DA, Makowski MR, Bigalke B, Beerbaum P, Nagel E. Cardiovascular magnetic resonance myocardial feature tracking detects quantitative wall motion during dobutamine stress. *J Cardiovasc Magn Reson* 2011; **13**: 58 [PMID: 21992220 DOI: 10.1186/1532-429X-13-58]

26 **Schuster A**, Morton G, Hussain ST, Jogiya R, Kutty S, Asrress KN, Makowski MR, Bigalke B, Perera D, Beerbaum P, Nagel E. The intra-observer reproducibility of cardiovascular magnetic resonance myocardial feature tracking strain assessment is independent of field strength. *Eur J Radiol* 2013; **82**: 296-301 [PMID: 23246014 DOI: 10.1016/j.ejrad.2012.11.012]

27 **Schuster A**, Paul M, Bettencourt N, Morton G, Chiribiri A, Ishida M, Hussain S, Jogiya R, Kutty S, Bigalke B, Perera D, Nagel E. Cardiovascular magnetic resonance myocardial feature tracking for quantitative viability assessment in ischemic cardiomyopathy. *Int J Cardiol* 2013; **166**: 413-420 [PMID: 22130224 DOI: 10.1016/j.ijcard.2011.10.137]

28 **Semelka RC**, Tomei E, Wagner S, Mayo J, Caputo G, O'Sullivan M, Parmley WW, Chatterjee K, Wolfe C, Higgins CB. Interstudy reproducibility of dimensional and functional measurements between cine magnetic resonance studies in the morphologically abnormal left ventricle. *Am Heart J* 1990; **119**: 1367-1373 [PMID: 2141222]

29 **Posina K**, McLaughlin J, Rhee P, Li L, Cheng J, Schapiro W, Gulotta RJ, Berke AD, Petrossian GA, Reichek N, Cao JJ. Relationship of phasic left atrial volume and emptying function to left ventricular filling pressure: a cardiovascular magnetic resonance study. *J Cardiovasc Magn Reson* 2013; **15**: 99 [PMID: 24168103 DOI: 10.1186/1532-429X-15-99]

30 **Pellicori P**, Zhang J, Lukaschuk E, Joseph AC, Bourantas CV, Loh H, Bragadeesh T, Clark AL, Cleland JG. Left atrial function measured by cardiac magnetic resonance imaging in patients with heart failure: clinical associations and prognostic value. *Eur Heart J* 2015; **36**: 733-742 [PMID: 25336215 DOI: 10.1093/eurheartj/ehu405]

31 **Dodson JA**, Neilan TG, Shah RV, Farhad H, Blankstein R, Steigner M, Michaud GF, John R, Abbasi SA, Jerosch-Herold M, Kwong RY. Left atrial passive emptying function determined by cardiac magnetic resonance predicts atrial fibrillation recurrence after pulmonary vein isolation. *Circ Cardiovasc Imaging* 2014; **7**: 586-592 [PMID: 24902586 DOI: 10.1161/CIRCIMAGING.113.001472]

32 **Cameli M**, Lisi M, Mondillo S, Padeletti M, Ballo P, Tsioulpas C, Bernazzali S, Maccherini M. Left atrial longitudinal strain by speckle tracking echocardiography correlates well with left ventricular filling pressures in patients with heart failure. *Cardiovasc Ultrasound* 2010; **8**: 14 [PMID: 20409332 DOI: 10.1186/1476-7120-8-14]

33 **Obokata M**, Negishi K, Kurosawa K, Arima H, Tateno R, Ui G, Tange S, Arai M, Kurabayashi M. Incremental diagnostic value of la strain with leg lifts in heart failure with preserved ejection fraction. *JACC Cardiovasc Imaging* 2013; **6**: 749-758 [PMID: 23747067 DOI: 10.1016/j.jcmg.2013.04.006]

34 **Cameli M**, Ciccone MM, Maiello M, Modesti PA, Muiesan ML, Scicchitano P, Novo S, Palmiero P, Saba PS, Pedrinelli R. Speckle tracking analysis: a new tool for left atrial function analysis in systemic hypertension: an overview. *J Cardiovasc Med (Hagerstown)* 2014; Epub ahead of print [PMID: 24838034 DOI: 10.2459/JCM.0000000000000073]

35 **Antoni ML**, ten Brinke EA, Atary JZ, Marsan NA, Holman ER, Schalij MJ, Bax JJ, Delgado V. Left atrial strain is related to adverse events in patients after acute myocardial infarction treated with primary percutaneous coronary intervention. *Heart* 2011; **97**: 1332-1337 [PMID: 21613636 DOI: 10.1136/hrt.2011.227678]

36 **Di Salvo G**, Caso P, Lo Piccolo R, Fusco A, Martiniello AR, Russo MG, D'Onofrio A, Severino S, Calabró P, Pacileo G, Mininni N, Calabró R. Atrial myocardial deformation properties predict maintenance of sinus rhythm after external cardioversion of recent-onset lone atrial fibrillation: a color Doppler myocardial imaging and transthoracic and transesophageal echocardiographic study. *Circulation* 2005; **112**: 387-395 [PMID: 16006491 DOI: 10.1161/CIRCULATIONAHA.104.463125]

37 **D'Andrea A**, Caso P, Romano S, Scarafile R, Cuomo S, Salerno G, Riegler L, Limongelli G, Di Salvo G, Romano M, Liccardo B, Iengo R, Ascione L, Del Viscovo L, Calabrò P, Calabrò R. Association between left atrial myocardial function and exercise capacity in patients with either idiopathic or ischemic dilated cardiomyopathy: a two-dimensional speckle strain study. *Int J Cardiol* 2009; **132**: 354-363 [PMID: 18255178 DOI: 10.1016/j.ijcard.2007.11.102]

38 **Gabrielli L**, Enríquez A, Córdova S, Yáñez F, Godoy I, Corbalán R. Assessment of left atrial function in hypertrophic cardiomyopathy and athlete's heart: a left atrial myocardial deformation study. *Echocardiography* 2012; **29**: 943-949 [PMID: 22954405 DOI: 10.1111/j.1540-8175.2012.01719.x]

39 **Habibi M**, Chahal H, Opdahl A, Gjesdal O, Helle-Valle TM, Heckbert SR, McClelland R, Wu C, Shea S, Hundley G, Bluemke DA, Lima JA. Association of CMR-measured LA function with heart failure development: results from the MESA study. *JACC Cardiovasc Imaging* 2014; **7**: 570-579 [PMID: 24813967 DOI: 10.1016/j.jcmg.2014.01.016]

40 **Imai M**, Ambale Venkatesh B, Samiei S, Donekal S, Habibi M, Armstrong AC, Heckbert SR, Wu CO, Bluemke DA, Lima JA. Multi-ethnic study of atherosclerosis: association between left atrial function using tissue tracking from cine MR imaging and myocardial fibrosis. *Radiology* 2014; **273**: 703-713 [PMID: 25019562 DOI: 10.1148/radiol.14131971]

41 **Rahimtoola SH**, Dilsizian V, Kramer CM, Marwick TH, Vanoverschelde JL. Chronic ischemic left ventricular dysfunction: from pathophysiology to imaging and its integration into clinical practice. *JACC Cardiovasc Imaging* 2008; **1**: 536-555 [PMID: 19356479 DOI: 10.1016/j.jcmg.2008.05.009]

42 **Kowallick JT**, Joseph AA, Unterberg-Buchwald C, Fasshauer M, van Wijk K, Merboldt KD, Voit D, Frahm J, Lotz J, Sohns JM. Real-time phase-contrast flow MRI of the ascending aorta and superior vena cava as a function of intrathoracic pressure (Valsalva manoeuvre). *Br J Radiol* 2014; **87**: 20140401 [PMID: 25074791 DOI: 10.1259/bjr.20140401]

43 **Zhang S**, Joseph AA, Voit D, Schaetz S, Merboldt KD, Unterberg-

Buchwald C, Hennemuth A, Lotz J, Frahm J. Real-time magnetic resonance imaging of cardiac function and flow-recent progress. *Quant Imaging Med Surg* 2014; **4**: 313-329 [PMID: 25392819 DOI: 10.3978/j.issn.2223-4292.2014.06.03]

44 **Voit D**, Zhang S, Unterberg-Buchwald C, Sohns JM, Lotz J, Frahm J. Real-time cardiovascular magnetic resonance at 1.5 T using balanced SSFP and 40 ms resolution. *J Cardiovasc Magn Reson* 2013; **15**: 79 [PMID: 24028285 DOI: 10.1186/1532-429X-15-79]

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