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*J Appl Physiol* 83:1152-1158, 1997.

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# Restoration of fluid balance after exercise-induced dehydration: effects of alcohol consumption

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**Shirreffs, Susan M., and Ronald J Maughan.** Restoration of fluid balance after exercise-induced dehydration: effects of alcohol consumption. *J. Appl. Physiol.* 83(4): 1152–1158, 1997.—The effect of alcohol consumption on the restoration of fluid and electrolyte balance after exercise-induced dehydration [ $2.01 \pm 0.10\%$  (SD) of body mass] was investigated. Drinks containing 0, 1, 2, and 4% alcohol were consumed over 60 min beginning 30 min after the end of exercise; a different beverage was consumed in each of four trials. The volume consumed ( $2,212 \pm 153$  ml) was equivalent to 150% of body mass loss. Peak urine flow rate occurred later ( $P = 0.024$ ) with the 4% beverage. The total volume of urine produced over the 6 h after rehydration, although not different between trials ( $P = 0.307$ ), tended to increase as the quantity of alcohol ingested increased. The increase in blood ( $P = 0.013$ ) and plasma ( $P = 0.050$ ) volume with rehydration was slower when the 4% beverage was consumed and did not increase to values significantly greater than the dehydrated level ( $P = 0.013$  and  $P = 0.050$  for blood volume and plasma volume, respectively); generally, the increase was an inverse function of the quantity of alcohol consumed. These results suggest that alcohol has a negligible diuretic effect when consumed in dilute solution after a moderate level of hypohydration induced by exercise in the heat. There appears to be no difference in recovery from dehydration whether the rehydration beverage is alcohol free or contains up to 2% alcohol, but drinks containing 4% alcohol tend to delay the recovery process.

rehydration; water balance

THE DIURETIC ACTION of alcohol has been well recognized for many years and has been described in numerous publications, including the early papers of Murray (16) and Eggleton (5). The mechanism of action is via inhibition of vasopressin secretion (19, 20), and the degree of diuresis is proportional to the amount of alcohol consumed (5).

It has been shown that to obtain effective rehydration after dehydration induced by sweat loss, it is necessary to replace the electrolytes as well as the water lost during the dehydration process (3, 8, 13, 15, 17, 18); these electrolytes can be ingested either by consuming a drink to replace the water or by eating solid food together with water (14).

Because of the known diuretic effects of alcohol, the view that alcohol-containing drinks should be avoided when rehydration is desired is widely promulgated, but there appears to be little evidence to support this. Eggleton (5) suggested in her paper of 1942 that the ingestion of drinks containing small quantities of alcohol by subjects who were in a state of water deficit did not seriously impair the effectiveness of rehydration. Volume replacement is important, and the palatability of fluids will have a major impact on the volume that is

consumed. It is necessary to consume a volume of fluid greater than the volume of sweat lost if complete restoration of fluid balance is to occur (22). While it is not usual for large volumes of the most commonly consumed beverages, namely tea, coffee, water, and soft drinks, to be consumed over a short time period, relatively large volumes of alcoholic beverages such as beer are frequently observed to be consumed; this is one factor that may work in favor of beer as a rehydration fluid. Flear et al. (7) reported the case of a man who drank 9 liters of beer, with a sodium content of 1.5 mmol/l, in the space of 20 min.

The majority of beers have a sodium concentration in the range of 3–5 mmol/l; the potassium concentration will depend on the amount of malt added in the brewing process and is usually in the range of 8–10 mmol/l (10). As a result of the low electrolyte content of beer, it will not enable rehydration to be achieved as effectively as a specially designed oral rehydration solution (6). The aim of the present study was to investigate the effects of consuming alcohol-containing drinks, during recovery from a moderately hypohydrated state resulting from sweat loss induced by exercise in the heat, on the restoration of whole body water balance and blood volume recovery. The study was designed to establish whether alcohol exerts a diuretic action when consumed by individuals in a water- and electrolyte-depleted state induced by exercise in a warm, humid environment.

## METHODS

**Subjects.** Six healthy male volunteers acted as subjects for this study, which was carried out with the approval of the local Ethics Committee. All subjects were accustomed to consuming alcoholic beverages on an occasional basis. Written consent to participate was provided by all subjects after the nature of the study had been explained to them. All were habitually physically active, but none was highly trained at the time of the study. Physical characteristics were age of  $36 \pm 9$  (SD) yr, height of  $178 \pm 2$  cm, and body mass of  $73.4 \pm 4.0$  kg. Peak oxygen uptake ( $\dot{V}O_{2\text{peak}}$ ) was measured by a discontinuous incremental exercise test to volitional exhaustion on a cycle ergometer during a preliminary visit to the laboratory. It was defined as the highest value reached during the test and amounted to a mean of  $50.9 \pm 2.1$  ml·kg<sup>-1</sup>·min<sup>-1</sup>.

**Experimental design.** The experimental procedure consisted of three phases: 1) exercise-induced dehydration, 2) beverage ingestion, and 3) monitoring of fluid balance for a further 6 h. Four experimental trials were undertaken by each subject, and in each trial a different beverage was ingested after the exercise-induced dehydration: one was an alcohol-free beer (*trial 0%*), and the other drinks consisted of the same alcohol-free base to which was added 1, 2, or 4% alcohol (*trials 1%, 2%, and 4%*, respectively). The beverage composition was identical between drinks in all respects except for the alcohol content; all had a sodium concentration

of 2 mmol/l and a potassium concentration of 10 mmol/l. All trials commenced in the afternoon and began 6 h after a meal, the amount, composition, and time of consumption of which were kept constant for all trials. The consumption of plain water was permitted up to 3 h before the start of the experiment. Trials took place at 7-day intervals so that each was conducted on the same day of the week for each subject; Barnett and Maughan (1) demonstrated that no acclimatization effect was found, in terms of any change in heart rate, rectal temperature, skin temperature, oxygen consumption, and total sweat loss during 1 h of moderate-intensity exercise (55%  $\dot{V}O_{2\text{peak}}$ ) undertaken in the heat at weekly intervals. Therefore, separating exercise bouts by 1 wk was concluded to be a valid method for comparing the effects of different treatments on unacclimatized subjects during exercise in the heat. For the 2 days preceding the first trial, subjects kept records of their food and drink consumption and physical activities, and this was then reproduced on the 2 days before each of the subsequent trials. Additionally, subjects were asked to abstain from strenuous exercise for the 2 days before each trial. The trials were undertaken in a randomized order, which was blind to the subjects, but some were able to tell the high-alcohol beverages (2 and 4%) from the other drinks (0 and 1%).

All subjects completed a familiarization trial, 1 wk before the first experimental trial, in which they followed the experimental procedure to be used in the subsequent trials, except that it was terminated 2 h after the end of the rehydration period. Blood samples were not collected on this familiarization trial from subjects who had previously participated in investigations of a similar nature.

**Protocol.** On reaching the laboratory, subjects rested in a seated position in a room maintained at a temperature of  $\sim 24^{\circ}\text{C}$ . Fifteen minutes after the subjects sat down, a small (21-gauge) butterfly cannula was introduced into a superficial forearm vein and a venous blood sample was collected without stasis. Part (2.5 ml) of this sample was added to  $\text{K}_2$ -EDTA, and duplicate 100- $\mu\text{l}$  aliquots were removed and deproteinized by addition to 900  $\mu\text{l}$  of ice-cold 0.3 N perchloric acid. A second part of each blood sample (2.5 ml) was added to a chilled  $\text{K}_2$ -EDTA tube. The remainder of the blood sample (3.0 ml) was allowed to clot before being centrifuged, and the serum was then removed. After the blood sample was collected, subjects were asked to produce a urine sample by emptying their bladders as completely as possible; the volume of this sample was measured and an aliquot was retained. Subjects then showered and dried before nude body mass was measured.

Dehydration was induced by intermittent cycle ergometer exercise in the heat. The exercise period was preceded by a 10-min period during which subjects were immersed to the neck in warm ( $42^{\circ}\text{C}$ ) water to elevate body temperature and reduce the amount of exercise necessary to achieve the required sweat loss. Subjects then performed a series of 10-min bouts of exercise at an intensity corresponding to  $\sim 60\%$  of  $\dot{V}O_{2\text{peak}}$ . Exercise was performed in a climatic chamber maintained at a temperature of  $34 \pm 0^{\circ}\text{C}$  and a relative humidity of  $65 \pm 1\%$ . Exercise periods were separated by 5-min rest periods during which subjects removed their clothing, dried themselves, and were weighed. The intention was to dehydrate each subject by 2% of body mass; exercise continued until body mass had fallen by almost 2% of the preimmersion value, with the remaining mass loss being met by the sweat loss that continued for a short time after exercise. After a cool shower, subjects dried thoroughly before the final body mass measurement was made. Subjects dressed and returned to sit in a comfortable environment ( $\sim 25^{\circ}\text{C}$ )

within 15 min of the end of exercise. After  $\sim 10$  min of seated rest, a 21-gauge venous cannula was again inserted into a superficial forearm vein and was flushed with isotonic saline. A further 5 min elapsed before the first postexercise blood sample was withdrawn; this was, therefore, collected 30 min after the end of exercise. A urine sample was then obtained; for this, as for all samples, subjects were instructed to empty their bladder as completely as possible, and the entire volume was collected.

Over the following 60 min, subjects consumed one of the rehydration beverages. The drink was given in a volume equal to 150% of the estimated sweat loss, assuming that all of the measured body mass loss was accounted for by sweat loss, and was given in four equal volumes, one in each 15-min period.

Further blood and urine samples were collected at the end of the rehydration period (0 h) and at 1, 2, 4, and 6 h thereafter. Subjects remained within the laboratory environment at all times and were seated for at least 15 min before collection of each blood sample to minimize the effects of postural changes on the redistribution of water between the body water compartments.

**Analytic methods.** The EDTA-treated blood sample was used for measurement of hemoglobin concentration (cyanmethemoglobin method) and packed cell volume (by spun hematocrit). The values so obtained were used to calculate changes in blood, red cell, and plasma volumes by using the equations described by Dill and Costill (4); all calculations were made relative to the values obtained 30 min after the end of exercise. Blood ethanol concentration was measured spectrophotometrically on the deproteinized samples by using an alcohol dehydrogenase-based reaction (2). Serum sodium and potassium concentrations were measured by flame photometry (clinical flame photometer model 410C; Corning, Halstead, Essex, UK) and serum chloride concentration by coulometric titration (chloride meter, Jenway, Dunmow, Essex, UK). Serum osmolality was measured by freezing-point depression (Gonotec Osmomat 030 cryoscopic osmometer, Clanden Scientific, Hants, UK). Urine electrolyte concentrations and osmolality were measured by the same methods used for the serum samples. The chilled EDTA-treated blood samples were collected before exercise, 30 min after exercise, and at 1, 2, and 6 h after the end of the rehydration period. These were used for measurement of plasma vasopressin and angiotensin II concentrations by radioimmunoassay (Euro-Diagnostica, Cornwall, UK).

**Statistical analysis.** Descriptive data are presented throughout the text and in Tables 1–3 and Figs. 1–5 as means  $\pm$  SD or as median (range) where they were found not to be normally distributed. Statistical comparisons were made after establishing the normality or otherwise of the distribution of the data points. Analysis was by repeated-measures analysis of variance followed by one-way analysis of variance and Tukey's multiple-range test or Dunnett's test or the Kruskal-Wallis and Mann-Whitney tests where appropriate. Differences between and within trials were considered significant where  $P < 0.05$ .

## RESULTS

The preexercise body mass was the same for all trials (*trial 0%*:  $73.4 \pm 4.6$  kg; *trial 1%*:  $73.1 \pm 4.7$  kg; *trial 2%*:  $73.7 \pm 4.0$  kg; *trial 4%*:  $73.2 \pm 4.0$  kg), and the same degree of reduction in body mass occurred over the four trials (*trial 0%*:  $1.45 \pm 0.13$  kg; *trial 1%*:  $1.49 \pm 0.10$  kg; *trial 2%*:  $1.52 \pm 0.10$  kg; *trial 4%*:  $1.44 \pm 0.08$  kg). This corresponded to a mean reduction over all trials of

$2.01 \pm 0.10\%$  of the preexercise body mass. The exercise time ( $33 \pm 12$  min) necessary to produce the required degree of sweat loss was not different between trials. There was also no evidence of any adaptation over the 3 successive wk of the experiment: the exercise time for the first trial was  $33 \pm 15$  min, for the second trial  $36 \pm 14$  min, for the third trial  $35 \pm 12$  min, and for the fourth trial  $30 \pm 9$  min. Because the sweat loss was the same in all trials, there was no difference between trials in the volume of fluid ingested: total fluid intake for *trial 0%* was  $2,178 \pm 190$  ml, for *trial 1%* was  $2,240 \pm 146$  ml, for *trial 2%* was  $2,275 \pm 154$  ml, and for *trial 4%* was  $2,155 \pm 125$  ml, giving an overall mean volume of  $2,212 \pm 153$  ml. The quantities of sodium and potassium ingested were the same on each trial and amounted to a mean of  $4.4 \pm 0.2$  and  $22.1 \pm 0.7$  mmol, respectively.

**Blood ethanol concentration.** In *trial 0%*, no alcohol was ingested, whereas a mean of  $17.7 \pm 1.2$ ,  $35.9 \pm 2.4$ , and  $68.0 \pm 3.9$  g of ethanol was consumed in *trials 1%*, *2%*, and *4%*, respectively. The alcohol from the beverages was absorbed, and the measured peak blood ethanol concentrations in each trial were 0 (0–1), 2 (0–4), 7 (5–10), and 21 (18–24) mmol/l for *trials 0%*, *1%*, *2%*, and *4%*, respectively (Fig. 1).

**Urine output and fluid balance.** The volume of urine excreted after rehydration varied over time on all trials (Fig. 2). For *trials 0%*, *1%*, and *2%*, the peak rate of urine production occurred over the 1-h period ending 1 h after the end of the rehydration period, but for *trial 4%* this was delayed by 1 h and occurred over the 1-h period ending 2 h after the end of the rehydration period. Additionally, at 4 h after the end of the rehydration period, the urine production over the preceding 2 h had declined markedly to 129 (89–219), 179 (76–428), and 126 (82–266) ml in *trials 0%*, *1%*, and *2%* respectively, but in *trial 4%*, over the same time period, urine production amounted to 470 (134–654) ml. By the end of the study period, 6 h after the end of the rehydration period, urine production over the preceding 2 h had declined to or very close to basal levels in all trials [*trial 0%*: 68 (48–140) ml; *trial 1%*: 53 (36–83) ml; *trial 2%*: 60 (42–78) ml; *trial 4%*: 73 (54–132) ml].

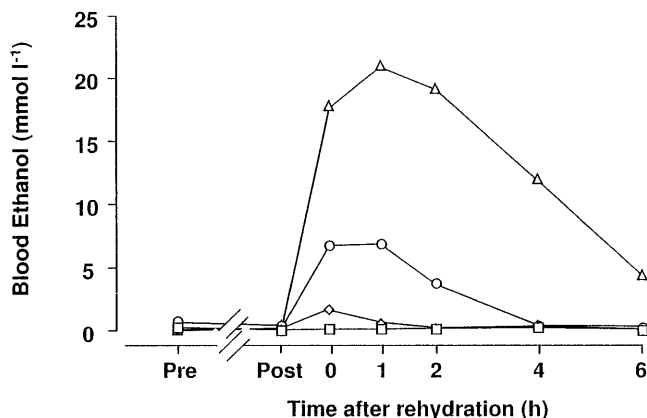


Fig. 1. Blood ethanol concentration over time. Pre, preexercise; Post, postexercise. Points are median values. □, *trial 0%*; ◇, *trial 1%*; ○, *trial 2%*; △, *trial 4%*.

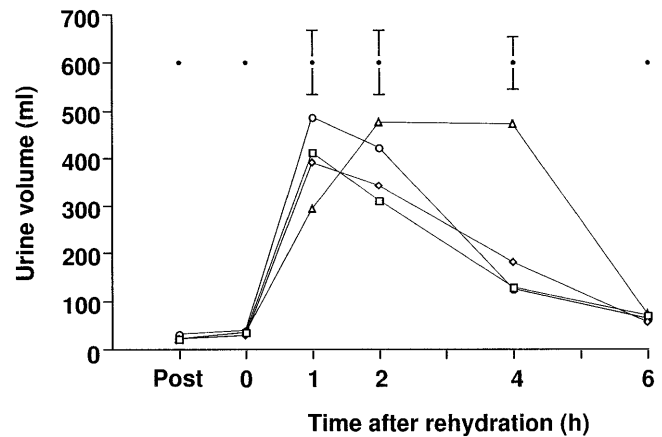


Fig. 2. Urine output over time. Preexercise sample is not shown. Points are mean values. At top are pooled SE bars at each time point; this is SE calculated by using each subject's data from each trial at each time point. □, *trial 0%*; ◇, *trial 1%*; ○, *trial 2%*; △, *trial 4%*.

The cumulative urine output was calculated up to each time point for the entire period after rehydration (Table 1). There were no significant differences between trials in the cumulative urine volume at any time point. Toward the end of the study, at 4 and 6 h after the end of the rehydration period, the general pattern for cumulative urine output was for the volume excreted to be greatest when the largest quantities of alcohol had been consumed. The fraction of the ingested fluid that was retained amounted to  $59.3 \pm 15.7$ ,  $53.1 \pm 11.0$ ,  $50.0 \pm 16.0$ , and  $40.7 \pm 16.7\%$  for *trials 0*, *1*, *2*, and *4%*, respectively.

Whole body net fluid balance, relative to the initial euhydrated state, was calculated from the sweat loss, the volume of fluid consumed, and the urine output (Fig. 3). There were no differences between trials at any time point with regard to whole body net fluid balance. With dehydration, there was a reduction in whole body net fluid balance to the same extent on each trial; this amounted to  $1,500 \pm 103$  ml over all trials. Because the same volume of drink was consumed on each trial, subjects were positively hydrated to the same extent on each trial at the end of the rehydration period. After this time no other food or fluid was consumed, but urine formation continued, returning subjects toward a state of negative fluid balance. The same general pattern was found for whole body net fluid balance in all trials.

**Urine composition.** The quantities of sodium, potassium, and chloride excreted in the urine after rehydration were not influenced by the drink consumed (Table 2) and amounted to the same total on each trial. Urine osmolality changed over the duration of each trial and in general was inversely related to the urine output.

**Blood, plasma, and serum measurements.** Analysis of the preexercise blood sample confirmed that the measured parameters were in all cases within the normal range obtained in this laboratory for adult men after a 6-h fast: hematocrit, 37–46%; hemoglobin concentration, 130–170 g/l; serum osmolality, 283–293 mosmol/kgH<sub>2</sub>O; sodium concentration, 133–143 mmol/l; potassium concentration, 3.5–5.0 mmol/l; and chloride concentration, 98–105 mmol/l.



Table 1. Cumulative volume of urine produced up to and including each time point from the end of the rehydration period until the end of the study

Time After Rehydration, h	Trial 0%	Trial 1%	Trial 2%	Trial 4%	P Value
0	33 (19–88)	27 (22–34)	38 (27–69)	34 (12–69)	0.501
1	439 (175–864)	425 (345–588)	520 (357–625)	323 (123–755)	0.643
2	721 (339–1,474)	834 (582–933)	941 (577–1,261)	747 (564–1,435)	0.843
4	875 (473–1,597)	1,062 (673–1,258)	1,131 (672–1,397)	1,348 (698–1,968)	0.320
6	942 (557–1,650)	1,108 (721–1,307)	1,184 (729–1,455)	1,457 (752–2,045)	0.307

Values are medians with range in parentheses given in ml.

Postexercise samples were not collected until 30 min after the end of the exercise period, and it is likely that some redistribution of body water took place during this time, but blood and plasma volumes were still less at this time than before exercise in all trials, with no differences between trials (Table 3). The mean decrease in blood and plasma volume over all trials was  $5.1 \pm 2.4$  and  $7.6 \pm 3.4\%$ , respectively. Both blood and plasma volumes increased over the rehydration period, but the increase did not reach significance with the 4% drink. One hour after the end of the rehydration period, the change in blood and plasma volume differed significantly between trials 0% and 4% such that it was less for trial 4% than for trial 0%, but at no other time were the differences between trials statistically significant. At the end of the study period, the general pattern was for the increases in both blood and plasma volume to be inversely related to the quantity of alcohol consumed.

Plasma angiotensin II concentration did not differ between trials at any time point, but the concentration did alter over the course of the experiment. The preexercise concentration, collected 6 h after a standard meal and 3 h after the last permitted intake of water, was  $25.1 \pm 16.0$  pg/ml over all trials, and with dehydration it increased to  $55.4 \pm 31.7$  pg/ml. After rehydration the concentration declined to values that were not different from the preexercise concentration.

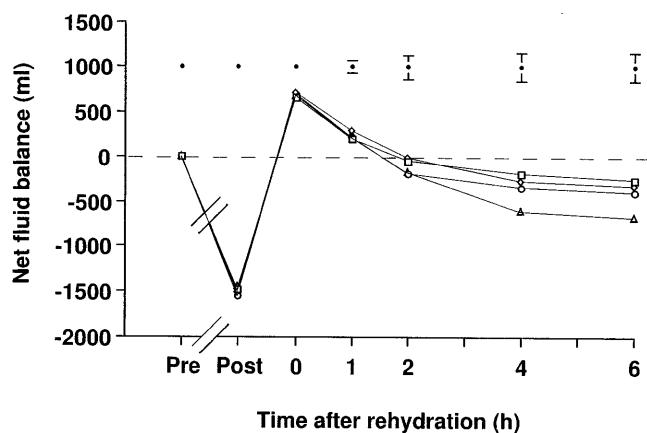


Fig. 3. Whole body net fluid balance calculated from estimated sweat loss, volume of fluid ingested, and urine output over course of experiment. Preexercise urine sample is not included in these calculations. Points are mean values. At top are pooled SE bars at each time point; this is SE calculated by using each subject's data from each trial at each time point. □, trial 0%; ◇, trial 1%; ○, trial 2%; △, trial 4%.

Serum osmolality increased with dehydration on all trials; the increase was the same in each trial and amounted to  $5 \pm 4$  mosmol/kgH<sub>2</sub>O over all the trials (Fig. 4). After consumption of the 0% alcohol beverage, the serum osmolality decreased, and at 1 and 2 h after the end of the rehydration period it was below the initial levels before returning to the preexercise levels by 4 h after the end of the rehydration period. For the 1% alcohol trial, serum osmolality after rehydration did not differ from the preexercise values at any time. Ingestion of the 2% alcohol beverage caused the serum osmolality to increase over the rehydration period to a level greater than the dehydrated level. By 1 h after the end of rehydration, serum osmolality had declined from this value, but the osmolality was still greater at this time relative to the preexercise value. By 2 h after the end of the rehydration period the osmolality had returned to initial levels. After consumption of the 4% alcohol beverage, serum osmolality increased substantially above the dehydrated value and remained at this elevated level until 4 h after the end of the rehydration period. It was not until 6 h after the end of the rehydration period that serum osmolality had returned to the preexercise levels, although it was still greater than the values measured in the trial 0% at this time.

Table 2. Cumulative urine electrolyte output after rehydration

Time After Rehydration, h	Trial 0%	Trial 1%	Trial 2%	Trial 4%	P Value
<i>Sodium</i>					
0	3.0 ± 1.1	3.0 ± 0.9	3.7 ± 1.2	3.4 ± 1.8	0.758
1	6.4 ± 2.4	7.8 ± 1.8	9.0 ± 2.5	7.2 ± 3.6	0.434
2	10.0 ± 3.7	11.7 ± 2.8	12.3 ± 2.9	10.6 ± 5.3	0.711
4	16.2 ± 5.9	17.3 ± 5.4	19.0 ± 3.6	18.8 ± 8.8	0.837
6	23.2 ± 7.0	22.2 ± 8.0	24.3 ± 5.2	27.0 ± 11.5	0.783
<i>Potassium</i>					
0	2.5 ± 0.6	2.2 ± 0.6	2.6 ± 0.9	1.9 ± 0.8	0.445
1	4.2 ± 0.8	4.5 ± 2.3	4.0 ± 1.4	3.1 ± 1.1	0.514
2	6.2 ± 1.0	6.8 ± 3.2	5.2 ± 1.8	4.4 ± 1.4	0.265
4	10.2 ± 1.5	10.6 ± 3.5	8.6 ± 2.6	7.9 ± 2.4	0.287
6	15.6 ± 3.5	13.9 ± 3.6	12.6 ± 3.0	12.2 ± 3.6	0.620
<i>Chloride</i>					
0	1.8 ± 1.0	1.8 ± 1.0	2.3 ± 1.5	1.8 ± 1.5	0.870
1	4.8 ± 2.2	5.0 ± 1.4	6.0 ± 2.5	4.3 ± 2.2	0.584
2	7.8 ± 2.6	7.3 ± 1.0	8.2 ± 3.2	6.8 ± 2.6	0.804
4	13.3 ± 3.8	11.0 ± 1.3	11.3 ± 4.4	10.2 ± 3.8	0.474
6	18.8 ± 4.5	14.2 ± 3.3	14.0 ± 5.9	14.3 ± 5.6	0.288

Values are means ± SD given in mmol.

Table 3. Blood and plasma volume changes

Time After Rehydration, h	Trial 0%	Trial 1%	Trial 2%	Trial 4%	P Value
<i>Blood volume change</i>					
Pre	5.2 ± 2.3	4.9 ± 2.0	5.3 ± 2.0	5.1 ± 3.1	0.994
Post	0.0	0.0	0.0	0.0	
0	5.9 ± 3.2	3.4 ± 2.7	4.6 ± 2.4	2.2 ± 1.1	0.101
1	5.8 ± 2.4	3.9 ± 1.3	3.2 ± 1.5	2.1 ± 1.6	0.013
2	4.2 ± 2.0	4.0 ± 2.3	2.9 ± 2.3	1.9 ± 2.6	0.323
4	5.4 ± 1.9	4.2 ± 1.1	4.1 ± 2.0	2.9 ± 1.9	0.147
6	5.0 ± 2.0	4.2 ± 1.1	3.4 ± 1.6	3.1 ± 1.9	0.232
<i>Plasma volume change</i>					
Pre	7.6 ± 3.4	7.0 ± 2.4	8.4 ± 4.3	7.4 ± 4.5	0.928
Post	0.0	0.0	0.0	0.0	
0	9.0 ± 5.3	4.9 ± 4.4	6.7 ± 4.2	2.9 ± 2.6	0.111
1	8.4 ± 3.8	5.5 ± 2.2	5.0 ± 2.4	3.2 ± 3.3	0.050
2	6.1 ± 2.7	5.9 ± 4.3	5.1 ± 4.5	2.6 ± 4.1	0.409
4	9.0 ± 3.2	6.5 ± 2.3	7.6 ± 4.3	4.4 ± 3.1	0.138
6	8.1 ± 3.1	7.4 ± 2.7	6.0 ± 3.4	5.3 ± 3.4	0.452

Values are means ± SD given as percent change from postexercise value. Samples were taken immediately before (Pre) and 30 min after end of (Post) dehydration period and then at 0, 1, 2, 4, and 6 h after end of rehydration period. Statistical differences are described in the text.

These changes largely reflect the pattern of change in the blood alcohol concentration (Fig. 1). When serum osmolality was corrected for the contribution of ethanol in the blood (9), the differences between trials disappeared ( $P = 0.480$ ; Fig. 4).

Plasma vasopressin concentration did not differ between trials at any time, although it changed over the time course of each trial (Fig. 5). The preexercise concentration, collected 6 h after a standard meal and 3 h after the last permitted intake of water, was  $5.3 \pm 1.5$  pg/ml over all trials, and with dehydration it increased to  $6.1 \pm 1.9$  pg/ml. After rehydration, the concentration declined to levels that tended to be lower than the preexercise concentration; in *trial 4%*, but not in any of the other trials, this reduction was statistically significant.

Serum sodium, potassium, and chloride concentrations did not differ between trials at any time, although they changed over the time course of each trial. The general pattern for the serum sodium and chloride concentrations was for an increase of  $\sim 2$  mmol/l with dehydration and a return to preexercise levels after

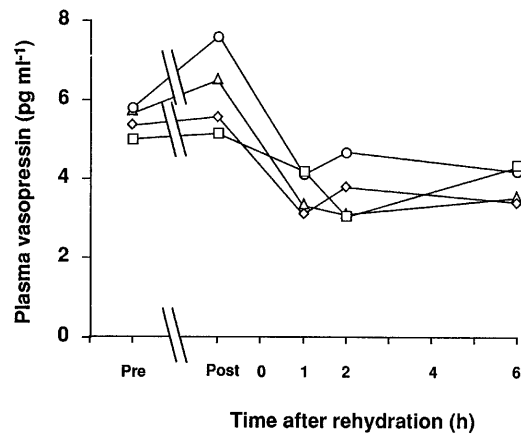


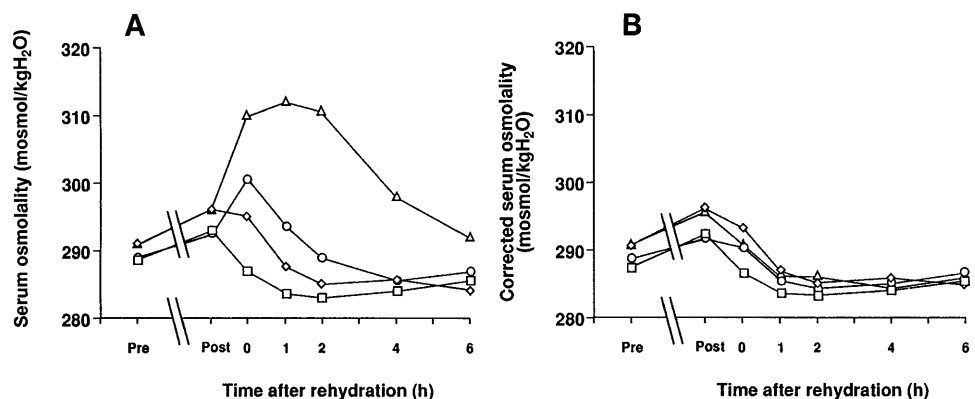
Fig. 5. Plasma vasopressin concentration over time. Points are median values. □, *trial 0%*; ◇, *trial 1%*; ○, *trial 2%*; △, *trial 4%*.

rehydration; for serum potassium concentration, there was a tendency for a decrease over the rehydration period and little change thereafter.

## DISCUSSION

The results of this study suggest that the diuretic effect of alcohol is substantially blunted when alcohol is consumed by individuals who are in a state of hypohydration induced by exercising in the heat. There was a tendency for increased urine production as the quantity of alcohol consumed increased, but only when the 4% alcohol beverage was consumed did the difference in the fraction of ingested fluid retained approach statistical significance: post hoc power analysis of the data from the six subjects indicated an 89% chance of detecting a difference of 18% (the mean difference between *trials 0%* and *4%* in the fraction of ingested fluid retained). Had this been a real difference, the chances of detecting it, given the number of subjects and the intersubject variability, was, therefore, fairly high. There was a significant reduction in the rate of recovery of blood volume when the 4% alcohol beverage was consumed. Overall, there was a tendency for the extent of the recovery to be inversely proportional to the alcohol content of the beverage. There were no differences in any measured parameter between the responses obtained with the alcohol-free beverage and with the 1 or 2% alcohol beverage trials. Therefore,

Fig. 4. Serum osmolality (A) and serum osmolality corrected for osmole contribution of ethanol (B) over time. Points are median values. □, *trial 0%*; ◇, *trial 1%*; ○, *trial 2%*; △, *trial 4%*.



providing that a sufficient volume of drink is consumed after exercise-induced dehydration [i.e., a volume greater than the volume of sweat lost (22)], there appears to be no difference in the restoration of hydration status after dehydration whether the beverage consumed is alcohol free or contains up to 2% alcohol.

Despite the suggestion by Eggleton in 1942 (5) that this may be the case when alcohol is consumed by subjects in a water-depleted state and the further discussion on the topic by Kleeman et al. (11), there appear to have been no systematic studies undertaken to investigate the effects on fluid balance of consumption of alcohol after a moderate level of dehydration. Eggleton (5) commenced her investigations into alcohol diuresis after her subjects fasted for 2–2.5 h, at which time she gave them, in a 300-ml volume, either a small (8-g) or large (>50-g) quantity of alcohol; she observed that the urine volume produced over the 2.5 h after ingestion ranged from 82 to 114 ml when 8 g of alcohol was consumed and from 642 to 858 ml when the larger quantity of alcohol was consumed. She explained these findings by attributing the retention of much of the ingested fluid when the 8 g of alcohol were consumed to the fact that the subjects were studied in the fasted state and thus were in water deficit at the time of consumption. The mean amounts of alcohol consumed in the present investigation were 0, 17.7, 35.9, and 68.0 g in trials 0%, 1%, 2%, and 4%, respectively, and these were ingested in a volume of 2,155 ml. Kleeman et al. (11) investigated the diuretic action of alcohol after its consumption in various states: positive water balance resulting from water loading, positive water balance from hypertonic sodium chloride infusion, and venous congestion of the lower limbs. Although the last two conditions have the effect of increasing vasopressin levels, which also occurs when in a dehydrated state, the subjects were either in a euhydrated or hyperhydrated state in these investigations. Roberts (19) reported that alcohol causes dehydration by inhibiting the release of vasopressin and that this occurs even when dehydration is present. However, the dehydration investigated in Roberts' paper was the result of chronic alcohol ingestion, and there must be some doubt as to whether this result applied to the present situation of dehydration induced by exercise and heat exposure.

The volume of urine produced is largely determined by circulating levels of vasopressin, and one of the factors known to reduce these levels is an increased plasma osmolality. Alcohol ingestion causes an increased plasma osmolality, but it has previously been shown that alcohol is ineffective as an osmole for stimulating vasopressin release in euhydrated individuals (9). From the results of the present investigation, it is apparent that this also holds true for hypohydrated individuals because despite large differences in the concentration of ethanol in the blood, there was no effect on the circulating vasopressin levels. Alcohol has also been shown to act independently of the osmotic effect by inhibiting vasopressin secretion directly (20), and this is the mechanism by which alcohol has been

shown to have its diuretic effect. In the present study there was no difference between trials in plasma vasopressin concentration at any point at which it was measured after rehydration, although in trial 4%, but not on any of the other trials, the concentration did decline significantly relative to the preexercise value.

The time course of urine output was different in trial 4% from that in the other three trials. It can be calculated from Table 1 that just over 40% of the total volume of urine produced over the whole recovery period after drink ingestion had been excreted over the first hour after the end of the rehydration period when the 0, 1, and 2% alcohol beverages were consumed but that only 22% had been excreted up to the equivalent time in the 4% trial. By 2 h after the end of the rehydration period, ~77% of the total 6-h urine volume produced had been excreted in trials 0%, 1%, and 2%, but only 51% had been excreted by this time in trial 4%. This delay in urine production may be due to a slower rate of gastric emptying and hence increased delay between ingestion of the test drink and water absorption with the 4% alcohol drink. There is some evidence for a slowing of gastric emptying by alcohol, but it is not clear whether this is a result of the nutrient density, the high osmolality of concentrated alcohol solutions, or a specific pharmacological effect of alcohol on the intestinal tract (23).

The quantity of sodium ingested with the drinks in the present study amounted to only  $4.4 \pm 0.2$  mmol. This is low relative to the amounts estimated to be lost in the sweat, given an exercise-induced sweat sodium concentration of 20 to 80 mmol/l (12, 21) and a sweat loss of ~1,480 ml, and it is certainly less than the urinary output of sodium after rehydration, which amounted to ~24 mmol over all trials. However, the quantity of potassium ingested amounted to  $22.1 \pm 0.7$  mmol, which was probably sufficient to replace the sweat losses incurred, given an exercise-induced sweat potassium concentration of 4–8 mmol/l (12, 21). It may also have provided some of the potassium excreted in the urine after exercise, given that the loss after rehydration amounted to ~14 mmol over all trials.

In summary, it is clear that the addition of alcohol to drinks ingested after exercise-induced dehydration has a tendency to promote an increased urine output relative to that produced after consumption of an alcohol-free beverage with otherwise identical composition. This effect is small, however, at low (<2%) alcohol concentrations.

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