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ORIGINAL ARTICLE

Effects of weight on blood pressure at rest and during exercise

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Body weight (BW) and blood pressure (BP) have a close relationship, which has been accounted for by hormonal changes. No previous study has evaluated the effect of wearing an external weight vest on BP to determine whether there is a simple mechanism between BW and BP. Seventeen healthy volunteers underwent weight reduction (WR) through caloric restriction. Before and after WR, BW, body fat percentage and BP at rest and during exercise were measured. Before and after WR, exercise testing was performed twice with the random allocation of a weight vest (10 kg) during one of the tests. Linear regression was used to detect independent associations between BP and the weight vest, BW and body fat percentage. BW decreased from 89.4 ± 15.4 kg to 79.1 ± 14.0 kg following WR ($P<0.001$). WR led to significant decreases in BP at rest (from 130.0/85.9 mm Hg to 112.5/77.8 mm Hg, $P<0.001$ for systolic and diastolic BPs) and during exercise. The weight vest significantly increased BP at rest (to 136.1/90.7 mm Hg before and 125.8/84.6 mm Hg after WR) and during exercise. Linear regression analysis identified an independent association between the weight vest and BP ($P=0.006$ for systolic BP and $P=0.009$ for diastolic BP at rest). This study demonstrates that wearing an external weight vest has immediate effects on BP at rest and during exercise independent of BW or body fat. More research is needed to understand the physiological mechanisms between weight and BP.

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INTRODUCTION

An increased body weight (BW) is an established risk factor for hypertension, and BW reduction is associated with a decrease in blood pressure (BP) at rest and during exercise.[1–8] The precise pathophysiologic mechanisms leading to an increased BP with weight gain have not been elucidated and are still a matter of debate.[9–16] Some studies have provided evidence that obesity activates the renin–angiotensin–aldosterone system, leading to increased renal sodium retention and increased peripheral vascular resistance.[9–11] Other studies have shown that overweight and obesity are associated with increased activity of the sympathetic nervous system, thus contributing to a higher BP in obese subjects.[12–16]

To the best of the authors' knowledge, no previous study has attempted to determine whether there is an immediate effect of weight on BP at rest or during exercise. Therefore, this study evaluated the effects of a diet-induced moderate weight reduction (WR) and an additional weight load created by wearing an external weight vest before and after WR on BP at rest and during exercise in healthy volunteers. The main hypothesis of this study was that an additional weight load created by wearing an external weight vest leads to an immediate increase in BP at rest and during exercise.

METHODS

Study population

Volunteers with an age ⩾25 years who were willing to lose weight were eligible for participation in this cross-over intervention study. Patients with severe hypertension (⩾180 mm Hg systolic BP and/or ⩾110 mm Hg diastolic BP), patients with a history of cardiovascular events or severe pulmonary disease, and patients unable to perform exercise tests were excluded. Therefore, the study population was expected to be middle-aged, moderately overweight and rather healthy with a low cardiovascular risk profile. The study was approved by the local ethics committee (application no. 985, Lucerne, Switzerland). All study participants provided written informed consent.

Baseline examination

All study participants underwent a baseline examination before WR. Patient history was assessed, including cardiovascular risk factors and medication. Weight and height as well as waist and hip circumference were measured, and the body mass index was calculated based on the measured weight and height (kg m^{-2}). Body composition was determined using bioelectric impedance (BF 300, Omron Healthcare, Kyoto, Japan) to measure the body fat percentage. Resting BP and heart rate were measured using the oscillometric method with an automated system (BP-200 Plus, Schiller, Baar, Switzerland). For the measurement, the study participant was placed on a chair in a sitting position,

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and an appropriately sized cuff was placed around the upper arm at approximately the level of the heart. BP measurement was only started after 2 min of rest and was repeated three times on each arm. For the purpose of this study, the mean systolic and diastolic BPs of all six measurements (of three measurements on each arm) were used.

At baseline before WR, all study participants underwent two subsequent bicycle exercise tests with a fully automated system (Cardiovit CS-200, Schiller). One of the two exercise tests was performed while the participants were wearing an additional weight load of 10 kg with the use of an external weight vest (Sport-Thieme, St Gallen, Switzerland). A weight load of 10 kg was chosen to correspond approximately to the expected weight loss after WR. The weight vest was randomly allocated to the first or second exercise test using a computer-generated random number. Otherwise, the protocol was identical during the two exercise tests. The exercise test was performed in an upright position. Workload was increased using a linear ramp protocol by 25 W min^{-1} to the maximal tolerated level. Therefore, participants with higher exercise capacity required more time to attain maximal strain than participants with lower exercise capacity. To measure BP, the Cardiovit system is equipped with an automated oscillometric device (BP-200 Plus, Schiller) that also analyzes Korotkoff sounds triggered by the QRS complex, a method with proven validity for BP measurement during exercise.[17] An appropriately sized cuff was placed around the upper left arm. For the purpose of this study, systolic and diastolic BPs were measured at rest, after 3 min of strain, at maximal strain and after 2 min of recreation following maximal strain. All these BP measurements were taken with the participant remaining seated on the bicycle.

All study participants underwent resting electrocardiography. Study participants also underwent 24-h acoustic cardiography (Audicor, Inovise Medical., Portland, OR, USA).[18,19] This diagnostic technique simultaneously records electrocardiography and cardiac acoustic data. The time interval from the onset of the QRS to the peak intensity of the first heart sound is termed the electromechanical activation time and is prolonged in systolic heart failure.

Weight reduction

After the baseline examination, all participants received nonspecific dietary counseling regarding strategies for achieving a negative energy balance through dietary means. Counseling was performed by physicians. The aim of the dietary intervention was to achieve a negative energy balance to attain the planned WR of ⩾5% of the baseline BW. The recommended dietary strategies were either a reduction of the caloric intake by eating less from all substrates (no specific diet was prescribed), a protein-sparing modified fast or a combination thereof. To facilitate individual implementation of the dietary recommendations, no fixed caloric restrictions were prescribed, but the principles of an energy- and substrate-reduced diet (primarily carbohydrates and fat) were provided. Only the aimed long-term energy deficit (that is, 7000 kcal kg^{-1} weight loss) was explained to the participants; no specific recommendations were made. Protein-sparing modified fast counseling entailed an individualized maximally tolerable reduction of carbohydrate and fat intake and an adequate intake of protein (that is, 10 g of protein per 10 kg of ideal BW) from low-fat dietary protein sources (lean meat, lean fish, eggs, milk and milk products). Salad and vegetable intake was not controlled, with the exception of low-fat preparation techniques. If a participant strictly followed the protein-sparing modified fast regimen, he ingested between 700 and 900 kcal day^{-1} (macronutrient ratio of protein/fat/carbohydrates was approximately 50%/20–30%/20–30%). Some participants ate a normal lunch and a protein-sparing modified fast-conforming dinner to enhance lipid oxidation during the night time period. All other lifestyle factors (for example, exercise, smoking and alcohol consumption habits) were maintained at the usual level. No specific recommendations regarding sodium intake were provided.

The participants were invited to the follow-up examination 12 weeks after dietary counseling. If they failed to achieve their target weight, additional dietary and motivational counseling was offered, and the follow-up examination was postponed for 12 weeks. After 24 weeks, all study participants were invited to the follow-up examination regardless of whether they had successfully reduced their weight. Before the follow-up examination was performed, a weight stabilization period of at least 2 weeks was obligatory. During this stabilization period, the participants ate a mixed diet according to their energy needs (that is, energy intake corresponded to the energy requirements). Through this stabilization period, a theoretical effect of the diet on BP and other measured parameters on the test day was minimized.

Follow-up examination

The follow-up examination was identical to the baseline examination and comprised measurements of BP, heart rate, weight and fat mass. Identical to the baseline examination, two subsequent exercise tests were performed with random allocation of an external weight vest to one of the two tests.

Statistical methods

Data were analyzed using Stata software (Stata 11.2, StataCorp LP, College Station, TX, USA). A *P*-value <0.05 was considered significant. For continuous variables, means and s.d. are provided. For two-group comparisons, Student's *t*-test was used after confirming a normal data distribution. The Mann–Whitney rank-sum test was used for non-normally distributed continuous variables. Distributional differences between categorical variables were assessed using the χ^2 test and Fisher's exact test. Changes in BP, BW and body fat percentage between the baseline and follow-up examinations were calculated. Multiple linear regression models were used to evaluate associations between systolic BP, diastolic BP or heart rate (dependent variables) and independent variables (wearing a weight vest, BW and body fat percentage). An *a priori* sample size calculation was performed based on data from a previous study.[7] To detect a change in BP between baseline and follow-up at a significance level of 5% and a power of 80%, 11 study participants were required for systolic BP at rest, 17 study participants for diastolic BP at rest, 9 study participants for systolic BP at maximal strain and 28 study participants for diastolic BP at maximal strain. To detect a 10% change in BP with and without wearing a weight vest (assuming that the s.d. corresponds to 10% of the measured BP values), eight study participants were needed at a significance level of 5% and a power of 80%.

RESULTS

Of all eligible volunteers who were asked to participate in the study, four were excluded (three refused study participation and one had a history of a cardiovascular event) (Figure 1). Twenty-three volunteers underwent the baseline examination. Six volunteers failed to lose

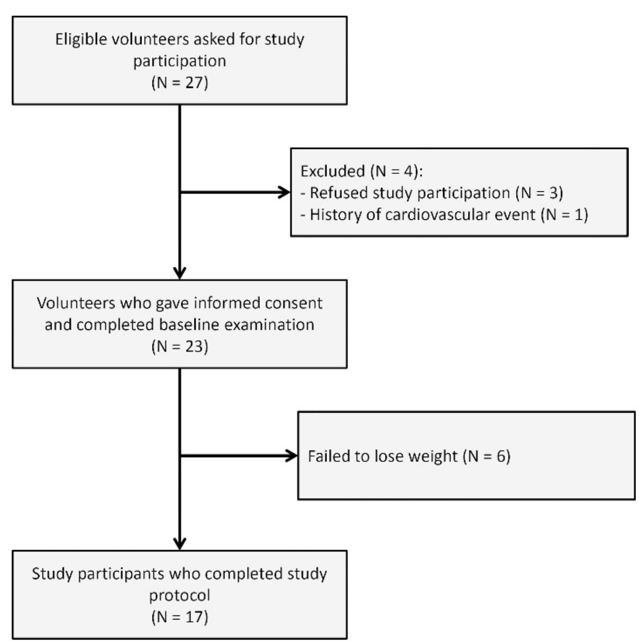

Figure 1 Flowchart.

Table 1 Baseline characteristics

Characteristics	*Study participants* (N = *17*)
Age, years	45.0 ± 9.5
Female sex, *n* (%)	8 (47.1)
Height, cm	172.0 ± 9.3
Weight, kg	89.4 ± 15.4
BMI, $kg\,m^{-2}$	30.3 ± 5.3
Waist-to-hip ratio	0.91 ± 0.07
Body fat percentage, %	31.1 ± 7.7
BP[a], mm Hg	
Systolic	134.5 ± 14.1
Diastolic	89.7 ± 10.2
Heart rate, beats min^{-1}	76.2 ± 10.1
Cardiovascular risk factors	
Hypertension, *n* (%)	3 (17.7)
Dyslipidemia, *n* (%)	1 (5.9)
Diabetes, *n* (%)	0 (0.0)
Smoker[b], n (%)	7 (41.2)
Current	1 (5.9)
Family history of CAD, *n* (%)	3 (17.7)
Medication	
ACE inhibitor, *n* (%)	1 (5.9)
Statin, *n* (%)	1 (5.9)
Electrocardiogram	
Heart rate, beats min^{-1}	69.3 ± 8.1
PQ duration, ms	163 ± 25
QRS duration, ms	90 ± 12

Abbreviations: ACE, angiotensin-converting enzyme; BMI, body mass index; BP, blood pressure; CAD, coronary artery disease.
[a]Mean resting BP from the three measurements on each arm of the sitting participant.
[b]Former or current smoker.

weight, resulting in 17 study participants who completed the study protocol.

The baseline characteristics of the study participants are shown in Table 1. The mean age was 45.0 ± 9.5 years (range 27.0–59.2 years). Nearly half of the study participants (47.1%) were female. The mean body mass index was 30.3 ± 5.3 $kg\,m^{-2}$ (range 20.5–41.9 $kg\,m^{-2}$). The prevalence of cardiovascular risk factors was low, and only one study participant was on a prescription for an antihypertensive drug (Table 1). There were no significant differences in baseline characteristics between the study participants and the six volunteers who failed to lose weight.

Changes in measurements between baseline and follow-up

Between baseline and follow-up, weight decreased from 89.4 ± 15.4 kg to 79.1 ± 14.0 kg ($P<0.001$). The mean WR was 10.4 ± 2.9 kg (range 5–15 kg), corresponding to a relative WR of 11.7% (range 6.9–15.7%). Accordingly, the body mass index decreased from 30.3 ± 5.3 $kg\,m^{-2}$ to 26.7 ± 4.7 $kg\,m^{-2}$ ($P<0.001$), and the body fat percentage decreased from 31.1 ± 7.7% to 26.3 ± 8.5% ($P<0.001$). Waist circumference decreased from 101.8 ± 12.2 cm to 92.2 ± 11.9 cm ($P<0.001$) and the waist-to-hip ratio decreased from 0.91 ± 0.07 to 0.88 ± 0.07 ($P<0.001$).

The mean resting BP from the three measurements on each arm of the sitting participants decreased from 134.5 ± 14.1 mm Hg to 123.0 ± 10.9 mm Hg for systolic BP ($P<0.001$) and from 89.7 ± 10.2 mm Hg to 83.6 ± 7.5 mm Hg for diastolic BP ($P<0.001$). The mean systolic BP decrease was 11.4 ± 7.1 mm Hg (range 1.1–22.3 mm Hg), corresponding to a relative systolic BP reduction of 8.2% (range 1.0–16.0%). The mean diastolic BP decrease was 6.1 ± 5.7 mm Hg (range 3.7–15.9 mm Hg), corresponding to a relative diastolic BP reduction of 6.5% (range 4.8–14.6%).

The BP and heart rate measurements during the bicycle exercise tests at baseline and follow-up are shown in Table 2. BW reduction was associated with significant decreases in BP at rest and during exercise regardless of whether the study participant was wearing an external weight vest. Effects of BW reduction on heart rate were less evident. Wearing a weight vest was associated with significant increases in systolic and diastolic BP at rest and during exercise before and after WR, whereas there was no evidence of an effect on heart rate. Figure 2 shows the systolic and diastolic BPs before and after WR and with and without an external weight vest, respectively. Wearing an external weight vest after WR led to systolic and diastolic BPs comparable to the BP values found without a weight vest before WR. The maximally achieved strain during bicycle exercise testing was similar before and after BW reduction: without an external weight vest, 206 ± 47 W at baseline *vs.* 209 ± 51 W at follow-up ($P=0.400$); with an external weight vest, 205 ± 46 W at baseline *vs.* 206 ± 47 W at follow-up ($P=0.835$).

Between baseline and follow-up, heart rate during the resting electrocardiography significantly decreased from 69.3 ± 8.1 beats min^{-1} to 63.8 ± 7.9 beats min^{-1} ($P=0.002$). The PQ duration decreased from 163 ± 25 ms to 158 ± 27 ms ($P=0.07$), and the QRS duration decreased from 90 ± 12 ms to 89 ± 11 ms ($P=0.03$). The QT duration significantly increased from 377 ± 20 ms to 390 ± 20 ms ($P=0.008$).

The 24-h electrocardiography recording revealed that the heart rate reduction after WR was predominantly a reduction of resting heart rate and heart rate during sleep (heart rate during sleep decreased from 66.2 ± 7.2 beats min^{-1} to 62.8 ± 6.6 beats min^{-1}, $P=0.045$), whereas heart rate during the daytime remained unchanged (77.5 ± 7.8 beats min^{-1} before and 76.5 ± 9.3 beats min^{-1} after WR, $P=0.65$). No significant change in the electromechanical activation time was found.

Associations of independent variables with BP and heart rate

The associations of the independent variables (wearing a weight vest, total BW and body fat percentage) with BP and heart rate during bicycle exercise testing in a multiple linear regression are shown in Table 3. There was strong evidence for an association between the weight vest and BP at rest and some evidence for its association with BP during exercise. There was also strong evidence of an independent association between body fat percentage and systolic and diastolic BPs at rest and at all levels of exercise. The evidence for an association between total BW and BP was weaker, whereas the association between BW and heart rate was stronger.

Additional analyses

Six study participants failed to lose BW. Failure to lose weight in these participants was due to a lack of motivation and psychological stress factors. There were no significant differences in their baseline characteristics compared with the 17 study participants who completed the study protocol. Three of these six study participants also underwent the follow-up examination. Their BW remained unchanged (change from 98.7 ± 14.8 kg at baseline to 100.0 ± 17.7 kg at follow-up; $P=0.53$). There were no significant differences in BP or heart rate at rest or during exercise between baseline and follow-up.

Table 2 BP and heart rate during bicycle exercise testing at baseline (before weight reduction) and follow-up (after weight reduction) without and with weight vest

	Without weight vest			*With weight vest*				
	Baseline	*Follow-up*	P-*value*[a]	*Baseline*	*Follow-up*	P-*value*[a]	P-*value*[b]	P-*value*[c]
BP and heart rate at rest								
Systolic BP, mm Hg	130.0 ± 16.8	112.5 ± 9.7	<0.001	136.1 ± 15.9	125.8 ± 15.1	<0.001	0.03	<0.001
Diastolic BP, mm Hg	85.9 ± 10.3	77.8 ± 7.7	<0.001	90.7 ± 10.5	84.6 ± 6.8	0.003	<0.001	<0.001
Heart rate, beats min^{-1}	93.8 ± 12.5	91.1 ± 11.9	0.35	94.2 ± 10.1	86.7 ± 13.2	0.02	0.90	0.18
BP and heart rate after 3-min strain								
Systolic BP, mm Hg	171.1 ± 28.1	158.3 ± 19.1	0.02	180.1 ± 32.2	167.9 ± 23.8	0.02	0.11	0.03
Diastolic BP, mm Hg	86.5 ± 15.5	78.5 ± 12.0	0.07	91.2 ± 15.9	85.8 ± 12.5	0.12	0.008	0.05
Heart rate, beats min^{-1}	139.4 ± 8.9	137.8 ± 11.5	0.52	137.7 ± 9.0	135.9 ± 8.8	0.35	0.54	0.42
BP and heart rate at maximal strain								
Systolic BP, mm Hg	201.1 ± 24.6	188.4 ± 21.5	0.004	211.0 ± 23.5	198.5 ± 18.6	0.02	0.008	0.008
Diastolic BP, mm Hg	92.4 ± 14.5	86.9 ± 9.4	0.10	93.9 ± 12.1	90.0 ± 10.2	0.19	0.58	0.06
Heart rate, beats min^{-1}	164.4 ± 12.4	164.5 ± 10.2	0.98	164.9 ± 10.3	162.8 ± 10.6	0.30	0.82	0.34
BP and heart rate after 2-min recreation								
Systolic BP, mm Hg	171.7 ± 25.0	158.8 ± 19.9	0.03	180.4 ± 30.2	164.0 ± 22.9	0.006	0.14	0.35
Diastolic BP, mm Hg	82.0 ± 8.8	74.5 ± 9.3	0.001	85.0 ± 9.7	77.1 ± 11.2	0.002	0.06	0.11
Heart rate, beats min^{-1}	124.4 ± 14.1	119.5 ± 14.3	0.06	127.9 ± 13.8	121.6 ± 12.8	0.002	0.16	0.22

Abbreviation: BP, blood pressure.
[a]*P*-value for the comparison of BP and heart rate between baseline and follow-up.
[b]*P*-value for the comparison of BP and heart rate without and with weight vest at baseline.
[c]*P*-value for the comparison of BP and heart rate without and with weight vest at follow-up.

Wearing an external weight vest uniformly led to increases in systolic BP (of up to 15.7 mm Hg) and diastolic BP (of up to 12.0 mm Hg) at baseline and follow-up in these study participants as well; however, because of the small number of participants, the increases were not significant.

DISCUSSION

This study revealed several findings. First, systolic and diastolic BPs at rest and during exercise and heart rate at rest decreased with WR. Second, wearing an external weight vest led to an immediate increase in systolic and diastolic BPs at rest and during exercise. Third, the increase in BP induced by wearing an external weight vest was independent of BW or body fat.

This study is in agreement with findings from previous studies reporting a marked BP decrease after WR.[1–8] The previously reported 'rule of thumb' of a 10% BP reduction by a 10% WR was confirmed in this study, not only for BP at rest but also for BP during exercise.

This study is the first to provide evidence that wearing an external weight vest leads to an immediate increase in BP at rest and during exercise. Using the results of this study, the authors can only speculate on potential mechanisms for these findings. Presumably, only sympathetic nervous system activity accounts for these rapid BP changes. In fact, previous studies have shown that sympathetic nervous system activity is involved in rapid BP changes, for example, in diurnal BP variation and white coat hypertension.[15,16] There may be other unexplored mechanisms beyond sympathetic nervous system activity because the weight vest had no effect on heart rate. If sympathetic activity had a key role in the rapid BP increase caused by an external weight vest, a more pronounced effect of the weight vest on heart rate would have been expected. Other potential mechanisms explaining the relationship between the weight vest and BP, such as renin–angiotensin–aldosterone system activation or changes in blood volume, are rather improbable, considering the time delay required for changes in such mechanisms.

This study also supports the findings from other studies underscoring the important effect of body fat on BP.[8,20,21] The physiologic mechanisms explaining the association of body fat and BP have been investigated in several studies.[9–15] To the best of the authors' knowledge, this study is the first to document the importance of body fat for BP at rest and during exercise.

This study had several limitations. First, it comprised healthy volunteers. The results of this study may therefore be generalized only with caution to hypertensive or otherwise comorbid patients. Second, the sample of 17 study participants was rather small. However, the sample size calculation performed *a priori* suggests that the sample size was not too small to provide reliable results for nearly all study questions under investigation. The occurrence of type II error is conceivable in some of the nonsignificant results of this study, particularly diastolic BP during exercise. Third, some of the significant results of this study might be the consequence of using multiple testing and of a lack of *a priori* primary end point definition. However, we preferred not to adjust for multiple comparisons to minimize interpretation errors, as the data are not random but actual observations in nature.[22] Fourth, this study was not designed to differentiate between the effects of caloric restriction and exercise level on BP. Indeed, the observed effects of WR on BP are the result of caloric restriction, not exercise, because according to the study protocol, WR had to be achieved through diet and not an increase in exercise level. Fifth, according to current evidence, BP measurement during exercise may be imprecise for several reasons. In particular, measured diastolic BP may be lower than true diastolic BP.[17] However, the device used for BP measurement during exercise

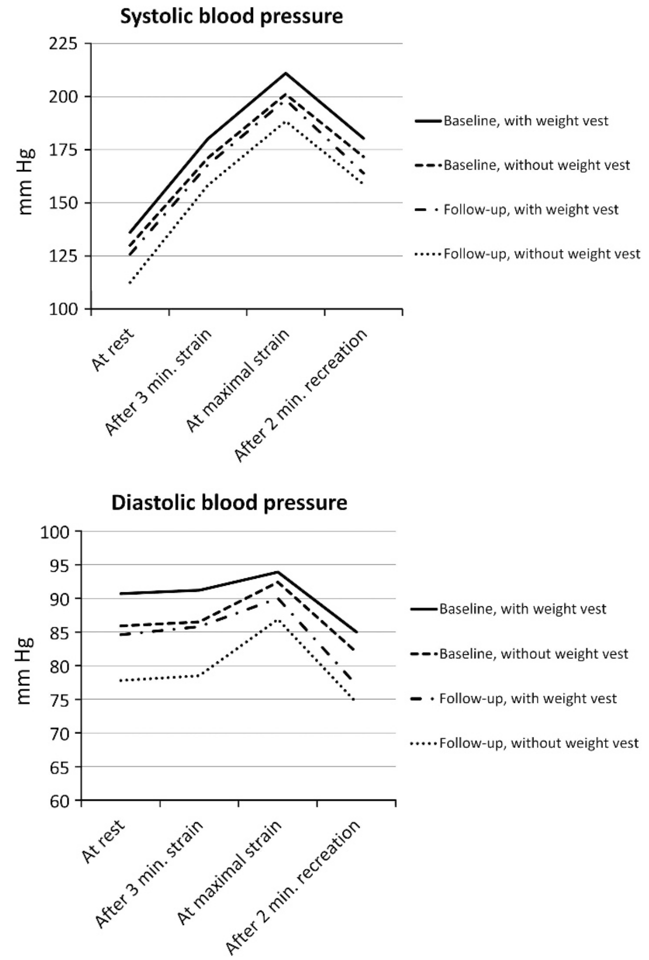

Figure 2 Systolic and diastolic blood pressures (BPs) during a bicycle exercise test before and after weight reduction and with and without an external weight vest.

analyzed Korotkoff sounds triggered by QRS complexes, a method with proven validity for BP measurement during exercise.[17]

The results of this study have important clinical and research implications. First, this study supports the need for BW reduction in overweight subjects to diminish their cardiovascular risk burden.[23–28] This study demonstrated that a BW reduction of approximately 10% led to a BP reduction similar to the previously reported reduction achieved with single-drug antihypertensive therapy.[29] Second, this study suggests that the mechanisms accounting for the relationship between weight and BP are still unclear. Further research is needed to clarify these mechanisms. Such a future study should assess rapid changes in sympathetic activity in addition to rapid BP changes and should also assess the efficiency of physical exercise (for example, by measuring VO_2 consumption and lactate during exercise). Furthermore, 24-h ambulatory BP monitoring should be performed to identify potential differences in nighttime BP decreases, and the long-term effects on BP of a WR lasting longer than 12–24 weeks should be investigated.

In conclusion, this study demonstrated that a moderate WR through caloric restriction led to a marked decrease in systolic and diastolic BPs at rest and during exercise in healthy subjects. Wearing an external weight vest resulted in an immediate increase in resting BP and exercise BP, independent of BW or body fat, thereby questioning the established physiologic mechanisms of the relationship between weight and BP.

Table 3 Associations of weight vest, total body weight and body fat percentage with resting and exercise BP or heart rate during bicycle exercise testing in multiple linear regression

	Wearing of a weight vest		*Total body weight*		*Body fat percentage*	
	Coefficient[a]	*P-value[a]*	*Coefficient[a]*	*P-value[a]*	*Coefficient[a]*	*P-value[a]*
BP and heart rate at rest						
Systolic BP	9.65	0.006	0.26	0.04	0.70	0.003
Diastolic BP	5.85	0.009	0.20	0.02	0.13	0.39
Heart rate	−2.00	0.47	0.27	0.009	0.15	0.42
BP and heart rate after 3-min strain						
Systolic BP	9.29	0.14	−0.07	0.78	0.97	0.02
Diastolic BP	6.03	0.08	−0.05	0.69	0.52	0.03
Heart rate	−1.76	0.41	−0.04	0.62	0.49	0.001
BP and heart rate at maximal strain						
Systolic BP	10.03	0.03	0.42	0.01	1.06	0.001
Diastolic BP	2.26	0.41	−0.11	0.28	0.53	0.006
Heart rate	−0.62	0.80	0.30	0.001	0.003	0.98
BP and heart rate after 2-min recreation						
Systolic BP	6.97	0.21	−0.11	0.59	1.60	<0.001
Diastolic BP	2.79	0.26	0.02	0.85	0.33	0.05
Heart rate	2.79	0.35	0.48	<0.001	−0.12	0.55

Abbreviation: BP, blood pressure.
[a]Coefficients and *P*-values adjusted for the other independent variables (wearing of a weight vest, total body weight and body fat percentage) in the multiple linear regression model.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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