

Advances in the Application of Non-Invasive Myocardial Work in Assessing Left Ventricular Function and Prognosis After Percutaneous Coronary Intervention in Patients with Acute Myocardial Infarction

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Abstract: Timely assessment of left ventricular function, prognosis prediction, and subsequent adjustment of clinical treatment strategies are crucial for improving clinical outcomes in patients with acute myocardial infarction (AMI) undergoing percutaneous coronary intervention (PCI). Traditional assessment methods, such as cardiac magnetic resonance imaging and conventional echocardiography, have limitations, including high cost, time consumption, or insufficient sensitivity. Non-invasive Myocardial Work (MW) technology, by combining speckle tracking and left ventricular pressure-strain loops, dynamically quantifies myocardial mechanical properties, providing a novel non-invasive approach for assessing AMI patients after PCI. This article analyzes recent literature, elaborates on the principles of MW technology and its application in left ventricular function evaluation, dynamic monitoring of postoperative myocardial function, and guiding clinical treatment decisions after PCI in AMI patients. It also discusses the current limitations of MW technology and its future prospects, aiming to explore the clinical value of MW technology in the assessment of AMI patients after PCI.

Keywords: Acute Myocardial Infarction; Noninvasive Myocardial Work; Percutaneous Coronary Intervention Operation.

1. Introduction

Cardiovascular diseases are one of the leading causes of death worldwide today, among which acute myocardial infarction (AMI) is widely recognized as one of the major challenges in the field of clinical cardiology [1]. Although the popularization of percutaneous coronary intervention (PCI) therapy and the use of pharmacologic thrombolysis have significantly reduced the short-term mortality rate of AMI patients, this does not mean that the long-term prognosis of these patients is guaranteed.

Therefore, how to accurately assess the recovery of left ventricular function in AMI patients after PCI, dynamically monitor postoperative myocardial function, and guide clinical treatment decisions in the early stage has become an urgent problem to be solved. Currently, the commonly used methods for evaluating left ventricular function include cardiac magnetic resonance imaging (CMRI), radionuclide myocardial perfusion imaging, conventional echocardiography, and speckle tracking echocardiography (STE). However, these examinations have limitations such as long examination time, high cost, or insensitivity to early subtle changes in the myocardium; even STE is affected by myocardial loading conditions. In recent years, non-invasive myocardial work (MW) technology, as a relatively new echocardiographic examination method, has been increasingly widely used, especially in the field of AMI. This technology overcomes the aforementioned limitations. Research results have demonstrated that MW technology has advantages of good sensitivity, real-time performance, and high cost-effectiveness, and it is regarded as a reliable indicator for evaluating global and segmental left ventricular systolic function as well as prognosis [2, 3]. MW technology can promptly identify high-risk groups of AMI patients who

are at risk of myocardial ischemia-reperfusion injury, and assist clinicians in taking corresponding active treatment measures, which is of great significance for improving the prognosis of AMI patients. This article mainly reviews the research progress of MW technology in evaluating left ventricular function and prognosis of AMI patients after PCI.

2. Pathophysiological Mechanisms of Acute Myocardial Infarction After PCI

In patients with AMI, acute coronary occlusion leads to myocardial cell ischemia. Although PCI can restore blood flow and alleviate myocardial ischemia, it may trigger myocardial ischemia-reperfusion injury (IRI). During IRI, myocardial cells generate a large amount of reactive oxygen species (ROS) and inflammatory mediators, which cause myocardial cell damage and cardiac insufficiency [4]. Both such myocardial damage and IRI can further stimulate local and systemic inflammatory responses, resulting in elevated levels of inflammatory cytokines such as C-reactive protein (CRP) and interleukin-6 (IL-6). This process can lead to left ventricular remodeling (LVR) after myocardial infarction and is associated with the occurrence of major adverse cardiovascular events (MACE) postoperatively [5]. Although PCI can improve myocardial perfusion and slow down the progression of left ventricular remodeling, left ventricular remodeling after PCI remains a factor related to patients' prognosis, requiring timely administration of medications and implementation of cardiac rehabilitation management [6,7].

3. Overview of Non-Invasive Myocardial Work Using Echocardiography

The MW technology using echocardiography is an innovative non-invasive technique first proposed by Russel et al. in 2012, and it is also one of the new technologies that have attracted much attention in the field of cardiac function assessment in recent years [8, 9]. This technology acquires segmental myocardial STE and combines it with cuff pressure to construct a non-invasive LVPSL, which replaces invasive pressure measurement. By taking into account the impact of loading conditions on left ventricular myocardial systolic function, this technology improves the accuracy of cardiac function assessment [10]. In animal experiments and relevant clinical studies, the area of LVPSL showed a high correlation with invasive micromanometers ($r=0.96$) and pressure-volume loops ($r=0.99$). Additionally, radionuclide myocardial perfusion imaging further confirmed that LVPSL was significantly correlated with myocardial oxygen consumption and glucose metabolism levels ($r=0.81$). These research results verify the biological rationality of this technology from both functional and metabolic perspectives. The key innovation of the non-invasive echocardiographic MW technology lies in the real-time dynamic coupling of strain analysis and left ventricular pressure curve [11]. The algorithm of this technology innovatively overcomes the limitation that traditional strain parameters are susceptible to preload and afterload, enabling it to more accurately and quantitatively reflect the degree of myocardial contraction [12].

The parameters related to MW technology mainly include myocardial work index (MWI), Myocardial Constructive Work (MCW), Myocardial Wasted Work (MWW), and myocardial work efficiency (MWE). These parameters integrate the mechanical properties, energy metabolism, and hemodynamic information of the myocardium, providing a comprehensive quantitative method for the evaluation of myocardial function.

(1) MWI: It quantifies the global mechanical work of the left ventricle from mitral valve closure to opening, encompassing the work performed during both the isovolumic contraction phase and isovolumic relaxation phase. The conversion efficiency of myocardial energy to mechanical work is intuitively reflected by the area of the pressure-strain loop (PSL).

(2) MCW: It refers to the effective work that promotes ventricular ejection, including the positive work from myocardial shortening during the systolic phase and the negative work from moderate prolongation during the isovolumic relaxation phase. It directly corresponds to the energy contribution to cardiac output.

(3) MWW: It reflects energy loss, including the negative work from abnormally prolonged myocardial contraction during the systolic phase and the positive work from inappropriately shortened myocardial relaxation during the isovolumic relaxation phase. This type of work does not contribute to effective ventricular ejection but increases myocardial oxygen consumption.

(4) MWE: It is calculated using the formula $MCW/(MCW + MWW)$, and reveals the efficiency of converting myocardial energy into effective hemodynamic work.

4. Prediction of Prognosis in AMI Patients After PCI Using Non-Invasive Myocardial Work Echocardiography

4.1. Quantitative Evaluation of Early Postoperative Myocardial Function

Compared with conventional echocardiographic parameters, MW parameters based on the LVPSL are more sensitive in evaluating postoperative myocardial function in patients with AMI [8]. Jolanda Sabatino et al. treated patients with severe coronary heart disease via PCI and performed echocardiographic examination immediately after the operation [13]. The results showed a significant improvement in myocardial work. The study confirmed the important clinical value of early revascularization after coronary artery occlusion, and indicated that MW parameters have higher sensitivity and specificity ($AUC = 0.835$) than traditional longitudinal strain and postsystolic strain index in evaluating myocardial function recovery after PCI. The above studies demonstrate that MW technology is of great significance for the quantitative evaluation of myocardial function in AMI patients after PCI; however, they do not fully consider the risk of myocardial reperfusion injury in AMI patients following PCI.

For AMI patients, the presence of microvascular perfusion (MVP) impairment after PCI often indicates an adverse clinical outcome [14]. A study applied MW technology to evaluate left ventricular systolic function in AMI patients after PCI and explore its role in assessing myocardial perfusion. The results showed that 2D-global longitudinal strain (2D-GLS), global work index (GWI), global constructive work (GCW), and global work efficiency (GWE) had high accuracy in diagnosing poor perfusion in AMI patients after PCI (for MWE: AUC 0.770, sensitivity 88%, specificity 54.5%; for GCW: AUC 0.725, specificity 90.9%, sensitivity 48%) [15]. This study suggests that MW technology provides a new and sensitive method for evaluating myocardial microcirculation in AMI patients after PCI. In the same year, a study by Wenying Jin et al. [16] reached similar conclusions, finding that GWI exhibited good sensitivity (86.8%) but relatively low specificity (53.7%) in identifying MVP, with an AUC of 0.712. The results confirm that MW parameters provide incremental value for MVP evaluation in AMI patients after PCI. However, the methodologies of the above studies all have certain limitations. In these studies, myocardial contrast echocardiography was used to determine the presence of myocardial microperfusion impairment. The filling process of the contrast agent in the myocardium is susceptible to interference from various factors, and even slight deviations may lead to misjudgment of the contrast agent signal. Additionally, myocardial contrast echocardiography has limited ability to detect the absolute quantification of myocardial blood flow, which in turn affects the accurate reflection of the true state of myocardial perfusion.

4.2. Dynamic Monitoring of Postoperative Myocardial Function

4.2.1. Short-Term Postoperative Evaluation of Cardiac Function Recovery

Wang Xinhe et al. [17] found that the MW parameters of acute myocardial infarction (AMI) patients significantly

improved at 7 days after PCI: specifically, global wasted work (GWW) decreased remarkably, while global work index (GWI), global work efficiency (GWE), global constructive work (GCW), and global longitudinal strain (GLS) increased significantly ($P<0.05$). Additionally, all preoperative and postoperative MW parameters in the multi-vessel disease group were inferior to those in the single-vessel disease group ($P<0.05$). These findings further verify the effectiveness of MW technology in evaluating AMI patients after PCI, and also indicate a negative correlation between the extent of myocardial damage and the effect of functional recovery—i.e., the greater the extent of myocardial damage, the poorer the recovery of myocardial work. However, this study only compared MW parameters of AMI patients before and after admission, and between those with single-vessel and multi-vessel disease; it did not use cardiac magnetic resonance (CMR) technology to verify the extent and severity of myocardial involvement. Given the above limitations, it is suggested in future studies to incorporate CMR technology as a method for clearly locating and quantifying the range and severity of myocardial damage. This will provide robust data support for the intrinsic association between MW parameters and actual myocardial damage, thereby enhancing the persuasiveness of research conclusions and their clinical guiding significance. In summary, MW technology shows high potential in optimizing the short-term evaluation of cardiac function recovery in AMI patients after PCI, but further verification is required.

4.2.2. Long-term Prediction of Postoperative Left Ventricular Remodeling and Adverse Cardiovascular Events

Left ventricular remodeling is a common pathophysiological process in patients with acute myocardial infarction (AMI) after PCI, and it is closely associated with the occurrence of major adverse cardiovascular events (MACE). Based on this, researchers have used MW technology to explore its role in predicting left ventricular remodeling and the occurrence of MACE in AMI patients after PCI. A study by Lustosa et al. [18] found that global longitudinal strain (GLS), global work index (GWI), and global constructive work (GCW) could effectively reflect the dynamic changes of different left ventricular remodeling patterns. Particularly in patients with inconsistent remodeling, myocardial work impairment was more severe and recovery was limited (values were $-13\pm5\%$, 1022 ± 319 mmHg%, and 1164 ± 432 mmHg% respectively). This indicates that MW parameters have promising application prospects in predicting left ventricular remodeling. However, the aforementioned study is a single-center study, which carries the risk of selection bias. In the future, it is recommended to conduct multi-center cohort studies to perform stratified analysis on the impact of different clinical characteristics on the predictive efficacy of MW.

Given that most AMI patients present with segmental infarction, whether myocardial work in the infarcted segment can predict left ventricular remodeling and major adverse cardiovascular events (MACE) in AMI patients after PCI has become a focus of attention in the field. A study by Patrick Meimoun et al. [19] found that the impairment of myocardial constructive work (MCW) in the infarcted segment was significantly correlated with indicators such as ejection fraction ($r=0.58$) and global longitudinal strain (GLS) ($r=-0.67$); particularly in patients with concurrent MACE, the impairment of MCW was more pronounced ($P<0.01$). This

study verified the value of MW technology in evaluating left ventricular function recovery and predicting MACE in AMI patients after PCI. The research results of Paula Lustosa [20] and Wei Wang [21] supported the above findings and further verified that the difference in MWE between the infarcted and non-infarcted segments (delta-WE) could predict early left ventricular remodeling (sensitivity: 69%, specificity: 74%, $AUC = 0.770$ [20]). Patients with high delta-WE were more likely to experience MACE. The imbalance in myocardial work between the infarcted and non-infarcted segments promotes the occurrence of left ventricular remodeling, which also suggests that we should further focus on the value of delta-WE in predicting left ventricular remodeling and MACE.

At a more microscopic level, the prognosis of patients with AMI is closely associated with microvascular perfusion (MVP). The results of a study by Sun Siyao et al. [22] showed that segmental MWE was significantly correlated with MVP status ($P<0.05$), and regional MW parameters could serve as markers for predicting the subsequent occurrence of major adverse cardiovascular events (MACE) in AMI patients, providing a new perspective for clinical risk stratification. However, most current studies focus on global myocardial work indices. To better evaluate regional myocardial work, standardized methods for regional analysis still need to be improved.

4.2.3. Postoperative Adjunctive Risk Stratification

To summarize the above, MW technology can not only identify cardiac structural changes in AMI patients after PCI but also predict the occurrence of major adverse cardiovascular events (MACE) (e.g., heart failure), thereby enabling effective risk stratification. Postoperative risk stratification after PCI is crucial for improving patients' treatment outcomes and survival rates. Studies have shown [23] that MW parameters can serve as predictive indicators in risk stratification models (optimal cutoff value: 1165 mmHg%, sensitivity: 69%, specificity: 54%). This compensates for the insensitivity and poor timeliness of traditional assessment methods, such as left ventricular ejection fraction (LVEF) and relevant biomarkers [24]. A study [25] demonstrated that parameters related to MW technology can provide earlier warning of heart failure after PCI, thereby guiding risk stratification. The results showed that patients with an improvement in MWE of $<10\%$ within 3 months after surgery had a 2.5-fold increased risk of cardiovascular death, which is superior to the assessment using a single left ventricular ejection fraction measurement. Another study [26] indicated that for the low-risk group (LVEF $> 50\%$ and normal global longitudinal strain [GLS]), a decrease in global work index (GWI) of $>15\%$ suggests the need to upgrade the risk level to moderate and intensify follow-up.

However, it still has certain limitations: (1) The level of equipment and professionals in the ultrasound departments of some primary hospitals is limited, making it difficult to meet the needs of patients for timely risk stratification evaluation based on MW technology and the formulation of individualized intervention plans. (2) There are differences in the degree of benefit among different patients. Elderly patients with multiple comorbidities have more complex conditions, which makes the interpretation of MW parameters more difficult and is not conducive to risk stratification evaluation and the development of targeted treatment plans. To address the above drawbacks, Transformer-based

time-series models can integrate ultrasound indicators and other clinical information at different postoperative time points [27]. By virtue of their self-attention mechanism, these models explore the evolutionary patterns of indicators such as myocardial strain rate and torsion angle, and establish personalized risk evolution characteristics. Relevant clinical trials have shown [28] that the mean C-index of this model reaches 0.72, while that of the traditional scoring system is 0.64. The Transformer-based model has higher prognostic accuracy and good potential for risk stratification. Furthermore, a study [29] used interpretable machine learning methods to establish a predictive model for heart failure in AMI patients, and achieved optimal predictive performance (AUC = 0.922) through the XGBoost algorithm with SHAP (SHapley Additive exPlanations) technology. Therefore, in the future, machine learning principles and methods can be used to integrate MW parameters and establish risk prediction models, thereby enabling rapid assessment of individualized risks in various populations. This approach can not only help primary hospitals quickly identify high-risk AMI patients but also provide more guidance for the individualized treatment of AMI patients, further improving patient prognosis and reducing the incidence of cardiovascular events.

In summary, MW technology shows high application potential in the long-term prediction of left ventricular remodeling and major adverse cardiovascular events (MACE), as well as in risk stratification, for patients with AMI after PCI. However, further research is needed to verify its clinical effectiveness.

4.3. Postoperative Guidance for Clinical Treatment Decisions

Based on the aforementioned functional assessments, MW technology can also guide the formulation of PCI treatment strategies for patients with AMI. Studies have pointed out [30] that MW technology can evaluate the early prognosis of adverse vascular events (e.g., heart failure) in AMI patients after PCI. By monitoring MW-related parameters, it can identify high-risk patients to adjust pharmacotherapeutic regimens and guide subsequent treatment.

Recent randomized clinical trials have shown that revascularization of non-culprit lesions is beneficial for patients with ST-segment elevation myocardial infarction (STEMI) [31]. However, the optimal timing for PCI of non-culprit vessels remains unknown [32]. A study has demonstrated [33] that the instantaneous wave-free ratio can instantly assess the physiological significance of non-culprit lesions and enable immediate intervention, thereby reducing major adverse cardiovascular events (MACE). Nevertheless, the application of MW technology in guiding revascularization strategies for non-culprit lesions is still in the exploratory stage. In the future, it is expected to combine MW parameters with the instantaneous wave-free ratio to complement the advantages and disadvantages of the two technologies, making them more clinically meaningful for guiding decisions regarding non-culprit vessel lesions in AMI patients after PCI. In conclusion, the application of MW technology in revascularization strategies for non-culprit lesions still needs continuous exploration and improvement in clinical practice to further provide more individualized and effective treatment regimens for AMI patients after PCI.

4.4. Technology Expansion and Multimodal Integration

MW technology primarily conducts dynamic assessments of myocardial status from a mechanical perspective, but it faces certain challenges in clinical application [34]: (1) It has suboptimal sensitivity to microcirculatory damage (including microvascular embolism and edema), and verification via CMR technology is still required; (2) It cannot accurately locate the infarct site at the microscopic level or calculate parameters such as infarct area. Currently, CMR remains the gold standard for accurately evaluating myocardial conditions after infarction [35]. A latest study [36] combined Late Gadolinium-Enhanced Cardiac Magnetic Resonance Imaging (LGE-CMR) with MW technology and found that, in AMI patients after PCI, the MWI, MCW, and MWE in the core infarct area were significantly lower than those in the remote areas without late gadolinium enhancement ($P < 0.05$), and these parameters showed a significant negative correlation with the transmural extent of infarction ($P < 0.05$). The results suggest that MW parameters can effectively quantify the degree of local myocardial damage and reveal functional heterogeneity in remote areas through mechanical characteristics, providing a biomechanical basis for their use as prognostic markers. By multimodally integrating LGE-CMR and MW technology, this study offers a new approach for myocardial viability assessment. In the future, it is expected to construct a multimodal model that couples radionuclide imaging perfusion parameters, CMR-derived quantitative fibrosis parameters, and myocardial work parameters, and establish a three-dimensional cardiac function map based on these multimodal data. This integration of multiple imaging and physiological data will enable multidimensional information aggregation of myocardial tissue structure, function, metabolism, and blood perfusion, advancing the time window for cardiac function prognosis prediction and providing more robust support for clinical diagnosis and treatment.

In recent years, deep learning technology has achieved breakthrough progress in the field of cardiac function assessment. A multimodal data fusion method based on the ResNet-3D network architecture has been used to construct an interpretable assessment system for myocardial microcirculatory damage [37, 38]. This provides a new perspective: in the future, based on deep learning methods, accurate quantitative assessment and spatial localization analysis of myocardial microperfusion damage can be achieved by coupling the time-related mechanical features of dynamic ultrasonic strain curves with the structural and functional parameters of multimodal images such as MR and CT. This model utilizes a multi-source modal data registration model to extract time-frequency domain features from the obtained myocardial dynamic strain sequences. Simultaneously, it integrates hemodynamic parameters from MR first-pass perfusion imaging and microvascular anatomical features from CT myocardial angiography. Finally, a multi-task convolutional neural network is employed to construct a nonlinear coupling model of multi-dimensional features. In the damage localization phase, the network model locates perfusion-strain decoupling regions through an attention mechanism and optimizes spatial localization accuracy using a conditional random field, thereby realizing accurate mapping of myocardial microcirculatory damage based on pathophysiological features at the voxel-level

resolution.

To summarize the above, the adoption of deep learning-based multimodal technology is expected to compensate for the limitations of single-modal imaging in hemodynamic perfusion diagnosis. Establishing a multimodal assessment model that integrates mechanical mechanics, functional metabolism, and anatomical structure will provide an interdisciplinary technical foundation for the early diagnosis, therapeutic effect evaluation, and pathological mechanism research of myocardial ischemic diseases, thereby realizing a novel application of artificial intelligence technology in diagnostic work within the field of medical imaging.

5. Current Challenges and Future Directions

Although MW technology plays a unique role in the clinical postoperative prognostic evaluation of patients with AMI, its clinical application still faces challenges, and its future research focus lies in the following aspects: (1) Technical perspective: There are significant differences in the sensitivity and specificity of MW parameters across various studies, which may be related to sample size, characteristics of the enrolled patient population (infarction location, number of diseased vessels), and different types of equipment. Additionally, the general applicability and recognition of its data in large samples remain poor. For image data acquisition and the selection of regions of interest (ROIs), MW technology primarily relies on manual judgment. To more fully clarify the application scope and predictive role of MW technology in AMI patients, it is necessary to further expand the sample size, design multicenter, large-sample studies of the same type, and determine the application limitations of MW in subgroups such as single-vessel disease, infarction at different locations, and different types of infarction. (2) Clinical translation: Most studies are small-scale, single-center explorations with limited data. There is a lack of multicenter data verification, and comparative studies with gold-standard assessments such as cardiac magnetic resonance (CMR) are insufficient. Further large-scale prospective cohort studies are needed to confirm its efficacy in postoperative prognostic evaluation—for example, evaluating the correlation between MW parameters and CMR-based imaging analysis results of myocardial fibrosis, and establishing thresholds for clinical decision-making. (3) Emerging research directions: Automatic analysis assisted by artificial neural networks may overcome the subjectivity and time-consuming nature of manual analysis. For instance, strain loop segmentation algorithms based on deep learning have improved analysis speed in other cardiac patient populations; however, the generalization ability of this method in the clinical postoperative application of AMI patients still needs to be verified. (4) Unexplored populations in clinical practice: MW technology has not yet been further explored in certain patient populations in clinical settings. In future development, MW technology can be used to guide the management of AMI patients in the intensive care unit (ICU) and predict adverse cardiovascular events in special populations such as stroke patients [39,40].

6. Conclusion

In summary, non-invasive myocardial work echocardiography plays a crucial role in the early detection, monitoring, and management of patients with AMI after PCI.

By effectively evaluating myocardial function and ischemic risk, it improves patient prognosis and provides a new perspective and method for the clinical assessment of AMI patients. Non-invasive myocardial work echocardiography needs to achieve continuous breakthroughs in technical optimization, clinical validation, and multimodal integration to become a routine tool for prognostic assessment after acute myocardial infarction.

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