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Left Atrial Remodeling After Anterior STEMI: A Randomized Trial of Continuous High-Intensity Versus Moderate-Intensity Aerobic Training in Post-PCI Cardiac Rehabilitation

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Abstract

Background and Aim: Myocardial infarction (MI) triggers adverse structural and functional cardiac remodeling. While moderate-intensity exercise-based cardiac rehabilitation (CR) improves recovery, emerging evidence suggests higher-intensity regimens may yield greater benefits. Although high-intensity interval training has demonstrated safety and efficacy in cardiac populations, the impact of high-intensity continuous aerobic training (HICT) on left atrial (LA) mechanics post-primary percutaneous coronary intervention (PCI) for anterior wall ST-segment elevation MI (STEMI) remains underexplored. This study aims to investigate the impact of HICT versus moderate-intensity continuous training (MICT) on LA mechanics in patients post-primary PCI for anterior STEMI.

Materials and Methods: In a single-center randomized controlled trial at Aim Shams University Hospital, 60 adults 1-month post-primary PCI for anterior STEMI were randomized to 6 weeks of CR involving either high-intensity continuous training [HICT; 80-90% peak heart rate (HR)] or (MICT; 50-70% peak HR). Participants completed 18 treadmill sessions (3/week). Diastolic function and LA mechanics (reservoir, conduit, contractile strains) were assessed via two-dimensional speckle-tracking echocardiography pre- and post-intervention.

Results: This study examined patients with a mean age of 51.82 years, predominantly male (91.7%). Both the HICT group and the comparator group exhibited improvements in LA mechanics and diastolic function, though intergroup differences were statistically non-significant. HICT group demonstrated numerically greater gains in LA reservoir strain (5.67±4.39% vs. 3.80±3.32%, $P = 0.115$) and LA contractile strain (-2.93±4.27% vs.-1.33±3.74%, $P = 0.110$). Similarly, reductions in diastolic indices were comparable between groups: E/A (0.14±0.12 vs. -0.14±0.14, $P = 0.927$) and E/E' (-0.25±0.16 vs. -0.30±0.34, $P = 0.568$). While trends favored HICT, no outcome reached statistical significance, suggesting comparable efficacy between interventions.

Conclusion: HICT and MICT show comparable safety and efficacy in enhancing cardiac function, suggesting exercise intensity may be tailored to patient preference or tolerance.

Keywords: High-intensity exercise, left atrial strain, cardiac rehabilitation, primary PCI, anterior STEMI.

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INTRODUCTION

Myocardial infarction (MI) induces substantial structural alterations in the heart, affecting both systolic and diastolic functions. Advances in diagnostic and therapeutic strategies have significantly reduced mortality rates from acute MI; however, rehabilitating acute MI (AMI) survivors remains a pressing public health concern.[1] For patients with ST-segment elevation MI (STEMI) who undergo primary percutaneous coronary intervention (PCI), moderate-intensity exercise is commonly recommended during cardiac rehabilitation (CR) to enhance cardiac function.[2] Emerging evidence, however, suggests that high-intensity exercise may provide superior benefits compared to moderate-intensity regimens in improving cardiovascular outcomes.[3]

CR programs traditionally include aerobic, resistance, and endurance exercises, with aerobic exercise categorized into low, moderate, and high intensities. Initially, low-intensity aerobic exercise was favored due to fears of triggering cardiac events.[4] However, research later confirmed the safety and effectiveness of moderate-intensity exercise in enhancing cardiovascular fitness and reducing risks. More recently, high-intensity interval training (HIIT) has gained recognition for significantly improving cardiovascular health, endothelial function, and patient prognosis. Despite early concerns, studies indicate that sustained high-intensity exercise when kept below the myocardial ischemic threshold is not only safe but may also boost myocardial blood flow and heart function. This evolution reflects a shift toward incorporating higher-intensity regimens as evidence of their benefits and safety grows.[3,5] Compared to HIIT, high-intensity continuous aerobic training (HICT) may be psychologically more acceptable to some cardiac patients, especially those in the early phase of rehabilitation. The structured nature of HIIT can promote confidence, reduce exercise-related anxiety, and improve adherence to long-term rehabilitation programs.

High-intensity continuous exercise is linked to reduced all-cause mortality and a lower risk of heart disease, independent of workout duration, and it is more effective than moderate-intensity exercise in improving cardiovascular risk factors, particularly through enhancing VO_2 peak. Biologically, high-intensity exercise triggers heightened calcium release, adenosin trifosfat turnover, and carbohydrate utilization, leading to metabolite, ion, and free radical accumulation. This accumulation is key to the activation of Ca+/calmodulin-dependent protein kinase II and AMP-activated protein kinase, which collectively stimulate the gene expression for peroxisome proliferator-activated receptor gamma coactivator 1-alpha. This cascade increases mitochondrial protein synthesis rates, resulting in greater mitochondrial content compared to moderate-intensity exercise, thereby enhancing metabolic and endurance adaptations.[2,6]

After a MI, the heart often undergoes adverse remodeling, leading to increased stiffness, impaired function, and collagen buildup. Exercise counteracts these effects by reducing fibrosis, promoting angiogenesis, and improving heart contraction and mitochondrial efficiency. These benefits arise through the modulation of hormonal systems (renin-angiotensin-aldosterone), the regulation of enzymes (matrix metalloproteinases), and the reduction of oxidative stress.[7] Speckle tracking echocardiography (STE) is highlighted as a sensitive imaging tool to assess heart deformation and strain, surpassing traditional metrics like ejection fraction. Left atrial (LA) strain analysis via STE has emerged as a sensitive tool to assess LA mechanics, which are critical for ventricular filling and cardiac output. In patients with anterior STEMI treated with primary PCI, LA dysfunction often precedes structural remodeling and heart failure.[8]

This study investigates whether HICT is safe and effective for improving LA strain in patients recovering from anterior wall STEMI after primary PCI. While HIIT is known to be safe and effective, there is limited evidence on HICT in cardiac populations. The researchers hypothesize that HICT will lead to greater improvements in LA strain compared to moderate-intensity continuous training (MICT); aiming to address this evidence gap and evaluate HICT's potential benefits in cardiac rehabilitation.

METHODS

Study Design and Population

This six-month randomized controlled trial (February-August 2024) enrolled 60 adult patients at Aim Shams University Hospital's Cardiac Rehabilitation Unit. Participants had undergone successful primary PCI for anterior STEMI at least three weeks prior and achieved complete revascularization. They were randomized via a computer-generated method between March and May 2024. Ethical (approval number: MS 215/2024, date: 13.03.2025) was secured, and written informed consent was obtained, with confidentiality and privacy assured for all participants.

Patients were excluded if they had significant cardiac conditions [e.g., severe left ventricular (LV) dysfunction, decompensated heart failure, hemodynamic instability, severe valvular disease, uncontrolled arrhythmias, angina at low workloads], physical or musculoskeletal limitations, incomplete revascularization, major comorbidities (severe hepatic/renal impairment, chronic obstructive pulmonary disease, morbid obesity, clinical depression), or high-risk features identified during symptom-limited modified Bruce protocol stress testing [e.g., symptoms below 5 metabolic equivalents (METS), silent ischemia with ≥2 mm ST-segment depression].

This randomized controlled trial assigned patients to two groups: Group A received HICT, while Group B (the control group) underwent MICT as part of cardiac rehabilitation. Both groups were monitored over a six-week follow-up period.

Initial Risk Stratification and Exercise Prescription

Prior to the CR program, patients underwent a comprehensive evaluation. This included recording demographic data (age, gender, occupation, smoking history), assessing cardiovascular risk factors and comorbidities, performing general and systematic physical examinations, and screening for musculoskeletal limitations that could affect exercise capacity.

Before starting rehabilitation, patients underwent laboratory testing (complete blood count, urea, creatinine, electrolytes, hemoglobin A1c, cardiac biomarkers) and a 12-lead electrocardiogram (ECG). Risk stratification was performed via a symptom-limited treadmill stress test (modified Bruce protocol) to determine maximal heart rate (HR_{max}) and HR reserve (HRR). High-risk criteria included symptoms at <5 METS, ventricular arrhythmias, abnormal hemodynamics, or silent ischemia (ST-segment depression ≥2 mm). Exercise intensity was tailored using the Karvonen formula, with high-intensity training targeting ≥60% HRR (≥80% HR_{max}) and moderate-intensity training set at 40-60% HRR (60-80% HR_{max}).[9]

Exercise Training Protocol

Patients completed an 18-session supervised treadmill exercise program over six weeks (3 sessions/week). Each 40-minute session included:

1. Warm-up: Ten minutes.

2. Main training phase: Twenty minutes at prescribed intensity (treadmill speed/incline adjusted to achieve target heart rate).

3. Cool-down: Ten minutes.

Continuous ECG monitoring was used during sessions, and patients were instructed to report symptoms (e.g., chest pain, dizziness). Participants who missing three consecutive sessions were excluded.

Echocardiographic Assessment

Echocardiographic evaluations were performed by experienced echocardiographers before and after the rehabilitation program. Echocardiographers were blinded to the study groups. LA strain was assessed using two-dimensional STE in apical four-chamber and two-chamber views, following American Society of Echocardiography/European Association of Cardiovascular Imaging guidelines. The LA endocardium was traced to define the region of interest, which was adjusted for thinner atrial walls. Strain curves were generated for 12 left atrium LA segments to calculate global longitudinal strain (GLS) for reservoir, conduit, and contractile phases. Reservoir strain was measured during systole, conduit strain during passive LA emptying, and contractile strain during active atrial contraction.

Diastolic function was assessed by measuring mitral peak early (E) and atrial (A) flow velocities, mitral annular septal and lateral velocities (e'), and calculating E/A and E/e' ratios. LA dimensions were measured in the parasternal long-axis view, and LA volumes (maximal and minimal) were calculated using the biplane area-length method.

STE measurements in this study were independently reviewed by more than one experienced echocardiographer. In cases of discrepancy, consensus was reached through joint review to ensure accuracy and consistency of the measurements. This consensus-based approach, performed by skilled operators following standardized protocols, enhances the reliability of the reported strain values.

Sample Size Calculation

The sample size was calculated using the power analysis and sample size 15 program, with a power of 80% and an alpha error of 5%. Based on the findings of D'Andrea et al.[3], which demonstrated that HIIT led to reverse cardiac remodeling and improved diastolic and systolic function as assessed by standard echocardiography, an effect size difference of 0.8 was assumed between the two groups for LA function parameters. Accounting for a 10% dropout rate, a total of 60 patients (30 per group) were deemed necessary.

Statistical Analysis

Data were analyzed using the (SPSS, version 21). Continuous variables were described using appropriate measures of central tendency and dispersion, expressed as mean ± standart deviation, and compared using t-tests. Categorical variables were summarized as percentages and analyzed using chi-square tests. Pearson correlation and multivariate linear regression analyses were performed to evaluate the relationships between variables. All statistical tests were two-tailed, with statistical significance set at $P \leq 0.05$.

RESULTS

The demographic and risk factor profiles were comparable between the moderate- and high-intensity groups, with no statistically significant differences observed. Age, gender distribution, smoking habits, and comorbidities such as diabetes mellitus, hypertension (HTN), and ischemic heart disease (IHD) were comparable, providing a balanced baseline between the study groups ($P > 0.05$ for all variables) Table 1.

Table 1: Demographic data and risk factors among the study groups

		Moderate intensity (n=30)	High intensity (n=30)	*P*-value
Age	Mean ± SD	54.13±10.47	49.5±11.58	0.109
	Range	33-70	24-68	
Gender				
Female	n (%)	4 (13.3%)	1 (3.3%)	0.161
Male	n (%)	26 (86.7%)	29 (96.7%)	
Smoker	n (%)	18 (60.0%)	21 (70.0%)	0.417
Shisha	n (%)	3 (10.0%)	1 (3.3%)	0.301
Hashish	n (%)	2 (6.7%)	6 (20.0%)	0.129
DM	n (%)	13 (43.3%)	6 (20.0%)	0.052
HTN	n (%)	9 (30.0%)	11 (36.7%)	0.584
IHD	n (%)	3 (10.0%)	4 (13.3%)	0.688
CVS	n (%)	3 (10.0%)	1 (3.3%)	0.301
Alcohol	n (%)	0 (0.0%)	1 (3.3%)	0.313
Single Kidney	n (%)	1 (3.3%)	0 (0.0%)	0.313
Tramadol	n (%)	1 (3.3%)	1 (3.3%)	>0.99
Paroxysmal AF	n (%)	1 (3.3%)	0 (0.0%)	0.313
Hypothyroidism	n (%)	1 (3.3%)	1 (3.3%)	>0.99
HCV	n (%)	0 (0.0%)	1 (3.3%)	0.313
Dyslipidemic	n (%)	1 (3.3%)	0 (0.0%)	0.313
Family History	n (%)	3 (10.0%)	2 (6.7%)	0.64

P-value < 0.05 was considered statistically significant.

DM: Diabetes mellitus, HTN: Hypertension, IHD: Ischemic heart disease, CVS: Cerebrovascular stroke, AF: Atrial fibrillation, HCV: Hepatitis C virus, SD: Standard deviation

Table 2: Echocardiographic parameters before and after exercise among continuous high intensity group

Continuous high intensity group		Before (n=30)	After (n=30)	*P*-value
LA reservoir strain %	Mean ± SD	21.6±7.79	27.27±10.08	**<0.001**
	Range	6-36	7-45	
LA conduit strain %	Median (IQR)	-11.5 (-15- -7)	-14 (-19--10)	**<0.001**
	Range	-23--3	-31--3	
LA contractile strain %	Median (IQR)	-10 (-14--5)	-13 (-16--9)	**<0.001**
	Range	-21--1	-24--2	
LA diameter	Mean ± SD	38.57±4.48	38.57±4.48	-
	Range	32-47	32-47	
LA volume max (biplane)	Mean ± SD	51.87±22.17	50.6±19.82	**<0.001**
	Range	22-132	26-107	
E/A	Mean ± SD	1.17±0.22	1.03±0.14	**<0.001**
	Range	0.9-1.5	0.9-1.3	
E/E’	Mean ± SD	7.73±0.92	7.48±0.9	**<0.001**
	Range	6.25-9.3	6-9	

P-value < 0.05 was considered statistically significant.

LA: Left atrial, E/A. Early-to-atrial diastolic velocity ratio, E/E’: Early diastolic velocity to annular velocity ratio, SD: Standard deviation, IQR: Interquantile range

Table 3: Echocardiographic parameters before and after exercise in moderate intensity group.

Moderate intensity group		Before (n=30)	After (n=30)	*P*-value
LA reservoir strain %	Mean ± SD	27.3±8.88	31.1±8.63	**<0.001**
	Range	10-46	17-47	
LA conduit strain %	Median (IQR)	-13 (-19--7)	-17.5 (-23--10)	**<0.001**
	Range	-31-0	-33--5	
LA contractile strain %	Median (IQR)	-13.5 (-16--10)	-15 (-18--12)	0.014
	Range	-24--4	-25--6	
LA diameter	Mean ± SD	37.23±4.09	37.23±4.09	–
	Range	29-47	29-47	
LA volume max (biplane)	Mean ± SD	45±18.97	42.03±14.24	0.336
	Range	21-110	18-74	
E/A	Mean ± SD	1.17±0.2	1.03±0.15	**<0.001**
	Range	0.9-1.6	0.9 -1.5	
E/E’	Mean ± SD	8.03±1.14	7.73±1.02	**<0.001**
	Range	6-10	6-9.5	

P-value < 0.05 was considered statistically significant.

LA: Left atrial, E/A. Early-to-atrial diastolic velocity ratio, E/E’: Early diastolic velocity to annular velocity ratio, SD: Standard deviation, IQR: Interquantile range

Table 4: Mean differences of echocardiographic parameters between both groups

	Moderate intensity (n=30)	High intensity (n=30)	*P*-value
LA reservoir strain %	3.80±3.32	5.67±4.39	0.115
LA conduit strain %	-3.13±3.66	-3.03±3.97	0.789
LA contractile strain %	-1.33±3.74	-2.93±4.27	0.110
LA volume max (biplane)	-2.97±16.59	-1.27±13.45	0.778
E/A	-0.14±0.14	-0.14±0.12	0.927
E/E’	-0.30±0.34	-0.25±0.16	0.568

Date are are presented in mean ± standard deviation. *P*-value < 0.05 was considered statistically significant.

LA: Left atrial, E/A: Early-to-atrial diastolic velocity ratio, E/E’: Early diastolic velocity to annular velocity ratio

In the group that exercised at HICT, significant improvements were observed in echocardiographic parameters after exercise. LA reservoir strain, LA conduit strain, and LA contractile strain all showed statistically significant increases ($P < 0.001$. Additionally, LA volume maximum and E/A ratio significantly decreased ($P < 0.001$ for both), while E/E’ showed a modest but significant reduction ($P < 0.001$). The LA diameter remained unchanged Table 2.

In the group that exercised at MICT, significant increases were noted in LA reservoir strain, LA conduit strain, and LA contractile strain after exercise ($P < 0.001$, < 0.001, and < 0.014, respectively). E/A and E/E’ ratios showed significant decreases ($P < 0.001$ for both). No significant changes were observed in LA diameter or LA volume maximum ($P = 0.336$) Table 3.

The mean differences in echocardiographic parameters between MICT and HICT groups were not statistically significant for any variable ($P > 0.05$). Changes in LA reservoir strain, LA conduit strain, LA contractile strain, LA volume maximum, E/A, and E/E’ were comparable between the two groups Table 4.

DISCUSSION

Current guidelines for CR in anterior STEMI patients post-primary PCI emphasize moderate-intensity training. However, emerging evidence indicates that high-intensity training (e.g., HIIT) may offer superior improvements in cardiac function compared to traditional moderate-intensity regimens, with HIIT being demonstrated as safe and effective.[3] Despite this, a critical evidence gap persists regarding the safety and efficacy of HICT in this population. Further research is needed to validate HICT’s role in optimizing recovery and cardiovascular outcomes.

Echocardiographic GLS is increasingly recognized as a more sensitive marker than traditional ejection fraction for detecting subtle LV dysfunction. Post-myocardial infarction, LA strain (LAS) serves as a prognostic tool, where progressive improvement may signal positive remodeling and atrial functional recovery, while persistently reduced strain could indicate ongoing dysfunction.[10] Serial monitoring of LAS during follow-up enables clinicians to assess therapeutic efficacy and tailor treatment strategies, offering a dynamic approach to optimizing patient management in cardiovascular care.

This study evaluated the effects of (HICT, Group 1) versus (MICT, Group 2), on LAS in 60 anterior STEMI patients post-primary PCI, randomized during cardiac rehabilitation. The cohort had a mean age of 51.82 years, with a pronounced male predominance (91.7%), consistent with established gender disparities in cardiovascular disease prevalence.[11] Both groups exhibited similar baseline age and gender profile, minimizing confounding variables when assessing exercise intensity impact. These findings align with prior research (e.g., Elbarbary et al.[12]) which identified higher STEMI incidence in males, particularly those aged 56-65, underscoring the demographic relevance of this population for CR studies.

The male predominance in this study (91.7% male) poses a significant limitation to the generalizability of findings, particularly for CR applications in women. Physiologically, women typically exhibit lower baseline peak oxygen uptake (VO_2 peak) than men, and while both sexes benefit from CR, men often achieve greater improvements in VO_2 peak post-rehabilitation.[13] This sex-based disparity in exercise responsiveness suggests that training modalities optimized for male-dominated cohorts may not equally benefit female patients. Consequently, the results of this study, derived from a predominantly male sample, may not fully represent outcomes for the broader cardiac population, underscoring the need for future research with gender-balanced cohorts to validate and refine sex-specific CR strategies.

This study identified HTN (33.3%), smoking (65%), dyslipidemia (53.3%), and diabetes (48.3%) as dominant comorbidities in anterior STEMI patients, reinforcing the critical role of risk factor management in IHD. These findings align with global patterns: Bhardwaj et al.[14] reported similar risk profiles [smoking, HTN, low high-density lipoprotein (HDL), high triglycerides] in young Indian AMI patients, noting the predominance of STEMI in males and frequent left anterior descending artery (LAD) involvement. Similarly, Elkersh et al.[15] observed high rates of smoking (63.5%), HTN (57.5%), diabetes (60.5%), and dyslipidemia (57%) in Egyptian acute coronary syndrome (ACS) patients. Collectively, these studies highlight smoking and metabolic disorders as pivotal, modifiable drivers of cardiovascular events, particularly in males, and underscore the need for targeted preventive strategies across diverse populations.

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Both MICT and HICT groups demonstrated significant improvements in LA strain parameters-reservoir, conduit, and contractile strains-following cardiac rehabilitation, suggesting exercise-induced benefits on atrial function regardless of intensity. These enhancements likely stem from mechanisms such as improved blood flow, reduced atrial stiffness, and adaptive myocardial remodeling.[16] Increased LA reservoir strain reflects greater atrial compliance and optimized ventricular filling, while elevated conduit strain indicates enhanced passive cardiac filling. Improved contractile strain underscores more effective atrial contraction, critical for maintaining cardiac output.[17,18] Importantly, LA strain improvements correlated with reduced diastolic dysfunction severity, as evidenced by inverse relationships with LV filling pressures (E/E' ratio).[19] While both regimens promoted favorable cardiac adaptations, the study highlights exercise's broad role in ameliorating atrial mechanics and diastolic function, independent of intensity.

Our findings align with those of Huang et al.[20], who observed notable enhancements in LA strain measurements after engaging in moderate-intensity exercise. A study by Reddy et al.[21] further showed that high-intensity interval exercise notably enhanced LAS highlighting its significance as a marker of improved atrial function.

The study found no statistically significant differences in LA reservoir, or conduit strain improvements between HICT and MICT groups, though a non-significant trend favored HICT. Both regimens similarly enhanced LA reservoir, conduit, and contractile strains, suggesting comparable efficacy in improving atrial function. These findings align with prior studies Yang et al.[22] and Zheng et al.[23] which reported equivalent LA strain improvements across exercise intensities, implying a potential functional threshold where further intensity increases may not yield additional benefits. The lack of significance may reflect insufficient sample size to detect subtle differences, highlighting the need for larger trials to clarify optimal exercise intensity for atrial remodeling.

The study observed no significant changes in structural LA parameters-LA diameter and maximum LA volume-across both moderate-intensity (MICT) and HICT groups, despite functional improvements in atrial mechanics. Exercise enhanced myocardial efficiency and functional performance (e.g., strain metrics) without inducing structural remodeling, a finding consistent across exercise intensities. These results align with Andrea et al.[3], Fukuta[24], and Caminiti et al.[16], who similarly reported stable LA dimensions despite functional gains, even in older adults.[24] Collectively, these studies suggest that exercise-driven benefits in LA function arise from adaptive physiological mechanisms (e.g., improved compliance, contractility) rather than structural alterations, reinforcing the concept that functional improvements can occur independently of changes in atrial size or volume.

Both MICT and HICT groups exhibited significant improvements in diastolic function, marked by reductions in E/A and E/E' ratios, indicative of enhanced ventricular filling and reduced LV filling pressures. These findings align with prior studies: Alves et al.[25] and Pearson et al.[26] demonstrated diastolic improvements with moderate exercise, while Amundsen et al.[27] reported similar benefits with high-intensity interval training. Notably, no statistically significant differences in E/A or E/E′ improvements were observed between MICT and HICT groups, consistent with the study by Trachsel et al.[28], which found comparable efficacy across exercise intensities. This underscores that both regimens similarly optimize diastolic function, likely through shared mechanisms such as improved myocardial compliance and reduced stiffness.

No complications were reported in either the moderate-intensity or high-intensity exercise groups, indicating that both exercise intensities are safe.

Our study compared the effects of HICT and MICT on LA mechanics in cardiac patients. Both regimens were safe and equally effective in improving LA and diastolic function, with no statistical differences observed between groups. The lack of significance may reflect true equivalence in efficacy, as both intensities could induce similar physiological adaptations (e.g., cardiovascular strain sufficient for beneficial remodeling). This supports personalized exercise prescriptions-HICT for time efficiency in tolerant patients; and MICT as a safer alternative for others. However, limitations such as a small sample size (increasing type II error risk). Larger studies are needed to confirm these findings and clarify whether minimal true differences exist.

Study Limitation

This study has several limitations. First, its single-center design, relatively small sample size, and male-predominant cohort may restrict the generalizability of the results to broader populations, including women and diverse clinical settings. Second, the short follow-up period limited the ability to assess the long-term effects of high-intensity exercise on cardiac function and cardiovascular health outcomes. Third, the reliance on HR monitoring without complementary measures such as the Rate of Perceived Exertion may have provided an incomplete picture of exercise intensity and patient effort.

The non-significant differences in secondary outcomes may be attributed to the study not being adequately powered to detect them.

Despite these limitations, the findings support integrating supervised high-intensity exercise programs into CR protocols, particularly given their benefits in improving LAS. To optimize outcomes, programs should be personalized to patient tolerance and implemented with stringent safety protocols, including screening for contraindications and continuous physiological monitoring. Future research should prioritize multi-center trials with larger, more representative cohorts, extended follow-up periods, and standardized intensity assessments (e.g., combining RPE with HR) to evaluate long-term efficacy, safety, adherence, and cardiovascular outcomes.

CONCLUSION

HICT and MICT show comparable safety and efficacy in enhancing cardiac function, suggesting exercise intensity may be tailored to patient preference or tolerance. While statistical equivalence could reflect true biological similarity, limitations like underpowered design or participant heterogeneity warrant further research to validate clinical implications.

Ethics

Ethics Committee Approval: This study was approved by the Ain Shams University Faculty of Medicine Research Ethics Committee (approval number: MS 215/2024, date: 13.03.2025).

Informed Consent: Written informed consent was obtained, confidentiality and privacy were assured for all participants, and the study was secured.

Footnotes

Authorship Contributions

Surgical and Medical Practices: A.H.A.H., R.R.E., Concept: A.K.A.A., T.K.A., Design: A.H.A.H., T.K.A., R.R.E., Data Collection or Processing: A.K.A.A., A.H.A.H., R.R.E., Analysis or Interpretation: A.K.A.A., T.K.A., R.R.E., Literature Search: A.K.A.A., A.H.A.H., R.R.E., Writing: A.H.A.H., T.K.A.

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