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MINERAL CONCENTRATIONS IN HUMAN SWEAT DURING EXERCISE*

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ABSTRACT

Sweat losses during exercise in hot and humid environment may be as high as 10 l/d. The issue of mineral losses in sweat is important because of the risk of deficiency of some elements. The average values for mineral concentrations in human sweat, usually reported in the literature are: 20-80 mmol/l for sodium, 4-8 mmol/l for potassium, 0-1 mmol/l for calcium, 5-15 μmol/l for zinc, 1-10 μmol/l for iron, 2-10 μmol/l for copper and 0.3-1.5 mmol/l for magnesium. Several factors, which influence sweat composition are also discussed in this paper. A review of the literature on sweat composition indicates that significant amounts of sodium, potassium, calcium, zinc, and copper may be lost in sweat, especially under conditions of profuse sweating. These losses are particularly important for people on marginal and deficient diets, in spite of the conservation mechanisms observed for some elements (sodium, chloride, zinc). Acclimatization to exercise in the heat will result in lower excretion of sodium and chloride but other element concentrations will still be high. Sweat losses of these minerals should be included as part of the total daily output in balance studies and in the estimation of requirements. At present state of knowledge we cannot say that supplementation of any elements due to their dermal loss is necessary, but athletes training in hot and humid environments should be aware of this problem and should pay more attention to their diet.

Keywords: sweat composition, electrolytes, minerals, exercise, mineral balance

There is considerable disagreement among investigators about sweat losses of some elements especially in relation to their total daily losses and requirements. This is caused mainly by large variations in the results from studies on mineral losses in sweat, reflecting variations between individuals, differences due to experimental conditions and differences due to the method of sweat collection. There are relatively many studies of electrolyte concentration in sweat, and the average values that are usually reported are about 20-80 mmol/l for sodium, 4-8 μmol/l for potassium and 0-1 μmol/l for calcium (35). However limited data exist on trace mineral losses in sweat. Knowledge of dermal losses of minerals in humans is important for a number of reasons: it will give necessary information for the accurate determination of mineral balance; it will determine whether, and to what extent, mineral requirements are increased under sweating conditions, and finally, it will lead to better understanding of the body's excretory mechanisms.

The issue of mineral losses in sweat may be especially important for people living and working in hot and humid environment, where losses of sweat may be as high as 10 l/d or more (44). Athletes training

*The Polish version of the article was published in Medicina Sportiva 5 (2): 89-98, 2001 and exercising in such conditions can be at special risk of deficiency, especially as their dietary mineral intake is quite often insufficient (6, 12). It has been shown for sedentary individuals that sweat loss of sodium, potassium and calcium should be included in balance studies and estimations of requirements, otherwise the results are not correct (9, 10, 52). The results of studies on sweat mineral loss in athletes should also be included in studies on mineral balance and requirements in athletes and in studies on the composition of sports drinks. But there is still a need for reliable information about sweat composition of exercising people. The aim of this work was to review the literature on mineral concentrations in human sweat during exercise and an attempt to give some suggestions for future study.

Sodium

Sodium concentration in human sweat, reported in the literature, is within the range of 13 and 146 mmol/l (3, 7, 10, 14, 15, 16, 18, 20, 26, 34, 45, 54). There are some discrepancies in the results obtained by different authors, which may be the result of different experimental conditions, e.g. different methods of sweat collection. Other factors may also be important, as will be discussed later.

The Reference Nutrient Intake for sodium is 1600 mg/d (for adults) (8) and according to the most recent Polish recommendations, minimal intake by active people should be 625 mg/d (55). But intake is usually higher (10, 55) and in normal conditions, when daily sweat loss is about 0.5 l (5), sweat sodium loss should not be dangerous. However, for people living, working or exercising in a hot, humid environment, when sweat secretion reaches 10 l/d or more, sodium sweat losses may be important. Robinson and Robinson (44) suggested that for the average, unacclimatized man beginning work in excessive heat, the addition of about 2 g of salt (corresponds to 34 mmol of sodium) in each litre of water ingested to maintain water balance, should be an adequate supplement to his usual daily, dietary salt intake. After acclimatization sodium concentration in sweat decreases (16, 18, 44) and probably supplementing the salt intake at meal times according to taste is equivalent to the output, but even then addition of sodium to drinks, especially during and after exercise, is recommended not only to replace its loss in sweat, but also to stimulate water (and glucose) absorption in the jejunum, and thus allow for better rehydration (35). Maughan (35) suggested that rehydration drinks should have a sodium concentration similar to that of sweat.

Consolazio and coworkers (10) estimated that sodium excretion in the sweat in a hot, humid environment accounted for more than 50% of the total daily excretion. They concluded that these losses should be considered in balance studies since otherwise balance and daily minimal allowances data would be greatly misinterpreted. Bergeron and co-workers (3) estimated daily losses of sodium (with sweat sodium included) in 20 acclimatized to the heat tennis players on 3 days of round-robin tournament play (i.e., 2 singles matches followed by 1 doubles match per day) in a hot environment (temperature about 32°C and humidity about 50%) and compared the results with dietary intake of sodium. The conclusion was that estimated daily losses of sodium (males: 159 mmol/d, females: 87 mmol/d) were met by the players' dietary intakes (males: 279 mmol/d, females: 179 mmol/d). But these are only the estimates of daily losses and intake of electrolytes was not well controlled.

Potassium

Potassium concentration in human sweat ranges from 3 to 20 mmol/l (3, 10, 14, 15, 16, 18, 20, 26, 33, 34, 45, 54).

The Reference Nutrient Intake and Polish recommendations for potassium are 3500 mg/d (for adults) (8, 55). Consolazio and co-workers (10) estimated that potassium excreted in sweat under conditions that produce profuse sweating, accounted for approximately 30-50% of the total excretion and that potassium balances, after including the sweat potassium loss, were on the negative side for all of their subjects. Conclusions about the relationship between potassium excretion in sweat and the total daily potassium excretion are often contradictory. Some authors suggest that sweat potassium losses are negligible, while the others say that they can be as high as that lost in diarrhoea (in 10, 34), even in acclimatized individuals, because sweat potassium concentration does not decrease after acclimatization (16, 34, 44). The study of Bergeron et al. (3), mentioned before, indicate that the average estimated daily potassium losses during multiple tennis matches played on 3 successive days in a hot environment were significant (31 mmol/d for males and 19 mmol/d for females), but that they were met by daily potassium intake.

Calcium

The average calcium loss measured by Vellar and Askevold (53) were 0.2 mmol/l in cell-free sweat, Shirreffs and Maughan (45) reported 1.3 mmol/l as the average sweat calcium concentration, Costa and co-workers - 1.8 mmol/l and Verde and co-workers (54) obtained values as high as 2.4 mmol/l. Mitchell and Hamilton (38) observed that calcium concentration in sweat decreased during a 3 hour collection period from 1.3 to 0.1 mmol/l.

The Reference Nutrient Intake for calcium is 700 mg/d (8), Polish recommendations for highly active adults are 900-1200 mg/d (55). Balance studies by Consolazio et al (9) showed that sweat calcium concentration averaged 21% of the total output in a temperate environment and 37% during exercise in the heat. They demonstrated also that people living and working in a hot, humid environment, consuming a low-calcium diet (440 and 600 mg/d) were in negative balance when sweat calcium losses were included. They stressed again the necessity of considering dermal losses in balance studies and estimation of requirements, especially under conditions which induce profuse sweating (9, 53).

Zinc

Zinc concentrations in studies of Aruoma and co-workers (2) varied from 6.4 to 12.7 µmol/l for samples taken from different body sites. The average zinc loss measured by Tipton and co-workers (49) were 13.3 µmol/l during exercise in a neutral temperature and 8.0 µmol/l in a hot temperature. Omokhodion and Howard (40) reported 5.5 µmol of zinc per litre of sweat lost. Other reported values are between 2,9 and 19,5 µmol/l (7, 17, 22, 42).

The Reference Nutrient Intake for zinc is 7.0 mg/d for women and 9.5 mg/d for men (8). In the Polish recommendations it is 13 and 16 mg/d for woman and men respectively (55). Milne et al. (37) showed in their balance study that the amount of zinc excreted in sweat had substantial influence on the calculation of zinc balance, but Jacob et al. (23) estimated that the surface zinc losses increased the dietary requirements by only 5%. However, these balance studies were performed on sedentary individuals, and prolonged exercise and training have been reported to lead to decreases in zinc plasma levels (2, 6, 12, 49). Tipton and co-workers explained this effect by the high sweat zinc losses, combined with increased metabolic demands and often reported low zinc intake by athletes.

On the other hand, a gradual reduction of zinc loss in sweat during depletion and a subsequent increase after supplementation was observed (17, 23, 37, 42). Jacob and co-workers (23) suggested that this might reflect a homeostatic mechanism for conservation of zinc.

Iron

Aruoma and co-workers (2) reported the iron losses in sweat in the range of 3.6-8.9 μmol/l, depending on the site of the body where sweat was collected. Lamanca and co-workers (31) observed an average sweat iron loss of 3.2 μmol/l for men and 7.5 μmol/l for women. In an experiment by Paulev and co-workers (41), the concentration of iron in cell-rich samples was 5.2 μmol/l and in cell-free samples it was 2.4 μmol/l. Other authors, presenting results from non-exercise induced sweat, gave values of sweat iron concentration between 4.5 and 21 μmol/l (10, 23, 24, 42, 50, 52). Brune and co-workers (5) introduced an extensive procedure of cleaning their subjects before sweat collection and excluded the sweat sample from the first period to avoid contamination from desquamated epithelial cells and from the ducts of sweat glands. Iron loss in cell-free sweat was under 1 μmol/l and in cell-rich sweat it was about 2-4 μmol/l, which was at the lower end of the range reported by other authors.

The Reference Nutrient Intake for iron is 8.7 mg/d for men and 14.8 mg/d for women (8). In the Polish recommendations it is 16 and 18-19 mg/d respectively (55). Blood donors, menstruating women and pregnant women are in the group of possible iron deficiency and in some cases iron supplementation is recommended (8). Clarkson (6) reviewed the results of many studies of iron status in athletes: some of them showed that athletes are another group at risk of iron deficiency, but others did not support these findings. The term „sports anaemia" is often used to describe the condition in athletes when haemoglobin levels are at the lower end of the normal range or below. The reason for this is still unclear but in many cases it is believed to be due to an expansion of the plasma volume. Generally, prolonged exercise increases the rate of iron metabolism and endurance athletes, especially menstruating women and athletes consuming a poor diet (e.g. those restricting their energy intake, which is often accompanied by insufficient intake of many nutrients), can be at risk. Some studies showed that, in relation to total iron losses, significant amounts of iron may be lost in sweat (10, 38, 41, 52). Lamanca and co-workers (31) estimated that one hour of exercise in a warm, humid environment, increased the total iron losses by 20% (for male and female runners) and the average female runner in their studies was in negative iron balance. On the other hand, Brune and co-workers (5), suggested that the importance of sweat iron loss is usually overestimated because of contamination of iron from epithelial cells desquamated under the hot and humid conditions necessary to induce sweating. This corresponds well with recent data by Nachtigall et al. (39), who used a very sensitive technique of radio-iron labelling and demonstrated that amount of iron excreted through sweat glands is only a small contribution to the total iron loss observed in runners (^{56}Fe activity found in sweat sample was <0.004% of the dosage). They also demonstrated that no substantial amounts of iron derived from the haemoglobin pool are excreted by sweating because ^{56}Fe activities were found in sweat samples only on the first day after the oral administration of ^{56}Fe and no later even under conditions of intensive training and competition. The results of this radio-isotope study showed that gastrointestinal blood loss was the main reason for negative iron balance in runners.

Copper

Copper concentrations in sweat reported in the literature range from: 1.5-1.8 μmol/l (23), 8-14 μmol/l (2), 7.7 μmol/l (40), to as high as 20-24 μmol/l (7, 22).

The Reference Nutrient Intake for copper is 1.2 mg/d for adult men and women (8). The Polish recommendations are much higher: 2.0-2.5 mg/d (55). It was estimated that the surface losses of copper increased the dietary requirements (by balance measurements) by 25-30% (23). There is no basis to suggest that athletes may be copper deficient (6). The normal dietary copper content is probably adequate, but this problem should be reviewed for people (including athletes) under conditions of profuse sweating.

Other elements

There are also some studies where other element concentrations in human sweat were measured. Concentration of magnesium was 0.3-1.7 mmol/l (7, 10, 14, 15, 34, 45, 54), manganese: 0.06-0.4 μmol/l (7, 40), nickel: 0.9-2.2 μmol/l (7, 22, 40), lead: 0.3-0.6 μmol/l (7, 22), cadmium: 0.2 μmol/l (7), aluminium: 0.6 μmol/l (40).

The main anion excreted in sweat is chloride and its concentration is usually between 8 and 60 mmol/l (7, 14, 16, 18; 26, 45, 54). A significant positive correlation was found between sodium and chloride concentrations and between potassium and chloride concentrations (47).

Factors, which influence sweat composition

Differences in excretion of minerals between individuals were reported by most authors of sweat composition studies. They may be explained by differences in diet consumed, degree of acclimatization, training status, and differences between males and females. Some differences observed among the data given by various authors may be dependent on methods of sweat collection and generally on the experimental conditions e.g. the temperature used to induce sweating, which influence sweating rate.

Diet

One of the reasons why the results presented in the literature are so different might be varied dietary intake of studied elements by subjects. It has been shown that sodium and chloride concentrations fall as deficiency of salt develops (15, 36). The same was observed for zinc (17, 37, 42). Prasad and co-workers (42) observed that content of iron in the sweat of iron-deficient subjects was significantly reduced, but only when total sweat was taken into account. These results would suggest that the body in deficiency tends to conserve some elements by their decreased secretion in sweat. On the other hand, Malhotra and co-workers (34) reported that potassium loss in sweat did not show any drop with increasing potassium deficiency in the body. This suggests that there is no apparent mechanism of conservation of potassium loss in sweat. Authors furthermore suggest that observed conservation of potassium through reduced urinary excretion may not be sufficient to prevent occurrence of deficiency, when intake is not adequate. Thus there are relatively greater chances of occurrence of potassium deficiency in hot and humid environments than there are for sodium, for which efficient hormonal conservation mechanism exists.

Degree of acclimatization

Acclimatization to the heat is characterised by an earlier onset of sweating, more profuse sweating and reduced concentration of some elements, e.g. sodium and chloride (16, 28, 29, 44, 51). This effect was not observed for potassium concentration in sweat (16, 34).

Training status

Physical training has been shown to improve the secretory activity of the human sweat gland (46, 47). It has been explained by a central mechanism in which stimulation of the heat centre by exercise induced hyperthermia increases the mechanisms regulating the temperature in deep parts of the body. There is also some evidence for the role of peripheral mechanisms in activation of sweating by exercise training. Training alters the function and morphology of the sweat glands. An improved secretory capacity of the sweat glands has been attributed to an increase in cholinergic sensitivity of these glands.

Sex differences

In the same experimental conditions sweat rates of male subjects are higher than of females (3, 4, 19, 22, 27, 31), but there appears to be an inverse relationship between the volumes of the sweat excreted and the concentrations of the elements. It was reported that concentration of sodium and chloride (7), iron (31, 50), zinc and copper (22) were lower in male subjects.

Methods of sweat collection

Various procedures of sweat sampling are used in studies on sweat composition, including arm bags (9, 11, 15, 26, 50), capsules (1, 25), gauze-pads (3, 54) and the washdown method (5, 11, 14, 45).

Kuno (30) has shown that individuals vary in their distribution of sweating areas (some people sweat mostly on the back, while the others on the chest, etc.). Auroma et al (2) compared concentrations of iron, copper and zinc at different body sites. Higher values were obtained when abdomen and chest sweat was analyzed, in comparison to arm and back. These results indicate that using only local sweat for analysis can be misleading. The arm bag (or leg bag) method is criticized for interfering with the evaporation of sweat from the skin surface, which influences sweat secretion and composition (4, 7, 21). It has been shown for sodium and potassium (15, 26), calcium (11), chloride (43) and some trace elements (7) that the arm bag sweat collection method leads to a misleadingly high estimate of the total body sweat concentrations. This method can be used only to determine changes in sweat composition due to adaptation to different stimuli.

The most accurate and reproducible method of whole body sweat loss and composition is the whole body washdown method (7, 21, 32, 44, 45).

Sweating rate

Concentrations of some of the elements measured are influenced by sweat flow rates. Sodium concentration is significantly higher at higher sweating rate (13, 14, 28, 47, 54). It is probably due to reduced ductal reabsorption (44, 48). Calcium concentration in sweat is inversely related to the rate of sweating (38, 53, 54). There was no relationship between potassium concentrations at the higher and at the lower sweating rates (13). Tipton and coworkers (49) found that the sweat zinc concentrations were significantly higher in neutral temperatures (lower sweating rate), than in hot environments (higher sweating rate). Iron concentration was unaffected by the sweating rate (38).

Conclusions

A review of the literature on sweat composition indicates that significant amounts of sodium, potassium, calcium, zinc, and copper can be lost in sweat, especially under conditions of profuse sweating. These sweat losses are particularly important for people on marginal and deficient diets, in spite of the conservation mechanisms observed for some elements (sodium, chloride, zinc). Acclimatization to exercise in the heat will result in lower excretion of sodium and chloride but other element concentrations will still be high. Sweat losses of these minerals should be included as part of the total daily output in balance studies and in the estimation of requirements. However, it seems that iron loss in sweat is small and that it probably does not significantly change iron balance.

There are still too few studies on mineral balance, especially studies performed on athletes, to give any suggestions about mineral requirements for athletes and the possible need for supplementation. There is a need for more complete study of mineral balance and turnover in athletes. The whole body washdown technique is recommended for such experiments. However, people training and exercising, especially in hot, humid environments should be aware of the potential mineral losses under these conditions and should pay more attention to their diet.

The mechanisms of mineral excretion by sweat glands and the factors which influence them are still not well understood and need further research.

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