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ORIGINAL ARTICLE

**Claire Cuisinier · Jacques Michotte de Welle
Roger K. Verbeeck · Jacques R. Poortmans
Roberta Ward · Xavier Sturbois · Marc Francaux**

Role of taurine in osmoregulation during endurance exercise

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Abstract Taurine is released by contracting muscles, but its actual role remains unspecified. In this study, we investigated whether the exercise-stimulated release of taurine from muscle into the plasma regulates the modification of osmolality induced by intramuscular osmolyte production. Six subjects performed 90 min of cycling exercise (at 70% maximum power output) on two occasions, with (HC) or without (DC) fluid intake. Taurine content was determined in plasma, blood cells and urine before and after the endurance events, together with plasma osmolality. Plasma osmolality increased by 4% in the DC experiment ($P < 0.01$), but remained stable in the HC condition. The exercise also induced changes in the mean (SD) plasma taurine content to a greater degree in HC [+63 (26)%] than in DC [+33 (18)%; $P < 0.05$], supporting the hypothesis that taurine is released into the plasma via an osmoregulatory process. However, the higher plasma taurine content in HC was not related to changes in renal taurine. In addition, the increase of taurine in plasma was not related to its release from blood cells since their taurine concentration increased by 70% both in HC [429 (77) to 680 (82) μM; $P = 0.003$] and in DC [451 (57) to 731 (34) μM; $P < 0.001$]. The lack of correlation between plasma volume modification and the mass ratio of taurine would exclude a major role for taurine exchange in plasma volume regulation. Sodium ($R = 0.967$, $P < 0.001$), chloride ($R = 0.917$, $P < 0.001$) and osmolality ($R = 0.924$, $P < 0.001$) seem to be the main regulators of plasma volume changes during exercise. In conclusion, changes in the plasma taurine content during endurance exercise is related to an osmoregulatory process, but this alone does not control plasma volume changes.

Keywords Plasma · Muscle · Osmolyte · Ion · Blood cells

C. Cuisinier · J. Michotte de Welle · X. Sturbois
M. Francaux (✉)
Institut d'Education Physique et de Réadaptation,
Faculté de Médecine, Université Catholique de Louvain,
1 Place Pierre de Coubertin, 1348 Louvain-la-Neuve, Belgium
E-mail: marc.francaux@edph.ucl.ac.be
Fax: +32-10-472093

R.K. Verbeeck
Unité de Pharmacocinétique, Métabolisme,
Nutrition et Toxicologie, Ecole de Pharmacie,
Faculté de Médecine, Université Catholique de Louvain,
1200 Brussels, Belgium

J.R. Poortmans
Institut Supérieur d'Education Physique et de Kinésithérapie,
Université Libre de Bruxelles, 1000 Brussels, Belgium

R. Ward
Unité de Biochimie, Faculté des Sciences,
Université Catholique de Louvain,
1348 Louvain-la-Neuve, Belgium

Introduction

Taurine, 2-aminoethanesulphonic acid, is an intracellular amino acid that is present in relatively low concentrations in the plasma and interstitial media. In man, plasma taurine concentration ranges from 29 to 49 μM (Cuisinier et al. 2001; Gutierrez et al. 1999; Maggs et al. 1995), and from 165 to 199 μM in the interstitial muscle space (Blomstrand and Saltin 1999; Gutierrez et al. 1999). By contrast, the intracellular taurine level in the vastus lateralis muscle is 50 and 62 mmol·(kg dry weight)$^{-1}$ in sedentary subjects and endurance-trained men, respectively (Blomstrand and Saltin 1999; Graham et al. 1995).

Although taurine is abundant in muscle, its function remains uncertain. Recently, we have shown that the myofilament calcium sensitivity and the mechanical characteristics of muscle contraction are dependent on taurine concentration (Cuisinier et al. 2000). According to Huxtable (1992), taurine appears to regulate cellular osmoregulation. This observation was initially established in marine invertebrates where it was demonstrated that high intracellular taurine may be involved in the regulation of osmotic pressure. Furthermore, in resting conditions, a close linear relationship was demonstrated

between the salinity of the surrounding milieu and the concentration of taurine in the echinoderm *Asterias rubens* (Jacobsen and Smith 1968). When exposed to a hyposmotic environment, cells respond initially by rapid swelling followed by an active extrusion of intracellular osmotically active solutes such as inorganic ions or organic molecules, including taurine. This second phase, named the regulatory volume decrease (RVD) process, is associated with a leakage of taurine from many different cell types (Kirk and Kirk 1993; Sanchez-Olea et al. 1996). Recently, Sejersted and Sjogaard (2000) correlated skeletal muscle swelling at the onset of exercise with increased intracellular osmolality (Ward et al. 1996). This phenomenon was followed subsequently by RVD, which is achieved by a loss of potassium and chloride ions, although a more important mechanism may be the loss of amino acids, which include the sulphonated amino acid taurine (Sejersted and Sjogaard 2000).

There is considerable evidence to show that contracted muscles will release taurine. For example, studies of femoral arteriovenous differences suggest that contracting muscles release taurine (Graham et al. 1991, 1995), while repeated stimulations of isolated mouse muscles induce the release of taurine into the bathing solution (Cuisinier, unpublished observations). Therefore, the increase in plasma taurine content observed during endurance events such as a marathon or a 100-km run was attributed to the release of muscle taurine (Cuisinier et al. 2001; Ward et al. 1999). However, the physiological importance of this taurine shift has not been investigated previously.

The aim of the present study was to investigate taurine release during endurance exercise under two different osmotic conditions, with and without fluid intake. We hypothesised that during endurance exercise, taurine could be released from skeletal muscle according to osmotic conditions, which would be related to the hydration status of the individual.

Methods

Subjects

Six healthy men volunteered for this study. The subjects were informed of the nature of the protocol, which was approved by the Ethical Committee of the Faculty of Medicine of the Université Catholique de Louvain, and their written approval to participate was obtained. The physical characteristics [mean (SD)] of the subjects were as follows: age, 21 (2) years; height, 182 (7) cm; body mass, 74 (5) kg; maximum oxygen uptake ($\dot{V}O_{2peak}$), 57 (4) ml·kg^{-1}·min^{-1} and maximum power output (MPO) 360 (20) W. $\dot{V}O_{2peak}$ and MPO were determined during an incremental exercise test on a cycloergometer (Ergoline 800) within 2 weeks prior to the beginning of the experiments.

Experimental protocol

Each subject participated in two experimental protocols during which they exercised on a cycle ergometer for 90 min in either a dehydrated condition (DC) or a hydrated condition (HC). The protocols were randomised and executed 1 week apart. The subject pedalled at 60 rpm for 7 min at 40% MPO to warm up, followed by 83 min at 70% MPO. All experimental trials began at 9.00 a.m., 90 min after a standard breakfast. The breakfast was composed of two French croissants and 150 ml of orange juice, which did not contain caffeine or taurine. An overnight urine sample was collected (pre-exercise sample) and an aliquot of urine was frozen for further analysis. The time period for the urine collection together with the urinary volume were recorded.

At the laboratory, each subject was measured and weighed naked and a temperature probe was placed ~15 cm deep into the rectum. Rectal temperature and the heart rate were monitored throughout the experiment. The subject dressed himself with sport shoes, cotton socks, a slip and cotton shorts. The subject remained seated on a cycloergometer for 15 min to allow stabilisation of the position-dependent plasma volume (Pastene et al. 1996). During this period, a venous catheter was introduced into a superficial forearm vein so that blood samples could be collected 2 min before the start of the exercise (pre-exercise level) and then subsequently every 15 min. Blood specimens were divided between 2-ml vials, which contained ethylenediaminetetraacetic acid (EDTA), and 6-ml vials containing lithium heparin. Specimens were immediately centrifuged for 12 min at 1,500 *g* to isolate the plasma.

In the DC experiment, the subject performed the whole exercise period without any fluid intake. In the HC experiment, the subject drank a standardised volume of water at 37°C, which contained a low concentration of ions (130 μM Na^+, 10 μM K^+, 110 μM Ca^{2+}, 50 μM Mg^{2+}, 140 μM Cl^-, 40 μM SO_4^{2-}, 30 μM NO_3^-, 250 μM HCO_3^-, and 120 μM SiO_2). One minute before starting the exercise, the subject ingested an initial bolus of 8 ml water·(kg body mass)$^{-1}$ followed by five additional boli of 2 ml·(kg body mass)$^{-1}$ every 15 min (Rehrer et al. 1990). This represents an average intake of 1300 ml over the 90-min exercise period.

Immediately after the exercise, urine was collected, the time period for the urine collection plus the urinary volume were recorded and an aliquot was frozen. Within 5 min after the cessation of the exercise, the subject was dried with a towel and weighed naked. Changes of body mass allowed calculation of the water lost during exercise corrected by the volume of drinking solution.

Analytical procedures

Haemoglobin concentration was measured in triplicate in heparinised blood by the cyanmethaemoglobin method (Sigma Diagnostics). Haematocrit ratio (Hct) was determined in duplicate by 10-min centrifugation (15,290 *g*) of heparinised blood. Hct ratios are expressed as % and corrected for plasma trapped with packed red cells (0.96) and for venous-to-total body Hct ratio (0.93; Costill and Fink 1974). The changes in plasma volume relative to the pre-exercise value (ΔPV) were calculated on the basis of haemoglobin concentrations and Hct, as described previously (Dill and Costill 1974).

White cell, red cell and platelet counts were assayed in the EDTA blood specimens with an ADVIA 120 Hematology System (Bayer, USA). Lactate concentration was measured in the heparinised plasma sample by quantitative enzymatic determination achieved by absorbance of NADH assayed spectrometrically at 340 nm (Sigma Diagnostics). Myoglobin concentration was measured in heparinised plasma by photometric determination of turbidity formed by agglutinated anti-human myoglobin antibody and plasma myoglobin (Dade Behring). The plasma osmolality of heparinised plasma was measured by freezing-point depression (Fiske osmometer). Chloride, potassium and sodium ion concentrations were determined in heparinised plasma by ion-sensitive electrodes (Cobas Integra, Roche Diagnostic Systems).

Taurine concentrations were determined by high-performance liquid chromatography (HPLC) of urine, whole blood and plasma samples. Proteins were precipitated by addition of 1 ml 5-sulphosalicylic acid 10% (w/v) to 1 ml urine or whole blood; or by addition of 1 ml 5-sulphosalicylic acid 3.5% (w/v) to 1 ml plasma. The supernatant was recovered after 10 min centrifugation at

3000 rev·min^{-1} (1,500 *g*) and neutralised with NaOH (pH = 7). The filtrate was passed through a 0.2 μm pore diameter filter (Vel) and taurine concentration was determined by HPLC after derivatisation with O-phthaldialdehyde (OPA). The OPA solution was prepared as follows: 27 mg OPA was dissolved in 1 ml HPLC-grade methanol, 10 μl *β*-mercaptoethanol was added and the solution was stored at 4°C. Before analysis, 25 μl of the OPA solution was diluted with 1 ml 0.1 M sodium tetraborate buffer (pH 9.3). A 25-μl aliquot of the OPA solution was added to a 25-μl sample, which was allowed to react for 2 min in the dark before injection onto the HPLC column. An external standard of taurine 25 μM was assayed after every four samples. The HPLC (equipped with a Kontron Instruments 420 pump) delivered 0.6 ml·min^{-1} of a filtered and degassed mobile phase (0.1 M K_2HPO_4, 0.134 mM EDTA, 28% HPLC-grade methanol, 72% millipore H_2O, and H_3PO_4 was added to obtain a pH of 7.7 for blood and urine and 6.4 for plasma). Separation of the amino acids was achieved by a reverse-phase column (BAS, 100·3.2 mm, Biophase-II, ODS 3 μm) and detected spectrometrically at 340 nm (Kontron Instruments HPLC 332 detector). The taurine concentration was evaluated by measuring the area under the peak (Integrator 4290 Varian) and corrected for dilutions during sample preparation.

Excretion of taurine in the urine was calculated by multiplying the urinary taurine concentration and urinary flow rate. Renal clearance of taurine was calculated by dividing the taurine excretion by the plasma taurine concentration. During the exercise period, plasma taurine concentration fluctuated such that an averaged plasma taurine concentration was calculated by measuring the gross area under the concentration/time curve.

Taurine concentration ([taurine]) in the blood cells was calculated as follows:

$$[\text{taurine}]_{\text{Bloodcells}} = \left\{ [\text{taurine}]_{\text{Blood}} - \left[[\text{taurine}]_{\text{Plasma}} \bullet \frac{(100 - \text{Htc})}{100} \right] \right\} \bullet \frac{100}{\text{Htc}} \quad (1)$$

Taurine or plasma ion concentrations were corrected for dilution due to plasma volume changes (Corr PV) by the formula:

$$[\text{taurine or ion}]_{\text{CorrPV}} = [\text{taurine or ion}] \bullet \left(\frac{100 + \Delta\text{PV}}{100} \right) \quad (2)$$

Mass ratios (MR) of plasma taurine or plasma ion were determined as follows:

$$\text{MR} = \frac{[\text{taurine or ion}]_{\text{CorrPV}}}{[\text{taurine or ion}]_{\text{Pre-exercise}}} \quad (3)$$

Statistics

All data are expressed as mean (SD). Differences were assessed for statistical significance by a paired Student's *t*-test, or whenever appropriate, an analysis of variance with subjects ($n = 6$) as a random factor and conditions (hydrated or dehydrated) and time (pre-exercise or post-exercise) as two factors. When differences were found to be significant, paired Student's *t*-tests were used as post-hoc. The increase in plasma taurine concentration was evaluated by measuring the slope of the linear regression calculated between the onset of exercise and the 90th min of cycling. A paired Student's *t*-test was carried out to compare slopes. Correlations between variables of interest were calculated by a Bravais-Pearson correlation coefficient. The level of statistical significance was set at 0.05 ($^*P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$).

Results

During the 90 min of cycling at 70% MPO, heart rate reached 171 (16) bpm, rectal temperature increased from 37.5 (0.3) to 39.5 (0.5)°C, plasma lactate reached 3.2 (1.3) mM, while plasma myoglobin concentration did not change [35 (19) and 44 (24) μg·l^{-1} before and after exercise, respectively]. None of these variables were significantly different between DC and HC protocols.

In both experimental conditions, the number of red cells and platelets similarly increased during exercise [from 4.73 (0.31) to 4.86 (0.21) $\times 10^6$ cells·mm^{-3} and from 245,000 (72,000) to 323,000 (88,000) cells·mm^{-3}, respectively]. However, the increase in white cell number, corrected for changes in plasma volume, was significantly higher in DC than in HC.

The loss of body water, calculated as the difference between the fluid intake and the body mass decrease, was greater in DC [–1.7 (0.3) l] than in HC [–0.7 (0.4) l; $P < 0.001$, Student's *t* test].

The plasma volume of subjects in DC decreased by 7.6 (2.3)% after 15 min of exercise ($P < 0.001$, Student's *t*-test) and remained stable or even slightly decreased [–8.7 (5.1)%] at the end of the 90-min cycling bout. A similar decrease in plasma volume [–7.0 (5.0)%] was observed during the first 15 min of the exercise in HC. Nevertheless, under these conditions, the plasma volume had returned almost to its initial value on completion of 1 h of cycling [–2.8 (5.3)%]. After this time, the plasma volume decreased further to –6.1 (4.9)% and –7.0 (6.1)% of initial plasma volume at the 75th and 90th min of cycling, respectively (Fig. 1).

Taurine balance

Plasma taurine concentration increased by 76% in HC ($P = 0.006$, Student's *t*-test) and by 44% in DC ($P = 0.004$, Student's *t*-test) at the end of the 90 min of

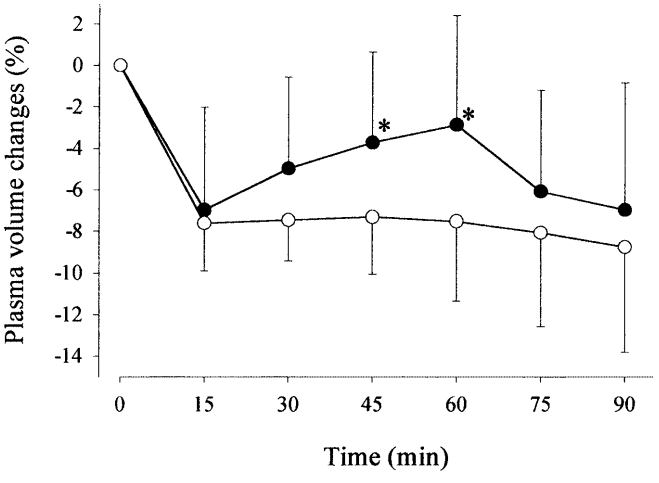

Fig. 1. Changes (mean ± SD) in plasma volume (%) during 90 min of cycling at 70% maximum power output (MPO) in dehydrated (○) or hydrated conditions (●) ($n = 6$). Statistical significant differences ($^*P < 0.05$) between hydrated and dehydrated conditions were calculated for each period of time by paired Student's *t*-test

cycling (Fig. 2). However, the slopes of the linear regression (see methods) were not significantly different ($P = 0.078$, Student's t-test). Nevertheless, the observed increase in plasma taurine concentration could be due either to an increase in plasma taurine content or a reduction of plasma volume. As shown in Fig. 1, plasma volume decreased both in HC and DC at the end of the exercise in comparison to the pre-exercise value, the decrease being higher in the dehydrated state. After correction for changes in plasma volume, a significant difference was observed between DC and HC plasma taurine level ($P = 0.036$, Student's t-test, Fig. 2).

By the end of exercise, blood taurine concentration increased from 194 (29) to 313 (32) μM in HC ($P = 0.007$, Student's t-test) and from 204 (22) to 337 (19) μM in DC ($P < 0.001$, Student's t-test). This increase in whole blood could be attributed to increases in both plasma and blood cells. In blood cells, taurine concentration increased from 429 (77) μM at the start of exercise to 680 (82) μM after 90 min of cycling in HC ($P = 0.003$, Student's t-test), and from 451 (57) to 731 (34) μM in DC ($P < 0.001$, Student's t-test). However, no statistical differences were observed between HC and DC.

The changes in urinary taurine excretion between the pre-exercise value [0.23 (0.17) and 0.43 (0.43) $\mu mol \cdot min^{-1}$ in HC and DC, respectively] and the post-exercise one [0.61 (0.30) and 0.40 (0.37) $\mu mol \cdot min^{-1}$ in HC and DC, respectively] were not different in HC and DC (NS, ANOVA).

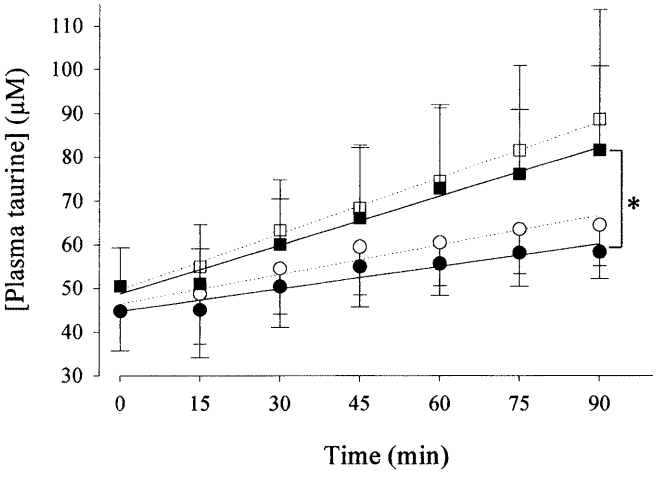

Fig. 2. Changes (mean ± SD) of plasma taurine concentrations (μM) during 90 min of cycling at 70% MPO in dehydrated (○) or hydrated conditions (❑) ($n = 6$). *Closed symbols* represent the corresponding data corrected for changes in plasma volume, the corresponding standard deviation being represented with a larger cap ($n = 6$). Statistical differences between hydrated and dehydrated conditions were calculated separately for plasma taurine concentration data and plasma taurine concentration data corrected for plasma volume changes. Evolution of plasma taurine concentrations, corrected or not for changes in plasma volume, were evaluated by the slope of the linear regression calculated between the onset and the 90th min of cycling. Paired Student's t-tests were carried out to compare slopes in hydrated and dehydrated HC and DC; $^*P < 0.05$

Renal taurine clearance showed a higher increase during the exercise in HC than in DC ($P = 0.040$, ANOVA). The urinary clearance of taurine increased in HC ($P = 0.041$, Student's t-test), whereas it did not reached significance in DC ($P = 0.357$, Student's t-test, Fig. 3). In addition, pre-exercise clearance values were not significantly different between HC and DC (NS, Student's t-test).

Ion balance

Table 1 shows plasma osmolality and sodium, chloride, potassium and taurine concentrations before and after the exercise. Osmolality, sodium and chloride concentrations did not change between the beginning and the end of the cycling exercise in the HC group, whereas their concentrations increased in DC. However, these changes can be partially attributed to a decrease in plasma volume (Fig. 1). Therefore, the data corrected by the pre-exercise values revealed changes in the amount of plasma osmolyte, sodium, chloride, potassium or taurine. The MRs for osmolality, sodium and chloride were not different or even decreased during the cycling in both HC and DC. No difference was observed between experimental conditions. Moreover, plasma taurine and potassium concentrations were increased during the exercise in both HC and DC. Corrections for plasma volume changes showed an increased in both taurine and potassium plasma content, which was greater in HC than in DC (Table 1).

As shown in Fig. 4, plasma volume changes are highly correlated with osmolality MR ($R = 0.924$, $P < 0.001$), sodium MR ($R = 0.967$, $P < 0.001$) and chloride MR ($R = 0.917$, $P < 0.001$), but not with

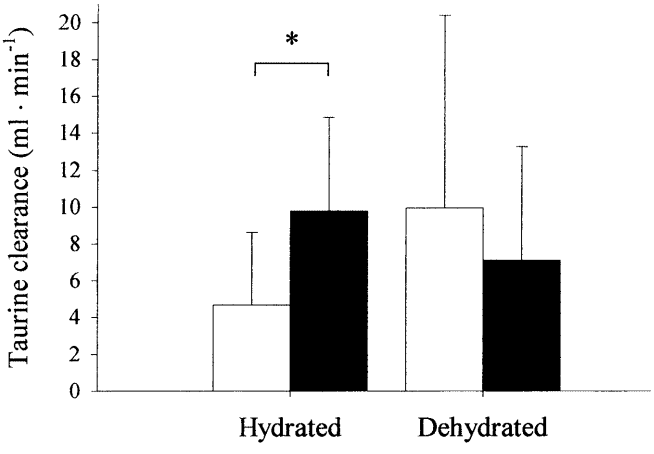

Fig. 3. Urinary taurine clearance ($ml \cdot min^{-1}$) for hydrated and dehydrated conditions before (*white*) and after (*black*) ($n = 6$) 90 min of cycling at 70% MPO is shown here (mean ± SD). Statistical analysis was carried out by an analysis of variance, revealing a significant difference between the hydrated and dehydrated conditions in the increase in taurine excretion ($P = 0.040$). Paired Student's t-tests were then performed to compare the evolution of the taurine concentration within each condition ($^*P < 0.05$)

Table 1. Plasma osmolality, sodium, chloride, potassium and taurine data before (*Pre-ex*) and after (*Post-ex*) 90 min of cycling at 70% maximum power output (MPO, n = 6) in two different hydration conditions: for the hydrated condition (*HC*) the subjects ingested an initial bolus of 8 ml water·(kg body mass)$^{-1}$ at the beginning of the exercise followed every 15 min by five additional boli of 2 ml·(kg body mass)$^{-1}$, while in the dehydrated condition (*DC*), no intake of liquid were allowed. Data are presented as the mean (SD) concentrations (mosmol·kg^{-1}) and mass ratios (*MR*), which are the ratios between concentrations corrected for plasma volume changes and concentrations at the onset of the exercise. Paired Student's *t*-tests were applied (*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$)

Variable	(Concentration) or MR	HC			DC			Post-HC *vs* Post-DC
		Pre-ex	Post-ex	Pre-ex *vs* Post-ex	Pre-ex	Post-ex	Pre-ex *vs* Post-ex	
Osmolality	(mosmol·kg^{-1})	291.3 (6.5)	293.2 (5.9)	NS	291.5 (3.0)	302.0 (2.9)	**	*
	MR	1	0.94 (0.06)	NS	1	0.95 (0.06)	NS	NS
Sodium	(mmol·l^{-1})	138.7 (2.5)	138.2 (2.1)	NS	139.0 (0.6)	141.8 (0.8)	**	*
	MR	1	0.93 (0.06)	*	1	0.93 (0.06)	*	NS
Chloride	(mmol·l^{-1})	106.3 (2.3)	106.0 (2.5)	NS	106.2 (1.2)	109.4 (2.5)	*	*
	MR	1	0.93 (0.08)	NS	1	0.94 (0.06)	NS	NS
Potassium	(mmol·l^{-1})	3.9 (0.1)	5.2 (0.3)	***	4.1 (0.5)	5.2 (0.3)	**	NS
	MR	1	1.24 (0.07)	***	1	1.14 (0.09)	*	*
Taurine	(μmol·l^{-1})	50.5 (8.8)	88.7 (25.1)	**	44.8 (9.1)	64.5 (9.3)	**	NS
	MR	1	1.63 (0.26)	**	1	1.33 (0.18)	**	*

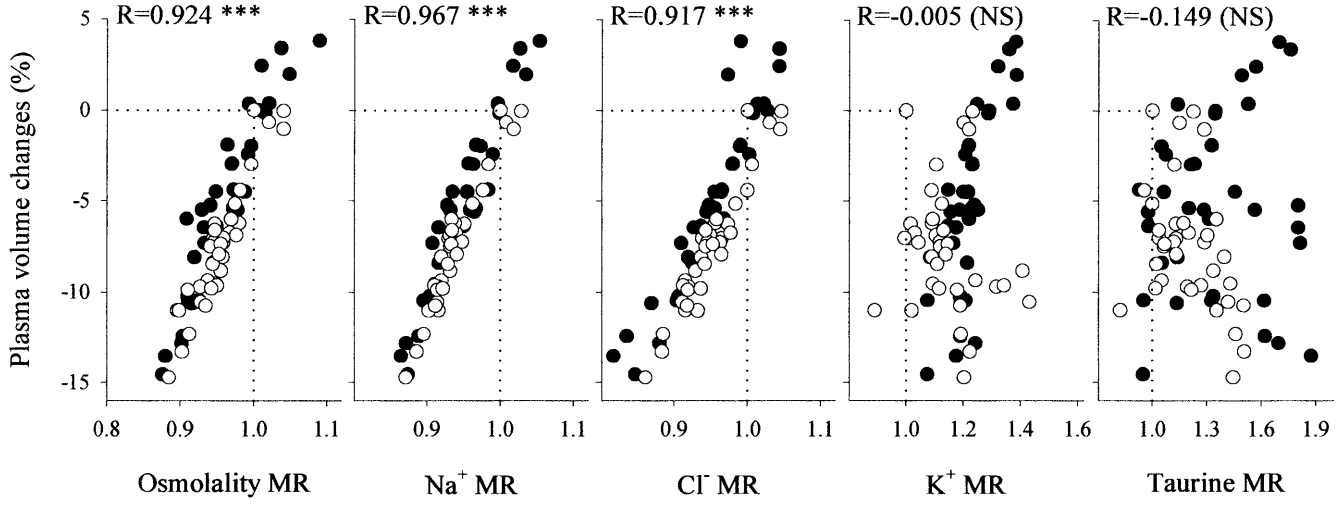

Fig. 4. Correlation between plasma volume changes (%) and plasma osmolality, sodium, chloride, potassium and taurine mass ratio (*MR*) calculated as the concentration of taurine or ion corrected for changes in plasma volume divided by the pre-exercise concentration of taurine or ion. Data were taken during two 90-min cycling bouts at 70% MPO at the onset of the exercise and every subsequent 15 min in dehydrated (○) and in hydrated conditions (●) ($n = 6$). The correlation coefficient and its statistical significance are indicated: ***$P < 0.001$, NS $P = 0.05$

potassium MR ($R = -0.005$, NS) or with taurine MR ($R = -0.149$, NS). However, potassium and taurine values showed a statistical correlation ($R = 0.570$, $P < 0.001$).

Discussion

Plasma taurine content

The plasma osmolality had increased at the end of the 90 min of cycling exercise in DC subjects, whereas the fluid intake in HC maintained the plasma osmolality (Table 1). Assuming that the changes in muscle osmolality were similar during both exercising tests, this observation is in agreement with the hypothesis of our experimental protocol. The gradient of osmolality between the extra- and the intracellular medium would be expected to be higher in HC than in DC. During exercise, the increase in muscle osmolality is commonly attributed to lactate production (Lang et al. 1998) and to phosphorylcreatine breakdown (Sejersted and Sjogaard 2000). The higher osmolality generates the driving force for solute-free fluid movement into the muscle (Nielsen et al. 1986; Ward et al. 1996), which leads to swelling. Subsequently, an RVD process would occur with the release of ions (mostly potassium and chloride) and other osmotically active solutes including taurine from the cell (Lang et al. 1998). The present study confirms that the intracellular osmolytes potassium, chlorine and taurine are extruded from the muscle during exercise (Cuisinier et al. 2001; Graham et al. 1991, 1995), due to an RVD. Thus, the release of taurine and potassium should be higher when the gradient of osmolality is greater (i.e. in HC).

Figure 2 shows that plasma taurine concentration was increased by 76% in HC, but by only 44% in DC at the end of the 90-min cycling exercise. However, the difference between the two protocols was not significant. Nevertheless the observed increases in concentrations could have been caused by an increase in solute content or a decrease in plasma volume (Fig. 1). When corrected for plasma volume variations, the increase in plasma taurine content was significantly higher in HC (62%) than in DC (30%, $P = 0.036$; Fig. 2).

Taurine concentration in muscle is approximately 500 times higher than in plasma (Blomstrand and Saltin 1999; Graham et al. 1995); a small change in permeability of muscle membrane could result in taurine release into the plasma. Munjal et al. (1983) reported that muscle membrane permeability is assessed by the appearance of myoglobin in plasma. Our myoglobin plasma levels were similar both prior to and after the exercise and between HC and DC trials. Such results support previous studies in which it was shown that cycling exercise in trained subjects is not accompanied by increases in muscle membrane permeability (Noakes 1987).

Taurine in blood cells

Plasma and whole-blood taurine concentrations are not correlated under normal physiological conditions (Anderson et al. 1988; Trautwein and Hayes 1990). In these present studies, we identified that the concentration of taurine was approximately four times higher in whole-blood than in plasma (Fig. 2). The taurine concentration in red blood cells is five times higher than in plasma (Proenza et al. 1994), while taurine concentrations of 20 mmol·(kg cell water)$^{-1}$ have been found in platelets and leukocytes (Jacobsen and Smith 1968; Trautwein and Hayes 1990). Theoretically, the observed increase in plasma taurine that we identified during exercise could be due to a release of taurine from blood cells. Contrary to this hypothesis, the present data show that the taurine content in blood cellular elements was increased substantially during exercise both in HC and DC. Thus, plasma taurine changes cannot originate from blood cells, although the latter appears to play a buffering role by attenuating plasma taurine increase. Cuisinier et al. (2001) showed that taurine concentration in cell-rich plasma was not modified after a marathon run. It is therefore likely that the erythrocytes are responsible for the taurine content increase in blood cellular elements.

While the osmolality of blood cells does not change during exercise, in the present study the osmolality of the surrounding plasma did increase (Table 1). In vitro studies have shown that when suspended in a hyperosmotic medium, various types of cells elevate their intracellular KCl and taurine by active uptake as part of a the process of regulatory volume increase (for review see Kwon and Handler 1995). The observed increases in blood cell taurine concentrations or the reported increases in blood cell potassium content (Sejersted and Sjogaard 2000) during exercise could contribute to the osmoregulatory response subsequent to an increased plasma osmolality. However, in vivo studies that report a potassium shift into red blood cells during exercise are conflicting (reviewed in Sejersted and Sjogaard 2000). The muscle at rest is able to take up potassium that has been released previously by working muscles during endurance exercise (Chin et al. 1997; Lindinger et al. 1990; Sejersted and Sjogaard 2000). Similarly, during intermittent exercise, potassium released by the working muscle is taken up by the same muscle during the recovery period (Medbo et al. 2000). Inactive muscle and blood cells probably act as buffers of both the taurine and potassium released by the exercising muscle to regulate plasma osmolality.

Renal filtration of taurine

An impaired renal excretion of taurine may also explain the changes in plasma taurine content. In the present study, no significant increases in taurine excretion rates were observed. This is in good agreement with previous investigations performed during a 100-km run (Decombaz et al. 1979) or a marathon run (Cuisinier et al. 2001). The renal clearance of taurine did not change in DC, but did increase in HC. On the contrary, Decombaz et al. (1979) showed that amino acids such as taurine, with a resting clearance above 1 ml·min^{-1}, had a reduced clearance during a 100-km run. This observation was attributed to a reduction in blood flow associated with long-term exercise. However, other studies have not reported significant decreases of amino acid renal clearance during exercise (Cuisinier et al. 2001; Vlcek and Stemberk 1990). In the present study, taurine clearance was almost doubled in the HC trial, together with a higher plasma taurine concentration. The increased clearance could thus be attributed to an increased glomerular filtration or to a modification of the tubular reabsorption process. Indeed, the taurine transport activity of kidney cell decreases after incubation with media containing a high concentration of taurine (Jones et al. 1991). Therefore, taurine excretion by the kidney cannot explain the observed increase in plasma taurine.

Taurine and plasma volume regulation

During the 90 min of cycling, the plasma taurine concentration increased by less than 0.1 mM. Thus, it contributed very little to the 10 mosmol·kg^{-1} increase in plasma osmolality. Moreover, neither taurine nor potassium plasma content was correlated with the changes in plasma volume (Fig. 4). Thus, it can be assumed that both taurine and potassium leave the muscle to regulate the muscle osmolality, but neither of these molecules can explain the plasma volume changes induced by exercise.

In contrast, plasma sodium and chloride levels were correlated with changes in plasma volume. Plasma sodium decreased together with plasma volume during the first 15 min of the exercise. At later time points, when the plasma volume returned to pre-exercise values, sodium levels again altered in parallel (Fig. 4). These data confirm previous studies showing the importance of sodium in the regulation of extracellular fluid shifts (Greenleaf et al. 1998).

In conclusion, the present study suggests that plasma taurine content increases during endurance exercise due to an osmoregulatory process. We postulate that taurine is released by contracting muscles and taken up by other tissues, such as blood cells, which play an important role in osmotic regulation.

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