Am J Transl Res 2025;17(4):2434-2444
www.ajtr.org /ISSN:1943-8141/AJTR0163006

Review Article

Advances in cardiac ultrasound speckle tracking technology for assessing left ventricular systolic function after adjuvant radiotherapy following breast-conserving surgery for breast cancer

Xin Yang[1], Wen-Jun Zhou[2], Guo-Ping Chen[1], Zong-Fen Zhang[1], Fang Yi[1]

[1]*Department of Ultrasound Medicine, Guang'an People's Hospital, Guang'an 638099, Sichuan, China;* [2]*Department of Urology, Guang'an People's Hospital, Guang'an 638099, Sichuan, China*

Received December 31, 2024; Accepted March 19, 2025; Epub April 15, 2025; Published April 30, 2025

Abstract: Breast-conserving surgery is a widely used treatment for breast cancer, often followed by adjuvant therapy such as adjuvant paclitaxel and trastuzumab (APT). While APT effectively reduces local recurrence and distant metastasis, it may also impair left ventricular systolic function. Speckle tracking imaging (STI) is a noninvasive ultrasound technique that quantitatively evaluates overall cardiac function. It allows for the assessment of myocardial fibrosis, myocardial injury, and overall systolic function, making it a valuable tool in clinical practice. This review discusses recent advances in the use of STI for evaluating left ventricular systolic function following APT in breast cancer patients.

Keywords: Breast cancer, breast-conserving surgery, adjuvant paclitaxel and trastu-zumab, speckle tracking imaging, ultrasound

Basic principles of speckle tracking imaging (STI)

STI is based on tracking natural acoustic markers within myocardial tissue to measure strain and strain rate, thereby assessing myocardial deformation and function [1]. By quantifying myocardial strain, strain rate, and tissue shear stress (TVS), STI can provide an objective assessment of myocardial fibrosis [2]. In the early stages of fibrosis, TVS values are low and show a strong correlation with strain rate. As fibrosis progresses, TVS values increase [3]. Thus, STI can quantify the extent of myocardial fibrosis by analyzing TVS values in myocardial tissue [4].

TVS is negatively correlated with overall left ventricular (LV) contractile function and positively correlated with local myocardial contractility. This means that as overall left ventricular function deteriorates, TVS values increase [5]. Left ventricular ejection fraction (LVEF) is widely regarded as a key measure of cardiac function, with lower values indicating reduced contractility [6]. STI assesses global left ventricular function by measuring myocardial stiffness and strain rate [2]. Higher myocardial fibrosis results in increased myocardial stiffness, which is reflected by STI measurements [7]. Since LVEF varies across different myocardial regions, STI allows for regional peak strain analysis to provide a more comprehensive assessment.

Following adjuvant paclitaxel and trastuzumab (APT), strain rate and strain energy can be measured to evaluate myocardial injury, with the ratio of peak strain rate serving as a key indicator [8]. A significant difference in strain rate before and after APT suggests impaired left ventricular systolic function (LVSF). Studies have shown that in individuals with left ventricular contractile dysfunction, TVS values are significantly elevated compared to healthy individuals [9]. Conversely, in individuals with normal LVSF, TVS values in commissural myocardial tissues are notably lower than in healthy individuals [10]. These findings suggest that STI

https://doi.org/10.62347/CDAI6188

provides a quantitative approach for assessing global LVSF following APT.

Strain rate

Residual viscosity refers to the ability of cardiomyocytes to deform under stress. When myocardial tissue is subjected to stress, not all of it is uniformly transmitted to cardiomyocytes, resulting in an uneven distribution of mechanical forces [11]. Therefore, myocardial strain capacity exhibits anisotropic behavior. A higher strain rate value indicates a greater ability of the myocardial structure to deform under stress [12]. Thus, strain rate can quantitatively reflect the extent of myocardial injury.

In general, the distribution of strain rate within myocardial tissue follows a specific pattern: strain rate is higher near the central axis of the myocardium and lower in peripheral regions [13]. However, as extracellular matrix accumulation increases, myocardial fibrosis worsens, and the strain rate difference between fibrotic and normal myocardial tissue gradually diminishes [14].

Due to alterations in the internal environment of breast cancer patients and the effects of chemotherapy drugs administered before and after APT, cardiac function in these patients is significantly impaired. Early postoperative evaluation is therefore crucial [15]. Studies have shown that left ventricular systolic function declines progressively over time following APT [16]. STI provides a quantitative assessment of myocardial contractility impairment:

(1) In the early phase of LV dysfunction (0-1 week post-APT), STI values are positively correlated with LVEF.

(2) In the mid-stage of dysfunction (1-4 weeks post-APT), STI values become negatively correlated with LVEF.

(3) In the late stage of dysfunction (4-12 weeks post-APT), STI values again show a positive correlation with LVEF [17].

Additionally, studies have reported a gradual decline in myocardial strain rate at different time points after APT [18]. These findings suggest that STI enables the quantitative evaluation of myocardial injury across different postoperative phases.

Strain energy

Strain energy represents the deformation ability of myocardial elastic fibers, reflecting both cardiomyocyte energy states and myocardial stiffness. It is an essential indicator of cardiac systolic and diastolic function [19]. Under normal physiologic conditions, higher elastic fiber content corresponds to greater strain energy [20]. Following APT, myocardial elastic fiber content progressively declines, leading to a reduction in strain energy. Once elastic fiber content falls below a critical threshold, pathological changes, including myocardial fibrosis and systolic dysfunction, become evident [21].

Based on this analysis, myocardial elastic fiber content remains relatively high in the early postoperative period. However, with time, elastic fiber content decreases, eventually leading to fibrosis and pathological changes. As fibrosis progresses, elastic fiber content continues to decline. Therefore, myocardial fibrosis can be quantitatively assessed by monitoring changes in elastic fiber content within the early (≤1 week) and intermediate (≤1 month) postoperative periods. Strain energy measured by STI correlates with strain rate, demonstrating high sensitivity and specificity in detecting myocardial impairment.

Peak strain

Peak strain refers to changes in LVEF across different myocardial orientations, particularly from the LV apex toward the base and other myocardial segments. It is considered an essential index of LVSF [22]. Peak strain primarily reflects myocardial fibrosis, which is linked to collagen fiber proliferation after APT, leading to progressive myocardial stiffening and systolic dysfunction [23]. Thus, peak strain serves as a valuable marker for evaluating myocardial fibrosis and overall left ventricular contractility.

However, peak strain values vary by location. Studies indicate that at the LV apex, peak strain is positively correlated with LVEF, whereas at the right ventricular apex, peak strain is negatively correlated with LVEF at the right ventricular apex [24]. Peak strain provides a quantitative estimate of global LV systolic function and is generally positively correlated with LVEF [25]. Therefore, evaluating peak strain values across different myocardial regions can help determine the extent of myocardial fibrosis and assess global LVSF following APT.

Overall LVSF

LVEF is classified into different impairment levels [26]: (1) Mild impairment: LVEF 40%-49%; (2) Moderate impairment: LVEF 30%-39%; (3) Severe impairment: LVEF <30%; (4) Under normal conditions, LVEF 50%-70% indicates good overall ventricular function. However, LVEF <50% suggests severe impairment of LVSF.

Following APT, overall LVSF declines, with the severity depending on patient age, disease duration, tumor stage, and whether mitral valve replacement was performed [27]. Compared to breast cancer patients without recurrence, those who experienced relapse within two years post-surgery exhibited significantly lower LVEF, and those who relapsed within three years showed further reduction in LVEF [28]. These findings suggest that early detection of LVEF post-APT is crucial for assessing overall LVSF.

Value of STI in assessing LV contractility

LV dysfunction after APT can be attributed to multiple factors, including myocardial fibrosis, myocardial injury, and cardiomyocyte loss [29]. The decline in LVSF contributes to increased cardiac load and reduced cardiac output after APT [30].

The Left ventricular end-diastolic volume (LVEDV) reflects the left ventricle's ability to maintain diastolic function, and its reduction indicates impaired diastolic capacity [31]. A higher cumulative APT dose is associated with a greater decrease in LVEDV. Therefore, a comprehensive evaluation is required to assess the decline in LV contractility after APT.

Research has shown that myocardial fibrosis is a key contributor to LVEDV reduction post-APT. The severity of myocardial fibrosis is directly correlated with the extent of LVEDV decline [32]. Since myocardial fibrosis is pronounced after APT, patients experience a marked reduction in contractility, making STI an effective tool for assessing left ventricular function.

Studies have also reported that following APT, overall LV contractility declines, while myocardial fibrosis increases [33]. Moreover, STI has prognostic value, with research indicating that its application post-APT can reduce hospital stays by 20% [34]. However, no study has definitively proven that STI is superior to traditional echocardiography in predicting postoperative LVSF changes. Therefore, a comprehensive evaluation combining multiple diagnostic modalities is necessary to accurately assess patient prognosis.

Routine echocardiography

Conventional echocardiography, based on two-dimensional imaging, evaluates long-term LV remodeling by measuring LVEDV and other relevant parameters, such as LVEF [35]. Cardiomyocyte loss after APT contributes to changes in LVEDV. When cardiomyocyte loss exceeds 30%, it is considered indicative of myocardial injury [36]. Thus, echocardiography has limitations in assessing post-APT LV dysfunction.

Studies have shown that pre-APT, the correlation between overall LVSF and LVEDV is weak ($r=-0.29$, $P<0.001$) [37]. However, post-APT, the correlation between overall LV contractile function and LVEDV is not well established. Therefore, evaluating left ventricular contractile function prior to APT remains challenging. While conventional echocardiography provides some insight into LVSF, it does not accurately reflect overall myocardial contractility changes post-APT.

LV strain measurement

Compared to conventional echocardiography, STI provides a more accurate assessment of LV contractile function. Studies have shown that STI is more sensitive in evaluating global LV contractility than traditional echocardiography [38]. Due to morphologic and fiber alterations in the myocardium following APT, conventional strain measures may not reliably assess LVSF. However, STI can directly reflect myocardial damage through strain measurements, allowing for a more precise evaluation of LVSF [39].

Additionally, STI can assess LV contractility in patients with preoperative structural changes or dysfunction based on strain measurements [2]. Therefore, integrating STI with other diagnostic methods is essential for a comprehensive postoperative evaluation in breast cancer patients undergoing APT.

Two-dimensional STI (2D-STI)

STI is a noninvasive echocardiographic technique that quantitatively evaluates myocardial strain and strain rate, providing real-time continuous imaging across multiple planes. It is widely used due to its noninvasiveness, ease of application, and high reproducibility [40].

Studies suggest that compared to conventional two-dimensional STI, advanced STI methods provide more accurate assessments of myocardial deformation. However, these methods may require high frame-rate imaging [41]. Therefore, conventional echocardiography should be supplemented with STI for a more comprehensive evaluation of LV dysfunction in APT patients.

Research has shown that after APT, conventional echocardiography may not accurately assess myocardial tension and stiffness, whereas STI can more precisely evaluate these measuements [42]. However, there are limited studies on the application of STI in assessing LVSF post-APT, with most research being cross-sectional. The role of STI in evaluating cardiac function after adjuvant therapy following breast-conserving surgery remains controversial. Further studies are needed to explore its clinical value.

Strain rate imaging technology

Strain rate imaging is a noninvasive echocardiographic technique based on tissue elasticity and is applicable in various organs, including the heart, brain, liver, and lungs [43, 44]. Currently, there are two primary principles for measuring strain rate:

Elasticity-based measurement: Studies have shown that when the compression strain rate exceeds the elasticity rate of myocardial tissue, the reduction in LVEDV is significantly greater than the decline in elasticity rate [45].

Strain-based measurement: Barber et al. [46] found that when myocardial tissue undergoes tensile stress, myocardial contraction strain rate changes significantly, leading to a greater reduction in LVEDV than in elastic rate.

Research has also indicated a significant negative correlation between LVEDV and LVEF in breast cancer patients receiving APT [9]. Post-APT, myocardial damage increases, while LVEDV decreases. Therefore, LVEDV and LVEF are closely associated with the extent of apoptosis-induced myocardial damage, which can be quantitatively assessed using strain rate imaging.

Effect of APT on left ventricle

APT is a systemic treatment aimed at reducing local relapse and metastasis while improving the quality of life of breast cancer patients. However, APT can also lead to myocardial damage, reduced LVSF, and other cardiac adverse effects. Recent studies have shown that APT induces myocardial fibrosis and fibrosis-related myocardial injury, which can impact patient prognosis [47].

The National Comprehensive Cancer Network (NCCN) guidelines recommend LVEF as the gold standard for assessing cardiac function. LVEF is commonly evaluated using two parameters: the left ventricular end-diastolic volume index (LVEDVI) and the left ventricular end-systolic volume index (LVESVI) [48]. However, these parameters do not always provide an accurate assessment of overall LV function, particularly in APT-treated patients. Specifically, they may not precisely reflect LVEF changes or the extent of myocardial injury. Therefore, there is a need for advanced techniques that can accurately evaluate LVSF before and after APT, with STI emerging as a promising tool for this purpose.

Several studies have explored the relationship between myocardial fibrosis and LVEF in APT-treated patients. Research has shown that myocardial fibrosis progressively worsens in breast cancer patients receiving APT, correlating with a decline in LVEF [49]. One study found that as LVEDVI increased, both LVEDV and LVESVI also increased, suggesting a possible link between decreased LVEF, myocardial fibrosis, and impaired LVSF during APT therapy. However, another study comparing pre- and post-APT LVEF in breast cancer patients reported a decline in LVEF following APT, though the difference was not statistically significant [50].

Some researchers argue that there is no clear correlation between APT-induced myocardial fibrosis, cardiomyocyte damage, and the severity of LV systolic dysfunction [51]. Therefore, when evaluating LVEF before initiating APT, it is essential to consider the degree of myocardial fibrosis and cardiomyocyte damage. It remains uncertain whether these pre-existing conditions worsen after APT or if they are directly associated with a poor prognosis.

Clinical application of STI

STI has been widely adopted in clinical practice and has demonstrated value in evaluating LV function following APT [52]. Studies have shown that STI assessments conducted over six months postoperatively can better predict the risk of postoperative decline in LVSF [34]. Additionally, STI can predict a reduction in LVEDVI, although its predictive value for long-term prognosis remains statistically insignificant [53]. These findings highlight some limitations in using STI for assessing LVSF after breast cancer surgery.

Nevertheless, some researchers believe that STI provides a more accurate representation of overall LV function and can reflect long-term postoperative changes in LVSF [32]. Extensive studies have demonstrated that incorporating STI into routine echocardiographic testing after breast-conserving surgery allows for a more precise evaluation of changes in LVSF [19].

STI also serves as an effective diagnostic tool for assessing LV diastolic dysfunction in patients undergoing breast-conserving surgery for early-stage breast cancer [19]. In patients with decreased LVSF, STI has demonstrated strong clinical predictive value.

Early prediction of LVSF decline after breast-conserving surgery

With advancements in ultrasound technology, STI has become a more precise tool for assessing LV function, particularly in early-stage patients. Multiple factors contribute to the decline in LVSF following breast-conserving surgery, necessitating a thorough understanding of these causes for effective prevention. Studies have demonstrated that the risk of postoperative LV systolic dysfunction is associated with patient age, tumor size, histologic grade, and differentiation degree. Specifically, older age, larger tumor size, higher histologic grade, and lower differentiation are linked to a greater risk of postoperative LV function decline [54].

Moreover, impaired LVSF may contribute to tumor recurrence and reduced survival following breast-conserving surgery [55]. Studies have shown that a decline in LV contractility after surgery correlates with reduced 5-year survival, particularly in cases where tumors exhibit rapid growth [56]. Therefore, early detection of LVSF decline after breast-conserving surgery may help assess the risk of tumor recurrence and postoperative survival, allowing for timely intervention to mitigate surgical risk.

Currently, prospective studies investigating the decline in LVSF after breast-conserving surgery are limited. However, early assessment and intervention are critical in high-risk patients. Conventional echocardiography can be used to monitor LVSF through key indicators such as LV end-diastolic volume (LVEDV), LV end-systolic diameter (LVESD), and LV end-diastolic volume index (LVEDVI). These measauements help differentiate between localized LV dysfunction and a global decline in LVSF. It is important to note that global LV systolic dysfunction is not an inevitable consequence of breast-conserving surgery and should be considered only when routine echocardiography detects a significant decline.

Assessment of postoperative long term LV function

Studies have shown that LV dysfunction following APT is closely associated with the onset and progression of cardiac insufficiency. The diagnostic sensitivity and specificity of the LV global performance index (PI) measured by conventional echocardiography range from 86.4% to 95.5% and from 97.5 to 99.3%, respectively [31]. While these values indicate high accuracy, they do not show statistical significance in diagnosing myocardial performance index. Therefore, conventional echocardiographic measurements alone may not be sufficient for accurately assessing long-term LV function after surgery.

STI provides a more precise assessment of global LV function. In particular, STI enables the quantitative evaluation of global LV function, making it valuable for long-term postoperative monitoring. Extensive studies have demonstrated that STI better reflects long-term LV function changes postoperatively. Research suggests that STI assessments conducted three months after surgery can predict the reduction of LV performance in patients receiving adjuvant radiotherapy [57]. Additionally, STI has been found to be more sensitive than conventional echocardiography in detecting alterations in global LV performance following adjuvant radiotherapy [58].

Following adjuvant radiotherapy, the global LV performance decreases, and STI provides a more accurate assessment of this decline. Furthermore, studies have indicated that STI offers higher sensitivity and specificity than conventional echocardiography in measuring LVEF [59]. After adjuvant radiotherapy, LVEF declines, whereas STI provides a more consistent and reliable measurement of LVSF. Following adjuvant radiotherapy, the global LV performance decreases, and STI provides a more accurate assessment of this decline. Furthermore, studies have indicated that STI offers higher sensitivity and specificity than conventional echocardiography in measuring LVEF [59]. After adjuvant radiotherapy, LVEF declines, whereas STI provides a more consistent and reliable measurement of LVSF.

Guiding antitumor therapy after breast-conserving surgery

The primary goal of adjuvant radiotherapy and chemotherapy following breast-conserving surgery is to reduce tumor recurrence and improve patient survival rates [60]. However, there is currently no standardized protocol for antitumor therapy in breast cancer patients post-surgery. Studies have consistently shown that patients undergoing radiotherapy and chemotherapy after breast-conserving surgery experience a greater decline in LVSF [61]. Furthermore, patients with poorer LVSF at the start of chemotherapy tend to have worse prognoses [62].

Accurately assessing the effects of antitumor therapy on LV function is crucial for optimizing postoperative treatment strategies. Some researchers have suggested that STI can be used to evaluate the impact of radiotherapy and chemotherapy on LV function. Studies indicate that STI can effectively track changes in LVSF in patients undergoing radiotherapy and chemotherapy and is inversely correlated with LVEF [63]. In chemotherapy-treated patients, STI can also reflect changes in LV systolic function and has a positive correlation with LVEF. However, some studies have raised concern that STI assessment before initiating antitumor therapy may induce psychological stress in patients [64].

Guiding postoperative health management in breast cancer patients

With advancements in STI technology, its application in cardiovascular disease monitoring and health management is expanding. Studies suggest that STI can serve as a prognostic indicator for breast cancer patients postoperatively [40]. Early STI assessment after breast-conserving surgery has been shown to predict more accurately long-term postoperative outcome.

Additionally, some researchers advocate for STI as a simple yet effective method for guiding postoperative health management in breast cancer patients [65]. Regular STI monitoring and evaluation can help improve long-term health outcomes in patients undergoing breast-conserving surgery.

Integration with other technologies

With ongoing technological advancements, STI is expected to provide greater benefits when combined with other imaging modalities, particularly in predicting long-term LV function post-surgery. Currently, the combination of STI with conventional echocardiography is the primary approach for assessing long-term LV function [66].

Studies have found that STI results are highly consistent with conventional echocardiography, enabling a more precise prediction of long-term LV function in postoperative patients [67]. However, STI has some limitations, such as its reduced sensitivity to cardiac volume changes and inability to capture certain myocardial strain alterations. Additionally, STI has limitations in older patients due to age-related changes in myocardial compliance.

In summary, numerous studies have highlighted the clinical value of STI in predicting LV function after breast-conserving surgery for breast cancer. However, due to limitations in study populations, sample sizes, and analytical methods, there is still insufficient evidence to confirm the high specificity, sensitivity, and accuracy of STI in this context.

Summary and future prospects

APT plays a crucial role in improving survival outcomes in breast cancer patients following breast-conserving surgery, but its effect on overall cardiac function remains a significant concern. As a quantitative, noninvasive ultrasound technique for evaluating global cardiac function, STI offers valuable insight into LVSF after APT. However, research in this area remains limited.

Preliminary studies have confirmed the feasibility of STI in assessing global LVSF after APT, but further validation of its accuracy is needed. Existing research on STI-based LVSF assessment post-APT is limited by small sample sizes, with most studies conducted in Chinese populations. Therefore, the sensitivity, specificity, and accuracy of STI in evaluating LV function after APT in breast cancer patients require further investigation.

With technological advancements and the emergence of new studies, STI is expected to become a standard tool for assessing LV function changes post-APT. However, current research on STI's numerical evaluation of LVSF is constrained by small sample sizes, inconsistent inclusion criteria, and limited case numbers, affecting the accuracy and reliability of STI-based assessments. Future studies should focus on addressing these limitations to enhance STI's clinical utility in evaluating LV function after APT.

Disclosure of conflict of interest

None.

Address correspondence to: Fang Yi, Department of Ultrasound Medicine, Guang'an People's Hospital, No. 1, Section 4, Binhe Road, Guang'an District, Guang'an 638099, Sichuan, China. Tel: +86-0826-2600242; E-mail: yifang136@outlook.com

References

[1] Zhang W, Zhang B, Wu T, Li Y, Qi X, Tian Y, Chen J and Luo H. Value of two-dimensional speckle-tracking echocardiography in evaluation of cardiac function in small fetuses. Quant Imaging Med Surg 2024; 14: 8155-8166.
[2] Lisi M, Cameli M, Mandoli GE, Pastore MC, Righini FM, D'Ascenzi F, Focardi M, Rubboli A, Mondillo S and Henein MY. Detection of myocardial fibrosis by speckle-tracking echocardiography: from prediction to clinical applications. Heart Fail Rev 2022; 27: 1857-1867.
[3] Gherbesi E, Gianstefani S, Angeli F, Ryabenko K, Bergamaschi L, Armillotta M, Guerra E, Tuttolomondo D, Gaibazzi N, Squeri A, Spaziani C, Pizzi C and Carugo S. Myocardial strain of the left ventricle by speckle tracking echocardiography: from physics to clinical practice. Echocardiography 2024; 41: e15753.
[4] Torres WM, Spinale FG and Shazly T. Speckle-tracking echocardiography enables model-based identification of regional stiffness indices in the left ventricular myocardium. Cardiovasc Eng Technol 2020; 11: 176-187.
[5] Tan CMJ and Lewandowski AJ. The transitional heart: from early embryonic and fetal development to neonatal life. Fetal Diagn Ther 2020; 47: 373-386.
[6] Mele D, Andrade A, Bettencourt P, Moura B, Pestelli G and Ferrari R. From left ventricular ejection fraction to cardiac hemodynamics: role of echocardiography in evaluating patients with heart failure. Heart Fail Rev 2020; 25: 217-230.
[7] Anqi Y, Yu Z, Mingjun X, Xiaoli K, Mengmeng L, Fangfang L and Mei Z. Use of echocardiography to monitor myocardial damage during anthracycline chemotherapy. Echocardiography 2019; 36: 495-502.
[8] Walker V, Lairez O, Fondard O, Pathak A, Pinel B, Chevelle C, Franck D, Jimenez G, Camilleri J, Panh L, Broggio D, Derreumaux S, Bernier MO, Laurier D, Ferrières J and Jacob S. Early detection of subclinical left ventricular dysfunction after breast cancer radiation therapy using speckle-tracking echocardiography: association between cardiac exposure and longitudinal strain reduction (BACCARAT study). Radiat Oncol 2019; 14: 204.
[9] Lu S, Sun Y, Li Q, Liu Y, Cui H and Liang X. Three-dimensional speckle-tracking echocardiography to evaluate left ventricular function of patients with breast cancer after anthracycline chemotherapy. Altern Ther Health Med 2023; 29: 388-393.
[10] Hendrickson T, Mancino C, Whitney L, Tsao C, Rahimi M and Taraballi F. Mimicking cardiac tissue complexity through physical cues: a review on cardiac tissue engineering approaches. Nanomedicine 2021; 33: 102367.
[11] Cerrito LF, Bergamini C, Dolci G, Fiorio E and Ribichini FL. Early functional and structural changes of the left atrium in a patient with

trastuzumab: related cardiotoxicity. Minerva Cardioangiol 2019; 67: 359-360.
[12] Singh G and Chanda A. Mechanical properties of whole-body soft human tissues: a review. Biomed Mater 2021; 16.
[13] Truong VT, Palmer C, Wolking S, Sheets B, Young M, Ngo TNM, Taylor M, Nagueh SF, Zareba KM, Raman S and Mazur W. Normal left atrial strain and strain rate using cardiac magnetic resonance feature tracking in healthy volunteers. Eur Heart J Cardiovasc Imaging 2020; 21: 446-453.
[14] Lunde IG, Rypdal KB, Van Linthout S, Diez J and González A. Myocardial fibrosis from the perspective of the extracellular matrix: mechanisms to clinical impact. Matrix Biol 2024; 134: 1-22.
[15] Barroso-Sousa R, Tarantino P, Tayob N, Dang C, Yardley DA, Isakoff SJ, Valero V, Faggen M, Mulvey T, Bose R, Hu J, Weckstein D, Wolff AC, Reeder-Hayes K, Rugo HS, Ramaswamy B, Zuckerman D, Hart L, Gadi VK, Constantine M, Cheng K, Briccetti F, Schneider B, Garrett AM, Marcom K, Albain K, DeFusco P, Tung N, Ardman B, Nanda R, Jankowitz RC, Rimawi M, Abramson V, Pohlmann PR, Van Poznak C, Forero-Torres A, Liu M, Ruddy KJ, Zheng Y, Rosenberg SM, Gelber RD, Trippa L, Barry W, DeMeo M, Burstein H, Partridge A, Winer EP, Krop I and Tolaney SM. Cardiac outcomes of subjects on adjuvant trastuzumab emtansine vs paclitaxel in combination with trastuzumab for stage I HER2-positive breast cancer (ATEMPT) study (TBCRC033): a randomized controlled trial. NPJ Breast Cancer 2022; 8: 18.
[16] Broberg AM, Geisler J, Tuohinen S, Skytta T, Hrafnkelsdóttir ÞJ, Nielsen KM, Hedayati E, Omland T, Offersen BV, Lyon AR and Gulati G. Prevention, detection, and management of heart failure in patients treated for breast cancer. Curr Heart Fail Rep 2020; 17: 397-408.
[17] Liu X, Duan K, Zhu F, Zhang H and Zhang S. Observation of changes in left atrial and left ventricular function in patients with hypertensive disorders of pregnancy based on myocardial strain. Ann Palliat Med 2021; 10: 606-614.
[18] Banke A, Schou M, Ewertz M, Dahl J, Frederiksen PH, Videbaek L, Cold S and Møller JE. Immediate evaluation of global longitudinal strain at initiation of trastuzumab treatment in breast cancer patients. Echocardiography 2021; 38: 1702-1710.
[19] Locquet M, Spoor D, Crijns A, van der Harst P, Eraso A, Guedea F, Fiuza M, Santos SCR, Combs S, Borm K, Mousseaux E, Gencer U, Frija G, Cardis E, Langendijk H and Jacob S. Subclinical left ventricular dysfunction detected by speckle-tracking echocardiography in breast cancer patients treated with radiation therapy: a six-month follow-up analysis (MEDIRAD EARLY-HEART study). Front Oncol 2022; 12: 883679.
[20] Hussein TM and Criscione JC. A new strain energy function representing the passive behavior of the myocardium. J Biomech Eng 2023; 145: 111004.
[21] Nhat GM, Hai NH, Duc VT, Tri HHQ and Hoa CN. Features of trastuzumab-related cardiac dysfunction: deformation analysis outside left ventricular global longitudinal strain. Front Cardiovasc Med 2024; 11: 1291180.
[22] Wang Z, Qin W, Zhai Z, Huang L, Feng J, Guo X, Liu K, Zhang C, Wang Z, Lu G and Dong S. Use of spectral tracking technique to evaluate the changes in left ventricular function in patients undergoing chemotherapy for colorectal cancer. Int J Cardiovasc Imaging 2021; 37: 1203-1213.
[23] Tuohinen SS, Skytta T, Huhtala H, Virtanen V, Kellokumpu-Lehtinen PL and Raatikainen P. Left ventricular speckle tracking echocardiography changes among early-stage breast cancer patients three years after radiotherapy. Anticancer Res 2019; 39: 4227-4236.
[24] Fan JL, Su B, Zhao X, Zhou BY, Ma CS, Wang HP, Hu SD, Zhou YF, Ju YJ and Wang MH. Correlation of left atrial strain with left ventricular end-diastolic pressure in patients with normal left ventricular ejection fraction. Int J Cardiovasc Imaging 2020; 36: 1659-1666.
[25] Porcari A, Merlo M, Crosera L, Stolfo D, Barbati G, Biondi F, De Angelis G, Paldino A, Pagnan L, Belgrano M, Cova MA, Pinamonti B, Vitrella G and Sinagra G. Strain analysis reveals subtle systolic dysfunction in confirmed and suspected myocarditis with normal LVEF. A cardiac magnetic resonance study. Clin Res Cardiol 2020; 109: 869-880.
[26] Lam CSP and Solomon SD. Classification of heart failure according to ejection fraction: JACC review topic of the week. J Am Coll Cardiol 2021; 77: 3217-3225.
[27] Zhu J, Xie S, Ji H, Gu X and Wu J. Evaluation of anthracycline-induced subclinical LV dysfunction by using myocardial composite index and two-dimension speckle tracking echocardiography technique. Front Cardiovasc Med 2022; 9: 936212.
[28] Aula H, Skyttä T, Tuohinen S, Luukkaala T, Hämäläinen M, Virtanen V, Raatikainen P, Moilanen E and Kellokumpu-Lehtinen PL. ST2 levels increased and were associated with changes in left ventricular systolic function during a three-year follow-up after adjuvant radiotherapy for breast cancer. Breast 2020; 49: 183-186.

[29] Li T, Zhuang H, Wang Y, Li J, Zhu D and Cui M. Two-dimensional speckle tracking echocardiography in evaluating radiation-induced heart damage. Asia Pac J Oncol Nurs 2021; 9: 119-124.

[30] Upshaw JN, Finkelman B, Hubbard RA, Smith AM, Narayan HK, Arndt L, Domchek S, DeMichele A, Fox K, Shah P, Clark A, Bradbury A, Matro J, Adusumalli S, Carver JR and Ky B. Comprehensive assessment of changes in left ventricular diastolic function with contemporary breast cancer therapy. JACC Cardiovasc Imaging 2020; 13: 198-210.

[31] Peverill RE. Changes in left ventricular size, geometry, pump function and left heart pressures during healthy aging. Rev Cardiovasc Med 2021; 22: 717-729.

[32] Coutinho Cruz M, Moura Branco L, Portugal G, Galrinho A, Timóteo AT, Rio P, Ilhão Moreira R, Mendonça T, Leal A, Gameiro F, Duarte Oliveira S, Luz R and Cruz Ferreira R. Three-dimensional speckle-tracking echocardiography for the global and regional assessments of left ventricle myocardial deformation in breast cancer patients treated with anthracyclines. Clin Res Cardiol 2020; 109: 673-684.

[33] Fawzy AA, El-Menyawi KA, Sallam WM and Zahran ME. Two-dimensional speckle tracking echocardiography in chemotherapy-induced cardiotoxicity in females with breast cancer. Cardiooncology 2024; 10: 13.

[34] Zhang L, Zhang R, Shuai P, Chen J and Yin L. A global case meta-analysis of three-dimensional speckle tracking for evaluating the cardiotoxicity of anthracycline chemotherapy in breast cancer. Front Cardiovasc Med 2022; 9: 942620.

[35] El-Sherbeny WS, Sabry NM, El-Saied SB and Elnagar B. Detection of right ventricular dysfunction by three - dimensional echocardiography and two - dimensional speckle tracking in breast cancer patients receiving anthracycline-based chemotherapy. Cardiooncology 2023; 9: 20.

[36] Canty JM Jr. Myocardial injury, troponin release, and cardiomyocyte death in brief ischemia, failure, and ventricular remodeling. Am J Physiol Heart Circ Physiol 2022; 323: H1-H15.

[37] Ho E, Brown A, Barrett P, Morgan RB, King G, Kennedy MJ and Murphy RT. Subclinical anthracycline- and trastuzumab-induced cardiotoxicity in the long-term follow-up of asymptomatic breast cancer survivors: a speckle tracking echocardiographic study. Heart 2010; 96: 701-707.

[38] Yu AF, Ho AY, Braunstein LZ, Thor ME, Lee Chuy K, Eaton A, Mara E, Cahlon O, Dang CT, Oeffinger KC, Steingart RM and Liu JE. Assessment of early radiation-induced changes in left ventricular function by myocardial strain imaging after breast radiation therapy. J Am Soc Echocardiogr 2019; 32: 521-528.

[39] Mandoli GE, Pastore MC, Vasilijevaite K, Cameli P, D'Ascenzi F, Focardi M, Mondillo S and Cameli M. Speckle tracking stress echocardiography: a valuable diagnostic technique or a burden for everyday practice? Echocardiography 2020; 37: 2123-2129.

[40] Morariu VI, Arnautu DA, Morariu SI, Popa AM, Parvanescu T, Andor M, Abhinav S, David VL, Ionescu A and Tomescu MC. 2D speckle tracking: a diagnostic and prognostic tool of paramount importance. Eur Rev Med Pharmacol Sci 2022; 26: 3903-3910.

[41] Xu H, Mao L, Liu H, Zhang Y and Yang J. Assessment of subclinical deterioration of right ventricular function by three-dimensional speckle tracking echocardiography in breast cancer patients undergoing anthracycline-based chemotherapy. Int J Gen Med 2021; 14: 885-893.

[42] Liu W, Li W, Li H, Li Z, Zhao P, Guo Z, Liu C, Sun L and Wang Z. Two-dimensional speckle tracking echocardiography help identify breast cancer therapeutics-related cardiac dysfunction. BMC Cardiovasc Disord 2022; 22: 548.

[43] Liu JE, Barac A, Thavendiranathan P and Scherrer-Crosbie M. Strain imaging in cardio-oncology. JACC CardioOncol 2020; 2: 677-689.

[44] Chaganti BT, Negishi K and Okajima K. Role of myocardial strain imaging in cancer therapy-related cardiac dysfunction. Curr Cardiol Rep 2022; 24: 739-748.

[45] Trivedi SJ, Choudhary P, Lo Q, Sritharan HP, Iyer A, Batumalai V, Delaney GP and Thomas L. Persistent reduction in global longitudinal strain in the longer term after radiation therapy in patients with breast cancer. Radiother Oncol 2019; 132: 148-154.

[46] Barber MJ. The influence of cardiac sympathetics and periods of ischemic insult upon myocardial blood flow, incidence of arrhythmia, electrical activity and myocardial infarction during coronary occlusion. 1980; [Epub ahead of print].

[47] Fourati N, Charfeddine S, Chaffai I, Dhouib F, Farhat L, Boukhris M, Abid L, Kammoun S, Mnejja W and Daoud J. Subclinical left ventricle impairment following breast cancer radiotherapy: Is there an association between segmental doses and segmental strain dysfunction? Int J Cardiol 2021; 345: 130-136.

[48] Denlinger CS, Sanft T, Baker KS, Broderick G, Demark-Wahnefried W, Friedman DL, Goldman M, Hudson M, Khakpour N, King A, Koura D, Lally RM, Langbaum TS, McDonough AL, Melisko M, Montoya JG, Mooney K, Moslehi JJ, O'Connor T, Overholser L, Paskett ED, Pepper-

corn J, Pirl W, Rodriguez MA, Ruddy KJ, Silverman P, Smith S, Syrjala KL, Tevaarwerk A, Urba SG, Wakabayashi MT, Zee P, McMillian NR and Freedman-Cass DA. Survivorship, version 2.2018, NCCN clinical practice guidelines in oncology. J Natl Compr Canc Netw 2018; 16: 1216-1247.

[49] van den Bogaard VAB, van Luijk P, Hummel YM, van der Meer P, Schuit E, Boerman LM, Maass SWMC, Nauta JF, Steggink LC, Gietema JA, de Bock GH, Berendsen AJ, Smit WGJM, Sijtsema NM, Kierkels RGJ, Langendijk JA, Crijns APG and Maduro JH. Cardiac function after radiation therapy for breast cancer. Int J Radiat Oncol Biol Phys 2019; 104: 392-400.

[50] Chen N, Liu A, Sun S, Wei H, Sun Q, Shang Z, Sun Y, Fu T, Wang H, Xia Y, Hua L, Hsi DH and Cong T. Evaluation of left atrial function and mechanical dispersion in breast cancer patients after chemotherapy. Clin Cardiol 2022; 45: 540-548.

[51] Esmaeilzadeh M, Urzua Fresno CM, Somerset E, Shalmon T, Amir E, Fan CS, Brezden-Masley C, Thampinathan B, Thevakumaran Y, Yared K, Koch CA, Abdel-Qadir H, Woo A, Yip P, Marwick TH, Chan R, Wintersperger BJ and Thavendiranathan P. A combined echocardiography approach for the diagnosis of cancer therapy-related cardiac dysfunction in women with early-stage breast cancer. JAMA Cardiol 2022; 7: 330-340.

[52] Tuohinen SS, Skyttä T, Huhtala H, Poutanen T, Virtanen V, Kellokumpu-Lehtinen PL and Raatikainen P. 3-year follow-up of radiation-associated changes in diastolic function by speckle tracking echocardiography. JACC CardioOncol 2021; 3: 277-289.

[53] Guo X, Zhang N, Wang N, Zhang Y, Liu Y, Pei M, Liu G and Jia X. Early detection of chemotherapy-induced cardiotoxicity in breast cancer patients: a comprehensive analysis using speckle tracking echocardiography. Front Cardiovasc Med 2024; 11: 1413827.

[54] Mincu RI, Lampe LF, Mahabadi AA, Kimmig R, Rassaf T and Totzeck M. Left ventricular diastolic function following anthracycline-based chemotherapy in patients with breast cancer without previous cardiac disease-a meta-analysis. J Clin Med 2021; 10: 3890.

[55] Wang SY, Lin KH, Wu YW, Yu CW, Yang SY, Shueng PW, Hsu CX and Wu TH. Evaluation of the cardiac subvolume dose and myocardial perfusion in left breast cancer patients with postoperative radiotherapy: a prospective study. Sci Rep 2023; 13: 10578.

[56] Naaktgeboren WR, Groen WG, Jacobse JN, Steggink LC, Walenkamp AME, van Harten WH, Stuiver MM, Aaronson NK, Aleman BMP, van der Meer P, Schaapveld M, Sonke GS, Gietema JA, van Leeuwen FE and May AM. Physical activity and cardiac function in long-term breast cancer survivors: a cross-sectional study. JACC CardioOncol 2022; 4: 183-191.

[57] Honaryar MK, Locquet M, Allodji R, Jimenez G, Pinel B, Lairez O, Panh L, Camilleri J, Broggio D, Ferrières J, De Vathaire F and Jacob S. Cancer therapy-related cardiac dysfunction after radiation therapy for breast cancer: results from the BACCARAT cohort study. Cardiooncology 2024; 10: 54.

[58] Tuohinen SS, Skyttä T, Poutanen T, Huhtala H, Virtanen V, Kellokumpu-Lehtinen PL and Raatikainen P. Radiotherapy-induced global and regional differences in early-stage left-sided versus right-sided breast cancer patients: speckle tracking echocardiography study. Int J Cardiovasc Imaging 2017; 33: 463-472.

[59] Onishi T, Saha SK, Delgado-Montero A, Ludwig DR, Onishi T, Schelbert EB, Schwartzman D and Gorcsan J 3rd. Global longitudinal strain and global circumferential strain by speckle-tracking echocardiography and feature-tracking cardiac magnetic resonance imaging: comparison with left ventricular ejection fraction. J Am Soc Echocardiogr 2015; 28: 587-596.

[60] Luz FACD, Marinho EDC, Nascimento CP, Marques LA, Duarte MBO, Delfino PFR, Antonioli RM, Araújo RA and Silva MJB. The effectiveness of radiotherapy in preventing disease recurrence after breast cancer surgery. Surg Oncol 2022; 41: 101709.

[61] Skyttä T, Tuohinen S, Luukkaala T, Virtanen V, Raatikainen P and Kellokumpu-Lehtinen PL. Adjuvant radiotherapy-induced cardiac changes among patients with early breast cancer: a three-year follow-up study. Acta Oncol 2019; 58: 1250-1258.

[62] Henson KE, McGale P, Darby SC, Parkin M, Wang Y and Taylor CW. Cardiac mortality after radiotherapy, chemotherapy and endocrine therapy for breast cancer: Cohort study of 2 million women from 57 cancer registries in 22 countries. Int J Cancer 2020; 147: 1437-1449.

[63] Tsai HR, Gjesdal O, Wethal T, Haugaa KH, Fosså A, Fosså SD and Edvardsen T. Left ventricular function assessed by two-dimensional speckle tracking echocardiography in long-term survivors of Hodgkin's lymphoma treated by mediastinal radiotherapy with or without anthracycline therapy. Am J Cardiol 2011; 107: 472-477.

[64] Allen WM, Foo KY, Zilkens R, Kennedy KM, Fang Q, Chin L, Dessauvagie BF, Latham B, Saunders CM and Kennedy BF. Clinical feasibility of optical coherence micro-elastography for imaging tumor margins in breast-conserving surgery. Biomed Opt Express 2018; 9: 6331-6349.

[65] Oliveira SP, Morgado P, Gouveia PF, Teixeira JF, Bessa S, Monteiro JP, Zolfagharnasab H, Reis M, Silva NL, Veiga D, Cardoso MJ, Oliveira HP and Ferreira MJ. Three-dimensional planning tool for breast conserving surgery: a technological review. Crit Rev Biomed Eng 2018; 46: 523-580.
[66] Shanishwara P, Vyas P, Joshi H, Patel I, Dubey G, Patel J and Sharma S. Role of speckle tracking echocardiography to predict left ventricular dysfunction post mitral valve replacement surgery for severe mitral regurgitation. J Saudi Heart Assoc 2022; 34: 157-162.
[67] Li Q, Zuo W, Liu Y, Chen B, Wu Y, Dong L and Shu X. Value of speckle tracking echocardiography combined with stress echocardiography in predicting surgical outcome of severe aortic regurgitation with markedly reduced left ventricular function. Rev Cardiovasc Med 2023; 24: 114.