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CLINICAL TRIAL REPORT

Innovative Cardiac Rehabilitation: Effects of Adaptive Postural Balance Exercise on Coronary Artery Disease and Type 2 Diabetes

Deyu Qin[1,2,*], Guangxin Liu[2,*], Jing Zhang[3], Shanshan Lin[4], Xinmeng Liu[2], Jingxiang Zhao[2], Qian Zhang[2], Mei Ma[2], Shusen Wang[5]

[1]The First Central Clinical School, Tianjin Medical University, Tianjin, 300070, People's Republic of China; [2]Department of Rehabilitation Medicine, Tianjin Chest Hospital, Tianjin, 300222, People's Republic of China; [3]Department of Endocrinology, Tianjin Chest Hospital, Tianjin, 300222, People's Republic of China; [4]Medical School, Nankai University, Tianjin, 300071, People's Republic of China; [5]Research Institute of Transplant Medicine, Organ Transplant Center, Tianjin First Central Hospital, School of Medicine, Nankai University, NHC Key Laboratory for Critical Care Medicine, Key Laboratory of Transplant Medicine, Chinese Academy of Medical Sciences, Tianjin, 300192, People's Republic of China

*These authors contributed equally to this work

Correspondence: Mei Ma; Shusen Wang, Email tjxkkfyxkm@126.com; shusen@vip.163.com

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Purpose: This study aimed to evaluate the effects of Adaptive Postural Balance Cardiac Rehabilitation Exercise (APBCRE) on glycolipid metabolism and exercise endurance in patients with coronary artery disease (CAD) and type 2 diabetes mellitus (T2DM). Specifically, we compared the efficacy of APBCRE with aerobic exercise (AE) alone and irregular exercise (IE).

Patients and Methods: This randomized controlled trial included 348 patients with CAD, comprising 261 patients with T2DM and 87 non-diabetic CAD patients as a control group. Participants were randomly assigned to one of four groups: the APBCRE group, the AE group, the IE group, or the non-diabetic AE control group. The intervention lasted 8 weeks, including a structured 6-week training phase. Metabolic markers and exercise endurance were assessed at baseline (week 1) and post-intervention (week 8). Cardiopulmonary exercise testing (CPET) was utilized to individualize exercise prescriptions and optimize intervention intensity.

Results: The APBCRE group demonstrated significant improvements in fasting blood glucose (FBG) (−11.34%, from 7.89 to 6.99 mmol/L, $p < 0.05$), HbA1c (−8.87%, from 7.20% to 6.56%, $p < 0.05$), and LDL-C levels (−12.21%, from 2.44 to 2.14 mmol/L, $p < 0.05$) compared to the AE and IE groups. While both APBCRE and AE improved lipid profiles, APBCRE demonstrated superior enhancements in exercise endurance, with $\dot{V}O_2$ max increasing by 18.71% (from 14.19 to 16.86 mL/min/kg, $p < 0.05$) and AT $\dot{V}O_2$ increasing by 16.00% (from 11.62 to 13.48 mL/min/kg, $p < 0.05$).

Conclusion: These findings support the efficacy of APBCRE in improving glycolipid metabolism, exercise endurance, and neuromuscular coordination in patients with CAD and T2DM compared to AE alone.

Keywords: type 2 diabetes mellitus, coronary artery disease, glycolipid metabolism, cardiopulmonary exercise testing

Introduction

Coronary artery disease (CAD) is primarily caused by atherosclerosis and is often associated with inadequate myocardial blood supply. Recent lifestyle changes have increased sedentary behavior globally, significantly increasing obesity and related cardiovascular diseases.[1] The World Health Organization (WHO) reports that the number of patients with cardiovascular diseases rose from 271 million in 1990 to 523 million in 2019, resulting in approximately 6.1 million deaths among individuals aged 30 to 70 years, making cardiovascular disease the leading cause of death worldwide.[2]

Type 2 diabetes mellitus (T2DM) is one of the most common comorbidities of CAD and exerts significant effects on the progression of CAD. Poor long-term glycemic control in diabetes often leads to endothelial dysfunction and chronic inflammation, exacerbating atherosclerosis and increasing cardiovascular events.[3] Patients with diabetes are almost twice

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as likely to develop CAD compared to non-diabetic individuals, thus complicating the management of those with both conditions.[4]

While pharmacotherapy effectively reduces glycated hemoglobin (HbA1c) in patients with T2DM,[5] this approach is often associated with adverse effects,[6] increased financial burden,[7] and a diminished quality of life.[8] In addition, current rehabilitation strategies, including standard aerobic exercise and medication, may not fully address the comprehensive needs of patients with both CAD and T2DM.

Traditional aerobic exercise alone is often hindered by low patient adherence due to concerns over cardiovascular complications and insufficient personalized guidance.[9] Similarly, pharmacological approaches alone fail to adequately improve exercise capacity and may not sufficiently target the underlying metabolic dysfunctions in these patients. Therefore, non-pharmacological interventions, such as exercise-based rehabilitation, which offer a holistic approach to both metabolic and cardiovascular health, are essential.

Adaptive postural balance cardiac rehabilitation exercise (APBCRE), a novel intervention integrating aerobic exercise with balance training and guided by cardiopulmonary exercise testing (CPET), provides a personalized and adaptable approach. By tailoring the program to each patient's specific capabilities, APBCRE enhances exercise adherence while improving metabolic function and cardiovascular health. Research has demonstrated that APBCRE not only increases exercise tolerance but also reduces cardiovascular risks, underscoring its potential to overcome the limitations of traditional rehabilitation methods.

Exercise plays a significant role in improving cardiovascular health and metabolic parameters,[10] with studies demonstrating that systematic aerobic and resistance training can substantially enhance glycolipid metabolism and overall cardiovascular function. However, adherence to exercise programs among patients with CAD and T2DM remains a challenge, as many struggle to maintain long-term exercise regimens due to perceived risks and a lack of individualized guidance. This gap in adherence and effectiveness highlights the need for more tailored and accessible rehabilitation strategies.[11]

In this study, we aimed to evaluate the effects of APBCRE on glycolipid metabolism and exercise endurance in patients with CAD and T2DM, compared with aerobic exercise alone (AE). We implemented an 8-week intervention framework, incorporating a structured 6-week training program guided by CPET, to assess metabolic and functional outcomes. Our objective was to determine the advantages of APBCRE in improving glycemic control, lipid profiles, and exercise endurance, thereby providing a more effective rehabilitation strategy to enhance metabolic outcomes and quality of life in this patient population.

Methods

Study Design

This study is a randomized controlled trial (RCT) designed to evaluate the effects of APBCRE on glycolipid metabolism in patients with T2DM. The trial was pre-registered on the Chinese Clinical Trial Registry (ChiCTR2300078066). Ethical approval for this study was obtained from the Institutional Review Board of Tianjin Chest Hospital (Approval Number: 2023KY-025-01), with approval granted on September 20, 2023. Participants were randomly assigned to one of three intervention groups: (1) adaptive postural balance training combined with aerobic exercise, (2) aerobic exercise alone, and (3) irregular exercise. Additionally, 87 non-diabetic CAD patients were included as a control group for comparative analysis. The control group was matched with the intervention groups based on age and gender. Unlike the intervention groups, the control group did not receive any structured exercise intervention, serving as a baseline reference for assessing the effects of exercise on glycolipid metabolism.

A total of 261 patients with T2DM who met the inclusion criteria were enrolled. As Tianjin Chest Hospital is a regional referral center for cardiovascular diseases, the majority of participants also had CAD. This high prevalence reflects the typical patient population at our center. Baseline assessments confirmed that all enrolled participants had both CAD and T2DM.

The intervention period lasted 8 weeks, comprising a structured 6-week exercise training program conducted in 12 sessions (twice per week). The first week was allocated for participant enrollment and baseline assessment, while the

final week was designated for post-intervention evaluations. Changes in glycolipid metabolism were assessed throughout the 6-week training phase.

Participant Recruitment

Participant recruitment commenced on December 4, 2023, with the first patient enrolled on the same date and the final participant enrolled on July 15, 2024. During this period, patients meeting the inclusion criteria were invited to participate in the study. The recruitment and allocation process is summarized in Figure 1, which outlines the steps from initial screening to the random assignment of participants into the intervention groups.

Baseline characteristics of all participants, including demographic and clinical data such as age, gender, medical history, and baseline glycolipid metabolism measures, are summarized in Table 1. These characteristics were assessed prior to the 8-week intervention program to ensure comparability between the groups.

The inclusion criteria were as follows: 1) newly diagnosed with type 2 diabetes or prediabetes, 2) able to cooperate with exercise rehabilitation, and 3) able to understand and sign the informed consent. The exclusion criteria included: 1) age <18 years or >75 years, 2) presence of neurological, muscular, or skeletal joint diseases affecting rehabilitation, 3) heart function classified as NYHA class III/IV, 4) severe diabetes-related complications, 5) pregnancy or lactation, 6) fever >38°C, 7) severe liver or kidney dysfunction, and 8) acute systemic diseases. Non-diabetic CAD patients were recruited as a control group, matched by age and gender.

All participants provided written informed consent and underwent further screening before participating in the 8-week intervention program.

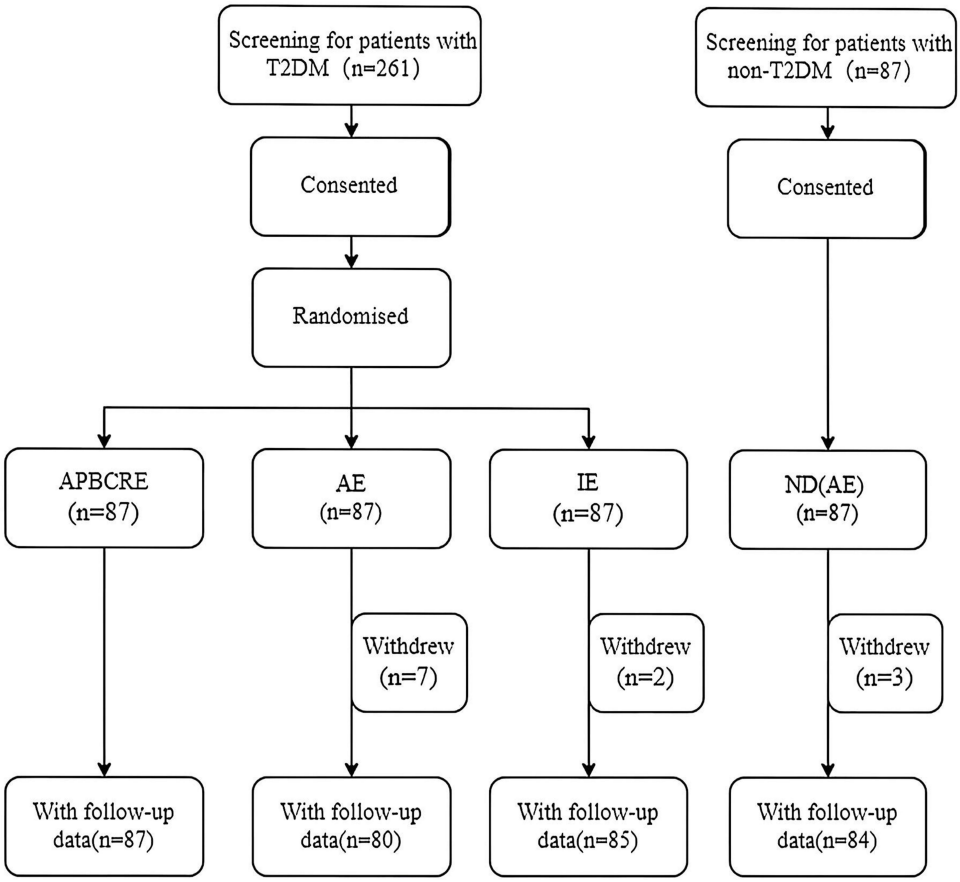

Figure 1 Participant flow chart illustrating the recruitment, grouping, and analysis processes in the study.

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Table 1 Baseline Characteristics

	APBCRE Group n=87, F=14, M=73	**Aerobic Exercise Group n=80, F=21 M=59**	**Irregular Exercise Group n=85, F=22, M=63**	**Non-Diabetic Group n=84, F=18, M=66**	**Total n=336, F=75, M=261**	***P* -value**	**Statistical value**
Age (years)	56.93 ± 10.65	57.64 ± 11.03	57.84 ± 7.66	54.98 ± 10.20	56.84 ± 9.98	0.232	F=1.437
AMI (%)	32.18%	27.50%	28.24%	28.57%	32.18%	0.496	F=0.685
PCI (%)	80.46%	73.75%	72.94%	70.24%	80.46%	0.628	F=0.597
PTCA (%)	82.76%	76.25%	75.29%	71.43%	82.76%	0.757	F=0.519
CABG (%)	2.30%	3.75%	3.53%	2.38%	2.30%	0.164	F=0.921
FBG (mmol/L)	7.89 ± 1.70	7.79 ± 1.47	7.50 ± 1.15	5.23 ± 0.47	7.11 ± 1.68	<0.001	F=79.829
HbA1c (%)	7.20 ± 1.16	7.08 ± 0.82	7.04 ± 0.87	5.66 ± 0.29	6.88 ± 1.04	<0.001	F=34.788
LDL-C (mmol/L)	2.44 ± 1.00	2.46 ± 0.83	2.53 ± 1.08	2.38 ± 0.82	2.45 ± 0.94	0.778	F=0.365
HDL-C (mmol/L)	1.00 ± 0.26	1.04 ± 0.28	1.02 ± 0.28	1.09 ± 0.30	1.04 ± 0.28	0.162	F=1.724
TG (mmol/L)	1.93 ± 1.15	2.01 ± 2.02	1.78 ± 0.86	1.75 ± 1.08	1.87 ± 1.33	0.545	F=0.712
TC (mmol/L)	3.86 ± 1.12	3.94 ± 1.13	4.00 ± 1.20	3.88 ± 1.02	3.92 ± 1.12	0.846	F=0.272
AT$\dot{V}O_2$(mL/min/kg)	11.62±2.91	11.334±2.244	-	11.470±2.698	11.48±2.63	0.782	F=0.247
$\dot{V}O_2$max (mL/min/kg)	14.19±3.20	13.771±3.079	-	13.923±3.310	13.97±3.19	0.688	F=0.375

Notes: Exercise-related metrics (AT$\dot{V}O_2$, $\dot{V}O_2$max) were not collected for the IE group, as indicated by a dash (-).
Abbreviations: APBCRE, Adaptive Postural Balance Cardiac Rehabilitation Exercise; F, Female; M, Male; AMI, Acute Myocardial Infarction; PCI, Percutaneous Coronary Intervention; PTCA, Percutaneous Transluminal Coronary Angioplasty; CABG, Coronary Artery Bypass Graft; FBG, Fasting Blood Glucose; HbA1c, Glycated Hemoglobin; LDL-C, Low-Density Lipoprotein Cholesterol; HDL-C, High-Density Lipoprotein Cholesterol; TG, Triglycerides; TC, Total Cholesterol; AT$\dot{V}O_2$, Oxygen Uptake at Anaerobic Threshold; $\dot{V}O_2$max, Maximal Oxygen Uptake.

Randomization and Blinding

To ensure comparability of baseline characteristics between groups and minimize selection bias, randomization was conducted by an independent statistician using SAS software to generate random number sequences. Block randomization with a block size of six was applied to maintain a relatively balanced number of participants across groups. The randomization sequence was concealed in sequentially numbered, opaque envelopes. After participant recruitment and screening were completed, the research coordinator opened the envelopes to implement allocation concealment.

While participants and intervention providers were not blinded due to the nature of the interventions, outcome assessors were blinded to group allocations to minimize measurement bias. Assessors followed a predefined protocol for evaluating outcomes, ensuring that the assessment process remained objective and unbiased.

Intervention

Each intervention group participated in an 8-week structured exercise program, consisting of both supervised and home-based components. The intervention period included a 6-week exercise training phase, conducted over 12 sessions (twice per week), with the first week designated for participant enrollment and baseline assessments, and the final week for post-intervention evaluations. Changes in glycolipid metabolism were assessed during the 6-week training phase.

The supervised sessions were conducted in a clinical setting under professional guidance, lasting approximately 60 minutes per session. Each session included a 5- to 10-minute warm-up, 40 minutes of moderate-intensity aerobic exercise (guided by CPET-determined anaerobic thresholds), and a 5- to 10-minute cool-down. Safety and adherence to the prescribed intensity were ensured by monitoring heart rate and perceived exertion.

For the home-based component, participants received detailed exercise plans specifying activities such as walking or light cycling, with each session lasting 30 to 40 minutes and performed twice weekly. Activity logs were maintained and reviewed during weekly follow-ups to reinforce consistency and adherence.

Adherence to the exercise protocol was monitored through attendance records during supervised sessions and self-reported activity logs. To reduce bias, self-reported logs were cross-verified with objective measures, including heart rate monitoring and step-count data collected during both supervised and home-based exercises. These objective data were regularly reviewed during weekly follow-ups to ensure consistency and reinforce adherence. Additionally, participants were encouraged to report any challenges encountered during home-based exercise sessions to enhance program compliance and address potential barriers.

The APBCRE group followed a combined exercise regimen that integrated posture and balance training with aerobic exercises. This innovative program was tailored using CPET results to ensure participants exercised within optimal thresholds. Supervised clinical sessions were complemented by home-based exercises to promote long-term adherence.

Participants in the AE group followed the same aerobic protocol as the APBCRE group but without the balance training component. The IE group engaged in unstructured, unsupervised activities based on personal habits, reflecting real-world exercise patterns among diabetes patients who have not received structured exercise prescriptions. The non-diabetic CAD control group performed the same supervised aerobic protocol as the AE group, serving as a baseline for comparing the effects of structured aerobic exercise on glycolipid metabolism in diabetic and non-diabetic populations.

The IE group was included to compare the effects of unstructured versus structured exercise, providing data to inform individualized exercise prescriptions for diabetes patients. It simulates a real-life scenario in which many diabetes patients are not yet engaged in professional exercise interventions. Since the study focuses on changes in glycolipid metabolism rather than differences in cardiovascular fitness, CPET or endurance measurements were excluded for the IE group during the study design phase. Therefore, the IE group serves as a control for "unstructured exercise intervention", with changes in metabolic parameters such as blood glucose and lipid levels being observed. The absence of cardio-pulmonary fitness data does not affect the study's conclusions.

The specific interventions for each group, including activity type, frequency, duration, and supervision status, are summarized in Table 2.

Outcomes

The primary outcome measure was glycated hemoglobin (HbA1c) levels, assessed at baseline (week 1) and post-intervention (week 8). Secondary outcome measures included fasting plasma glucose (FPG), low-density lipoprotein cholesterol (LDL-C), high-density lipoprotein cholesterol (HDL-C), total cholesterol (TC), and triglycerides (TG), all of which were assessed at baseline and post-intervention. These secondary outcomes were selected as key indicators of glycolipid metabolism, which are directly influenced by exercise interventions and are essential for evaluating the metabolic benefits of the program. Exercise endurance was assessed using CPET at baseline and after the 8-week intervention, with $\dot{V}O_2$ max and anaerobic threshold serving as the primary performance indicators.

Sample Size Calculation

To ensure sufficient statistical power to detect significant differences between groups, a sample size calculation was performed using G*Power software. Based on data from previous studies and the expected effect size (Cohen's d), the calculation was conducted to determine the required sample size. The effect size was set at Cohen's d = 0.5, representing

Table 2 Summary of Specific Interventions for Each Group, Including Activity Type, Frequency, Duration, and Supervision

Group	Intervention Description	Frequency	Duration	Supervision
APBCRE	1. Adaptive postural balance training 2. Aerobic exercise (guided by CPET)	2 sessions per week	60 minutes per session	Supervised
AE	Aerobic exercise (guided by CPET)	2 sessions per week	60 minutes per session	Supervised
IE	Unstructured exercise (self-paced, according to personal habits)	No fixed frequency	No fixed duration	Unsupervised
ND (AE)	Aerobic exercise (same as AE group)	2 sessions per week	60 minutes per session	Supervised

Notes: This table clearly outlines the interventions for each group, detailing the type of activities, frequency, duration, and supervision status.

a moderate effect, based on prior exercise interventions in similar populations. This effect size was selected as it is commonly observed in studies examining exercise-based interventions for metabolic outcomes in patients with type 2 diabetes and coronary artery disease. The significance level was set at $\alpha = 0.05$, and a desired power of 0.80 was chosen to minimize the risk of type II errors, ensuring that the study would have sufficient power to detect clinically relevant changes.

Assuming a moderate effect size between the AE and APBCRE groups in terms of glycated hemoglobin (HbA1c) levels, the sample size calculation indicated that at least 80 participants per group would be required to detect statistically significant differences. To account for potential dropouts (estimated at 10%), a final recruitment target of 87 participants per group was set to ensure an adequate sample size for the final analysis. This approach ensures sufficient power to detect significant differences in primary metabolic outcomes, such as HbA1c levels, between the groups.

Data Collection

During data collection, metabolic markers, including FPG, HbA1c, LDL-C, HDL-C, TC, and TG, were measured at baseline (week 1) and post-intervention (week 8). The 8-week intervention period included a 6-week structured training program, during which participants engaged in supervised exercise sessions. Exercise endurance was assessed using CPET at baseline and post-intervention, with $\dot{V}O_2$ max and anaerobic threshold serving as primary performance indicators. Adherence to the exercise protocol was monitored through attendance records during supervised sessions and self-reported physical activity logs, covering both supervised and home-based exercise activities. To further control for bias, self-reported activity logs were cross-verified with objective data (eg, heart rate monitoring) to minimize reporting bias.

Statistical Analysis

Statistical analysis was performed using SPSS (version 25.0, IBM Corp., Armonk, NY, USA). Continuous variables were expressed as mean ± standard deviation. The normality of the data was tested using the Shapiro–Wilk test. For normally distributed data, repeated measures ANOVA was used to account for within-subject variability. ANCOVA was also employed to adjust for baseline differences in metabolic markers, ensuring more robust results. Interaction effects were explored, and post-hoc tests were used for multiple comparisons. For non-normally distributed data, non-parametric tests, such as the Kruskal–Wallis test, were applied. A P-value < 0.05 was considered statistically significant.

Results

A total of 348 CAD patients were initially screened, with 261 diagnosed with T2DM and 87 non-diabetic patients. These patients were then randomly assigned to one of three groups: 87 in the APBCRE group, 87 in the AE group, and 87 in the IE group. During the intervention phase, 12 patients dropped out for personal reasons (7 from the AE group, 2 from the IE group, and 3 from the ND group). Since these patients had completed baseline data collection and their reasons for dropout were not significantly related to the study variables, a complete case analysis was performed. Data from patients who did not complete the intervention were excluded from the final analysis.

The final analysis included 87 patients in the APBCRE group, 80 in the AE group, 85 in the IE group, and 84 in the ND group. Given the low overall dropout rate (3.45%) and the relatively balanced distribution of dropouts across groups, it was concluded that excluding the dropout data would not introduce significant bias into the study results.

At baseline, no statistically significant differences were found between groups for most variables, including age, lipid profiles (LDL-C, HDL-C, TG, TC), and exercise capacity metrics (AT$\dot{V}O_2$, $\dot{V}O_2$max), as well as BMR ($P > 0.05$). The mean age of patients ranged from 54.98±10.20 to 57.84±7.66 years, with a balanced gender distribution across the four groups. As expected, FBG and HbA1c levels were significantly higher in the diabetes groups (APBCRE, AE, IE) compared to the non-diabetic control group ($P < 0.001$). Additionally, there were no significant differences between the groups regarding vascular revascularization procedures at baseline, including percutaneous coronary intervention (PCI), percutaneous transluminal coronary angioplasty (PTCA), and coronary artery bypass grafting (CABG) ($P > 0.05$). These baseline similarities ensured that the participant cohorts were sufficiently homogeneous, allowing for valid comparisons of intervention outcomes.

Comparison of AE and IE in Diabetic Patients: The Impact of Aerobic Exercise on Glycolipid Metabolism

Before and after the intervention, the AE and IE groups exhibited significant changes in several metabolic parameters. As shown in Figure 2, at week 8, the AE group demonstrated a significant reduction in FBG and HbA1c levels ($P < 0.001$, $P < 0.05$), whereas no significant changes were observed in the IE group. Regarding lipid parameters (Figure 3), the AE group showed a significant reduction in LDL-C and TC levels ($P < 0.05$, $P < 0.01$), while no significant changes were detected in HDL-C and TG levels in either group ($P > 0.05$). These findings indicate that aerobic exercise had a more substantial impact on improving glycolipid metabolism compared to irregular exercise.

Comparison of Glycolipid Metabolism and Exercise Endurance Between the AE and Non-Diabetic AE Groups

As shown in Figure 4, the non-diabetic aerobic exercise group [ND(AE)] exhibited minimal fluctuations in blood glucose levels at week 1 and week 8, with no significant changes observed. This indicates that aerobic exercise had a limited

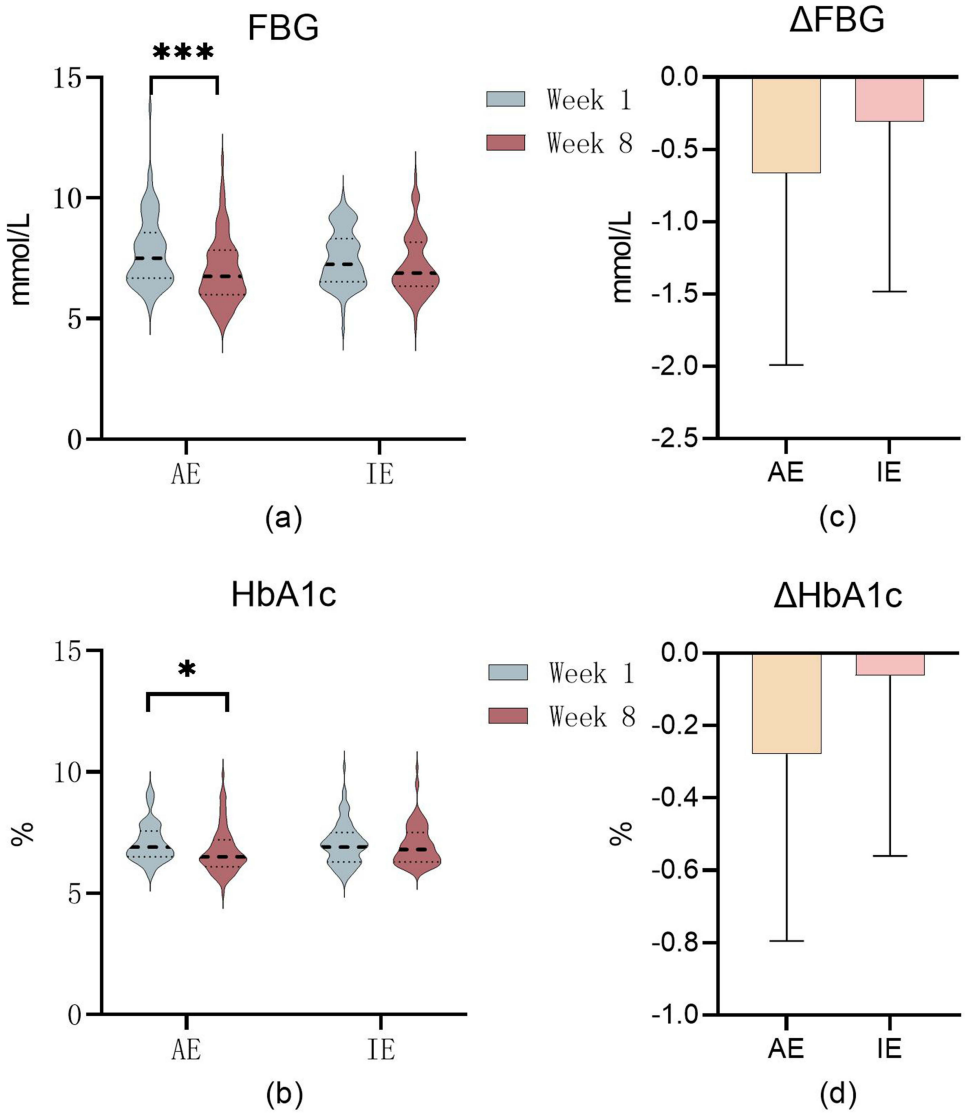

Figure 2 Changes in fasting blood glucose (FBG) and glycated hemoglobin (HbA1c) levels at week 1 and week 8 in the Aerobic Exercise (AE) and Irregular Exercise (IE) groups. (**a**) FBG levels (mmol/L) in the AE and IE groups. (**b**) HbA1c levels (%) in the AE and IE groups. (**c**) Change in FBG (ΔFBG) (mmol/L) in the AE and IE groups. (**d**) Change in HbA1c (ΔHbA1c) (%) in the AE and IE groups. ***P < 0.001, *P < 0.05 indicates significant within-group differences.
Abbreviations: FBG, Fasting Blood Glucose; HbA1c, Glycated Hemoglobin; AE, Aerobic Exercise; IE, Irregular Exercise.

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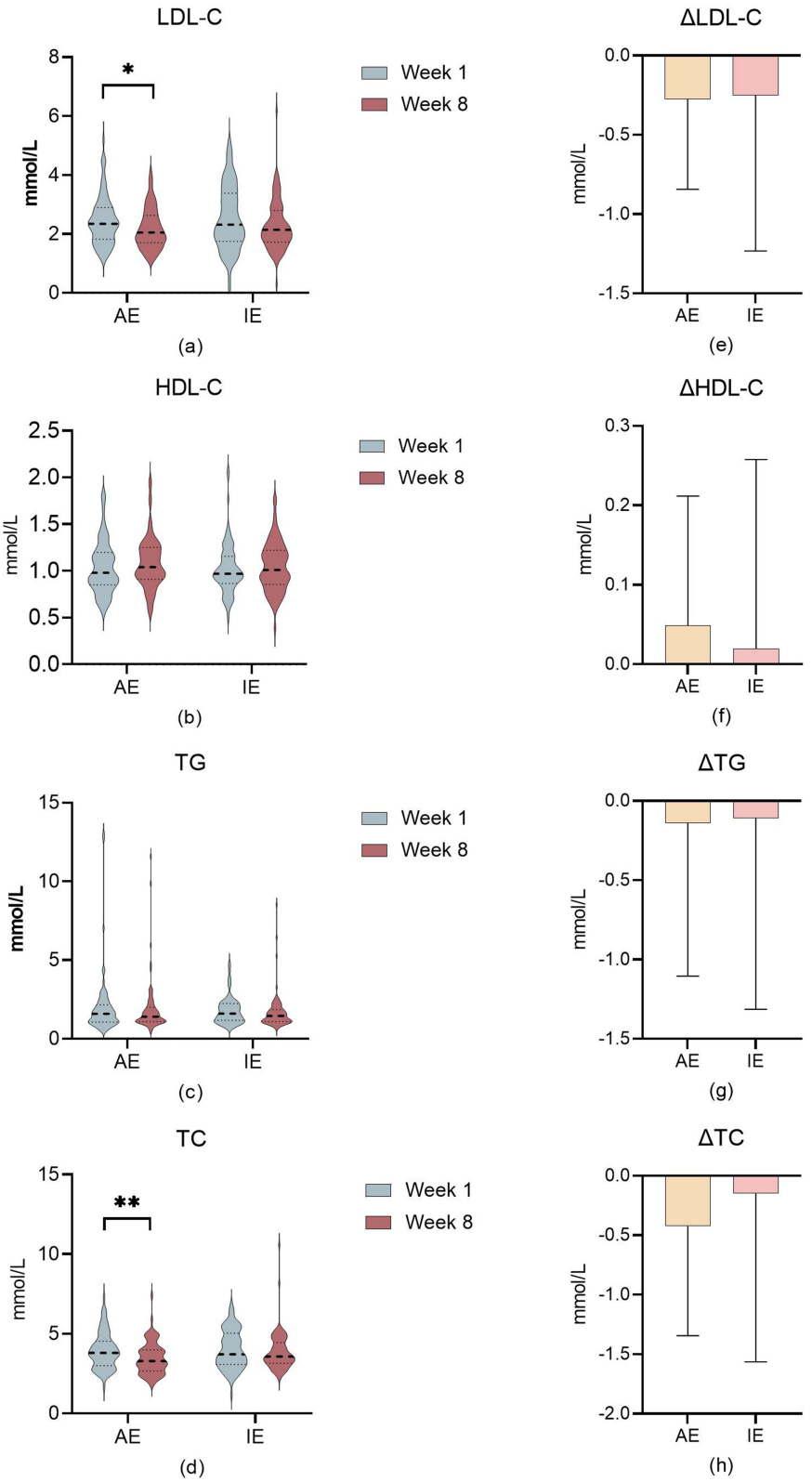

Figure 3 Changes in lipid profile markers at week 1 and week 8 in the AE and IE groups. (**a**) LDL-C levels (mmol/L). (**b**) HDL-C levels (mmol/L). (**c**) TG levels (mmol/L). (**d**) TC levels (mmol/L). (**e**) Change in LDL-C (ΔLDL-C) (mmol/L) in the AE and IE groups. (**f**) Change in HDL-C (ΔHDL-C) (mmol/L) in the AE and IE groups. (**g**) Change in TG (ΔTG) (mmol/L) in the AE and IE groups. (**h**) Change in TC (ΔTC) (mmol/L) in the AE and IE groups. *P < 0.05, **P < 0.01 indicates significant within-group differences. **Abbreviations**: LDL-C, Low-Density Lipoprotein Cholesterol; HDL-C, High-Density Lipoprotein Cholesterol; TG, Triglycerides; TC, Total Cholesterol.

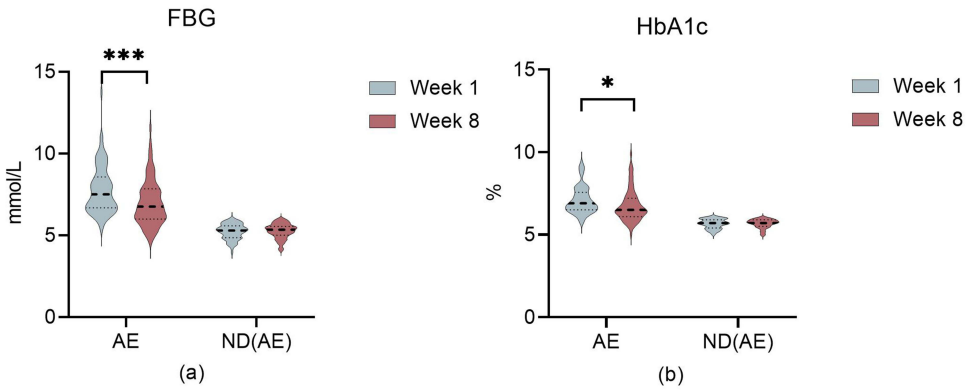

Figure 4 Changes in FBG and HbA1c levels at week 1 and week 8 in AE and non-diabetic AE groups [ND(AE)]. (**a**) FBG levels (mmol/L) in the AE and ND(AE) groups. (**b**) HbA1c levels (%) in the AE and ND(AE) groups. ***P < 0.001, *P < 0.05 indicates significant within-group differences.
Abbreviation: ND(AE), Non-Diabetic Aerobic Exercise Group.

effect on blood glucose levels in non-diabetic individuals and did not induce hypoglycemia, further supporting its safety for non-diabetic patients without the risk of dangerously low blood glucose levels.

Regarding lipid parameters (Figure 5), significant reductions in LDL-C and TC levels were observed in both the AE and ND(AE) groups ($P < 0.05$, $P < 0.01$). However, no significant changes were detected in HDL-C and TG levels in either group ($P > 0.05$).

Additionally, Figure 6 demonstrates significant improvements in maximal oxygen uptake ($\dot{V}O_2$max) exclusively in the ND(AE) group ($P < 0.01$, $P < 0.001$), with no significant changes observed in the AE group. These findings suggest that while aerobic exercise effectively improved lipid metabolism in both diabetic and non-diabetic individuals, only the non-diabetic group showed a significant enhancement in exercise endurance.

Comparison of Glycolipid Metabolism and Exercise Endurance Between the APBCRE and AE Groups

Significant differences in glycolipid metabolism and exercise endurance were observed between the APBCRE and AE groups at week 1 and week 8. As shown in Figure 7, FBG and HbA1c levels decreased significantly in the APBCRE group compared to the AE group, with the APBCRE group exhibiting more pronounced reductions ($P < 0.001$, $P < 0.05$).

As shown in Figure 8, both groups exhibited significant reductions in LDL-C and TC levels ($P < 0.05$, $P < 0.01$), while no significant changes were observed in HDL-C and TG levels in either group ($P > 0.05$).

In terms of exercise endurance (Figure 9), both anaerobic threshold (AT $\dot{V}O_2$)and maximal oxygen uptake ($\dot{V}O_2$ max) improved significantly in the APBCRE group compared to the AE group ($P < 0.001$).

These results suggest that the combination of postural balance and aerobic exercise in the APBCRE group led to greater improvements in blood glucose control, lipid metabolism, and exercise endurance than aerobic exercise alone.

Discussion

In this study, we investigated the effects of APBCRE on glycolipid metabolism in patients with CAD combined T2DM. Given the high prevalence of T2DM and CAD, effective management strategies are crucial. APBCRE demonstrated significant improvements in glycolipid metabolism, particularly in reducing fasting blood glucose, HbA1c, and LDL-C levels.

In our study, the APBCRE group demonstrated significant improvements in exercise endurance compared to the other groups. The proportion of patients in each group was displayed using stacked bar charts (Figures 6 and 9). The change in $\dot{V}O_2$max for patients in the APBCRE group after the intervention was 2.66 ± 2.21, which was statistically significant compared to the AE group ($P < 0.001$). Notably, although some patients exhibited a change in oxygen consumption <3.5 $mL \cdot kg^{-1} \cdot min^{-1}$, such improvements may still have a positive impact on quality of life and long-term health, especially in the context of cardiovascular disease and diabetes comorbidities. While the 8-week duration is relatively

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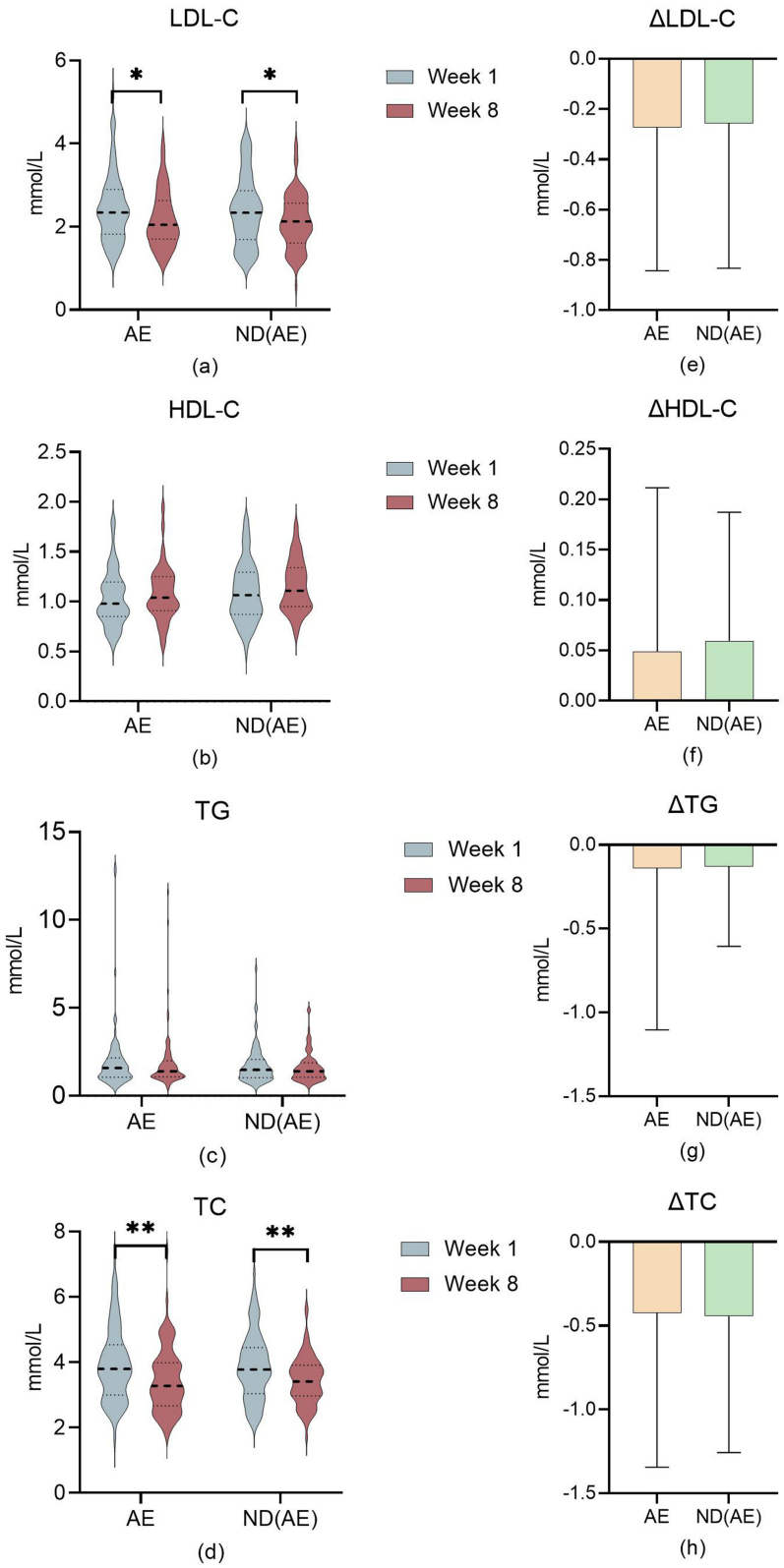

Figure 5 Changes in lipid profile markers at week 1 and week 8 in AE and ND(AE) groups. (**a**) LDL-C levels (mmol/L). (**b**) HDL-C levels (mmol/L). (**c**) TG levels (mmol/L). (**d**) TC levels (mmol/L). (**e**) Change in LDL-C (ΔLDL-C) (mmol/L) in AE and ND(AE) groups. (**f**) Change in HDL-C (ΔHDL-C) (mmol/L) in AE and ND(AE) groups. (**g**) Change in TG (ΔTG) (mmol/L) in AE and ND(AE) groups. (**h**) Change in TC (ΔTC) (mmol/L) in AE and ND(AE) groups. *P < 0.05, **P < 0.01 indicates significant within-group differences.

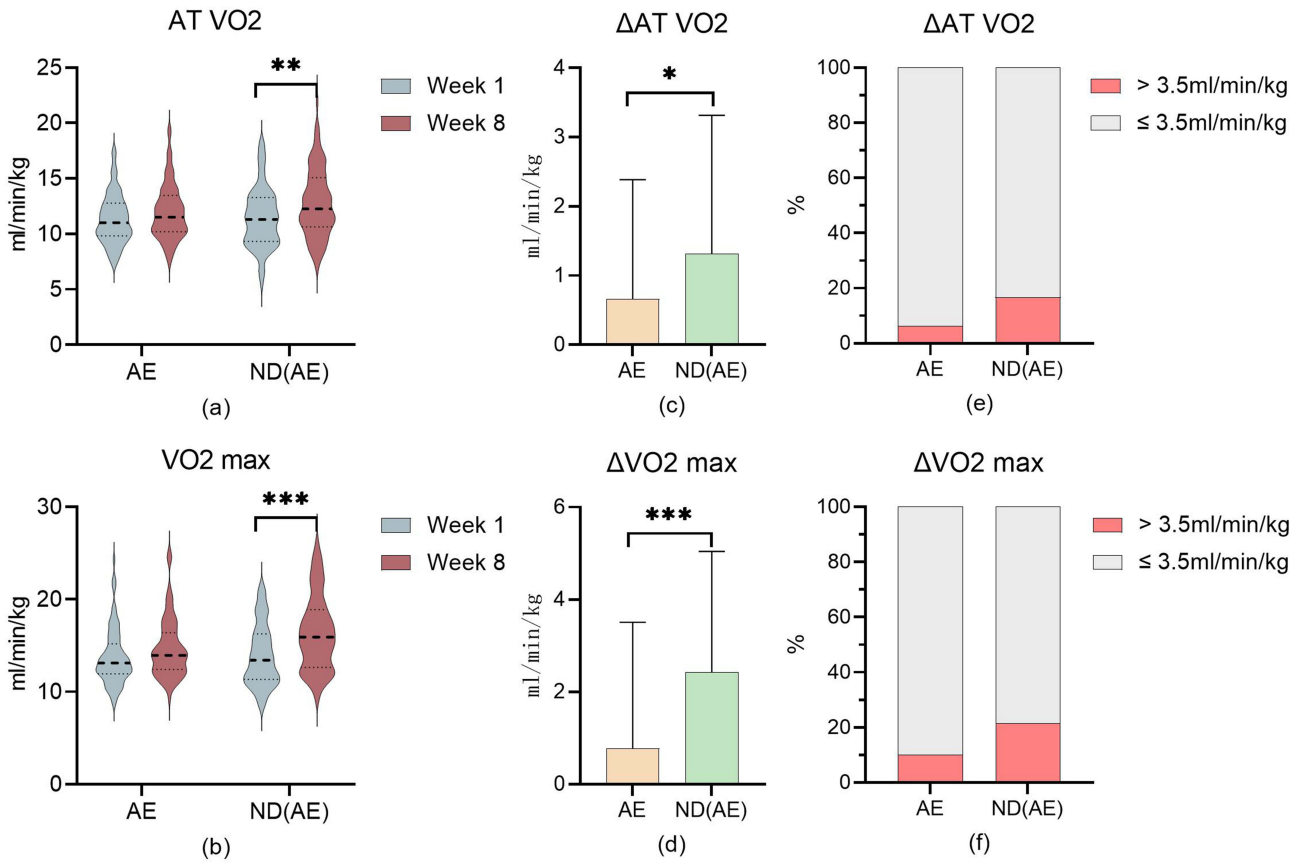

Figure 6 Changes in anaerobic threshold oxygen uptake (AT$\dot{V}O_2$) and maximal oxygen uptake ($\dot{V}O_2$max) at week 1 and week 8 in AE and ND(AE) groups. (**a**) AT$\dot{V}O_2$ levels (mL/min/kg). (**b**) $\dot{V}O_2$max levels (mL/min/kg). (**c**) Change in AT $\dot{V}O_2$ (ΔAT $\dot{V}O_2$) (mL/min/kg) in the AE and ND(AE) groups. (**d**) Change in $\dot{V}O_2$ max (Δ$\dot{V}O_2$ max) (mL/min/kg) in the AE and ND(AE) groups. (**e**) AT $\dot{V}O_2$ distribution by percentage, comparing AE and ND(AE) groups. (**f**) $\dot{V}O_2$ max distribution by percentage, comparing AE and ND(AE) groups. *P < 0.05, **P < 0.01, ***P < 0.001 indicates significant within-group differences.
Abbreviations: AT$\dot{V}O_2$, Anaerobic Threshold Oxygen Uptake; $\dot{V}O_2$max, Maximal Oxygen Uptake.

short, our center will continue to follow up with these patients, aiming to assess long-term benefits and further support their management.

The benefits of APBCRE can be attributed to its integrative approach, combining posture-balance training with aerobic exercise. Posture-balance training enhances neuromuscular coordination, improving muscle function and glucose utilization. Research supports that improved neuromuscular coordination enhances insulin sensitivity by facilitating glucose uptake in skeletal muscles.[12] In addition to these metabolic benefits, posture-balance training reduces the risk of falls and improves functional stability, which is particularly important for individuals with T2DM and CAD, who may experience motor impairments due to neuropathy. APBCRE likely exerts its effects by modulating the autonomic nervous system, and increasing parasympathetic activity, which is linked to improved metabolic function and reduced cardiovascular risk.[13,14] Previous studies have demonstrated that exercise interventions targeting balance and neuromuscular coordination can improve both physical performance and autonomic regulation, playing a critical role in managing metabolic diseases.[15,16]

Individualized exercise prescriptions guided by CPET allow precise control of exercise intensity, optimizing metabolic outcomes without overexertion.[15,16] This personalized approach ensures that each patient trains within their optimal range, minimizing the risk of adverse cardiovascular events. These findings suggest that APBCRE, with its focus on neuromuscular coordination and autonomic regulation, provides a superior strategy for improving metabolic health in patients with CAD combined with T2DM.

Our findings align with earlier studies highlighting the efficacy of combining aerobic exercise with balance training to improve HbA1c and LDL-C levels, as well as exercise endurance ($\dot{V}O_2$max).[17] These observations indicate the critical

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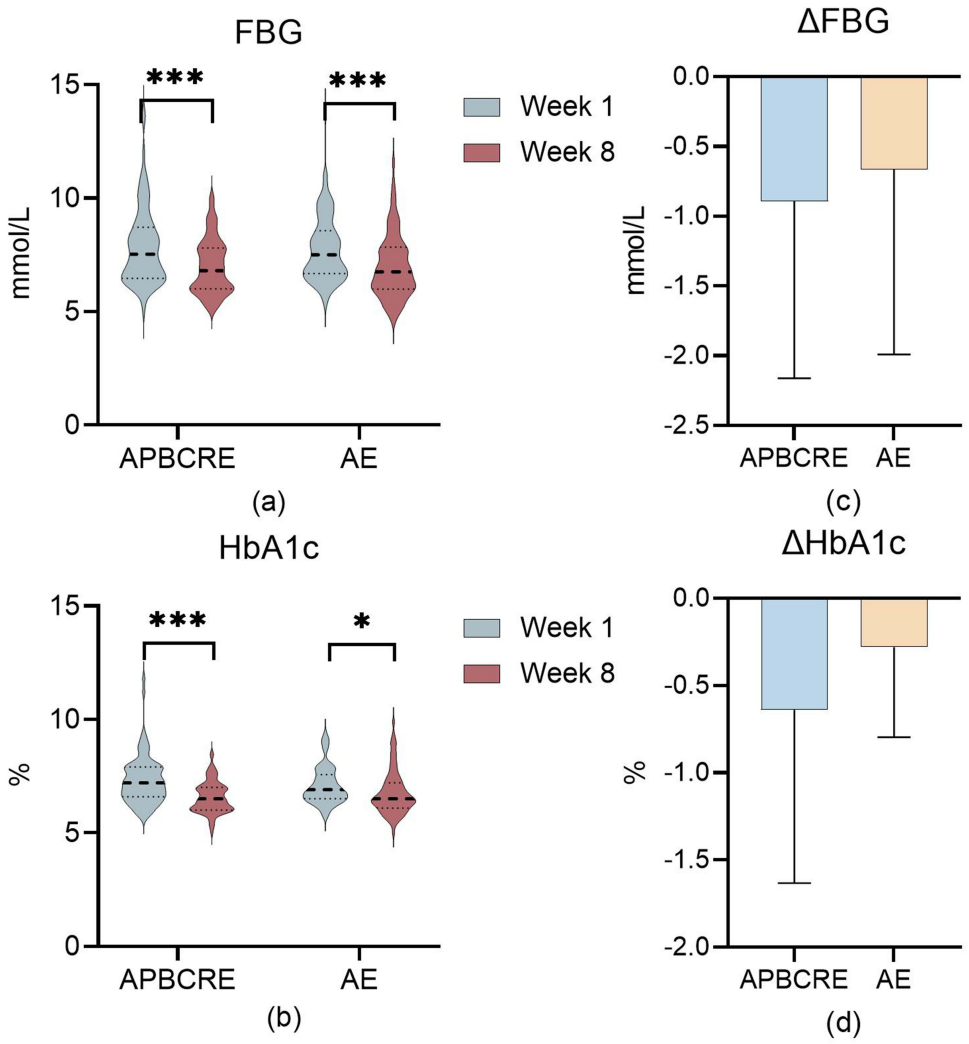

Figure 7 Changes in FBG and HbA1c levels at week 1 and week 8 in Adaptive Postural Balance Cardiac Rehabilitation Exercise (APBCRE) and AE groups. (**a**) FBG levels (mmol/L). (**b**) HbA1c levels (%). (**c**) Change in FBG (ΔFBG) (mmol/L) in the APBCRE and AE groups. (**d**) Change in HbA1c (ΔHbA1c) (%) in the APBCRE and AE groups. ***P < 0.001, *P < 0.05 indicates significant within-group differences.

role of tailored exercise strategies in optimizing CAD and T2DM management.[11] Compared to traditional aerobic exercise or strength training, the unique aspect of APBCRE lies in its integration of posture-balance training with aerobic exercise. This combination not only improves metabolic parameters, such as HbA1c and LDL-C levels, but also enhances neuromuscular coordination and functional stability. Research has shown that balance training is particularly beneficial for patients with T2DM and CAD, as these individuals often experience neuropathy, leading to decreased motor function. Traditional exercise interventions frequently overlook this aspect. Therefore, APBCRE offers a more comprehensive and individualized intervention, improving metabolic control while reducing fall risk and enhancing functional stability. This integrated approach may provide superior benefits compared to standard aerobic or strength training interventions, especially for patients with multiple comorbidities who may struggle with adherence to traditional exercise regimens.

Clinically, APBCRE represents an innovative and potentially cost-effective approach that not only focuses on improving metabolic parameters but also enhances motor function and postural control, which are often compromised in patients with CAD and T2DM. By integrating posture-balance training with aerobic exercise, APBCRE improves exercise tolerance and adherence, potentially reducing complications and enhancing quality of life. Additionally, the unique role of APBCRE in metabolic regulation arises from its ability to enhance neuromuscular coordination and

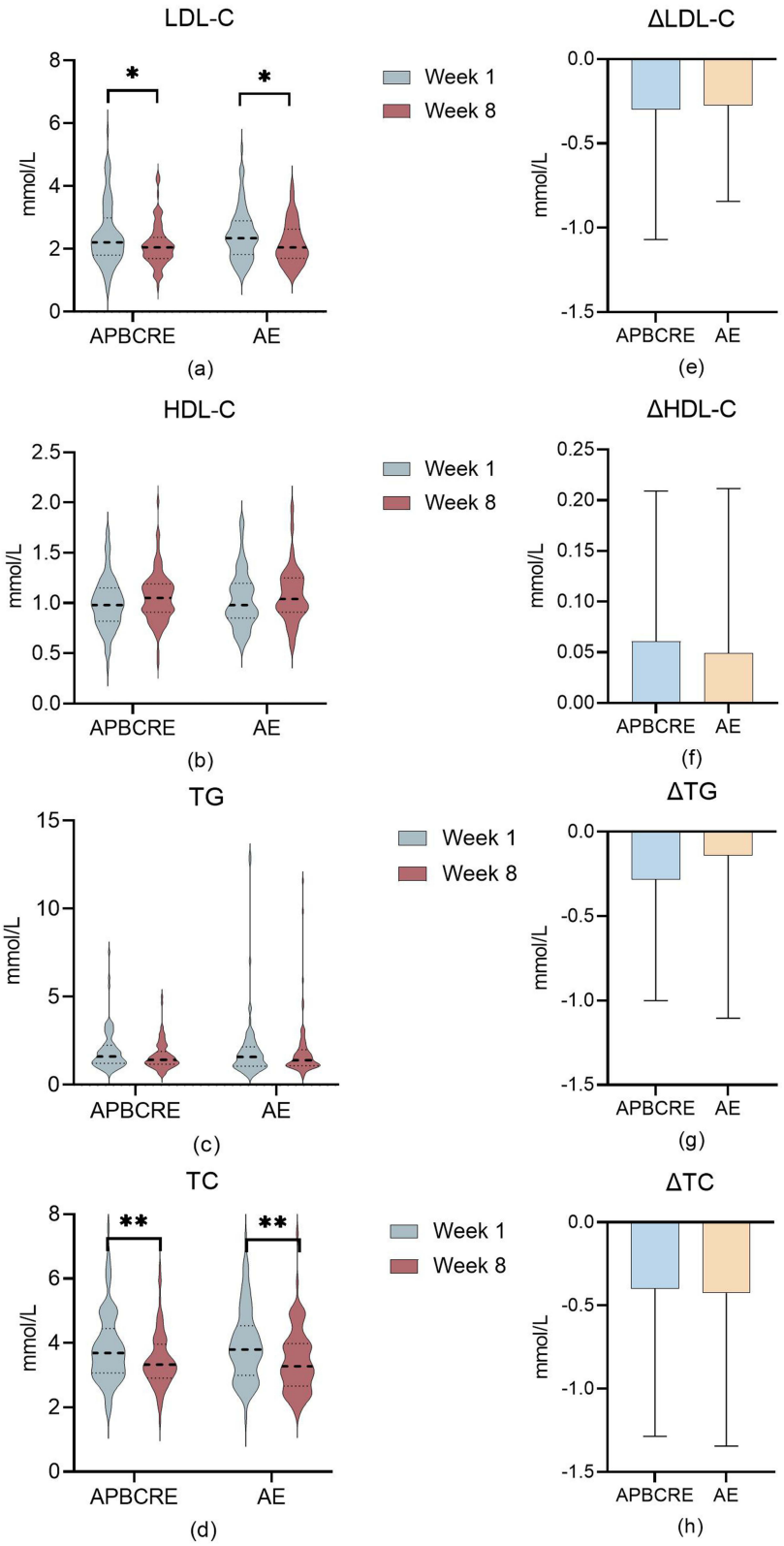

Figure 8 Changes in lipid profile markers at week 1 and week 8 in APBCRE and AE groups. (**a**) LDL-C levels (mmol/L). (**b**) HDL-C levels (mmol/L). (**c**) TG levels (mmol/L). (**d**) TC levels (mmol/L). (**e**) Change in LDL-C (ΔLDL-C) (mmol/L) in the APBCRE and AE groups. (**f**) Change in HDL-C (ΔHDL-C) (mmol/L) in the APBCRE and AE groups. (**g**) Change in TG (ΔTG) (mmol/L) in the APBCRE and AE groups. (**h**) Change in TC (ΔTC) (mmol/L) in the APBCRE and AE groups. *P < 0.05, **P < 0.01 indicates significant within-group differences.

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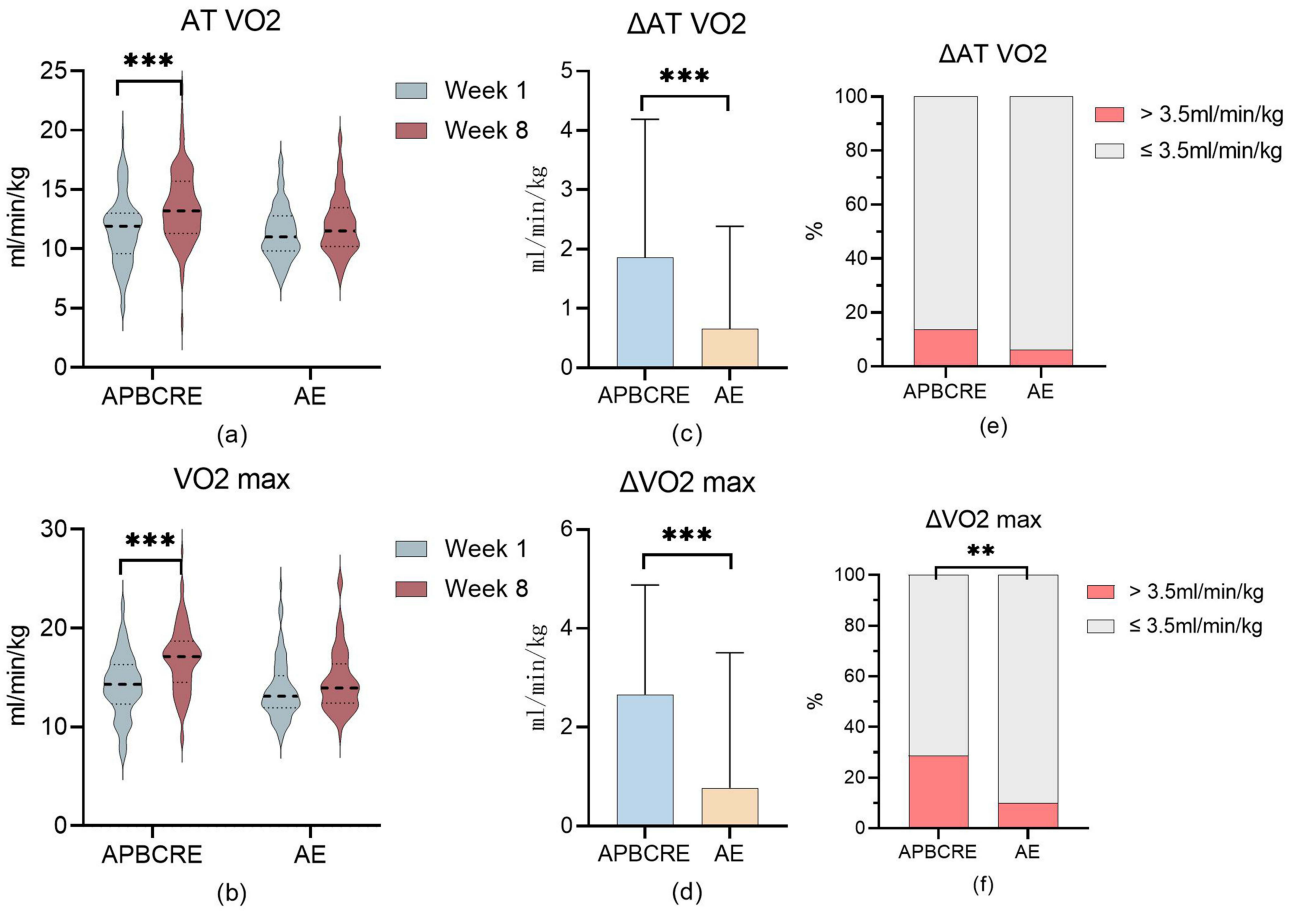

Figure 9 Changes in AT$\dot{V}O_2$and $\dot{V}O_2$max at week 1 and week 8 in APBCRE and AE groups. (**a**) AT$\dot{V}O_2$ levels (mL/min/kg). (**b**) $\dot{V}O_2$max levels (mL/min/kg). (**c**) Change in AT $\dot{V}O_2$ (ΔAT $\dot{V}O_2$) (mL/min/kg) in APBCRE and AE groups. (**d**) Change in $\dot{V}O_2$ max ($\Delta\dot{V}O_2$ max) (mL/min/kg) in APBCRE and AE groups. (**e**) AT $\dot{V}O_2$ distribution by percentage, comparing APBCRE and AE groups. (**f**) $\dot{V}O_2$ max distribution by percentage, comparing APBCRE and AE groups ***P < 0.001 indicates significant within-group differences. The double asterisk (**P) in subfigure f indicates a statistically significant difference between APBCRE and AE groups in the proportion of participants with $\Delta\dot{V}O^2$max > 3.5 mL/min/kg (P < 0.01).

overall physical capacity through balance training. This type of training facilitates glucose uptake and utilization by muscles, effectively lowering blood glucose levels.[16] APBCRE also influences autonomic nervous system regulation, particularly by enhancing parasympathetic activity, which positively impacts glycolipid metabolism and insulin sensitivity, resulting in significant reductions in HbA1c levels.[18]

APBCRE has demonstrated significant benefits in improving metabolic outcomes and exercise endurance, and its applicability extends beyond controlled research settings. In clinical practice, APBCRE could be integrated into outpatient cardiac rehabilitation programs, especially for patients with comorbidities such as diabetes or neurological disorders. Its combination of posture-balance training and aerobic exercise makes it a versatile option for enhancing cardiovascular and metabolic health. Furthermore, due to its low equipment requirements, APBCRE could be implemented in various healthcare settings, including primary care clinics, rehabilitation centers, and home-based programs. Given its efficacy, APBCRE offers a promising, cost-effective alternative to traditional rehabilitation approaches. Future studies should focus on cost-effectiveness analyses to evaluate its potential for widespread adoption in resource-limited settings.

Compared to other structured exercise interventions, APBCRE may offer better cost-effectiveness, particularly for patients who struggle with adherence to traditional exercise regimens due to motor impairments. The integration of posture-balance training with aerobic exercise could provide a more sustainable approach, improving long-term adherence and potentially reducing healthcare costs. Although a formal cost-effectiveness analysis has yet to be conducted,

future studies should explore the economic value of APBCRE, especially in resource-limited healthcare settings where cost-effective interventions are essential. These findings highlight the importance of individualized exercise prescriptions, guided by CPET, to optimize metabolic control and improve overall health in patients with CAD and T2DM.

While the 8-week intervention period provides valuable insights into short-term outcomes, the long-term effects of APBCRE remain to be assessed. Future studies should incorporate longer follow-up periods to evaluate the sustainability of these improvements and assess APBCRE's impact on cardiovascular events, quality of life, and other long-term health outcomes. Additionally, expanding the sample size and conducting multi-center trials would enhance the external validity of the results, facilitating broader application across diverse populations. These efforts will help validate and refine the findings, ensuring that APBCRE can be effectively implemented in clinical settings.

Conclusion

In conclusion, the results of this study suggest that APBCRE, an integrated approach combining posture-balance training with aerobic exercise, offers significant benefits in improving glycolipid metabolism and exercise endurance in patients with CAD and T2DM. APBCRE outperformed traditional aerobic exercise, demonstrating superior reductions in fasting blood glucose, HbA1c, and LDL-C levels, as well as greater improvements in exercise capacity. The combination of neuromuscular coordination and aerobic exercise in APBCRE not only enhances metabolic health but also improves functional stability and reduces fall risk, which is particularly important for patients with T2DM and CAD who may experience neuropathy and motor impairments.

Furthermore, the individualized exercise prescription guided by CPET ensures optimal intensity, promoting long-term adherence and minimizing cardiovascular risk. The short-term benefits are promising, and APBCRE represents a potentially cost-effective, holistic approach to managing CAD and T2DM, improving both metabolic parameters and quality of life for patients with these comorbidities.

Future research should explore the long-term effects of APBCRE, including its ability to sustain improvements in metabolic and cardiovascular health over extended periods. Additionally, expanding the intervention to populations with other chronic conditions or comorbidities beyond CAD and T2DM—such as individuals with hypertension, obesity, or neurological diseases—could provide valuable insights into the broader applicability of APBCRE. Further multi-center trials with larger and more diverse participant groups are essential to evaluate the sustainability of these improvements and assess the broader impact on long-term health outcomes, including quality of life and cardiovascular events.

Data Sharing Statement

The authors intend to share individual deidentified participant data underlying the results reported in this article.

The following data will be shared:

- Deidentified individual participant data related to baseline characteristics, intervention outcomes, and follow-up assessments.
- Study protocol, statistical analysis plan, and informed consent form.

Data will be available upon reasonable request by contacting the corresponding author at tjxkkfyxkm@126.com.

The data will be available beginning 12 months following article publication and will remain accessible for a period of 3 years.

Ethics Approval and Consent to Participate

This study was approved by the Institutional Review Board of Tianjin Chest Hospital (Approval Number: 2023KY-025-01) in accordance with the Declaration of Helsinki, with approval granted on 20th September 2023. Written informed consent was obtained from all individual patients included in the study.

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This trial was registered at the Chinese Clinical Trial Registry (ChiCTR) under the registration number ChiCTR2300078066.

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Disclosure

The author(s) report no conflicts of interest in this work.

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