©Journal of Sports Science and Medicine (2020) **19,** 460-468
http://www.jssm.org

Research article

Acute Effects of Winter Sports and Indoor Cycling on Arterial Stiffness

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Abstract

Sedentary lifestyle predisposes to endothelial dysfunction, increased arterial stiffness and cardiovascular diseases, all of which can be positively modified by regular physical exercise training. A decrease in physical activity during winter months coincides with higher rates of cardiovascular events. In order to identify winter sports suitable to overcome this seasonal exercise deficit and thus contribute to cardiovascular health, it was the aim of this study to compare immediate effects of cross-country skiing (XCS) and alpine skiing (AS) on arterial stiffness as an alternative to indoor cycling (IC). After baseline assessment, eighteen healthy subjects performed one session of XCS, AS, and IC in randomized order. Pulse wave analysis was conducted (Mobil-o-Graph®) before and 10-min after exercise. Parameters of arterial stiffness and wave reflection were reduced after XCS and IC, but not after AS: central systolic blood pressure (IC: -8.0 ± 5.4 mmHg; $p < 0.001$), amplitude of the backward pressure wave (IC: -1.4 ± 2.7 mmHg; $p < 0.05$), reflection coefficient (XCS: -6.0 ± 7.8%; IC: -5.7 ± 8.1%; both $p < 0.1$), and pulse wave velocity (IC by -0.19 ± 0.27 m/s; $p < 0.01$). Higher exercise intensities correlated with greater reductions of arterial stiffness (all $p < 0.05$). Single sessions of XCS, IC but not AS led to comparable improvement in arterial stiffness, which was even more pronounced during higher exercise intensities. With regard to arterial stiffness, IC and XCS emerge as more effective to counteract the winter exercise deficit and thus the deleterious cardiovascular effects of a sedentary lifestyle.

Key words: Alpine skiing, cross-country skiing, cycling, exercise intensity, physical activity, pulse wave analysis.

Introduction

Arterial stiffness is present in cardiovascular disease, which is still the leading cause of death in industrialized countries (Safar and Lacolley, 2007; Benjamin et al., 2018). Amongst other mechanisms, arterial stiffness results from changes of endothelial function, vascular smooth muscle tone, and vessel wall structure leading to less elastic arterial walls (O'Rourke and Hashimoto, 2007; Zieman et al., 2005). As a consequence, impaired cushioning function and hence impaired conversion of the pulsatile blood flow into a near continuous blood flow and thus increased pulse wave velocity (PWV) occur (Safar and Lacolley, 2007).

In healthy subjects, pulse waves are reflected in the periphery and return to the heart during diastole to support coronary artery flow. During atherogenesis, arteriolar and arterial constriction lead to wave reflection points closer to the heart (O'Rourke and Hashimoto, 2007; Laurent et al., 2006) and this occurs rather during systole than diastole, resulting in a summation of forward and reflected waves. A subsequent increase in aortic/central systolic blood pressure (cSBP) and a decrease in central diastolic blood pressure (cDBP) result in an augmented central pulse pressure (cPP), termed augmentation pressure (Safar and Lacolley, 2007; O'Rourke and Hashimoto, 2007). Another measure of wave reflection is the augmentation index (AIx), which is calculated from augmentation pressure and pulse pressure. The AIx is a combined measure of the effect of pulse wave reflection on central blood pressure and of arterial stiffness per se. It is therefore influenced by arterial stiffness of the larger arteries as well as endothelial dysfunction and vasoconstriction of the microcirculation. A high augmentation is therefore also a sign of loss of elasticity of the small vessels. Wave separation analysis also investigates wave reflections in terms of the magnitudes of forward (Pf) and backward (Pb) wave amplitudes and the reflection coefficient – a ratio of Pb and Pf (Wang et al., 2010; Chirinos et al., 2012). The above mentioned parameters of arterial stiffness have gained increasing interest over the past few years, and in part have been shown to be independent predictors of cardiovascular morbidity and mortality (Weber et al., 2012; Chirinos et al., 2012; Mitchell et al., 2010; Vlachopoulos et al., 2010). Furthermore, non-invasive methods were developed (e.g. oscillometric measurements obtained with Mobil-o-Graph®) and have previously been validated for cSBP (Wassertheurer et al., 2010; Luzardo et al., 2012), AIx (Wassertheurer et al., 2010; Luzardo et al., 2012), cDBP, cPP and PWV (Luzardo et al., 2012), against atonometric systems as well as invasive measurements (Weber et al., 2011), and have shown to be well comparable.

Prolonged exercise training induces anti-oxidant and anti-inflammatory effects, as well as flow-mediated shear stress, which improves nitric oxide (NO) release and bioactivity with subsequent smooth muscle relaxation, reduced peripheral resistance and finally reverse remodeling of the vessel wall, leading to a reduction of arterial stiffness (Seals, 2014; Niebauer et al., 2003). Both acute as well as long-term endurance training have been shown to improve endothelial function and arterial stiffness in several cardiovascular diseases (CVD) (Sixt et al., 2010; Desch et al., 2010).

During winter, physical activity commonly declines, which is associated with a worsening of cardiovascular risk factors such as cholesterol levels and blood

Received: 18 October 2019 / Accepted: 13 April 2020 / Published (online): 01 September 2020

pressure and subsequently arterial stiffening as well as death from CVD (Newman et al., 2009; Heffernan et al., 2007b). Therefore, it is paramount to identify sports that can be executed by a substantial percentage of the population also during winter. For this reason and encouraged by a previous study in which we observed that Alpine skiing (AS) was associated with lower arterial blood pressure values as compared with indoor cycling (IC) (Scheiber et al., 2009), we set out to assess the effects of two popular winters sports in Alpine and Nordic-regions, i.e. cross-country skiing (XCS) and AS, on arterial stiffness as compared to IC, which is commonly recommended but only infrequently performed as an alternative mode of exercise during winter. Based on previous research in our group (Stöggl et al., 2017; 2016a; 2016b) demonstrating that the three exercise modes XCS, AS and IC can be executed with a high physiological load (e.g. >90% maximum heart rate >84% VO_{2max}) over longer duration we hypothesized that both winter sports XCS and AS would be able to acutely improve arterial stiffness comparable with IC.

Methods

Participants

Participants for this study were recruited by personal communication. Informed consent was obtained from each participant. The research protocol was approved by the Ethical Committee of the State of Salzburg (415-EP/73/342-2014) and registered at ClinicalTrials.gov: NCT02082106. This study complied with the Declaration of Helsinki and patients gave written informed consent. Twenty-one healthy participants performed a baseline all-out cycle ergometry in order to assess their maximal oxygen uptake (VO_{2max}), maximal heart rate (HR_{max}) and peak lactate (Stöggl et al., 2016a; 2016b; 2017). Because of a technical defect, one measurement with the Mobil-o-Graph® is missing. Thus, after a drop-out of two participants for medical reasons, the cohort analyzed with regard to arterial stiffness comprised of 18 participants (11 males and 7 females) with a mean age of 48.2 (±12.5) (see Table 1).

Table 1. Baseline characteristics (mean ± standard deviation)

General characteristics	Overall (n = 18)	Male (n = 11)	Female (n = 7)
Age [years]	48.2 (±12.5)	47.7 (±12.2)	48.9 (±13.9)
Weight [kg]	80.3 (±14.7)	84.8 (±12.9)	73.2 (±15.6)
BMI [kg/m²]	26.1 (±4.6)	26.1 (±3.7)	26.1 (±6.2)
Body fat [%]	24.4 (±8.9)	19.7 (±7.4)	31.7 (±5.3)
relVO2max [ml/min/kg]	39.7 (±13.3)	44.9 (±12.6)	31.5 (±10.3)
relPmax [W/kg]	3.17 (±1.21)	3.62 (±1.21)	2.47 (±0.86)
HRmax [bpm]	169.9 (±15.5)	168.0 (±15.9)	173.0 (±15.7)

BMI = body mass index, HR_{max} = maximal heart rate, n = number of subjects, $relP_{max}$ = relative maximal power output, $relVO_{2max}$ = relative maximal oxygen uptake.

Study Design

The present study was carried out during the winter months January till March 2014 with the primary intention to compare energy expenditures between the winter sports XCS, AS, and IC (Stöggl et al., 2016a; 2016b; 2017). In brief, in addition to the baseline medical examination in the laboratory, all participants performed standardized exercise sessions of XCS, AS and IC with four different intensities and modes on non-consecutive days in a randomized order. For standardization purposes, participants were instructed to change neither their dietary habits nor their physical activity throughout the study period. Intensities in XCS and IC were calculated based on HR_{max} of the baseline all-out cycle ergometry (low intensity: 70% HR_{max}, moderate intensity: 80% HR_{max}, high intensity: 90% HR_{max}, high-intensity interval training – HIIT: >90% HR_{max}). Based on the difficulty to control exercise intensity by means of HR during AS and security reasons (skier needs to focus on the slope while skiing), the different exercise intensities were achieved by using different variations in skiing techniques: parallel ski steering (low intensity), carving long radii (moderate intensity) and dynamic short turn skiing [continuous high intensity and intermittent high intensity interval training (HIIT)]. For a schematic description of the exercise sessions, see Figure 1. Active recovery periods in between the intensity stages (low, moderate, high intensity) consisted of 2 min during IC (60% HR_{max}), and 2.3 ± 0.2 min during XCS. During AS, each descent was performed at one given intensity, while being interrupted by standing in line and sitting on the chair lift. The proportion of active skiing during one descent and ascent was 44 ± 5%. Based on the constraints of the field experiments, like the unavoidable influence of standing and transportation with the chair lift during AS, and possible transfer time on the XCS tracks to start each single exercise section at an adequate position on the track (e.g. skiing back to start in case of long downhill sections) there were differences in the total times between the three modes while similar exercise times. Total times for IC (without warm-up until the end of HIIT) were 36.0 ± 0.1 min, 42.8 ± 3.2 mins for XCS, and 69.2 ± 6.6 min for AS. For each of the exercise tasks participants wore a mobile breath-by-breath spirometer for volumes and flows (K4b²; Cosmed, ITA) and a HR monitor (Suunto, Ambit 2.0) throughout the entire activity. Blood lactate samples were taken after each of the four different exercise intensities [20 µl blood sample from the earlobe, amperometric-enzymatical analysis (Biosen S-Line Lab+, EKF-diagnostic GmbH, Magdeburg, Germany)].

Pulse wave analysis

Arterial stiffness was automatically measured using the portable device Mobil-o-Graph® (I.E.M. GmbH, Stolberg, GER) before (baseline) and after exercise. The Mobil-o-Graph® has previously been validated for cSBP (Wassertheurer et al., 2010; Luzardo et al., 2012), AIx (Wassertheurer et al., 2010; Luzardo et al., 2012), cDBP, cPP and PWV (Luzardo et al., 2012). Measurements were either carried out at the Institute of Sports Medicine for IC, or in a tempered room at the place of skiing (XCS, AS).

Room temperatures were controlled between the single testing sites. We analyzed those parameters of arterial stiffness calculated by the Mobil-o-Graph®, which have been shown to be predictors of future cardiovascular events (Weber et al., 2012; Chirinos et al., 2012; Mitchell et al., 2010; Vlachopoulos et al., 2010): cSBP, cPP, AIx,

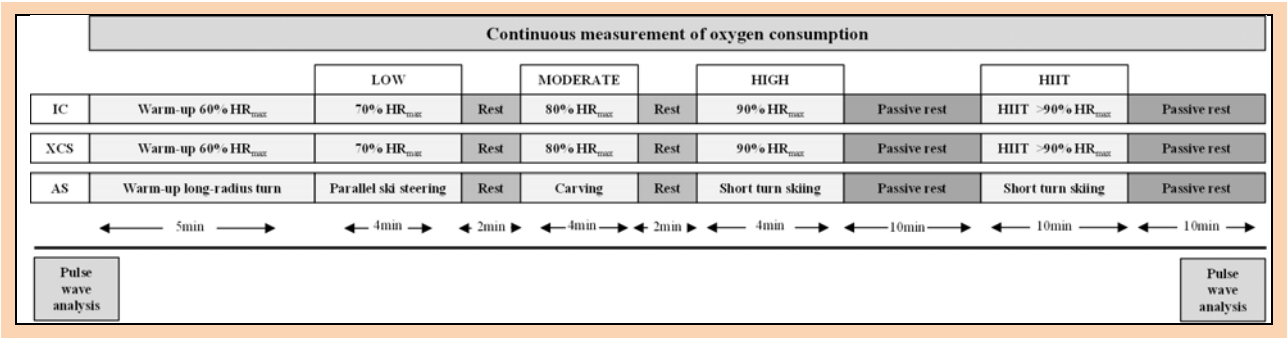

Figure 1. Composition of a single exercise session. Each session consisted of a 5 min warm-up, followed by 4 min at low, moderate and high intensities interspersed by 2 min active rest and a 10 min passive resting phase preceding a 10 min high intensity interval training (HIIT). HIIT included alternating intervals of 1 min at >90% (or short radius turns for alpine skiing) and 1 min at 60% of maximal heart rate (or active/passive resting for alpine skiing). This was followed by a passive resting phase of 10 min until pulse wave analysis measurement. Legend: AS: alpine skiing, HIIT: high intensity interval training, HR_{max}: maximal heart rate during maximal cycle ergometry, IC: indoor cycling, Pulse wave analysis: heart rate and pulse wave analysis measurement using Mobil-o-Graph®, Rest: active recovery at IC and passive recovery at XCS and AS of around 2 min, XCS: cross-country skiing.

the reflection coefficient, Pf and Pb as well as PWV. Measurement standardization was carried out according to the recommendations of Task Force III on clinical applications of arterial stiffness (Van Bortel et al., 2002). Participants were advised to refrain from eating, and drinking beverages containing caffeine for at least 3 hrs and from drinking alcohol for at least 10 hrs before assessments. Participants rested for at least 5 min in a room with no draught, no dazzling light and no loud noises at room temperature before the measurement. Neither the participants nor the person taking the measurements were allowed to talk during the procedure. Participants were asked to relax, not to move and not to fall asleep during measurements and were seated comfortably, with their backs supported, legs uncrossed and upper arms bared at heart level. Measurements were obtained from the non-dominant arm.

After one sham measurement, three consecutive recordings with a pause of one minute in between measurements were taken automatically by the Mobil-o-Graph®. A software-based automated quality control (HMS Client-Server v4.7.3, I.E.M. GmbH, GER) deleted measurements with a quality index >2. If this was the case, an additional measurement was conducted, to a maximum of 6 recordings in total. The mean interval between the first and last usable recording was 5.5 ± 1.6 min. Post exercise measurements were carried out 10 min post HIIT.

Parameters of oxygen consumption

Fitness levels were assessed by VO_{2max} (in ml/min/kg) of the all-out cycling ergometry. Even though acute exercise intensity control during the trials was performed with HR, we have chosen to use the exercise intensity based on VO_2 measures for further statistical analysis. Therefore, for each participant the mean VO_2 of the exercise session (VO_{2mean} in ml/min/kg) was related to the VO_{2max} of the all-out cycling ergometry [exercise intensity (%) = $(100*VO_{2mean})/VO_{2max}$]. As mentioned above, based on the possible differences in the total exercise time between participants within each exercise condition (during AS and XCS), the control of exercise intensity via HR or skiing style, and consequently assumed differences in the mean exercise intensity with respect to VO_2, two subgroups across all three exercise modalities were formed: subjects who achieved <50% VO_{2mean} / VO_{2max} and ≥50% VO_{2mean} / VO_{2max}.

Statistical analysis

Normal distributions were checked by the Shapiro-Wilk test. For an evaluation of the reproducibility between measurements on different testing days, the respective baseline parameters of HR and arterial stiffness (cSBP, cPP, AIx, reflection coefficient, Pf, Pb, PWV) were analyzed using intraclass correlation coefficient (ICC).

To test for the effects of XCS, AS and IC on arterial stiffness, repeated-measures ANOVA [2 times – before exercise and after exercise, 3 exercise modes (XCS, AS, IC) was conducted. In case of a significant main effect of time and/or a significant interaction effect of time x exercise mode, paired sample t-tests for post-hoc analysis between the pre to post exercise values were applied.

Univariate ANOVA was applied to test for the differences of exercise intensities between groups (IC, XCS, AS) using Tukey post-hoc analysis. Relationships between variables were calculated using Pearson's correlation coefficient. Thereby, pooled samples of all exercise sessions were used. Baseline arterial stiffness parameters were correlated with age as well as VO_{2max} (fitness level). Based on the discrepancy in exercise time and consequently mean exercise intensity between the three exercise modes, correlations were calculated between the change of the reflection coefficient, Pb, cSBP and PWV (parameters with significant reductions) due to acute exercise (post exercise measurement minus baseline measurement) and the intensities of the exercise sessions (VO_{2mean}/VO_{2max}). An alpha level of 0.05 was considered statistically significant. All analyses were performed using IBM SPSS Statistics Version 26.0.

Results

Reproducibility of measurements

The analyzed parameters of arterial stiffness possessed high reproducibility between measurements: PWV (ICC = 0.993, $p < 0.001$), cSBP (ICC = 0.897, $p < 0.001$), cPP (ICC = 0.737, $p < 0.001$), reflection coefficient (ICC = 0.706, $p = 0.001$), Pf (ICC = 0.734, $p < 0.001$) and Pb (ICC

= 0.740, p < 0.001). Only AIx possessed a low reproducibility (ICC = -0.377, p = 0.756).

Relationships with baseline parameters

The well-known relationship of arterial stiffness with age and fitness was present in the participants analyzed. PWV (r = 0.940, p < 0.001), the reflection coefficient (r = 0.614, p < 0.001) and Pb (r = 0.281, p < 0.05) were related to age. Baseline values of PWV (r = -0.494, p < 0.001) and of the reflection coefficient (r = -0.429, p = 0.001) were negatively correlated to fitness.

Effect of exercise on arterial stiffness and wave reflection

Exercise led to several changes in parameters of arterial stiffness and HR. As expected, resting HR pre to post exercise was increased in all exercise modes (main effect time: p < 0.001) with greater increases in IC and XCS compared with AS (interaction time x exercise: p < 0.01). Furthermore, XCS and IC significantly reduced several parameters of arterial stiffness while no changes were found in AS. cSBP, reflection coefficient and Pb were generally reduced (main effect time: p < 0.05; p < 0.01; p < 0.01). More pronounced reductions were found in IC for cSBP (Pre to post reduction of -8.0 ± 5.4 mmHg, p < 0.001), PWV (-0.19 ± 0.27 m/s, p < 0.01) and Pb (-1.3 ± 2.7 mmHg, p < 0.05) compared with XCS and AS. There was a trend for a reduction of Pb also after XCS (-1.3 ± 2.6 mmHg, p = 0.068). In addition, the reflection coefficient was reduced after IC by -5.8 ± 8.1% (p < 0.01) as well as after XCS by -6.1 ± 7.8% (p < 0.01), while values were unaltered for AS (Table 2).

Exercise intensity and arterial stiffness

Mean exercise intensities during the three exercise modes (VO_{2mean} in $\%VO_{2max}$) were associated with a reduction of arterial stiffness, which is illustrated in Figure 2. Exercise intensities were highest during IC (57.1 ± 7.3% of VO_{2max}), followed by XCS (52.2 ± 7.9% of VO_{2max}; p < 0.01 compared to IC), and AS (34.7 ± 7.1% of VO_{2max}; p < 0.001 compared to IC or XCS) (Table 3). Exercising at intensities higher than 50% of VO_{2max} however, significantly reduced cSBP, the reflection coefficient, Pb and PWV (Table 4). This possibly reflects, why in the present study AS, which was never more intense than 50% VO_{2mean}/VO_{2max}, did not reduce arterial stiffness.

Table 3. Metabolic parameters at indoor cycling, cross-country skiing and alpine skiing. Data are mean values (± standard deviation; n=18).

	IC	XCS	AS
peak HR (bpm)	164 (19)	172 (15)	162 (16)
mean HR (bpm)	137 (17)	147 (13)	139 (15)
% HR peak	96.1 (4.9)	101.6 (6.7)	95.6 (7.7)
% HR mean	80.7 (4.4)	86.4 (3.2)	82.2 (7.6)
peak lactate (mmol/L)	8.0 (2.9)	10.4 (2.2)	5.7 (2.8)
% lactate peak	91.4 (18.7)	126.5 (34.1)	70.7 (35.5)
peak VO_2 (ml/min/kg)	37.6 (11.9)	37.1 (10.3)[a]	31.1 (10.0)[b]
mean VO_2 (ml/min/kg)	22.3 (6.9)	20.3 (5.0)[a]	12.3 (2.5)[b]
% VO_2 peak	95.6 (11.5)	93.9 (12.0)[a]	85.4 (19.2)[b]
% VO_2 mean – exercise intensity	57.1 (7.4)	52.2 (7.9)[a]	34.7 (7.1)[b]

SD: standard deviation, IC: indoor cycling, XCS: cross-country skiing, AS: alpine skiing, HR: heart rate, bpm: beats per minute, mmol/L: millimol per liter, VO_2: oxygen uptake, % values: related to maximal values at all-out ergometry; peak: highest value measured in the high intensity interval session. [a] n=16, [b] n=15.

Discussion

The main findings of our study are twofold: Firstly, in healthy middle-aged participants arterial stiffness improves after one session of XCS and IC, but not AS and secondly, higher exercise intensities induce greater improvement in arterial stiffness.

Table 2. Changes of heart rate and parameters of arterial stiffness before and 10 min after different types of acute exercises of indoor cycling, cross-country skiing and alpine skiing. Data are mean value (± standard deviation; n = 18).

	Indoor cycling			Cross-country skiing			Alpine skiing			Repeated-measures ANOVA		
	Before	After	Change in %	Before	After	Change in %	Before	After	Change in %	Exercise mode (p)	Time (p)	Exercise mode x time (p)
HR [bpm]	62 (10)	85*** (15)	+38.4 (18.1)	64 (10)	90*** (14)	+43.2 (16.3)	65 (10)	84*** (16)	+29.7 (15.0)	0.254	<0.001	<0.01
cSBP [mmHg]	115.5 (11.1)	107.5*** (11.4)	-6.9 (4.5)	112.2 (12.5)	110.6 (13.1)	-1.2 (8.6)	112.1 (11.2)	112.2 (10.8)	+0.3 (7.1)	0.485	<0.05	<0.01
cPP [mmHg]	32.0 (5.6)	29.9 (6.1)	-5.4 (18.2)	32.6 (5.8)	31.4 (5.3)	-1.9 (17.3)	32.1 (6.6)	30.3 (6.0)	-3.7 (19.7)	0.318	0.051	0.970
AIx [%]	17.3 (11.4)	13.6 (4.9)	-4.5 (49.0)	15.3 (9.5)	15.2 (7.9)	+44.4 (121.1)	14.5 (5.8)	15.9 (6.1)	+29.9 (84.0)	0.997	0.858	0.523
reflection coefficient [%]	63.7 (8.1)	57.9** (8.2)	-8.3 (13.4)	63.0 (8.7)	56.9** (8.3)	-8.8 (13.5)	64.2 (10.4)	62.8 (6.4)	-0.1 (17.0)	0.070	<0.01	0.329
Pf [mmHg]	20.6 (3.2)	20.1 (3.7)	-0.9 (18.3)	21.2 (3.1)	21.2 (3.2)	+0.9 (14.7)	20.7 (3.0)	19.7 (3.4)	-4.3 (14.7)	0.295	0.333	0.722
Pb [mmHg]	13.1 (2.9)	11.8* (3.2)	-8.8 (22.3)	13.4 (2.9)	12.1 (2.7)	-7.1 (20.2)	13.4 (3.5)	12.4 (2.7)	-3.4 (23.8)	0.444	<0.01	0.948
PWV [m/s]	7.15 (1.36)	6.96** (1.34)	-2.6 (4.1)	7.09 (1.43)	7.12 (1.47)	+0.4 (4.9)	7.07 (1.48)	7.08 (1.45)	+0.4 (4.0)	0.817	0.342	<0.05

AIx: augmentation index, bpm: beats per minute, cPP: central pulse pressure, cSBP: central systolic blood pressure, HR: heart rate, Pb: amplitude of the backward pressure wave, Pf: amplitude of the forward pressure wave, PWV: pulse wave velocity; * p<.05: ** p<.01; *** p<.001: significance level before vs. after exercise.

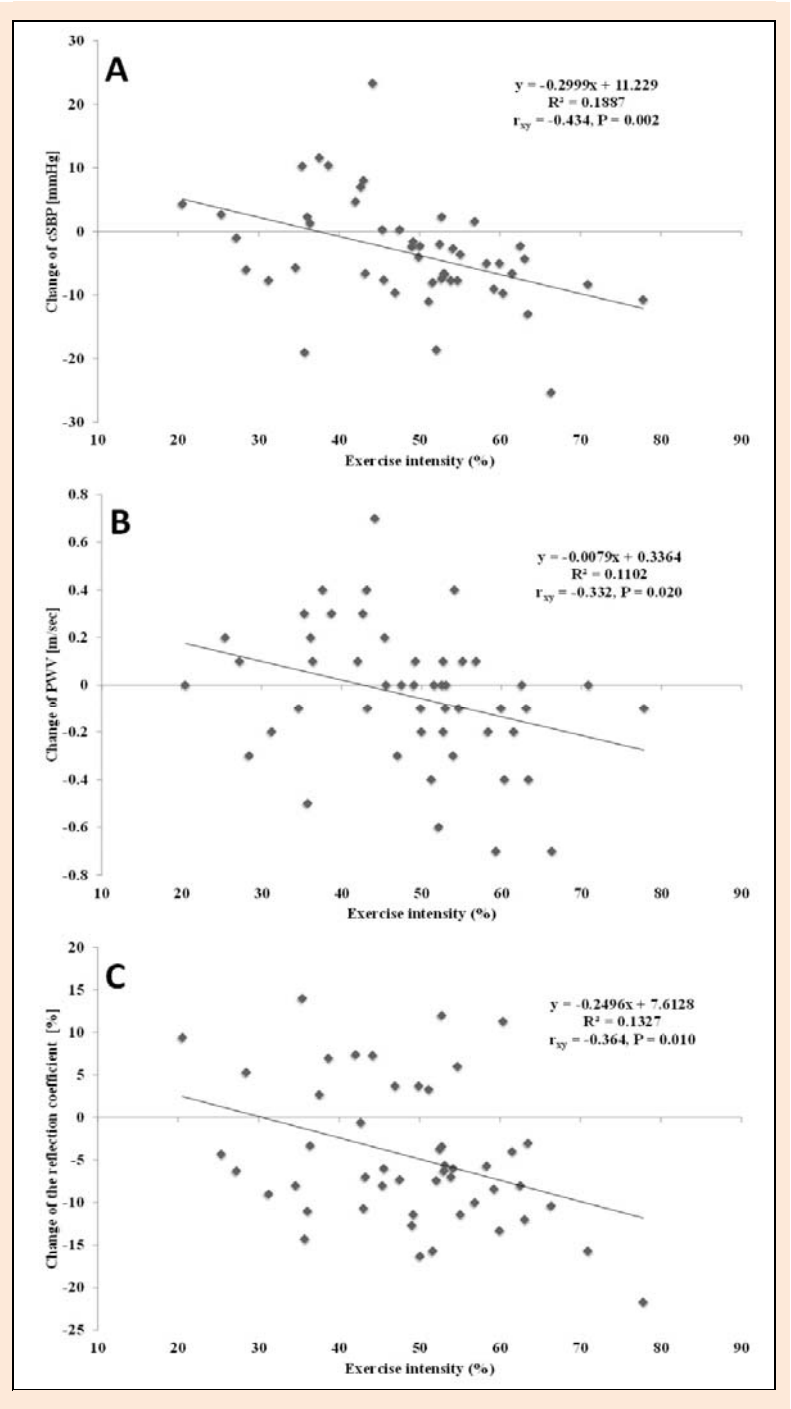

Figure 2. Exercise intensities and arterial stiffness. Relationship between exercise intensities and the change of A) central systolic blood pressure, B) pulse wave velocity and C) the reflection coefficient during exercise. Exercise intensities are defined by the mean relative oxygen uptake during an exercise session (VO_{2mean}, in ml/min/kg) related to the VO_{2max} of the all-out cycling ergometry [exercise intensity (%) = (100*VO_{2mean})/VO_{2max}]. cSBP: central systolic blood pressure, PWV: pulse wave velocity; r_{xy}: Pearson's correlation coefficient, p: p-value.

Exercise-induced effects on parameters of arterial stiffness

The influence of IC on arterial stiffness has been analyzed before. Similar to the IC sessions in the present study (36 min of cycling with a mean intensity of 57.1 ± 7.3% VO_{2max}), 30 min of cycle ergometry at 65% of VO_{2peak} decreased central PWV (Collier et al., 2010; Heffernan et al., 2007a) and peripheral PWV (Heffernan et al., 2007a). Furthermore, 30 min of intermittent IC was shown to reduce lower limb PWV (Tordi et al., 2010) and one hour of exercising on a cycle ergometer at 60% HR_{max} showed a trend for decreased regional PWV by 9.1% (McClean et al., 2011). These findings are corroborated by our study which not only confirmed effects of IC on PWC but found reductions of cSBP, Pb, and the reflection coefficient. Furthermore, and most importantly, this is the first study to assess the impact of the winter sports like XCS and AS on arterial stiffness in the real environment (field study). In brief, significant reductions of arterial stiffness and wave reflection were detected after XCS, but not after AS.

Table 4. Changes of heart rate and parameters of arterial stiffness during acute exercise below vs above intensities of 50% of VO_{2mean} (valid trials pooled for indoor cycling, cross-country skiing and alpine skiing). Data are mean value (± standard deviation).

	Exercise intensity <50% (n = 24)			Exercise intensity ≥50% (n = 25)			Repeated-measures ANOVA		
	Before	After	Change in %	Before	After	Change in %	Exercise intensity (p)	Time (p)	Exercise intensity x time (p)
HR [bpm]	64 (11)	83*** (15)	+30.6 (14.0)	63 (10)	88*** (14)	+41.4 (18.4)	0.589	<0.001	<0.05
cSBP [mmHg]	113.0 (11.7)	113.6 (10.8)	+0.9 (8.0)	113.9 (12.4)	106.7*** (12.4)	-6.3 (4.9)	0.359	<0.01	<0.001
cPP [mmHg]	32.8 (6.2)	32.4 (5.4)	+0.8 (17.9)	32.3 (5.8)	29.6 (5.7)	-6.6 (18.9)	0.255	0.087	0.178
AIx [%]	13.3 (5.6)	15.3 (7.7)	+27.8 (74.3)	17.5 (11.7)	15.0 (5.2)	+29.3 (109.5)	0.220	0.880	0.169
reflection coefficient [%]	64.1 (9.8)	61.6 (7.8)	-2.7 (13.3)	63.8 (8.1)	57.3*** (7.8)	-9.4 (14.0)	0.290	<0.001	0.089
Pf [mmHg]	21.0 (3.0)	21.3 (3.3)	+1.7 (13.1)	20.9 (3.3)	20.0 (3.4)	-2.9 (18.0)	0.359	0.488	0.245
Pb [mmHg]	13.6 (3.3)	13.1 (2.6)	-0.3 (21.2)	13.3 (2.9)	11.6** (2.9)	-11.2 (22.3)	0.215	<0.05	0.129
PWV [m/s]	7.16 (1.44)	7.24 (1.40)	+1.3 (3.9)	7.20 (1.45)	7.03** (1.49)	-2.4 (3.9)	0.836	0.242	<0.01

AIx: augmentation index, bpm: beats per minute, cPP: central pulse pressure, cSBP: central systolic blood pressure, HR: heart rate, Pb: amplitude of the backward pressure wave, Pf: amplitude of the forward pressure wave, PWV: pulse wave velocity; p-value: dependent t-test or Wilcoxon-signed rank test, respectively, * p<0.05: ** p<0.01; *** p<0.001: significance level before vs. after exercise.

Exercise intensity and arterial stiffness

A plausible reason why AS did not reduce arterial stiffness in the present study is because exercise intensities during descents are high but if calculated over the full length of the exercise sessions, which included waiting for and sitting on a chair lift, not high enough. Indeed, exercise intensities of a full session of AS are comparably lower than during XCS and IC. As shown in the current study, higher exercise intensities – as measured by the mean VO_2 - were linked to greater reductions of cSBP, PWV and the reflection coefficient (Figure 2), and mean exercise intensities were greatest at IC, followed by XCS and again lower during AS. These results indicate that a critical level of intensity is required to induce a positive effect on vascular elasticity. This reflects why in the present study AS, which was never more intense than 50% VO_{2mean}/VO_{2max}, did not reduce arterial stiffness. This is in agreement with a meta-analysis which concluded that the positive effect of aerobic exercise training on arterial stiffness is enhanced during exercise at higher intensities (Ashor et al., 2014). It could be hypothesized, that higher exercise intensities induce higher flow-mediated shear stress. As a result, higher NO release leads to a greater relaxation of smooth muscles with a subsequent greater reduction in arterial stiffness. (Seals, 2014, Niebauer et al., 2003). In addition, AS includes components of strength exercise which are known to promote arterial stiffness (Seals, 2014).

During the active skiing phases of AS similar peak and mean HRs were achieved as during IC while lactate levels and VO_2 were lower (Stöggl et al., 2016b, Stöggl et al., 2016a, Stöggl et al., 2017). This is in agreement with Krautgasser et al. (2011) who also observed similar peak HRs but lower lactate and VO_2 in elderly recreational alpine skiers compared to cycling, which was explained by higher static loading of the legs during AS in contrast to the dynamic cycling movement. Indeed, typical endurance exercises such as XCS and IC induce high cardio-respiratory demand, whereas AS requires – due to the primary involvement of isometric muscle contractions - both aerobic and anaerobic energy delivery. In AS the higher load on the lower extremity musculature might lead to limitations that prevent further cardio-respiratory exhaustion (Stöggl et al., 2017, Stöggl et al., 2016b, Stöggl et al., 2016a).

A dose-depended effect of exercise intensity on arterial stiffness has been observed in this study. This is in line with Goto et al. (2003) who reported that 12 wks of aerobic exercise training led to vasodilatory effects only if performed at moderate intensity of 50% VO_{2max}. It was hypothesized that training at 75% VO_{2max} might have led to increased oxidative stress and training at 25% VO_{2max} might not have induced sufficient NO production to improve vasodilation. The moderate intensities reported by Goto et al. (2003) nicely match those of XCS (mean intensity: 52.2 ± 7.9% VO_{2mean}/VO_{2max}) and IC (mean intensity: 57.1 ± 7.4% VO_{2mean} / VO_{2max}) in our study.

Limitations

The different exercise intensities during XCS and IC could be controlled by HR monitors, while during AS exercise intensity was modified by various skiing techniques. This was done for security reasons, since the participants had to focus on the slope conditions, the instructors pace and also other skiers in the measurement zone and not on the HR monitor (Stöggl et al., 2016a). Furthermore, the total time spent for each respective activity can be seen as a confounding factor. Therefore, the effects of AS on arterial stiffness might be diluted based on the 56% of the total time with low activity (standing in line, sitting on chairlift, breaks). Finally, to simplify the results presentation for the correlational analysis and the comparison between the two groups of mean exercise intensities (>50% vs. <50% VO_2) the pooled data across all three exercise modes were taken.

Therefore, a mix between independent and dependent samples was considered during the statistics. Indeed, when performing the same statistical analysis separately for all three exercise modes, comparable results were found.

Conclusion

In conclusion, in healthy middle-aged participants single training sessions of XCS and IC induced significant reductions of arterial stiffness in a dose-dependent manner of exercise intensity. This could not be found for AS, most likely due to the overall lower exercise intensity mainly caused by periodic breaks needed in order to ascend. Therefore, when striving for maximal effects on arterial stiffness also during AS, breaks should be kept to a minimum. However, future research about the effects of mean exercise intensity, passive breaks in between intermittent exercise and exercise duration needs to be performed to answer this question.

Acknowledgements

We would like to thank Manuel Hirner, Kathrin Hirner, Stephanie Feuchter and Markus Förmer for their assistance during the measurements and the ski resorts of Saalbach Hinterglemm and Flachau Winkel for granting us free access. This study was supported in part by an unrestricted grant of the State of Salzburg (EEM, MS). The experiments comply with the current laws of the country in which they were performed. The authors have no conflict of interest to declare.

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Key points

- In healthy middle-aged participants arterial stiffness improves after one session of cross-country skiing and indoor cycling but not alpine skiing
- the higher the exercise intensity the greater the improvement in arterial stiffness induced
- With regard to arterial stiffness, indoor cycling and cross-country skiing emerge as more effective to counteract the winter exercise deficit and thus the deleterious cardiovascular effects of a sedentary lifestyle.

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