

Excretion of Sodium, Potassium, Magnesium and Iron in Human Sweat and the Relation of Each to Balance and Requirements

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In two recent studies on calcium (Consolazio et al., '62a) and nitrogen (Consolazio et al., '62b) excretions in sweat, it was observed that sweat losses were fairly high, accounting for 18 to 30% of the total calcium excretion and 13 to 18% of the total nitrogen excreted, of men exposed to 100°F environmental temperatures. As a result of these fairly high excretions of calcium and nitrogen in sweat, other mineral contents were also investigated in relation to intake, balance and requirements. These minerals included sodium, potassium, magnesium, phosphorus and iron. In addition, the daily osmolarity was also computed from the freezing point of the sweat.

A considerable amount of data is available in the literature on the concentration of minerals in sweat, but very few, if any, of these studies have been related to balance and requirements. Many values for the sodium, potassium, magnesium, iron and phosphorous concentrations in sweat have been thoroughly reviewed by Schwartz ('60) and Altman and Dittmer ('61). Sodium values ranged from 13 to 104 mEq/liter of sweat (30 to 240 mg/100 ml), potassium from 2.3 to 16.0 mEq/liter (9 to 62 mg/100 ml), magnesium from 0.04 to 4.5 mg/100 ml, iron from 0.10 to 5.3 mg/hour, and phosphorus from 9 to 43 µg/100 ml of sweat.

The fairly high nitrogen and calcium excretions in sweat reported previously (Consolazio et al., '62a,b), especially during profuse sweating conditions, indicate that mineral losses in sweat may be sufficiently important to warrant further investigation. It is the opinion of investigators (Mitchell and Hamilton, '49; Mitchell

and Edman, '62) that sweat losses should be included as part of the total daily output in balance studies, otherwise erroneous conclusions can be drawn.

An attempt was made to design a study to answer some of the following questions: (a) what are the mineral losses in relation to high sweat rates; (b) what are the mineral losses in relation to the daily intake and their effect on balance studies; (c) what are the mineral losses in relation to mineral allowances and requirements; and (d) do these sweat losses decrease after acclimatization?

EXPERIMENTAL DESIGN

A study was conducted for a total of 32 days on three healthy young men. It consisted on an 8-day preliminary period (1) at 24°C (75°F) and 50% relative humidity (RH), four 4-day periods at 37.8°C (100°F) and 70% RH (1, 3, 4 and 5), and an 8-day recovery or adjustment period at 24°C (75°F) and 70% RH (6), and sweat rates were computed daily for each man. Sweat samples were collected during morning and afternoon periods. Since the quantities of sweat collected during the control and adjustment periods at 75°F were limited, no values will be reported in this paper. The daily physical activity was constant and consisted of only 30 minutes of moderate activity on the bicycle (ergometer), the remainder of the day being spent in sedentary type activities. When the men left the test area (evening) no moderate to heavy activities were permitted, the test subjects being closely supervised by the Metabolic Ward personnel, during these hours.

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All of the test phases were performed in an environmental chamber from 8:00 AM to 11:30 AM and from 12:30 PM to 4:30 PM daily with the exception of each fourth evening when the men slept overnight in the hot room at 100°F. At this time sweat samples were collected for 2- to 5-hour intervals to determine whether the sweat concentrations of the minerals were decreased with longer exposure to the heat.

The menus consisted of 4 diets that were rotated during each period. The diets supplied 8.7 gm of sodium, 2.49 gm of potassium, 343 mg of magnesium, 23.4 mg of iron and 1.41 gm of phosphorus per day. All food was offered and consumed at regular mealtimes and no other food was permitted during the day. Salt was the only mineral available ad libitum and was measured for each man during each period.

Chemical analyses of the food composites, urine, feces and sweat were performed for sodium, potassium (Baird, '53), magnesium, iron, and phosphorus (Consolazio and Johnson, '60). In addition freezing points (Fiske, '54) were performed on the daily sweats.

Sweat rates were measured for each period using the method of Adolph et al. ('47). These sweat rates were determined by measuring weight changes during the morning and afternoon periods and then adjusting for water intake, and for water loss in urine and feces. (Gaseous exchanges of respiration contributes a small quantity, which usually constitutes less than 1% of the observed decrease in body weight.) Sweat samples were collected daily during both the morning and afternoon periods for a total of 7.5 hours. These samples were collected in polyethyl-

ene bags which covered one whole arm, and were representative for the entire period each subject was in the chamber. The arm and the bag were rinsed with distilled water and dried before each collection period began.

Complete urine and fecal collections were made for 4-day periods coinciding with the repetition of the 4 diets utilized. Mineral balances were computed on each man for each period, based on the inclusion and exclusion of the minerals in sweat as a source of mineral loss.

RESULTS

The chemical analyses of the various minerals performed on the cell free sweat are presented in quantities/100 ml of sweat (table 1). This table also includes the means and standard deviations during the 7.5 hours' exposure to 100°F temperatures. After the first 4 days of acclimatization to heat, the potassium excretion in sweat ranged from 25 to 28 mg/100 ml; magnesium excretion ranged from 0.61 to 0.64 mg/100 ml, iron from 25 to 39 µg/100 ml, and phosphorus from 0.11 to 0.26 mg/100 ml of sweat. The mean excretion rate in milligrams per hour for the same exposure periods ranged from 78–106 mg for potassium, 2.0–2.4 mg for magnesium, 0.11–0.16 mg iron, and 0.45–0.81 mg/hour for phosphorus. The sodium excretion in sweat was quite variable due to the fact that salt intake was not controlled (table 1). The daily 7.5-hour mineral excretion and total osmolarity in sweat for 16 consecutive days at 100°F are compared in table 2.

On three separate occasions when the men spent 24 hours continuously at 100°F, it was observed that the sweat rate and the sodium, potassium and iron excretions in

TABLE 1
Concentration of minerals in sweat;¹ mean for three men for 16 days of exposure at 100°F (1961 study)

Minerals	Days' exposure							
	1-4		5-8		9-12		13-16	
Sodium, mg/100 ml	337	± 183.0 ²	113	± 67.5	118	± 99.4	420	± 296.3
Potassium, mg/100 ml	84	± 72.1	25	± 12.6	25	± 6.3	28	± 9.7
Magnesium, mg/100 ml	0.70	± 0.29	0.61	± 0.21	0.61	± 0.16	0.64	± 0.28
Iron, µg/100 ml	36.4	± 21.2	33.2	± 16.0	38.6	± 21.1	25.0	± 20.9
Phosphorus, mg/100 ml	0.155	± 0.119	0.260	± 0.152	0.109	± 0.087	—	—

¹ Concentration/100 ml of sweat as collected and centrifuged. Chemical analysis on supernatant fluid.

² Mean ± sd.

TABLE 2

Sweat excretion of minerals and total osmolarity; mean daily excretion of three men during daily 7.5-hour exposures at 100°F temperatures

Days of exposure 100°F	Sodium	Potassium	Magnesium	Iron	Phosphorus	Osmolarity ¹
	mg	mg	mg	mg	mg	milliosmoles
1	11176	2780	—	0.91	21.9	—
2	6210	3068	15.9	0.93	3.3	—
3	3535	658	18.5	1.13	3.8	194
4	—	—	—	—	—	221
5	2500	537	13.7	1.12	6.9	139
6	2379	555	15.4	0.81	5.4	131
7	—	—	—	1.12	—	143
8	4696	672	16.6	0.79	6.0	151
9	2623	660	17.3	0.76	3.1	112
10	3050	669	18.3	1.16	3.6	111
11	1644	516	18.6	1.26	5.2	111
12	4050	560	16.4	1.09	1.7	128
13	7090	772	17.5	0.83	—	120
14	7650	793	18.3	0.66	—	115
15	3380	757	18.6	1.41	—	135
16	6310	863	16.7	0.55	—	139

¹ -1.86°C for each 1000 milliosmoles.

TABLE 3

Diurnal variations of minerals in sweat, excretion per hour; mean for three men (1961 study)

Days at 100°F	Sodium			Potassium			Magnesium			Iron		
	7-8	11-12	14-15	7-8	11-12	14-15	7-8	11-12	14-15	7-8	11-12	14-15
hours ¹	mg	mg	mg	mg	mg	mg	mg	mg	mg	μg	μg	μg
0-3.5	375	234	944	57	74	108	3.2	2.3	2.8	159	107	179
4.5-8.5	844	289	1837	111	65	104	2.0	2.1	2.2	140	221	195
9.5-15	1235	1590	1331	115	101	82	2.2	1.8	1.5	110	155	84
15-23 (sleeping)	441	582	262	95	52	59	—	—	—	141	71	52
0-3.5 (next day)	626	945	841	90	85	115	1.8	2.2	2.2	101	193	73

¹ Zero time was 8 AM daily.

TABLE 4

Sodium balance, with and without sweat losses; mean for three men for 16 consecutive days (1961 study)

Days at 100°F	Intake	Output			Balance		Sweat as % of total output
		Urine	Feces	Sweat ¹	Sweat excluded	Sweat included	
	mg/day	mg/day	mg/day	mg/day	mg/day	mg/day	
1-4	10229	2600	105	5784	+7524	+1740	68.1
5-8	8729	2170	81	3188	+6478	+3290	58.5
9-12	8729	2360	95	2840	+6274	+3434	53.7
13-16	— ²	2440	94	6110	—	—	—

¹ Includes only sodium excreted in sweat while in environmental chamber for 7.5-hour period. During three overnight exposures to 100°F the sodium excreted in sweat averaged 902 mg/hour or 14.88 gm/the 16.5-hour period.

² Extra salt from shaker not recorded.

sweat were decreased by approximately 50% during the sleeping hours. On arising and being active again, the morning sweat mineral losses were again at a higher level (table 3).

Mineral balances, during the 7.5-hour collection period, were computed for sodium, potassium, magnesium, iron and phosphorus. These balances were calculated with and without the inclusion of

TABLE 5
Potassium balance, with and without sweat losses; mean for three men for
16 consecutive days (1961 study)

Days at 100°F	Intake	Output			Balance		Sweat as % of total output
		Urine	Feces	Sweat ¹	Sweat excluded	Sweat included	
	mg/day	mg/day	mg/day	mg/day	mg/day	mg/day	
1-4	2493	2150	89	1776	+254	-1522	44.3
5-8	2493	2400	83	588	+10	-578	19.1
9-12	2493	1860	103	596	+530	-66	23.4
13-16	2493	1820	72	796	+601	-195	33.5

¹ Includes only potassium excreted in sweat for 7.5 hours in environmental chamber. During the three overnight exposures to 100°F, the potassium excreted in sweat averaged 84 mg/hour for a total of 1.39 gm for the 16.5-hour period.

TABLE 6
Magnesium balance, with and without sweat losses; mean for three men for
16 consecutive days (1961 study)

Days at 100°F	Intake	Output			Balance		Sweat as % of total output
		Urine	Feces	Sweat ¹	Sweat excluded	Sweat included	
	mg/day	mg/day	mg/day	mg/day	mg/day	mg/day	
1-4	343	25.7	107	17.2	+210.3	+193.1	11.5
5-8	343	23.6	112	15.2	+207.4	+192.2	10.1
9-12	343	23.1	102	17.7	+217.9	+200.2	12.5
13-16	343	21.9	76	17.8	+245.1	227.3	15.4

¹ Includes only magnesium excreted in sweat for 7.5 hours in environmental chamber. During the three overnight exposures at 100°F, the magnesium excreted in sweat averaged 1.82 mg/hour for a total of 29.7 mg during the 16.5-hour period.

TABLE 7
Iron balance, with and without sweat losses; mean for three men for
16 consecutive days (1961 study)

Days at 100°F	Intake	Output			Balance		Sweat as % of total output
		Urine ¹	Feces	Sweat ²	Sweat excluded	Sweat included	
	mg/day	mg/day	mg/day	mg/day	mg/day	mg/day	
1-4	23.4		20.5	1.01	+2.9	+1.9	4.7
5-8	23.4		19.4	0.96	+4.0	+3.0	4.7
9-12	23.4		21.1	1.07	+2.3	+1.2	4.8
13-16	23.4		21.5	0.86	+1.9	+1.0	3.9

¹ Negligible output.

² Includes only iron excreted in sweat for 7.5 hours in environmental chamber. During the three overnight exposures at 100°F, the iron excreted in sweat averaged 0.102 mg/hour, a total of 1.68 mg for the 16.5-hour exposure.

TABLE 8
Phosphorus balance, with and without sweat losses; mean for three men for
16 consecutive days (1961 study)

Days at 100°F	Intake	Output			Balance	Sweat as % of total output
		Urine	Feces	Sweat		
	mg/day	mg/day	mg/day	mg/day	mg/day	
1-4	1405	770	9.8	9.9	+625	1.2
5-8	1405	891	7.8	6.1	+500	0.7
9-12	1405	896	8.7	3.4	+497	0.4
13-16	1405	868	8.1	—	+529	—

TABLE 9
Total daily excretion of minerals; mean for three men (1961 study)

	Total excretion		7.5 hours	16.5 hours	Sweat excretion as % of total excretion	
	7.5 hours	16.5 hours ¹			7.5 hours	16.5 hours
	gm	gm	mg/hour	mg/hour		
Sodium	4.51	14.9	601	902	62.8	88.7
Potassium	0.94	1.39	125	84	30.1	52.0
	mg	mg				
Magnesium	17.0	29.7	2.3	1.8	12.4	27.5
Iron	0.98	1.68	0.131	0.102	4.5	11.0

¹ Minerals excreted in sweat during the regular 7.5-hour daily exposure and for three evenings when the men spent the remaining daily time (16.5 hours) at 100°F.

the sweat mineral losses. The sodium balance varied due to the variation in daily intake (table 4). The potassium balance was positive when the sweat losses were excluded but were negative when the sweat losses were included, averaging -1522, -578, -66 and -195 mg/day for the 4 consecutive 100°F periods (table 5). Magnesium balances did not vary greatly when comparing the inclusion and exclusion of the sweat losses, due to the extremely high retention of magnesium (table 6). Iron balances, even though they were reduced by approximately one-half, were still on the low positive side (table 7). The quantities of phosphorus in sweat were so small in comparison to the total daily intake that they did not change the highly positive balances significantly (table 8).

The sweat losses during the 7.5-hour exposure periods are presented as percentage of the total excretion in tables 4-8. Sodium in sweat accounted for 54 to 68%, potassium for 19 to 44%, magnesium for 10 to 15%, iron for 4 to 5% and phosphorus for 0.4 to 1.2% of the total excretion of each respective element. If one included an average value for mineral losses in sweat during the remaining 16.5 hours of the day when the men were exposed to 100°F temperature (days 7, 11 and 15) the total daily mineral excretion in sweat was approximately doubled (table 9).

DISCUSSION

It has been mentioned previously that sweat collections were made daily using the polyethylene bag, that covered one

whole arm. The arm sweat which was representative for the entire period, was assumed to be comparable to the total body sweat. But a question arises whether this is a valid comparison. It has been shown by some investigators (Dill et al., '38; Johnston et al., '50; and Ladell, '48) that the various constituents of arm sweat are reasonably representative of the total body sweat. Van Heyniger and Weiner ('52) on the other hand are in disagreement, observing that the arm sweat is more concentrated than the rest of the body. Another factor to be considered is whether the arm bag will cause depression of the sweat rate. Collins and Weiner ('62) have observed a rapid depression of sweat gland activity in the forearm when the arm was covered with a sweat collection bag. Data are presented showing that the sweat rate is considerably less in humid environments than in dry conditions. These authors believe that the sweat depression in the arm bag may have been due to obstruction of the sweat gland ducts, by the excessive skin hydration.

Sodium is essential for the normal functioning of the body since it contributes to the acid-base balance of the body and since it is responsible in large measure, for the total osmotic pressure of the extracellular fluids (National Research Council, '58). Minimal allowances have not been established by the NRC due to lack of sufficient information, but it has been observed that a normal American intake will range from 3 to 7 gm of sodium/day. It has been reported (NRC, '58) that under normal conditions 90 to 95% of the

sodium intake is excreted in the urine and usually sweat sodium losses are not considered in sodium balance studies, under these conditions. Sodium can be excreted in sweat in fairly large quantities to disturb homeostasis and as a result seriously impair the economy of the organism (Schwartz, '60). Sodium excretion in sweat is variable, being dependent on physical activity, acclimatization, adrenal cortical activity, environmental temperature, humidity and body temperature. Under conditions of this study, where the daily sodium intake ranged from 8 to 10 gm/day, the losses of sodium in sweat accounted for more than 50% of the total daily excretion. Since the salt intake was *ad libitum* it was not possible to study the full effects of acclimatization on sodium excretion, but it was observed that the sweat sodium decreased appreciably during the first 12 days exposure to heat, which is in agreement with data reported in the literature. The sodium balance was highly positive by more than 3 gm even with the inclusion of the losses in sweat.

Potassium has been shown to be a required nutrient and is one of the principle basic elements in intracellular fluid, being found in greatest quantities within the cell. It is also a very important extracellular fluid constituent since it can influence muscular activity, notably the cardiac muscle, and can affect the excitability of the nerve tissue. Muscle protein repletions may demand an additional potassium intake of 2.7 mEq for each gram of nitrogen. The NRC ('58) has not established minimal allowances for potassium but a normal United States diet usually contains from 2.4 to 4.5 gm. An intake between 0.8 to 1.3 gm of potassium/day would be very close to the daily recommended allowances (NRC, '58). Potassium deficiencies, manifested by muscular weakness, increased nervous irritability, mental disorientation and cardiac irregularities, can be produced by gastrointestinal losses, by renal losses or by low potassium intake, and are frequently accompanied by metabolic alkalosis. The data in the literature are too limited to draw any specific conclusions on the relationship of potassium excretion in sweat and the total daily potassium excretion, as they may be related

to such variables as body temperature, acclimatization to extreme heat, sweat rate and physical exercise. In some instances appreciable quantities of potassium in sweat have been reported (Schwartz, '60; Altman and Dittmer, '61) in man, living and exercising in extremely hot environments, but Davidson et al. ('59) and the British Ministry of Agriculture ('59) believe that sweat potassium losses are usually negligible, in relation to the daily intake. The potassium excreted in sweat accounted for approximately 30% of the total daily excretion. If the potassium losses in sweat for the remainder of the day were included, these losses could account for up to 50% of the total daily excretion. The potassium balances, with the addition of the sweat potassium losses, were all on the negative side.

Even though magnesium is a very important cellular constituent, there is very limited information in the literature in relation to magnesium metabolism in the body. It is known that for normal function, cardiac and skeletal muscles and nervous tissue depend greatly on a proper balance between calcium and magnesium ions. Magnesium will replace the calcium in bone salts when there is a calcium deficiency, but magnesium in excess will inhibit calcification. Even though the NRC has set up no minimal allowance, it has been calculated that the daily magnesium intake of adults in the United States is between 250 to 350 mg/day (NRC, '58).

Unlike sodium and potassium, the magnesium excretion in sweat did not decrease appreciably during acclimatization. The sweat accounted for approximately 12.5% of the total daily excretion of magnesium but when the overnight sweat losses are included, this excretion could account for 25% of the total. This sweat loss did not greatly affect the magnesium balance, since the daily retention was approximately 200 mg/day. This retention may be in part compensation for the negative calcium balance reported in the same study (Consolazio et al., '62a), or it may be that the estimate of the minimal daily allowances of 250 to 300 mg of magnesium/day may be too high. Under the conditions of this study, the magnesium loss in sweat is relatively unimportant, but in studies on

low magnesium intakes, these losses should be considered.

Even though a few studies have been performed on the relationship of sweat losses of iron to the daily requirements, the quantitative importance of the cutaneous iron losses is still a disputed issue. It is the feeling of one group (Foy and Kondi, '57) that the inclusion of the integumental iron losses may possibly increase the iron requirements by as much as 50% under non-stress conditions, and that these excessive sweat losses in hot environments may be a contributing factor in the development of iron deficient anemias. On the other hand Hussain and Patwardhan ('59) feel that the body tends to conserve iron in the anemia state by reducing the losses through the skin. Dubach et al. ('55) using radio iron as a tracer observed that during maximum sweating in normal humans, from 0.33 to 0.52 mg of iron may be lost in sweat in a 24-hour period.

Comparisons have been made on the cell-rich and cell-free sweat iron (Hussain and Patwardhan, '59) showing that the cell rich portion is from 3 to 10 times more concentrated than the cell free sweat. It was concluded that the major portion was present in the products of cellular desquamation; and since active thermal sweating is always accompanied by cell desquamation, the loss of iron in sweat could be of far greater importance than is generally supposed.

Iron loss via the sweat amounted to approximately 1 mg during the exposure period, which was 4.5% of the total daily excretion. If the iron losses in sweat during the remainder of the day are included, they could account for as much as 11% of the total daily excretion.

With a fairly high iron intake of 23.4 mg/day, the iron balance was positive by approximately 1 mg/day when the sweat iron losses were included. These sweat iron excretions are fairly high, especially if one includes the evening losses.

Prior to the beginning of the study the test subjects were on leave at home for a three-week interval. Hence, it is assumed that they were eating a normal diet which may have been comparable to the experimental diet. With the exception of potassium all of the mineral balances were posi-

tive. Under these conditions, the subjects could have been increasing body mass, but this may not be probable since the subjects lost a total of 1.05 kg during the experimental periods at 100°F (table 10).

TABLE 10

Body weight changes; mean change for three men for each 4-day period (1961 study)

	Days	Mean change in weight	
		kg/period	kg/day
Control period	1-4	+ 0.14	
	5-8	+ 0.49	
100°F period	1-4	+ 0.17	+ 0.08
	5-8	- 0.21	
	9-12	- 0.64	- 0.066
	13-16	- 0.37	
Recovery period	1-4	+ 0.77	+ 0.08
	5-8	- 0.15	

It has been observed that sodium and potassium excretion in sweat decreased appreciably after acclimatization which is in agreement with data reported in the literature (Bass et al., '55; Dill et al., '38). On the other hand neither iron nor magnesium excretion in sweat decreased appreciably during acclimatization.

The data suggest that the excretion of sodium, potassium and iron in sweat are quite appreciable, especially under conditions that produce profuse sweating. These mineral losses must be considered in balance studies otherwise balance and daily minimal allowance data would be greatly misinterpreted. Studies in the literature where "equilibrium" was attained, under conditions of profuse sweating, should be reevaluated.

The concentration of phosphorus in sweat was found to be the lowest of any of the minerals analyzed in this study; averaging less than 0.5% of the total daily excretion. These values, which agree fairly well with data from other investigators, are relatively unimportant in computing balance studies.

The total osmolarity of sweat (freezing point) was decreased after acclimatization ranging from 116 to 141 milliosmoles after the acclimatization period. These values are comparable to other values for human sweat reported in the literature, and re-

viewed by Adams et al. ('58). These authors concluded that the osmotic concentration of sweat is hypotonic to serum and as the sweat increases, the osmotic concentration usually decreases.

SUMMARY

The results of this study show that a considerable quantity of sodium, potassium, magnesium and iron are lost in sweat of men during 16 consecutive days' exposure to environmental temperatures of 100°F. During a 7.5-hour collection period, the sweat excretions averaged 0.601 gm/hour for sodium, 0.125 gm/hour for potassium, 2.3 mg/hour for magnesium and 0.13 mg/hour for iron. Very small quantities of phosphorus are excreted in sweat, averaging between 0.45 to 0.81 mg/hour.

In the past, with the exception of sodium, very few investigators have recognized the fact that the mineral losses in sweat could be appreciable and as a result these losses have, all too frequently, been neglected in computing mineral balance. This could result in misinterpretation of the data, especially under conditions of profuse sweating. The total mineral loss should include the mineral loss in sweat. This in turn would help in estimating more realistically the minimal daily allowances of minerals.

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