

Arterial Stiffness and Physical Activity

Arterielle Steifigkeit und körperliche Aktivität

Summary

- **Cardiovascular diseases** are still the leading cause of morbidity and mortality worldwide. Current research indicates that arterial stiffness is an independent risk factor for cardiovascular diseases and represents a potential target for personalized prevention and therapeutic approaches.
- **Physical activity** is a low-cost intervention for vascular prevention via pleiotropic mechanisms (e.g., reduced systemic inflammation, improved endothelial function, reduced arterial stiffness).
- **In this clinical review** we (i) highlight the clinical significance of arterial stiffness, (ii) recap current measurement methods, (iii) summarize the current evidence of the effects of physical activity on arterial stiffness and (iv) outline future directions for arterial stiffness research in sports medicine.

KEY WORDS:

Prevention, Exercise, Vascular Aging, Cardiovascular Disease, Intervention, Inflammation, Cardiology

Introduction

Cardiovascular diseases (CVD) are still the leading cause of morbidity and mortality worldwide. The central underlying mechanisms of CVD are vascular aging and arteriosclerosis (figure 1). Arteriosclerosis is a collective term for different vascular diseases comprising atherosclerosis, arterial stiffness, arteriolosclerosis, and Mönckeberg medial calcific sclerosis (17).

In recent years, arterial stiffness has been increasingly recognized as an independent cardiovascular risk factor that contributes to cardiovascular diseases via distinct hemodynamic pathways. In this context, loss of large artery (especially aorta) compliance diminishes the Windkessel function, resulting in elevated pulsatile stress. The absence of an adequate impedance gradient facilitates the transmission of this pulsatile load into the microcirculation, disproportionately affecting high-flow, low-resistance organs such as the kidneys and brain. Increased stiffness of central arteries elevates pulse wave velocity and forwards wave amplitude while causing earlier reflection of pressure waves. The premature return of the reflected wave augments systolic pressure, causes isolated systolic hypertension (ISH), and promotes left ventricular hypertrophy (LVH). Moreover, the decline in diastolic pressure compromises coronary perfusion, further aggravating the myocardial alterations (17). Thus, a vicious circle is created, which promotes CVD heavily and needs early intervention. Preventive and therapeutic strategies for counteracting vascular aging emphasize stringent management of conventional cardiovascular risk factors, particularly blood pressure and lipid control,

along with smoking cessation and the adherence to a balanced diet and regular physical activity. Data from preclinical and clinical research increasingly highlight the potential of lifestyle-based interventions, such as physical activity, caloric restriction, and intermittent fasting, to mitigate vascular aging and slow the progression of arterial stiffening (1, 23, 33, 38, 44, 58). Pharmacological strategies that mimic the molecular effects of exercise, referred to as exercise mimetics, are additionally being explored as potential tools to prevent end-organ damage associated with vascular rigidity. Although the precise biological pathways through which physical activity modulates arterial stiffness are not yet fully elucidated, its pleiotropic vascular benefits are well documented (8, 21, 29, 37, 50). Regular physical activity attenuates chronic low-grade inflammation, delays cellular senescence, suppresses endothelin-1 (ET-1) and transforming growth factor-beta (TGF- β) signalling, and enhances endothelial function. Furthermore, it exerts favourable effects on major cardiovascular risk factors, including arterial hypertension and obesity, thereby contributing to overall vascular protection (11, 15, 20, 22, 39).

Measurement Methods

In recent years, the assessment of arterial stiffness using pulse wave velocity (PWV) measurements has gained further importance and recognition in clinical practice. The European guidelines on hypertension first recognized the clinical importance of

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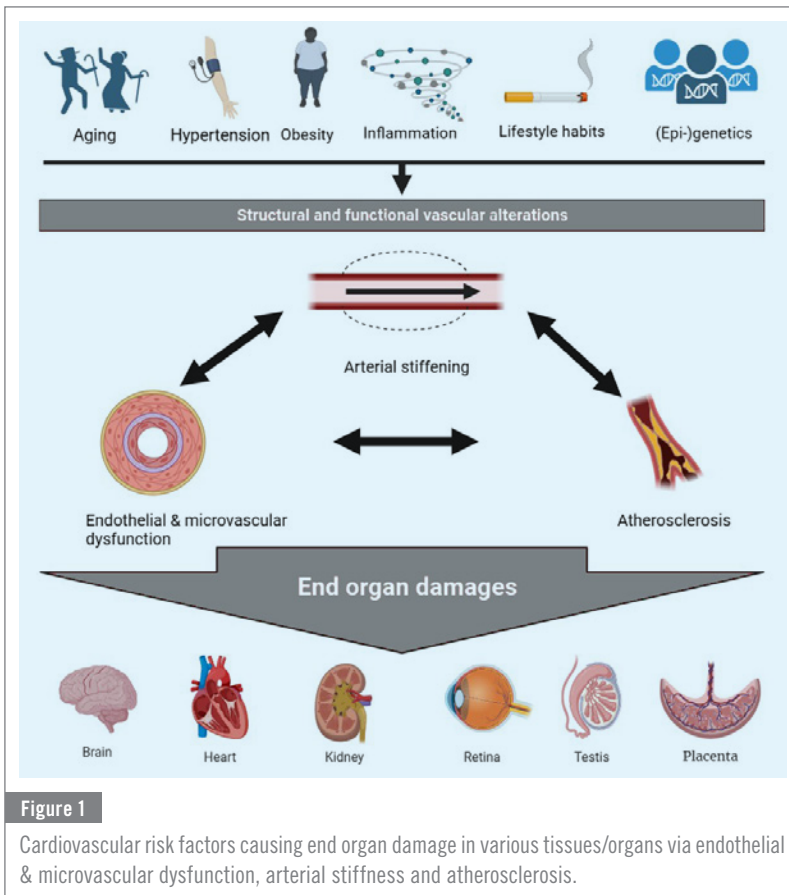


Figure 1
Cardiovascular risk factors causing end organ damage in various tissues/organs via endothelial & microvascular dysfunction, arterial stiffness and atherosclerosis.

assessing arterial stiffness in 2007 (54). More recently, the 2023 European Society of Hypertension (ESH) and the 2024 European Society of Cardiology (ESC) hypertension guidelines have explicitly recommended the use of PWV measurements for risk stratification in patients with hypertension (30,31). In comparison with traditional risk assessment tools, PWV evaluation offers particular value in younger and middle-aged individuals who present with low to moderate cardiovascular risk profiles, as it enables a more refined estimation of individual vascular risk (31).

Measures of central systolic blood pressure (cSBP), augmentation index (AIx), and PWV have consistently been shown to outperform peripheral blood pressure in predicting cardiovascular morbidity and mortality (4, 40, 52). Despite this, the widespread clinical application of arterial stiffness assessment remains limited, largely due to the heterogeneity of measurement techniques and the absence of universally accepted reference values (46).

Multiple invasive and non-invasive approaches are available to quantify arterial elasticity. Figure 2 provides an overview of the principal methodologies, outlining their underlying principles as well as their respective advantages and limitations.

Physical Activity and Vascular Prevention

Engagement in regular physical activity and / or structured physical exercise constitutes a highly cost-effective approach to both the prevention and management of numerous noncommunicable diseases, such as cardiovascular disease, diabetes mellitus, and dementia (56). Within this context, physical activity encompasses any skeletal muscle-driven movement that raises energy expenditure beyond resting metabolic levels, typically above approximately 1.0-1.5 metabolic equivalents (MET; 1 MET=1 kcal (4.184 kJ) · kg⁻¹ · h⁻¹). Physical activity can be categorized into two primary domains: leisure-time physical

activity (LTPA) and occupational physical activity (OPA). LTPA encompasses voluntary activities undertaken during free time, generally selected according to personal interests, preferences, and needs. In contrast, OPA refers to physical exertion performed as part of one's occupational tasks, typically carried out within the context of a conventional eight-hour workday (19). In contrast, physical exercise refers to a specific subset of LTPA that is intentionally planned, structured, and repetitive, with the aim of enhancing or maintaining physical fitness (6). According to current guidelines by the World Health Organization (WHO), adults should complete at least 150 minutes of moderate-intensity aerobic activity or 75 minutes of vigorous aerobic exercise per week, complemented by muscle-strengthening activities.

Physical Activity and Arterial Stiffness

The majority of existing studies have concentrated primarily on LTPA and its relationship to arterial compliance. Low-to-moderate-intensity physical activity such as walking, gardening and active commuting seems capable to lower arterial stiffness, as well (2, 18, 41).

To examine sex-specific associations between various domains of physical activity, including commuting, domestic activities, LTPA and OPA, and arterial stiffness, data from the Gutenberg Health Study (GHS) were analyzed in an observational study.

Results suggest deleterious effects of intense OPA on stiffness index. Interestingly, multivariable linear regression analyses revealed significant beneficial associations between repetitive physical activities, such as active commuting and leisure-time walking, and arterial elasticity in men, whereas these effects were not observed in pre-menopausal (2). Commuting activity generally decreases cardiovascular risk factors and is defined as any active transportation variant like walking or biking to (14).

Observing an older population, Hill et. al proved a higher general physical activity level and aerobic fitness to be associated with a lower PWV (18), but not strength, balance and BMI. They concluded that improving walking capacity is a key element of vascular prevention in the older population.

These findings implicate that low-to-moderate-intensity physical activities within the daily routine, like active commuting, walking or mind-body exercise may exert greater beneficial effects on arterial elasticity than expected. More research is needed to understand the associations of different types of fitness indices with arterial elasticity.

Physical Exercise and Arterial Stiffness

Accumulating evidence from systematic reviews and meta-analyses supports the notion that aerobic exercise training contributes to improvements in arterial compliance and reductions in vascular stiffness (3). The degree of benefit appears to be greater in individuals with higher initial arterial stiffness and with the application of more intensive exercise regimens. Similar improvements have been demonstrated in hypertensive cohorts, suggesting a beneficial role of physical exercise in vascular remodeling among patients with elevated blood pressure (26). Furthermore, Lan et al. (24) reported that the response of arterial elasticity to physical exercise differs across age groups, implying that exercise recommendations for vascular protection may need to be individualized according to age and physiological condition.

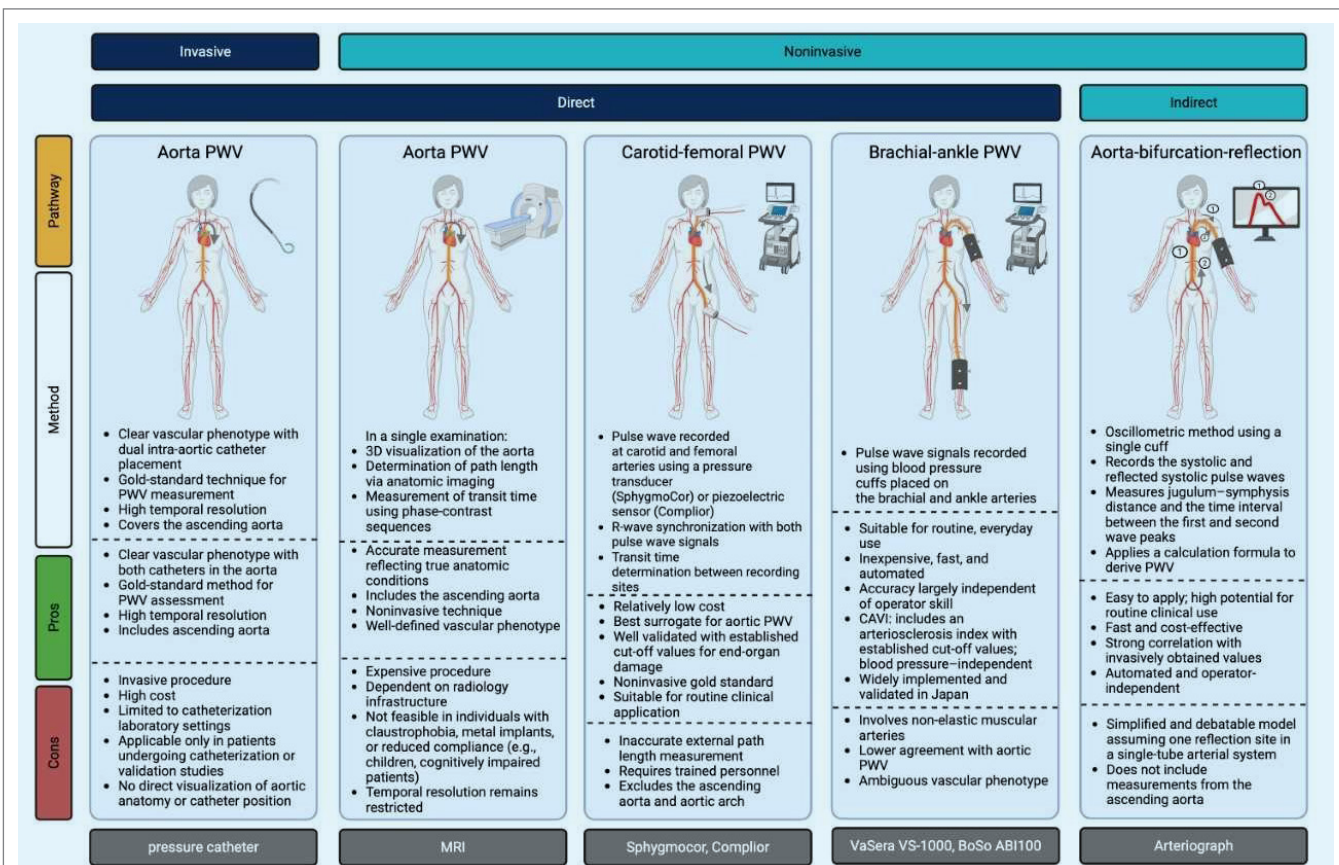


Figure 2

Overview for different methods and devices to measure the PWV. Different points were discussed and visualized: invasiveness, direct versus indirect measurement, pathway options, brief explanation of application, benefits, disadvantages and device examples.

The effect of resistance training, which targets improvements in muscle strength and power, on arterial stiffness appears to be intensity-dependent. Evidence from a meta-analysis indicates that high-intensity resistance training resulted in a significant 11.6% increase in arterial stiffness, whereas moderate-intensity resistance training produced no measurable change (32). Consequently, resistance training performed at moderate intensity seems not to adversely influence arterial elasticity and may therefore represent a safer and more suitable approach for middle-aged individuals (58). Zhang and colleagues presented in their meta-analysis further evidence of an intensity-dependent manner of resistance training effects on arterial elasticity, underlining that low- to moderate-intensity resistance exercise can be considered as an effective non-pharmacological strategy for the management of cardiovascular complications in young and middle-aged adults. Their findings indicate that low-to-moderate-intensity but not high-intensity resistance exercise effectively improves arterial stiffness among young and middle-aged adults (60). Additionally, the specific effects of isometric resistance training on arterial elasticity is not well understood.

Long-term data from Shibata et al. (45) revealed a dose-response relationship between habitual physical exercise and arterial elasticity: individuals who maintained high training frequencies over many years, such as master athletes, displayed more compliant central arteries than sedentary controls. However, not all evidence points toward a linear benefit. Some reports, such as those by Vlachopoulos et al. (53), suggest that athletes with very high training loads (e.g., marathon runners) may exhibit increased arterial stiffness relative to moderately active individuals. Possible underlying mechanisms include repeated exposure to elevated blood pressure during intense

exertion (so-called “exercise hypertension”), promoting endothelial damage, with subsequent healing processes and vascular fibrosis (16, 47), and augmented sympathetic nervous system activity. However, it is not yet clear up to date, whether higher arterial stiffness related to very high cumulative training loads demonstrates pathological adaptation or not.

Recent findings from the Master@Heart study (10) underscore the need for further research into the dose-dependent effects of physical exercise on vascular aging and arterial stiffness. As the most extensive study to date examining the relationship between lifetime exercise volume and coronary atherosclerosis, Master@Heart demonstrated that lifelong endurance athletes tend to have a higher plaque burden than non-athletes, yet experience fewer cardiovascular events, likely owing to increased plaque stability rather than plaque volume.

Although the precise biological pathways remain incompletely delineated, physical activity appears to exert wide-ranging, protective influences on vascular health (8, 21, 29, 37, 50). These effects include attenuation of chronic low-grade inflammation, reductions in cellular senescence, suppression of endothelin-1 and transforming growth factor- β (TGF- β) signaling, and enhancement of endothelial function. Moreover, regular activity favorably modulates several major cardiovascular risk factors, including arterial hypertension and obesity (11, 15, 20, 22, 39, 49, 55).

Does Intensity Matter?

Regular participation in aerobic training has been shown to decrease arterial stiffness, with the greatest improvements typically observed when exercise is performed at higher intensities and for extended durations (58). In a large me- ➤

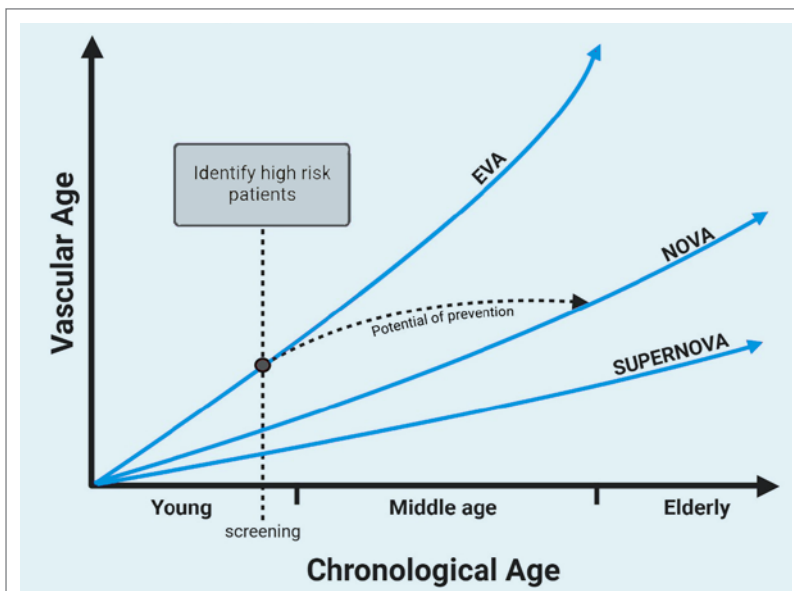


Figure 3

Lifetime vascular risk trajectories of early vascular aging in comparison to normal aging, and the potential benefit of early screening and primary/secondary prevention (in accordance to (61)). In this context, EVA (early vascular aging) is characterized by accelerated vascular aging and associated with earlier development.

ta-analysis, Ashor et. al found 42 randomized controlled trials with 1627 patients in terms of different exercise modalities and stiffness parameters such as PWV and AIx over 4 weeks. Significant improvements in arterial stiffness were observed with aerobic exercise. This effect was enhanced in participants with increased baseline arterial stiffness and greater aerobic exercise intensity (3). Generally, growing evidence suggests an inverse correlation of exercise intensity with arterial stiffness and PWV hence providing a powerful strategy to reduce cardiovascular risk (7, 25, 51). Apparently, pre-existing cardiorespiratory fitness levels play no significant role in the impact of high-intensity exercise on arterial compliance (7, 42).

Short-term vigorous aerobic exercise also decreases arterial stiffness significantly in older adults with type 2 diabetes, hypertension, and (28). This effect might be potentially useful for patients with resistant hypertension to decrease cardiovascular risk (27).

Furthermore, several studies have indicated that high-intensity interval training may serve as an effective exercise modality to reduce arterial stiffness. Although interval-based protocols often yield greater cardiometabolic improvements compared to continuous moderate-intensity aerobic (43), aerobic exercise remains the most consistently supported and widely recognized form of physical exercise (PE) for the prevention of arterial stiffening (44, 59).

Does Sex Matter?

The CVD burden for premenopausal women is significantly lower compared to age-matched men. After menopause, the sex gap narrows leading to the hypothesis that estrogen protects against CVD (12). Decreasing estradiol levels and gonadal aging cause endothelial dysfunction and oxidative stress (35). In various studies, Moreau and colleagues revealed that oestrogen substitution appears to play a permissive role in the exercise-induced effects on arterial stiffness (34, 36). Apparently, the decline in estrogen seems not to be the primary trigger of age-related arterial stiffening in women. Estrogen may rather play a facilitating role in mediating the beneficial effects of aerobic exercise on arterial

elasticity. The interaction between reduced estrogen levels and the vascular benefits of exercise training in postmenopausal women forms the basis of the “exercise timing hypothesis,” which proposes that aerobic exercise confers the best possible vascular benefits when initiated shortly after menopause (13, 33). These findings underline the pivotal role of estrogen in mediating vascular adaptations to aerobic exercise in women.

It remains uncertain, whether sex hormones exert a comparable modulatory influence on the vascular benefits of aerobic exercise in aging men. The inconsistencies among existing studies stem from variations in the type of exercise intervention, for instance, resistance training alone versus combined resistance and aerobic protocols, or from differences in the gonadal status of the participant populations.

Future Direction for Arterial Stiffness Research in Sports Medicine

Evidence suggests that the pathogenesis of CVD frequently begins during childhood, with cumulative exposure to adverse risk factors progressively manifesting as clinically apparent disease during adulthood, often at stages where only symptomatic management or damage limitation is possible (figure 3). Within the context of vascular aging, contemporary research distinguishes between three phenotypic patterns: early vascular aging (EVA), normal vascular aging (NOVA), and supernormal vascular aging (SUPERNOVA) (5). The EVA phenotype holds particular clinical relevance, as it reflects accelerated vascular deterioration and is closely linked to the premature onset of cardiovascular disease (CVD) (9). In contrast, individuals exhibiting SUPERNOVA characteristics may provide valuable insights into the mechanisms of vascular resistance and resilience to aging, thereby informing the development of personalized preventive and therapeutic strategies. This underscores the critical need for early, sensitive biomarkers, such as PWV, to identify at-risk individuals and to enable personalized prevention and intervention strategies targeting vascular health at its earliest stages.

Accumulating evidence reports the beneficial effects of physical activity and exercise on vascular aging and arterial stiffness. However, the optimal exercise intervention (e.g., type, intensity, duration, density) for arterial stiffness prevention and therapy remains to elusive and warrants further investigation.

Current physical activity guidelines recommend that adults engage at least 150 minutes of moderate-intensity aerobic activity or 75 minutes of vigorous aerobic exercise per week, and additional resistance training. Physical exercise has been shown to reduce arterial stiffness effectively across all age groups. However, the optimal type and intensity of exercise needed to elicit significant vascular benefits appear to be age dependent (3, 48). Evidence indicates that vigorous-intensity physical activity provides the most pronounced improvements in young adults (23), whereas a combined regimen of aerobic and resistance training is particularly effective in older individuals (24). For middle-aged adults, aerobic exercise performed at moderate to high intensity seems to confer the greatest benefits for arterial health (3, 24, 58). Active commuting, mind-body exercise or just increasing the walking distance for the eldest proved to be effective in improving arterial compliance thus providing effective tools for individually tailored treatment approaches (2, 18, 57).

These findings support the concept that age-specific, individualized exercise prescriptions may be essential for optimizing vascular health and preventing premature vascular aging. Collectively, the evidence underscores that personalization and continuity of exercise interventions are key determinants of long-term cardiovascular protection and its vascular effects depend on type, intensity, sequence, and endurance, all of which should be considered in future preventive strategies (summary box).

Conflict of Interest

The authors have no conflict of interest.

Ethics Approval

This manuscript is a clinical review based solely on previously published studies. No new participants or individual patient data were involved; therefore, ethical approval and informed consent were not required.

Summary Box

Key messages for physical activity recommendations aiming to reduce arterial stiffness:

- Low-to-moderate-intensity physical activities within the daily routine, like active commuting, walking or mind-body exercise may exert greater beneficial effects on arterial stiffness than expected.
- Exercise recommendations for vascular protection may need to be individualized according to age and physiological condition.
- Aerobic exercise remains the most consistently supported and widely recognized form of physical exercise for the prevention of arterial stiffening.
- High-intensity interval-based protocols often yield greater cardiometabolic improvements compared to continuous moderate-intensity aerobic training.

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