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ORIGINAL ARTICLE

Effects of training status on arterial compliance in able-bodied persons and persons with spinal cord injury

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Study design: An investigation on large and small artery compliance in 36 able-bodied persons and persons with spinal cord injury (SCI).

Objective: To evaluate the effect of various training states (endurance-trained vs untrained) on arterial compliance in individuals with chronic SCI of traumatic origin and in able-bodied individuals (matched for age, sex, height, and weight).

Setting: Tertiary rehabilitation center in Canada.

Methods: Large and small artery compliance were measured at the radial artery and physical activity was assessed via questionnaire.

Results: There was no significant difference in large artery compliance between groups. Small artery compliance was reduced markedly (5.8 ± 3.1 ml mm Hg$^{-1} \times 100$) in untrained persons with SCI, in comparison to all other groups. Small artery compliance of endurance-trained individuals with SCI was slightly (4%) higher than that observed in the untrained able-bodied individuals (8.6 ± 1.5 vs 8.2 ± 1.4 ml mm Hg$^{-1} \times 100$, respectively). Endurance-trained, able-bodied persons had greater small artery compliance (10.6 ± 2.3 ml mm Hg$^{-1} \times 100$) in comparison to the all other groups.

Conclusion: Endurance training is related to increased small artery compliance in able-bodied individuals and persons with SCI (who are matched for age, sex, height and weight). Endurance training may attenuate the decline in small artery compliance seen with SCI.

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INTRODUCTION

Approximately 85 500 Canadians live with spinal cord injury (SCI), with an estimated 4259 new cases per year. Of these individuals, 51% are the result of traumatic causes.[1] Marked advancements in medical treatment within the last few decades have contributed greatly to an increased lifespan among those living with SCI. As such, persons with SCI are susceptible to the same chronic conditions as the general able-bodied population.[2] In fact, cardiovascular disease (CVD) is the leading cause of death in individuals with chronic SCI (similar to able-bodied individuals). Unfortunately, persons with chronic SCI appear to be at an increased risk for CVD-related morbidity and mortality.[2,3] Moreover, the onset of CVD tends to occur earlier in persons with chronic SCI.[3]

Vascular dysfunction is considered to be an obligatory preliminary step in the process of arteriosclerosis and CVD.[4] Unfortunately, individuals with SCI appear to be particularly susceptible and prone to vascular dysfunction and, subsequently, the development of CVD.[2] Individuals with SCI exhibit a series of risk factors associated with vascular dysfunction, which include worsened lipoprotein profiles, abnormal glucose homeostasis, increased adiposity, elevated risk for deep vein thrombosis, hypertension, and reduced aerobic fitness.[2] Additionally, preliminary evidence indicates that individuals with SCI may have reduced arterial compliance and/or increased arterial stiffness in comparison to the general population.[5–7]

In recent years, non-invasive evaluations of arterial compliance have provided further insight into the risk for CVD. Importantly, changes in the compliance of small and large arteries precede (by years) the presence of plaques characteristic of atherosclerosis.[8] Changes in arterial compliance are important early predictors of the risk of CVD and CVD-related events.[4]

Physical inactivity is a major independent risk factor for CVD and premature mortality.[9] A physically inactive lifestyle and a reduction in physical function associated with a loss of motor function are thought to be key contributors to the higher CVD-related morbidity and mortality in individuals with SCI.[2] Physical inactivity is common among individuals with SCI,[10] leading to concomitantly low levels of cardiovascular fitness.[2,11] Moreover, persons living with SCI suffer from more inactivity-related illnesses in comparison to their able-bodied counterparts.[12]

Routine participation in physical activity promotes improvements in cardiovascular fitness and exercise tolerance in persons living with SCI.[2,10] Exercise training is an effective means to improve measures of cardiovascular health including aerobic fitness, glucose homeostasis and lipid lipoprotein profiles.[2] Additionally, there is increasing evidence in the able-bodied population that aerobically trained individuals have a higher arterial compliance (particularly small artery compliance) than their inactive counterparts.[13] Limited research has examined the effects of aerobic training on arterial

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compliance in persons with SCI. In particular, no study has compared well-matched, able-bodied individuals to persons living with SCI from across the physical activity continuum. Accordingly, the primary purpose of this investigation was to compare large and small artery compliance of untrained and endurance-trained persons with SCI and well-matched, able-bodied controls. We hypothesized that endurance-trained individuals would have better vascular health (as measured by arterial compliance) in comparison to less trained individuals. We also hypothesized that those individuals with SCI would have lower arterial compliance values in comparison to their able-bodied counterparts.

METHODS

Participants

Participant characteristics for the able-bodied and SCI participants are provided in Table 1. All of the participants with SCI had sustained traumatic SCI and were at least one year post injury (Table 2). Age-, height-, weight- and sex-matched able-bodied participants were used as the control groups for the SCI groups. This stringent matching was done to avoid the potential confounding influence of these variables (in particular age and weight) on the measurement of arterial compliance. The SCI groups (that is, untrained versus endurance-trained) were also matched for level and severity of injury (according to the American Spinal Injury Association Impairment Scale (AIS) score). Participants were also matched as closely as possible for time since injury (Table 2).

Participants were excluded if they had established cardiovascular or respiratory disease, an orthopedic condition that restricted ambulation (via a wheelchair for SCI), unstable angina and recent osteoporotic fracture. Participants currently experiencing autonomic dysreflexia were excluded (owing to the potential effects on blood pressure). One tetraplegic participant was not tested owing to the presence of symptoms of autonomic dysreflexia. This case of autonomic dysreflexia was unrelated to the testing procedures. This information was obtained from the potential participants and the on-site examining physician. Eligible participants provided written and informed consent. The study received approval from the university research ethics board and was conducted in accordance with the Declaration of Helsinki regarding experimentation with human participants.

Arterial Compliance Measurement

Arterial compliance was assessed non-invasively using an applanation tonometer (HDI/Pulse Wave CR-3000 CVProfilor Hypertension Diagnostics/Pulse Wave^{TM} CR-3000, Eagan, MN, USA) that measured radial artery pulse waves. After a 10-min supine rest period, radial arterial waveform acquisition of the right arm was obtained in conjunction with automated blood pressure on the left arm. A computer-based assessment of the diastolic pressure decay using a modified Windkessel model of the circulation allows the CVProfilor to provide an independent assessment of capacitive compliance, reflecting large conduit arteries and oscillatory (or reflective) compliance, reflecting smaller, more peripherally located arteries and arterioles. These compliance markers can serve as biomarkers of arterial dysfunction. The participants were asked to refrain from exercise for at least 24 h prior to testing, and to engage in an overnight fast prior to the assessment.

Level of physical activity

General physical activity was assessed by the Godin–Shephard Leisure Time Exercise Questionnaire. Participants that were engaging in physical activity levels less than Canada's recommended threshold (that is, 150 min per week of moderate-to-vigorous intensity exercise) over the last 3 months were considered to be untrained (inactive). It should be highlighted that the untrained individuals with SCI all participated below the recently created physical activity guidelines for SCI (that is, at least 20 min of moderate to vigorous intensity aerobic activity and moderate intensity strength training exercises two times per week).[10] The endurance-trained participants consisted of able-bodied and disabled individuals that engaged in a regimented endurance training program (on a daily basis). The endurance-trained individuals with SCI participated in daily endurance-type training designed for wheelchair racing. This included both field- and home-based training related to wheelchair wheeling/racing. The home-based training involved largely the usage of rollers designed for wheelchair use.

Table 1 Participant characteristics ($N=36$)

Measure	*Untrained SCI* (n = 9)	*Trained SCI* (n = 9)	*Untrained AB* (n = 9)	*Trained AB* (n = 9)
Male/female	4/5	4/5	4/5	4/5
Age (year)	32 ± 8	29 ± 7	29 ± 6	31 ± 8
Height (cm)	173 ± 8	173 ± 9	168 ± 5	171 ± 11
Weight (kg)	70 ± 11	70 ± 9	68 ± 15	69 ± 14
BMI (kg m^{-2})	24 ± 3	23 ± 3	24 ± 4	23 ± 2

Table 2 Clinical characteristics of participants with spinal cord injury

Years of injury	*Level of injury*	*Complete/incomplete*	*AIS Scale*
Untrained Inactive SCI			
17	T4	Complete	A
12	C6/7	Incomplete	B
8	C6/7	Incomplete	B
8	T10/11	Incomplete	B
6	T11/12	Complete	A
16	T7	Complete	A
8	C 4/5	Incomplete	B
14	T10	Complete	A
12	T4	Complete	A
Mean ± SD	6 Thoracic	5 Complete	5 AIS A
11 ± 4	3 Cervical	4 Incomplete	4 AIS B
Endurance-trained SCI			
18	T4	Complete	A
14	C6	Incomplete	B
3	C6/7	Incomplete	B
13	T10/T11	Incomplete	B
2	T11/12	Complete	A
16	T7/T8	Complete	A
14	C4/5	Incomplete	B
15	T10/T11	Complete	A
13	T3/4	Complete	A
Mean ± SD	6 Thoracic	5 Complete	5 AIS A
12 ± 5	3 Cervical	4 Incomplete	4 AIS B

ASI refers to the American Spinal Injury Association (AIS) Classification for the participants.

Statistical analysis

Participant data are reported as means ± s.d.. Analysis of variance was used to compare arterial compliance between training groups and able-bodied participants and participants with SCI. The α level was set *a priori* at $P<0.05$. All statistical analyses were performed using Statistica 6.0 (Stats Soft, Tulsa, OK, USA).

RESULTS

There were six thoracic-level injuries (paraplegics) and three cervical-level injuries (tetraplegics) in both of the SCI groups (Table 1), and

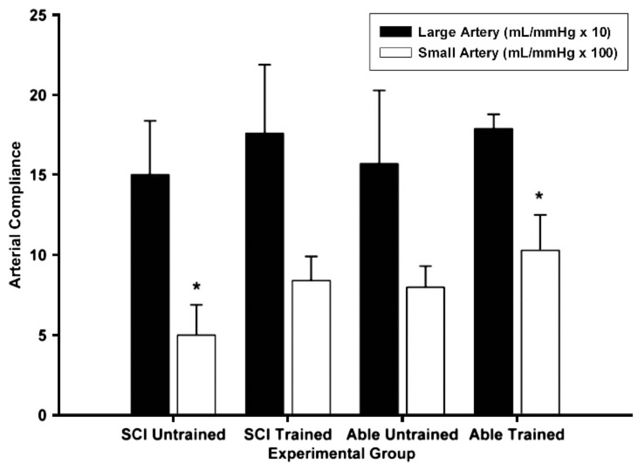

Figure 1 Effects of training status on large (ml mm Hg^{-1} × 10) and small artery compliance (ml mm Hg^{-1} × 100). *Significantly different from all other groups ($P<0.05$). Effect of training status on arterial compliance.

AIS scores ranged from A to B. There was no significant difference in age, height or weight amongst the participants (as per the research design). There was no significant difference in upper body motor scores for the tetraplegic groups (SCI untrained vs SCI trained = 21.0 ± 13.4 vs 21.0 ± 13.2, respectively).

There were significant differences in small artery compliance between groups (Figure 1). The untrained persons with SCI exhibited the lowest values for small artery compliance ($P<0.05$). The endurance-trained, able-bodied individuals had significantly greater small artery compliance than all other groups (10.6 ± 2.3 ml mm Hg^{-1} × 100). The small artery compliance of the endurance-trained individuals with SCI was ∼4% higher than that observed in the untrained able-bodied individuals (8.6 ± 1.5 vs 8.2 ± 1.4 ml mm Hg^{-1} × 100).

When examining the main effect of exercise training (that is, collapsed across able-bodied and SCI participants), endurance-trained individuals had significantly higher small artery compliance than the untrained participants (9.6 ± 2.2 vs 7.0 ± 2.7 ml mm Hg^{-1} × 100, respectively). There was no significant main effect for lesion level (tetraplegics vs paraplegics).

Large artery compliance was not significantly different between groups (Figure 1). However, large artery compliance did follow a similar pattern to small artery compliance with the largest mean values observed in the endurance-trained able-bodied individuals followed by the endurance-trained individuals with SCI, untrained able-bodied participants and then the untrained participants with SCI. Moreover, when collapsed across able-bodied participants and participants with SCI, endurance-trained individuals had a significantly higher large artery compliance than the untrained participants (18.3 ± 3.4 vs 15.4 ± 3.9 ml mm Hg^{-1} × 10, respectively).

DISCUSSION

The major new findings of this research investigation are: (1) small artery compliance is elevated in endurance-trained individuals with SCI in comparison to untrained persons with SCI, (2) both able-bodied and disabled endurance individuals have increased small artery compliance in comparison to their age-, weight-, and sex-matched untrained counterparts, and (3) small arterial compliance was markedly below normal levels in inactive persons with SCI. A particular strength of our approach was the careful matching of participants to limit the potentially confounding influence of age, height, weight, and sex.

Consistent with our hypothesis, we found elevated small artery compliance in endurance-trained individuals and in able-bodied individuals.[14] An important new finding of the present investigation is that the vascular benefits extend to endurance individuals with SCI. In fact, in the present study, the endurance-trained individuals with SCI had small artery compliance values that were above than that found in untrained able-bodied individuals. We also observed that untrained persons with SCI had markedly reduced arterial compliance in comparison to all other groups. This is consistent with other findings[5,6] reflecting the increased risk of vascular disease in untrained persons with SCI. The loss of supraspinal sympathetic vascular control and extreme physical inactivity are both recognized as potential factors for reduced vascular health in persons living with SCI.[15,16]

Collectively, our findings highlight the potential for endurance training to normalize and even enhance vascular function (as evaluated by arterial compliance). It is important to emphasize that previous research[17] has demonstrated that for every two-unit decrease in small artery compliance, there is a 50% increase in the risk of CVD-related events. Therefore, in our specific trial, the increased small artery compliance in the endurance-trained individuals (both SCI and able-bodied) may be associated with a clinically relevant reduction in the risk for CVD. These findings highlight the important health benefits of exercise training for both able-bodied and disabled individuals alike.

There are several plausible mechanisms through which such improvements following exercise training may occur. Even acute bouts of exercise have been found to increase arterial compliance.[13] It has been postulated that relaxation of vascular smooth muscle, which transfers stress from the less extensive collagen fibers to elastin fibers, is likely to account for the acute elevation in compliance. Furthermore, the potential of exercise training to normalize arterial compliance in individuals with SCI is supported by both able-bodied[18] and SCI literature.[6] Animal and human studies have also demonstrated elevated compliance with exercise training.[6,17] It is plausible that increased pulse pressure and mechanical distension during exercise sessions may stretch collagen fibers and modify crosslinking, resulting in an elevated arterial compliance.[19]

Individuals with SCI are at increased risk for CVD and one of the many contributing factors is endothelial dysfunction. Endothelial function is an early functional sign and small radial artery compliance is an early structural sign of arteriosclerosis. It is plausible that exercise training may normalize endothelial function and/or improve arterial compliance in SCI.[6,16]

The determinants of change in compliance differ between large (elastic) and small (muscular) arteries, which may explain why greater differences were seen in small artery compliance. We have demonstrated previously that functional electrical stimulation cycle training in SCI leads to greater changes in small (muscular) artery compliance than large artery compliance.[6] Generally, small artery compliance is considered to be a stronger predictor of the risk of CVD.[20] In large (elastic) arteries, collagen and elastin are key components and have central roles in the arterial function.[21] In smaller (muscular) arteries and arterioles, nitric oxide released from the endothelium has a significant role in determining caliber and compliance via its actions on smooth muscle.[8] It is in the small arteries and arterioles that endothelial dysfunction is most easily identified.[8] As such, measures of small artery compliance are thought to be important indicators of the risk of CVD and endothelial dysfunction.

Limitations

We recognize that the small sample size may limit the generalizability of our findings. However, the changes in small artery compliance were consistent across trained participants with SCI. Moreover, we employed stringent controls for various factors that are known to affect arterial compliance (including age, sex and weight). Therefore, there is compelling support for the ability of endurance training to normalize arterial compliance in persons living with SCI. It should be highlighted that it is likely that the differences between inactive individuals with SCI would even be greater if we had not carefully matched for body size.

We acknowledge that the measurement of physical activity in persons living with SCI is difficult. We have previously used the Godin–Shephard Leisure Time Questionnaire with success in persons living with SCI, but recognize that other surveys such as the PARA-SCI may provide additional information.[22] We also acknowledge that the direct measurement of peak (or maximal) aerobic power may have facilitated in the risk stratification of the participants. It is recommended that future studies of this nature use surveys such as the PARA-SCI and/or direct assessment of peak/maximal aerobic power.

We acknowledge that while exercise training offers numerous health benefits, there are practical limitations that may limit participation in physical activity in individuals with SCI (including increased cost of equipment, transportation to training facilities and the potential for increased staffing and training demands).[10] Additionally, the cross-sectional design of this study is a limitation as we only examined data from a single time point instead of over a period of time, the latter perhaps providing a more complete view of the effects of exercise training on arterial compliance. Future studies should attempt to examine the longitudinal changes that occur in vascular function and the effects of prolonged exercise interventions. Despite these limitations, it is clear that exercise training has the potential to lead to multiple health benefits, particularly marked changes in small artery compliance.

Future research should examine the differences in arterial compliance among persons with SCI (that is, tetraplegics vs paraplegics, and incomplete vs complete injury) before and after exercise training to further elucidate the effects of autonomic dysfunction and exercise on vascular function. Future research should also examine the role of novel exercise modalities (such as passive hybrid exercise) on vascular function in persons living with SCI.

CONCLUSIONS

In this investigation, we revealed that the small artery compliance of endurance-trained, able-bodied individuals and persons living with SCI is significantly higher than their inactive (age-, sex- and weight-matched) counterparts. It appears as though training is able to normalize small artery compliance in individuals with SCI. Since a reduction in small artery compliance has been found to be an independent risk factor for cardiovascular events, this research has profound implications for the long-term health of persons, with SCI providing direct support for the inclusion of exercise training in rehabilitation settings for this population. These findings have important implications for the long-term risk for CVD and quality of life in persons with SCI.

DATA ARCHIVING

There were no data to deposit.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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