Effect of Endurance Training on Hemoglobin Mass and $\dot{V}O_{2max}$ in Male Adolescent Athletes

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ABSTRACT

STEINER, T., T. MAIER, and J. P. WEHRLIN. Effect of Endurance Training on Hemoglobin Mass and $\dot{V}O_{2max}$ in Male Adolescent Athletes. *Med. Sci. Sports Exerc.*, Vol. 51, No. 5, pp. 912–919, 2019. **Purpose**: It is unknown, whether endurance training stimulates hemoglobin mass (Hb_{mass}) and maximal oxygen uptake ($\dot{V}O_{2max}$) increases during late adolescence. Therefore, this study assessed the influence of endurance training on Hb_{mass}, blood volume parameters, and $\dot{V}O_{2max}$ in endurance athletes and control subjects from age 16 to 19 yr. **Methods**: Hemoglobin mass, blood volume parameters, $\dot{V}O_{2max}$ and anthropometric parameters were measured in male elite endurance athletes from age 16 to 19 yr in 6-month intervals ($n = 10$), as well as in age-matched male controls ($n = 12$). **Results**: Neither the level of Hb_{mass} per lean body mass (LBM) ($P = 0.80$) nor the development of Hb_{mass} during the 3 yr ($P = 0.97$) differed between athletes and controls. Hb_{mass} at age 16 yr was 13.24 ± 0.89 g·kg^{-1} LBM and increased by 0.74 ± 0.58 g·kg^{-1} LBM ($P < 0.01$) from age 16 to 19 yr. There was a high correlation between Hb_{mass} at age 16 and 19 yr ($r = 0.77$; $P < 0.001$). Plasma volume, blood volume, and $\dot{V}O_{2max}$ were higher in athletes compared to controls ($P < 0.05$). Blood volume and $\dot{V}O_{2max}$ increased with age ($P < 0.01$, similarly in both groups). **Conclusions**: Endurance training volumes do not explain individual differences in Hb_{mass} levels nor Hb_{mass} and $\dot{V}O_{2max}$ development in the age period from 16 to 19 yr. The higher $\dot{V}O_{2max}$ levels of athletes may be partially explained by training-induced higher plasma and blood volumes, as well as other training adaptations. Since Hb_{mass} at age 16 yr varies substantially and the development of Hb_{mass} in late adolescence is comparably small and not influenced by endurance training, Hb_{mass} at age 16 yr is an important predictor for Hb_{mass} at adult age and possibly for the aptitude for high-level endurance performance. **Key Words**: BLOOD VOLUME, CO-REBREATHING, AEROBIC CAPACITY, ADOLESCENTS, MATURATION, TALENT IDENTIFICATION

Total hemoglobin mass (Hb_{mass}) and blood volume (BV) determine, to a large extent, the oxygen transport capacity of the blood and, consequently, maximal oxygen uptake ($\dot{V}O_{2max}$) (1). It is well known that elite adult endurance athletes are characterized by having up to ~40% higher levels of Hb_{mass} and BV than untrained subjects (2–5), and there exists a strong relationship between

Hb_{mass} and $\dot{V}O_{2max}$ (3,6) as well as between Hb_{mass} and endurance performance (7) even in groups of highly trained endurance athletes. Although endurance training from 6 wk up to 9 months in untrained or moderately trained subjects commonly comprises a 5% to 10% increase in Hb_{mass} (8–11), it seems that sea-level endurance training in highly trained adult endurance athletes exerts no (6,12) or only small (~3%) effects on Hb_{mass} (13,14). Observed training effects in untrained subjects cannot explain the large differences in Hb_{mass} between adult endurance athletes and sedentary subjects. Hence, the question whether the higher Hb_{mass} level in adult endurance athletes is due to several years of endurance training from childhood and adolescence to adulthood, better genetic dispositions, or a combination of both, has yet to be determined.

Although the considerable influence of a good genetic disposition is supported by study results showing a high $\dot{V}O_{2max}$ by virtue of a naturally high Hb_{mass} in adults with no training history (15), the influence of several years of endurance training from adolescence to adulthood is still not entirely clear. From recent cross-sectional data (5,16–18), it can be concluded that endurance-trained children and adolescent endurance-trained athletes have ~15% to 35% lower Hb_{mass} than adult athletes. There seems to be an increase of body weight-related Hb_{mass} with maturation from 9.6 g·kg^{-1} in 9.7-yr-old children (17) to 10.6 g·kg^{-1} in 13.8-yr-old

cyclists (19) to 12.0–12.4 $g \cdot kg^{-1}$ in endurance-trained male adolescents at age 16 yr (5,18). An upregulation of testosterone levels in boys during adolescence is a likely explanation of this training-independent increase, because there exists a close relationship between androgen levels and hemoglobin (Hb) concentration in puberty (20). Since Hb_{mass} levels of male endurance athletes at age 16 yr are still lower than the measured 14.6 $g \cdot kg^{-1}$ in adult endurance athletes (5), it has been suggested that the age period from 16 to 20 yr is probably a sensitive phase to elevate Hb_{mass} and, consequently, red blood cell volume (RBCV) with endurance training (5,18).

However, no data is available for the effects of endurance training on the evolution of Hb_{mass} at this age. From existing investigations with younger endurance athletes, it can be concluded that endurance training had no "additional" effect on the evolution of Hb_{mass} in adolescence. Eriksson (21) reported a 9% increase of absolute Hb_{mass} in 11- to 13-yr-old boys after 16 wk of training, but the effects vanished when Hb_{mass} was corrected for physical growth. Also, no effect of endurance training on the evolution of Hb_{mass} was reported after 12 months of training in cyclists age 11 to 15 yr (16) or after 18 months of training in endurance-trained athletes age 15 to 17 yr (18).

In contrast to the abovementioned investigations, Prommer et al. (17) very recently showed an effect of the activity level in children on the development of Hb_{mass} (7% increase after 2.5 yr with >4 h of training per week) independent of physical growth. However, these findings are, on the one hand, based on young (preadolescent) children and, on the other hand, are equivocal to the training effect, since a longitudinal control group was missing.

The aim of the present study was, therefore, to investigate the influence of endurance training on Hb_{mass}, BV parameters, and $\dot{V}O_{2max}$ in adolescent elite endurance athletes and age-matched non–endurance-trained control subjects from 16 to 19 yr of age.

MATERIALS AND METHODS

Subjects. Ten male adolescent endurance athletes (five XC-skiers and five triathletes) and a group of 12 age-matched, healthy, nonsmoking, and non–endurance-trained male subjects participated in the present study. As there are no Junior National Teams at age 16 yr in XC-skiing and triathlon, the inclusion criterion for athletes was a national top 15 overall ranking in either XC-skiing or triathlon in the season preceding the study period. A maximum of either 2 h endurance training per week or 3 h of team sports (disregarding school sport lessons) were set as upper limits for control subjects.

The study was approved by the Regional Ethic Committee in Berne, Switzerland (KEK-BE 019/08) and was carried out according to the recommendations of the Helsinki Declaration. All subjects and parents gave their written consent before any testing.

Study design. Hb_{mass}, BV, $\dot{V}O_{2max}$, anthropometric characteristics, and several venous blood parameters were assessed in all subjects at seven time points in 6-month intervals, resulting in a monitoring phase of 3 yr. The two visits per year took place in May and November, with athletes starting at the beginning of the off-season period (XC-skiers in May and triathletes in November), whereas controls were all measured for the first time in May or June. Before the first visit, subjects were required to complete a questionnaire for the assessment of the training load in the last 3 months. Throughout the entire study, both athletes and control subjects completed training log books for the assessment of the weekly endurance training volumes, excluding school sport lessons. Subjects had neither conducted altitude training 3 months before any testing nor donated blood during the study period. Subjects were asked to avoid performing strenuous exercise within 24 h of the measurements. All tests were carried out in Magglingen (Switzerland) at an altitude of 950 m.

Determination of hemoglobin mass and BV parameters. Hb_{mass} was measured and calculated using a slightly modified version of the optimized CO-rebreathing procedure by Schmidt and Prommer (22), as described in detail elsewhere (5). Briefly, a bolus of pure CO (CO doses were determined to be 1.2 $mL \cdot kg^{-1}$ for the athletes and 1.0 $mL \cdot kg^{-1}$ for the controls) was inhaled and capillary blood samples (35 μL) were taken from an earlobe and analyzed for percent carboxyhemoglobin (%HbCO) using a diode array spectrophotometer (ABL 800flex; Radiometer A/S, Copenhagen, Denmark) both before the inhalation of the CO bolus and at intervals of 6 and 8 min after. All CO rebreathing procedures were conducted by the same experienced investigator to avoid additional intertester variability. A typical error (TE) between 1.1% and 1.4% is observed in our laboratory from duplicate measurements of Hb_{mass} with the method described (23).

RBCV, BV, and plasma volume (PV) were calculated from Hb_{mass} using venous Hb concentration and venous hematocrit (Hct) (see Burge and Skinner for detailed description (24)):

$$RBCV = Hb_{mass}/MCHC \times 100$$

$$BV = RBCV \times (100/Hct)$$

$$PV = BV - RBCV$$

where MCHC is the mean corpuscular Hb concentration; Hct, hematocrit corrected to whole body Hct by the body/venous hematocrit ratio of 0.91.

Measurement of aerobic capacity ($\dot{V}O_{2max}$ test). The laboratory graded exercise tests to determine $\dot{V}O_{2max}$ were conducted on a treadmill (Model Venus, h/p/cosmos Sports & Medical GmbH, Traunstein, Germany) with an incline set at 4° throughout the test and with continuous measurement of $\dot{V}O_2$ using a breath by breath open-circuit system (Oxycon Pro, Erich Jaeger GmbH, Hoechberg, Germany). After a 5-min warm-up jog, control subjects began running at 7 $km \cdot h^{-1}$, and athletes ran at 9 $km \cdot h^{-1}$. The speed was

increased by 1 km·h^{-1} every minute for the first 3 min of the test, and thereafter, by 0.5 km·h^{-1} every 30 s until exhaustion. The $\dot{V}O_{2max}$ protocols were designed to induce exhaustion in the subjects after 5 to 9 min. The criteria of a plateau in oxygen uptake, a RER value of ≥ 1.10, and a heart rate close to the age-predicted maximum were used to determine whether the subjects reached $\dot{V}O_{2max}$ (25). $\dot{V}O_{2max}$ was determined as the highest value averaged over 30 s. Heart rate was continuously registered with a Polar HR-monitoring system (Polar S610i; Polar Electro Oy, Kempele, Finland).

Venous blood sampling and analysis. Venous blood was sampled on the subjects' arrival at the institute. After 15 min of rest in the supine position, two blood samples (4 mL for EDTA blood, 5 mL for blood serum) were drawn from the antecubital vein. Hemoglobin, Hct, and percent of reticulocytes were measured with automated hematology analyzers (ADVIA 120; Siemens Healthcare Diagnostics GmbH, Eschborn, Germany or Sysmex XE5000; Sysmex Corporation, Kobe, Japan). Soluble transferrin receptors were quantified with a biochemistry analyzer (Olympus AU 2700; Olympus Medical System Corporation, Tokyo, Japan). Serum erythropoietin (Immulite 2000; Siemens Healthcare Systems) and serum ferritin (Ftn) (ADVIA Centaur, Siemens Healthcare Systems) were measured with two different automated immunoassay systems.

Anthropometric measurements. Height, body mass, percent body fat, and lean body mass (LBM) of the subjects were assessed on all test days. Seven skinfold measurements (chest/pectoral, midaxillary, suprailiac, abdominal, triceps, subscapular, and thigh) were performed, and the percentage of body fat was calculated using the equations of Jackson and Pollock for body density (26) and, subsequently, the age-specific formulas of Heyward and Stolarczyk for percent body fat (27). All anthropometrical measurements were made by the same experienced investigator.

Assessment of biological age. The biological maturity status was estimated at the start of the study with a somatic method that compares the present stature with the projected adult stature (19).

Data analysis. All cardiovascular variables were scaled to LBM to account for general anthropometric growth in the observed age range and to correct for different amounts of body fat (17,28).

We performed linear mixed-effects analyses using the statistical programming language R (R 3.3.1, R Core Team, Vienna, Austria) with the lme4 package (29). We modeled the dependence of the anthropometric and cardiovascular parameters from the fixed effects age and group, with random effects for individual subjects (intercept and correlated slope for the effect of age). Models were constructed by sequentially adding fixed effects if justified by likelihood ratio tests ($\alpha < 0.05$). Absolute and percent body fat as well as blood Ftn were log-transformed for homoscedasticity of the model residuals (assessed by visual inspections for all models).

Bootstrap sampling ($n = 1000$) was used to calculate confidence limits for the fixed effects. Linear regression was used to determine the Pearson product correlation between Hb_{mass} at age 16 yr and Hb_{mass} at age 19 yr. Values are reported as mean $\pm$ SD. The analysis code is available as Supplemental Digital Content (see File, Supplemental Digital Content 1, Data analysis code, http://links.lww.com/MSS/B475).

RESULTS

Hb_{mass}, BV parameters, and $\dot{V}O_{2max}$. Hb_{mass} did not differ between athletes and controls ($P = 0.80$; Table 1). The modeled intercept for Hb_{mass} at age 16 yr was 13.24 ± 0.89 g·kg^{-1} LBM and Hb_{mass} increased from age 16 to 19 yr by 0.74 ± 0.58 g·kg^{-1} LBM ($P < 0.01$; Figure 1). The development of Hb_{mass} during the 3 yr did not differ between athletes and controls ($P = 0.97$). Hb_{mass} at age 16 yr was highly correlated with Hb_{mass} at age 19 yr ($r = 0.77$, $P < 0.001$). Plasma volume did not change with age ($P = 0.85$) but was higher in athletes compared to controls ($P < 0.01$). Blood volume and $\dot{V}O_{2max}$ both increased from 16 to 19 yr of age in both athletes and controls (BV, 5.6 ± 2.9 mL·kg^{-1};

TABLE 1. Hb_{mass}, BV parameters, and $\dot{V}O_{2max}$.

Group	Hb_{mass}			PV	BV	RBCV	$\dot{V}O_{2max}$		
Age (yr)	(g·kg^{-1} LBM)	(g)	(g·kg^{-1})	(mL·kg^{-1} LBM)	(mL·kg^{-1} LBM)	(mL·kg^{-1} LBM)	(mL·min^{-1}·kg^{-1} LBM)	(mL·min^{-1})	(mL·min^{-1}·kg^{-1})
Athletes ($n = 10$)									
16.0 ± 0.6	13.1 ± 0.9	760 ± 85	12.5 ± 0.9	62.4 ± 3.2	100.7 ± 3.9	38.3 ± 2.9	70.3 ± 3.6	4070 ± 375	66.9 ± 3.3
16.5 ± 0.6	13.3 ± 1.0	790 ± 97	12.7 ± 1.0	61.2 ± 5.2	101.7 ± 4.7	40.6 ± 2.0	72.9 ± 3.7	4316 ± 330	69.4 ± 3.7
17.0 ± 0.6	13.7 ± 1.2	828 ± 104	13.0 ± 1.2	60.4 ± 3.7	102.7 ± 3.6	42.4 ± 4.1	72.0 ± 2.2	4349 ± 400	68.4 ± 2.0
17.4 ± 0.6	13.7 ± 1.3	853 ± 116	13.0 ± 1.3	60.7 ± 4.1	103.9 ± 3.0	43.2 ± 3.6	73.0 ± 2.2	4542 ± 369	69.0 ± 2.2
17.9 ± 0.6	13.9 ± 1.3	872 ± 105	13.1 ± 1.3	64.0 ± 5.5	107.1 ± 6.6	43.1 ± 4.4	72.2 ± 4.0	4537 ± 473	67.8 ± 4.0
18.5 ± 0.6	13.8 ± 1.2	883 ± 125	13.1 ± 1.2	64.0 ± 4.1	108.3 ± 3.8	44.2 ± 3.7	74.9 ± 3.1	4776 ± 460	70.8 ± 2.9
19.0 ± 0.6	13.9 ± 1.2	899 ± 126	13.1 ± 1.2	61.2 ± 4.1	106.3 ± 6.2	45.1 ± 4.6	75.0 ± 3.7	4848 ± 462	70.6 ± 4.1
Controls ($n = 12$)									
15.9 ± 0.2	13.0 ± 1.0	752 ± 100	12.0 ± 1.1	58.2 ± 3.8	96.8 ± 5.8	38.6 ± 3.4	64.0 ± 4.5	3682 ± 378	59.2 ± 5.4
16.4 ± 0.2	13.2 ± 0.6	788 ± 86	12.0 ± 0.7	58.9 ± 4.2	96.6 ± 5.3	37.8 ± 2.0	63.0 ± 4.4	3766 ± 430	57.9 ± 4.3
17.0 ± 0.3	13.6 ± 0.9	820 ± 88	12.4 ± 1.0	56.4 ± 5.5	98.2 ± 7.1	41.8 ± 2.8	65.7 ± 4.4	3967 ± 347	60.3 ± 5.1
17.5 ± 0.3	13.8 ± 0.8	846 ± 97	12.8 ± 0.7	57.4 ± 4.2	99.4 ± 5.3	42.0 ± 2.7	67.1 ± 2.3	4099 ± 386	62.0 ± 3.2
17.9 ± 0.3	13.7 ± 0.8	854 ± 96	12.6 ± 0.7	56.5 ± 2.7	99.2 ± 5.2	42.8 ± 3.3	66.2 ± 3.9	4100 ± 299	60.8 ± 4.2
18.4 ± 0.3	13.8 ± 0.8	866 ± 96	12.6 ± 0.7	59.9 ± 4.0	101.9 ± 5.8	42.0 ± 2.7	66.4 ± 2.5	4151 ± 264	60.7 ± 3.3
19.0 ± 0.3	13.7 ± 0.9	866 ± 101	12.4 ± 0.8	56.1 ± 4.7	99.6 ± 6.8	43.5 ± 3.0	67.7 ± 3.2	4264 ± 364	61.1 ± 3.8

Values as mean ± SD.
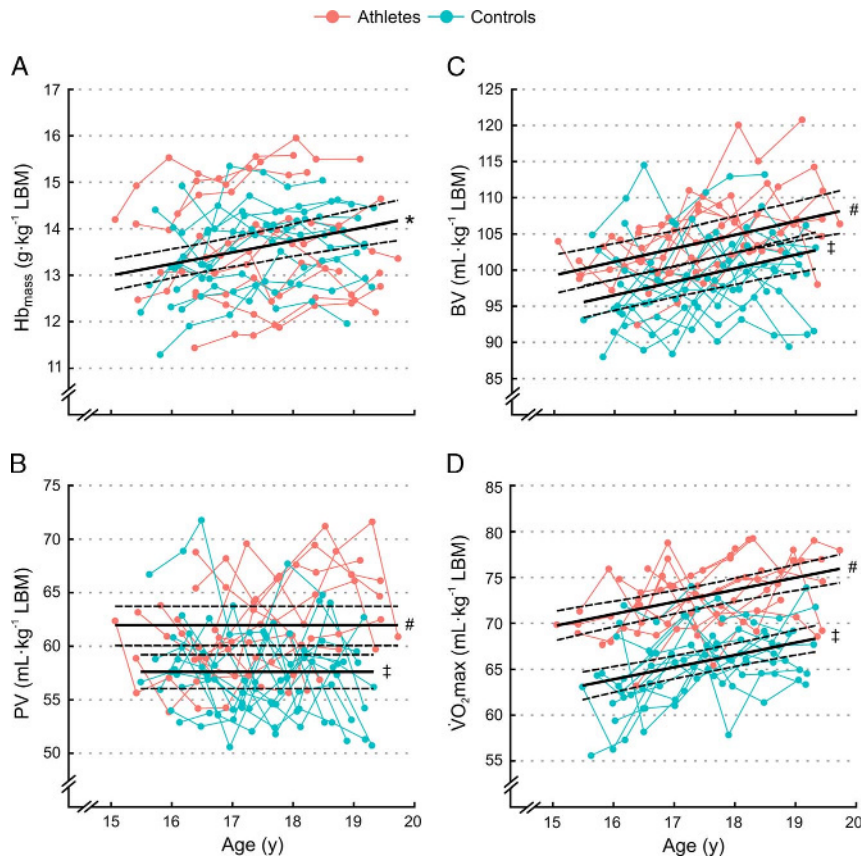
FIGURE 1—Individual development of (A) Hb_{mass}, (B) PV, (C) BV, and (D) $\dot{V}O_{2max}$ over the 3-yr study period for athletes (*red*) and controls (*blue*). *Solid lines* indicate the fixed effect of age with 90% confidence limits (*dashed lines*) for either both groups combined (*; combined fixed effect), or for athletes (#), and controls (‡) separately.

LBM, $P < 0.01$; $\dot{V}O_{2max}$, 4.0 ± 2.4 mL·min^{-1}·kg^{-1} LBM; $P < 0.01$) and were higher in athletes compared with controls ($P = 0.02$ and $P < 0.01$, respectively). There was no difference in the increase in BV ($P = 0.09$) and $\dot{V}O_{2max}$ ($P = 0.96$) between the groups.

The ratio of $\dot{V}O_{2max}$ to BV was 0.68 ± 0.05 min^{-1}, constant over the analyzed age range ($P = 0.83$) and not different between groups ($P = 0.07$). By contrast, the ratio of $\dot{V}O_{2max}$ to Hb_{mass} stayed constant with aging ($P = 0.68$) but was higher in athletes compared to controls (5.4 ± 0.4 mL·min^{-1}·g^{-1} and 4.9 ± 0.4 mL·min^{-1}·g^{-1} respectively, $P < 0.01$), whereas the ratio of $\dot{V}O_{2max}$ to PV increased with age ($P < 0.01$) but did not differ between groups ($P = 0.27$).

Peak velocity in the $\dot{V}O_{2max}$ test was higher ($P < 0.01$) in athletes (15.6 ± 0.5 km·h^{-1}) than controls (13.0 ± 0.8 km·h^{-1}) and did not increase with age ($P = 0.67$).

Blood parameters. Hb was lower ($P = 0.02$) in athletes (14.4 ± 1.1 g·dL^{-1}) than controls (15.1 ± 0.7 g·dL^{-1}) at all testing sessions and did not change in both groups over the study period ($P = 0.93$). Hct was similar between groups (at age 16 yr, athletes: $43.1\% \pm 3.1\%$, controls: $44.0\% \pm 1.1\%$, $P = 0.33$) and increased similarly ($P = 0.52$) in both groups from age 16 to 19 yr by $3.6\% \pm 1.1\%$ ($P < 0.01$).

Further, there were no differences between groups in percent reticulocytes (athletes: $0.8\% \pm 0.3\%$, controls: $0.8\% \pm 0.3\%$,

$P = 0.95$), serum erythropoietin (athletes: 10.9 ± 2.9 U·L^{-1}, controls: 10.6 ± 3.4 U·L^{-1}, $P = 0.59$), soluble transferrin receptor (athletes: 7.6 ± 1.2 nmol·L^{-1}, controls: 7.4 ± 1.5 nmol·L^{-1}, $P = 0.27$), or Ftn (athletes, 60 ± 30 µg·L^{-1}; controls, 47 ± 23 µg·L^{-1}, $P = 0.25$).

Anthropometric characteristics and endurance training volume. Body mass ($P = 0.57$), LBM ($P = 0.89$) and height ($P = 0.95$) did not differ between groups at all testing sessions, but athletes exhibited a lower absolute ($P = 0.02$) and percent body fat ($P < 0.01$; Table 2). All anthropometric characteristics increased over the observed age range (all $P < 0.01$), but the development of all parameters was not different between athletes and controls (all $P > 0.38$). Further, biological age at the study's start did not differ between groups ($P = 0.63$).

Athletes conducted a higher volume of endurance training than the control group ($P < 0.01$) and increased the training volume over the observed age range ($P = 0.01$; Table 2).

DISCUSSION

This study was the first to assess the influence of endurance training on Hb_{mass} and $\dot{V}O_{2max}$ development in adolescent male endurance athletes from age 16 to 19 yr. The major findings of the present study were: 1) Hb_{mass}

TABLE 2. Anthropometric characteristics and training volume.

Group	Body Mass	LBM	Body Fat	Percent Body Fat	Height	Endurance Training Volume
Age (yr)	(kg)	(kg)	(kg)	(%)	(cm)	(h·wk^{-1})
Athletes (n = 10)						
16.0 ± 0.6	60.9 ± 5.4	57.9 ± 4.7	2.9 ± 1.0	4.8 ± 1.2	176 ± 5	7.9 ± 1.6
16.5 ± 0.6	62.3 ± 5.8	59.3 ± 5.1	3.0 ± 0.9	4.7 ± 1.0	177 ± 5	7.9 ± 2.1
17.0 ± 0.6	63.6 ± 6.0	60.4 ± 5.2	3.2 ± 1.1	5.0 ± 1.3	178 ± 6	5.8 ± 1.6
17.4 ± 0.6	65.8 ± 5.5	62.3 ± 4.9	3.6 ± 0.8	5.4 ± 0.8	179 ± 6	9.4 ± 1.7
17.9 ± 0.6	66.8 ± 6.1	62.9 ± 5.3	4.0 ± 1.2	5.9 ± 1.3	179 ± 6	6.6 ± 2.0
18.5 ± 0.6	67.6 ± 6.5	63.8 ± 5.7	3.8 ± 1.1	5.6 ± 1.2	180 ± 6	10.3 ± 1.9
19.0 ± 0.6	68.7 ± 5.9	64.7 ± 5.4	4.0 ± 0.8	5.8 ± 0.9	180 ± 6	8.1 ± 2.2
Controls (n = 12)						
15.9 ± 0.2	62.6 ± 8.3	57.6 ± 5.7	5.0 ± 3.0	7.7 ± 3.5	176 ± 8	0.6 ± 0.6
16.4 ± 0.2	65.6 ± 9.2	59.8 ± 6.0	5.8 ± 3.4	8.4 ± 3.7	177 ± 8	0.3 ± 0.4
17.0 ± 0.3	66.3 ± 8.9	60.5 ± 6.1	5.8 ± 3.2	8.3 ± 3.5	178 ± 8	0.1 ± 0.1
17.5 ± 0.3	66.5 ± 8.8	61.1 ± 6.1	5.3 ± 3.0	7.7 ± 3.3	179 ± 8	0.2 ± 0.2
17.9 ± 0.3	67.8 ± 8.1	62.1 ± 5.9	5.7 ± 2.8	8.1 ± 3.1	179 ± 8	0.1 ± 0.3
18.4 ± 0.3	68.7 ± 7.8	62.7 ± 5.5	6.1 ± 2.6	8.6 ± 2.8	179 ± 8	0.3 ± 0.3
19.0 ± 0.3	70.2 ± 9.2	63.1 ± 5.4	7.2 ± 4.1	9.8 ± 4.0	180 ± 8	0.1 ± 0.1

Values as mean ± SD.

development was independent from endurance training volume in the age period from 16 to 19 yr in male adolescents; 2) interindividual Hb_{mass} levels at age 16 yr varied substantially more than the individual development of Hb_{mass} over the study period, which suggests Hb_{mass} level at age 16 yr is an important predictor for Hb_{mass} in adulthood; 3) athletes had higher training-induced PV, BV, and $\dot{V}O_{2max}$ than controls; 4) $\dot{V}O_{2max}$ development in the 3-yr study period was independent from training volume.

Hb mass. During the 3-yr study period, absolute Hb_{mass} increased by 18% in athletes and by 15% in controls. When scaling to LBM to account for general anthropometric growth in the observed age range (17) and to correct for different amounts of body fat, relative Hb_{mass} increased in both groups by 6% (0.74 g·kg^{-1} LBM). Surprisingly, the amount of endurance training influenced neither the initial Hb_{mass} level at age 16 yr nor the development of Hb_{mass} during the study period.

The available data demonstrate that endurance training in late adolescence does not yield the additional stimulating effects on Hb_{mass} that have been proposed for this age (5,17,18). Based on our mixed model, an increase of relative Hb_{mass} from ages 16 to 19 yr can be expected for 90% of the subjects, irrespective of training volume. Increases up to 1.90 g·kg^{-1} LBM (average increase +2 SD) are possible, but on average, 0.74 g·kg^{-1} LBM can be expected. In other words, at age 16 yr, adolescent male athletes should already have an Hb_{mass} of more than 14 g·kg^{-1} LBM to possibly reach levels at adult age of about 15.4 g·kg^{-1} LBM measured with the same methodology in adult elite endurance athletes (5). Hb_{mass} at age 19 yr was highly correlated with Hb_{mass} at age 16 yr and approximately three quarters of the variance of Hb_{mass} level at age 19 yr can be explained by the initial Hb_{mass} at age 16 yr. Hence, in contrast to our assumption from a cross-sectional study (5), Hb_{mass} at age 16 yr seems to have an important predictive value for Hb_{mass} at the end of adolescence, and due to the stability of Hb_{mass} with sea-level endurance training in adult elite endurance athletes (6,12), also for a high Hb_{mass} at adult age. Consequently, because Hb_{mass} is strongly related to $\dot{V}O_{2max}$

(3,5,6,11,15) as well as to endurance performance (7) in elite athletes, Hb_{mass} at age 16 yr is one possible candidate to estimate the aptitude for high-level endurance sports in adulthood. This is in line with the hypothesis of the prognostic value of Hb_{mass} for talent identification in younger athletes (16,17).

Compared with earlier studies utilizing identical or closely related methods with younger adolescent endurance athletes, our results differ on two points. First, previously reported relative Hb_{mass} levels for adolescent endurance athletes were 10% to 15% higher than in control subjects or nonendurance athletes (16,18). However, higher levels of Hb_{mass} for the endurance athletes in these investigations can most likely be explained by highly unbalanced proportions of male and female subjects, which makes the results prone to misinterpretation. Second, studies investigating the influence of endurance training on Hb_{mass} in adolescent endurance athletes (16,18,21) did not find significant increases in Hb_{mass} beyond the alterations explained by growth and maturation with endurance training. Only one study with preadolescent subjects reported a training effect of up to 7% on Hb_{mass} over 2.5 yr not caused by normal growth mechanisms (17). Unfortunately, no control group was included, and with the results of the present study in mind (6% increase of Hb_{mass} without endurance training over 3 yr), it can be hypothesized that nonactive subjects would have shown a similar increase in Hb_{mass}.

The mechanisms of individually different Hb_{mass} development remain unknown. We cannot determine the degree to which factors relating to erythropoiesis in adolescents and adults—such as varying levels of human growth hormone, insulin-like growth factors, or testosterone (20,30,31)—influenced Hb_{mass}, as we did not conduct any of these measurements. It is assumed that these factors could have influenced initial level variations at age 16 yr, as well as the development of Hb_{mass} during the study period. At the very least, the average increase of relative Hb_{mass} as an effect of aging could be attributed to higher testosterone and human growth hormone levels in this late phase of adolescence, as no relative increase has been observed with younger athletes and control subjects (16,18,21).

APPLIED SCIENCES

Blood volume parameters, and $\dot{V}O_{2max}$. Results suggest that the main cardiovascular adaptation to endurance training before reaching 16 yr of age and persisting up to 19 yr is an increased PV, and consequently BV. Blood volume increases further from age 16 to 19 yr, irrespective of training volume, due to the increase in Hb_{mass} and RBCV. It has been reported that higher BV and PV reduce cardiovascular and thermoregulatory strain and increase the buffering capacity of the blood, while a higher BV increases venous return and cardiac output (32) and thereby $\dot{V}O_{2max}$ (10,33). These adaptations most likely have a positive effect on endurance performance, as athletes were not endowed with higher levels of Hb_{mass} than their age-matched counterparts but reached significantly higher $\dot{V}O_{2max}$ levels and a higher endurance performance (final speed attained in the performance test on the treadmill). An increased BV due to PV expansion is also typically observed in routine measurements in adult athletes between the off-season and the competition season, indicating a higher endurance performance capacity during the competition season (unpublished results from our laboratory).

Because high $\dot{V}O_{2max}$ levels are not only dependent on cardiac output and the oxygen carrying capacity of the blood (i.e., Hb_{mass}) but also on factors like mitochondrial density and capillarization of the muscles (34), it should be obvious that endurance training could have influenced these parameters, and hence, $\dot{V}O_{2max}$ and endurance performance, without recognition in BV parameters and Hb_{mass}.

However, the increases in absolute (athletes, +19%; controls, +16%) and relative $\dot{V}O_{2max}$ (both about 6%) correspond very well with the development of Hb_{mass} and BV but not with that of PV. This suggests that the $\dot{V}O_{2max}$ increase during the 3-yr studied was based at least in part on the higher Hb_{mass} (and hence, BV). This fact is supported by constant ratios for $\dot{V}O_{2max}$ to Hb_{mass} and $\dot{V}O_{2max}$ to BV over the analyzed age range, while the $\dot{V}O_{2max}$ to PV ratio increased with age. The similar increase in relative $\dot{V}O_{2max}$ for athletes and control subjects over the study period surprised us. To our knowledge, this is the first controlled study to show this aspect in adolescents age 16 to 19 yr.

It is suggested that up to 50% of $\dot{V}O_{2max}$ is genetically and familial nongenetically inherited (35,36). Besides these genetically predisposed higher values, the trainability of $\dot{V}O_{2max}$ is also regarded as dependent on yet undetermined inherited characteristics (37,38). These two factors do not seem to be necessarily related, and therefore, it is hypothesized that both a phenotype that is superior with respect to aerobic power and one that is superior with respect to response to endurance training exist (39). Although no detailed genomic signature has been found so far that differentiates endurance athletes from sedentary subjects (40), it can be hypothesized, that an optimal gene–training (environment) interaction plays a preponderant role in the development of high-level endurance athletes. Due to our findings, it can be assumed that a similar model of diverse phenotypes could also be applicable to Hb_{mass} levels and development. On the one hand, Hb_{mass} levels varied substantially among control subjects with low volumes of training, indicating considerably different Hb_{mass} "starting" values, and on the other hand, the development of Hb_{mass} appears to be highly variable, irrespective of subjects' training volumes.

Strengths and Limitations of the Study

The adolescent athletes were selected on the grounds of competition results at age 16 yr, where the lack of a strong physiological predisposition could be partly compensated by high technical skills, a higher training volume, and a longer training history. In elite athletes, a lack of physiological talent is very unlikely due to the rigorous selection process from adolescent to adult athletes. Consequently, results are usually reported only for subjects with an extremely high aerobic capacity and a high endurance performance. Accordingly, lower Hb_{mass} values of the adolescent athletes compared to Hb_{mass} levels of elite athletes (3,5) could already be explained by selection bias. A replication of the measurements of junior athletes from sports with lower technical demands (e.g., runners), and hence, a higher relevance of physiological characteristics on endurance performance, may have yielded different results.

Although the endurance training volumes of the athletes appear rather low at first glance, it must be considered that only the volume of specific endurance training is reported to focus on the influence of endurance exercise on Hb_{mass} development. Moreover, endurance training volumes are similar to levels found in the study by Ulrich et al. (18) for comparable sports (distance running, canoeing) but considerably higher than in the cyclists ($5.9 \ h \cdot wk^{-1}$) from the study of Eastwood et al. (16). We are aware that, for example, swimmers train significantly more ($>20 \ h \cdot wk^{-1}$) in the same age spectrum. The chance to discover a training-induced erythropoietic stimulation as reported for untrained subjects (9) might have been greater for such athletes.

Moreover, we were surprised by the relatively high Hb_{mass} and $\dot{V}O_{2max}$ levels of the control subjects. However, it was not a prerequisite that the control subjects were completely untrained. They were allowed to conduct leisure activities; nevertheless, they have fulfilled the inclusion criteria of no more than 2 h of regular endurance training per week. Further, they should have met the characteristics of the athletes (age, low to moderate percentage of body fat) to the extent possible, and been able to complete a maximal exercise test on a treadmill. Therefore, we are convinced that because of our homogenous and very well-matched control group (same biological age at the study's start and same development of body mass, height, and LBM over the analyzed age range as the athletes), the influence of additional extensive endurance training (in addition to leisure activity) on Hb_{mass} could have been revealed. In addition, similar $\dot{V}O_{2max}$ levels (~58 $mL \cdot kg^{-1} \cdot min^{-1}$) were observed by

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Åstrand in untrained adolescent subjects up to 18 yr of age with a similar treadmill protocol (41).

CONCLUSIONS

Our results indicate that endurance training seems to have no additional effect on changes in Hb_{mass} over a 3-yr training period from ages 16 to 19 yr. A combination of high baseline Hb_{mass} values, as a result of optimal gene–environment interaction, and an inherent endowment to increase Hb_{mass} in late adolescence are assumed to be important factors to reach levels of Hb_{mass} as high as those observed in top endurance athletes. Hb_{mass} at age 16 yr seems to be an important predictor for Hb_{mass} in adulthood and consequently one puzzle piece for the aptitude for high-level endurance sports at adult age. Although higher PV and BV induced through training lead to higher $\dot{V}O_{2max}$ levels in athletes, longitudinal results indicate no additional effect of endurance training on the development of $\dot{V}O_{2max}$ from 16 to 19 yr. Which mechanisms lead to an overall increase of relative Hb_{mass} in late adolescence and individual differences in the development of Hb_{mass} at that age still needs to be examined.

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