Myocardial strain review and its potential use for prediction of clinical outcome in patients with heart trauma

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Abstract

The left ventricular systolic function is significant in defining the management of cardiac conditions. Lately measurement of myocardial strain is studied as a tool which characterizes left ventricular function better and carries prognostic utility.

This paper aims at reviewing the myocardial strain concept and how it might be useful in evaluating the patient with polytrauma cardiac injury. The myocardial muscle undergoes specific rotation in different compartments during different stages of contraction-relaxation. Generally, the apex and the base of the heart move in opposite directions.

There are different parameters which can be measured to describe and quantify heart function such as stroke volume, ejection fraction, cardiac output and strain. Several studies report the normal value of myocardial strain to be around - 20. The movement of myocardial tissue during the heat cycle allows measurement of myocardial strain, which is an index of deformation. The change in value of strain correlates with different cardiac conditions. The strain can be measured using different diagnostic tools, each of which has its unique utilities. The myocardial strain value is dependent on multiple factors such as age, sex, location. Moreover, researchers often claim integrability to be a major barrier to introduction of strain measurements to protocols. However, there are measures taken to standardize the procedure. Patients who have polytrauma with cardiac involvement have a range of structural changes, which makes possible the measurement of strain. It has a potential to predict future long-term complications.

Keywords: myocardial strain, myocardial deformation, echocardiography, cardiovascular magnetic resonance.

1. Introduction

The evaluation of systolic function of the left ventricle is a crucial characteristic which defines the clinical management and patient prognosis [1,2]. The functional defect of the heart muscle may present in changes of blood filling or ejection, therefore causing different clinical presentations of the condition. Currently, in clinical settings the assessment of left ventricular (LV) systolic function is done by measurement of ejection fraction (EF). Moreover, one of the classifications of heart failure is based on left ventricular ejection fraction (LVEF). Lately the LVEF is criticized more as it does not describe cardiac action and does not provide the difference between the healthy patients and patients with preserved ejection fraction (HFpEF). Assessment of myocardial deformation (strain) is a promising tool aiding improved characterization of patients [3]. The technical progress and different instrumental investigations allow evaluation of the myocardial function at whole and at specific regions in different cardiac conditions [1].

The cardiac injury incidence in patients with polytrauma is poorly studied as there is a range of clinical presentations depending on structure damage and absence of diagnostic criteria [4]. It might manifest severely in case of myocardial rupture, valvular damage, arrhythmias or might have delayed presentation. However, it was established that presence of cardiac damage itself is a predictor of poor outcome in patients. The pathophysiology of polytrauma is a complex net of different reactions of the body in response to injury. The cardiac injury taking place during and after the trauma causes the accordingly changes in myocardium, which in turn might affect the strain value. Currently, there are no studies analyzing the myocardial strain change in polytrauma patients. However, as change in strain in other cardiological conditions carries prognostic utility, it might be assumed that the measurement of myocardial strain has a potential of prognostic evaluation in posttraumatic patients too.

This review is focused on revision of myocardial deformation assessment tools, the correlation to clinical presentation and how it can be potentially used for patients with cardiac trauma.

2. Methodology

To prepare this review article, a comprehensive literature search was conducted to explore the topic of myocardial strain and myocardial deformation assessment using echocardiography and cardiovascular magnetic resonance (CMR). The search included publications indexed in PubMed, Google Scholar, and Elibrary databases. Combinations of keywords such as "myocardial strain", "myocardial deformation", "echocardiography", and "cardiovascular magnetic resonance" were used.

Inclusion criteria were: original research articles, review articles, meta-analyses, and clinical guideline recommendations published in English between 2014 and 2024.

Exclusion criteria were: case reports, non-original articles, articles without access to full texts, and duplicate publications.

As a result, 26 full-text articles were identified and reviewed. After applying the inclusion and exclusion criteria, 24 articles were selected for in-depth analysis and synthesis in this review.

3. Cardiac cycle and mechanics

The cardiac cycle is alternation of systole and diastole of different heart compartments, which allows blood pumping. The systole consists of isovolumic contraction, followed by ejection. The diastole consists of isovolumic relaxation, followed by diastolic filling phase. The cardiac cycle is often described using the pressure-volume diagram, which represents the change in these parameters during the cycle and stroke work. Basically, filling with blood stretches the tissue, which in turn elevates the pressure. The cardiac muscle performance depends on structural parameters such as

functionality of valves, size and shape of the ventricles, the contraction force itself [5].

The mechanics of the heart are different in distinct regions and during the cardiac cycle. Generally, the apex and base of the heart move in opposite directions when there is change in blood volume and in the same direction in isovolumic period. Sengupta et al reviewed this movement, which is also called twist or torsion, and suggested referring to it as rotation [6]. During the rotation, there is a circumferential movement of the left ventricle around the longitudinal axis [6]. So, during the systole there is a counterclockwise apical rotation and small clockwise rotation. During the diastole the clockwise apical rotation base counterclockwise rotation. However, during isovolumic contraction, there is a basal and apical counterclockwise rotation and during isovolumic relaxation, there is basal and apical clockwise rotation [1].

The quantification of the heart function can be done by measuring the several parameters of contraction such as stroke volume (SV), ejection fraction (EF), cardiac output (CO). SV is the amount of blood pumped by the heart per 1 beat. CO is a volume of blood, which the heart pumps within 1 minute. EF is a ratio of SV to end diastolic volume represented in percentages [5]. Measurement of EF currently faces criticism as it is volumetric in nature, has issues with reproducibility, depends largely on the experience of the person analyzing it and does not reflect regional function of the LV [7]. Lately, myocardial strain became one more significant index of cardiac function.

These parameters can be measured using a range of diagnostic tools including echocardiography, computed tomography (CT), magnetic resonance imaging (MRI), Multi Gated Acquisition Scan (MUGA). However, it is important to mention that the value of myocardial strain is different not only during the heart cycle but also at different heart 'layers'. It has been supposed for a long time that LV muscle is homogeneous, however actually its fibers do not contract and relax at the same time [8]. So, Marwick et al conducted measurement of myocardial strain in a healthy population using ST-echocardiography (Speckle Tracking) and reported normal value around -18% [9]. Another research group which investigated normal value of strain using echocardiography represented the reference from -24 to -16 [10]. Later, Taylor et al measured the normal value of myocardial strain in healthy population by Feature Tracking Cardiovascular Magnetic Resonance (FT-CMR) and presented that longitudinal one in endocardium is around -21%, in epicardium around -17% during the systole [2]. The systematic review investigating the myocardial strain normal value measured by FT-MRI reports the pooled mean value of -20% [11]. As systolic function defines the prognosis, the change in strain also carries prognostic utilities. One of the suggestions is considering Global longitudinal strain (GLS) <12% to correlate with severe dysfunction and worse prognosis [12]. Therefore, the average normal value can be approximated from these studies.

4. Myocardial deformation

Myocardial deformation is the change in the size and shape of the myocardium during the cardiac cycle. It can be longitudinal, circumferential and radial, depending on the stage of the cardiac cycle. Myocardial Strain in an index of ventricular myocardial deformation. So, for example during systole, there is negative longitudinal strain as muscle fibers shorten [13]. This explains the negative value of the normal value of myocardial strain. Circumferential strain measures the shortening of the myocardial wall due to the inward movement of the endocardial circumference. This shortening would still happen even in the absence of circumferential fibers. In practice, it measures the reduction in myocardial diameter as the wall thickens. This thickening is caused by the shortening of the wall, because the heart muscle is incompressible. Radial strain, aligned with the direction of the ultrasound beam, essentially represents

transmural strain. It is the cumulative result of both subepicardial and subendocardial radial deformations [13].

Global longitudinal strain is the most significant parameter for measuring the systolic LV function [12]. The mechanics of longitudinal left ventricular deformation is affected by myocardial disease the most. In the early stages of disease, circumferential strain and rotation may remain normal because the midmyocardial and epicardial function compensates to maintain LV systolic performance. As the disease progresses or following transmural damage, simultaneous dysfunction in the midmyocardial and subepicardial regions will impair LV movement mechanics, leading to a decrease in left ventricular ejection fraction (LVEF) [13]. Strain accurately describes contraction/relaxation because it measures myocardial

deformation directly, global right and left ventricular function, and regional wall deformation.

Myocardial deformation measurement has been studied as a risk prediction and evaluation for different conditions, including MI, ischemia, diabetic cardiomyopathy and myocarditis. For example, Haugaa et al investigated myocardial strain in post-myocardial infarction patients and outlined it to be the marker of arrhythmias in patients with preserved ventricular functions [14]. Another research group by Thavendiranathan et al conducted systematic review for measurement of strain by STE for detection of early chemotherapy cardiotoxicity and confirmed its predictive utilities [15].

In regard to heart failure, a range of studies conducting measurements at different stages were done. The review of the studies confirmed that myocardial strain is prognostic to outcomes and complications of heart failure, which might be a key factor in management of further guidance. The author also highlighted that one of the major barriers to introducing GLS measurement to guidelines are intervendor variability and the need for experienced specialists [16]. Despite this, the correlation of myocardial strain measurement with assessment of different cardiovascular conditions is studied extensively.

One of the largest studies investigating prognostic utility of GLS for all-cause mortality in HFrEF patients represented superior prediction in comparison to other echocardiography parameters, which goes along with the results reported by other studies. However, authors report limited prognostic value in women and patients presenting with atrial fibrillation [17]. In comparison, Trobs et al reported men and Afib with other factors such as obesity, diabetes, history of MI to be related to higher GLS in patients with heart failure [18]. They explain the sex-specific difference by physiologic differences such as lower cardiac muscle mass, effect of estrogen and existing comorbidities [18]. In regard to patients with HFpEF, Brann et al report GLS to be a predictor of future worsening [19]. Similarly, Haji et al. represent GLS to be prognostic of all-cause mortality in patients with coronary artery disease [20]. The functionality and predictive utility of the strain to its full extent is still being investigated.

5. Myocardial deformation assessment

The assessment of the myocardial strain is done using different diagnostic tools. At first, the strain measurements were done using Tissue Doppler imaging, however the limitations of this technique led to search and discovery of the new technique such as speckle tracking echocardiography (2D and 3D). As a result, other diagnostic tools were also analyzed for the possibility of strain measurements, and it was established that cardiac magnetic resonance is quite appropriate and informative. All of them have their own advantages and disadvantages. For example, echocardiographic measurements are more available, quick, portable, while magnetic resonance can be considered to be more precise. Moreover, there are different methods within the diagnostic tool, so by echocardiography it is possible to measure myocardial strain by Tissue Doppler method or by tracking speckles.

Echocardiographic methods:

Tissue Doppler imaging (TDI): Measurement of TDI strain requires an optimized 2D image and rapid frame rates to resolve regional velocities and calculate strain rate [21]. Proper alignment of the Doppler beam with the myocardial region of interest is crucial, as an angle of incidence exceeding 20 degrees will lead to inaccurate measurements. Strain is calculated from each sample volume and presented in a graphical format.

Later, more advanced techniques using speckle tracking allows measurement of different strains and makes measurement in a more precise manner [22]. Basically, speckles are a unique set of gray patterns on a digital image of the myocardium, which can be tracked during the cardiac cycle. It also does not require proper beam alignment as it does not depend on angle.

2D-STE: two-dimensional speckle tracking echocardiography: STE can increase the sensitivity of stress echocardiography and provide information on the location, extent, and severity of myocardial ischemia in combination with visual wall motion during Dobutamine stress echocardiography [23]. However, there are different methods and approaches to conduct 2D-STE, therefore the normal values would differ [13].

3D-STE: three-dimensional speckle tracking echocardiography is similar to 2D-STE, but the measurement in three directions is simultaneous. It also provides more details in terms of overall configuration, which in turn makes it more difficult to analyze. However, the image is more physiological and the level of automatization is higher [24].

Distinct structural changes in myocardium as a deformation cause change in strain value. For example, ischemic wall motion is referred to as passive motion, which in turn causes widening of apical septal compartments and reduced compression in the middle. There is also change in the strain value in distinct myocardial compartments in cardiomyopathies depending on the etiology of pathology. Moreover, even valvular heart disease causes a decrease in strain value [22]. Therefore, local and global myocardial strain measurements can be done to estimate the local effect in case of ischemia and overall effect on LV systolic function.

Cardiovascular magnetic resonance

CMR feature tracking: Feature tracking has been developed to monitor myocardial motions, including displacement and velocity, and to calculate cardiac deformation parameters such as strain and strain rate in CMR. It follows the movement of tissue between the epicardial and endocardial borders throughout the cardiac cycle using optical flow methods. In heart-failure patients, both left atrium longitudinal strain and strain rate were lower than in healthy subjects. Scarred segments showed lower contractile function, radial displacement, radial velocity, radial strain and longitudinal strain values compared with non-scar segments. Radial strain was shown to be the best parameter to discriminate between scarred segments and non-scarred ones [23].

CMR tissue tagging: The initial step typically involves identifying key cardiac events: end-diastole

(ED) and end-systole (ES). The next step is to define a region of interest that includes the myocardial wall, which is done by semi-automatically contouring the endocardial and epicardial borders either at ED, ES, or both. This segmentation step is crucial as it determines the set of points that will be tracked, introducing variability based on the user and the segmentation algorithm used. Finally, the region of interest is tracked throughout the cardiac cycle, strain curves are computed, and possibly post-processed. The reported measurements can include either the end-systolic strain or peak systolic strain.

Tissue tagging, feature tracking strategies can be applied in echocardiography as well as in magnetic resonance imaging. Amzulescu et al described the difference of the strategy in different imaging techniques and highlighted their features [7].

The calculation of strain and strain rate always depends on image quality; this can have an effect on the reliability and reproducibility of deformation parameters derived from echocardiographic images. Echocardiography is limited by acquisition angle and operator dependence. CMR is increasingly the method of choice because of its wide field-of-view, better image quality and reproducibility [23]. However, as there is no gold standard, the medical centers use the tool upon the availability of diagnostic methods. The table 1 below summarizes the myocardial deformation techniques in terms of their advantages and limitations.

Table 1 - Advantages and Limitations of strain measurement techniques

Method of assessment	Advantage	Limitations
TDE	Fast, cheap and portable	Dependence on acquisition angle and operating person
2D-STE	Tracking during the cardiac cycle, efficient, reliable and validated to MRI tagging	No unique measurement method (no standardization, difference depending on the operating person), time consuming
3D-STE	Measurement of strain in all direction at the same time, More physiological and faster analysis and better automatization	Image processing is more complicated. Depends on image quality. Vulnerable to artifacts
CMR	Better image quality and better reproducibility	Availability Not portable More expensive

Imaging myocardial deformation provides additional functional information compared to the traditional EF measurement. Echocardiography is currently the preferred method for clinical strain assessment, with GLS being the most reliable and reproducible parameter [25]. Other parameters might include Left Atrium reservoir strain and Global Work Index [26]. As GLS is dependent on multiple factors, numerous studies were done to establish association between its value and factor change. One of the largest studies was by Skaarup et al, who investigated age and sex specific normal values of GLS by conducting measurements among healthy populations. They report that normal GLS values for males are lower than for females. Moreover, for females the value tends to decrease with age, while for males this value is slightly elevated [27]. The effect of other factors such as existing medical conditions is still being investigated.

There are also other factors that influence the strain value such as image quality, choice of segmentation, choice of image clips, landmark and segmental contouring, choice of region to investigate [28]. Researchers commonly refer to intervendor variability as to a major barrier to clinical implementation. However, the European Association of Cardiovascular Imaging (EACVI) and American Society of Echocardiography (ASE) with Industry initiated the Task Force to standardize the imaging from physical and mathematical perspectives [29]. This would allow reproducing the measurements of the strain now, then during the follow up for measurement using the same strategy so that any radiologist could reproduce the examination.

6. Myocardial strain in polytrauma patients with heart involvement

As it was mentioned, the post-traumatic cardiac dysfunction has various presentations, depending on structures involved, such as dysrhythmias or changes in motion of cardiac muscle. Moreover, there is not only acute presentation, but also delayed one, such as in patients with systemic reaction to polytrauma or in those with multiple organ damage. Currently, there are no reported studies conducting measurements of myocardial strain in patients with polytrauma. First, current polytrauma guidelines and protocols recommend measurement of troponin level and ECG only as screening for heart injury. Then if required, echocardiogram and CT might be done for further investigations [30]. Secondly, due to the variety of the clinical presentation of heart injury, which might be even asymptomatic, there is no standardized guideline on how to diagnose patients with polytrauma [4].

One of the studies investigated metrics of baseball games to improve the safety measures on protection of children from trauma. As commotio cordis caused by hit of the ball to chest can lead to fatal cases, it needed more investigations on biomechanics of trauma. The authors evaluated the importance of factors such as ball stiffness, location of the hit and response of the body such as different forces at the moment of impact, rib deformation, LV strain by using a computational model. It is reported that the most significant factor affecting the LV strain by computational model was the velocity, so the most damaging hit was by the fastest ball, causing the highest strain. The rib deformation,

ball stiffness and reaction force did not affect the value of the LV strain. Authors highlight that the major limitation is that the computational model does not consider fluid within the heart being blood despite applying pressure imitating blood pressure [31]. Although this study is based on computer simulation investigating monotrauma, it shows that the different settings of the polytrauma can be simulated and studied too with subsequent studies in real life. As the hit by the ball affects the

LV strain, then any blunt chest traumas would have their own substantial effect.

Moreover, there are several other facts indicating that strain measurement would be informative in patients with polytrauma. For example, after the trauma the common structural injuries include intramural hematoma, papillary muscle rupture, septal injuries presenting with murmur and arrhythmias [4]. In case of blunt cardiac injury, the right ventricle is the most common region affected [32]. As these injuries affect the myocardial tissue itself, the architecture of layers becomes disrupted and there is an expected change in a strain value. Moreover, as there is prognostic correlation of change in strain with complications like arrhythmias in post-MI patients, these long-term complications might also be assessed with risk prediction. Next, the cardiac injury presents in different severity from asymptomatic to fatal cases. It is expected that patients with more severe clinical presentation would develop long-term cardiac

consequences. Therefore, it would be suggested to create the grading scale for heart involvement according to which patient evaluation would be conducted. It is also important to mention that the effect of cardiac injury on healthy patients would be different than on patients with existing cardiovascular disease. So, setting a computational model would allow checking theoretical differences in response to trauma. However, no computer simulation can mimic real life settings with all the details. Moreover, the measurements of LV myocardial strain on a computer model is nothing like by echocardiogram or magnetic resonance.

Today myocardial strain measurement is done on a variety of patients with a range of conditions. Some of them do not have a standard to establish diagnosis as it is in case of traumatic heart injury. One of such conditions is myocarditis, which is difficult to diagnose due to variability of clinical presentation. The authors of the study reported the results of GLS measurements using CMR in patients suspected with myocarditis. So, these measurements had improved utility as a prognostic technique. Farzaneh-Far and Romano suggest that if despite subendocardial located longitudinal fibers might be more prone to damage by pathologies, CMR recorded fibrotic and injury changes in myocardium in patients with myocarditis, then there

is very different connection between myocardial fibers, which needs to be investigated further [33]. Moreover, other study reports that myocardial strain reflects fibrosis by decreased strain value and cardiac remodeling. The authors suggest that fibrosis might play a role in rearrangement of layers between the sheets of cardiac muscle [34]. So, the myocardial strain value changes when there is a change in the architecture of the heart, therefore the impact or damage affecting fiber communication between each other results in a difference from normal value. As it was mentioned above, trauma causes structural changes in case of direct or blunt hit and the changes are expected when there is a later cardiac response to trauma. As future directions it is suggested to conduct the computational model studies to improve the study design and observe which changes are expected. Then, implementation to real life investigation with measurement of myocardial strain in different groups of patients with polytrauma can be done. Moreover, the effect of different mechanisms of trauma (blunt, penetrating, burn and others) should be compared to evaluate whether the long-term outcomes are similar. Next, it would be possible to investigate the change in myocardial strain in progress after definite periods and its response to treatment.

7. Conclusions

The biomechanics and cycle of the heart are complex processes that require a deep understanding of its anatomical structure and overall function. The characterization of LV systolic function can be done by measurement of the LV strain. The myocardial strain measurement can be done using different diagnostic tools. It does not only evaluate LV systolic function, but there are also correlations with change of strain value with long term complications.

Therefore, myocardial strain measurements are a valuable tool with prognostic utility. Currently, there are no standardized guidelines for strain measurement and there is an intervenor variability with the need for a skilled specialist to conduct the measurements. However, there are already measures initiated to standardize the procedure and create the guideline. There is a potential to use the strain measurements for evaluation of patients with polytrauma heart injury and a range of research areas in this unexplored topic.

Conflicts of Interest: The authors declare no conflicts of interest.

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Миокардтың деформациясына шолу және оның жүрек жарақаты бар науқастардағы клиникалық нәтижені болжаудағы әлеуеті

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Түйіндеме

Жүректің сол жақ қарыншасының систолалық функциясы жүрек ауруларын басқаруда маңызды рөл атқарады. Соңғы уақытта миокардтық деформацияны өлшеу – сол жақ қарыншаның қызметін неғұрлым дәл сипаттайтын және болжамдық маңызы бар құрал ретінде зерттеліп жүр.

Бұл мақала миокардтық деформация ұғымына шолу жасап, оның көп жарақат алған және жүрекке зақым келген науқастарды бағалаудағы әлеуетін қарастырады.

Миокард бұлшықеті жиырылу мен босаңсу кезеңдерінде әртүрлі бөліктерде белгілі бір бұрылысқа ұшырайды. Жалпы алғанда, жүректің ұшы мен негізі қарама-қарсы бағытта қозғалады. Жүрек қызметін сипаттап, сандық түрде бағалау үшін әртүрлі параметрлер өлшенеді: соққы көлемі (SV), шығарылу фракциясы (EF), жүрек шығару көлемі (CO), деформация. Бірқатар зерттеулер бойынша, миокардтық деформацияның қалыпты мәні шамамен -20-ны құрайды. Жүрек циклindeгі миокард тінінің қозғалысы оның деформациясын өлшеуге мүмкіндік береді. Бұл деформация көрсеткіші – жүрек бұлшықетінің пішінінің өзгеру дәрежесін сипаттайтын индекс. Бұл көрсеткіштің өзгеруі жүрек ауруларының әртүрлі түрлерімен байланысқа ие. Деформацияны әртүрлі диагностикалық құралдармен өлшеуге болады, олардың әрқайсысының өзіндік артықшылықтары бар. Миокардтық деформация көрсеткіші жасқа, жынысқа және анатомиялық аймаққа

байланысты әртүрлі болуы мүмкін. Сонымен қатар, зерттеушілер бұл әдісті клиникалық хаттамаларға енгізудегі басты кедергілердің бірі ретінде оның интеграциялану қиындығын атап өтеді. Алайда бұл процедураны стандарттауға бағытталған шаралар қабылдануда. Жүрекке зақым келген көп жарақат алған науқастарда құрылымдық өзгерістердің кең ауқымы байқалады, бұл деформацияны өлшеуге мүмкіндік береді. Бұл көрсеткіш ұзақ мерзімді асқынуларды болжауға әлеуетті құрал бола алады.

Түйін сөздер: жүрек бұлшықетіндегі ішкі кернеуі, миокардтың деформациясы, эхокардиография, жүректің магниттік-резонанстық томографиясы.

Обзор внутримиокардиального напряжения и его потенциальное применение для прогнозирования клинических исходов у пациентов с травмой сердца

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Резюме

Систолическая функция левого желудочка играет важную роль в определении тактики ведения сердечно-сосудистых заболеваний. В последнее время измерение деформации миокарда изучается как инструмент, который лучше характеризует функцию левого желудочка и обладает прогностической ценностью. Цель данной статьи — рассмотреть понятие миокардной деформации и ее возможную полезность в оценке пациентов с политравмой и сердечным повреждением. Миокард подвергается специфическому вращению в различных отделах в разные фазы сокращения и расслабления. Как правило, верхушка и основание сердца движутся в противоположных направлениях. Существует несколько параметров, которые можно измерить для описания и количественной оценки функции сердца: ударный объем (SV), фракция выброса (EF), сердечный выброс (CO), деформация. Ряд исследований указывает, что нормальное значение миокардной деформации составляет около -20. Движение миокардиальной ткани в течение сердечного цикла позволяет измерить деформацию миокарда, которая представляет собой индекс изменения формы ткани. Изменение значения деформации коррелирует с различными кардиологическими состояниями. Деформация может измеряться с использованием различных диагностических методов, каждый из которых имеет свои особенности и преимущества.

Значение миокардной деформации зависит от множества факторов, таких как возраст, пол, анатомическое расположение. Кроме того, исследователи часто указывают, что одной из основных преград к внедрению этого показателя в клинические протоколы является сложность интеграции. Тем не менее предпринимаются шаги по стандартизации этой процедуры. У пациентов с политравмой и вовлечением сердца наблюдаются различные структурные изменения, что делает возможным измерение деформации. Этот показатель обладает потенциалом для прогнозирования долгосрочных осложнений.

Ключевые слова: внутримиокардиальное напряжение, деформация миокарда, эхокардиография, магнитно-резонансная томография сердца.