

# Ventricular-Arterial Coupling in Endurance-Trained Athletes and Sedentary Adults

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# Abstract

## Aims

Ventriculo-arterial coupling (VAC) reflects the integrative interaction between cardiac function and arterial load and is a key determinant of cardiovascular efficiency. Endurance training is associated with favourable adaptations in both ventricular and arterial properties, but comprehensive comparisons of VAC between endurance-trained athletes and sedentary individuals remain limited. This study aimed to compare VAC and related cardiovascular characteristics between physically active and sedentary adult men.

## Methods and results

In this cross-sectional study, 66 healthy men (33 physically active, 33 sedentary; mean age  $43.6 \pm 4.5$  years) underwent assessment of haemodynamics, metabolic profile, echocardiography, arterial stiffness, and cardiorespiratory fitness. VAC was evaluated using a Pulse wave velocity / Global longitudinal strain (PWV/GLS) and arterial elastance / end systolic elastance (Ea/Ees) ratio.

## Results

Physically active participants exhibited lower resting heart rate, lower brachial and central diastolic blood pressure, and a more favourable metabolic profile, including higher HDL cholesterol and lower triglycerides and glucose (all  $p < 0.01$ ). Peak oxygen consumption was markedly higher in physically active individuals ( $p < 0.001$ ). Cardiac assessment revealed higher stroke volume, greater indexed myocardial mass, and more favorable diastolic function (higher E/A and lower E/E') in the physically active group. PWV/GLS was significantly lower in physically active individuals ( $p = 0.047$ ), whereas Ea/Ees showed a non-significant trend towards lower values.

## Conclusions

Endurance-trained adults display a more favorable cardiovascular phenotype at rest, characterized by lower arterial stiffness and improved ventriculo-arterial coupling. These findings support the concept that long-term endurance training promotes efficient cardiovascular integration.

## Introduction

Ventriculo-arterial coupling (VAC) reflects the integrated interaction between left ventricular contractile properties and arterial load and is a key determinant of cardiovascular efficiency and cardiac energetics. By capturing the balance between ventricular performance and vascular properties, coupling indices provide important insight into cardiovascular function in health and disease, including ageing,

hypertension, and heart failure, where increased arterial stiffness and afterload contribute to impaired efficiency and functional limitation (1).

Regular endurance exercise induces coordinated adaptations in both the arterial and cardiac systems. Aerobic training has been associated with lower central arterial stiffness, reduced effective arterial elastance, and preserved myocardial deformation, alongside structural and functional cardiac adaptations that support efficient stroke volume generation (2–4). Previous work has examined VAC during exercise, following training interventions, or across different exercise doses, demonstrating that physical activity can modulate coupling behaviour through parallel vascular and ventricular adaptations (5).

Despite growing interest in VAC, direct comparisons of baseline coupling profiles between endurance-trained and sedentary individuals remain limited. In particular, traditional elastance-based indices such as the effective arterial elastance to end-systolic elastance ratio ( $E_a/E_{es}$ ) may be insensitive to subtle differences at rest when arterial and ventricular properties adapt concurrently (6). Composite indices integrating arterial stiffness and myocardial mechanics, such as the PWV/GLS ratio, may therefore provide complementary insight into resting coupling efficiency, but have been less frequently explored in physically active populations (7, 8).

Therefore, the aim of this study was to compare VAC and related cardiovascular parameters at rest between endurance-trained athletes and sedentary individuals. By combining classical elastance-based measures with indices integrating arterial stiffness and myocardial deformation (PWW/GLS), this study sought to characterise baseline coupling profiles associated with habitual endurance training in healthy adults.

## Methods

### Study population

This cross-sectional observational study was conducted within the *Hemodynamics, Cardiac Physiology and Exercise* project, a collaboration between the University of Coimbra and the Polytechnic Institute of Coimbra. Healthy adult men aged  $\geq 35$  years were recruited in Coimbra, Portugal, between November 2022 and April 2023. Participants were classified as physically active or sedentary based on habitual exercise behaviour. Physically active participants were defined as master athletes who regularly trained for and/or participated in competitive endurance-based sports, whereas sedentary controls performed  $< 60$  minutes of structured exercise per week. Exclusion criteria included known cardiovascular disease, uncontrolled hypertension, cardiomyopathy, valvular heart disease, or incomplete data for primary outcome variables. All participants provided written informed consent. The study was approved by the Ethics Committee of the Faculty of Sport Sciences and Physical Education, University of Coimbra (CE/FCDEF-UC/00012022), and conducted in accordance with the Declaration of Helsinki.

## Variables assessed

All participants underwent standardized assessment of haemodynamics, metabolic profile, cardiac structure and function, arterial stiffness, and cardiorespiratory fitness.

Brachial and central blood pressures were measured at rest using an oscillometric device with pulse wave analysis (AGEDIO®, IEM GmbH)(9–12). Carotid–femoral pulse wave velocity (PWV) was obtained as an index of arterial stiffness (10, 11). Fasting venous blood samples were collected for analysis of glucose and lipid profile (total cholesterol, low-density lipoprotein cholesterol (LDL-C), high-density lipoprotein cholesterol (HDL-C), and triglycerides). Transthoracic echocardiography was performed by a single experienced operator using a Vivid system (GE Healthcare), following international guidelines (13–15). Left ventricular ejection fraction, stroke volume, indexed myocardial/ventricular mass, global longitudinal strain (GLS), and Doppler-derived indices of diastolic function (E/A and E/E') were obtained from averaged measurements across three cardiac cycles. Maximal oxygen uptake ( $\text{VO}_{2\text{peak}}$ ) was assessed during a graded cardiopulmonary exercise test on a cycle ergometer with breath-by-breath gas exchange analysis (COSMED K4b2). Peak  $\text{VO}_2$  was defined as the highest 30-s average achieved during the test(16).

## Ventriculo-arterial coupling

The VAC was assessed using two complementary approaches. A novel index was calculated as the ratio between Pulse wave velocity and Global longitudinal strain (PWV/GLS). Traditional VAC was expressed as the ratio between effective arterial elastance ( $E_a$ ) and end-systolic elastance ( $E_{es}$ ), derived from non-invasive haemodynamic and echocardiographic measurements. These indices were selected a priori as primary markers of cardiovascular coupling efficiency (15, 17).

## Statistical analysis

Continuous variables are presented as mean  $\pm$  standard deviation. Between-group comparisons were performed using independent-samples t-tests or one-way ANOVA. Normality and variance assumptions were evaluated visually and with Levene's test; results were confirmed using robust approaches where appropriate. Statistical significance was set at  $p < 0.05$ . Analyses were performed using IBM SPSS Statistics version 28.

## Results

### Study population characteristics

A total of 66 participants were included in the study, comprising 33 physically active individuals and 33 sedentary controls. The two groups were similar in age ( $43.1 \pm 4.7$  vs.  $44.1 \pm 4.3$  years;  $p = 0.389$ ). Brachial diastolic blood pressure (bDBP) was lower in physically active participants compared with

controls ( $74.6 \pm 8.1$  vs.  $80.7 \pm 10.5$  mmHg;  $p = 0.010$ ), whereas brachial systolic blood (bSBP) pressure did not differ significantly between groups ( $126.7 \pm 8.5$  vs.  $131.8 \pm 15.6$  mmHg;  $p = 0.104$ ). Resting heart rate was markedly lower in the physically active group ( $51.3 \pm 8.1$  vs.  $63.6 \pm 10.4$  bpm;  $p < 0.001$ ). Regarding metabolic variables, physically active participants exhibited higher HDL-C levels ( $43.9 \pm 9.6$  vs.  $36.2 \pm 11.2$ ;  $p = 0.004$ ), lower triglyceride concentrations ( $75.3 \pm 28.6$  vs.  $118.6 \pm 66.7$ ;  $p = 0.001$ ), and lower fasting glucose levels ( $79.8 \pm 14.4$  vs.  $92.2 \pm 17.1$ ;  $p = 0.002$ ). Total cholesterol did not differ between groups ( $p = 0.298$ ), while LDL-C showed a non-significant trend towards lower levels in physically active individuals ( $p = 0.071$ ). Peak oxygen consumption was available in 63 participants (controls  $n = 32$ ; physically active  $n = 31$ ) and was substantially higher in the physically active group ( $47.1 \pm 10.4$  vs.  $32.9 \pm 6.9$  ml·min<sup>-1</sup>·kg<sup>-1</sup>;  $p < 0.001$ ), Table 1.

Table 1

Participant characteristics, cardiac function, arterial stiffness, and ventriculo-arterial coupling

| Variables                                                                                                                                                                                                                                                                                                                                                                                       | Controls<br>(n = 33) | Physically active (n = 33) | Total<br>(n = 66) | p-value |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------|----------------------------|-------------------|---------|
| <b>Demographics and haemodynamics</b>                                                                                                                                                                                                                                                                                                                                                           |                      |                            |                   |         |
| Age (years)                                                                                                                                                                                                                                                                                                                                                                                     | 44.1 ± 4.3           | 43.1 ± 4.7                 | 43.6 ± 4.5        | 0.389   |
| bSBP (mmHg)                                                                                                                                                                                                                                                                                                                                                                                     | 131.8 ± 15.6         | 126.7 ± 8.5                | 129.2 ± 12.7      | 0.104   |
| bDBP (mmHg)                                                                                                                                                                                                                                                                                                                                                                                     | 80.7 ± 10.5          | 74.6 ± 8.1                 | 77.6 ± 9.8        | 0.010   |
| Heart rate (bpm)                                                                                                                                                                                                                                                                                                                                                                                | 63.6 ± 10.4          | 51.3 ± 8.1                 | 57.5 ± 11.1       | < 0.001 |
| Peak VO <sub>2</sub> (ml/min/kg)*                                                                                                                                                                                                                                                                                                                                                               | 32.9 ± 6.9           | 47.1 ± 10.4                | 39.9 ± 11.3       | < 0.001 |
| <b>Metabolic profile</b>                                                                                                                                                                                                                                                                                                                                                                        |                      |                            |                   |         |
| Total cholesterol (mg/dL)                                                                                                                                                                                                                                                                                                                                                                       | 189.3 ± 53.6         | 176.5 ± 45.1               | 182.9 ± 49.6      | 0.298   |
| LDL-C (mg/dL)                                                                                                                                                                                                                                                                                                                                                                                   | 91.4 ± 33.7          | 76.6 ± 31.5                | 84.0 ± 33.2       | 0.071   |
| HDL-C (mg/dL)                                                                                                                                                                                                                                                                                                                                                                                   | 36.2 ± 11.2          | 43.9 ± 9.6                 | 40.1 ± 11.1       | 0.004   |
| Triglycerides (mg/dL)                                                                                                                                                                                                                                                                                                                                                                           | 118.6 ± 66.7         | 75.3 ± 28.6                | 97.0 ± 55.4       | 0.001   |
| Glucose (mg/dL)                                                                                                                                                                                                                                                                                                                                                                                 | 92.2 ± 17.1          | 79.8 ± 14.4                | 86.0 ± 16.9       | 0.002   |
| <b>Cardiac structure and function</b>                                                                                                                                                                                                                                                                                                                                                           |                      |                            |                   |         |
| LVEF (%)                                                                                                                                                                                                                                                                                                                                                                                        | 55.6 ± 2.6           | 56.9 ± 3.4                 | 56.3 ± 3.1        | 0.086   |
| Stroke volume (ml)                                                                                                                                                                                                                                                                                                                                                                              | 63.5 ± 13.6          | 72.2 ± 13.8                | 67.9 ± 14.3       | 0.012   |
| MVE/SC (g/m <sup>2</sup> )                                                                                                                                                                                                                                                                                                                                                                      | 85.5 ± 11.8          | 98.9 ± 12.2                | 92.2 ± 13.7       | < 0.001 |
| E/A ratio                                                                                                                                                                                                                                                                                                                                                                                       | 1.34 ± 0.37          | 1.65 ± 0.36                | 1.50 ± 0.39       | 0.001   |
| E/E' ratio                                                                                                                                                                                                                                                                                                                                                                                      | 7.90 ± 2.07          | 6.97 ± 1.40                | 7.44 ± 1.82       | 0.036   |
| <b>VAC variables</b>                                                                                                                                                                                                                                                                                                                                                                            |                      |                            |                   |         |
| GLS                                                                                                                                                                                                                                                                                                                                                                                             | 19.61 ± 2.88         | 19.78 ± 2.23               | 19.69 ± 2.56      | 0.783   |
| PWV (m/s)                                                                                                                                                                                                                                                                                                                                                                                       | 7.74 ± 0.90          | 7.19 ± 0.72                | 7.47 ± 0.86       | 0.008   |
| Values are mean ± SD. <i>p</i> -values derived from one-way ANOVA.                                                                                                                                                                                                                                                                                                                              |                      |                            |                   |         |
| * Peak VO <sub>2</sub> available in 63 participants (controls <i>n</i> = 32; physically active <i>n</i> = 31).                                                                                                                                                                                                                                                                                  |                      |                            |                   |         |
| Abbreviations: bSBP/bDBP, brachial systolic/diastolic blood pressure; PWV, carotid–femoral pulse wave velocity; cSBP/cDBP, central systolic/diastolic blood pressure; GLS, global longitudinal strain; LVEF, left ventricular ejection fraction; MVE/SC, myocardial/ventricular mass indexed; VAC, ventriculo-arterial coupling; Ea, effective arterial elastance; Ees, end-systolic elastance. |                      |                            |                   |         |

| Variables                                                                                                                                                                                                                                                                                                                                                                                       | Controls<br>(n = 33) | Physically active (n = 33) | Total<br>(n = 66) | p-value |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------|----------------------------|-------------------|---------|
| <b>Demographics and haemodynamics</b>                                                                                                                                                                                                                                                                                                                                                           |                      |                            |                   |         |
| cSBP (mmHg)                                                                                                                                                                                                                                                                                                                                                                                     | 125.6 ± 17.5         | 121.1 ± 11.5               | 123.4 ± 14.9      | 0.220   |
| cDBP (mmHg)                                                                                                                                                                                                                                                                                                                                                                                     | 80.7 ± 10.5          | 74.6 ± 8.1                 | 77.6 ± 9.8        | 0.010   |
| Ea                                                                                                                                                                                                                                                                                                                                                                                              | 1.94 ± 0.42          | 1.63 ± 0.31                | 1.78 ± 0.40       | 0.001   |
| Ees                                                                                                                                                                                                                                                                                                                                                                                             | 2.43 ± 0.54          | 2.16 ± 0.43                | 2.29 ± 0.50       | 0.026   |
| PWV/GLS                                                                                                                                                                                                                                                                                                                                                                                         | 0.404 ± 0.082        | 0.368 ± 0.059              | 0.386 ± 0.073     | 0.047   |
| Ea/Ees                                                                                                                                                                                                                                                                                                                                                                                          | 0.811 ± 0.085        | 0.766 ± 0.105              | 0.788 ± 0.098     | 0.060   |
| Values are mean ± SD. <i>p</i> -values derived from one-way ANOVA.                                                                                                                                                                                                                                                                                                                              |                      |                            |                   |         |
| * Peak VO <sub>2</sub> available in 63 participants (controls <i>n</i> = 32; physically active <i>n</i> = 31).                                                                                                                                                                                                                                                                                  |                      |                            |                   |         |
| Abbreviations: bSBP/bDBP, brachial systolic/diastolic blood pressure; PWV, carotid–femoral pulse wave velocity; cSBP/cDBP, central systolic/diastolic blood pressure; GLS, global longitudinal strain; LVEF, left ventricular ejection fraction; MVE/SC, myocardial/ventricular mass indexed; VAC, ventriculo-arterial coupling; Ea, effective arterial elastance; Ees, end-systolic elastance. |                      |                            |                   |         |

## Cardiac structure and function

Left ventricular ejection fraction (LVEF%) did not differ between groups ( $56.9 \pm 3.4$  vs.  $55.6 \pm 2.6\%$ ;  $p = 0.086$ ). The stroke volume was higher in physically active participants ( $72.2 \pm 13.8$  vs.  $63.5 \pm 13.6$  ml;  $p = 0.012$ ). Indexed myocardial/ventricular mass (MVE/SC) was higher in the physically active group ( $98.9 \pm 12.2$  vs.  $85.5 \pm 11.8$  g·m<sup>-2</sup>;  $p < 0.001$ ). Indices of diastolic function demonstrated a higher E/A ratio ( $1.65 \pm 0.36$  vs.  $1.34 \pm 0.37$ ;  $p = 0.001$ ) and a lower E/E' ratio ( $6.97 \pm 1.40$  vs.  $7.90 \pm 2.07$ ;  $p = 0.036$ ) in physically active individuals, Table 1.

## Arterial stiffness and ventriculo-arterial coupling

The PWV was lower in physically active participants compared with sedentary controls ( $7.19 \pm 0.72$  vs.  $7.74 \pm 0.90$  m·s<sup>-1</sup>;  $p = 0.008$ ). GLS was similar between groups ( $19.78 \pm 2.23$  vs.  $19.61 \pm 2.88$ ;  $p = 0.783$ ). The cDBP was lower in the physically active group ( $74.6 \pm 8.1$  vs.  $80.7 \pm 10.5$  mmHg;  $p = 0.010$ ), whereas cSBP did not differ between groups ( $p = 0.220$ ). The Ea was lower in physically active participants ( $1.63 \pm 0.31$  vs.  $1.94 \pm 0.42$ ;  $p = 0.001$ ), and Ees was also lower ( $2.16 \pm 0.43$  vs.  $2.43 \pm 0.54$ ;  $p = 0.026$ ).

The PWV/GLS was lower in physically active individuals compared with controls ( $0.368 \pm 0.059$  vs.  $0.404 \pm 0.082$ ;  $p = 0.047$ ). The Ea/Ees ratio was numerically lower in physically active participants but did

not differ significantly between groups ( $0.766 \pm 0.105$  vs.  $0.811 \pm 0.085$ ;  $p = 0.060$ ), Table 1.

## Discussion

The principal finding of this study is that endurance-trained adults exhibit a more favourable ventriculo-arterial coupling profile at rest compared with sedentary individuals. This profile was characterised by lower PWV, reduced effective arterial elastance, and a significantly lower PWV/GLS ratio, alongside preserved myocardial deformation. Collectively, these findings indicate that habitual endurance training is associated with a haemodynamic state of reduced vascular load and efficient ventricular–arterial interaction under resting conditions(6). Given the central role of VAC in cardiovascular efficiency and cardiac energetics, these results support the concept that long-term endurance training promotes a cardiovascular phenotype associated with improved baseline mechanical efficiency(1, 18).

The lower PWV observed in endurance-trained participants is consistent with evidence demonstrating that sustained aerobic exercise is associated with preserved central arterial compliance and reduced arterial stiffness (2, 3). Lifelong and long-term endurance training have been shown to attenuate age-related arterial stiffening, contributing to lower pulsatile load and improved VAC (18). In parallel, the reduced effective arterial elastance observed in the trained group reflects a lower net arterial load imposed on the left ventricle, a key determinant of coupling efficiency. Together, these arterial adaptations likely underpin the more favourable baseline coupling profile observed in trained individuals and align with prior reports indicating that aerobic training preferentially influences the arterial component of VAC (4).

A notable observation of the present study was that the PWV/GLS ratio significantly differentiated trained and sedentary individuals, whereas the traditional  $E_a/E_{es}$  ratio demonstrated a consistent direction but did not reach statistical significance. This pattern is physiologically plausible, as parallel reductions in both arterial elastance and ventricular elastance may preserve the coupling ratio despite meaningful improvements in overall cardiovascular efficiency(1). Composite indices integrating arterial stiffness and myocardial mechanics may therefore be particularly sensitive to subtle between-group differences in baseline coupling. In this context, PWV/GLS appears to capture integrated vascular–myocardial interactions that may not be fully reflected by elastance ratios alone under resting conditions (7, 8).

Despite similar GLS between groups, endurance-trained individuals exhibited higher stroke volume, greater indexed myocardial mass, and more favourable diastolic indices, consistent with an adaptive cardiac phenotype associated with chronic endurance conditioning. These structural and functional characteristics likely support efficient ventricular–arterial interaction by enabling adequate stroke volume generation at lower arterial load (2). Large athlete cohorts have demonstrated that such adaptations represent physiological remodelling rather than maladaptive change, particularly when accompanied by preserved myocardial deformation and favourable coupling profiles(19). The present

findings extend this concept by situating these cardiac adaptations within a broader haemodynamic framework of baseline ventriculo-arterial efficiency (20).

VAC represents a central determinant of cardiovascular efficiency and energetic cost, factors closely linked to functional capacity and heart failure pathophysiology(8). The present findings demonstrate that endurance-trained adults exhibit a haemodynamic profile at rest characterised by reduced arterial load and coordinated ventricular–arterial interaction. Such a profile may confer haemodynamic reserve and mechanical efficiency that are relevant to cardiovascular health across the lifespan. These observations support the integration of coupling-based indices into preventive and mechanistic research frameworks aimed at understanding early cardiovascular adaptation and resilience(1, 8).

## Conclusion

In healthy middle-aged men, habitual endurance training is associated with a more favourable baseline VAC profile, characterised by lower arterial stiffness, reduced effective arterial elastance, and preserved myocardial deformation. The observed differences were captured more consistently by composite indices integrating arterial and myocardial properties than by elastance ratios alone, highlighting the multidimensional nature of coupling at rest. Together, these findings indicate that endurance-trained individuals exhibit a haemodynamic phenotype of reduced vascular load and efficient ventricular–arterial interaction under resting conditions, supporting the relevance of coupling-based measures for characterising cardiovascular adaptation associated with long-term physical activity.

## Declarations

Conflict of Interest

Ethics declaration

This study was approved by the Ethics Committee of the Faculty of Sport Sciences and Physical Education, University of Coimbra (CE/FCDEF-UC/00012022). The study was conducted in accordance with the principles of the Declaration of Helsinki.

Consent to Participate declaration

Written informed consent was obtained from all participants prior to their participation in the study.

Consent to Publish declaration

Not applicable.

Clinical Trial Number

Not applicable. This was a cross-sectional observational study and was not a clinical trial.

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

### Author Contributions

The authors' contributions were made following the CRediT (Contributor Roles Taxonomy). AC: investigation and/or resources; AJ: methodology, visualization, writing (review and editing); AT: visualization, writing (review and editing); AV: investigation and/or resources; IC: conceptualization, data curation, formal analysis, funding acquisition, methodology, validation, writing the original draft, visualization; TP: conceptualization, data curation, formal analysis, methodology, validation, writing the original draft, visualization; PMN: methodology, validation, writing the original draft, visualization; HH: methodology, visualization, writing (review and editing); PV: writing (review and editing). All authors read and approved the final version;

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