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WATER CONSUMPTION BY MAN IN A WARM ENVIRONMENT: A STATISTICAL ANALYSIS

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The mechanism(s) that regulate water consumption in man are not well defined. Osmotic factors (23,28), body fluid volume (26), volume receptors (11), mouth dryness (4,13), food intake (1), and various combinations of these (7,17,21) have been implicated. Exogenous parameters such as heat, physical exertion, and water deprivation (8,9,12), and cold (18,19) also act to modify the drinking response. There is a paucity of information concerning the interrelationships of the many metabolic variables that might be associated with the regulation of voluntary water intake. The purpose of this study was to analyze, statistically, the relationships between 22 selected metabolic variables and the mean daily ad libitum water consumption in 87 young men.

METHODS

Data on voluntary water intake, along with a host of other metabolic variables, were available from a previous field nutritional investigation (20) on 100 fit basic trainees living in a hot, moist environment - Camp Atterbury, Indiana - during the summer of 1955. The observations made on 87 of these men were selected for this analysis. Observations on the other 13 were not utilized because of missing data. For a two-week period (PI and PII) 78 of these men had subsisted on a fixed diet comprised of items from the 5-in-1 military ration and the remaining 9 on Field Ration A (fresh and frozen foods) fed at levels sufficient to maintain the body weight constant (3,450 kcal/day). We have no evidence that the FRA group differed from the men on 5-in-1. The data utilized were those taken in the second week (PII) of this 2-week period that extended from 22 June through 5 July 1955. In a few instances, information from the second week was not available so comparable data from the first preperiod (PI) were used. In the preperiod the mean maximum and minimum dry bulb temperatures were 32.0 and 15.6 C, respectively. The relative humidity at 1630 hr averaged 49%. The weather was relatively cool in the first week, for on 5 days the maximum temperature did not exceed 32.0 C and the minimum frequently fell to around 10 C. In the second week it was hot and humid. On two of those days the maximum temperature rose above 37.7 C.

The program of the field function tests during PII was as follows: Day 1 - resting metabolism test; Day 2 - 3-hr test in the A.M.; Day 3 - acclimatization test in the P.M.; Day 4 - deuterium oxide test and physical examination; and Day 5 - water diuresis test. The resting oxygen consumption (14) was measured during the resting metabolism test. This variable was included because Wedgewood et al. (25) found a correlation of 0.80 between interstitial fluid volume and basal metabolic rate and extracellular fluid volume and basal metabolism. The 3-hr test provided data on serum total osmolarity, sodium, potassium, and chloride (5); hematocrit (27); resting urinary osmolarity; resting osmotic clearance; resting creatinine clearance (10); resting minute urinary vol; 17-ketosteriods (24); lying pulse rate; and body fat (2,3). Urine formation during exercise, urine formation after exercise, rate of sweating, and the acclimatization index (15) (sweat rate/65 kg body wt/Δ rectal temperature) were measured during the acclimatization test.

The voluntary water intake for each subject was the average daily consumption over the 6-day period. The subjects were allowed free, but measured, consumption of water. Control was accomplished by issuing daily to each subject a canteen filled with water. The canteen was refilled with water at each meal and the number of refills were recorded. Other liquids, such as cocoa, tea, and coffee, were allowed only at meal times and their volumes were added to the water intake. The drinking water contained 6 mg/100 ml of Na, 2 mg/100 ml of K, 55 mg/100 ml of Ca, and Cl and P were not present in significant amounts.

A 24-hr urinary specimen was collected each day from each subject. Ten percent of the daily volume and urine collected during the 3-hr and acclimatization tests were added to 5-day urinary pools. Specimens collected during the water diuresis test were omitted from the pool. Sodium, K, and Cl analyses were performed on the pooled specimens.

The statistical analysis was performed by the Computation and Analysis Branch at Ames Research Center on an IBM 7094/40 DCS system. The stepwise linear regression program was devised by the University of California at Los Angeles Health Sciences Computing Facility (6).

A sequence of multiple linear regression equations of the form:

$$Y = a_0 + a_1X_1 + a_2X_2 + . . . + a_iX_i + . . . + a_nX_n$$

were fitted in a stepwise manner to the data. The dependent variable was voluntary water intake. At each step of the computation, one independent variable X_i $(i = 1, 2, . . ., 22)$ was added to the regression equation. The variable added was the one which made the greatest reduction in the error sum of squares. It was the variable that had the highest partial correlation with the dependent variable, given the variables that had already been included in the regression equation. In this analysis 23 separate variables were measured on each of the subjects.

RESULTS

Table 1 presents the sample means and standard deviations of the 23 variables. It also indicates the sequence in which the 22 independent variables were added to the multiple linear regression equation. R is the partial correlation coefficient at any step i, given the previous i-1 steps (i = 1, 2, . . ., 22). R^2 is the fraction of the total sum of squares attributable to regression at any step i. Hence, $1 - R^2$ measures the fraction attributable to deviation from regression; the failure of the regression equation at any step i to account for the variation in Y, water intake. The column headed "F-value to enter" indicates whether the addition of the i^{th} independent variable to the i-1 independent variables already present in the multiple linear regression equation achieves a statistically significant reduction in the deviation about regression. In other words, is the added information, obtained by introducing the new X_i to the list of i-1 independent variables already in the equation, statistically significant? Table 1

The F-values (Table 1) suggested that the first six variables (No. 6 mean daily urinary vol, No. 1 serum osmolarity, No. 17 lying pulse rate, No. 9 mean daily urinary Cl, No. 8 mean daily urinary K, and No. 20 rate of sweating) accounted for 62% of the variation in water consumption and the introduction of these variables into the equation was, in each case, highly significant. The addition of the next two variables (No. 3 serum K and No. 21 17-ketosteroids), though reducing the unexplained variation from 38 to 35%, did not add any new significant information. The further addition of the remaining 14 variables accounted for only 71% of the variation, an increase of only 9%.

Table 2 presents the coefficients of the regression on Y and the results of the analysis of variance of the first six variables. The standard deviation of the water intake was reduced from 900.01 to 575.74. An equation was constructed that estimates the water consumption from the first six variables. The relation between the estimated versus the actual water intakes using the estimation equation is shown in Fig. 1. The dash line represents the line of perfect fit. Care must be taken in interpreting Fig. 1 because the estimated water intake represents the result of six variables whose multiple correlation is 0.787 with the actual water intake. These results apply only in situations similar to those used in this experiment where the water intake is in the range of 1,950 to 5,850 ml/day. Extending this equation to other situations and ranges of drinking is not warranted and must await further investigation.

<Table 2

<Fig. 1

Due to the significant linear correlations between certain of the independent variables (Table 3), five variables (No. 7 mean daily urinary Na, No. 10 resting minute urinary vol, No. 11 resting urinary osmolarity, No. 12 urine/serum osmotic ratio, and No. 14 exercise urinary vol) were eliminated from the analysis. The results of the multiple linear regression analysis computed with these five independent variables

<Table 3

eliminated were identical, through the first eight steps, with the previous results. Furthermore, due to a significant ($p < 0.05$) linear correlation between variables No. 6 (mean daily urinary vol) and No. 8 (mean daily urinary K) and variables No. 6 and No. 9 (mean daily urinary Cl), two new calculated variables were introduced, X_{23} and X_{24}. X_{23} was the product of No. 6 and No. 8 and X_{24} the product of No. 6 and No. 9. The following five variables (X_{24}, 1, 8, 20, and 17), in that sequence, were statistically significant with R^2 equal to 60%. These results were essentially identical with the previous analysis in Table 2.

DISCUSSION AND CONCLUSIONS

When interpreting these results it must be kept in mind that the 22 variables were arbitrarily selected for their possible relationship to voluntary water intake. This selection would account for the fact that the 22 variables accounted for only 71% of the variation. However, six of the 22 variables accounted for 62% of the variation in water intake. These six variables, based on the statistical results of the analysis, were the most important. The six variables again are: 1) mean daily urinary vol, 2) serum osmolarity, 3) lying pulse rate, 4) mean daily urinary Cl, 5) mean daily urinary K, and 6) rate of sweating. Four of the six variables were concerned with the loss of water from the body; the other two were not. A priori it would seem that serum osmolarity would be related to water intake. The inclusion of lying pulse rate cannot be explained satisfactorily. It might be a reflection of the serum K concentration. Considering the six variables above, water intake was related to more variables associated with water and osmotic loss than to variables associated with the osmotic content of the body. However, since there are many intervening steps between osmotic-fluid loss and water intake (osmotic-fluid loss → fluid volume - serum osmolarity → volume receptors - osmoreceptors → neural connections → act of drinking) which might tend to obscure the precise interrelationship and "since it is better to weigh the evidence than to count it" (21) no firm conclusion can be drawn. Suffice it to say that some combination of fluid-osmotic loss and osmotic content of the blood are related to water intake.

The serum osmolarity (Table 1) was highly related ($p < 0.001$) to voluntary water intake while the major serum ions - Na, K, and Cl, analyzed individually, showed a lesser relationship. This would suggest that the osmoreceptors react to the total osmotic concentration of the blood rather than to the individual ions.

Since the sodium concentration is the major osmotically active solute in the serum (16), the reason for the high relationship of serum osmolarity to water intake ($p < 0.001$) and the low relationship of serum sodium to water intake ($p < 0.8$) (Table 1) is not readily apparent even though the serum osmolarity and Na were measured on the same serum samples. The linear correlation (Table 3) between serum Na and water intake ($r = 0.143$) was also very low. Serum Cl was significantly related (Table 3) to serum osmolarity ($p < 0.001$), to serum Na ($p < 0.01$), and to water intake ($p < 0.01$) which suggests that the anions might be of greater importance in stimulating drinking than has been previously realized. The correlation (Table 3) between mean daily urinary Na and Cl was very high (r = 0.970) but low in the serum (r = 0.286). Towbin (22) has suggested that the Cl concentration was the critical factor in the mechanism of stimulation of the "water" receptors in the cat's tongue.

It is recognized that many factors come into play from the arousal of thirst to its satiation. The results suggest that some combination of body osmolarity and body fluid volume is associated with voluntary water intake. The loss of water (mean daily urinary volume and rate of sweating), mean daily urinary potassium and chloride, serum osmolarity, and lying pulse rate accounted for 62% of the variation in voluntary water intake.

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TABLE 1. Results of regression analysis

Variable no.	Variable	Units	Step no.	Sample		Multiple				
				Mean	Standard deviation	R	R^2	$1 - R^2$	F-value to enter	Probability
6	Mean daily urinary vol	ml/day	1	1257.8	373.87	0.4759	0.2265	0.7735	24.8859	< 0.001
1	Serum osmolarity	mosm/L	2	282.6	5.62	.5936	.3524	.6476	16.3286	<.001
17	Lying pulse rate	beats/min	3	62.1	8.40	.6522	.4253	.5746	10.5418	<.005
9	Mean daily urinary Cl	mEq./day	4	224.1	62.73	.6943	.4821	.5179	8.9790	<.005
8	Mean daily urinary K	mEq./day	5	67.6	16.65	.7331	.5374	.4626	9.6907	<.005
20	Rate of sweating	ml/hr	6	1028.2	156.94	.7870	.6193	.3807	17.2198	<.001
3	Serum K	mEq./L	7	4.2	.31	.7946	.6314	.3686	2.5928	<.15
21	17-ketosteroids	mg/2 hr	8	1.4	.47	.8038	.6460	.3540	3.2166	<.10
14	Exercise urine vol	ml/min	9	.4	.27	.8095	.6553	.3447	2.0757	<.20
4	Serum Cl	mEq./L	10	102.3	2.70	.8135	.6618	.3382	1.4544	<.25
19	Resting O_2 consumption	ml/M^2 - min	11	168.7	22.68	.8181	.6693	.3307	1.7068	<.25
15	Body fat	% body wt	12	5.9	2.74	.8227	.6769	.3231	1.7374	<.25
10	Resting min urine vol	ml/min	13	1.2	.87	.8252	.6809	.3191	.9216	<.50
13	Resting osmotic clearance	ml/min	14	2.8	.86	.8299	.6887	.3113	1.8054	<.25
11	Resting urinary osmolarity	µosm/min	15	827.6	321.95	.8338	.6952	.3048	1.5150	<.25
22	Post exercise urine vol	ml/min	16	.6	.33	.8390	.7039	.2962	2.0399	<.20
16	Acclimatization index		17	580.9	265.49	.8404	.7062	.2939	.5464	<.50
18	Resting creatinine clear	ml/min	18	179.8	33.07	.8416	.7083	.2918	.4998	<.50
12	Urine/serum osmotic ratio		19	2.9	.90	.8419	.7088	.2913	.1061	<.75
7	Mean daily urinary Na	mEq./day	20	221.3	60.43	.8421	.7092	.2910	.0785	<.80
2	Serum Na	mEq./L	21	134.4	2.81	.8423	.7095	.2907	.0766	<.80
5	Hematocrit	vol %	22	44.2	2.87	.8424	.7097	.2905	.0367	<.80
23	Water intake	ml/day		3256.3	900.01					

TABLE 3. Intercorrelation matrix

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1 Serum osmolarity	1.00	-0.035	0.036	0.606*	-0.187	0.001	-0.023	-0.028	0.014	-0.301†	-0.201	0.226	-0.315*	-0.062	-0.006	-0.007	0.020	-0.012	0.012	0.186	-0.059	-0.167	0.358*
2 Serum Na		1.00	.346†	.266†	.030	.061	.076	-.203	.041	.283†	.116	-.204	.203	-.146	-.008	-.116	-.011	-.114	-.172	.019	-.061	-.084	.143
3 Serum K			1.00	.087	-.026	.032	.081	-.269	.035	.026	-.123	-.073	.080	-.126	.006	.162	-.104	-.116	-.192	-.046	-.285†	.077	.254
4 Serum Cl				1.00	-.373*	-.014	.031	.011	.068	-.197	-.101	.229	-.147	-.025	.015	.055	-.072	-.076	-.110	.226	-.177	-.067	.286†
5 Hematocrit					1.00	.089	.135	-.051	.084	.180	.016	-.322†	.062	.069	-.027	-.031	-.019	.050	.059	-.218	.105	.079	-.020
6 Mean daily urinary vol						1.00	.263	.280†	.320†	.387*	.295†	-.395*	.247	.422*	-.014	-.326	.093	.146	.193	.042	.043	.524*	.476*
7 Mean daily urinary Na							1.00	.168	.970*	.141	.112	-.003	.201	.016	-.161	-.085	.082	-.030	.129	-.002	-.046	.113	.327†
8 Mean daily urinary K								1.00	.282	.061	.216	.013	.073	.343†	.066	-.093	.223	.143	.137	.246	.329†	.309†	-.115
9 Mean daily urinary Cl									1.00	.134	.118	.006	.182	.082	-.146	-.109	.073	.042	.164	.005	-.021	.174	.371*
10 Resting min urinary vol										1.00	.697*	-.800*	.773*	.167	-.104	-.008	.059	.176	.043	-.043	.201	.151	.061
11 Resting urinary osmolarity											1.00	-.347†	.822*	.361*	.027	.019	.199	.349*	.078	.181	.506*	.073	.076
12 Urine/serum osmotic ratio												1.00	-.507*	-.066	.199	-.015	-.030	-.019	-.100	.112	.016	-.181	-.061
13 Resting osmotic clearance													1.00	.177	.018	.083	.079	.270	.168	.143	.258	.115	.157
14 Exercise urine vol														1.00	.034	-.002	.059	.284†	-.049	.194	.293†	.749*	.068
15 Body fat															1.00	-.061	-.106	.096	-.148	.231	-.019	.016	.073
16 Acclimatization index																1.00	-.091	-.067	-.033	.253	-.156	-.020	-.018
17 Lying pulse rate																	1.00	-.028	.242	-.123	.099	.022	-.216
18 Resting creatinine clearance																		1.00	-.046	.302†	.308†	.103	.163
19 Resting O_2 consumption																			1.00	-.117	.099	.073	.098
20 Rate of sweating																				1.00	.186	-.003	.319†
21 17-ketosteroids																					1.00	-.005	.011
22 Post-exercise urine vol																						1.00	.073
23 Water intake																							1.00

*R = ±0.349 is significant with $p < 0.001$

†R = ±0.277 is significant with $p < 0.01$

TABLE 2. Analysis of variance for six variables

Source	Degree of freedom	Sum of squares	Mean square	F-ratio	P
Due to regression	6	43,145,282.5	7,190,880.4	21.69	< 0.001
Error	80	26,517,723.5	331,471.5		

$R = 0.787$ $R^2 = 0.62$ $1 - R^2 = 0.38$

Standard error = 575.74

Variable no.	Variable	Coefficient	Standard error of coefficient
		$a_0 = -11,502.40$	
1	Serum osmolarity	$a_1 = 45.81$	11.3088
6	Mean daily urinary vol	$a_2 = 1.1524$	0.1799
8	Mean daily urinary K	$a_3 = -18.86$	4.2049
9	Mean daily urinary Cl	$a_4 = 4.3881$	1.0594
17	Lying pulse rate	$a_5 = -18.72$	7.7406
20	Rate of sweating	$a_6 = 1.7671$	0.4258

$\tilde{Y}$ water intake (ml) = -11,502.40 + 45.81 (serum osmolarity, mosm/L)

+1.1524 (mean daily urinary vol, ml/day)

-18.86 (mean daily urinary K, mEq./day)

+4.3881 (mean daily urinary Cl, mEq./day)

-18.72 (lying pulse rate, beats/min)

+1.7671 (rate of sweating, ml/hr)

FIGURE TITLE

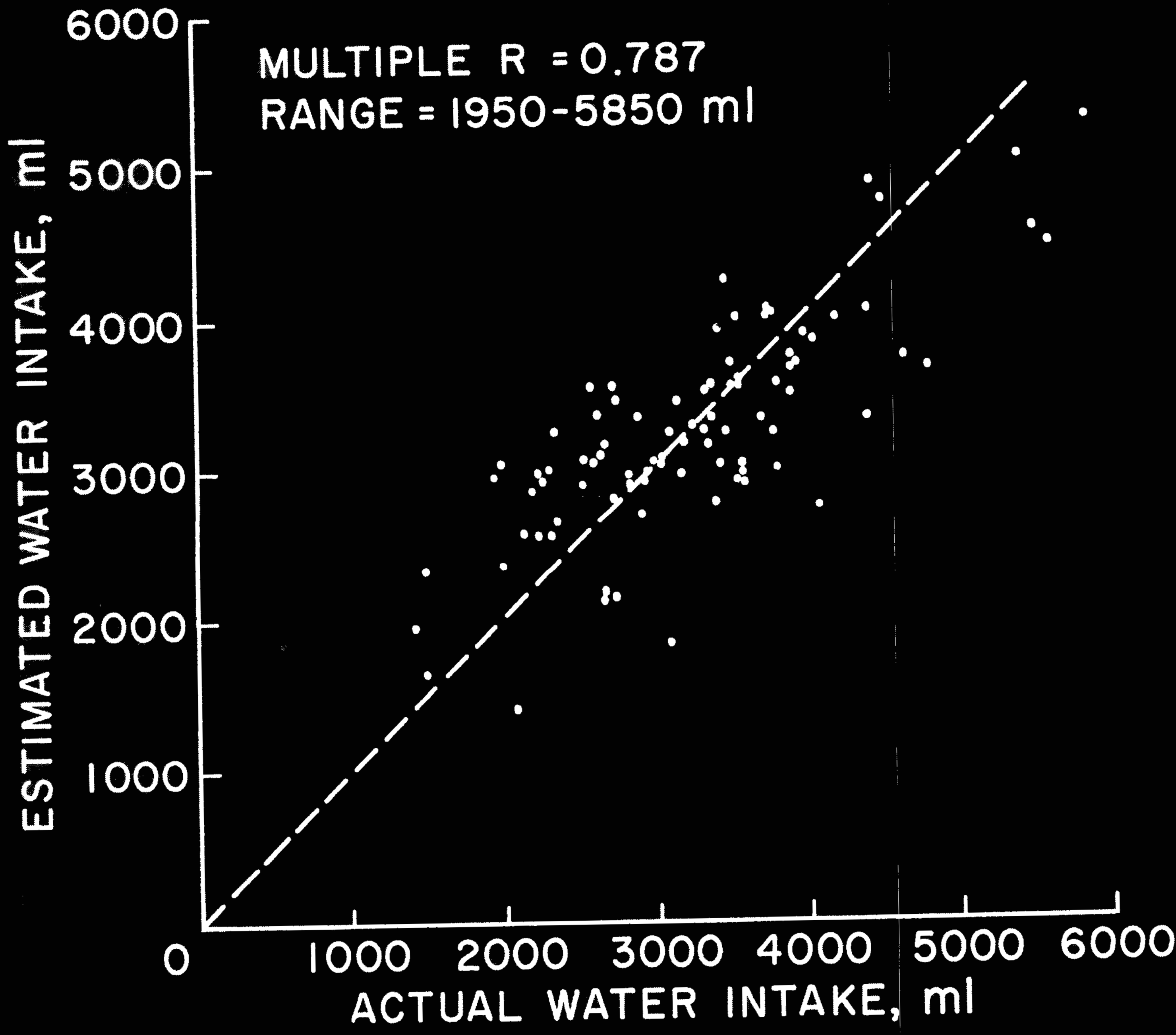
Fig. 1.- Estimated versus actual water intake.

ABSTRACT

Twenty-two metabolic variables were examined using step-wise linear regression analysis for their possible relationship to voluntary water consumption in 87 young men. Six variables: 1) mean daily urinary vol, 2) serum osmolarity, 3) lying pulse rate, 4) mean daily urinary Cl, 5) mean daily urinary K, and 6) rate of sweating accounted for 62% of the variation in water intake. The addition of the remaining 16 variables accounted for only 71% of the variation. An equation was constructed that estimated water intake from these six variables. The anions, particularly Cl, might be of greater importance in influencing drinking than has been previously realized. The data suggest that some combination of body osmolarity and body fluid volume is associated with voluntary water intake in man.

INDEX TERMS

water consumption in man heat exercise statistical analysis



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