Total Hemoglobin Mass and Blood Volume of Elite Kenyan Runners

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ABSTRACT

PROMMER, N., S. THOMA, L. QUECKE, T. GUTEKUNST, C. VÖLZKE, N. WACHSMUTH, A. M. NIESS, and W. SCHMIDT. Total Hemoglobin Mass and Blood Volume of Elite Kenyan Runners. *Med. Sci. Sports Exerc.*, Vol. 42, No. 4, pp. 791–797, 2010. Several East Africans are among the most successful runners worldwide. The physiological reasons underlying this superiority are, however, not yet known. **Purpose**: To evaluate the total hemoglobin mass (tHb-mass) and blood volume (BV) of Kenyan runners and their adaptation to near sea level. **Methods**: tHb-mass, BV, and $\dot{V}O_{2max}$ were determined in 10 male Kenyan runners (10-km best time = 28:29 ± 00:27 min) residing at an altitude of 2090 m over the course of a 6-wk training camp at sea level. Their values were compared with those of elite German runners (10-km best time = 30:39 ± 00:24 min). **Results**: Kenyans are characterized by significantly lower body mass (Kenyans = 57.2 ± 7.0 kg; Germans = 66.5 ± 6.3 kg) and body mass index (Kenyans = 18.5 ± 0.9; Germans = 20.4 ± 0.9). Relative tHb-mass (Kenyans = 14.2 ± 1.0 $g \cdot kg^{-1}$; Germans = 14.0 ± 0.7 $g \cdot kg^{-1}$) and BV (Kenyans = 101.9 ± 4.5 $mL \cdot kg^{-1}$; Germans = 99.6 ± 5.8 $mL \cdot kg^{-1}$) were similar in both groups but were decreased in Kenyans during the stay at near sea level (absolute tHb-mass from 813 ± 90 $g \cdot mL^{-1}$ to 767 ± 90 g, $P < 0.001$; BV from 5828 ± 703 $g \cdot mL^{-1}$ to 5513 ± 708 mL, $P < 0.01$). Relative $\dot{V}O_{2max}$ was similar in both groups (Kenyans 71.5 ± 5.0 $mL \cdot kg^{-1} \cdot min^{-1}$; Germans 70.7 ± 3.7 $mL \cdot kg^{-1} \cdot min^{-1}$). **Conclusion**: The oxygen transport of the blood cannot explain the superior endurance performance of Kenyan runners. Most measured parameters are in the same range as those of elite German runners, and tHb-mass even deteriorates after an adaptation to near sea level. **Key Words:** OXYGEN TRANSPORT, ALTITUDE, PLASMA VOLUME, ERYTHROPOIETIN, $\dot{V}O_{2max}$, ADAPTATION TO NORMOXIA

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Kenyan runners have dominated middle- and long-distance running events over the last four decades. Possible reasons for this performance superiority range from the physiological to the biomechanical, social, and economic, but none of them appears to be exclusively responsible. So far, physiology studies showed that running economy (28,33) and fractional use of $\dot{V}O_{2max}$ (7,33) are higher in Kenyan runners. To explain this phenomenon, research has focused on oxygen consumption at the muscular level. However, no significant differences were found in the proportions of the different muscle fiber types, capillary density, and oxidative enzyme citrate synthase activity between elite Scandinavian and Kenyan runners (27). Only 3-hydroxyacyl-CoA-dehydrogenase activity was 20% higher in the Kenyans (27); however, this cannot entirely account for their high-endurance performance.

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Therefore, one may assume that oxygen transport in the blood is superior in Kenyan runners as a result of long-term adaptation to altitude. Increased hemoglobin concentration ([Hb]) as shown by Moore et al. (23) hints to an adaptation but does not reflect the amount of oxygen being transported through the circulation. To characterize the oxygen transport, the total hemoglobin mass (tHb-mass) and blood volume (BV) have to be quantified because these factors predominantly determine oxygen supply and are strongly correlated with $\dot{V}O_{2max}$ (31). Data from elite Colombian cyclists native to moderate altitude (2600 m) indicate that they posseses approximately 60% higher tHb-mass and approximately 50% higher BV than untrained near sea level residents and 11% and 9% higher values, respectively, than elite cyclists from near sea level (29). One could therefore hypothesize that Kenyans living and training at altitudes of >2000 m improve their oxygen transport in a similar way and therefore perform better. However, such a beneficial effect could be eliminated when commuting to near sea level, for example, Europe, to participate in international championships. Because of the missing hypoxic stimulus, tHb-mass decreases within several weeks (5) and may affect performance. The amount of time it takes for the oxygen transport of moderate altitude natives to deteriorate under near sea level conditions has not yet been elucidated.

The aims of this study were (i) to characterize the tHb-mass and BV of elite Kenyan runners to find out whether these contribute to their performance superiority and (ii) to clearly determine the maximal time span that can be spent at low altitude before competitions before the deterioration of oxygen transport.

METHODS

Subjects. Ten elite male Kenyan runners were invited to participate in a 6-wk study in Bayreuth, Germany. All of them lived and trained around the city of Eldoret (2090 m), which is located in the North Rift Valley. Eight of the athletes were long-distance runners, with a 10-km mean (±SD) performance best time of 28:29 ± 00:27 min, and two of them specialized in 1500 m (3:41 and 3:38 min). At the time the investigation was started, the athletes were in the competition phase of their training cycle and participated in several international meets for 6 wk in Germany. The weekly training volume in Kenya was reported to be 177.4 ± 56.5 km. The mean training experience was 5.9 ± 4.4 yr, and professional running was started at an average age of 19.6 ± 4.1 yr. All athletes had run to school for 12 ± 1.9 yr and completed 14 ± 7 $km \cdot d^{-1}$ during this time. Eight of them belonged to the Nandi Kalenjis tribe, and all were born at altitudes between 1900 and 2200 m.

The control group was composed of 11 elite German runners (range of athletic disciplines = 3000 m to marathon). Two of them participated in the world championships, one in the European championships, and three were German champions. All athletes signed a written informed consent form before participating. The study was approved by the local ethics committee of the University of Erlangen-Nuernberg, Germany (for anthropometric data, see Table 1).

Design of the study. The Kenyan runners were monitored for a period of 40 d during normal training, which was organized and supervised by an accompanying Kenyan trainer and manager, with whom they were familiar from Eldoret. The first blood test was carried out in Nairobi, Kenya, at an altitude of 1660 m 12 h after they had left Eldoret. All further tests were performed in Germany (Bayreuth) at 340 m. BV, tHb-mass, [Hb], hematocrit (Hct), and reticulocytes were determined seven times (once every week) from a cubital vein, the first time 26–30 h (day 2) after arrival at near sea level. Additional blood samples were taken on day 2 as well as on days 21 and 33 to analyze erythropoietin (EPO) and ferritin concentrations. After familiarizing the athletes with the treadmill, an incremental test to the subjects' exhaustion was carried out to determine $\dot{V}O_{2max}$ 11 d after arrival (day 12). Three incremental field tests were performed on days 4, 20, and 34. Body fat was determined five times during the 6 wk.

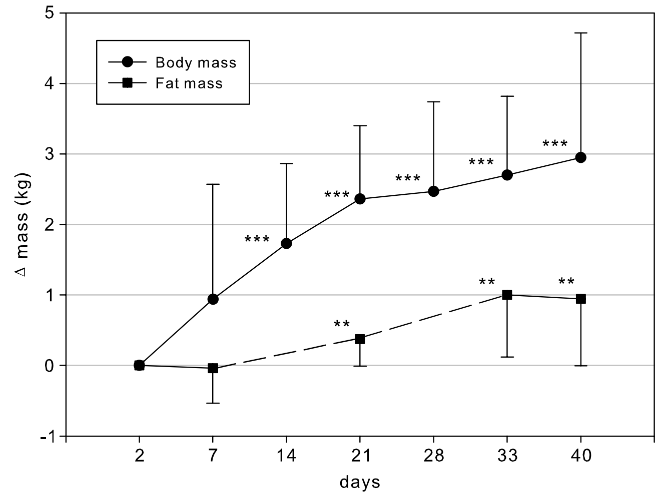

FIGURE 1—Changes in body mass and fat mass of Kenyan runners during the 6-wk stay at near sea level. Values are presented as mean and SD. Significant differences from the initial value are indicated by *P < 0.05, **P < 0.01, and ***P < 0.001.

Procedures and protocols. Four skinfold measurements (Slimguide® Caliper; Creative Health Products, Michigan) were performed (triceps, biceps, suprailiac, and subscapular), and the percent body fat was calculated using the formula of Durnin and Womersley (12). Using this method, a small bias cannot be excluded because there is evidence of a slightly different fat distribution in African populations compared with Caucasians (18), which, however, is not proven for Kenyans.

BV and tHb-mass were measured according to the "optimized CO rebreathing method" as described by Gore et al. (14), Prommer and Schmidt (24), and Schmidt and Prommer (30). The typical error of this method obtained in

TABLE 1. Anthropometric and performance data.

	Kenyan Runners (n = 10)	German Runners (n = 11)
Anthropometric data		
Age (yr)	25.5 ± 4.0	25.2 ± 2.4
Height (cm)	175.7 ± 10.0	180.3 ± 6.6
Body mass (kg)	57.2 ± 7.0**	66.5 ± 6.3
Body mass index ($kg \cdot m^{-2}$)	18.5 ± 0.9**	20.4 ± 0.9
Body surface ($kg \cdot m^2$)	1.70 ± 0.16*	1.83 ± 0.1
Body fat (%)	9.9 ± 2.1	10.5 ± 2.5
Performance data		
$\dot{V}O_{2max}$ ($L \cdot min^{-1}$)	4.09 ± 0.56*	4.71 ± 0.47
Relative $\dot{V}O_{2max}$ ($L \cdot kg^{-1} \cdot min^{-1}$)	71.5 ± 5.0	70.7 ± 3.7
Relative $\dot{V}O_{2max}$ ($L \cdot kg^{-0.75} \cdot min^{-1}$)	196.5 ± 14.6	201.5 ± 10.2
10-km best time (min)	28:29 ± 00:27	30:39 ± 00:24

Values are presented as mean ± SD.
Significance of differences between the groups: * P < 0.05 and ** P < 0.01.

TABLE 2. tHb-mass and BV.

	Kenyan Runners (n = 10)	German Runners (n = 11)
tHb-mass (g)	813 ± 89*	935 ± 117
BV (mL)	5828 ± 703*	6642 ± 913
Plasma volume (mL)	3368 ± 479*	3929 ± 648
Red cell volume (mL)	2460 ± 293	2727 ± 339
Relative tHb-mass ($g \cdot kg^{-1}$)	14.2 ± 1.0	14.0 ± 0.7
Relative BV ($mL \cdot kg^{-1}$)	101.9 ± 4.5	99.6 ± 5.8
Relative plasma volume ($mL \cdot kg^{-1}$)	58.8 ± 4.0	59.3 ± 5.4
Relative red cell volume ($mL \cdot kg^{-1}$)	43.1 ± 3.1	40.9 ± 2.0

Values are presented as mean ± SD.
Demonstrated are absolute and relative tHb-mass and BV.
Significance of differences between the Kenyans and the Germans: * P < 0.05.

our laboratory is 1.4% and is in accordance with the typical error published by Gore et al. (14).

In Nairobi, [Hb] was measured photometrically in triplicate (HemoCue® HB201+; HemoCue AB, Angelholm, Sweden). In Germany, [Hb] and Hct samples were assessed by an automated Coulter Counter (Cell Dyn 3500; Abbott, Ludwigshafen, Germany). The reticulocyte count was determined by using a Sysmex® R-500 (Sysmex Corporation, Kobe, Japan).

Plasma–ferritin concentrations were measured by a chemiluminescence immunoassay (ADVIA Centaur; Siemens HealthCare, Erlangen, Germany). Concentrations of EPO were determined using a manual human erythropoietin immunoassay (sandwich ELISA) according to the manufacturer's instructions (Quantikine® IVD®; R&D Systems, Abingdon, UK).

The laboratory incremental test was carried out on a treadmill (Ergo XELG2; Woodway Weil am Rhein, Germany). The initial speed was set to $12\ km \cdot h^{-1}$ and was increased by $2\ km \cdot h^{-1}$ every 3 min. Measurement of $\dot{V}O_{2max}$ was performed using MetaMax II (Cortex, Germany), a portable breath-by-breath indirect calorimetry system. The ventilatory volume was assessed by a volume sensor (Triple V sensor), which works with a turbine flowmeter. O_2 concentrations were measured by electrochemical detection and CO_2 concentrations by infrared method. The device was calibrated on every testing day for ambient pressure and gas concentrations (O_2 and CO_2, two-point calibration) using a certified calibration gas (5% CO_2 and 15% O_2) and ambient air. In addition, every test was preceded by a one-point calibration to ambient air. Calibration of the volume sensor was performed before each test using a 3.0-L calibration syringe. The main criterion for the assessment of $\dot{V}O_{2max}$ was the occurrence of a leveling off in $\dot{V}O_2$. At this point, $\dot{V}O_2$ values were averaged at least over a period of 30 s to calculate $\dot{V}O_{2max}$. The three field tests were carried out on a

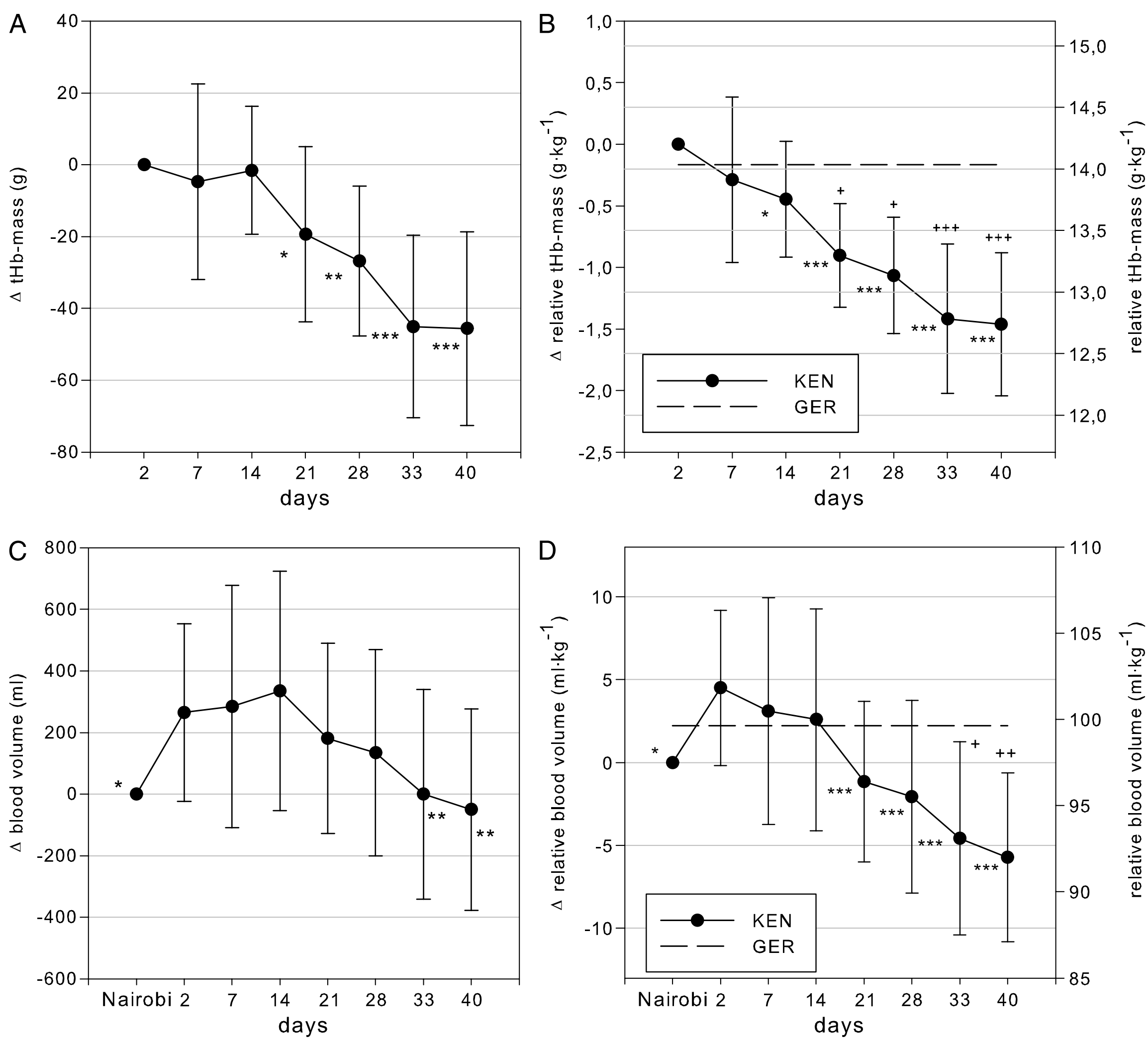

FIGURE 2—Changes in absolute (A) and relative (B) tHb-mass and absolute (C) and relative (D) BV of Kenyan runners during the 6-wk stay at near sea level. The dashed lines (B and D) represent the mean absolute value of the German group. Significant differences within the Kenyan group against day 2 are indicated as *P < 0.05, **P < 0.01, and ***P < 0.001. Significance of differences between the Kenyan and German groups is represented by ^{+}P < 0.05, ^{++}P < 0.01, and ^{+++}P < 0.001.

APPLIED SCIENCES

track starting with 8 km·h^{-1} for 3 min, increasing the speed every minute by 1 km·h^{-1} until exhaustion. $\dot{V}O_{2max}$ was determined by the same indirect calorimetry system as in the laboratory.

Data analyses. For statistical analysis, the Statistical Package for the Social Sciences for Windows (version 15; SPSS Inc., Chicago, IL) was used. Unpaired *t*-tests were applied to compare values of the German with those of the Kenyan runners. An ANOVA with repeated measures followed by a paired *t*-test was done to evaluate the changes of the parameters in the Kenyan runners. To correct the *t*-tests for multiple comparisons, the Bonferroni correction was used. To detect any dependencies between two variables, for example, for $\dot{V}O_{2max}$ and tHb-mass, a linear regression analysis was performed.

RESULTS

Body and fat mass. When the Kenyan runners arrived in Germany, their body mass was 9.3 kg lower compared with that of the Germans (Table 1) and increased from 57.2 ± 7.0 kg to 60.2 ± 7.9 kg during the 6 wk. The total increase of 3.0 ± 1.8 kg can be attributed to an augmentation in fat mass of 0.95 ± 0.95 kg and in lean body mass of 2.05 ± 1.01 kg (Fig. 1).

Hemoglobin mass and BV. Absolute tHb-mass was 13% lower in the Kenyans compared with that in the German runners 26–30 h (day 2) after arrival to near sea level. In accordance, blood and plasma volumes were also 12% and 14% lower, respectively (Table 2). When relating the values to body mass, the Kenyans showed nearly identical values in all parameters (Table 2). During the stay in Germany, total tHb-mass remained stable within the first 2 wk but then dropped by 45 g (6%) to 767 ± 88 g on day 33 (Fig. 2A), after which it remained on this lower level. Relative tHb-mass also decreased by 1.5 to 12.8 ± 0.8 g·kg^{-1} and was already observed to be significantly lower in week 2 (Fig. 2B).

Absolute BV increased rapidly after the participants arrived in Germany by 4.8% compared with the value initially calculated in Nairobi and reached its peak after 2 wk (+6%). Thereafter, it continuously decreased to the baseline values measured at altitude in week 5 (Fig. 2C). Relative BV was similar to that of the German runners after arrival from altitude and also decreased during the subsequent 6 wk (Fig. 2D). As shown in Table 3, plasma volume showed a similar time course as BV but was always higher at near sea level compared with the value determined at altitude.

Hematological values. As a result of plasma volume expansion, [Hb] dropped by 0.7 g·dL^{-1} after arrival at near sea level, reaching almost the same value as that of the German runners (Table 3). During the stay at Bayreuth, [Hb] remained at this lower level until day 40. The same behavior was observed for Hct values. Reticulocyte count did not differ between the groups but transiently declined in the Kenyan runners after 7 d (Table 3). EPO concentration was relatively low after the participants' arrival in Germany and significantly increased within the following weeks to similar values as those observed in the German runners. Ferritin concentration behaved in the same fashion (Table 3).

Maximal performance tests. Relative $\dot{V}O_{2max}$ obtained on the treadmill after familiarization was not different between the Kenyan and the German runners (Table 1). The field test performed on day 4 yielded similar absolute values (3.95 ± 0.55 mL·min^{-1}) as the treadmill test 8 d later (difference $P = 0.133$). Absolute $\dot{V}O_{2max}$ remained at a similar level (3.83 ± 0.54 mL·min^{-1}, day 20) until day 34 (3.87 ± 0.53 mL·min^{-1}), whereas the relative values were significantly reduced from 69.6 ± 4.9 mL·kg^{-1}·min^{-1} to 65.2 ± 3.9 mL·kg^{-1}·min^{-1} (day 20) and 65.4 ± 4.3 mL·kg^{-1}·min^{-1} (day 34), respectively, because of the increase in body mass.

DISCUSSION

For decades, it was assumed that the high performance of Kenyan runners in endurance disciplines is at least partly owing to improved oxygen transport to the muscle as a result of their adaptation to altitude as well as to training and genetic selection. The results of this study, however, show that the key factors of oxygen transport, that is, tHb-mass and BV, are not better developed in Kenyan runners than in comparable German runners.

tHb-mass. The relative tHb-mass of 14.2 ± 1.0 g·kg^{-1} of the Kenyan runners representing their values at altitude is similar to that of the German runners (14.0 ± 0.7 g·kg^{-1}). Although the relative tHb-mass of the Kenyans is approximately 25% and 14% higher than that in untrained subjects from near sea level and moderate altitude (31), respectively,

TABLE 3. Hematological values and BV during the 6-wk lasting stay at sea level.

Kenyans (*n* = 10)	Nairobi	Day 2	Day 7	Day 14	Day 21	Day 28	Day 33	Day 40	Germans (*n* = 11)
[Hb] (g·dL^{-1})	16.1† ± 0.7	15.4 ± 1.0	15.3 ± 1.0	15.2 ± 0.9	15.2 ± 0.8	15.2 ± 0.8	15.2 ± 0.6	15.3 ± 0.9	15.5 ± 1.2
Hct (%)	48.6† ± 2.4*^{,a}	46.5 ± 2.9	46.8 ± 2.6	46.5 ± 1.6	46.7 ± 1.4	46.6 ± 1.4	46.1 ± 1.3	46.1 ± 2.1	45.4 ± 3.1
Reticulocyte (%)		1.3 ± 0.4	1.1† ± 0.3	1.3 ± 0.4	1.2 ± 0.3	1.4 ± 0.3	1.3 ± 0.2	1.4 ± 0.4	1.1 ± 0.4^{b}
EPO (mIU·mL^{-1})		5.6 ± 2.1**			8.6† ± 3.2		8.6†† ± 3.4		9.3 ± 2.5
Ferritin (ng·dL^{-1})		49 ± 31			76†† ± 40		71† ± 40		74 ± 36
Red cell volume (mL)		2460 ± 293	2482 ± 302	2489 ± 307	2440 ± 324	2411 ± 317*	2327†† ± 268**	2294†† ± 291**	2727 ± 339
Plasma volume (mL)	3103† ± 352**^{,a}	3368 ± 479*	3366 ± 569*	3410 ± 521	3304 ± 490*	3287 ± 494*	3235 ± 444*	3219† ± 441*	3929 ± 648

Values are presented as mean ± SD.

[a] Calculated from the [Hb] determined at Nairobi and the mean corpuscular hemoglobin concentration (MCHC) of day 2.

[b] $n = 6$.

Significance of differences within the Kenyan group against day 2: †$P < 0.05$ and ††$P < 0.01$.

Significance of differences between the groups: * $P < 0.05$ and ** $P < 0.01$.

this unexpectedly low value of the Kenyans compared with the Germans is a surprising result. It is well known that athletes who live and train at altitude, for example, Columbian cyclists from 2600 m, have 11% greater tHb-mass and 9% greater BV compared with trained near sea level cyclists (6,29). Also, many altitude training studies report an augmented tHb-mass of 6.5% to 8.0% after 3–4 wk of training sessions above 2000 m for at least 14 $h \cdot d^{-1}$ (31). One explanation for the lack of increased tHb-mass may be that East Africans developed different altitude adaptation strategies within their evolutionary history (at least 100,000 yr compared with south Amerindians who have inhabited the Andean plateau for ~11,000 yr (2)). This theory seemed to be supported by examining [Hb] in these populations. Male Andean highlanders from 3600 m have [Hb] values of approximately 18.0 $g \cdot dL^{-1}$ (3), whereas East African males from the same altitude have substantially lower values (15.9 $g \cdot dL^{-1}$ (4)). On the other hand, Claydon et al. (9) demonstrated higher plasma volumes in the Ethiopian highlanders compared with the Andean population, which may be applied to the Kenyan tribes living at moderate altitude. Whether the lower [Hb] of the East Africans is attributable to hemodilution or to other adaptations of the oxygen transport system should be decided by further investigations.

[Hb] of 16.1 $g \cdot dL^{-1}$ in the Kenyan runners measured in our study at Nairobi coincides well with the observations of Beall et al. (4) and is in accordance with the values reported by Moore et al. (23), who showed [Hb] of 16.4 $g \cdot dL^{-1}$ in Kenyan athletes at 2100–2350 m. The continuous decrease in tHb-mass from week 3 at near sea level, however, is evidence for an effect of moderate altitude on tHb-mass (Fig. 2A). Thirty-three days after arrival to near sea level, tHb-mass was reduced by 45 g (6%) and remained at this level. This magnitude of tHb-mass deadaptation from moderate altitude corresponds very well with the mean increase of 7% reported in a meta-analysis as the effect of training at moderate altitude in sea level athletes (31). The reduction in tHb-mass can be attributed to the transiently suppressed EPO concentration because of the hyperoxic environment. After adapting tHb-mass to near sea level conditions, EPO is adjusted to values found in the German runners. Also, the change in ferritin concentration, reflecting higher iron availability at the end of the near sea level stay, hints at a decreased erythropoiesis. An additional reason for the increase in ferritin concentration might be the augmented consumption of meat in Germany.

Other influencing factors on tHb-mass during the stay at near sea level, such as a reduction in training volume or neocytolysis, can mostly be excluded. Training volume was reported to be similar in Germany and Kenya. In addition, the appearance of neocytolysis described by Rice et al. (25) 3–7 d after descent from 4380 m to sea level (~0 m), which was accompanied by an 80% decrease in plasma EPO, is rather unlikely because the difference in altitude was only approximately 1800 m and the suppression of plasma EPO reached only 35% after the participants' arrival in Germany. The missing hypoxic stimulus of 40 d induces a continuous reduction of tHb-mass, leading to a mean relative tHb-mass value of 12.8 $g \cdot kg^{-1}$ (body mass increase included, Fig. 2B), which is significantly below the value of the German runners (14.0 $g \cdot kg^{-1}$) and comparable with values found in moderately trained athletes (31). We therefore conclude that the prevailing tHb-mass cannot account for the excellent performance of these runners.

BV. Relative BV of the Kenyan runners was in the same range as that of the German runners (Table 2 and Fig. 2D), which is typical for highly trained endurance athletes. Heinicke et al. (17) showed very similar values (105 ± 9 $mL \cdot kg^{-1}$) in elite runners from near sea level, approximately 30% higher than values found in untrained near sea level residents.

In contrast with tHb-mass, BV quickly adapts to normoxia and is characterized by a phase of rapid increase followed by an approximately 2-wk plateau and a subsequent decrease. The physiological mechanisms for the initial effect at sea level can be related to a transiently decreased diuresis and to intracorporal fluid shifts (26). The rapid increase of 265 ± 288 mL approximately within the first 30 h (Fig. 2C) may be attributed primarily to a shift from the extravascular to the intravascular bed (20), resulting in a decrease in [Hb] of −0.7 ± 0.7 $g \cdot dL^{-1}$ and Hct of −1.9% ± 2.1%, respectively (Table 3). The total augmentation of 336 ± 389 mL until day 14 is directly reflected in the increase in plasma volume of 307 ± 343 mL and a further slight drop in [Hb] (Table 3). The magnitude and the time course of BV changes are comparable with that found by several other studies reporting an increase in plasma volume of approximately 600 mL 2–3 d after returning from altitudes of 4350 m (13,26). Also, [Hb] and Hct determined in Kenyan runners after 7 d at low altitude were nearly identical with those found in the present study, showing 15.2 $g \cdot dL^{-1}$ and 45% (23) and mirroring the hemodilution processes.

The increase in renal water retention due to the inhibition of atrial natriuretic factor secretion (8) and stimulation of aldosterone release (32) is also reflected by the augmentation in body mass (Fig. 1). The total increase in lean body mass of 2.0 ± 1.0 kg is presumably due mainly to an augmentation in body water content. The increase in fat mass could be related to the unfamiliar and higher caloric German food that the athletes were forced to adapt to by their Kenyan trainer and manager.

The subsequent decrease in BV of 386 ± 318 mL from day 14 until day 40 (Fig. 2C) is due to both the decline in red cell volume of 195 ± 98 mL and plasma volume (−191 ± 273 mL). The mechanism underlying this reduction in BV remains unknown. Our hypothesis is that BV decreases with the normoxia-induced reduction of red blood cells, whereas plasma volume is down-regulated via the adjusted [Hb] to a new set point.

Regarding the hematological parameters, within the first 14 d at near sea level, the Kenyan runners face equal

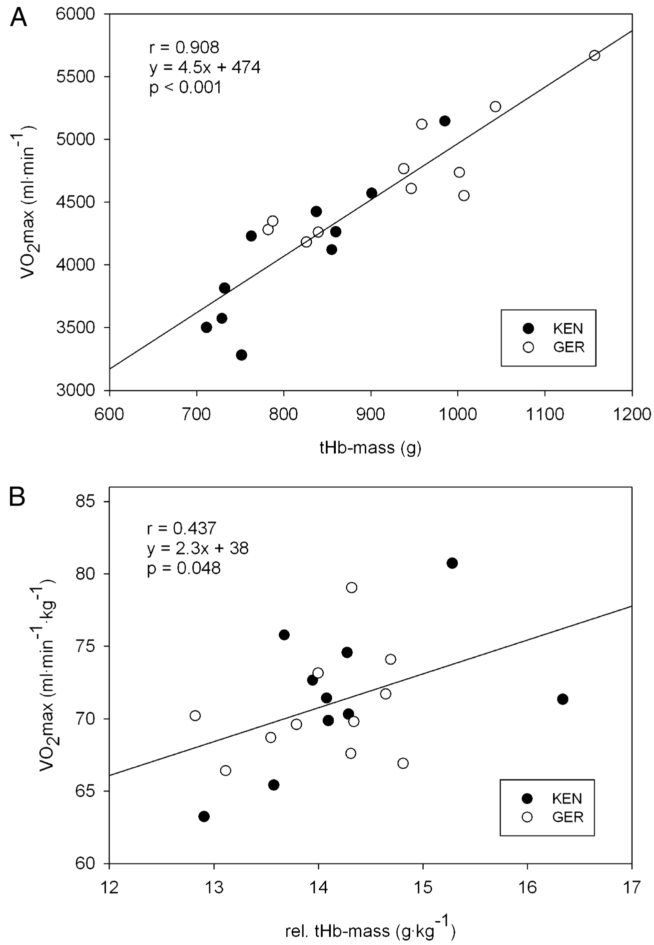

FIGURE 3—Linear regression analysis between absolute tHb-mass and $\dot{V}O_{2max}$ (A) and relative tHb-mass and $\dot{V}O_{2max}$ (B). Data of Kenyan and German runners are shown.

conditions to those of their German opponents. However, because of the subsequent decrease in tHb-mass and increase in body mass, the Kenyans are at a disadvantage during longer stays at near sea level.

$\dot{V}O_{2max}$. Relative $\dot{V}O_{2max}$ of the Kenyan runners was below the values obtained by Saltin et al. (28), which may be partly due to the different methods used for oxygen uptake measurements. The results are, however, similar to the values of Coetzer et al. (10) and Lucia et al. (22), who reported 71.5 mL·kg^{-1}·min^{-1} in elite black South African distance runners and 73.8 mL·kg^{-1}·min^{-1} in elite Eritrean runners, respectively. Similar to the findings of Saltin et al. (28), the present study showed no differences in the relative $\dot{V}O_{2max}$ of the Kenyans compared with the German runners, although their 10-km performance time was considerably lower (Table 1). This result again indicates that $\dot{V}O_{2max}$ becomes a less sensitive predictor of performance when $\dot{V}O_{2max}$ values of elite runners are in the same high range (11).

The strong relationship between absolute tHb-mass, BV, and endurance performance is well documented (1,17,19) and also observed in this study in both groups (tHb-mass, $r = 0.91$; BV, $r = 0.83$; Fig. 3A). However, when relating tHb-mass values to body mass, the relationship becomes less strong (tHb-mass, $r = 0.44$, $P < 0.05$; Fig. 3B) because of the very homogenous test groups. As is well known from the literature and also demonstrated in Figure 3, an alteration in tHb-mass by 1 g is associated with a change in $\dot{V}O_{2max}$ by approximately 4 mL·min^{-1} (15,31). Because tHb-mass decreases in the Kenyan group by 45 g, one may expect a decrease in $\dot{V}O_{2max}$ by ~180 mL·min^{-1} (~4.5%), which, however, cannot be observed here ($\dot{V}O_{2max}$ = −2.0% and −1.4% at days 20 and 34, respectively). Alterations in $\dot{V}O_{2max}$ due to changes in altitude, however, do not necessarily have to be associated with changes in tHb-mass as discussed by Levine and Stray-Gunderson (21) and by Gore and Hopkins (16). Therefore, it has to be assumed that additional factors apart from tHb-mass, for example, an increased maximal cardiac output, gain importance in regulating $\dot{V}O_{2max}$ in the Kenyan group.

The superior performance of the Kenyan runners in long-distance competitions (e.g., marathon) cannot be attributed to higher $\dot{V}O_{2max}$ and seems to depend on other factors, such as higher running economy (22,28,33) and/or higher fractional use of $\dot{V}O_{2max}$ (7,33).

CONCLUSION

The oxygen transport of the blood, that is, tHb-mass and BV, cannot explain the superior endurance performance of Kenyan runners. All of these parameters are in the same range when compared with those of elite German runners, and tHb-mass even deteriorated after adaptation to near sea level.

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