The effect of work level and dietary intake on water balance and the excretion of sodium, potassium and iron in a hot climate

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1. The dietary intake, and urinary, cutaneous and faecal loss of water, sodium, potassium and iron have been studied in young men living and performing moderate work in a hot climate. The dietary intakes of K and Fe were lowered during part of the study.

2. The subjects were already somewhat acclimatized to heat; further acclimatization was achieved when they were performing work, and this was assessed in terms of the increase in their rate of sweating.

3. The subjects tended to be in marginally negative Na balance, partly owing to lowered Na intakes. Intakes and outputs of K were in balance. Losses of K in sweat amounted to 15% of intake when the dietary level was reduced.

4. The subjects were slow in adapting to changes in Fe intake, 8 d being an insufficient period for adaptation after their intake had been halved. Losses of Fe in sweat were approximately 0·3 mg/d, or one-third of the estimated requirement for absorbed Fe.

5. It is concluded that Fe losses in sweat could be a significant factor in Fe depletion if dietary Fe was low or unavailable, as there was no evidence that a low intake and absorption affected sweat losses.

In an earlier paper (Weiner, Willson, El-Neil & Wheeler, 1972) we reported an investigation into the effect of a low-nitrogen diet and a moderate work-load on the N excretion of young men who had spent all their lives in a hot climate. In particular, we considered N losses in sweat, as these are especially relevant to the nutritional status of workers in tropical climates. We found that N losses by sweating were small, decreasing when the dietary N intake was low. The faecal and urinary losses accounted for over 90% of the output both on high and low N intakes.

In addition to N, assessments were also made of water, sodium, potassium and iron balances, again with particular reference to the contribution made by sweating to the daily losses of these constituents. All of these constituents are relevant to the nutritional adjustments and stresses peculiar to hot climates. Maintenance of an adequate Na and water balance is essential for workers performing physical activity in hot conditions. In view of the prevalence of anaemia and the frequency of low Fe intake in the tropics, skin loss could have an important effect on Fe status. European studies

Table 1. *Age, mean body-weight, and height of the six Tanzanian male adults*

Subject	Age (years)	Body-wt* (kg)	Height (m)
FK	26	68·24	1·745
CM	25	67·53	1·800
JS	23	53·14	1·660
FM	24	63·24	1·670
GU	24	53·01	1·630
EM	24	57·85	1·770

* Mean values: subjects weighed immediately on waking.

(Bothwell, 1970) suggest that more Fe is lost from skin than from urine and that skin losses could account for as much as one-third of the total absorbed Fe. Loss of K in sweat is of some interest in view of the finding of severe muscle K depletion in protein-energy malnutrition (Waterlow, Cravioto & Stephen, 1960). Information on the Fe and K balances of normal tropical subjects (either children or adults) is meagre.

This investigation was carried out on young adults who were following an ordinary routine of moderate work and consuming their customary foods. The changes made in their routine for the purpose of this investigation were (*a*) to increase their activity and sweat output in one experimental period, (*b*) to decrease the N intake in a further experimental period. Salt intakes were kept at constant levels chosen by the subjects, and water was freely available. It was found that on the low-N diet there was an associated reduction in both K and Fe intake, so for these nutrients we were also able to study the effects of a reduced intake on losses, particularly in the sweat.

EXPERIMENTAL

The following is a brief account of our experiment, which has been described more fully in a previous paper (Weiner *et al.* 1972).

The volunteer subjects were six male Tanzanian medical students, and the study was carried out in Dar es Salaam, Tanzania, during April, May and June 1969. Details of age, weight and height are given in Table 1.

The three experimental periods (Table 2) each consisted of a 'run-up' period (3 d in studies 1 and 2, 5 d in study 3), during which equilibration on a constant diet was established, followed by the study period of 3 d. During the study period the diet was strictly controlled, excreta were collected, and careful note was kept by personal diaries of the subjects' activity throughout the 24 h.

In studies 2 and 3, the work consisted of rhythmic stepping using a step 230 mm high, at environmental temperatures (average 32° dry-bulb, 28° wet-bulb) similar to the outside shade temperatures. Apart from this work, the subjects had a set routine of reporting to the laboratory, where they carried out a number of simple tasks such as recording environmental temperatures and acting as clerks in connexion with tests going on.

During each study period the ingredients and quantity of the subject's diet were

Table 2. *Work level, range of dietary intake, and water loss from skin of the six Tanzanian male adults in the three study periods*

Study period	Work level	Range of dietary intake* N (g/d)	Na (mequiv./d)	K (mequiv./d)	Fe (mg/d)	Water (l/3d)	Skin water loss (l/3d)
1	Habitual activity (high N intake)	10–13	150–200	65–90	28–45	10·1–12·2	3·9–7·6
2	Habitual activity and 2 h work/d (high N intake)	10–13	150–200	65–90	28–45	10·6–15·2	5·1–11·3
3	As 2 (low N intake)	4–6	150–200	55–75	15–24	11·0–14·1	5·9–7·6

* Individual values are shown in Tables 2–4, and in Table 3 of Weiner *et al.* 1972.

kept constant. Food was cooked in distilled water, without salt, in aluminium utensils. Each subject was given a weighed allowance of salt for the day. The amount of this allowance was chosen by the subject and adjusted to his taste during the run-up period. Distilled water for drinking was freely available, and the subjects measured their own water intakes. The diets were based on the menu of the medical students' hostel, where they were prepared, but in studies 1 and 2, relatively generous quantities of meat, milk and fruit were provided. In study 3 all protein-rich foods were excluded in order to provide a low-N diet, and this brought about reduced intakes of Fe and K also. A moderate amount of alcohol was included in the diets (approximately 10 g alcohol/man per d).

The subjects were weighed daily in the nude, on a Spido man-balance, immediately on waking and again before retiring at night. Urine and faeces were collected during the study periods, and whole-body sweat was also collected by washing the subjects twice daily in distilled water and rinsing their clothes and towels. A sample of the washings was taken for analysis. The volume of sweat (CW (ml)) produced daily was calculated as follows:

$$CW = F + D - (U + S + \Delta w) - 300 - C,$$

where CW = cutaneous water loss (ml), F = weight of food intake (g), D = volume of fluid intake (ml), U = volume of urine produced (ml), S = weight of faeces produced (g), Δw = change in body-weight (g), 300 = arbitrary value for respiratory loss (ml), and C = CO_2 output $- O_2$ intake (g). Water balance (ml) was calculated from input and output as follows:

$$W = FW + D + A + M - (U + SW + CRW),$$

where W = positive or negative water balance (ml), FW = water content of food (by analysis) (ml), D = volume of fluid intake (ml), A = water from the metabolism of alcohol (ml), M = metabolic water produced (ml), U = volume of urine produced (ml), SW = water content of faeces (ml), and CRW = cutaneous and respiratory water loss (CW + 300) (ml). The alcohol content of the subjects' drinks was calculated from the food composition tables of McCance & Widdowson (1960). Metabolic water

production (M) is generally calculated from dietary protein (P), fat (F) and carbohydrate (C) as follows:

$$M = 0{\cdot}41P + 1{\cdot}08F + 0{\cdot}55C.$$

We assumed that, in studies 1 and 2, the proportions of these nutrients were P:F:C = 1:1:5, these being the proportions found in normal diets. For the low-N diet in study 3, we took the proportions as P:F:C = 0·25:1:5. The correctness of these assumptions was confirmed by chemical determination of the N and energy contents of the diets (Weiner *et al.* 1972).

A final correction was made in the calculation for the difference in weight between O_2 intake and CO_2 output, which was taken to be 115 g/d.

During the run-up periods, whole-body sweat was also collected under conditions of controlled hyperthermia by means of the hyperthermia test bed (Fox, 1967). Sweat output estimated by both of these methods was used to assess the subjects' degree of acclimatization to heat.

Analytical methods

All food and faeces were homogenized, sampled and dried before analysis. Whole-body sweat was filtered; thus calculations of the nutrient content of sweat do not include cell debris.

Na and K were determined in urine and sweat by means of an EEL Clinical flame photometer (Evans Electroselenium Limited, Halstead, Essex). Dried food and faeces were ashed at 450° in a muffle furnace, and the ash was taken up in dilute HCl. The Na and K contents of this solution were then measured with the flame photometer.

The Fe determinations presented greater technical problems because of the risk of contamination. Most of the work was done in a room which had been washed down beforehand; reagents for the urine and sweat analyses were rendered Fe-free before use; all glassware was washed in dilute HCl and glass-distilled water, and metallic equipment was covered with aluminium foil. The Fe content of urine and sweat was determined as described by Man & Wadsworth (1969), who modified the method of Bothwell & Mallett (1955). This method involves the formation of a coloured complex between ferrous iron and bathophenanthroline. Food and faeces were analysed by the method of Wootton (1958) as modified by Hegarty (1966). The material was digested with concentrated nitric acid, and the colour was developed by the addition of perchloric acid.

RESULTS

Water balance

Table 3 shows the subjects' water intake and output. In studies 2 and 3, in response to the extra work in a very warm room, our subjects drank more fluid (analysis of variance gives $P < 0{\cdot}002$) and produced more sweat (as cutaneous loss) than in study 1. Paired t tests showed that the sweat rates during the controlled hyperthermia tests were also significantly increased in studies 2 and 3, indicating that the subjects had undergone some degree of acclimatization to the additional heat load (Weiner *et al.* 1972). The faecal losses of water remained, on average, similar throughout. In

Table 3. *Water intake and output of six Tanzanian male adults for each study period*

		Total for 3 d (ml)					
			Output				
Study period	Subject	Intake*	Urine	Cutaneous and respiratory	Faecal water	Balance	Balance (ml/d)
1	JS	10109	3405	6722	448	−466	−155
	FK	10706	6195	3921	1077	−487	−162
	CM	12211	4305	7608	361	−63	−21
	EM	11202	5405	5323	335	+139	+46
	GU	10984	5525	4365	606	+488	+163
	FM	11650	6257	4890	268	+235	+78
	Mean	11144	5182	5472	516	−26	−8
2	JS	11880	2610	9512	392	−634	−211
	FK	13481	4395	8526	386	+174	+58
	CM	15231	3350	11284	229	+368	+123
	EM	11122	4105	6863	347	−193	−64
	GU	10615	4880	5063	585	+87	+29
	FM	11217	4770	6110	524	−187	−62
	Mean	12258	4018	7893	410	−64	−21
3	JS	12387	5390	7024	448	−475	−158
	FK	13711	7490	6321	751	−851	−284
	CM	14055	6185	7632	440	−202	−67
	EM	11058	3355	7567	484	−348	−116
	GU	11850	5035	5937	572	+306	+102
	FM	12159	5115	7477	333	−766	−255
	Mean	12537	5428	6993	505	−389	−130

* For method of calculation, see p. 129.

study 2 the cutaneous loss was greater than in study 1 and there was a reduced urine output. In study 3 the cutaneous loss was greater than in study 1, but was not accompanied by a reduction in urine output.

In all the studies the maximum individual negative water balance, over a 3 d period, was 6% of intake; the mean balances for the whole group were −0·2%, −0·5% and −3·1% of intake in studies 1–3 respectively. The results thus show that during the first two 3 d periods the subjects were regulating their water balance quite efficiently, but to a lesser extent during the third period. When intakes of individual days were considered, we find that on thirty out of fifty-four occasions our subjects were in some degree in negative water balance, but the extremes of the range of positive and negative were +574 and −710 ml/d, thus not exceeding 1·3% of total body-weight.

Na and K balance

Tables 4 and 5 show the subjects' intakes and outputs of Na and K during the three study periods. Wilson, Olney, Brooks, Myrden, Ball & Moore (1954) showed that the average reproducibility of isotopic studies of Na turnover was 4%; under the conditions of these experiments, and taking the error of collection and analysis into account, we do not consider a calculated 'balance' for Na or K to be significant unless

Table 4. *Sodium intake, excretion and balance of six Tanzanian male adults for each study period*

Study period	Subject	Total for 3 d (mequiv.) Intake	Output: Urine	Output: Sweat	Output: Faeces	Balance	Balance (mequiv./d)
1	JS	456	521	35	17	−117	−39
	FK	523	718	19	44	−258	−86
	CM	420	381	29	27	−17	−6
	EM	590	520	33	29	+8	+3
	GU	591	504	35	21	+31	+10
	FM	532	552	25	20	−65	−22
	Mean	519	533	29	26	−70	−23
	Mean/d	173	178	10	9	—	—
2	JS	651	599	71	12	−31	−10
	FK	564	505	45	31	−18	−6
	CM	469	442	62	12	−37	−12
	EM	488	491	77	27	−107	−36
	GU	532	515	74	12	−69	−23
	FM	504	485	53	18	−53	−18
	Mean	535	506	64	19	−53	−18
	Mean/d	178	169	21	6	—	—
3	JS	691	639	56	56	−60	−20
	FK	502	538	43	59	−138	−46
	CM	462	432	82	53	−105	−35
	EM	538	474	89	32	−57	−19
	GU	525	400	75	45	+5	+2
	FM	488	447	71	14	−44	−15
	Mean	534	488	69	43	−67	−22
	Mean/d	178	163	23	14	—	—

it exceeds ±5% of intake. On this basis, subjects GU and FM were in Na balance throughout. Subjects JS, CM and EM were each in negative balance during one of the three studies, to the extent of 11–12% of intake. The sixth subject, FK, was in marked negative balance in studies 1 and 2, and his urine excretion in study 1 was surprisingly high.

For the group as a whole, the average Na intake remained fairly constant for each of the three studies (173–178 mequiv./d) despite the change in diet in study 3. Of the excreta, the urine loss accounted for 89, 85 and 81% of total loss in studies 1–3 respectively. Urine losses were also very close to intake, and our subjects' sweat Na loss was low compared with that found by Collins, Eddy, Hibbs, Stock & Wheeler (1971) or by McCance, El-Neil, El-Din, Widdowson, Southgate, Passmore, Shirling & Wilkinson (1971). The sweat loss, though small (about 6% of intake), doubled in studies 2 and 3 compared with study 1. This increase, which was accompanied by a reduction in urine Na loss, represents the outcome of an increase both of sweat Na concentration (see Table 7) and sweat Na loss (Table 3). The high sweat Na concentrations in studies 2 and 3 may possibly reflect the result of a higher skin temperature during the exercise period (Weiner & van Heyningen, 1952). The fact that the sub-

Table 5. *Potassium intake, output and balance of six Tanzanian male adults for each study period*

Study period	Subject	Total for 3 d (mequiv.) Intake	Output: Urine	Output: Sweat	Output: Faeces	Balance	Balance (mequiv./d)
1	JS	225	137	34	53	+1	+0·3
	FK	196	143	28	52	−24	−8·0
	CM	208	111	38	46	+13	+4·3
	EM	273	196	19	67	−9	−3·0
	GU	245	171	17	54	+3	+1·0
	FM	225	153	18	24	+30	+10
	Mean	229	152	26	49	+2	+0·7
	Mean/d	76	51	9	16	—	—
2	JS	229	166	52	55	−44	−15
	FK	208	121	44	49	−6	−2·0
	CM	239	186	56	34	−37	−12
	EM	266	188	20	71	−11	−3·7
	GU	216	171	20	57	−32	−10
	FM	210	167	20	52	−29	−9·7
	Mean	228	166	35	53	−26	−8·7
	Mean/d	76	55	12	17	—	—
3	JS	191	120	24	68	−21	−7·0
	FK	163	120	26	49	−32	−11
	CM	191	115	35	52	−11	−3·7
	EM	224	151	22	48	+3	+1·0
	GU	186	107	19	64	−4	−1·3
	FM	193	139	23	50	−19	−6·3
	Mean	191	125	25	55	−14	−4·7
	Mean/d	63	42	8	19	—	—

jects were near to Na balance accounts for the absence of any reduction in salt loss in the sweat during the acclimatization periods of studies 2 and 3.

The subjects maintained a balance between K intake and output in study 1; there was a tendency for a small negative balance in studies 2 and 3. The fall in K intake in the third study was associated with the greatly decreased N intake, but a fall in the urine loss largely compensated for this reduction in K intake. There was also a marked fall in the K concentration of the sweat in study 3 (see Table 7) but, because of the increased sweat output (Table 3), the total output was little different from that in study 1. There is an indication, therefore, that the level of dietary K intake can affect both the concentration in sweat and the output in urine. In this investigation the K loss in sweat represented 15% of total intake in studies 2 and 3 and 10% in study 1, accounting, therefore, for a greater proportionate loss by sweat than was found with Na.

Fe balance

The subjects' intake and output of Fe are shown in Table 6 and the concentration of Fe in the sweat in Table 7. In studies 1 and 2 they were in positive balance, of the order of 10% of intake, and they were in negative balance in study 3. This negative balance was the result of a reduced intake of Fe, with no change in faecal or sweat

Table 6. *Iron intake, output and balance of six Tanzanian male adults for each study period*

Study period	Subject	Total for 3 d (mg) Intake	Output: Urine	Output: Sweat	Output: Faeces	Balance	Balance (mg/d)
1	JS	99·6	0·25	1·99	69·1	+28·4	+9·8
	FK	123·9	0·48	1·37	74·2	+47·8	+15·9
	CM	127·6	1·02	1·09	68·4	+57·1	+19·0
	EM	98·9	0·49	0·74	74·6	+22·1	+7·6
	GU	93·3	1·11	0·80	65·4	+24·0	+8·0
	FM	83·8	0·60	0·76	44·1	+38·4	+12·8
	Mean	104·5	0·66	1·13	66·0	+36·3	+12·1
	Mean/d	34·8	0·22	0·38	22·0	—	—
2	JS	122·1	0·13	1·30	88·7	+32·0	+10·7
	FK	111·2	1·71	1·20	63·7	+44·6	+14·9
	CM	132·8	0·49	1·13	63·6	+67·6	+22·5
	EM	109·8	0·60	0·68	90·5	+18·0	+6·0
	GU	103·9	0·57	0·80	78·4	+24·1	+8·0
	FM	82·1	0·68	0·64	82·5	−1·2	−0·4
	Mean	110·3	0·70	0·96	77·9	+30·8	+10·3
	Mean/d	36·8	0·23	0·32	26·0	—	—
3	JS	47·2	0·69	0·83	98·0	−52·3	−17·4
	FK	44·5	0·62	0·90	88·9	−45·9	−15·3
	CM	46·0	0·58	1·56	49·9	−6·0	−2·0
	EM	70·7	0·34	1·11	68·7	−2·7	−0·9
	GU	61·1	0·65	0·74	80·7	−21·0	−7·0
	FM	45·6	0·52	0·96	67·0	−22·9	−7·6
	Mean	52·5	0·57	1·02	75·5	−25·1	−8·4
	Mean/d	17·5	0·19	0·34	75·2	—	—

excretion. There was a lower sweat Fe concentration in studies 2 and 3, which was associated with the increase in sweat output, since total Fe excretion remained constant. Sweat Fe output never exceeded 2% of intake, but if the amount of dietary Fe absorbed is taken as the difference between intake and faecal excretion, then sweat excretion accounted for approximately 3% of dietary Fe absorbed in studies 1 and 2, and always exceeded urinary Fe output.

DISCUSSION

Rothstein, Adolph & Wills (1947) have shown that at high rates of sweating (400–1000 ml/h), despite unrestricted access to drinking-water, a voluntary deficit of 3% of body-weight is often reached at the end of 5 or 6 h; they state (p. 260) that 'water deficits accumulate between meals and are made good whenever a meal is eaten'. They cite two instances where deficits of 2200 and 1300 ml were reduced to balances of −140 and +90 ml respectively after a meal and fluid had been taken.

As a group, the subjects at Dar es Salaam, living their ordinary lives with moderate activity in hot, humid conditions, appeared to be in fairly close water balance when observed over 3 d periods. The total water imbalance/d was only 53 ml and the most extreme overnight deficit observed was 1·3% of total body-weight. The individual

Table 7. *Concentrations of sodium, potassium and iron in 24 h collections of whole-body sweat from six Tanzanian male adults for each study period*

Study	Subject	Na (mequiv./l)	K (mequiv./l)	Fe (mg/l)
1	JS	4·99	4·85	0·283
	FK	4·86	7·17	0·350
	CM	3·90	5·11	0·146
	EM	6·46	3·72	0·145
	GU	6·70	3·25	0·153
	FM	2·62	3·02	0·127
	Mean	4·92	4·52	0·201
2	JS	7·68	5·62	0·141
	FK	5·25	5·13	0·140
	CM	5·59	5·05	0·102
	EM	11·75	3·65	0·104
	GU	15·70	4·24	0·170
	FM	8·61	3·25	0·104
	Mean	9·10	4·39	0·127
3	JS	7·91	3·39	0·117
	FK	7·59	4·59	0·159
	CM	10·97	4·68	0·209
	EM	11·33	2·80	0·141
	GU	12·54	3·18	0·124
	FM	9·44	3·06	0·128
	Mean	9·96	3·62	0·146

daily values do, however, show a wider range than would be suggested by those given by Rothstein *et al.* (1947). Though twenty of the fifty-four observations were within the range of −140 and +90 ml cited by Rothstein and co-workers, the remainder were outside these values, the standard deviation being 280. Edholm (1972) found that soldiers in Aden, whose sweat rates were very high, also show average daily water balances which fluctuate greatly from day to day.

Interpretation of the results for Na excretion is made difficult by the very high urinary Na output of subject FK in study 1, which was considerably higher than his own or the other subjects' outputs in any other period. There is some reason to suspect that his intake was underestimated, and his urine Na values were equally high on each successive day of the balance. Apart from this one very divergent result, our subjects were generally in slightly negative Na balance. We do not regard them as having been Na-depleted, and some of them were able to achieve almost complete balance. However, it is of interest that they were eating a salt-free diet and adding measured quantities of salt 'at table'. It is possible that some of them slightly underestimated their salt needs, being unaccustomed to eating salt-free food, and hence tended to go into negative balance. It appears that, in this study, 3–5 d was not a long enough period for all the subjects to adjust to eating salt-free food.

Although the K intakes fell in study 3, there was no significant change in K balance and our subjects appeared to be in equilibrium.

The uniformly positive Fe balances in studies 1 and 2, and negative balances in study 3, show that our subjects were somewhat slow in adapting to changes in their dietary Fe intake. The diet in studies 1 and 2 contained more meat than the average

hostel diet, and Fe is particularly well absorbed from meat (Conrad, 1970). Between studies 1 and 2 the faecal excretion of Fe had risen from an average of 22 mg/d to 26 mg/d, showing that adaptation was taking place; and when the intake was approximately halved, in study 3, the faecal excretion remained high, although the run-up period had been 5 d long, and the study itself continued for 3 d. Thus, although the body's Fe absorption mechanisms can react to blood loss within 3–5 d (Conrad, 1970), changes in the diet did not produce such rapid adaptation.

The mean sweat losses of Fe were constant throughout the study and were unaffected either by increased sweating or by the diet. Green, Charlton, Seftel, Bothwell, Mayet, Adams, Finch & Layrisse (1968) found that whole-body Fe turnover amounted to 1–2·5 mg/d; they observed no effect associated with heavy sweating but found an increased turnover when the diet was rich in Fe. Our range of output (sweat + urine) was 0·5–0·6 mg/d, and we did not observe a dietary effect; but the studies are not exactly comparable since Green *et al.* consider total cutaneous loss, whereas our analyses were of cell-free sweat.

FAO (1970) recommends that diets should be sufficient to provide 1 mg absorbable Fe/d, taking into account an average daily urinary, faecal and cutaneous loss of 14 μg/kg. Thus, in our subjects, sweating could have accounted for one-third of absorbed Fe and, since sweat Fe losses did not appear to decrease when the subjects went into negative balance, it seems possible that this could be an important component of Fe loss in circumstances in which only a small quantity of Fe is absorbed. This would not necessarily occur in all anaemic people, since Fe absorption is increased in such subjects; but when diets are rich in Fe-binding substances such as phytic acid or egg proteins, or deficient in ascorbic acid which promotes Fe absorption, skin losses might become significant. A varied diet, containing legumes and animal proteins other than egg, is of particular importance in maintaining Fe absorption.

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