Immediate Effects of Aerobic Exercise on Arterial Stiffness in Men with Different Blood Glucose Levels: Postprint

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Abstract

Objective: To investigate the immediate effects of aerobic exercise on arterial stiffness in populations with different blood glucose levels.

Methods: This study included subjects who participated in both the 6th follow-up physical examination of the Kailuan Study (2018-2020) and completed brachial-ankle pulse wave velocity (baPWV) measurements before and after the two-stage power bicycle load test. According to fasting blood glucose levels, the participants were divided into quartile groups: Q1 (n=220): <5.00 mmol/L, Q2 (n=240): 5.00~<5.40 mmol/L, Q3 (n=230): 5.40~<5.81 mmol/L, Q4 (n=234): $ $5.81 mmol/L. Generalized linear models were used to analyze the differences in baPWV changes before and after the two-stage power bicycle load test among different blood glucose level groups.

Results: A total of 924 subjects met the inclusion criteria, with a mean age of (36.93$±$7.72) years. The baPWV measured immediately after 7 minutes of the two-stage power bicycle load test decreased by an average of 36 cm/s compared with the resting level. After adjusting for relevant confounding factors, the decrease in baPWV in the lowest quartile (Q1) group was 18.96 (95%CI -36.96, -0.96) cm/s greater than that in the highest quartile (Q4) group of fasting blood glucose level.

Conclusion: Aerobic exercise can immediately improve the degree of arterial stiffness, but hyperglycemia attenuates the beneficial effect of aerobic exercise on arterial stiffness, and this adverse effect is independent of traditional cardiovascular disease risk factors such as body mass index (BMI) and hypertension.

Full Text

The Immediate Effects of Aerobic Exercise on Arterial Stiffness in a Male Population with Different Blood Glucose Levels

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Abstract

Objective To investigate the immediate effect of aerobic exercise on arterial stiffness in people with different blood glucose levels. **Methods** Participants included individuals who both attended the sixth follow-up physical examination of the Kailuan Study from 2018 to 2020 and completed brachial-ankle pulse wave velocity (baPWV) measurements before and after the secondary load test of a cycle ergometer. According to fasting blood glucose levels, subjects were grouped into quartiles: Q1 (n=220): <5.00 mmol/L, Q2 (n=240): 5.00-<5.40 mmol/L, Q3 (n=230): 5.40-<5.81 mmol/L, and Q4 (n=234): $ 5.81mmol/L.AgeneralizedlinearmodelwasusedtoanalyzedifferencesinbaPWVchangesbeforeandafterthe
*Results**Atotalof924subjectsmettheinclusioncriteria, withameanageof(36.93±$7.72) years. baPWV measured immediately after 7 minutes of the cycle ergometer secondary load test decreased by an average of 36 cm/s from resting levels. After adjusting for relevant confounding factors, the group with the lowest fasting glucose (Q1) showed a 18.96 cm/s greater decrease in baPWV (95%CI: -36.96, -0.96) compared to the group with the highest fasting glucose (Q4). **Conclusion** Aerobic exercise can immediately improve arterial stiffness, but hyperglycemia attenuates this beneficial effect. This adverse effect is independent of traditional cardiovascular risk factors such as body mass index (BMI) and hypertension.

Keywords Pulse wave velocity; Aerobic exercise; Fasting blood glucose; Arterial stiffness; Cardiovascular disease

Introduction

Aerobic exercise is a cornerstone for the prevention and treatment of chronic non-communicable diseases [1-4]. Regular long-term aerobic exercise not only reduces body weight [5], lowers blood glucose [6], and improves lipid metabolism [7], but also prevents atherosclerosis and arterial stiffening, thereby preventing cardiovascular and cerebrovascular diseases [8]. Even in secondary prevention of cardiovascular diseases [9], aerobic exercise plays a pivotal role. Consequently, various guidelines recommend aerobic exercise as a primary component of a healthy lifestyle.

Previous research on the benefits of aerobic exercise has primarily focused on long-term cardiovascular health and outcomes [10-13]. Studies examining short-term or immediate effects have mainly investigated the impact on blood pressure, with only a few small-sample studies observing the effects on arterial stiffness, yielding inconsistent conclusions. Kobayashi et al. [14] found that arterial stiffness improved immediately after aerobic exercise in 11 healthy young men. Another study of 24 young diabetic individuals found no significant immediate improvement in arterial stiffness following aerobic exercise [15]. Since hyperglycemia is a known factor that increases arterial stiffness [16-19], we hypothesized that elevated blood glucose might attenuate the beneficial effects of aerobic exercise on arterial stiffness. To test this hypothesis, we utilized data from the Kailuan Study (registration number: ChiCTR-TNC-11001489) combined with data from the 2020 fifth National Physical Fitness Survey to analyze the immediate effects of aerobic exercise on arterial stiffness, measured as brachial-ankle pulse wave velocity (baPWV), in populations with different blood glucose levels.

Methods

1.1 Study Population

The Kailuan Study (registration number: ChiCTR-TNC-11001489) is an investigation and intervention study of cardiovascular disease risk factors based on a functional community population. Initiated in July 2006, Kailuan General Hospital and its 10 affiliated hospitals have been responsible for conducting health examinations for active and retired employees of the Kailuan Group, with follow-ups every two years. To systematically assess national physical fitness status and provide evidence for policies to enhance population health, the State General Administration of Sport conducted the fifth National Physical Fitness Survey in 2020. Using industry as the sampling unit, 1,200 male employees aged 20-49 years were randomly selected from four Kailuan Group enterprises based on the distribution characteristics of typical coal industry occupations. The test battery included a cycle ergometer secondary load test, sit-and-reach test, cardiopulmonary endurance test, and body fat percentage measurement. Building upon the original measurements, this study added baPWV measurements before and after the cycle ergometer secondary load test. The study population comprised individuals who both participated in the sixth follow-up physical examination of the Kailuan Study from 2018 to 2020 and completed baPWV measurements before and after the cycle ergometer secondary load test.

1.2 Inclusion and Exclusion Criteria

Inclusion criteria: (1) Participants in the 2018-2020 sixth follow-up physical examination of the Kailuan Group who were selected for the 2020 fifth National Physical Fitness Survey; (2) Individuals who completed baPWV measurements both before and after the cycle ergometer secondary load test; (3) Individuals who agreed to participate and provided informed consent.

Exclusion criteria: (1) Individuals with missing fasting blood glucose data; (2) Individuals with incomplete cycle ergometer secondary load test data. This study adhered to the Declaration of Helsinki and was approved by the Ethics Committee of Kailuan General Hospital (approval number: [2006] Ethics No. 5). All participants provided informed consent.

1.3 Measurements

1.3.1 Epidemiological Survey and Anthropometric Measurements The epidemiological survey included age, gender, history of hypertension and dyslipidemia, medication use, smoking history, alcohol consumption habits, and physical exercise patterns. Anthropometric measurements included height, weight, systolic blood pressure, diastolic blood pressure, and heart rate. Biochemical indicators included triglycerides, total cholesterol, high-density lipoprotein cholesterol (HDL-C), low-density lipoprotein cholesterol (LDL-C), and high-sensitivity C-reactive protein (hs-CRP). Detailed methods have been described in previously published literature from our research group [20-21].

1.3.2 Fasting Blood Glucose Measurement Participants fasted for at least 8 hours, and 5 mL of fasting elbow venous blood was drawn between 7:00-9:00 AM on the examination day. After centrifugation at 3,000 r/min for 10 minutes at room temperature (24°C) with a centrifuge radius of 13 cm, the supernatant serum was collected and fasting blood glucose was measured within 4 hours. The hexokinase method was used, with a coefficient of variation not exceeding 2% at 5.6 mmol/L and an upper linear limit of 33.3 mmol/L. Measurements were performed using a Hitachi 7600 automatic biochemical analyzer with reagent kits provided by Zhongsheng Beikong Biotechnology Co., Ltd. Professional laboratory technicians strictly followed the operating manual, with batch quality control performed.

1.3.3 Cycle Ergometer Secondary Load Test All examinations were conducted on-site at room temperature (22-25°C). The GMCS-GLC3 cycle ergometer (produced by Tianjin Xinghe Zhongbang Engineering Consulting Co., Ltd.), uniformly equipped by the National Physical Fitness Monitoring Center, was used for the secondary load exercise test. All participants were prohibited from smoking, drinking alcohol, consuming caffeine, and engaging in vigorous activity within 12 hours before the test. Before the cycle ergometer test, participants rested for at least 15 minutes before measurement of resting blood pressure, heart rate, and baPWV. Participants then performed a 7-minute secondary load test on the cycle ergometer, maintaining a pedaling speed of 60 rpm throughout. The initial 30 seconds served as a zero-load warm-up phase, with load increased by one level (25W) every 3 minutes for a total of two increments, followed by a final 30-second zero-load recovery phase. Exercise heart rate was monitored in real-time using a heart rate monitor placed on the medial side of the midpoint of the right upper arm. Maximum oxygen consumption (VO_2max) was calculated and uploaded by the cycle ergometer' s built-in system.

1.3.4 Measurement of baPWV, Blood Pressure, and Heart Rate

baPWV was measured using the BP-203RPE network-based arteriosclerosis detection device (produced by Omron Healthcare China Co., Ltd.) before and after the cycle ergometer secondary load test. During measurement, all participants wore light clothing, lay supine on a measurement bed without a pillow, placed their hands palm-up beside their bodies, and remained quiet. Medical staff aligned the upper arm cuff bladder marker with the brachial artery and the lower limb cuff bladder marker on the medial side of the ankle joint, with electrocardiogram acquisition devices clipped to both wrists. Two measurements were taken for each participant, with the second measurement used as the final result. This study used the larger value of baPWV from the left and right sides for analysis. Blood pressure values from the right upper limb were used for analysis. Mean arterial pressure was calculated as (1/3 systolic pressure + 2/3 diastolic pressure).

1.4 Grouping Method

Based on fasting blood glucose quartiles, participants were divided into four groups: Q1: <5.00 mmol/L, Q2: 5.00–<5.40 mmol/L, Q3: 5.40–<5.81 mmol/L, and Q4: $ $5.81 mmol/L.

1.5 Definitions and Diagnostic Criteria

Hypertension was defined according to the *Chinese Guidelines for the Prevention and Treatment of Hypertension (2018 Revision)* [22] as systolic blood pressure $ $140 mmHg and/or diastolic blood pressure $ $90 mmHg without antihypertensive medication, or a history of hypertension or current use of antihypertensive medication. **Hyperlipidemia** was defined according to the *Chinese Guidelines for the Prevention and Treatment of Dyslipidemia in Adults* as meeting any of the following criteria: (1) total cholesterol >5.72 mmol/L; (2) triglycerides >1.70 mmol/L; (3) HDL-C <0.91 mmol/L; or (4) LDL-C >3.64 mmol/L.

Body mass index (BMI) was calculated as weight (kg)/height^2 (m^2). **Smoking** was defined as consuming at least one cigarette per day on average in the past year. **Alcohol consumption** was defined as drinking an average of 100 mL of white liquor (alcohol content $ $50%) daily for $ $1 year. **Physical exercise** was defined as exercising $ $3 times per week for $ $30 minutes per session.

1.6 Statistical Methods

Data were entered by uniformly trained professionals from each hospital and compiled and uploaded to an Oracle database by Kailuan General Hospital. SAS 9.4 software was used for statistical analysis. Normally distributed continuous variables were expressed as mean ± standard deviation ($\bar{X} \pm S$), with intergroup comparisons using one-way ANOVA and pairwise multiple comparisons using Scheffe' s method. Data before and after the cycle ergometer secondary load test were compared using paired t-tests. Non-normally distributed continuous variables were expressed as median (P25, P75), with intergroup comparisons using Kruskal-Wallis test and pre-post comparisons using paired rank-sum test. Categorical variables were expressed as number (%) and compared using ^{2} test. $P<0.05$ was considered statistically significant.

Using the difference in baPWV before and after the cycle ergometer secondary load test as the dependent variable and quartile blood glucose groups as the independent variable, generalized linear regression models were used to evaluate differences in baPWV changes before and after exercise across different blood glucose level groups (with Q4 as the reference). **Sensitivity analyses** were conducted to address potential confounding: (1) To account for potential effects of inconsistent timing of post-exercise baPWV measurement, participants with interval measurement time >26.28 minutes (95th percentile) were excluded and the generalized linear analysis was repeated; (2) To address potential effects of hypertension and antihypertensive medication use on baPWV differences, participants with hypertension and those using antihypertensive medication were separately excluded and the analysis repeated. $P<0.05$ (two-tailed test) indicated statistical significance.

A total of 1,200 Kailuan Group employees were sampled for the fifth National Physical Fitness Survey, of whom 1,128 participated in the 2018-2020 sixth follow-up physical examination. After excluding 116 individuals who did not complete baPWV measurements before and after the cycle ergometer test, 86 with missing fasting blood glucose data, and 2 with incomplete cycle ergometer test data, 924 participants were included in the final statistical analysis.

Results

2.1 Comparison of General Characteristics

All participants were male with a mean age of (36.93$±$7.72) years. According to fasting blood glucose quartiles, the numbers of participants in groups Q1 through Q4 were 220, 240, 230, and 234, respectively, with fasting glucose levels of 4.74 (4.50–4.88), 5.20 (5.10–5.30), 5.57 (5.50–5.69), and 6.22 (5.99–6.59) mmol/L. The highest fasting glucose group (Q4) had significantly higher age, waist circumference, systolic blood pressure, diastolic blood pressure, and LDL-C compared to the lowest glucose group (Q1) ($P<0.01$). The proportions of hypertension, hyperlipidemia, and antihypertensive medication use were also higher in Q4 than in the other three groups ($P<0.01$). See .

2.2 Comparison of baPWV Before and After Load Test Across Different Glucose Groups

The resting baPWV for all participants was (1375.98$±$209.61) cm/s. Scheffe's pairwise multiple comparisons showed that the highest fasting glucose group (Q4) had higher resting baPWV levels compared to Q1, Q2, and Q3 groups ($P<0.05$). baPWV decreased after the cycle ergometer secondary load test in all four quartile groups ($P<0.01$). Compared to resting baPWV, the average decrease was 36.0 cm/s across different blood glucose levels. See .

2.3 Generalized Linear Model Analysis of Blood Glucose Effects on baPWV Changes

In Model 1, resting baPWV was adjusted. Model 2 additionally adjusted for age, BMI, waist circumference, hs-CRP, smoking, alcohol consumption, and physical exercise based on Model 1. Model 3 further adjusted for hypertension without medication, hypertension with medication, hyperlipidemia, peak heart rate, ΔHR, ΔMAP, and interval measurement time. After these adjustments, compared with Q4, baPWV changes in Q1, Q2, and Q3 were -18.96 [95%CI: -36.96, -0.96] cm/s, -12.37 [95%CI: -29.35, 4.60] cm/s, and -15.23 [95%CI: -31.95, 1.49] cm/s, respectively. See .

2.4 Sensitivity Analysis

After separately excluding participants with hypertension (n=318), those using antihypertensive medication (n=92), and those with interval measurement time above the 95th percentile (>26.28 min, n=47), generalized linear analysis was repeated. The changes in baPWV across different glucose groups after the cycle ergometer secondary load test were similar to the main analysis results, though the differences were not statistically significant (see -).

Discussion

The key finding of this study is that while aerobic exercise does improve arterial stiffness, hyperglycemia attenuates this beneficial effect, and this adverse effect is independent of traditional cardiovascular risk factors such as BMI and hypertension.

Previous studies on the effects of aerobic exercise on arterial stiffness have shown significant improvements in peripheral arterial stiffness in healthy populations [23]. Magalhães et al. [24] demonstrated that aerobic exercise could reduce peripheral arterial stiffness (carotid distal pulse wave velocity, cdPWV) in diabetic patients. Another study of 11 healthy young men with a mean age of 21 years showed decreased peripheral arterial stiffness (leg pulse wave velocity, LPWV) after 30 minutes of aerobic exercise [14]. Our study found that baPWV measured immediately after a cycle ergometer secondary load test decreased by an average of 36 cm/s from resting levels in young men with different blood glucose levels (36.93$±$7.72 years). This result is similar to Kingwell et al. [25], who found that arterial stiffness decreased by 80 cm/s immediately after 30 minutes of cycle ergometer exercise in healthy men with a mean age of 24 years.

Our study observed differences in the magnitude of baPWV reduction after the cycle ergometer test across different blood glucose levels. After adjusting for multiple confounding factors, the lowest fasting glucose group (Q1) showed a 18.96 cm/s greater decrease in baPWV compared to the highest fasting glucose group (Q4). In contrast to our findings, a randomized crossover trial found no significant improvement in arterial stiffness after aerobic exercise in hyperglycemic individuals (n=24) [15]. Cooke et al. [26] found differential immediate effects of aerobic exercise on arterial stiffness between type 2 diabetic patients (n=66) and non-diabetic individuals (n=61), with diabetic patients showing a 1.6 m/s increase in arterial stiffness immediately after 15 minutes of vigorous exercise compared to non-diabetic individuals. These discrepancies may be due to more intense exercise protocols, smaller sample sizes, and the use of carotid-femoral pulse wave velocity (cfPWV) as the arterial stiffness measure in previous studies. cfPWV primarily evaluates central arterial stiffness, and research indicates that aerobic exercise has inconsistent effects on different arterial segments [27], with central arterial stiffness increasing relative to resting levels immediately after exercise while peripheral arterial stiffness decreases. These factors may explain the differences from our results.

Although our study found differences in the immediate reduction of baPWV after the cycle ergometer test across blood glucose levels, with more pronounced decreases in lower glucose groups compared to higher glucose groups, this observational study cannot explore specific mechanisms. Based on previous research, possible mechanisms include: chronic hyperglycemia leads to advanced glycation end-product formation, with glucose cross-linking with collagen in arteries, altering the critical balance between elastin and collagen. Hyperglycemia activates protein kinase C, leading to reactive oxygen species production and inflammation, which changes the structural and functional integrity of the vascular wall [28, 29]. These inherent changes in arterial wall properties in hyperglycemic individuals may weaken the positive effects of aerobic exercise on arterial stiffness, resulting in inconsistent effects across different blood glucose levels. Additionally, given that short-duration cycle ergometer tests are unlikely to affect vascular structure, differences are primarily attributed to functional changes. Short-term aerobic exercise increases blood flow velocity, generating shear stress that induces vascular endothelial cells to release vasodilatory factors including prostaglandins, nitric oxide, and other substances, causing vascular smooth muscle relaxation and promoting vascular functional improvement, thereby reducing arterial stiffness [30-32]. Hyperglycemic individuals may exhibit impaired vascular endothelial cell function and dysregulated nervous system activity [33], which may explain why baPWV improvement is less pronounced after aerobic exercise in this population.

Lifestyle modification and management of multiple risk factors remain primary prevention measures for cardiovascular disease, with aerobic exercise recommended as a main component of a healthy lifestyle across various guidelines. Systematic reviews and meta-analyses indicate that long-term aerobic exercise is needed to reduce arterial stiffness in adults [23]. However, our results show that even a single bout of aerobic exercise can reduce peripheral arterial stiffness. Research suggests that the immediate effect of short-duration aerobic exercise on baPWV represents functional rather than structural changes [23], and these changes are not sustained, with values returning to baseline. Since short-term aerobic exercise does not provide sufficient stimulus to promote structural arterial changes, increasing the frequency (total duration) of aerobic exercise may help maintain the beneficial effects on arterial stiffness over time, leading to structural vascular improvements. For hyperglycemic individuals, more aggressive exercise prescriptions may be needed to provide sufficient stimulus to induce arterial structural changes and compensate for the adverse effects of hyperglycemia. Therefore, clinicians should design different exercise programs for different populations to improve arterial stiffness and delay vascular aging.

This study has several limitations. The population has substantial heterogeneity. First, all participants were young men, which limits generalizability to middle-aged, elderly, or female individuals. Second, glucose values were determined based on a single fasting glucose measurement, which may introduce some misclassification bias regarding glucose status. Finally, due to site constraints, only a single post-exercise measurement was obtained, limiting the generalizability of the results. More repeated measurements of arterial stiffness after aerobic exercise are needed to further investigate whether and for how long the improvements in arterial stiffness are sustained.

In summary, a single bout of aerobic exercise can improve arterial stiffness, with an immediate post-exercise decrease observed, but hyperglycemia attenuates this beneficial effect.

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