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Myocardial deformation imaging in anesthesia and perioperative medicine: a non systematic review

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Abstract : Measuring the systolic function of the left ventricle (LV) is essential in clinical practice. However, the complex organization of the myocardial fibers whose contraction results in the ejection of the stroke volume renders this assessment challenging. The ejection fraction of the left ventricle (LVEF) has long been the most popular measure of the systolic function of the left ventricle despite its numerous technical and non-technical limitations. More recently, the development of speckle-tracking echocardiography allowed the widespread adoption of myocardial deformation imaging indices such as the strain and the strain rate. Strain, and in particular, global longitudinal strain (GLS) has quickly gained popularity as an additional measure of the systolic function of the left ventricle. In comparison with the ejection fraction, GLS is easier to use, more reproducible, and more sensitive to mild changes in myocardial contractility. Strain is an interesting tool for diagnosis and prognostic stratification in both surgical and non-surgical patients. The purpose of this review is to describe the principles of strain use and to review its main applications, while focusing on the aspects relevant to the practice of anesthesia and intensive care medicine.

Key Words : Strain ; left ventricle ; ejection fraction ; anesthesia.

Introduction

The assessment of the systolic function of the left ventricle (LV) is essential in clinical practice. The measure of the ejection fraction (LVEF) has been the cornerstone of this assessment for several decades (1). The ejection fraction is not only useful to guide treatment strategy but is also a good predictor of outcome when below 40 %. However, the LVEF is much less useful for risk stratification when approaching normal values (2). In addition, the ejection fraction has several technical and non-technical limitations. Technical limitations include, among others, frequently foreshortened ventricular views, inaccurate endocardial border detection, and the dependence on geometrical assumptions. The ejection fraction is also extremely load-dependent and influenced by changes in LV geometry unrelated to the actual contractility such as LV hypertrophy. Some but not all of these limitations can be overcome by the use of three-dimensional echocardiography (3).

Over the last decade, myocardial deformation imaging has emerged as an additional measure of the LV systolic function ; Strain being currently the most popular measure of myocardial deformation.

Functional anatomy of the LV wall

The fibers of the left ventricular wall form a double helix. Their angle changes continuously from the subendocardium to the subepicardium. As a result, the left ventricular wall undergoes a combination of complex movements during systole including an inward displacement, a radial thickening, a longitudinal and a circumferential shortening, and a twisting motion (Fig. 1). This organization is mechanically efficient since a 15 % shortening of the myofibers results in an ejection fraction greater than 60 % (4).

Measurement of Strain and Strain rate (SR)

Myocardial strain imaging was first developed using tissue Doppler echocardiography (TDE) (5). TDE allows the measurement of the natural strain, ie the deformation of a particular myocardial segment relative to its length at a previous time instance (t). Although the technique was found of value, its angle-dependency and the cumbersomeness of the

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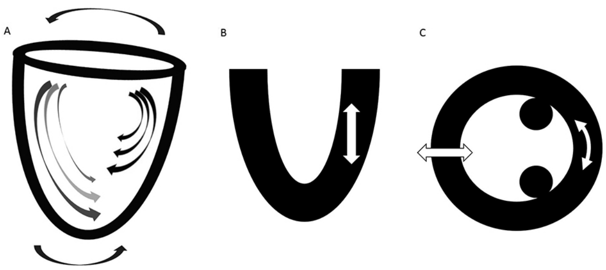

Fig. 1. — A. Schematic representation of the arrangement of the myocardial fibers within the wall of the left ventricle (LV). Looking at the heart from the apex, the subendocardial fibers (black) form a right-handed helix whereas the subepicardial fibers (grey) form a left-handed helix. Between the two layers, in the midwall, the fibers are arranged circumferencially (not shown). As a result, during systole, the left ventricle undergoes a complex motion including a clockwise rotation of the apex and a counterclockwise rotation of the base. This motion can be broken down into several components illustrated in B and C. B. Longitudinal shortening of the LV wall during systole. C. Radial thickening and circumferential shortening of the LV wall during systole.

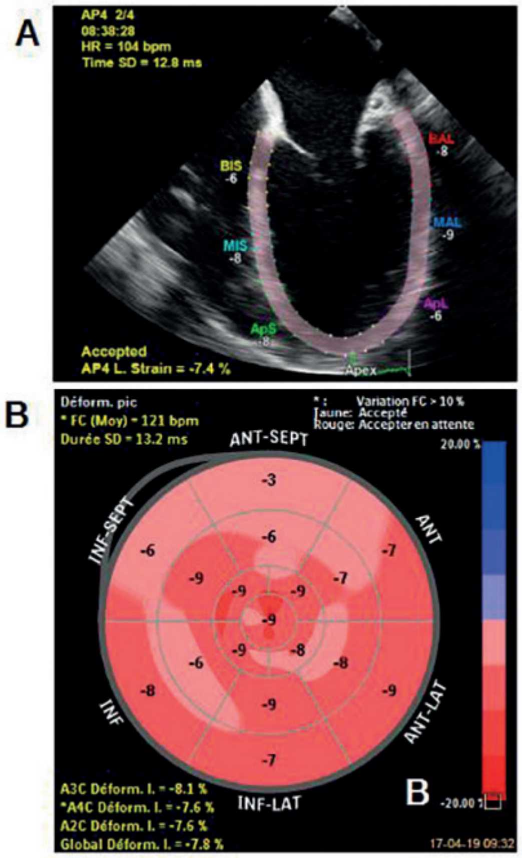

Fig. 2. — 2D peak-systolic longitudinal strain in a patient with severely impaired left ventricular function. A. Regional strain value in the mid-esophageal four-chamber view of the left ventricle. B. Strain bullseye shows markedly impaired strain values in all myocardial segments. The strain values are even worse in the anteroseptal territory.

analyzes hindered the widespread adoption of TDE-derived strain. The popularity of strain grew up together with the development of Speckle tracking echocardiography (STE) (6). Speckles artifacts are small "grey dots" that result from the interaction between the ultrasound beam and the myocardial structure. The appearance of some of them remains stable throughout the cardiac cycle so that they can be used as fingerprints to track the deformations of the myocardium in different directions. Like cardiac magnetic resonance, STE allows the measurement of the Langranian strain, which is defined as the change in length of a myocardial segment over its initial length (L_0) (7). The strain is dimensionless and is often reported as percent.

Two-dimensional speckle tracking echocardiography (2D-STE) allows the measurement of longitudinal, radial and circumferential strain values of the different myocardial segments. The global strain in a particular direction is the average of all the segmental strain values in this direction. Among the different strain components, the global longitudinal strain (GLS) is by far the best studied and validated (8). Since the ventricle shortens along its longitudinal axis during systole, the longitudinal strain is negative ; a more negative value indicates a better contractility.

The measurement of the longitudinal strain requires the acquisition of the three main apical or mid-esophageal views of the left ventricle and a capable software package. The operator places markings at the mitral valve annulus and at the apex before semi-automated border detection and tracking of clusters of speckles provide a quantitative assessment of myocardial deformation (Fig. 2).

Strain can be measured using both transthoracic echocardiography (TTE) and transesophageal echocardiography (TEE). There are however important limitations to the use of TEE to measure the strain. The fact that the region of interest lies in the far field, the interposition of the mitral valve, the frequent foreshortening of the apex as well as the differences in temporal and spatial resolution between TEE and TTE probes significantly impact on the tracking of speckles. As a result, the two techniques do not lead to interchangeable results (9). In addition, when TEE is performed under general anesthesia, the effects of anesthetic drugs and mechanical ventilation may further affect the results. On average, TEE slightly overestimates GLS in comparison with TTE.

Also, the comparison between strain values obtained using software packages from different vendors initially revealed an unacceptable degree of heterogeneity (10). This has markedly improved following the effort of a joint standardization task force between the industry and professional societies (11). The GLS is considered normal when >20% in absolute value(12). The development of three-dimensional speckle-tracking echocardiography (3D-STE) now allows the simultaneous measurement of the different dimensional components of strain on a single 3D-dataset. 3D-STE has the potential to overcome some limitations of 2D-STE including apical foreshortening and out-of-plane displacement of speckles (13). In addition, 3D-STE is independent of geometrical assumptions and likely better reflects the function of the myocardial fibers, which are arranged obliquely as described above. Finally, 3D-STE allows the measurement of new parameters such as the area change ratio and the twist (14). However, 3D-STE still requires further validation.

The strain rate (SR) is the change in strain per unit of time. It describes the rate of shortening or lengthening of the myocardium over time and is expressed as per second of unit measurement. Similarly to strain, myocardial shortening results in negative SR values whereas thickening and lengthening produce positive SR. SR reaches a peak value at mid-systole and then declines towards zero at end-systole. During diastole SR peaks twice, respectively at the early and late phase corresponding to the E and A waves of the transmitral flow (7). SR has potential advantages over strain. It is less influenced by the loading conditions, has a better ability to identify the culprit lesion during acute coronary syndrome (15) and better predicts prolonged hospital stay after aortic valve replacement (16). However, major limitations still preclude its widespread use in clinical practice. Its measurement is more difficult as a result of a lower signal/noise ratio. The interpretation of the SR curve is more prone to error, in particular for inexperienced users, and last but not least, there is no clear consensus over the normal values. As a result, SR will not be discussed further in this review (17).

Comparison between GLS and LVEF

Two-dimensional-STE GLS is easier to measure and less influenced by image quality than 2D Simpson's biplane LVEF (18). This results in a low intra-observer and inter-observer variability(19), even among inexperienced echocardiographers (20). GLS seems to primarily reflect the activity of the most vulnerable subendocardial fibers. As a result, it is more sensitive to subtle changes in myocardial contractility than LVEF. This has long been used for the early recognition of chemotherapy-induced cardiotoxicity where the alterations of GLS precede the decrease in LVEF (21). GLS could also better reflect the actual contractility of the left ventricle in patients with LV hypertrophy or small ventricular cavities in whom LVEF overestimates the left ventricular systolic function (22).

Like the LVEF, strain is influenced by the loading conditions and therefore does not measure load-independent contractility. Strain rate, in particular in the radial direction, seems less sensitive to loading conditions (23).

Clinical applications of strain in non-surgical patients

GLS was first adopted in non-surgical patients before its value was recognized in perioperative medicine. It is beyond the scope of this review to describe in details all the applications of strain in non-surgical patients. We will nevertheless provide the reader with a summary of the most commonly recognized indications for strain measurement.

Detection of chemotherapy-induced cardiotoxicity

As mentioned above, strain is more sensitive to early changes in myocardial contractility than LVEF. In patients developing chemotherapy-induced cardiotoxicity, GLS starts declining sooner than LVEF. A 15 % relative reduction in GLS identifies chemotherapy-induced cardiotoxicity with a high sensitivity and specificity and should prompt a change in treatment regimen (21).

Detection of coronary artery disease (CAD)

GLS is significantly reduced in patients with moderate to severe coronary artery disease (-16.5 % in patients with CAD versus -19.7 % in patients without CAD). It could improve the prediction of CAD over exercise electrocardiography in patients having chest pain and a normal resting LVEF (24). In patients with suspected CAD, impaired regional strain values and typical strain patterns such as post-systolic shortening may further reinforce the suspicion (Fig. 3) (25).

Heart Failure

Heart failure (HF) is commonly classified according to the ejection fraction (26) but can also fall into three morphological phenotypes : HF with predominant longitudinal dysfunction, HF with

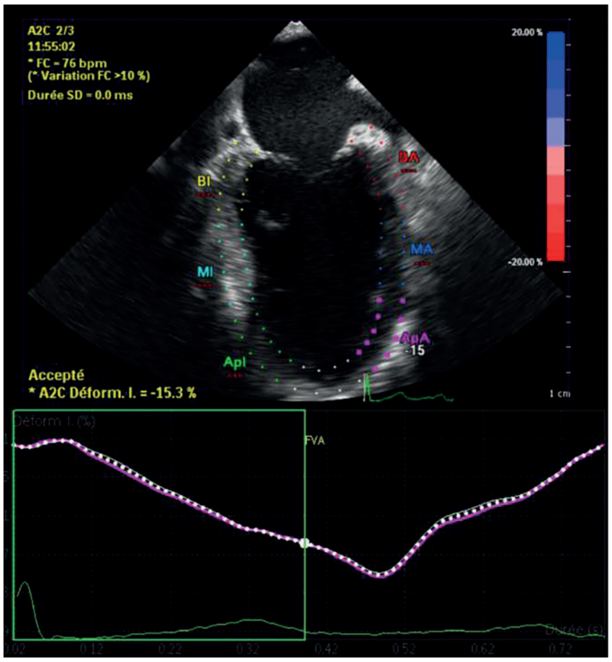

Fig. 3. — Typical post-systolic contraction of the Anterior Apical Segment (ApA) suggesting myocardial ischemia. The peak strain value occurs after the closure of the aortic valve (FVA), which corresponds to the end of the mechanical systole.

transmural dysfunction, and HF with predominant circumferential dysfunction (27).

Heart failure with preserved ejection fraction (HFpEF) accounts for at least half of the heart failure cases and seems to carry a prognosis, which is at least as bad as heart failure with reduced ejection fraction. Patients with HFpEF have an ejection fraction ≥ 50 % (28). Symptoms of heart failure in these patients are thought to result, at least in part, from diastolic dysfunction. However, GLS is also significantly altered in the vast majority of patients with HFpEF (29). Therefore, GLS possibly has a role in the diagnosis of HFpEF in addition to the parameters of diastolic function. In addition, GLS also has a prognostic value in these patients (30). It is noteworthy that in HFpEF, the circumferential strain and twist remain normal or may even be increased because of the compensatory hypertrophy and unopposed contraction of the subepicardial layer (27).

In HFrEF all the layers of the myocardial wall are usually affected and consequently, the three components of strain are impaired. In these patients, GCS seems to have an interesting prognostic value beyond the ejection fraction (31).

The GLS pattern can also help identify the etiology of heart failure. This is particularly well demonstrated for the differential diagnosis of hypertrophic heart diseases. For example, patients with an inherited hypertrophic obstructive cardiomyopathy typically show a markedly reduced septal longitudinal strain whereas LV hypertrophy related to aortic stenosis or chronic hypertension is associated with nonspecific mild GLS reduction. GLS is usually preserved in the athlete's heart while cardiac amyloïdosis is characterized by an apical sparing pattern (32).

Strain as predictor of outcome

One of the major interests of strain is its strong relationship with patient outcomes in various cardiac diseases. Firstly, in unselected patients with a LVEF >35 %, GLS was found to have an incremental value over clinical variables to predict all-cause mortality (33). In patients suffering ST-elevation myocardial infarction, the GLS value measured within 24 hour is a strong predictor of adverse events including death, myocardial infarction, stroke and heart failure (Hazard Ratio after adjusting for LVEF, 1.17 ; 95%CI, 1.07-1.29) (34). GLS is also useful to identify subclinical LV dysfunction and refine prognosis in patients suffering heart valve diseases. In patients who suffer asymptomatic degenerative mitral valve regurgitation and have a normal LVEF, a GLS > -20% was significantly associated with adverse cardiac events during a three-year follow-up period (35). Furthermore, a preoperative GLS > -19.9 % was found to predict long-term postoperative LV dysfunction after mitral valve repair, regardless of the preoperative LVEF (36). In patients with any degree of asymptomatic aortic stenosis, GLS was shown to be an independent predictor of death and adverse cardiac events (37). Likewise, in asymptomatic patients with aortic regurgitation, a GLS value < -19,3 % rules out the need for aortic valve surgery with a negative predictive value of 100 % (38). Altogether, these data suggest that GLS could help determine the optimal timing of intervention in asymptomatic patients suffering heart valve diseases.

Strain in perioperative and intensive care medicine

GLS and outcome in adult cardiac surgery

GLS measured preoperatively by transthoracic echocardiography predicts the need for a prolonged inotropic support and 30-day mortality regardless of the LVEF value and regardless of the EuroSCORE (39). Similarly, intraoperative measured GLS using TEE is an independent risk factor for low cardiac output syndrome after on-pump adult cardiac surgery (40) and for prolonged hospitalization after aortic valve replacement (16). The preoperative value of 3D Global Area Strain (GAS) also predicts 1-year event-free survival in adult patients undergoing cardiac surgery regardless of the EuroSCORE and the type of surgery (41).

Right Ventricular Strain

Although strain was first used to measure the systolic function of the left ventricle, it can also be applied to the right ventricle (RV) (42). Using strain as a surrogate of the right ventricular systolic function is attractive. Indeed, the assessment of the RV function using conventional echocardiographic parameters is rendered challenging by the complex geometry of the RV. As a result, there is no single best indicator of RV function. Similarly to what was described for the left ventricle, the right ventricular wall consists of external circumferential fibers and internal longitudinal fibers. The latter accounts for 80 % the RV contractility. The RV longitudinal strain therefore best reflects RV systolic function. Finally, since the contraction of the RV free wall accounts for most of the RV stroke volume, the RV free wall strain is recommended over the RV global strain although further evidence is needed. In addition, widely applicable reference values are still to be established (43).

Technically, the RV strain can be measured using either TTE or TEE. Initially, software packages developed for the left ventricle were used to calculate the RV strain before dedicated solutions become available. Although the values obtained with these two approaches are clearly not interchangeable, they both accurately reflect RV systolic function (44).

One of the most promising uses of RV strain in perioperative medicine is the assessment of RV systolic function before the implantation of a left ventricular assist device (LVAD). Indeed, the RV strain value measured during preoperative TTE has an incremental value over clinical risk scores and other echocardiographic measurements for predicting right heart failure after LVAD implantation (45, 46). Interestingly, two studies found no relationship between RV strain measured using intraoperative TEE images and post-operative RV dysfunction (47, 48). The reasons for this discrepancy remain unclear but preoperative TTE and intraoperative TEE are clearly not interchangeable in this indication. Beyond RV dysfunction after LVAD implantation, RV GLS was also found to carry an independent prognostic value after adult cardiac surgery(49).

Strain and Diastolic Function

Patients with diastolic dysfunction are at increased risk of morbi-mortality after both cardiac (50) and non-cardiac surgery (51). The ability to assess diastolic function intraoperatively is therefore of potential value. However, current recommendations for the diagnosis of diastolic dysfunction, which are based on the size of the left atrium, tissue Doppler imaging of the mitral valve annulus, transmitral Doppler flow pattern and the velocity of tricuspid regurgitation flow do not apply to anesthetized patients (52). 2D-STE strain allows direct measurement of the LV relaxation during diastole. A recent study revealed that two new strain-derived indices measured during intraoperative TEE, E_{wave}/Diastolic Strain and E_{wave}/10xDiastolic Strain Rate, better correlate with the pulmonary capillary wedge pressure than traditional doppler-based indices such as E/e' (53).

Diastolic dysfunction can also be diagnosed and the left atrial pressure can be estimated by directly measuring the left atrial strain during the reservoir phase (54). Recently, the peak LA strain value was found to have a better agreement with invasively determined LA pressure than the algorithm from the 2016 guidelines (55).

Left atrial strain and postoperative atrial fibrillation

Atrial fibrillation is one of the most common complications following adult cardiac surgery and is likely related to some degree of atrial dysfunction (56). Interestingly, the preoperative value of left atrial strain was found to be an independent predictor of atrial fibrillation after both aortic (57) and mitral valve surgery (58).

Strain in Intensive Care Medicine

LV strain may also be useful in intensive care patients, in particular in patients with sepsis. Indeed, sepsis alters both myocardial contractility and loading conditions (59). As a result, the LVEF does not adequately reflect the actual LV systolic function in these patients. Although various studies yielded conflicting results, there is evidence suggesting that impaired LV GLS identifies inadequate tissue oxygenation (60) and predicts death in sepsis and septic shock patients whereas LVEF does not (61).

Conclusion

In conclusion, strain, and more specifically the global longitudinal strain is increasingly used to quantify the systolic function of the left ventricle. Beyond its ability to guide treatment, strain also carries a prognostic value both in surgical and non-surgical patients. As a result, anesthesiologists and intensivists are likely to be more and more confronted to reports including strain values and to measure strain themselves to refine the assessment of their patients. A good understating of the basic principles of strain measurements and of the clinical implications of abnormal strain is therefore of value to our specialty.

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