Effects of Endurance Training on Blood Pressure, Blood Pressure–Regulating Mechanisms, and Cardiovascular Risk Factors

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***Abstract*—**Previous meta-analyses of randomized controlled trials on the effects of chronic dynamic aerobic endurance training on blood pressure reported on resting blood pressure only. Our aim was to perform a comprehensive meta-analysis including resting and ambulatory blood pressure, blood pressure–regulating mechanisms, and concomitant cardiovascular risk factors. Inclusion criteria of studies were: random allocation to intervention and control; endurance training as the sole intervention; inclusion of healthy sedentary normotensive or hypertensive adults; intervention duration of ≥4 weeks; availability of systolic or diastolic blood pressure; and publication in a peer-reviewed journal up to December 2003. The meta-analysis involved 72 trials, 105 study groups, and 3936 participants. After weighting for the number of trained participants and using a random-effects model, training induced significant net reductions of resting and daytime ambulatory blood pressure of, respectively, 3.0/2.4 mm Hg ($P<0.001$) and 3.3/3.5 mm Hg ($P<0.01$). The reduction of resting blood pressure was more pronounced in the 30 hypertensive study groups (−6.9/−4.9) than in the others (−1.9/−1.6; $P<0.001$ for all). Systemic vascular resistance decreased by 7.1% ($P<0.05$), plasma norepinephrine by 29% ($P<0.001$), and plasma renin activity by 20% ($P<0.05$). Body weight decreased by 1.2 kg ($P<0.001$), waist circumference by 2.8 cm ($P<0.001$), percent body fat by 1.4% ($P<0.001$), and the homeostasis model assessment index of insulin resistance by 0.31 U ($P<0.01$); HDL cholesterol increased by 0.032 mmol/L^{-1} ($P<0.05$). In conclusion, aerobic endurance training decreases blood pressure through a reduction of vascular resistance, in which the sympathetic nervous system and the renin-angiotensin system appear to be involved, and favorably affects concomitant cardiovascular risk factors. **(*Hypertension*. 2005;46:667-675.)**

Key Words: exercise ■ blood pressure ■ risk factors

Regular physical activity is considered a cornerstone in the prevention and management of hypertension.[1–3] Epidemiological studies indicate that greater physical activity or fitness is associated with a lower blood pressure (BP), and meta-analyses of randomized controlled trials have shown that chronic dynamic aerobic endurance training is able to reduce BP.[3] Previous meta-analyses, including the most recent ones,[4–6] focused on resting BP and did not report on other outcomes, such as ambulatory BP monitoring (ABPM), mechanisms to explain the BP-lowering effect of exercise, and the influence on concomitant risk factors. The number of eligible randomized controlled trials and study groups has since substantially increased, which allows a more precise estimate of the overall effect of exercise training, more powerful subgroup analyses, and analyses of the determinants of the response. Moreover, a number of studies reported on ambulatory BP, BP-regulating mechanisms, and other cardiovascular risk factors. Therefore, the main aims of the current meta-analysis were to examine the influence of chronic dynamic aerobic endurance training on resting and ambulatory BP, on BP-regulating mechanisms, and on concomitant cardiovascular risk factors, such as body fatness, waist circumference, blood lipids, and glucose/insulin dynamics.

Methods

Selection of Studies

A database of randomized controlled trials on the effect of exercise training on BP was started in 1985,[7] updated in 1994[8] and 1999,[9] and again for the current meta-analysis. We conducted a comprehensive literature search with the MEDLINE computerized database for studies published up to December 2003, with medical subject headings exercise or training and BP and text words running, cycling, and swimming. The reference lists of published articles and reviews on the topic were checked to identify other eligible studies. Selection criteria for inclusion in the meta-analysis were as follows: random allocation of participants to training and control groups in parallel group studies or to phases in case of crossover design; healthy sedentary normotensive or hypertensive adults; dynamic aerobic exercise training, designed to increase endurance performance, as the sole intervention difference with the control group or

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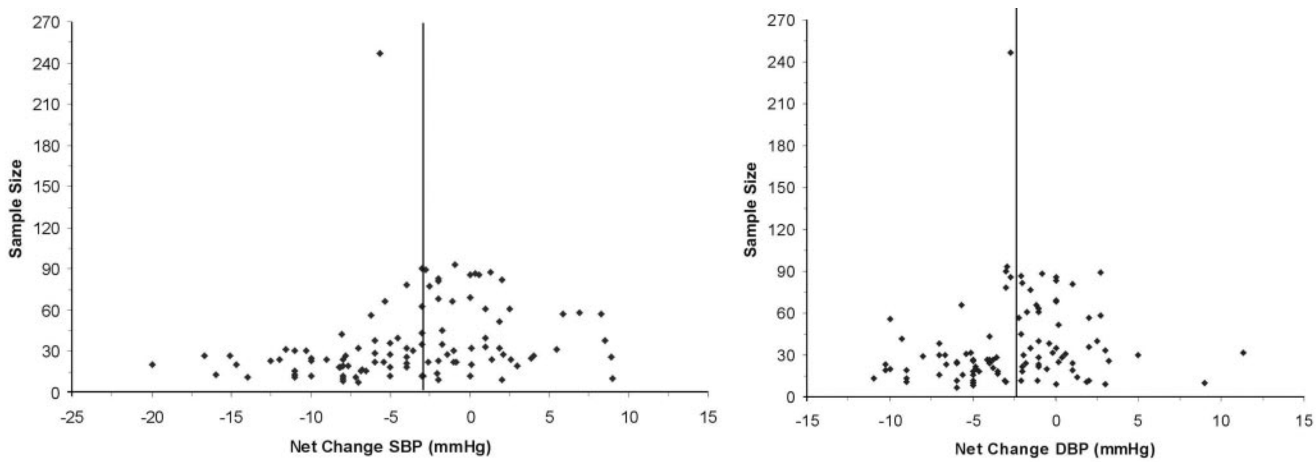

Figure 1. Funnel plots of net changes in SBP (left) and DBP (right) vs study group sample size. The vertical line represents the mean BP change, weighted for the number of participants in the training group.

phase; intervention duration of ≥4 weeks; reporting of BP in the intervention and control groups or phases; and full publication in a peer-reviewed journal. Among the 73 randomized controlled trials that met these criteria,[10–81] 32% reported the BP response to training in different subgroups or submitted their subjects to different training regimens so that 106 study groups were available for analysis.

Data Extraction

The following data were extracted independently by the 2 authors: study design, sample size, characteristics of participants and training programs, details on BP measurement, and the effects of the intervention on the variables of interest. The primary outcome was resting BP in the sitting position, and if not available, BP in the supine position. Secondary outcome variables included demographic and anthropometric characteristics and data on exercise performance, ABPM, BP-regulating mechanisms, and cardiovascular risk factors. Training intensity, which was expressed differently in the various reports, was recalculated as percentage of heart rate (HR) reserve (HRres) according to the following formula: % of HRres=[(% of maximum HR [HRmax]·HRmax)]−(resting HR [HRrest])/(HRmax−HRrest). Blood lipids, glucose, and insulin are expressed in SI units; the homeostasis model assessment (HOMA) index was calculated according to the formula of Matthews.[82] Study groups were classified in 3 subgroups on the basis of average baseline BP: normal BP (<120/80 mm Hg), prehypertension (120 to 139/80 to 89 mm Hg), and hypertension (≥140/90 mm Hg).[1]

For the description of the baseline characteristics of the study groups, we calculated mean values by combining mean baseline data from the training group and the control group, weighted by the number of participants in each group. For each study group, the net effect of training on the outcome variables was calculated as the difference between the mean changes in the training group and the mean changes in the control group in case of a parallel group design; for crossover trials, the net treatment effect was the difference in BP measured at the end of the training and sedentary periods, respectively. Changes are expressed in absolute units, except for hemodynamic and neurohumoral variables for which percentage changes are reported.

Statistical Analyses

Statistical analyses were done using SAS version 8.2 (SAS Institute, Inc). Differences between the baseline descriptive means of the 3 BP groups were analyzed using 1-way ANOVA; the Scheffé F test was used for post hoc pairwise comparisons. The Kruskal–Wallis test was used to analyze differences in training program characteristics between subgroups. Because of the potential statistical heterogeneity among study groups, the random-effects model was used as the default method to estimate the overall effect sizes of training.[83] SAS Proc Mixed was applied to take into account within and between study group variations. The pooled effect sizes of training were calculated by weighting for the number of participants in the training group. This was preferred above weighting for the inverse of the variance because we had to impute the variance in 87% of the study groups, in which case the use of imputed SDs in a meta-analysis is not recommended.[84] Only variables that were reported in ≥10 study groups were included in the meta-analysis. Univariate weighted regressional analyses were performed to determine the association among changes in BP and characteristics of participants and training programs. The possibility of publication bias was explored by plotting net changes in BP against sample size for each study group.[85] A 2*P*-value of ≤0.05 was considered significant.

Results

Publication Bias

Visual inspection of the funnel plots (Figure 1) shows that net changes in systolic BP (SBP) and diastolic BP (DBP) are roughly symmetrical around the mean effect size line.

Overview of Trials

After exclusion of 1 trial in which the Finapres device was used to measure BP,[75] 72 trials comprising 105 study groups and 3936 participants remained for analysis. Sample size of the trials at baseline varied from 8 to 357 participants (median 32). The overall percentage of dropouts was 11.1% (range 0 to 49). Mean age ranged from 21 to 83 years (median 46.6); 32 study groups involved only men, 31 only women, 40 included both genders, and gender was not reported in 2 groups. Average baseline resting BP ranged from 100.6 to 162.5 mm Hg (median 128.1) for SBP and from 61.4 to 107.0 mm Hg (median 81.6) for DBP. Trial design was as follows: parallel comparisons in 59 trials; a 2-way crossover design in 8; a 4×4 Latin square design in 2; a 3×3 Latin square design in 2; and a 1-way crossover design in 1. Study duration varied from 4 to 52 weeks (median 16). Average training frequency ranged from 1 to 7 days per week (median 3), and average intensity was between 30% and 87.5% of HRres (median 65). Each training session lasted from 15 to 63 minutes (median 40) after exclusion of warm-up and cool-down activities and involved mainly walking, jogging, running, or cycling. Training was supervised in 67 study groups, comprised supervised and unsupervised sessions in

TABLE 1. Baseline Characteristics of 72 Randomized Controlled Trials According to Baseline BP

	Normal Pressure	Prehypertension	Hypertension	*P* Value*
No. of				
Trials	15	33	28	
Study groups	28	46	31	
Trained subjects	599	1087	492	
Subject characteristics				
Age (years)	38.3±15.1 (25)	47.8±11.7(46)†	52.7±11.8(31)‡	<0.001
Gender (n)				
Only men	11	16	5	
Only women	14	14	3	
Men and women	3	16	21	
Unknown	0	0	2	
VO_2max (mL · kg^{-1} · min^{-1})	31.5±6.4 (25)	31.5±6.3 (39)	29.2±7.0 (17)	NS
HR (bpm^{-1})	71.9±8.1 (18)	71.1±9.3(23)	73.9±4.4 (23)	NS
Height (cm)	168.8±6.4 (13)	169.9±6.5 (33)	167.2±7.5 (17)	NS
Weight (kg)	69.6±6.7 (18)	75.9±9.3 (36)	77.9±11.4(26)‡	<0.05
BMI (kg/m^2)	25.4±1.9 (18)	26.3±2.4 (35)	27.8±2.9 (19)‡	<0.05
Risk factors				
BP (mm Hg)				
SBP	113.4±5.1 (28)	127.2±4.3 (46)†	146.7±8.1(31)‡§	<0.001
DBP	71.8±3.9 (28)	80.5±4.2 (43)†	92.2±7.4(31)‡§	<0.001
Body fat (%)	27.4±3.2 (6)	32.1±4.4 (15)	31.1±6.4 (9)	NS
Cholesterol (mmol/L^{-1})				
Total	5.3±0.57 (10)	5.8±0.51 (16)	5.4±0.51 (5)	NS
HDL	1.4±0.21 (16)	1.4±0.25 (16)	1.3±0.12 (6)	NS
LDL	3.7±0.54 (14)	3.6±0.47 (12)	3.4±0.17 (4)	NS
Triglycerides (mmol/L^{-1})	1.3±0.31 (16)	1.5±0.38 (17)	1.5±0.46 (6)	NS
Glucose (mmol/L^{-1})	5.04±0.28 (4)	4.8±0.30 (9)	5.3±0.58 (5)	NS
Insulin (IU/L^{-1})	10.0±0.00 (2)	10.2±5.2(10)	13.4±4.9 (7)	NS
Training characteristics				
Duration (weeks)	22 [4–52] (28)	16 [4–52] (46)	12 [4–52] (31)	NS
Frequency (No. per week^{-1})	3 [1−7] (28)	3 [2–7] (46)	3 [2–7] (31)	NS
Intensity (% HRres)	65.5 [30–87.5] (26)	65 [36–85] (46)	65 [30–87] (30)	NS
Duration per session (minutes)	30 [25–60] (28)	45 [15–63.3] (45)	40 [25–60] (31)	NS

All values, except gender and the training characteristics, are reported as mean±SD. The training characteristics are reported as median [range].

The No. of available study groups is given between brackets.

Statistical analyses: *Overall *P* value; †, ‡, and § refer to significant differences between groups ($P \leq 0.05$); † and ‡, compared with normal BP; §, compared with prehypertension.

VO_2max indicates maximal oxygen uptake.

23 groups, and was home-based in 8; there was no information on training location or supervision in 7 groups.

Based on average baseline BP, 28 study groups* were classified as normotensive, and 48 and 29 study groups, respectively, as prehypertensive† and hypertensive.‡ Two prehypertensive study groups[15,30] in which subjects were on antihypertensive treatment were included in the hypertensive subgroup. Ten normotensive,[11,31,42,49,56,69] 18 prehypertensive,§ and 3 hypertensive study groups[23,45,79] gave no information on antihypertensive medication. Participants had been taken off medication in 2 and 6 prehypertensive[40] and hypertensive study groups,[16,19,26,29,59,64] respectively; 6 hypertensive study groups[14,30,46,54,61,71] reported that all or some of their participants were on treatment during the study. As shown in Table 1, hypertensive participants were significantly older and had a higher body mass index (BMI) than participants from other subgroups. The training program

*References 11, 17, 27, 28, 31–34, 42, 48, 49, 55, 56, 60, 69.

†References 10, 12, 13, 15, 20, 21, 24, 25, 30, 35–41, 43–45, 47, 50–52, 57, 58, 66, 68–70, 73, 74, 76, 78, 80.

‡References 14–16, 18, 19, 22, 23, 26, 29, 30, 45, 46, 53, 54, 59, 61–65, 67, 71, 72, 77, 79, 81.

§References 12, 21, 36, 37, 39, 45, 51, 52, 68, 69, 73, 80.

TABLE 2. Baseline Data for the Training Groups and Weighted Net Changes in Response to Dynamic Aerobic Endurance Training

Variable	Subgroup	n	No. of Subjects	Baseline	Net Change	*P* Value Within Groups	*P* Value Among Groups
VO_2max (mL · kg^{-1} · min^{-1})	Normal pressure	25	554	31.6 (28.9; 34.3)	3.5 (2.5; 4.4)	<0.001	
	Prehypertension	39	852	31.5 (29.5; 33.4)	3.9 (3.1; 4.6)	<0.001	NS
	Hypertension	17	279	29.2 (25.6; 32.8)	4.4 (3.7; 5.1)	<0.001	
HR (bpm^{-1})	Normal pressure	18	306	71.0 (67.1; 74.9)	−7.1 (−9.3; −5.0)	<0.001	
	Prehypertension	23	404	71.9 (67.9; 75.8)	−4.4 (−5.6; −3.2)	<0.001	NS
	Hypertension	23	340	74.4 (72.4; 76.3)	−4.5 (−6.5; −2.6)	0.001	
BP (mm Hg)							
SBP	Normal pressure	28	599	114.3 (112.8; 115.9)	−2.4 (−4.2; −0.6)	<0.01	
	Prehypertension	46	1087	127.2 (125.9; 128.5)	−1.7 (−3.1; −0.29)	<0.05	<0.001
	Hypertension	30	492	145.4 (142.4; 148.4)	−6.9 (−9.1; −4.6)	<0.001	
DBP	Normal pressure	28	599	73.0 (71.8; 74.1)	−1.6 (−2.4; −0.74)	<0.001	
	Prehypertension	44	1063	80.3 (79; 81.6)	−1.7 (−2.6; −0.75)	<0.001	<0.001
	Hypertension	30	492	92.3 (89.5; 95.1)	−4.9 (−6.5; −3.3)	<0.001	
Weight (kg)	Normal pressure	18	321	69.5 (66.1; 73.0)	−1.2 (−1.8; −0.6)	<0.001	
	Prehypertension	36	817	75.6 (72.3; 78.9)	−1.3 (−1.8; −0.76)	<0.001	NS
	Hypertension	26	435	78.6 (73.9; 83.3)	−1.1 (−1.6; −0.57)	<0.001	
Body fat (%)	Normal pressure	6	93	26.6 (24.03; 29.2)	−1.7 (−3.4; −0.011)	<0.05	
	Prehypertension	16	472	31.1 (28.4; 33.8)	−1.4 (−1.9; −0.92)	<0.001	NS
	Hypertension	9	154	30.9 (26.0; 35.8)	−0.79 (−1.6; 0.051)	0.062	

Values are given as weighted mean (95% CL). Net mean changes were calculated as the difference between the mean changes in the training group and mean changes in the control group in case of a parallel group design, and as the differences measured at the end of the training period and at the end of the sedentary period in case of a cross-over design.

VO_2max indicates maximal oxygen uptake.

characteristics were not significantly different among the 3 subgroups.

BP Assessment

We used BP measurements in the sitting and supine position from, respectively, 40 and 21 trials, whereas 11 trials did not report the measurement position. Only 10 trials reported that the person who measured BP was unaware or blinded for the treatment allocation. For studies that reported on the type of instrument, 30 used a conventional sphygmomanometer, 9 an automatic device, and 20 a random-zero device. ABPM was performed in 11 study groups, either by the oscillometric (n=6) or by the auscultatory technique (n=5).

Changes in Resting and Ambulatory BP

In individual studies, the average net changes in resting BP ranged from −20.0 to +9.0 mm Hg for SBP and from −11.0 to +11.3 mm Hg for DBP. The overall weighted net effect on BP was −3.0 (95% confidence limit [CL], −4.0 to −2.0)/−2.4 (95% CL, −3.1 to −1.7) mm Hg ($P<0.001$). The effect was greatest in the hypertensives, as shown in Table 2. Changes in BP did not significantly differ with regard to the instrument used for BP measurement or trial design. Daytime ambulatory BP (including 24-hour BP in 2 trials that only reported 24-hour BP) averaged 134.8 (95% CL, 130.2 to 139.4)/85.6 (95% CL, 82.2 to 88.9) mm Hg.¶ The exercise-induced weighted net change in BP averaged −3.3 (95% CL, −5.8 to −0.9)/−3.5 (95% CL, −5.2 to −1.9) mm Hg ($P<0.01$).

Changes in Secondary Outcomes

Overall, maximal oxygen uptake (VO_2max) increased by 4.0 mL/min^{-1} · kg^{-1} (95% CL, 3.5 to 4.5), HRrest decreased by 4.8 bpm^{-1} (95% CL, −5.7 to −3.9), weight by 1.2 kg (95% CL, −1.5 to −0.90), and percent body fat by 1.4% (95% CL, −1.8 to −0.96; $P<0.001$). The training-induced changes were significant in each BP subgroup, as shown in Table 2. Because of the smaller number of observations, results on blood lipids, glucose, and insulin are only reported for all study groups combined (Table 3). Overall, HDL cholesterol showed a significant increase, whereas glucose, insulin, and the HOMA index decreased. There were no significant interactions between these changes and the BP status at baseline. In the studies that reported on blood lipids, the net training-induced changes in BP averaged −1.4 mm Hg (95% CL, −2.7 to −0.2; $P<0.05$) for SBP and −1.5 mm Hg (95% CL, −2.5 to −0.5; $P<0.01$) for DBP. These changes averaged −2.2 (95% CL, −4.7 to +0.3) mm Hg ($P=0.09$) and −2.7 (95% CL, −3.9 to −1.5) mm Hg ($P<0.001$), respectively, for the studies on glucose/insulin dynamics.

Changes in abdominal visceral fat were assessed in 14 study groups, involving 315 trained subjects, either by the waist circumference (n=9) or by the waist-to-hip ratio (n=8). Waist circumference averaged 91.3 cm (95% CL, 81.9 to 100.7) at baseline and decreased by 2.8 cm (95% CL, −4.0 to −1.7) in response to training ($P<0.001$). Baseline waist-to-

¶References 20, 24, 29, 40, 44, 50, 57, 65, 74, 77.

TABLE 3. Baseline Data for the Training Group and Weighted Net Changes in Response to Dynamic Aerobic Endurance Training

Variable	n	No. of Subjects	Baseline	Net Change	*P* Value
Cholesterol (mmol/L^{-1})					
Total	31	688	5.5 (5.3; 5.8)	−0.040 (−0.13; 0.045)	NS
HDL	38	923	1.4 (1.3; 1.4)	0.032 (0.0050; 0.059)	<0.05
LDL	30	796	3.6 (3.4; 3.8)	−0.078 (−0.30; 0.15)	NS
Triglycerides (mmol/L^{-1})	39	958	1.4 (1.3; 1.5)	−0.11 (0.24; 0.0095)	0.07
Glucose (mmol/L^{-1})	18	439	5.0 (4.8; 5.2)	−0.15 (−0.20; −0.11)	<0.001
Insulin (IU/L^{-1})	19	376	11.6 (9.2; 14.0)	−1.4 (−2.2; −0.53)	<0.005
HOMA index	14	306	2.1 (1.6; 2.5)	−0.31 (−0.53; −0.094)	<0.01

Values are reported as weighted mean (95% CLs).

hip ratio was 0.90 (95% CL, 0.83 to 0.97) and was reduced by 0.0092 (95% CL, −0.0180 to −0.0004) after training ($P<0.05$). In the 14 study groups together, the overall percentage changes in waist circumference or waist-to-hip ratio averaged −2.3% (95% CL, −3.3 to −1.3; $P<0.001$); BP had changed by −1.2 mm Hg (95% CL, −3.5 to +1.0; $P=0.25$) for SBP and by −1.8 mm Hg (95% CL, −3.0 to −0.6; $P<0.01$) for DBP in these study groups.

Changes in Hemodynamics

Hemodynamic measurements were reported in 18 study groups,‖ in which cardiac output (CO) was measured by the CO_2-rebreathing technique (n=15), dye dilution (n=1), echocardiography (n=1), or impedance cardiography (n=1). After exclusion of the latter study[64] because of the questionable validity of the technique, training reduced mean BP by 4.3%, or 4.7 mm Hg (95% CL, −6.9 to −2.5; $P<0.001$). CO did not change, whereas systemic vascular resistance (SVR) decreased significantly by 7.1% ($P<0.05$). HR decreased by 9.3% or 6.8 bpm^{-1} (95% CL, −9.4 to −4.3; $P<0.001$) and stroke volume increased by 15.5% ($P<0.001$; Figure 2).

‖References 17–19, 22, 27, 30, 33, 39, 43, 44, 64, 70.

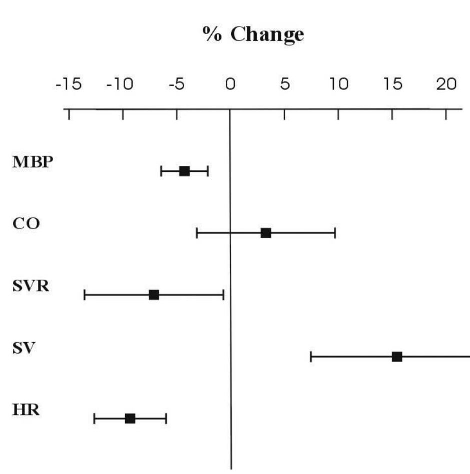

Figure 2. Net training-induced changes in hemodynamic variables. Values are shown as mean net percentage changes and corresponding 95% CLs. MBP indicates mean BP; SV, stroke volume.

Changes in Plasma Norepinephrine and Plasma Renin Activity

Twelve trials** involving 16 study groups reported an average net reduction of plasma norepinephrine (PNE) by 28.7% (95% CL, −39.8 to −17.6; $P<0.001$) after training. BP was reduced by −8.8 (95% CL, −11.0 to −6.6)/−7.1 (95% CL, −8.6 to −5.5) mm Hg in these study groups ($P<0.001$). The 10 study groups[17–19,22,24,59,62,63] that reported on plasma renin activity (PRA) showed a significant decrease of PRA by 19.8% (95% CL, −35.0 to −4.7; $P<0.05$); the BP changes averaged −10.6 (95% CL, −13.9 to −7.3)/−7.0 (95% CL, −8.9 to −5.1) mm Hg ($P<0.001$).

Metaregression Analysis

There were no significant relationships between the training-induced net changes in BP and, respectively, age, BMI, and the net changes in weight and waist circumference among the study groups. Whereas time per session and training frequency, intensity, and mode were not significantly related to the BP response, the BP decrease was more pronounced with greater increases in VO_2max ($r=0.24$, $P<0.05$ for SBP; $r=0.40$, $P<0.001$ for DBP). Finally, the BP reduction became smaller with longer total study duration ($P<0.05$).

Discussion

The main findings of the current meta-analysis of randomized controlled trials on the effects of chronic dynamic aerobic endurance training are: (1) that training lowers BP and that the net BP response is more pronounced in hypertensives than in nonhypertensives; (2) that the BP reduction is based on a decrease in SVR, in which the sympathetic nervous system and the renin-angiotensin system appear to be involved; and (3) that training is associated with favorable effects on other cardiovascular risk factors.

In the current meta-analysis, we analyzed the effect of endurance training on BP according to the recent Seventh report of the Joint National Committee on Prevention, Detection, Evaluation and Treatment of High Blood Pressure BP classification[1] and found that the BP decrease was most pronounced in the hypertensive study groups (−6.9/−4.9 mm Hg), but that significant BP reductions were also observed in normotensive (−2.4/−1.6 mm Hg) and prehy-

**References 16–19, 22, 27, 30, 33, 54, 59, 63, 64.

pertensive groups (−1.7/−1.7 mm Hg). A number of limitations should be considered (ie, that participants are aware of their allocation to control or intervention in training studies, and that several important scientific criteria have not always been observed, such as regular follow-up of the control subjects, attention to possible changes in other lifestyle factors, and blinded or automated BP measurements). However, the fact that net daytime ambulatory BP was reduced to a similar extent as conventional BP in the overall analysis (−3.3/−3.5 mm Hg) supports the BP-lowering effect of endurance training. Another limitation is that the time between the last training session and the measurements is usually not reported. However, it is unlikely that the observed reduction of BP results from an acute effect of the last exercise session. It has indeed been shown that if BP decreases after an acute bout of exercise, BP returns to pre-exercise levels within 12 to 16 hours.[86] It is reasonable to assume that measurements in training studies are performed ≥1 day after the last exercise session.

Individual studies were usually inconclusive and often contradictory with regard to the hemodynamic mechanisms of the BP response.†† The meta-analysis reveals a significant reduction of SVR without change in CO. The fact that the decrease of HR is counterbalanced by an increase in stroke volume with unchanged CO is compatible with the generally accepted effect of aerobic endurance training on resting hemodynamics.[87] A decrease in the activity of the autonomic nervous system is most likely involved in the training-induced reduction of BP and SVR, as evidenced by the, on average, 29% lower PNE levels in the fit state when compared with untrained values. The lack of an effect on BP during sleep,[88,89] when sympathetic activity is low, is compatible with a role for the sympathetic nervous system in the hypotensive effect of endurance training. Nevertheless, it should be noted that forearm venous PNE levels may not accurately reflect the activity of the sympathetic nervous system in training studies. The 20% decrease of PRA supports the involvement of the renin-angiotensin system.[8,90,91] Furthermore, the reduced level of PRA suggests that the reduction in the activity of the sympathetic nervous system also affects the kidney, which is the most potent factor in long-term BP regulation.[92] The reduction of insulin resistance may also have contributed to the favorable effect on BP. Improvement of endothelial function is another potentially important mechanism,[62,63] but the available data are few and not suitable for meta-analysis. Finally, we observed significant average decreases in weight and abdominal obesity in response to training. The fact that the latter changes were not significantly related to the BP changes in the metaregression analyses among study groups does not exclude a causal role in the BP response to training because of the many differences between study groups, the multiple potential mechanisms involved in the BP response, and, with regard to abdominal obesity, the small number of study groups.

††References 17–19, 22, 27, 30, 33, 39, 43, 44, 70.

In the current overview, we restricted the selection of studies to those that reported on the effect of chronic aerobic endurance training on BP, but we also extracted data on concomitant cardiovascular risk factors. We observed decreases of weight, body fat, waist circumference, and insulin resistance; HDL cholesterol increased significantly, whereas triglycerides tended to decrease. These findings are compatible with an overall improvement of cardiovascular risk. It has been estimated that a 2-mm Hg reduction of SBP results in a 6% reduction in stroke mortality and a 4% reduction in mortality attributable to coronary heart disease; the percentage reductions amount to 14% and 9%, respectively, for a 5-mm Hg decrease of BP.[1] However, it is difficult to exactly quantify the overall risk reduction associated with all observed changes,[93] but the findings are compatible with the evidence from epidemiological prospective follow-up studies that physical activity and fitness are inversely related to the incidence of cardiovascular disease and mortality[94]; the benefits of moderately vigorous activity and of greater fitness have also been shown in hypertensive patients.[95–97]

Our results were obtained with training programs that involved dynamic endurance exercises for an average of 40 minutes per session, 3 times per week, at an intensity of 65% of HRres, and lasting 16 weeks, resulting in a significant increase in VO_2max. Despite the wide variation in several characteristics of the training programs among studies, we found no significant relationships between BP response and training characteristics, except for a lesser BP reduction with longer total trial duration, possibly related to loss of compliance. Although training characteristics were in general not predictive for the BP response, the magnitude of the BP reduction was significantly associated with the gain in VO_2max.

Results from meta-analyses have to be interpreted with some caution, but, although meta-analyses are no substitute for large well-designed controlled trials, the meta-analytical technique is probably the best method to systematically review previous work.[98] Advantages are the greater precision of the estimates and the enhanced statistical power. Potential disadvantages are the heterogeneity of studies and publication bias. Despite strict selection criteria, studies may differ in several respects, but this potential problem is addressed by applying the random-effects model and by exploring the heterogeneity of studies by subgroup analyses and metaregression techniques. Publication bias relates to the fact that studies with negative outcomes are less likely to be published, but the funnel plots of the current meta-analysis do not suggest that publication bias did occur. Finally, we restricted the meta-analysis to full publications in peer-reviewed journals because data from abstracts that remain unpublished may not be reliable and usually contain insufficient information; in addition, it is not possible to identify all relevant unpublished material.

Perspectives

The results of the meta-analysis show that aerobic endurance training favorably affects BP, body weight, body fat, waist circumference, blood lipids, and insulin sensitivity, and support the general view that physical activity is important, not only for the prevention of cardiovascular disease but also in the management of hypertension. Nevertheless, physical activity is low, particularly in Western societies, and many hypertensive patients do not exercise. The lack of association between the BP response and training intensity within the studied range could suggest that low-to-moderate physical activity would suffice to obtain the various health benefits of exercise, but this should be proven in randomized controlled trials in which the effects of different training intensities on BP and various risk factors should be addressed. In the meantime, it is recommended to encourage physical activity in the management of hypertension and to monitor compliance at regular intervals to safeguard adherence.

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