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The Influence of Basal Metabolic Rate on Blood Pressure Among Indigenous Siberians

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ABSTRACT Hypertension is an important global health issue and is currently increasing at a rapid pace in most industrializing nations. Although a number of risk factors have been linked with the development of hypertension, including obesity, high dietary sodium, and chronic psychosocial stress, these factors cannot fully explain the variation in blood pressure and hypertension rates that occurs within and between populations. The present study uses data collected on adults from three indigenous Siberian populations (Evenki, Buryat, and Yakut [Sakha]) to test the hypothesis of Luke et al. (Hypertension 43 (2004) 555–560) that basal metabolic rate (BMR) and blood pressure are positively associated independent of body size. When adjusted for body size and composition, as well as potentially confounding variables such as age, smoking status, ethnicity, and degree of urbanization, BMR was positively correlated with systolic blood pressure (SBP; $P < 0.01$) and pulse pressure (PP; $P < 0.01$); BMR showed a trend with diastolic blood pressure (DBP; $P = 0.08$). Thus, higher BMR is associated with higher SBP and PP; this is opposite the well-documented inverse relationship between physical activity and blood pressure. If the influence of BMR on blood pressure is confirmed, the systematically elevated BMRs of indigenous Siberians may help explain the relatively high blood pressures and hypertension rates documented among native Siberians in the post-Soviet period. These findings underscore the importance of considering the influence of biological adaptation to regional environmental conditions in structuring health changes associated with economic development and lifestyle change. Am J Phys Anthropol 000:000–000, 2008. ©2008 Wiley-Liss, Inc.

Hypertension, defined in adults as systolic blood pressure (SBP) at or above 140 mm Hg or diastolic blood pressure (DBP) at or above 90 mm Hg, is a major global health problem (WHO, 2002; Chobanian et al., 2003; WHO/FAO, 2003; Kearney et al., 2005). The World Health Organization (WHO, 2002) estimates that as many as one billion people worldwide have elevated blood pressure, and that hypertension is responsible for more than seven million deaths annually. Although previously viewed as a problem of industrialized nations, hypertension is currently increasing at a rapid pace in most developing nations as the result of lifestyle and demographic shifts related to economic development and urbanization (McGarvey and Baker, 1979; Waldron et al., 1982; Pollard et al., 1991; WHO/ISH, 2003; Kearney et al., 2005).

The sequelae of high blood pressure include coronary heart disease, heart failure, stroke, peripheral arterial disease, and kidney disease (Kaplan, 2002; Chobanian et al., 2003; Kannel and Wilson, 2003). A number of risk factors are associated with the development of hypertension, including excess body fat, physical inactivity, high dietary sodium, low dietary potassium, elevated alcohol consumption, and chronic psychosocial stress; these risk factors, however, cannot fully explain the variation in blood pressure and hypertension prevalence that occurs within and between human populations (Kotchen and Kotchen, 1999; Kaplan, 2002; Hollenberg, 2003; Adair and Dahly, 2005; Guyton and Hall, 2006). Genetic and developmental factors also play an important role in the pathophysiology of elevated blood pressure, but the complex and multifactorial nature of hypertension has complicated the search for specific genetic contributors and relevant physiological pathways (Lifton et al., 2001; Kaplan, 2002; Cusi et al., 2003; Barker and Godfrey, 2004; Adair and Dahly, 2005; Agarwal et al., 2005; Cowley, 2006). At present, the specific causes of hypertension are unknown in nearly all (90% to 95%) individuals (i.e., essential or primary hypertension) (Kaplan, 2002; Guyton and Hall, 2006).

Recent research among Nigerians and African Americans has suggested a link between maintenance energy costs and blood pressure; after adjusting for the effects of age, sex, body size, and body composition, basal metabolic rate (BMR) exerts a positive influence on both SBP and

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DBP (Luke et al., 2004). This link, if confirmed, may shed light on global variation in blood pressure, given the presence of interpopulation differences in BMR (Quenouille et al., 1951; Roberts, 1952, 1978; Schofield, 1985; Leung et al., 2000; Leonard et al., 2002b, 2005a; Cole and Henry, 2005). Indigenous Siberians, like native high-latitude populations in North America, have systematically elevated BMRs relative to body mass, surface area, and fat-free mass (FFM) standards (Galloway et al., 2000; Leonard et al., 2002b, 2005a; Snodgrass et al., 2005a). Metabolic elevation appears to reflect a physiological adaptation to chronic and severe cold stress experienced in the circumpolar environment; this relationship with climate is supported by geographic studies that demonstrate a strong negative association between BMR and mean annual temperature, which remains when controlled for differences in body size (Roberts 1952, 1978; Leonard et al., 1999, 2005a). Thus, the influence of heightened maintenance costs may help explain the relatively high blood pressures and hypertension prevalence rates documented among native Siberians in the post-Soviet period (Kozlov et al., 2003; Sorensen, 2003; Snodgrass, 2004; Leonard et al., 2005b; Sorensen et al., 2006).

The present study uses data collected on adults from three indigenous Siberian populations (Evenki, Buryat, and Yakut) to test the hypothesis of Luke et al. (2004) that BMR and blood pressure are positively associated independent of age, body size, body composition, and selected lifestyle variables.

MATERIALS AND METHODS

Study populations

The Evenki are an indigenous Tungusic-speaking population of reindeer herders distributed throughout the boreal forest (*taiga*) of northern Siberia (Forsyth, 1992). It appears that the Evenki were initially reindeer hunters who gradually began to herd and breed reindeer as wild reindeer populations declined (Vasilevich, 1946). Evenki herding was traditionally structured by family lineages but was restructured during Soviet collectivization when the state took control over reindeer herds. Most Evenki were forced to settle into permanent cooperative communities (brigades), which were responsible for reindeer herding activities (Forsyth, 1992). Traditionally, the Evenki subsisted by herding reindeer and fishing, and additionally hunted and trapped for commercial purposes (Forsyth, 1992). At the last major census (1989), the total Evenki population numbered approximately 30,000 (Fondahl, 1997). Today, although many Evenki are still involved in a reindeer-based economy, increasing numbers are employed in other economic sectors or are unemployed. Additional information can be found in Leonard et al. (1994, 1996, 2002a).

The Buryat are descendants of Mongol populations that settled around Lake Baikal at the boundary of the northern forest (Forsyth, 1992). Traditionally, the Buryat were transhumant cattle herders and hunters; however, many Buryat living west of Lake Baikal settled into permanent villages, subsisting through a mixture of cattle herding and agriculture. The Buryat population was relatively large at the time of Russian contact and increased substantially during the Russian and Soviet periods; the most recent figures show the Buryat population numbers over 400,000 (Forsyth, 1992; Fondahl, 1997). Today, most rural Buryat subsist off agricultural products and market foods, as well as the products of cattle, which are fed through locally grown crops (Humphrey and Sneath, 1999).

The Yakut (Sakha) are a relatively large (~380,000 individuals) indigenous group concentrated in northeastern Siberia (Forsyth, 1992; Jordan and Jordan-Bychkov, 2001). Traditionally, they practiced a variable subsistence strategy largely dictated by regional ecology (Tokarev and Gurvich, 1964). In the remote taiga, hunting and fishing were the main activities, whereas in the Lena River Valley transhumant pastoralism (horse and cattle) was the focus of the subsistence economy. Although members of the Turkic language family, genetic studies of the Yakut indicate closer links with other indigenous Siberian groups (e.g., Evenki, Buryat, and Yukagir) than with other Turkic populations (Pakendorf et al., 1999; Pakendorf, 2003; Zlojutro et al., 2003). Yakut lifeways were dramatically altered during the period of Soviet collectivization; rural groups were forced to abandon traditional land use patterns and settled into fishing villages, farms, and fur-trapping collectives (Forsyth, 1992; Mote, 1998; Jordan and Jordan-Bychkov, 2001). Following the collapse of the Soviet Union in 1991, economic and political transformations had devastating effects for the Yakut who were dependent on the government for wages and deliveries of food and essential goods (Balzer, 1995; Kempton, 1996; Sorensen, 2003). Like other indigenous Siberians, most Yakut returned to traditional subsistence practices in order to meet needs no longer met by the government. Today, most rural Yakut populations rely on a mixture of subsistence activities (e.g., herding, fishing, and foraging), government wages and pensions, private-sector salaries, and profits from "cottage" industries (Craumer, 1994; Jordan and Jordan-Bychkov, 2001; Crate, 2006).

Participants

All studies were cross-sectional and data were collected among volunteers recruited from local communities. Evenki participants included 63 adults (16-53 years old; 43 females, 20 males) from the Stony Tunguska region of central Siberia (63°N, 97°E); data were collected during summer and early fall of 1995 as part of a larger project on the ecology and genetic diversity of indigenous Siberians (see additional information in Leonard et al., 1994, 1996; Galloway et al., 2000). Data were collected in village health posts among residents of Baykit (pop. ~6000), Poligus (pop. ~500), and local herding brigades. The Human Subjects Review committee at the University of Guelph approved the research protocol and consent was obtained from all participants.

Buryat participants included 135 adults (16-74 years old; 83 females, 52 males) from the southern Siberian village of Gakhani (pop. 1000), located in the Ust-Orda Buryat Autonomous Okrug region of southern Siberia about 200 km Northwest of Irkutsk, in the steppe region West of Lake Baikal (53°N, 104°E) (Sorensen et al., 1999; Mosher, 2002). Data were collected during the summer of 1998. The Institutional Review Board of the University of Florida approved the protocol and consent was obtained from all participants.

Yakut participants included 123 adults (18-56 years old; 73 females, 50 males) from the rural Siberian village of Berdygestiakh, 62°N, 127°E (pop. 4900), in the Gorny district of the Sakha Republic (Snodgrass et al., 2005a). All data collection took place at the Gorny Regional Medical Center during the late summer of 2003 (see additional information in Snodgrass et al., 2005a). The Institutional Review Board of Northwestern University approved the study protocol and informed consent was obtained from all participants.

Anthropometry

Anthropometric dimensions were recorded for all participants using standard procedures, as described previously (Snodgrass et al., 2006a). Body composition was assessed using two derived measures: Body mass index (BMI; kg/m^2) and body fat (BF) percentage. BF was estimated according to the sum of four skinfolds (triceps, biceps, subscapular, and suprailiac), measured to the nearest 0.5 mm with Lange skinfold calipers (Beta Technology, Santa Cruz, CA), and using the sex- and age-specific equations of Durnin and Womersley (1974). Fat-free mass (FFM) was calculated as body mass less fat mass.

Blood pressure

Arterial blood pressure was recorded as systolic blood pressure (SBP) and diastolic blood pressure (DBP). Pulse pressure (PP), which serves as an indicator of arterial stiffness and blood vessel wall inflammation and is a predictor of cardiovascular disease mortality (Darne et al., 1989; Kaplan, 2002; Haider et al., 2003), was calculated as the difference between SBP and DBP.

Evenki blood pressure measurements were made by one observer using a manual sphygmomanometer with the participant in a relaxed and seated position in standard measurement posture and in a postabsorptive state. All participants had blood pressure measurements taken on one occasion (in the morning or early afternoon following collection of metabolic data). Buryat blood pressure was measured by one observer using a manual sphygmomanometer with the participant in a relaxed and seated position in standard measurement posture. All participants had blood pressure measurements taken on one occasion (in the evening following anthropometric data collection and dietary recall interview). Participants had been seated for a minimum of 5 min before blood pressure measurement (Mosher, 2002).

Yakut blood pressure measurements were collected by one observer using an Omron HEM-412C manual inflation oscillometric blood pressure monitor (Vernon Hills, IL). For each participant, blood pressure was measured two separate times, taken at least 10 min apart, following standard practice; all blood pressure measurements were taken on the same visit and during the morning or early afternoon. The average of the two measurements was used in all analyses. All participants were in a postabsorptive state and had rested for at least 30 min before the measurement of blood pressure.

Basal metabolic rate

All basal metabolic rate (BMR) measurements were made under standard conditions (i.e., in a thermoneutral environment, with the participant in a postabsorptive condition [after a 12-h fast], and with the participant relaxing in a supine position) via indirect calorimetry. Participants were familiarized with the procedure and equipment before measurement in order to minimize anxiety. In order to track participant anxiety level, heart rate was simultaneously measured using either a Polar Vantage XL or S610 heart rate monitor (Woodbury, NY) depending on the study population. Participants had rested quietly in a supine position for a minimum of 20 min before measurement of BMR. All BMR measurements were taken in the morning or early afternoon. Once breathing and heart rate stabilized, oxygen consumption (VO_2, L/min) and CO_2 production (VCO_2, L/min) were recorded every minute for 10 min; the average of each of these measurements was used in all analyses. Respiratory quotient (RQ) was continuously recorded and an average was calculated for each participant. BMR was then calculated by converting VO_2 to kilojoules per day (kJ/day) based on RQ using the modified Weir formula (Weir, 1949; McArdle et al., 1991).

Evenki and Buryat BMR measurements were made using an AeroSport TEEM 100 metabolic analyzer (Ann Arbor, MI), as described previously (Sorensen et al., 1999; Galloway et al., 2000). For all Evenki and Buryat participants, the research protocol required participants to sleep in the health outposts overnight (Sorensen et al., 1999; Galloway et al., 2000; Mosher, 2002). Yakut BMR measurements were collected using a MedGraphics VO2000 open-circuit metabolic analyzer (St. Paul, MN) with MedGraphics Breeze Lite software, as described previously (Snodgrass et al., 2005a). All Yakut participants reported to the medical facility in the morning after an overnight fast.

Measured BMR was compared with predicted values based on standards for body mass and FFM. BMR standards for body mass were based on the sex- and age-specific Oxford predictive equations of Henry (2005). BMR was predicted from FFM based on the general predictive equation of Cunningham (1991).

Statistical methods

Student's *t*-tests (two-tailed) were used to assess differences between males and females for anthropometric, blood pressure, and metabolic variables. Measured versus predicted BMR (for body mass and FFM) was compared using paired-sample *t*-tests (two-tailed). One-way ANOVAs with Scheffé's post-hoc tests were used to assess interpopulation variation in blood pressure. Pearson's correlations were used to assess interrelationships between anthropometric, blood pressure, and metabolic variables. Multiple regression analyses with blood pressure measures as the dependent variable (SBP, DBP, and PP) were used to estimate the relative contribution of BMR to blood pressure while considering age, sex, FFM, fat mass, smoking status (i.e., active smoker vs. nonsmoker), ethnicity (Evenki, Buryat, or Yakut), and degree of urbanization (i.e., residence in village vs. town). All statistical analyses were performed using SPSS 12.0. Comparisons were considered statistically significant at $P < 0.05$. All results are expressed as means ± standard deviations unless otherwise noted.

RESULTS

Descriptive statistics for anthropometric, blood pressure, and metabolic data for the total sample (199 females, 122 males) are presented in Table 1. Among females, 12.6% of individuals were classified as obese (i.e., BMI > 30.0), 19.6% were classified as overweight (BMI = 25.0 to 29.9), and 67.8% of individuals were classified as of normal body weight or underweight (BMI < 25.0) according to (WHO, 2000) categories. Among males, 6.6% of individuals were classified as obese, 13.9% were classified as

TABLE 1. Descriptive statistics for anthropometric and blood pressure data[a,b,c]

Measure	Females (n = 199)	Males (n = 122)
Age (years)	33.1 (12.5)	31.6 (11.7)
Height (cm)	155.5 (6.5)*	168.2 (7.2)
Body mass (kg)	58.6 (12.7)*	64.9 (12.3)
BMI (kg/m^2)	24.2 (4.8)**	22.9 (3.7)
Sum of skinfolds (mm)	86.5 (32.9)*	48.4 (27.7)
Body fat (%)	34.9 (6.5)*	19.4 (7.3)
Fat-free mass (kg)	37.6 (5.5)*	51.7 (6.3)
Fat mass (kg)	21.1 (8.0)*	13.3 (7.6)
SBP (mm Hg)	126.8 (25.0)***	133.1 (19.1)
DBP (mm Hg)	79.5 (13.7)***	82.6 (12.5)
PP (mm Hg)	47.3 (15.8)	50.6 (12.4)

[a] All values are presented as means and standard deviations.
[b] Differences between females and males are statistically significant at: * $P < 0.001$; ** $P < 0.01$; *** $P < 0.05$.
[c]BMR was collected on a subset of 169 females and 115 males.

TABLE 2. Measured BMR (means and standard error of the mean [SEM]) versus predicted BMR[a]

	Females (n = 169)	Males (n = 115)
BMR vs. body mass		
Measured (kJ/day)	5,766 (66)*	7,200 (108)*
Predicted (kJ/day)	5,395 (41)	6,591 (70)
Percent deviation (%)	+7.1	+9.5
BMR vs. fat-free mass		
Measured (kJ/day)	5,766 (66)*	7,200 (108)*
Predicted (kJ/day)	4,912 (36)	6,239 (54)
Percent deviation (%)	+17.7	+15.2

[a] Differences between measured and predicted are statistically significant at: * $P < 0.001$.

TABLE 3. Blood pressure means for females and males by population

	SBP (mm Hg)	DBP (mm Hg)	PP (mm Hg)
Females			
Evenki	125.7 (26.0)	81.1 (13.6)[a]	44.6 (16.4)
Buryat	134.4 (27.1)[a]	83.1 (13.9)[a]	51.4 (18.9)[a]
Yakut	118.7 (18.8)[b]	74.4 (12.2)[b,c]	44.3 (9.3)[b]
Males			
Evenki	125.5 (17.9)	80.5 (11.5)	45.0 (11.3)[a]
Buryat	133.9 (19.5)	85.4 (12.9)	48.5 (12.9)[a]
Yakut	135.5 (18.6)	80.5 (12.1)	55.0 (11.0)[b,c]

[a] Significant difference ($P < 0.05$) compared with Yakut.
[b] Significant difference ($P < 0.05$) compared with Buryat.
[c] Significant difference ($P < 0.05$) compared with Evenki.

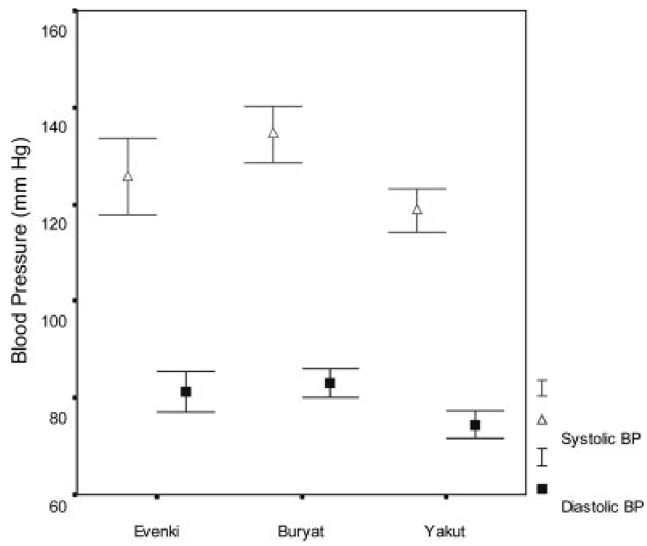

Fig. 1. Systolic and diastolic blood pressure (mm Hg) means (with 95% confidence intervals) for females from three indigenous Siberian groups.

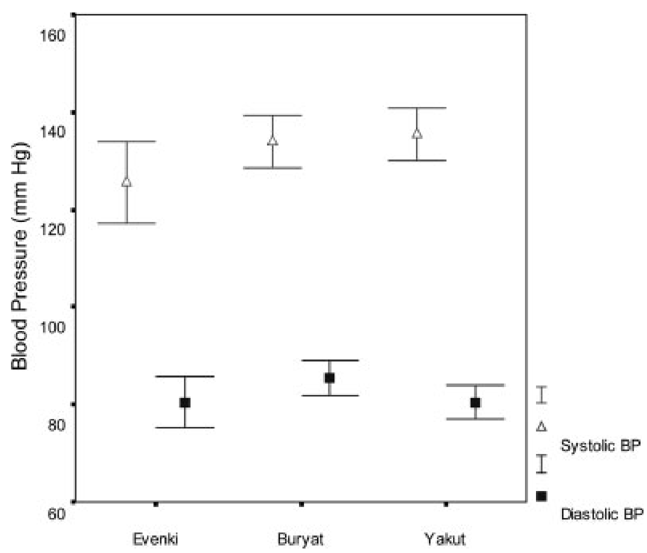

Fig. 2. Systolic and diastolic blood pressure (mm Hg) means (with 95% confidence intervals) for males from three indigenous Siberian groups.

overweight, and 79.5% of individuals were classified as of normal body weight or underweight.

Measured and predicted BMRs (± SEM) relative to body mass and FFM standards were available for a subset of 284 individuals (169 females, 115 males) (Table 2). Males had significantly higher measured BMRs than females (7200 ± 108 vs. 5766 ± 66 kJ/day; $P < 0.001$). Both males and females showed similar and statistically significant elevations in BMR over that predicted by body mass (7200 ± 108 vs. 6591 ± 70 kJ/day in males [$P < 0.001$] and 5766 ± 66 vs. 5395 ± 41 kJ/day in females [$P < 0.001$]). Both males and females showed statistically significant elevations in BMR over predicted for FFM (7200 ± 108 vs. 6239 ± 54 kJ/day in males [$P < 0.001$] and 5766 ± 66 vs. 4912 ± 36 kJ/day in females [$P < 0.001$]).

Among females in the total sample, 28.1% of individuals were classified as hypertensive (SBP ≥140 or DBP ≥90 mm Hg), 36.7% as prehypertensive (SBP 120-139 or DBP 80-89 mm Hg), and 35.2% as normotensive (SBP <120 and DBP <80 mm Hg) according to current criteria (Chobanian et al., 2003). Among males, 39.3% of individuals were classified as hypertensive, 43.4% as prehypertensive, and 17.2% as normotensive. Table 3 presents blood pressure measures according to population. Among females, there were significant differences by population for SBP ($P < 0.001$), DBP ($P < 0.001$), and PP ($P < 0.01$) (see Fig. 1). Among males, significant population differences were evident for PP ($P < 0.01$), but not SBP (P = 0.131) or DBP (P = 0.097) (see Fig. 2).

In the total sample with sexes combined, age was correlated with SBP (r = 0.375; $P < 0.001$), DBP (r =

TABLE 4. *Correlation matrix for anthropometric, metabolic, and blood pressure data for indigenous Siberian females*[a]

	BMR (kJ/day)	Age (year)	Body mass (kg)	BMI (kg/m^2)	FFM (kg)	Fat mass (kg)	SBP (mm Hg)	DBP (mm Hg)	PP (mm Hg)
BMR (kJ/day)	1	−0.035	0.541*	0.454*	0.483*	0.526*	0.256**	0.206**	0.208**
Age (year)		1	0.247*	0.372*	0.011	0.381*	0.484*	0.438*	0.386*
Body mass (kg)			1	0.919*	0.922*	0.964*	0.340*	0.374*	0.213**
BMI (kg/m^2)				1	0.787*	0.934*	0.407*	0.437*	0.265*
FFM (kg)					1	0.785*	0.241**	0.274*	0.146***
Fat mass (kg)						1	0.378*	0.410*	0.247**
SBP (mm Hg)							1	0.822*	0.869*
DBP (mm Hg)								1	0.432*
PP (mm Hg)									1

[a] Correlations are statistically significant at: * $P < 0.001$; ** $P < 0.01$; *** $P < 0.05$.

TABLE 5. *Correlation matrix for anthropometric, metabolic, and blood pressure data for indigenous Siberian males*[a]

	BMR (kJ/day)	Age (year)	Body Mass (kg)	BMI (kg/m^2)	FFM (kg)	Fat Mass (kg)	SBP (mm Hg)	DBP (mm Hg)	PP (mm Hg)
BMR (kJ/day)	1	−0.122	0.541*	0.393*	0.536*	0.468*	0.234***	0.125	0.230***
Age (year)		1	0.196***	0.381*	−0.077	0.379*	0.172	0.309**	-0.048
Body mass (kg)			1	0.893*	0.876*	0.916*	0.199***	0.247**	0.056
BMI (kg/m^2)				1	0.654*	0.923*	0.246**	0.320*	0.055
FFM (kg)					1	0.608*	0.134	0.134	0.071
Fat mass (kg)						1	0.210***	0.291**	0.031
SBP (mm Hg)							1	0.768*	0.763*
DBP (mm Hg)								1	0.171
PP (mm Hg)									1

[a] Correlations are statistically significant at: * $P < 0.001$; ** $P < 0.01$; *** $P < 0.05$.

0.383; $P < 0.001$), and PP ($r = 0.242$; $P < 0.001$). Among females, age was correlated with SBP ($r = 0.484$; $P < 0.001$), DBP ($r = 0.438$; $P < 0.001$), and PP ($r = 0.386$; $P < 0.001$) (Table 4). Among males, age was correlated with DBP ($r = 0.309$; $P = 0.001$) and marginally with SBP ($r = 0.172$; $P = 0.06$) but not PP ($r = −0.048$; $P = 0.601$) (Table 5).

The influence of BMR on blood pressure was assessed initially with pair-wise correlations, and in subsequent analyses with multiple regressions to adjust for potentially confounding factors. The initial analysis was performed with sexes combined; 284 individuals (169 females, 115 males) had complete information on BMR and blood pressure. BMR was positively correlated with SBP ($r = 0.321$; $P < 0.001$), DBP ($r = 0.227$; $P < 0.001$), and PP ($r = 0.286$; $P < 0.001$). Subsequent analyses examined sexes independently. Among females, BMR was significantly correlated with SBP ($r = 0.256$; $P = 0.001$), DBP ($r = 0.206$; $P < 0.01$), and PP ($r = 0.208$; $P < 0.01$) (Table 4). Among males, BMR was correlated with SBP ($r = 0.234$; $P < 0.05$) and PP ($r = 0.230$; $P < 0.05$), but not DBP ($r = 0.125$; $P = 0.182$) (Table 5).

Multiple regression analysis was used to estimate the relative contribution of BMR to blood pressure variation. A regression model with sex, age, FFM, fat mass, smoking status, ethnicity, degree of urbanization, and BMR explained 19% of the variation in SBP; BMR was a significant predictor of SBP in this model ($P = 0.002$) (Table 6). In a regression model with DBP as the dependent variable, 23% of the variation was explained; however, BMR was not a significant predictor of DBP, although it showed a trend ($P = 0.079$) (Table 6). In another iteration, but with PP as the dependent variable, BMR was a significant predictor of PP ($P = 0.002$). Similar results were documented when BMI was substituted for FFM and fat mass in regression models (results not shown). Sex did not have a significant effect in any of the multiple regression models.

DISCUSSION

This study documented elevated mean blood pressure among all three indigenous Siberian groups. Although these data are not representative of the individual populations or native Siberians as a whole, they do suggest a cause for concern. Among the pooled sample of females, 64.8% of participants were classified as hypertensive or prehypertensive and the blood pressure mean was 126.8/79.5 mm Hg. Among males, 82.7% of participants had suboptimal blood pressure, and the blood pressure mean was 133.1/82.6 mm Hg. The overall high blood pressure and hypertension prevalence rates documented here are consistent with findings from other studies conducted among native Siberian populations in the post-Soviet period (Kozlov et al., 2003; Sorensen, 2003; Sorensen et al., 2006), although a few relatively isolated coastal groups have somewhat lower blood pressure (Nikitin et al., 1981; Shephard and Rode, 1996). Taken together, blood pressure among indigenous Siberians is considerably higher than that documented in most traditionally living indigenous groups and isolated populations in developing nations; for both these groups, the prevalence of hypertension rarely exceeds 5% and they show at most a minimal age-related increase in blood pressure (Carvalho et al., 1989; Pavan et al., 1999; Cooper, 2003). Hypertension occurs in Siberian men at a similar frequency as seen in much of Europe and at a higher frequency than many developed nations, such as Canada and the United States; however, hypertension prevalence rates are even higher in parts of eastern Europe and Russia (Cooper, 2003; Wolf-Maier et al., 2003). Although hypertension is less prevalent in Siberian women than in men, it occurs

TABLE 6. Multiple regression models for prediction of blood pressure among indigenous Siberians (sexes combined)

Variable	Coefficient (SE)	β	P	Model r^2 and P
Systolic blood pressure				0.19/<0.001
Constant	89.009 (11.815)		<0.001	
Sex[a]	9.214 (6.744)	0.227	=0.173	
Age (years)	0.294 (0.135)	0.156	<0.05	
Fat-free mass (kg)	−0.185 (0.319)	−0.085	=0.563	
Fat mass (kg)	0.515 (0.279)	0.213	=0.066	
Smoking status[b]	2.125 (2.384)	0.052	=0.374	
Urbanization[c]	−2.809 (5.975)	−0.057	=0.639	
Ethnicity	−1.038 (1.522)	−0.082	=0.496	
BMR (kJ/day)	0.004 (0.001)	0.272	=0.002	
Diastolic blood pressure				0.23/<0.001
Constant	62.514 (7.315)		<0.001	
Sex[a]	7.262 (4.175)	0.281	=0.083	
Age (years)	0.179 (0.083)	0.149	<0.05	
Fat-free mass (kg)	−0.108 (0.197)	−0.078	=0.584	
Fat mass (kg)	0.567 (0.172)	0.370	=0.001	
Smoking status[b]	1.916 (1.476)	0.074	=0.195	
Urbanization[c]	3.144 (3.699)	0.100	=0.396	
Ethnicity	−2.737 (0.942)	−0.341	<0.01	
BMR (kJ/day)	0.002 (0.001)	0.149	=0.079	

[a] Sex: 0, female; 1, male.
[b] Smoking status: 0, no; 1, yes.
[c] Urbanization: 0, village; 1, town.

at rates similar to many industrialized nations. Mean blood pressure and hypertension prevalence rates are considerably higher in indigenous Siberians than most other circumpolar groups, including the North American and Greenland Inuit (Shephard and Rode, 1996; Bjerregaard et al., 2003). These differences may reflect the distinct social and political history of native Siberians and, specifically, the effects on indigenous health of idiosyncratic lifestyle changes in post-Soviet Russia (Snodgrass et al., 2007).

The results of the present study are consistent with recent findings of Luke et al. (2004) showing that BMR is positively associated with blood pressure measures (SBP and DBP) independent of age, sex, body size, and body composition among a large sample of Nigerians (n = 996) and African Americans (n = 452). When adjusted for body size and composition, as well as a variety of potentially confounding variables such as age, smoking status, ethnicity, and degree of urbanization, BMR among indigenous Siberians was positively associated with SBP and PP. Thus, higher BMR is associated with higher blood pressure. In fact, BMR was the strongest predictor of blood pressure in multiple regression models for both SBP and PP. These results suggest a causal relationship between BMR and blood pressure; the cross-sectional nature of this study, however, does not allow conclusions to be drawn on causality.

In addition to BMR, other factors not considered in these analyses almost certainly contribute to the relatively high blood pressure documented among indigenous Siberians. First, low physical activity within the context of economic development and lifestyle change is likely to elevate blood pressure, given the strong negative correlation between physical activity level and blood pressure documented in other studies (Paffenbarger et al., 1991; Wareham et al., 2000; WHO, 2002; Simons-Morton, 2003; Luke et al., 2005). This influence, however, does appear to be independent from that of BMR, as Luke et al. (2004) documented that the association between BMR and blood pressure remained after adjustment for physical activity. Activity data from a small sample of Yakut adults (n = 28) measured using the doubly labeled water method showed a trend toward a relationship between low activity level and higher blood pressure; as expected, those individuals who participated in fewer subsistence activities had lower activity levels (Snodgrass, 2004; Snodgrass et al., 2006b).

Second, chronic psychosocial stress likely plays an important role in the development of high blood pressure among indigenous Siberians. A general pattern documented in other settings shows a relationship between economic modernization, heightened levels of chronic psychosocial stress, and elevated blood pressure (Dressler, 1982, 1999; Dressler et al., 1987; Schall, 1992; Bindon et al., 1997); the ongoing social and economic transformations in Siberia are likely to have similar effects. This is almost certainly compounded by psychosocial stress related to the legacy of catastrophic economic and social changes in Russia over the past two decades, as has been documented among ethnic Russians and indigenous Siberians (Bobak and Marmot, 1996; Marmot and Bobak, 2000; Kozlov et al., 2003). Our research among the Yakut suggests that economic marginalization and emerging economic inequality increase stress levels and elevate blood pressure, especially among men (Sorensen et al., 2002; Snodgrass, 2004; Snodgrass et al., 2005b). Those individuals with relatively low monthly incomes and men who watched more hours of television had higher blood pressure. This latter effect was independent of other factors (e.g., body composition), perhaps resulting from increased psychosocial stress related to receiving social and economic ideas of modernization through television that may be unattainable (Dressler, 1991). A limitation of the present study is that although all the research was conducted during the post-Soviet period, data collection among the different study populations was conducted in different years.

Finally, dietary factors (e.g., increased salt, energy, fat, and alcohol consumption) are likely to contribute to blood pressure elevation among indigenous Siberians, given that economic changes in the post-Soviet period have led to shifts in both overall energy intake and dietary composition (Leonard et al., 1994, 1996, 2002a; Sorensen, 2003; Sorensen et al., 2005). However, the accurate quantification of energy intake in human populations is notoriously difficult and remains a formidable obstacle in population-level research in remote field locations. Analyses of 24-hour dietary recall data collected for a subsample of Evenki and Buryat participants found that only dietary energy intake (kcal/day) was significantly correlated with blood pressure (Leonard et al., in press). In addition, BMR remained a significant predictor of systolic blood pressure even when dietary energy intake was entered into the multivariate model presented in Table 6. Conversely, preliminary results from our research among the Yakut did not find an association between processed market food consumption and blood pressure (Snodgrass, 2004; Snodgrass et al., 2005b). Clearly, more research is needed to clarify the influence of diet and other lifestyle factors on blood pressure among indigenous Siberians.

If the influence of BMR on blood pressure is confirmed, it would represent an important step toward understanding cardiovascular risk among indigenous Siberians in the post-Soviet era. Even relatively small differences in blood pressure can have important health consequences. For example, clinical data suggest that lowering SBP by 10 mm Hg can reduce total mortality risk by 30% (Barker and Godfrey, 2004).

The link between BMR and blood pressure could also represent a pathway linking biological adaptation to regional environment conditions (i.e., metabolic elevation related to chronic and severe cold stress experienced in the circumpolar environment) with health changes associated with economic development. This is important given the growing concern for the role of underlying biological differences, especially between populations, in structuring variation in chronic disease patterns documented in modernizing populations (Shephard and Rode, 1996; Ruiz-Pesini et al., 2004; Wallace, 2005; Fridlyand and Philipson, 2006). Over the past few decades, studies of indigenous Siberians have demonstrated that like low-latitude populations, the prevalence rates of overweight and obesity have risen with economic development and urbanization; these changes largely reflect decreased physical activity and consumption of market foods high in saturated fats and refined sugars (e.g., Rode and Shephard, 1995; Shephard and Rode, 1996; Leonard et al., 2002a; Snodgrass et al. 2006a, 2006b). Blood cholesterol levels, however, remain relatively low among Siberians (e.g., Young et al., 1995; Leonard et al., 2005b; Sorensen et al., 2005), and the limited information on plasma glucose concentrations suggests that diabetes remains relatively uncommon (Young et al., 1992; Snodgrass et al., 2008). Hypertension, as documented in the present study, appears to be a particularly acute problem among Siberians. Taken together, this suite of cardiovascular risk factors differs from those observed in other modernizing populations, such as the Pima Indians of North America (see Weyer et al., 2000). The emergence of these contrasting patterns of chronic disease likely reflects the combined effects of distinct social and political processes and underlying biological differences, reflecting adaptation to local or regional environmental conditions.

At present, the mechanism responsible for the association between BMR and blood pressure is unknown. Here, we briefly consider four possible explanatory mechanisms. First, as suggested by Luke et al. (2004), heightened sympathetic tone (i.e., the background activity of the sympathetic nervous system [SNS]) associated with upregulated BMR could elevate blood pressure. The SNS, including tonic sympathetic activity, is closely involved with energy regulation, and sympathetic stimulation can lead to a twofold increase in BMR (Blaak et al., 1993; Monroe et al., 2001; Guyton and Hall, 2006). Variation in sympathetic tone and sympathetic β-adrenergic sensitivity have been suggested to contribute to population differences in energy expenditure (Saad et al., 1991; Spraul et al., 1993; Monroe et al., 2001). Pima Indians from the southwest United States, for example, have relatively low SNS activity and reduced sensitivity to β-adrenergic stimulation; this predisposes them to obesity yet reduces risk of associated cardiovascular complications (Spraul et al., 1993; Tataranni et al., 1998).

Second, the association between BMR and blood pressure may be mediated by thyroid hormones. Both clinical hyperthyroidism and hypothyroidism can lead to elevated blood pressure, and there is compelling evidence that subclinical thyroid "dysfunction" precipitates changes in cardiovascular function and blood pressure regulation (Fommei and Iervasi, 2002; Danzi and Klein, 2003; Fazio et al., 2004). Thyroid hormone levels (T_3 [triiodothyronine] and T_4 [thyroxine]) are closely related to BMR through their direct effects on rates of oxidative metabolism in most tissues (Al-Adsani et al., 1997; Danzi and Klein, 2003; Guyton and Hall, 2006). This explanatory model is particularly intriguing in regards to Siberian hypertension, given the well-documented relationship between climatic factors and thyroid hormone regulation. An extensive literature has documented that exposure to cold temperatures and shifts in photoperiod lead to upregulation of thyroid hormones in indigenous and nonindigenous high-latitude populations, resulting in increased thermogenesis and adenosine triphospate (ATP) turnover (Smals et al., 1977; Tkachev et al., 1991; Salijukov et al., 1992; Levine et al., 1995; Bojko, 1997; Silva, 2003). Our research among the Evenki has documented a link between free T_4 levels and BMR in the Evenki, as well as higher levels of free T_4 compared with nonindigenous Russian residents living in the same communities (Leonard et al., 1999).

A third potential mechanism linking BMR and blood pressure is oxidative stress, with increased formation of reactive oxygen species (ROS) heightening oxidative damage and precipitating increases in blood pressure. Present evidence supports a role for ROS in the pathophysiology of hypertension through multiple mechanisms, including endothelial remodeling, inflammatory processes, altered nitric oxide regulation, and renal dysfunction (Rathaus and Bernheim, 2002; Touyz, 2004; Rodríguez-Iturbe et al., 2004; Touyz and Schiffrin, 2004). Among mammals, increased mass-specific BMR generally leads to increased oxidative damage and a shorter lifespan, apparently reflecting increased production of ROS (Adelman et al., 1988; Ku et al., 1993; Speakman et al., 2002); however, other factors are undoubtedly important, including the extent of uncoupling of mitochondrial oxidative phosphorylation and life history tradeoffs in investment in antioxidant defenses (Adelman et al., 1988; Ku et al., 1993; Finkel and Holbrook, 2000; Speakman et al., 2002).

Finally, developmental effects could link adult blood pressure with BMR. Relatively low birth weights are associated with higher blood pressure later in life

(Barker et al., 1989; Barker, 1998; Barker and Godfrey, 2004; Adair and Dahly, 2005); these negative health effects appear to be magnified when low birth weight is associated with rapid postnatal growth (Adair and Dahly, 2005; Barker et al., 2005). Given the importance of genetic effects on BMR (Bogardus et al., 1986; Bouchard et al., 1989; Bouchard and Tremblay, 1990; Rice et al., 1996; Goran, 1997; Wu et al., 2004; Jacobson et al., 2006), including indirectly through the influence on body size and body composition, a potential pathway to adult hypertension is through life history trade-offs in maternal energy allocation. In this model, heightened maternal maintenance costs would impair fetal growth, program cardiovascular and renal physiology, and increase risk of hypertension in adulthood. The rapid changes in lifestyle that have resulted from economic development among indigenous Siberians (e.g., increased energy availability, decreased physical activity, and increased consumption of salt, refined sugars, and saturated fats) could magnify the effects of low birth weight on adult disease. On a final note, recent research has also shown that low birth weight is associated with a relatively high resting heart rate and high sleeping metabolic rate (Phillips and Barker, 1997; Weyer et al., 2000), raising the intriguing possibility of developmental programming of metabolic regulation.

We hope that the present findings will stimulate further research exploring the influence of BMR on blood pressure, and the role of adaptation to regional environmental conditions in structuring health changes associated with economic development and lifestyle change.

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