Exercise-Based Cardiac Rehabilitation in Acute Myocardial Infarction Management: Global Status, Multimodal Interventions, and Personalized Strategies (Postprint)

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Abstract

Acute myocardial infarction (AMI), as one of the leading causes of mortality and disability from cardiovascular diseases globally, has seen the optimization of its long-term postoperative management strategies become a focal issue of concern in the medical community. Exercise-based cardiac rehabilitation (EBCR), as a core intervention recommended by evidence-based medicine, demonstrates significant efficacy in improving cardiopulmonary function, alleviating psychological stress, and enhancing quality of life through integrating diversified exercise modalities and personalized management strategies. With the deep integration of precision medicine, intelligent technology, and psychosocial interventions, the promotion and implementation of EBCR in resource-limited regions has encountered new development opportunities. However, the global popularization of EBCR still faces multiple obstacles; particularly in areas with scarce medical resources, its application scope is significantly restricted by factors such as service accessibility, economic burden, and patient compliance. This study comprehensively reviews the global implementation status, regional disparity characteristics, and multidimensional interventions and personalized strategies of EBCR, and conducts in-depth discussions on development pathways such as intelligent technology application, policy guarantee system construction, and interdisciplinary collaborative innovation, aiming to provide more targeted theoretical support and practical guidance for AMI rehabilitation management.

Full Text

Preamble

Review and Monograph

Exercise-Based Cardiac Rehabilitation in Acute Myocardial Infarction Management: Global Perspectives, Multimodal Interventions, and Personalized Strategies

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Abstract Acute myocardial infarction (AMI) remains one of the leading causes of mortality and disability worldwide, making the optimization of long-term post-procedural management a key focus in cardiovascular medicine. Exercise-based cardiac rehabilitation (EBCR), as a core intervention recommended by evidence-based medicine, has demonstrated significant benefits in enhancing cardiopulmonary function, alleviating psychological stress, and improving overall quality of life by integrating diverse exercise modalities with personalized management strategies. The rapid advancement of precision medicine, smart technologies, and psychosocial interventions has provided new opportunities for the expansion of EBCR, particularly in resource-limited settings. However, the global implementation of EBCR still faces substantial challenges, including limited healthcare accessibility, economic constraints, and poor patient adherence, especially in regions with insufficient medical resources. This study systematically reviews the global landscape of EBCR implementation, regional disparities, and the efficacy of multidimensional interventions and personalized approaches. Furthermore, it explores future directions in the integration of intelligent technologies, policy frameworks, and interdisciplinary collaborations, aiming to provide targeted theoretical insights and practical guidance for optimizing AMI rehabilitation management.

[**Key words**] Acute myocardial infarction; Exercise-based cardiac rehabilitation; Multimodal intervention; Personalized management; Precision medicine; Smart technology; Psychosocial intervention; Adherence; Global implementa-

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1 Global Status and Disparities in Exercise-Based Cardiac Rehabilitation

Acute myocardial infarction (AMI) represents a major global cardiovascular disease with high mortality and morbidity. Although therapeutic strategies such as percutaneous coronary intervention (PCI) have significantly improved short-term survival, long-term management remains challenging. Post-PCI patients frequently experience ventricular remodeling and recurrent cardiovascular events, substantially affecting long-term prognosis and reducing quality of life [1-2]. Guideline-recommended cardiac rehabilitation (CR) has emerged as a critical intervention, with exercise-based cardiac rehabilitation (EBCR) serving as the core component that effectively reduces cardiovascular event incidence, improves cardiopulmonary function, and extends survival [3-4]. Psychosocial disorders such as anxiety and depression commonly afflict AMI patients, acting as significant barriers to CR participation and increasing the risk of adverse cardiovascular events [5]. Meta-analyses have demonstrated that EBCR reduces all-cause mortality and hospitalization rates while improving mental health and health-related quality of life (HRQoL) [6]. Advancing research in CR has propelled the development of multimodal exercise protocols, including aerobic exercise, resistance training, low-intensity training, moderate-intensity continuous training (MICT), and high-intensity interval training (HIIT), creating a diversified selection system that significantly enhances individualized patient adaptation [7-9]. Rehabilitation pathway design must precisely match patient age characteristics, psychological assessment data, and baseline fitness levels, as this individualized adaptation mechanism directly influences the long-term prognostic efficacy of EBCR [10]. Technological innovations such as wearable biosensors and remote rehabilitation platforms are transforming rehabilitation medicine, with real-time physiological parameter tracking combined with dynamic protocol optimization effectively improving treatment adherence and reducing CR risk events [11-14]. Globally, EBCR implementation shows marked regional disparities: lower-middle-income countries (LMICs) face constraints from weak medical infrastructure and professional workforce shortages, while high-income countries (HICs) grapple with healthcare cost pressures and insufficient patient engagement [9]. A critical scientific challenge in CR implementation involves effectively integrating diversified intervention modalities with customized strategies to meet the differential needs of patient populations [4,14-15]. Clinical practice urgently requires systematic integration of multidimensional intervention approaches, with dynamic optimization of individualized rehabilitation pathways gradually emerging as a crucial breakthrough in CR research transformation.

1.1 Disparities in Global Participation Rates and Underlying Causes

EBCR maintains significant clinical value in the comprehensive management of coronary heart disease (CHD), substantially improving AMI patient outcomes. Multiple studies [6,16] have demonstrated that EBCR not only effectively reduces all-cause mortality and readmission risk but also shows clear advantages in cardiovascular risk factor modification, including blood pressure control, lipid management, and weight control, with its secondary preventive role achieving broad consensus. However, despite these clinical benefits, global EBCR participation remains low. Data indicate [17-18] that pre-pandemic participation rates in Europe were below 15%, while in the United States, only 5% participated over the past 15 years, with the pandemic further straining healthcare resources and compressing rehabilitation service accessibility. Although HICs have relatively robust rehabilitation systems, service utilization remains limited; in LMICs, constrained by medical resource gaps, weak infrastructure, and patient awareness factors, over 50% of rehabilitation needs remain unmet [19].

The stark disparities in rehabilitation participation stem from complex, multifactorial causes. Imbalanced medical resource allocation across regions and insufficient grassroots service accessibility constitute primary bottlenecks. Rural populations show urgent rehabilitation needs, yet limited transportation and infrastructure result in lower participation willingness and rates compared to urban residents. A study of 1,809 patients revealed that rural populations had a rehabilitation participation rate of only 11.9%, with higher rehabilitation barrier scores than urban residents ($P<0.01$), highlighting the substantial rehabilitation challenges faced by rural patients [20]. A multinational multicenter study across eight countries involving 1,213 patients identified that geographic isolation severely restricts rehabilitation service accessibility, with patients in medically underserved areas struggling to access timely rehabilitation services [21]. Even in HICs with well-established healthcare systems, geographic factors significantly impact participation rates. Canada has established approximately 170 CR programs, yet northern regions remain nearly devoid of services, with imbalanced regional medical resource distribution significantly increasing patient difficulty in accessing services [22].

Economic burden represents another major barrier to rehabilitation participation. In some countries, citizens may need to spend more than half their annual income to complete a full CR program, whereas in HICs this expenditure typically accounts for less than 10% of annual income. Globally, approximately 2.41 billion people urgently need CR services; resource allocation imbalances, particularly in LMICs, combined with funding shortages and lack of medical reimbursement mechanisms, severely constrain EBCR accessibility [23-24]. Patients also face hidden costs such as transportation and accommodation, which further exacerbate economic burden and weaken rehabilitation willingness. Cognitive biases also impede participation, as many patients harbor misconceptions about EBCR, mistakenly believing that rehabilitation training will increase cardiac strain and therefore avoiding it. Each rehabilitation session reduces mortality or readmission probability by 2%, with risk decreasing by 10% after completing five CR sessions [17,25-26]. Cultural beliefs and social environments also influence CR adoption, as some patients worry that rehabilitation training may cause disease recurrence and consequently resist EBCR [18].

1.2 Innovative Models and Technological Approaches

Community-based cardiac rehabilitation (CBCR) has emerged in recent years to enhance EBCR accessibility and patient adherence. Studies show that 65.3% of patients successfully participated in CBCR, with only 5.3% dropping out during follow-up [27]. CBCR improves patient HRQoL, psychological status, and exercise endurance, reducing anxiety and depression while increasing 6-minute walk test distance by an average of 57.42 meters [22,24,27]. In resource-scarce regions, CBCR similarly reduces cardiovascular event recurrence risk by decreasing transportation and economic burdens while increasing program participation rates [28]. The CBCR model promotes widespread health intervention application, proving particularly suitable for low-income populations. In sub-Saharan Africa, telemedicine reduced patient waiting times by 30% and medical costs by 20%, improving local residents' access to healthcare services [29]. Iterative innovation in telemedicine technology is breaking through traditional geographic limitations. In Uganda, 40% of rural patients obtained professional services through telemedicine, reducing long-distance medical needs by 50% [30]. Wearable technology significantly improves patient adherence. Healthcare institutions can monitor patient exercise volume, heart rate, and other data in real-time, enabling precise remote management that substantially improves maximal oxygen uptake (VO2max) in AMI patients through remote rehabilitation, thereby supporting subsequent treatment [31].

1.3 Policy Support and Educational Promotion

Healthcare policy adjustments profoundly impact EBCR participation, with out-of-pocket expenses directly affecting rehabilitation adherence. If initial rehabilitation assessment costs exceed $25.40, participation rates drop sharply by 30.9%; each additional $10 in out-of-pocket expenses reduces average rehabilitation participation frequency by 0.41 sessions [25]. Alleviating economic burden is crucial for patient participation. Improving EBCR participation rates requires policy intervention, with optimization of medical insurance policies, promotion of remote rehabilitation, and reduction of patients' financial burden all contributing to enhanced accessibility.

Multinational practices have validated the effectiveness of policy interventions in improving CR participation. The United States' "Million Hearts" program increased EBCR participation from below 20% to 70% through financial assistance and free rehabilitation services [23]. Such policy models demonstrate diverse implementation forms in Commonwealth countries: the United Kingdom adopts joint action between healthcare systems and non-profit organizations, Australia establishes a bidirectional collaboration mechanism between the Heart

Foundation and government, while Ontario, Canada, meets low-income group needs through public insurance programs. Important strategies for improving adherence also include health education. Systematic health education increases patient rehabilitation adherence rates by 30%, with online education platforms breaking geographic restrictions and increasing rural participation rates by 25% [32]. Educational lectures for new patients can effectively alleviate anxiety and accelerate integration into the rehabilitation environment [33]. Cultural adaptation concepts demonstrate unique value in LMICs; Pakistan' s "Getting Better Bite by Bite" project improved rehabilitation knowledge acceptance and participation continuity by integrating traditional religious elements with modern medical understanding through localized psychological intervention design [34]. Uneven medical resource allocation limits EBCR program popularization, urgently requiring breakthroughs in establishing standardized intervention pathways and optimizing regional implementation plans [6].

2 Multimodal Interventions in Exercise-Based Cardiac Rehabilitation

2.1 Aerobic Exercise: The Foundation of EBCR

Aerobic exercise has been widely proven to improve cardiovascular health and reduce adverse cardiovascular events, forming the core EBCR intervention. Multiple clinical trials [6,35-37] have confirmed that CR reduces mortality risk by 63% in acute coronary syndrome patients and 38% in coronary artery bypass grafting patients, while decreasing reinfarction risk by 47%, cardiovascular mortality by 36%, and all-cause mortality by 26%. Aerobic exercise significantly enhances myocardial functional adaptation, manifested by increased stroke volume, improved cardiac systolic and diastolic function, and reduced ventricular remodeling [36]. Mechanistic studies reveal that heart rate variability significantly improves after 4 weeks of EBCR in myocardial infarction patients; after 6 months of continuous intervention, muscle sympathetic nerve activity decreases, arterial systolic pressure declines, and autonomic blood pressure regulation capacity enhances, promoting hemodynamic parameters toward physiological states [38-39]. Exercise-mediated anti-inflammatory effects constitute another key mechanism. Research shows that exercise-induced cytokine responses are specific, not causing significant elevation of classical pro-inflammatory factors like tumor necrosis factor-α and interleukin (IL)-1β, but instead temporarily increasing IL-6 concentration to activate IL-10 secretion and IL-1 receptor antagonist release pathways, forming an anti-inflammatory protective barrier that alleviates pathological cardiovascular damage [40]. In practical application, guidelines recommend exercise intensity be controlled at 40%-80% of peak oxygen uptake (VO2peak): frail or elderly patients should adopt low-intensity training at 40%-50% VO2peak, while physically fit individuals may utilize MICT or HIIT to maintain VO2peak at 60%-80% [41]. For patients constrained by facility limitations or poor adherence, wearable device applications become effective solutions for remote CR. Real-time monitoring of heart rate and exercise volume through wearable devices enables optimization of individualized training protocols, improving aerobic exercise adherence and training effectiveness [33,42].

2.2 Resistance Training and Aerobic Intensity Graded Training: Key Complements to EBCR

Resistance training occupies a critical position in EBCR protocols, effectively improving exercise tolerance and optimizing skeletal health indicators by enhancing muscle strength in AMI patients. Research evidence demonstrates that EBCR interventions produce multifaceted functional improvements, with combined resistance and multi-intensity aerobic training strategies showing particularly significant clinical effects [41-43]. Comparing rehabilitation responses between post-PCI heart failure AMI patients reveals that AMI patients demonstrate faster improvements in muscle strength recovery and training adaptation, suggesting that pathological type differences may affect intervention responsiveness. Furthermore, this study found that postoperative patient muscle torque growth showed moderate correlation with peak oxygen uptake ($r=0.51$, $P<0.01$), indicating that muscle strength enhancement may participate in cardiopulmonary function recovery mechanisms. Systematic review results further support these findings. Yamamoto et al.' s [44] meta-analysis showed that resistance training produced moderate-to-large effect size improvements across multiple dimensions. Middle-aged patients exhibited lower and upper limb strength improvements of 0.65 (95%CI=0.35~0.95) and 0.73 (95%CI=0.48~0.99) standardized mean differences (SMD), respectively, with peak oxygen uptake increasing by 0.92 (95%CI=0.12~1.72) $mL \cdot kg^{-1} \cdot min^{-1}$; elderly patients showed significant improvements in upper limb strength (1.18 SMD, 95%CI=0.56~1.80) and daily activity capacity (0.61 SMD, 95%CI=0.21~1.01). These results suggest that EBCR combined with resistance training can synergistically promote muscle reconstruction and cardiopulmonary function recovery across different age groups and coronary artery disease pathologies. Early research controversies regarding resistance training' s cardiovascular risk have been resolved by recent evidence showing that medically supervised low-to-moderate intensity training (40%-60% one-repetition maximum) produces blood pressure changes essentially equivalent to same-intensity aerobic exercise. Studies have confirmed that hemodynamically stable CHD patients can not only improve cardiovascular adaptability but also enhance metabolic indicators and psychological health status through low-to-moderate intensity resistance training [45]. Low-intensity training and MICT protocols introduced during AMI early rehabilitation demonstrate good safety, with heart failure patients receiving 2-week interventions showing significantly reduced cardiac mortality and readmission rates compared to conventional rehabilitation groups [46]. In-depth analysis of this training mode' s positive effects on heart failure patients with different ejection fractions revealed that compared to control groups, heart failure with reduced ejection fraction (HFrEF) patients showed decreased cardiac mortality (31.3% vs 0.0%, $P=0.002$), while heart failure with mid-range ejection fraction (HFmrEF) patients showed reduced readmission rates (22.1% vs 3.6%, $P=0.008$). Additionally, when AMI patients' end-tidal carbon dioxide partial pressure ($PETCO_2$) at anaerobic threshold during cardiopulmonary exercise testing was $ $3.5 mmHg (1 mmHg=0.133 kPa), their readmission risk increased significantly (OR=0.635, 95%CI=0.463~0.871, P=0.005), suggesting this indicator' s important application value in early EBCR efficacy assessment and prognostic prediction while validating resistance training' s clinical safety and effectiveness as a rehabilitation intervention.

Aerobic exercise intensity grading continues to generate research attention in EBCR. HIIT can achieve synergistic improvement in ventricular structure and function by inhibiting progressive ventricular wall thinning and improving diastolic function [47]. During 16-week training periods, its effects on ventricular remodeling show volume-dependency with clear dose-dependent characteristics. Furthermore, short-duration HIIT protocols (single session time $ $20 minutes, with high-intensity phases $ 10minutes)demonstrateuniquetherapeuticvalueinclinicalpractice.Undersafety−assuredconditions, short−durationHIITeffectivelydelayspathologicalventricularremodelingprogressionth basedsupportforindividualizedCRprescriptionformulation.Studiesonelderlypopulations[48]showedthatcom exercisecontrols, resistancetraining, HIIT, andcombinedtrainingsignificantlyimprovedBMI(P $0.0001), body fat percentage (P=0.03), aerobic endurance (P=0.03), low-density lipoprotein (P=0.04), and blood glucose levels (P=0.02), though how to optimally combine resistance training with HIIT requires further investigation. A major future EBCR development focus involves identifying training modes with optimal patient suitability, necessitating integration of resistance training into aerobic exercise to balance HIIT' s efficiency with MICT' s high adherence.

2.3 Aerobic and Mind-Body Balance: Synergistic Effects in EBCR

Swimming, as a low-impact, whole-body exercise, demonstrates significant potential benefits in EBCR, particularly in improving exercise capacity, enhancing muscle strength, and improving HRQoL. Research indicates that swimming training effectively improves cardiovascular function and promotes cardiac functional recovery, providing an entertaining yet functional exercise modality for AMI patients with stable heart failure and CHD [49-50]. Swimming training' s multidimensional health benefits give it auxiliary intervention potential within EBCR systems, though implementation requires strict adherence to personalized exercise prescriptions under medical supervision. Meanwhile, yoga' s mind-body integration characteristics show broad application prospects in CR. Research demonstrates that yoga interventions can optimize physiological indicators, regulate emotions, alleviate psychological stress, reduce 10-year cardiovascular disease risk, and improve Framingham risk scores, providing comprehensive health management strategies for EBCR [51]. Yoga' s regulatory function on the autonomic nervous system has been confirmed. In AMI patients receiving standard medical treatment, regular yoga training effectively reestablishes dynamic balance between sympathetic and parasympathetic nerves, not only enhancing parasympathetic activity and heart rate variability parameters but also significantly reducing adverse cardiovascular event rates by improving stress adaptation capacity, while synchronously improving HRQoL and psychosocial function [52]. Swimming emphasizes cardiopulmonary endurance enhancement, while yoga excels at promoting neural regulation and psychological health. In EBCR, both modalities possess distinct characteristics and complementary advantages. Their potential synergistic effects may enable more comprehensive and personalized treatment strategies for CR patients. Integrating cardiopulmonary endurance training with mind-body regulation may more effectively promote dual improvement in cardiovascular health and quality of life, jointly building CR bridges.

2.4 Combined Training and Multidimensional Interventions: Comprehensive EBCR Strategies

Combined training, integrating aerobic and resistance exercise, is recognized as an effective strategy for maximizing cardiovascular health improvements. Research confirms that compared to single-mode aerobic exercise, combined training significantly improves cardiorespiratory fitness, increases muscle strength, and optimizes body composition [53]. Meta-analyses further demonstrate that combined training reduces body fat percentage (SMD=-2.30, 95%CI=-3.59~-1.02), decreases trunk fat (SMD=-0.56, 95%CI=-0.96~-0.15), and promotes fat-free mass increase (SMD=0.90, 95%CI=0.39~1.36) [54]. Resistance training shows clear advantages in improving upper and lower limb muscle strength, with SMDs of 1.07 (95%CI=0.51~1.63) and 0.77 (95%CI=0.21~1.33), respectively [55]. Short-term intervention studies reveal that 8-week combined training reduces diastolic blood pressure, increases lean body mass, and significantly improves cardiopulmonary health, showing superior effects in hypertensive and high cardiovascular risk populations [55]; long-term intervention studies indicate that 8 months of continuous training stabilizes blood pressure and improves exercise capacity, while oxidative stress level regulation requires longer intervention periods for consolidation [56]. Elderly patients also benefit from combined training, showing enhanced muscle strength (SMD=0.60, 95%CI=0.43~0.77), improved aerobic capacity (SMD=2.71, 95%CI=1.96~3.45), and HRQoL improvement (SMD=-5.71, 95%CI=-9.85~-1.56) [57]. PRIME-HF study data show that the 8-week PRIME training protocol significantly increased VO_2peak by 2.4 $mL \cdot kg^{-1} \cdot min^{-1}$ (P=0.004), demonstrating superior efficacy compared to traditional interventions [57]. Recent research progress indicates that multidimensional intervention strategies based on resistance training systems combined with aerobic exercise intensity grading standards (low-intensity, MICT, or HIIT) are gradually developing into emerging rehabilitation models, opening comprehensive treatment options for clinical practice [7-9].

Exercise intervention is not the sole core of combined training; systematic integration of nutritional management and psychological support has become a key pathway for optimizing multidimensional rehabilitation effects. Depression incidence in AMI patients is significantly higher than in the general population

(15%-20% vs 4.8%), and inadequate intervention worsens cardiovascular prognosis. Cognitive behavioral therapy (CBT) has been proven to alleviate 25%-30% of depressive symptoms and improve rehabilitation adherence [58]; at the dietary strategy level, Mediterranean diet can reduce major cardiovascular event risk by 31% (RR=0.69, 95%CI=0.53-0.91) and 28% (RR=0.72, 95%CI=0.54~0.95) in high cardiovascular risk populations [59]. The synergistic effect of psychological support and nutritional intervention enables EBCR protocols to present multidimensional benefits in HRQoL improvement and long-term prognosis optimization. Expanding multidimensional intervention models based on the EBCR framework has become an inevitable trend for optimizing synergistic development of cardiopulmonary fitness and muscle function, involving multidimensional integration effects of the bio-psycho-social medical model.

3 Personalized Strategies in Exercise-Based Cardiac Rehabilitation

3.1 Customized Exercise Interventions: Precision Exercise Protocol Design

In EBCR, meticulous design of personalized pathways constitutes a key success factor. Elderly AMI patients receiving individualized exercise training showed significant improvements in heart rate recovery, VO_2peak, and ventilatory efficiency (P<0.001), while those receiving conventional exercise advice alone showed no similar benefits [60]. The American College of Sports Medicine strongly recommends progressive personalized exercise strategies for elderly patients to enhance muscle strength and endurance while minimizing injury risk and improving adherence [61]. After 8 weeks of comprehensive CR, elderly patients showed significantly decreased LDL-C levels (P<0.001), improved exercise capacity (P<0.001), and enhanced quality of life scores, with significant improvements in both physical and emotional dimension scores [62]. Even when elderly patients have lower CR participation rates, individualized training can produce health benefits comparable to younger patients, significantly optimizing overall health status [63]. For physically fit younger populations, HIIT demonstrates unique advantages in VO_2max gains. Research results show that 8-week HIIT intervention can increase VO_2max by an average of (6.5%$\pm 2.4\times 20 sprotocol (3.3\pm 2.4\times 30 sgroup. In 3,000 mendurancetesting, theHIITgroupachieved (5.9\pm 3.2\times 3$ 0.01)$, withsignificantnegativecorrelationbetweenthetwochanges; improvementsinmetabolicsyndromecorein$ increase and visceral fat reduction (P<0.05) [64-65], confirming synergistic effects of cardiopulmonary function optimization on metabolic regulation. Compared with continuous moderate exercise, intermittent training HIIT and MICT demonstrate superior biological effects in metabolic sensitivity, BMI regulation, and insulin resistance mitigation, providing evidence-based support for developing EBCR protocols for younger individuals.

For female AMI patients facing rehabilitation challenges, psychological factors have been identified as key variables affecting prognosis. JUG et al.' s [68] research indicates that female patients have significantly higher psychological support needs than males, with increased psychological intervention effectively improving CR participation rates. TURNER et al.' s [69] study further confirms that targeted psychological counseling and peer support can enhance patients' confidence in overcoming disease and improve long-term cardiovascular disease prognosis. The synergistic effect of EBCR protocols and psychological interventions essentially constructs a novel therapeutic paradigm with dual bio-psycho action targets.

3.2 Integration of Psychological and Behavioral Factors: Enhancing Rehabilitation Adherence and Efficacy

Psychological and behavioral factors play crucial roles in AMI patient rehabilitation. Kinesiophobia prevalence among cardiac patients reaches as high as 61.0% (95%CI=49.4%~72.6%), with CHD patients showing 63.2% prevalence (95%CI=45.2%~81.3%), significantly affecting exercise adherence and highlighting the clinical importance of early psychological intervention in CR [70]. AMI patients commonly experience comorbid psychological issues such as depression and anxiety after the acute phase, which not only increase disease burden but may also create key obstacles restricting rehabilitation progress [5]. CBT significantly improves patient self-efficacy by correcting erroneous beliefs and establishing positive coping mechanisms; motivational interviewing techniques enhance intrinsic motivation for behavioral change through goal-directed dialogue patterns [71-72]. From a behavioral medicine perspective, exercise avoidance behaviors often stem from risk perception biases and rehabilitation knowledge deficits, requiring intervention protocols to address both physiological and psychological dimensions. Systematic health education strategies significantly improve patient acceptance of exercise therapy by explaining rehabilitation mechanisms and clarifying cognitive misconceptions. Research confirms that structured educational interventions reduce kinesiophobia scale scores and double the proportion of patients regularly participating in rehabilitation training [73-74]. Constructing an intervention system integrating psychological and behavioral dimensions has become an important research direction for breaking through traditional CR model bottlenecks.

3.3 Technology Integration and Innovation: Driving Precision in Personalized Rehabilitation

EBCR is maturing through technological innovation, enabling realization of personalized rehabilitation protocols. Medical teams can optimize rehabilitation protocols using detailed data such as heart rate, step count, and exercise intensity monitored in real-time through smartwatches and other wearable devices, making rehabilitation processes more precise and manageable. Research shows [75] that smart device-based remote rehabilitation protocols can increase VO_2peak in AMI patients by 1.56 $mL \cdot kg^{-1} \cdot min^{-1}$ after 3 months of intervention, with efficacy comparable to traditional offline rehabilitation. For patients with poorer baseline functional capacity, VO_2peak improvement is more significant at 2.46 $mL \cdot kg^{-1} \cdot min^{-1}$, accompanied by 60m increase in 6-minute walk distance (P=0.045), further validating remote personalized CR's clinical value in high-risk subgroups. Technology empowerment enables rehabilitation processes with data-driven characteristics, with enhanced patient autonomy and security directly promoting treatment adherence improvement. Remote medical systems break geographic barriers, allowing quality resources to cover remote and medically underserved areas, achieving universal rehabilitation services, with remote monitoring combined with real-time guidance constructing continuous management loops. A meta-analysis showed that remote CR significantly improved patient VO_2peak and HRQoL, with intervention completion rates reaching 80%, demonstrating excellent feasibility and adherence [76]. During the pandemic prevention and control period, low-contact rehabilitation protocols effectively avoided nosocomial infection risks, with continuous home-based interventions alleviating subjects' medical environment anxiety [77]. The wave of artificial intelligence (AI) is profoundly transforming the CR field. Cardiovascular event risk assessment, previously limited by traditional methods, now achieves precise risk prediction and personalized intervention through AI' s deep mining of massive data and construction of advanced algorithm models. Exercise prescriptions optimized through machine learning (ML) technology can substantially improve patient treatment compliance and rehabilitation effectiveness [78]. Home-based rehabilitation models, long constrained by lack of professional guidance and immediate feedback, have been revolutionized by the organic integration of telemedicine and AI, spawning the innovative "hospital guidance + home rehabilitation" pathway. This approach not only improves patient cardiopulmonary endurance but also brings new hope for behavioral management and treatment adherence, ushering EBCR long-term management into a new development stage [79].

3.4 Socioeconomic and Cultural Adaptation: Improving Rehabilitation Accessibility and Participation

Social resource allocation patterns and cultural cognitive models jointly shape CR service accessibility characteristics. Economically underdeveloped regions commonly experience structural medical resource imbalances, urgently requiring establishment of community ecology-based differentiated intervention frameworks. Precise economic support deployment must advance synergistically with cultural adaptation mechanisms, integrating community medical resource networks to construct CR service delivery systems covering different social strata. Economically disadvantaged groups face dual dilemmas: CR participation directly affects health reconstruction processes, while medical expenditure pressures may exacerbate family economic vulnerability. At the cultural conceptual level, cognitive biases manifest as some patients equating rehabilitation training with "weakness labels," leading to symbolic cognition that causes significant regional differences in service utilization. Economic incentive measures increased CR completion rates from 11% to 42% in low socioeconomic status patients, rising further to 62% under combined interventions, significantly improving adherence [80]. Remote areas constrained by transportation conditions and medical resource insufficiency have long experienced stagnant CR implementation effects at 11.2%. Telemedicine significantly reduces CR non-completion risk (OR=0.26), while rehabilitated patients' readmission and mortality risks decrease by approximately 35% (HR=0.65) within 12 months, demonstrating technology' s important potential in improving adherence and outcomes [81]. The synergistic application of economic assistance and technological means not only breaks through regional medical resource limitations but also alleviates economic pressure and expands service accessibility through dual pathways, effectively improving CR implementation effects. Cultural background differences directly constrain clinical adoption depth of CR protocols. Culturally adapted CR programs have proven to have good acceptability and safety, effectively improving cardiovascular risk factors, with success dependent on community-led design, cultural sensitivity training, and organic integration of traditional practices [82]. Culturally adapted CR interventions for ethnic minority communities help improve patient participation and program completion rates, while incorporating religious and cultural elements into rehabilitation environments enhances emotional identification and treatment acceptance among traditional community patients [83]. Residence more than 16 km from rehabilitation centers is the strongest predictor of EBCR non-participation (OR=1.75), with smoking, chronic comorbidities, male gender, and retirement status also being significant influencing factors, suggesting that optimizing resource layout and sociocultural adaptation are key pathways to improving rehabilitation accessibility and participation [84]. Healthcare system cultural inclusivity reconstruction and socioeconomic support are becoming crucial pathways for optimizing CR outcomes.

4 Advanced Strategies and Future Directions

4.1.1 Optimizing Personalized Initiation Timing: EBCR can significantly reduce all-cause mortality and recurrent infarction risk in AMI patients [6,26,85]. While all-cause mortality showed no statistical difference during extended follow-up periods (RR=0.91, 95%CI=0.75~1.10), the intervention strategy demonstrated significant effects on cardiovascular-specific mortality (RR=0.58, 95%CI=0.43~0.78) and MI incidence (RR=0.67, 95%CI=0.50~0.90) [85]. Determining optimal initiation timing directly affects intervention efficacy, prompting academic efforts to construct precision individualized implementation models. Initiating EBCR within 2 weeks post-AMI is safe and beneficial, not impairing left ventricular ejection fraction (LVEF) and myocardial function while promoting cardiac functional recovery [86]. The feasibility of early exercise intervention is also corroborated by other studies; in a 6-week follow-up study, patients receiving exercise intervention showed significantly improved LVEF without observed exercise-related adverse events [87]. Left ventricular systolic and diastolic function can also be significantly improved through exercise training initiated within 1 week post-AMI. Another retrospective analysis found that compared to conventional rehabilitation, early home-based exercise intervention resulted in lower postoperative complication rates (3.45% vs 17.54%, $P<0.05$) with significantly improved LVEF and HRQoL scores [88]. Current evidence reveals positive effects of early EBCR on cardiac structural remodeling and functional recovery [89]. Subsequent meta-analyses validated these conclusions, finding that EBCR intervention during the acute phase (within 1 week) showed advantages over the recovery phase (2-4 weeks) in improving LVEF, left ventricular end-systolic diameter, and increasing VO_2peak [89]. However, myocardial healing processes accompany rehabilitation benefit attenuation phenomena; implementing EBCR beyond 4 weeks not only reduces cardiac functional recovery magnitude but may also trigger cardiac adaptation disorders [86]. Clinical observations show that early EBCR does not significantly increase cardiovascular adverse event risk [90]; age, comorbidities, and economic factors cause some groups to miss optimal intervention windows, while lifelong EBCR training can effectively maintain left ventricular systolic function and delay post-AMI structural abnormalities [91]. ZHANG et al.' s [92] meta-analysis found that AMI patient rehabilitation requires breaking through single exercise training modes, integrating physiological status assessment, psychological adaptability analysis, and personalized goal setting to form multidimensional intervention systems, suggesting that clinical practice needs to establish dynamic EBCR implementation frameworks that precisely regulate intervention timing based on pathological staging and tolerance thresholds to achieve long-term prognosis optimization through adherence management under safety-assured conditions.

4.1.2 Exploring Optimal Exercise Mode and Intensity Combinations: Exercise mode and intensity optimization represents an important direction in EBCR research and practice. Different implementation modes produce multidimensional impacts on patient health outcomes. EBCR protocols improved Minnesota Living with Heart Failure Questionnaire scores by 7.11 points (95%CI=-10.49~-3.73) and relatively reduced all-cause hospitalization risk by 30% (RR=0.70, 95%CI=0.60~0.83) [93], with clinical value reflected in dual dimenloads in heart failure populations may cause psychological stress and adherence issues [94]; MICT protocols show relatively lower exercise endurance improvement due to intensity controllability advantages but achieve higher long-term participation rates, reaching 80% [65,93]. These complementary characteristics suggest that training parameters should be dynamically adjusted based on patient cardiopulmonary function baseline levels. In EBCR mode selection processes, precision intervention strategies must be implemented considering comprehensive factors including patient physical status, psychological adaptation level, and rehabilitation progression. MICT has universal advantages, while HIIT specifically enhances rehabilitation effects in individuals with higher cardiopulmonary function reserves. Hybrid exercise models integrating HIIT' s efficiency with MICT' s adherence advantages are becoming an emerging direction in EBCR. Through dynamic exercise load regulation, these protocols can match rehabilitation needs across different tolerance threshold populations, enhancing rehabilitation confidence while ensuring training safety and achieving sustained execution of medium-to-long-term exercise prescriptions [95].

Remote monitoring and smart devices have significantly advanced refined implementation of EBCR in individualized rehabilitation. Studies show that combining remote CR monitoring with personalized feedback increased patient adherence rates from 29.2% to 80.8%, with interventions significantly improving metabolic indicators including increased high-density lipoprotein levels and decreased BMI, while also alleviating anxiety and depression levels, demonstrating remote CR' s comprehensive potential in improving multidimensional health indicators [96].

4.1.3 Challenges and Strategies for Long-Term Adherence and Behavioral Change: EBCR effectiveness hinges on patient long-term adherence, yet patients face numerous challenges in practice. Even though short-term rehabilitation substantially improves HRQoL, only 30%-50% of patients maintain initial exercise levels after 12 months [97]. Reduced treatment adherence is constrained by multiple factors: weak patient cognition of rehabilitation value, incomplete social support networks, and complex psychological mechanism interference; economically disadvantaged groups and female patients face triple pressures from economic burden, family caregiving needs, and social role conflicts, presenting significant challenges to rehabilitation program sustainability [98]; severe homogenization of exercise prescriptions and lack of personalized guidance cause continuous decay in patient participation enthusiasm, particularly prominent during long-term rehabilitation processes. Smart monitoring devices and remote support systems synergistically applied can effectively overcome traditional rehabilitation model limitations, with research confirming that this strategy provides alternative pathways for groups unable to participate in offline CR, not only improving treatment adherence but also significantly improving multiple physiological indicators [27,30]. Real-time data tracking combined with dynamic incentive mechanisms breaks geographic restrictions and assists patients in establishing continuous rehabilitation behavior patterns. Intervention models combining CBT strategies with community support provide practical directions for improving long-term adherence in elderly patients and socially unsupported populations [71,98].

4.2 Technology Innovation Driving Intelligence and Precision

Cardiovascular disease diagnosis and treatment is undergoing an intelligent precision transformation, with AI and ML technologies driving personalized rehabilitation system construction. Virtual reality (VR), augmented reality (AR), and other digital therapeutics break through traditional CR models, enabling dynamic treatment process optimization. ML systems integrate multidimensional data including electronic medical records, ECG signals, and novel biomarkers to construct risk assessment frameworks supporting clinical decision-making. CCHIA database research confirmed that integrated random forest and XGBoost algorithms significantly improved prognostic assessment efficacy, with random forest model C-statistics reaching 0.83, representing a 12% improvement over logistic regression baseline; introducing hemodynamic indicators such as pre-ejection period and brachial ejection time increased algorithm sensitivity to 91%, advancing CR secondary prevention strategies to implement comprehensive interventions during early disease stages [99].

In the CR field, AI technology significantly enhances personalization of patient rehabilitation experiences. AI algorithms monitor patient heart rate, respiration, and exercise status in real-time, dynamically adjusting rehabilitation intensity accordingly to ensure safety and optimize rehabilitation effects. The SmartCare-CAD study confirmed this: remote rehabilitation models using wearable devices improved patient physical activity and HRQoL, reduced medical resource consumption, and brought great convenience to patients restricted by geographic location or economic conditions [100]. Nevertheless, psychological factors cannot be ignored during EBCR processes, particularly kinesiophobia as a major obstacle to rehabilitation participation. 54%-70% of HF patients experience varying degrees of exercise fear, a psychological barrier closely related to reduced exercise capacity, emotional disorders, and poor rehabilitation adherence that may persist for extended periods during patient rehabilitation [71,101]. VR and AR technology applications provide innovative solutions for rehabilitation medicine. Immersive virtual environments can simulate real exercise scenarios, enabling patients to conduct gait coordination training, balance function recovery, and cardiopulmonary endurance enhancement under safe, controlled conditions, directly promoting motor system function reconstruction. For medium-low risk patient populations, interactive training modes in three-dimensional space can significantly optimize motor function performance [102-103]. Meta-analyses indicate that VR-assisted EBCR shows significant advantages over conventional therapy in anxiety and depression intervention, with its immersive scene construction capability driving traditional CR system iterative upgrading [104]. Smart wearable devices continuously capture ECG signals, blood oxygen concentration, and body surface temperature parameters through multimodal sensing technology, relying on ML models for dynamic physiological indicator analysis. Once monitoring data exceed safety thresholds, device terminals trigger immediate warning mechanisms to guide patients toward timely intervention or contact with medical personnel. This innovative model integrating edge computing and mobile medicine provides new technical paradigms for precise CR guidance. A prospective cohort study of 16,741 elderly women showed that higher daily step counts correlated with lower all-cause mortality risk; when step count reached approximately 7,500 steps, health benefits stabilized with limited additional gains from further increases [105]. Researchers using wrist-worn heart rate monitors and triaxial accelerometers for continuous patient activity monitoring and personalized feedback have achieved effectiveness in improving physical activity and HRQoL in low-risk CHD patients through remote rehabilitation plans, comparable to traditional rehabilitation but at lower implementation cost [106]. If patient activity decreases by 50%, monitoring systems can trigger alerts for timely intervention [100,107]. The fusion of AI, ML, AR, and smart wearable devices continuously promotes CR field intelligence and precision development, laying foundations for achieving more efficient and scientific cardiovascular disease rehabilitation goals.

4.3.1 Integration of Psychological Support and Nutritional Intervention: Depression and anxiety are common among CHD patients, increasing mortality probability and reducing HRQoL [108-109]. CBT can significantly improve mental health in CHD, heart failure, and atrial fibrillation patients, providing positive rehabilitation support, as confirmed by related systematic meta-analyses [110-111]. Integration of mental health and nutritional intervention represents a key future EBCR development direction. CBT rehabilitation models can effectively reduce patient depression and improve HRQoL [112]. Patients with major depressive disorder should receive regular depression screening, and according to primary care guidelines, may adopt CBT combined with selective serotonin reuptake inhibitor intervention strategies when necessary to improve psychological status, rehabilitation adherence, and long-term efficacy [113-114]. Additionally, individualized nutritional intervention holds important significance in cardiovascular health improvement. Related studies show that increased dietary fiber intake can effectively reduce cardiovascular risk, while omega-3 fatty acid supplementation helps mitigate inflammatory responses and stabilize cardiac rhythm, showing significant effects in preventing and adjuvantly treating cardiovascular diseases [115-116]. Although EBCR shows significant effects in improving mental health and quality of life, current EBCR-related research remains insufficient, with many areas awaiting in-depth investigation.

4.3.2 Integration of Precision Medicine and Molecular Diagnostics: Rapid development in genomics and metabolomics provides new technical support for individualized and precision rehabilitation intervention strategies for cardiovascular disease patients. Research shows that PNPLA3 I148M (rs738409) and other gene variants are not only closely related to metabolic disorders but may also increase individual cardiovascular death risk, holding important reference value for rehabilitation pathway design [117]. Meanwhile, metabolomics-level research indicates that short-chain fatty acids (such as propionic acid, butyric acid, etc.) play key roles in maintaining cardiovascular system homeostasis and regulating immune function, with their levels serving as important indicators for measuring rehabilitation progress and effectiveness [118]. Multi-omics joint analysis-based research further reveals exercise intervention' s extensive effects at multiple tissue levels, with skeletal muscle, liver, and myocardium showing systematic changes in protein expression, metabolic pathways, and mitochondrial function. Integration of such multidimensional biological data improves rehabilitation effect prediction accuracy, providing theoretical basis for precise individualized exercise prescription formulation [119]. Additionally, for complex pathological states such as chronic inflammation and viral infections, amino acid metabolism abnormalities are considered key intervention targets, particularly tryptophan, glutamine, and arginine metabolic pathways whose roles in immune regulation, membrane repair, and cellular stress are receiving increasing attention, holding important significance for advancing precision rehabilitation intervention models [120].

4.3.3 Construction of Ecosystem-Based Rehabilitation Models: Ecosystem rehabilitation models are receiving increasing attention in cardiac rehabilitation applications. This model emphasizes multidisciplinary collaboration and individual-environment interaction, integrating physiological, psychological, and social factors to construct patient-centered rehabilitation pathways [121]. Digital means, ing cardiopulmonary function reserve, and enhancing HRQoL. However, clinical practice still faces multiple challenges including insufficient patient treatment adherence, uneven medical resource allocation, and socioeconomic condition constraints, particularly prominent in LMICs. With deepening rehabilitation medicine research, individualized exercise prescription has become an important research direction in this field, with multidimensional intervention schemes combining aerobic exercise intensity grading and resistance training providing more precise rehabilitation strategies for patients with different clinical characteristics. Notably, the synergistic application of psychological intervention and nutritional support further enhances overall rehabilitation efficacy. Meanwhile, technological innovation is reshaping traditional rehabilitation models, with wearable device and remote monitoring technology applications significantly improving rehabilitation service accessibility and patient adherence.

Looking forward, EBCR development will focus on three dimensions: precision rehabilitation, resource integration, and intelligent application. Through developing individualized rehabilitation protocols, constructing multidisciplinary collaboration systems, and applying digital health tools, EBCR popularization will be effectively promoted. Essentially, EBCR has transcended simple medical intervention to become an important model of proactive health management. Through continuous optimization of rehabilitation strategies, integrating technological innovation and medical resources, more quality rehabilitation services will be provided for AMI patients, thereby effectively reducing the global disease burden of cardiovascular diseases.

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Note: Figure translations are in progress. See original paper for figures.