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ORIGINAL ARTICLE

The impact of obesity on physiological responses during prolonged exercise

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Background: Prolonged, moderate-intensity exercise training is routinely prescribed to subjects with obesity. In the general population, this type of exercise can lead to fluid and sodium imbalance. However, little is known whether obesity alters the risk of fluid and sodium imbalances.
Objective: This study examined physiological responses, such as core body temperature, fluid and sodium balance, in lean (BMI < 25), overweight (25 < BMI < 30) and obese (BMI > 30) subjects during prolonged moderate-intensity exercise.
Subjects: A total of 93 volunteers (24–80 years), stratified for BMI, participated in the Nijmegen Marches and walked 30–50 km at a self-selected pace. Heart rate and core body temperature were recorded every 5 km. Subjects reported fluid intake, while urine output was measured and sweat rate was calculated. Baseline and post-exercise plasma sodium levels were determined, and urinary specific gravity levels were assessed before and after exercise.
Results: BMI groups did not differ in training status preceding the experiment. Exercise duration (8 h 41 ± 1 h 36 min) and intensity (72 ± 9% HR_{max}) were comparable across groups, whereas obese subjects tended to have a higher maximum core body temperature than lean controls ($P = 0.06$). Obese subjects demonstrated a significantly higher fluid intake ($P < 0.001$) and sweat rate ($P < 0.001$), but lower urine output ($P < 0.05$) compared with lean subjects. In addition, higher urine specific gravity levels were observed in obese versus lean subjects after exercise ($P < 0.05$). Furthermore, plasma-sodium concentration did not change in lean subjects after exercise, whereas plasma-sodium levels increased significantly ($P < 0.001$) in overweight and obese subjects. Also, overweight and obese subjects demonstrated a significantly larger decrease in body mass after exercise than lean controls ($P < 0.05$).
Conclusion: Obese subjects demonstrate a larger deviation in markers of fluid and sodium balance than their lean counterparts during prolonged moderate-intensity exercise. These findings suggest that overweight and obese subjects, especially under strenuous environmental conditions, have an increased risk to develop fluid and sodium imbalances.
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Keywords: dehydration; hypernatremia; core body temperature; fluid balance; body mass index

Introduction

Obesity is a rapidly growing problem in western countries. Obesity is associated with a markedly increased risk to develop chronic diseases later in life, such as type 2 diabetes, cardiovascular diseases and cancer.[1–6] An inactive lifestyle has a dominant role in the development of obesity and its related health problems.[7–9] Indeed, physically active obese subjects have a reduced risk to develop diabetes mellitus, and report better fasting glucose levels and cardiovascular risk profiles compared with their physically inactive peers.[10–13] Therefore, exercise training is routinely prescribed to individuals with obesity,[14–16] with a preference for moderate-intensity exercise that can be performed for prolonged periods (for example brisk walking). Although the health benefits are well described, little is known about the physiological responses during endurance exercise in obese subjects.

Prolonged exercise is associated with significant fluid loss and an increase in core body temperature.[17] These exercise induced physiological changes may result in the development

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of hyperthermia, dehydration and sodium imbalance, consequently followed by impaired aerobic exercise performance levels and potential health problems.[17–21] Obesity may be related to altered physiological responses to exercise. For example, because of the larger body surface area and a greater number of sweat glands, obese subjects typically have larger fluid losses.[22] Second, obese subjects demonstrate an altered thermoregulatory response.[23] Previous studies showed that body mass index (BMI) was related to the occurrence of heat disorders in highly trained, young soldiers.[24,25] It is, however, unknown whether obesity in the general population is related to the development of fluid and sodium imbalances during prolonged exercise.

Therefore, the purpose of this study was to assess whether physiological responses to prolonged moderate-intensity exercise in obese subjects differ from overweight and lean subjects. For this purpose, we examined exercise intensity, core body temperature, fluid and sodium parameters in a large, heterogeneous group of subjects before, during and immediately after prolonged exercise. We hypothesized that obese subjects demonstrate a larger fluid loss and a higher core body temperature compared with lean peers, which might result in a higher incidence of dehydration and hypernatremia. This study is of particular clinical interest as prolonged, moderate-intensity exercise is typically prescribed to patients with obesity.

Methods

Subjects

A total of 93 participants of the Nijmegen Marches (an annual 4-day walking event in The Netherlands) were included and stratified for BMI. Subjects were defined as lean (BMI <25), overweight (BMI 25–30) or obese (BMI >30 kg m^{-2}) (Table 1). Data were collected during the first day of this walking march only. A written informed consent was obtained from all participants before the start of the study. This study was approved by the Medical Ethical Committee of the Radboud University Nijmegen Medical Centre, and was conducted in accordance with the Declaration of Helsinki.

Experimental design

At baseline (1 or 2 days before the exercise bout), subject characteristics and body composition were measured under controlled conditions (Figure 1). Moreover, fluid balance was examined by a blood and urine sample. Immediately before the start of exercise, fluid balance and core body temperature were examined. Thereafter, subjects participated in the first day of the Nijmegen Marches and walked 30 km (31%), 40 km (47%) or 50 km (22%). During exercise, fluid balance, core body temperature and exercise intensity were measured

Table 1 Subject characteristics and details about physical activity and the presence of prescribed medicines and pathology presented per BMI group

	BMI <25	*BMI 25–30*	*BMI >30*	P-*Value*
Demographic characteristics				
Gender (men:women)	15:16	15:16	18:13	—
Age (years)	56 ± 19	56 ± 11	53 ± 9	0.61
Height (cm)	174 ± 11	174 ± 9	174 ± 9	0.96
Weight (kg)	69.6 ± 11.0	83.0 ± 8.7[1]	100.4 ± 10.9[1,2]	<0.001
BMI (kg m^{-2})	22.8 ± 1.9	27.4 ± 1.4[1]	33.0 ± 2.0[1,2]	<0.001
Body fat (%)	29 ± 6	35 ± 6[1]	39 ± 5[1,2]	<0.001
Lean body mass (kg)	49.4 ± 10.6	54.4 ± 8.7	61.8 ± 10.4[1,2]	<0.001
Body-surface area (m^2)	1.83 ± 0.20	1.98 ± 0.16[1]	2.15 ± 0.17[1,2]	<0.001
Abdominal circumference (cm)	85 ± 8	96 ± 6[1]	110 ± 9[1,2]	<0.001
Waist circumference (cm)	93 ± 6	102 ± 6[1]	111 ± 7[1,2]	<0.001
Waist-to-hip ratio	0.91 ± 0.07	0.94 ± 0.06	0.99 ± 0.08[1,2]	<0.001
Health status				
Physical activity				
Sports (hours per week)	3.8 ± 4.2	2.1 ± 2.7	2.9 ± 4.4	0.61
Training status (km per year)[a]	568 ± 642	467 ± 693	577 ± 577	0.54
Mean arterial pressure (mm Hg)	98 ± 11	104 ± 11	106 ± 12[1]	0.021
Use of prescribed medicines	14 (45%)	20 (65%)	25 (81%)[1]	—
Diuretics	1 (3%)	1 (3%)	4 (13%)	—
Anti-hypertensive drugs	4 (13%)	8 (26%)	10 (32%)	—
Statins	3 (10%)	3 (10%)	5 (16%)	—
Pathology	17 (55%)	22 (71%)	20 (65%)	—
Hypertension	6 (19%)	8 (26%)	10 (32%)	—
Hypercholesterolemia	4 (13%)	4 (13%)	7 (23%)	—
Skin disease	2 (7%)	7 (23%)	5 (16%)	—
Osteoporosis	3 (10%)	3 (10%)	2 (7%)	—
Asthma	1 (3%)	4 (13%)	5 (16%)	—
Diabetes	1 (3%)	0 (0%)	4 (13%)	—

Abbreviation: BMI, body mass index. [1,2]*Post-hoc* significant difference in relation to BMI <25 and BMI 25–30 groups, respectively. [a]Ln-transformation was applied as a non-Gaussian distribution was present.

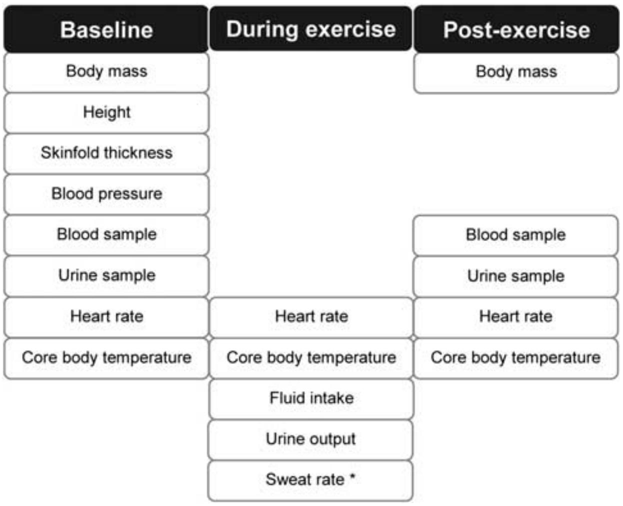

Figure 1 Schematic overview of measurements during the study. *Sweat rate was calculated by combining body weight, fluid intake and urine output data.

every subsequent 5 km. Immediately after finishing, exercise intensity and core body temperature were measured again, while fluid balance was re-assessed (Figure 1).

Measurements

Subject characteristics. Body mass was measured using a Seca 888 scale (Hamburg, Germany). Body surface area was calculated according to the formula of Dubois *et al*.[26] A four-point skinfold thickness measurement (biceps, triceps, sub-scapular, supra-iliac) was obtained in order to calculate the lean body mass.[27] Waist circumference was measured midway between the lower rib margin and iliac crest. Hip circumference was measured at the level of widest circumference over greater trochanters. Waist-to-hip ratio was calculated as waist circumference divided by hip circumference. Resting heart rate and blood pressure were measured twice using an automated sphygmomanometer (M5-1 intellisense, Omron Healthcare, Hoofddorp, The Netherlands) after 5-min seated rest. Finally, all subjects completed a questionnaire about their physical activity (hours of sport participation per week), training status (walking-specific training history in the year preceding the walking march) and health status (pathology and use of medication).

Fluid balance. The relative change in body mass (in %) between the measurement immediately before the start and directly after finishing was calculated and dehydration was defined as a body mass loss of 2% or more.[17,28] Furthermore, all subjects received written and individual oral instructions concerning the registration of their fluid intake. During exercise, subjects were allowed to drink *ad libitum*, while they registered the time (in blocks of 1 h), amount (using standard sized cups and bottles) and type ('water', 'sports drink' or 'other') of their individual fluid intake in a diary.

Urine analysis. The 5-ml urine sample that was provided by all subjects was immediately analyzed to determine urine specific gravity (Clinitek Status Analyzer; Siemens Healthcare Diagnostics, Tarrytown, NY, USA). Values of $\geqslant 1.030\,g\,ml^{-1}$ indicate dehydration.[21,29] To determine the amount of urine output, subjects were instructed to exclusively urinate into a specialized collecting bag (Roadbag/Ladybag; KETs GmbH, Köln, Germany). Bags were collected and weighed at the laboratory within 0.1 g accuracy (PT 1500; Sartorius AG, Göttingen, Germany).

Sweat rate. Sweat rate ($mL\,h^{-1}$) was calculated by combining body weight, fluid intake and urine output data using the formula: Sweat rate ($ml\,h^{-1}$) = (pre-exercise body weight − post-exercise body weight + fluid intake − urine output)/exercise duration.[21]

Blood analysis. Two ml of venous blood was drawn in order to determine plasma levels of sodium, hematocrit and hemoglobin (Rapidpoint 400, Siemens Healthcare Diagnostics Inc., Tarrytown, NY, USA). Hyponatremia and hypernatremia were defined as a plasma sodium concentration of $\leqslant 135\,mmol\,l^{-1}$ and $\geqslant 145\,mmol\,l^{-1}$, respectively.[30,31] Relative changes in plasma volume (%), were calculated from changes in blood hematocrit and hemoglobin concentrations according to Dill and Costill's equation.[32]

Core body temperature. Core body temperature was determined using a portable telemetry system (CorTemp system, HQ Inc, Palmetto, FL, USA), which has been demonstrated to be safe and reliable.[33,34] Participants ingested an individually calibrated telemetric temperature sensor the evening preceding the experiment. Core body temperature was measured using an external recorder and determined as the average of three consecutive measurements on each occasion. The highest value of the core body temperature during the exercise bout was presented as peak core body temperature.

Exercise intensity. Heart rate was measured simultaneously with core body temperature (that is, three consecutive measurements), using a two-channel ECG chest band system (Polar Electro Oy, Kempele, Finland). Mean heart rate during exercise was calculated as the average heart rate, excluding the values measured directly before the start and after the finish. Exercise intensity was calculated by dividing the mean heart rate during exercise by the maximal predicted heart rate (208–0.7 * age).[35]

Ambient conditions. Throughout the experiment, dry bulb, wet bulb and globe temperatures were measured every 30 min using a portable climate-monitoring device (Davis instruments inc., Hayward, CA, USA) positioned at the start/finish area. The wet bulb globe temperature index was calculated to gauge the heat risk, using the formula: wet bulb globe temperature = $0.1\ (T_{dry\ bulb}) + 0.7\ (T_{wet\ bulb}) + 0.2\ (T_{globe})$.[36]

Statistical analysis

All values were presented as mean ± s.d., unless indicated otherwise. Statistical analyses were performed using SPSS 16.0. The level of statistical significance was set at $P<0.05$. The normality of the data distribution was examined by the Kolmogorov–Smirnov test. When data demonstrated a non-Gaussian distribution, Ln-transformation was applied. Comparisons between groups were assessed using One-way ANOVA for continuously distributed data and a *post-hoc* test with a Bonferroni correction for multiple comparisons was performed in case of a statistically significant difference. To assess whether the three groups demonstrated a different time course of core body temperature, we performed a linear mixed model analysis. All other parameters that may demonstrate group differences over time were assessed using a two-way repeated measures ANOVA. A binary logistic regression analysis was used to model the relation between BMI-groups and binominal distributed data. Odds Ratios were computed for the overweight ($OR_{overweight}$) and obese subjects (OR_{obese}), with the lean subjects (BMI < 25) serving as a reference group. All Odds Ratios are presented with their 95% confidence intervals (CI).

Results

The three BMI groups were not different in age and height, but did demonstrate differences in body composition (Table 1). Physical activity level and the training status preceding the walking march were comparable between lean, overweight and obese subjects (Table 1). Also, no differences in the prevalence of cardiovascular diseases, diabetes or other diseases were reported (Table 1). Obese subjects, however, had a higher mean arterial blood pressure and used more prescribed medication than their lean counterparts (Table 1).

Exercise characteristics

All subjects successfully completed the exercise bout. The wet bulb globe temperature increased from 14.0 °C in the morning to a maximum of 25.0 °C in the afternoon. Walking distance, walking duration and walking speed did not significantly differ across groups (Table 2). Baseline core body temperature did not differ across groups (Table 2). Lean, overweight and obese subjects demonstrated a significant increase in core body temperature during exercise (Figure 2). However, the magnitude of this increase was significantly smaller in lean than in obese subjects ($P<0.001$), and showed a trend for a smaller increase in lean compared with overweight subjects ($P=0.073$). Also, the peak core body temperature tended to be higher in obese subjects compared with lean controls (Table 2). The exercise intensity was comparable between lean, overweight and obese subjects (71%, 71 and 75% of HR_{max}, respectively) (Table 2).

Fluid balance

Obese subjects reported a significantly greater fluid intake than lean subjects during exercise (Figure 3). Moreover,

Table 2 Exercise characteristics and fluid balance presented per BMI group.

	BMI <25	*BMI 25–30*	*BMI >30*	P-*Value*
Exercise characteristics				
Walking distance				
30 km	32%	36%	26%	—
40 km	42%	45%	55%	—
50 km	26%	19%	19%	—
Exercise duration (hh:mm)	8:34 ± 1:57	8:44 ± 1:25	8:46 ± 1:26	0.89
Speed ($km\,h^{-1}$)	4.8 ± 0.7	4.6 ± 0.8	4.7 ± 0.6	0.43
Baseline core body temperature (°C)	37.5 ± 0.4	37.6 ± 0.5	37.5 ± 0.3	0.58
Peak core body temperature (°C)	38.3 ± 0.3	38.4 ± 0.3	38.5 ± 0.3	0.06
Exercise intensity (%)	71 ± 10	71 ± 10	75 ± 8	0.16
Fluid balance				
Fluid intake ($ml\,h^{-1}$)	239 ± 80	297 ± 104	366 ± 129[1,2]	<0.001
Water (%)	61 ± 24	69 ± 21	62 ± 20	0.33
Sports drink (%)	10 ± 13	8 ± 12	18 ± 18[2]	0.018
Other (%)	29 ± 21	23 ± 19	20 ± 14	0.17
Sweat rate ($ml\,h^{-1}$)	258 ± 89	395 ± 117[1]	498 ± 169[1,2]	<0.001
Urine output ($ml\,h^{-1}$)[a]	75 ± 44	72 ± 59	44 ± 42[1]	0.029
Urine specific gravity ⩾1.030 $g\,ml^{-1}$	11 (36%)	16 (52%)	19 (61%)[1]	—
Calculated plasma volume change (%)	3 ± 11	4 ± 15	−6 ± 9[1,2]	0.003
Body mass change (kg)	−0.9 ± 0.8	−1.4 ± 0.8	−1.3 ± 1.0	0.049
Body mass change (%)	−1.2 ± 1.0	−1.6 ± 1.0	−1.2 ± 0.9	0.15
Dehydration; ⩾2% body mass loss	6 (20%)	8 (27%)	5 (16%)	—

Abbreviation: BMI, body mass index. [1,2]*Post-hoc* significant difference in relation to BMI <25 and BMI 25–30 groups, respectively. *P*-value refers to a One-Way ANOVA. [a]Ln-transformation was applied as a non-Gaussian distribution was present.

specification of fluid intake revealed that obese subjects had a slight but significant higher relative intake of sports drinks compared with the other BMI groups (Table 2). Overweight and obese subjects also demonstrated a significantly higher sweat rate compared with their lean counterparts (Figure 3). Although sweat rate was significantly related to body surface area ($P<0.001$, $r^2=0.45$, Figure 4), overweight ($200 \pm 58\,ml\,h^{-1}\,m^{-2}$) and obese ($226 \pm 70\,ml\,h^{-1}\,m^{-2}$) subjects still demonstrated significantly higher sweat rates than lean subjects ($133 \pm 36\,ml\,h^{-1}\,m^{-2}$) after correction for body surface area. Urine output in obese subjects was significantly lower than in lean subjects (Figure 3). Moreover, the incidence of post-exercise high urinary specific gravity ($\geqslant 1.030\,g\,ml^{-1}$), which is, a marker for dehydration, was significantly higher in obese subjects ($OR_{obese}=2.9$, CI = 1.0–8.1, $P=0.044$) compared with the lean controls (Table 2), while no group differences were found at baseline ($P=0.53$). Whereas obese subjects demonstrated a significant decrease in plasma volume after exercise ($P=0.001$), lean ($P=0.20$) and overweight ($P=0.21$) subjects demonstrated no change

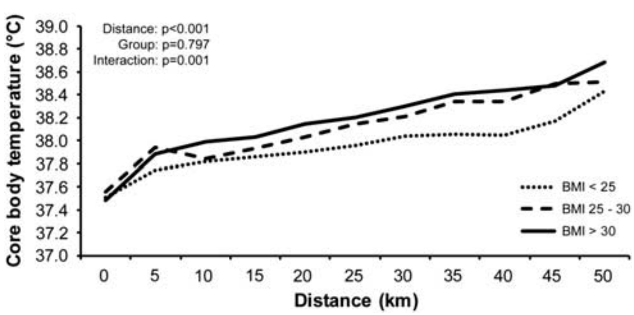

Figure 2 Time course of core body temperature in lean (dotted line), overweight (dashed line) and obese (solid line) subjects. Although baseline values were similar among groups, a significant increase in core body temperature was observed during exercise. Moreover, the change in core body temperature was different in overweight ($P<0.001$) and obese ($P=0.073$) subjects compared with the lean controls.

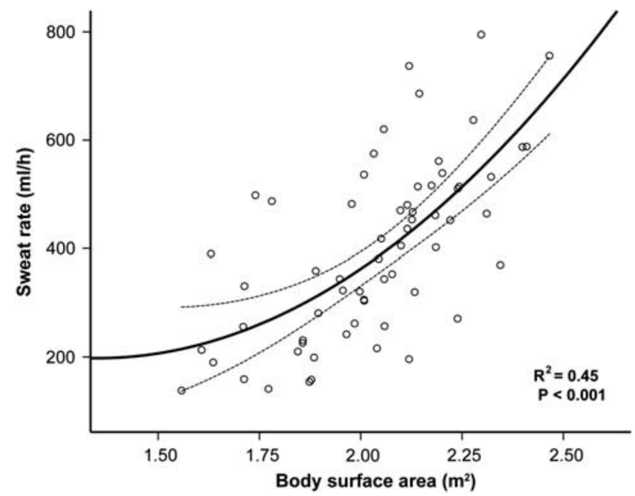

Figure 4 Sweat rate ($ml\,h^{-1}$) expressed per total body-surface area (m^2). A significant quadratic correlation was observed ($P<0.001$, $r^2=0.45$), so subjects with a high body-surface area demonstrate higher sweat rates compared with subjects with low body-surface area.

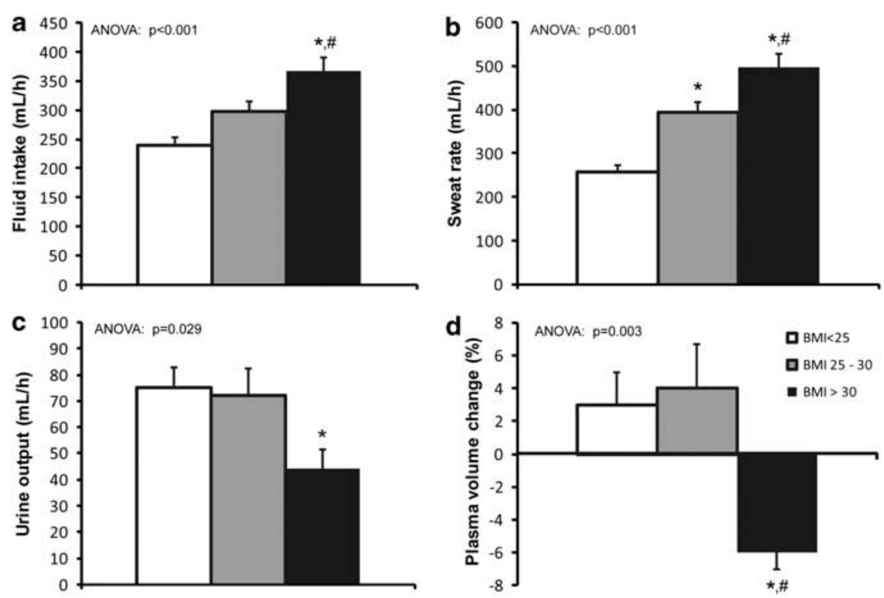

Figure 3 Fluid balance parameters (**a**: fluid intake, **b**: sweat rate, **c**: urinary output and **d**: plasma volume changes) presented per BMI group. Obese subjects showed a significantly higher fluid intake and higher sweat rate compared with overweight and lean subjects. Furthermore, obese subjects demonstrated also a significant lower urine output and decline in plasma volume compared with lean peers. Data are presented as mean ± s.d. *,# *Post hoc* significant from lean (*) and overweight (#) subjects, respectively.

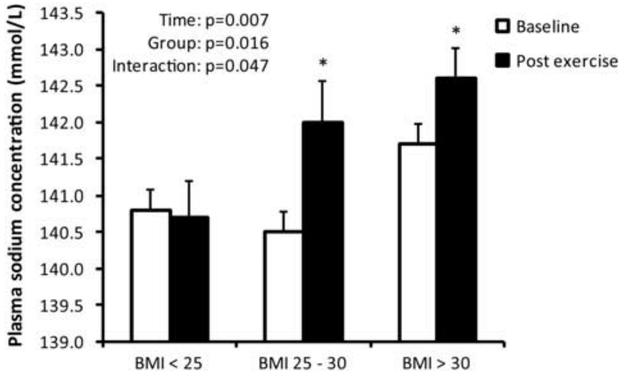

Figure 5 Plasma-sodium concentration in lean (BMI < 25), overweight (BMI 25–30) and obese (BMI > 30) subjects at baseline and directly post-exercise. Two-way repeated measures ANOVA revealed a significant time, group and interaction effect. Data are presented as mean ± s.d. **Post hoc* significant from baseline and significantly larger than the change in BMI < 25.

in plasma volume (Figure 3). Furthermore, overweight and obese subjects demonstrated a significantly larger decrease in body weight after exercise than the lean participants, but no differences were found when presented in relative terms (Table 2). Using body weight as a marker for dehydration, 20% of the total population met the criteria of dehydration, while no differences across groups were observed (Table 2).

Plasma-sodium concentration
Lean subjects demonstrated no change in their plasma-sodium concentration after prolonged moderate-intensity exercise (Figure 5). In marked contrast, a significant increase in post-exercise plasma-sodium levels was observed in overweight and obese subjects (Figure 5). Although 13% of our subjects demonstrated post-exercise hypernatremia, the incidence was not different among lean ($n = 2$, 7%), overweight ($n = 4$, 14%) and obese subjects ($n = 5$, 16%).

Discussion

This is the first study to examine the impact of obesity on physiological responses during prolonged moderate-intensity exercise. Walking duration, relative exercise intensity and training status were comparable across groups. We found that obese subjects tended to have a higher maximum core body temperature than lean controls. Furthermore, obese subjects demonstrated higher sweat rates, lower urine outputs and a higher fluid intake compared with their lean peers, accompanied by a larger decrease in body mass, decline in plasma volume, higher urine specific gravity and higher plasma-sodium levels. These group differences suggest that overweight, but especially obese subjects, are prone to develop fluid and sodium imbalances.

Participants walked at an average exercise intensity of 72% of their maximal predicted heart rate, which is comparable to ~60% of their VO_2max.[37,38] Although the exercise intensity was not different across BMI groups, we found significant differences in the time course of core body temperature. All groups demonstrated a relatively large increase during the first 5 km, followed by a slow, but gradual increase thereafter. Interestingly, the lean participants demonstrated a lower rate of increase in core body temperature than overweight and obese participants. This is in agreement with previous observations of a larger change in core body temperature in obese subjects compared with lean subjects when exposed to a comparable increase in physical activity level.[23] As sweating is the body's principal cooling mechanism,[18,21] obese subjects may also have an increased fluid loss. Indeed, obese subjects demonstrated a significantly higher sweat rate compared with lean subjects. Although the higher sweat rate in obese subjects was partly related to their larger body surface area (Figure 4),[22] the sweat rate expressed per square meter body surface area ($ml\,h^{-1}\,m^{-2}$) was still significantly higher in overweight and obese subjects.

The higher sweat rate in obese subjects was accompanied by a lower urine output and higher fluid intake compared with lean subjects. An explanation for the lower urine output in obese subjects may relate to arginine vasopressin secretion. Arginine vasopressin is a hormone that stimulates water reabsorption in the kidneys, and may therefore contribute to a lower urine output. Although we have not measured arginine vasopressin levels, previous studies demonstrated that an increased serum osmolality or a decreased plasma volume stimulate the secretion of arginine vasopressin.[39,40] Therefore, the decreased urinary output in obese subjects in our study might be the consequence of their higher sodium levels and decreased plasma volume (that is, more dehydrated status) compared with lean counterparts.

The higher fluid intake in obese subjects may also relate to the thirst stimulus. Previous studies showed that an increased serum osmolality or a decreased plasma volume stimulates the subject's thirst perception.[41,42] The significantly higher sodium levels in obese subjects, and thus higher osmolality, may have induced an increase in the thirst stimulus. In parallel, the decline in plasma volume, potentially followed by the release of angiotensin, could also stimulate thirst perception. Furthermore, obese subjects had a slightly larger intake of sports drink compared with their overweight counterparts (18 versus 8%, respectively). Taken together, the increased fluid intake and larger part of sports drinks in combination with a reduced urine output may enable obese subjects to compensate for the higher sweat rates in an attempt to regulate fluid balance.

In contrast to the larger variation in fluid intake and output in obese subjects, the incidence of dehydration, as defined by body mass change, was not different between lean, overweight and obese subjects. The identification of dehydration as applied in our study (body mass loss of ⩾2%) is based on athletes.[20,28] In athletes, 2% body mass loss equals a 3% total body water loss.[17] However, as fluid loss will predominantly occur from the lean body mass compartment, body composition may importantly impact the identification of dehydration. Adipose tissue consists of ∼10% water, whereas fat-free tissue (for example, muscle tissue) consists of 70–80% water.[43] Therefore, a 2% body mass loss in an obese individual (for example, 110 kg, 46% body fat percentage), equals 4.5% loss of total body-water content.[44] Thus, the classification of dehydration as >2% body mass loss may in fact underestimate the true presence of dehydration in obese and overweight subjects. To support this notion we have also examined post-exercise urinary specific gravity, which represents a useful method to identify dehydration.[21,29,45] Interestingly, using this measure, obese subjects had a ∼3 times higher risk to develop dehydration compared with lean subjects. This emphasizes that one should be careful with interpreting body mass changes in overweight and obese subjects.

Whereas lean subjects were able to maintain their plasma-sodium concentration during exercise, a significant increase was observed in overweight and obese subjects. These marked differences between groups may be explained by hypertonic sodium gain or net water loss.[31] Hypertonic sodium gain usually results from clinical interventions, but sodium loading (for example, ingestion of sodium chloride) is also accidentally reported.[31] Nevertheless, it is unlikely that overweight and obese subjects have consumed substantial amounts of sodium that can explain our findings. Alternatively, the increase in plasma sodium concentration may relate to the higher sweat rates in overweight and obese subjects (see above) compared with lean subjects. Plasma volume loss through sweating with a preserved amount of sodium, consequently leads to an increase in sodium levels. Taken together, our results show that obese subjects respond differently to prolonged moderate-intensity exercise under moderate ambient conditions compared with lean peers.

Clinical relevance

Moderate-intensity exercise is routinely prescribed as an effective strategy to lose weight and improve cardiovascular health.[14–16] Although exercise prescription to obese and overweight subjects includes shorter bouts of exercise compared with this study, our data are clinically relevant given the popularity of prolonged walking (for example, hill walking, pilgrimages and organized marches). Especially as we found in a recent study (unpublished data) that 40% of all participants of the Nijmegen Marches were overweight or obese. Nonetheless, all subjects were able to complete a prolonged exercise bout at ∼72% of their maximal heart rate, while no clinical signs or problems were observed. This indicates that moderate-intensity exercise, even in prolonged settings, is safe and well tolerated by overweight and obese subjects. However, obese subjects demonstrated different physiological responses compared with their lean peers. This suggests that obese subjects may be at risk to develop health problems related to thermoregulation, fluid- or sodium balance under more strenuous environmental conditions. Therefore future fluid-replacement guidelines should take BMI into account as a potential modifying factor.

Limitations

The strengths of this study are the inclusion of a large group of participants, the unique study design and completion of a prolonged exercise bout. However, some limitations should also be taken into account. First, BMI was used to define the lean, overweight and obese subjects. Although BMI provides no information regarding body composition, additional measurements revealed that body-fat percentage, body-surface area and waist-to-hip ratio differed significantly across groups. Therefore, we successfully included three different subgroups of obesity. Second, we estimated fluid loss by the assessment of urinary output and sweat excretion, thereby ignoring respiratory and gastrointestinal fluid losses.[46,47] However, metabolic water production in the muscles has been shown to compensate for respiratory fluid loss,[47,48] while gastrointestinal losses are normally negligible (that is, 100 ml per day).[46] Therefore, urinary excretion and sweat loss are considered the major determinants of total body-fluid loss.[17,45,47] Finally, urine specific gravity was used as marker of the fluid balance. Although this parameter can be influenced by large molecules (for example, with albuminuria) and may be subordinate to other fluid balance parameters (plasma osmolarity/urinary sodium concentration), this measure is easy to apply in field settings and provides valid information about the fluid status of a participant.[49] Despite potential limitations, the larger prevalence of high urine specific gravity levels in obese subjects was in agreement with the general finding of fluid imbalance in subjects with obesity.

In conclusion, obese subjects demonstrated higher sweat rates, lower urine outputs and a higher fluid intake compared with their lean peers during prolonged moderate-intensity exercise under moderate ambient conditions. The differences in fluid balance were accompanied by a larger decrease in body mass, higher urine specific gravity levels, higher plasma sodium levels and a decline in plasma volume in obese versus lean subjects. These changes suggest that overweight, but especially obese subjects, have an increased risk to develop fluid and sodium imbalances. To prevent impaired aerobic exercise performance levels and potential health problems, obese subjects should be advised to take precautions; in particular during exercise in strenuous environmental conditions.

Conflict of interest

The authors declare no conflict of interest.

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