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SOME EFFECTS OF CHANGE OF POSTURE ON WATER AND ELECTROLYTE EXCRETION BY THE HUMAN KIDNEY*

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Change of posture is known to be followed by alterations in the renal excretion of water and various urinary constituents. The earlier literature was summarized by Rosenbaum, Ferguson, Davis & Rossmeisl (1952). Change to the upright posture, whether by active standing (e.g. Kattus, Sinclair-Smith, Genest & Newman, 1949) or by passive tilting (e.g. Pearce & Newman, 1954), results in a rapid and marked decrease in urinary flow and in the outputs of sodium and chloride; the opposite changes occur after lying down (e.g. Kelser, Izbar, Estes & Warren, 1955). The effect of change of posture on the excretion of other urinary constituents, including potassium and inorganic phosphate, is less clear.

The renal mechanisms operative in these postural alterations in urinary excretions are incompletely understood. The cardiovascular effects of change of posture (Sjöstrand, 1953) include changes in renal haemodynamics (Smith, 1951) and when glomerular filtration rate (G.F.R.) alters it is difficult to evaluate the relative importance of glomerular and tubular factors, particularly in the short periods of observation used by most workers.

The main object of the present work was to attempt to demonstrate the importance of alterations in tubular activity in the renal adjustments to change of posture. It seemed likely that while acute alterations in renal water and electrolyte excretion could be attributable to changes in renal haemodynamics, the occurrence of more prolonged changes, particularly in urinary hydrion outputs, might indicate the participation of renal tubular factors. In the experiments reported here, the urinary outputs of water, sodium, chloride, potassium, inorganic phosphate, bicarbonate and ammonium, and urinary pH, have been followed for several hours before and after change of

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posture. Allowance was made for spontaneous diurnal rhythmic variations in urine outputs (Stanbury & Thomson, 1951), by comparing these experiments with controls in which the initial posture was maintained.

METHODS

Experiments were performed on three healthy adults. After waking in the morning a light breakfast was taken; no more food was ingested during an experiment, and no caffeine-containing fluids or smoking were allowed.

Four types of experiment were performed on each subject:

Group I, recumbent control experiments in which the subject remained in bed after waking for at least 6 hr.

Group II, experiments in which the subject remained in bed until mid morning, when he got up and then stood quietly for at least 3 hr.

Group III, control standing experiments, in which the subject travelled to the laboratory in the morning and then stood quietly for at least 4½ hr.

Group IV, experiments similar to group III, except that at some time between 10.00 and 11.00 hr, after standing for 1½–3 hr, the subject lay down and then remained recumbent for at least 3 hr.

Urine samples were collected by voluntary voiding every 30 or 60 min, and 100 ml. water was ingested hourly. To minimize bladder emptying errors the subject stood to void samples, and to minimize loss of carbon dioxide (Marshall, 1922) urine was collected and stored under liquid paraffin.

Analytical methods employed were as follows:

Sodium and potassium were estimated by flame photometer, EEL (Collins & Polkinhorne, 1952);
Chloride by electrometric titration (Sanderson, 1952);
Inorganic phosphate by the method of Fiske & Subbarow (1925);
Bicarbonate by that of Van Slyke & Neill (1924);
Ammonium by aeration and titration (Hawk, Oser & Summerson, 1947);
pH by glass electrode at 37° C;
Creatinine by the method of Bonsnes & Taussky (1945).

'Phosphate titratable acid' in the text refers to the fraction of urinary phosphate titratable to pH 7·4, and was calculated as described by Longson & Mills (1953).

The base-equivalence of any particular urinary inorganic phosphate concentration, at the prevailing urinary pH, was calculated as

$$P\,(2-x),$$

where P = molar phosphate concentration, and x = fraction of molar phosphate existing as monobasic dihydrogen phosphate, which was determined in the calculation of 'phosphate titratable acid'.

The urinary concentration of base-bound bicarbonate was calculated from the value of pK_1 at 38° C $= 6{\cdot}32 - 0{\cdot}5\sqrt{B}$ (McGee & Hastings, 1942); B was taken as $[Na]+[K]+[NH_4]$.

RESULTS

Four experiments of each type were performed, two on one subject (T) and one each on the other two subjects (B and C). In all the four control recumbent experiments there were changes attributable to the diurnal excretory rhythm in urine pH (Fig. 1), flow and the outputs of sodium, chloride, potassium and bicarbonate (Fig. 1), all of which increased from low early-morning values

to reach maximal values in mid morning, and then usually decreased towards the afternoon. Inorganic phosphate and ammonium outputs showed rhythmic variations in the reverse direction. In the control standing experiments on subjects T and C a clear diurnal rhythmic variation in urine excretion was also seen (Fig. 2), but the outputs of sodium, chloride and water were less. In subject B, however, there were no clear diurnal variations in the standing control experiment.

From any series of four experiments on one subject two comparisons can be made; first, between groups I and II experiments showing the effects of standing up as compared with continued recumbency, and secondly, between groups III and IV, showing the effects of lying down as compared with continued standing.

Urine flow, sodium and chloride

Comparison of groups I and II experiments shows that, within an hour of standing up, diminution occurred in urine flow and the outputs of sodium and chloride, which persisted during the prolonged maintenance of the new posture. In the third hour of standing the sodium outputs were between 30 and 70 μequiv/min compared with between 150 and 250 μequiv/min in corresponding recumbent periods, and flows in three of the four experiments were between 0·4 and 0·7 ml./min compared with between 2·0 and 3·4 ml./min. In one experiment on subject T the flow rose in the third hour of standing to 1·9 ml./min. Changes in chloride outputs were similar to those for sodium, but usually less. Conversely, lying down consistently increased urine flow and the outputs of sodium and chloride. Subjects B and C showed immediate increases and the difference from controls became more marked as the recumbent position was maintained. In subject T there was little difference from controls for the first 2 hr. After this there was an arrest of the diurnal decline, and by early afternoon an absolute increase in output occurred at a time of day when continued standing resulted in a further decline.

Potassium

The qualitative pattern of the diurnal rhythmic variations seen in control experiments was usually maintained after standing up. In subjects B and C there was an initial fall in output, and in C the output remained lower. In subject B and in one experiment on subject T, however, an absolute increase occurred in the third hour of standing at a time of day when a diurnal rhythmic decrease normally occurs. After lying down the potassium outputs in subject T were almost identical with those in the control standing experiments. Subject B showed a considerable increase in potassium output within an hour of lying down, but this was followed by a decrease towards control values. Subject C showed a much smaller transient increase.

Inorganic phosphate

Spontaneous diurnal rhythmic variations in inorganic phosphate outputs were conspicuous in the control recumbent and standing experiments on all three subjects, particularly T, with minimal outputs being found between 09.00 and 11.00 hr. Standing caused no evident modification of the diurnal increase in excretion in subjects B and T, but a small decrease in C. Similarly lying down had no apparent effect on outputs in any of the subjects, since the diurnal increase in outputs found in the standing experiments was similar to that present after lying down.

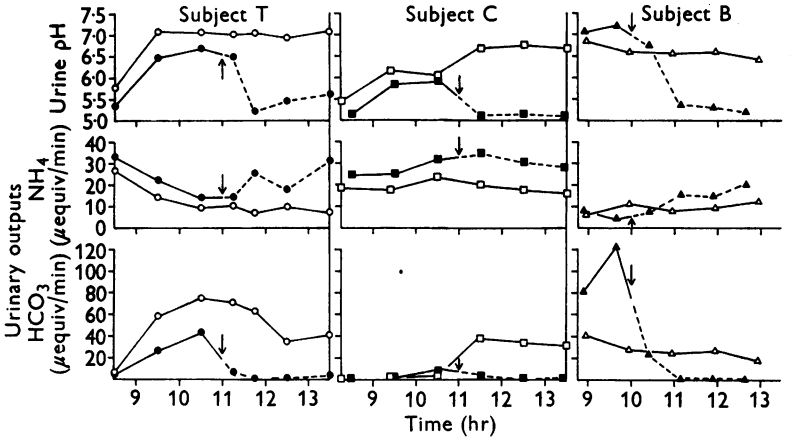

Fig. 1. Urine pH and the outputs of NH_4 and HCO_3 in expts. in which subjects B, C and T remained recumbent (B, △—△; C, □—□; T, ○—○) compared with expts. in which they changed from lying to standing (B, ▲---▲; C, ■---■; T, ●---●).

Acid and alkali excretion

In all subjects change of posture was followed by consistent alterations in urine acid–base balance as indicated by changes in urine pH, and in the outputs of bicarbonate, ammonium and phosphate titratable acid.

Standing after lying. In the three subjects urine pH values of over 6·5 were present in the later periods of continued recumbency; standing up, however, was followed by a decline to below 5·5 in subject T, and in subjects B and C the pH in the third hour of standing was below 5·2 (Fig. 1).

These changes in urine pH were accompanied by changes in total bicarbonate output (Fig. 1). Standing was followed by a rapid decrease in outputs in all subjects, and the difference from controls persisted on maintained standing. In subject T bicarbonate outputs were under 5 μequiv/min in the third hour after standing up compared with over 40 μequiv/min on continued recumbency, and in the other subjects there were similar reductions.

Conversely, standing up caused an increase in ammonium outputs, least marked in subject C. In the two recumbent controls in subject T, diurnal decreases in outputs to minimal values of about 10 μequiv/min in the 09.00–10.00 hr samples were followed by a maintenance of low outputs; standing up, however, was followed by a progressive increase to values of 30 μequiv/min in the third hour of standing. Subject B showed an output of 20 μequiv/min in the third hour of standing compared with 10 μequiv/min in the corresponding recumbent periods, and C 30 compared with 17 μequiv/min (Fig. 1).

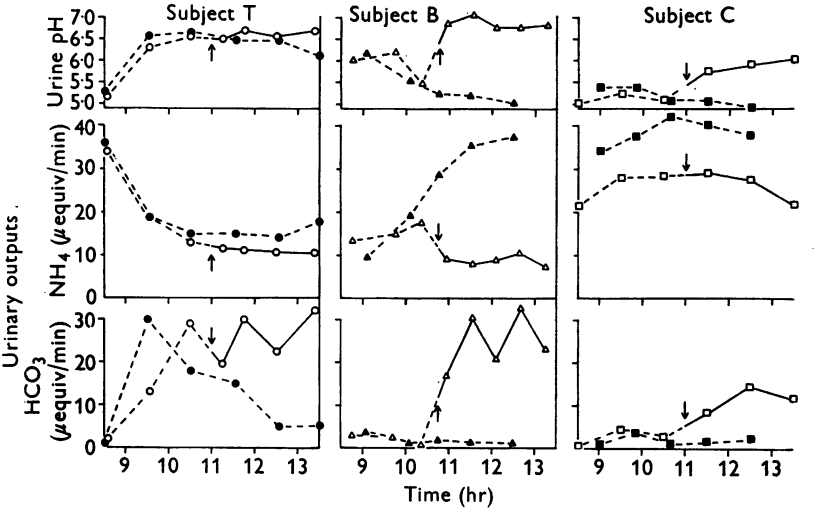

Fig. 2. Urine pH and the outputs of NH_4 and HCO_3 in expts. in which subjects B, C and T remained standing (B, ▲- - -▲; C, ■- - -■; T, ●- - -●) compared with expts. in which they changed from standing to lying (B, △- - —△; C, □- - —□; T, ○- - —○).

Lying after standing. Lying down was followed by an increase in the urine pH in all experiments, particularly in subjects B and C. In these subjects maintenance of standing was associated with a gradual fall in pH from early high values to about 5·0 by mid-day. After lying down, however, there was an increase to about 6·0 in C, and 7·0 in B and these high values were maintained to the end of the experiments. In subject T differences were only evident in the third hour of recumbency (Fig. 2).

These changes were accompanied by increases in bicarbonate outputs (Fig. 2). In subjects B and C the standing samples showed maximal values of 5 μequiv/min; after lying down the outputs increased in all subjects, and in the third hour of recumbency the outputs were between 13 and 30 μequiv/min compared with between 2 and 5 μequiv/min in the equivalent standing periods.

Ammonium outputs fell after the subjects lay down (Fig. 2), again least

marked in subject C. There was at least an arrest of the usual diurnal increase in ammonium output, and in some experiments there was a diminution in the later periods, compared with a rise when the subjects remained standing.

Creatinine

When subject B stood up, creatinine output fell from 1·33 to 1·10 mg/min and the output remained at this level in the subsequent periods. A smaller fall was seen in subject C and in one experiment on T, but the output then rose to the previous levels. In the other experiment on subject T there was not even a temporary fall. After lying down there were no consistent alterations in creatinine outputs in subjects C and T apart from early transient increases. In B, however, outputs were slightly higher in all periods after lying down.

Urinary ionic pattern

Since the absolute outputs of some of these various urinary constituents altered in opposite directions after change of posture, there was a considerable modification of the urinary ionic pattern. Of the normal urinary cations, Na^+, K^+ and NH_4^+ were determined in these experiments; of the urinary anions, Cl', HCO_3' and inorganic phosphate. The sum of $[Na+K+NH_4]$ gives the concentration of determined cations (m-equiv/l.) in any sample, and the sum of [Cl + HCO_3 + base-equivalence (P) of molar phosphate] gives the concentration of determined anions.

An indication of the relative changes in cation outputs may be obtained by calculating the percentage of determined anion output (A) covered by the particular cation ($Na:A$, $K:A$ and $NH_4:A$). Similarly, data on individual anions can be presented as the percentage of the determined cation output (B) covered by the particular anion ($Cl:B$, $HCO_3:B$ and $P:B$). In most collection periods the sum of ($Na:A+K:A+NH_4:A$) exceeded 100%, since the sum of the determined cations exceeded the sum of the determined anions by 20–30 μequiv/min. In any one experiment this cation excess remained fairly constant and there was no evidence of the participation of undetermined anions in the renal response to change of posture.

Fig. 3 shows the effect of standing up on these ionic excretory percentages, compared with a recumbent control, in subject T. Comparison of Fig. 3 with Fig. 4 shows that while the absolute sodium output varied in the control recumbent experiment between 60 and 250 μequiv/min, the percentage of excreted anion covered by sodium ($Na:A$) remained more constant between 60 and 70. Standing up, however, resulted in a fall in $Na:A$ to about 40% in later periods. Standing produced the opposite changes in $K:A$ and $NH_4:A$ (Fig. 3). After an early rise, $K:A$ remained fairly constant at about 30% on continued recumbency, whereas standing up was followed by a rise to about 55%. In the control recumbent experiment, $NH_4:A$ showed a diurnal de-

crease to below 5% in the later periods; standing up, however, caused an increase to 30%.

Cl:*B* remained fairly constant at about 80% on maintained recumbency, and standing up produced only a temporary rise, but HCO_3:*B* showed marked changes. In the control recumbent experiment there was a rise from early values of 3% to over 20%, accompanying the diurnal increase in absolute

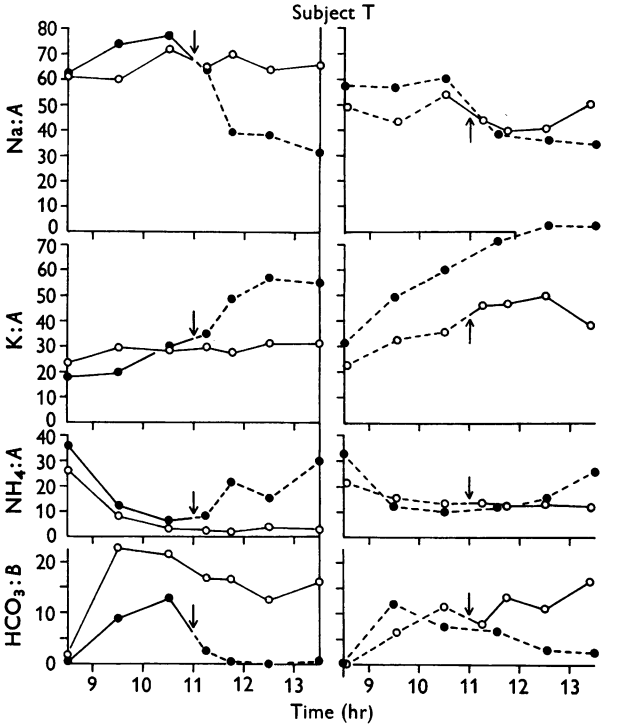

Fig. 3. Percentage of determined urinary anion (*A*) covered by Na (Na:*A*), K (K:*A*) and NH_4 (NH_4:*A*), and the percentage of urinary cation (*B*) covered by HCO_3 (HCO_3:*B*): *left*, an expt. in which subject T remained lying (○—○) compared with an expt. in which he changed from lying to standing (●—·-·-●); *right*, an expt. in which subject T remained standing (●-·-·-●) compared with an expt. in which he changed from standing to lying (○-·-·—○).

bicarbonate output. Standing up, however, resulted in the amount of base covered by bicarbonate becoming negligible. The P:*B* percentage was almost unaffected by standing.

Lying down caused the opposite changes (Fig. 3); Na:*A* increased while K:*A* and NH_4:*A* decreased, and HCO_3:*B* increased while Cl:*B* showed a small decrease. Similar results were found in the other subjects, the changes in NH_4:*A* and HCO_3:*B* being especially marked in subject B.

Hydrion excretion

An assessment of the magnitude of urinary hydrion excretion may be made by summing the output of ammonium and phosphate titratable acid and subtracting base-bound bicarbonate output (Longson & Mills, 1953). Examples of urinary outputs of hydrion for subject T are given in Fig. 4. In the recumbent and standing control experiments diurnal rhythmic variations in hydrion outputs were evident. Lying down caused a marked decrease in hydrion excretion and, conversely, standing up was followed by an increase in hydrion output. Similar results were obtained in the other subjects, being particularly evident in subject B.

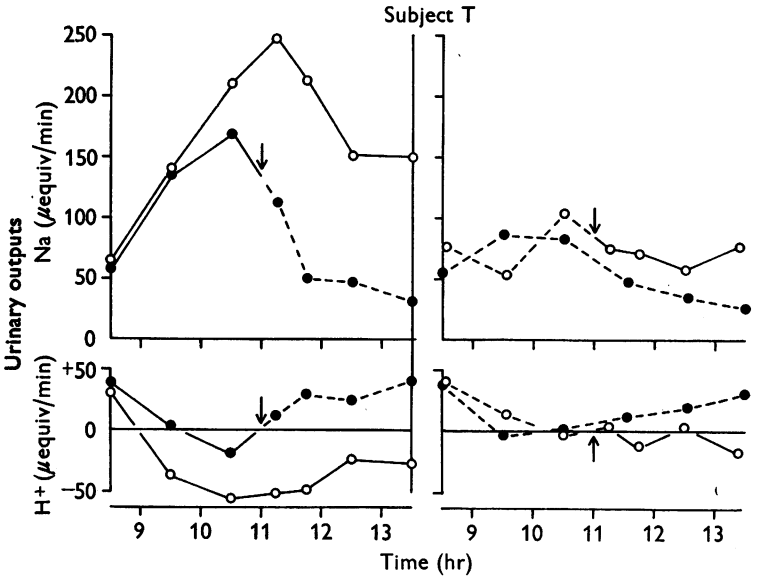

Fig. 4. Urinary outputs of Na and hydrion (H^+): *left*, an expt. in which subject T remained recumbent compared with an expt. in which he changed from lying to standing; *right*, an expt. in which subject T remained standing compared with an expt. in which he changed from standing to lying. Symbols as in Fig. 3.

DISCUSSION

The acute reductions in urine flow and in outputs of sodium and chloride observed after standing, and the reverse changes after lying down, confirm the abundant observations in the literature (Lewis, Buie, Sevier & Harrison, 1950; McCance, 1951; Viar, Oliver, Eisenberg, Willis, Lombardo & Harrison, 1951; Chalmers & Squires, 1953; Goodyer & Seldin, 1953; Netravisesh, 1953; Holland & Stead, 1954; Pearce & Newman, 1954); in addition, the present experiments show that these changes persist for many hours. The present findings that change of posture had comparatively little prolonged effect on

absolute potassium and phosphate outputs, when allowance was made for diurnal rhythmic variations, supplement previous reports on potassium (e.g. Kattus *et al.* 1949; Viersma & ten Holt, 1950; Viar *et al.* 1951; Rosenbaum Nelson, Strauss, Davis & Rossmeisl, 1953; Bachman & Youmans, 1953) and phosphate (Kattus *et al.* 1949; Pearce & Simmons, 1954).

There are few observations in the literature on acid–base changes after alteration of posture. Bachman & Youmans (1953) and Pearce & Simons (1954) found no change in ammonium excretion in the upright position, while Goodyer & Seldin (1953) claimed a slight decrease; absence of effect on titratable acid excretion, in spite of a consistent change in pH and bicarbonate excretion, has been reported (Pearce & Simmons, 1954). Changes in urine bicarbonate excretion and pH are evident in the data of White, Rosen, Fischer & Wood (1926) and Bazett, Thurlow, Crowell & Stewart (1924); a fall in the ratio Cl:(Na + K) with a rise in pH after lying down was noted by Mills & Stanbury (1952), and this suggests a rise in bicarbonate excretion. The present consistent effect of change of posture on urinary pH and on the outputs of bicarbonate and ammonium was often only made evident by comparison with control experiments in which the initial posture was maintained, and by prolonged maintenance of the new posture.

The ionic pattern of urine samples after change of posture shows that, apart from the changes in absolute output of sodium, there were also changes in the magnitude of sodium excretion relative to the other ionic constituents. Thus the decrease in absolute sodium output caused by standing was relatively greater than the decrease in total determined anion output, so that sodium covered a smaller proportion of the excreted anion. The increase in $K:A$ on standing, even where no appreciable alteration in absolute output of potassium occurred, and the considerable increase in $NH_4:A$, even though the absolute increase in ammonium output was small, reflect the decrease in total anion outputs.

Change of posture had a striking effect on the relative contribution of bicarbonate to the acid–base balance of the urine; on standing, bicarbonate covered a very small proportion of excreted base, while in recumbency the proportion was much higher. Changes in $Cl:B$ were less obvious, except where considerable changes in $HCO_3:B$ occurred, when $Cl:B$ altered in the opposite direction.

The occurrence of little change in the percentage of excreted base covered by inorganic phosphate, despite an unaltered molar phosphate output in the presence of altered base output, seemed to be secondary to the alteration in urinary pH. On standing, for example, the reduction in urinary pH led to a lowered base-equivalence of the molar phosphate output which paralleled the reduction in total base excretion, so that the percentage $P:B$ showed little change.

The intrarenal mechanisms involved in the renal response to change of posture

Alterations in urinary excretion of water and electrolytes might be due to change in filtered load, or in quantitative tubular reabsorption, or to a combination of both. As a possible factor in any change of filtered load, change in plasma sodium concentration can be excluded (Kattus *et al.* 1949; Epstein, Goodyer, Lawrason & Relman, 1951; Pearce & Newman, 1954; Thomas, 1956), and there is no evidence of alteration in plasma potassium concentration (Thomas, 1956).

The presence of any alteration in G.F.R. after change of posture (White & Rolf, 1948; Epstein *et al.* 1951; Goodyer & Seldin, 1953) is a complication in any attempt to assess the possible participation of change in tubular function in renal postural responses. Most suggestions of an altered tubular reabsorption of sodium have depended on the demonstration of marked alterations in sodium excretion when changes in endogenous creatinine or inulin clearances were small or absent (Viar *et al.* 1951; Epstein *et al.* 1951; Pearce & Newman, 1954; Thomas, 1956) or of a larger percentage alteration in sodium excretion than in G.F.R. (Chalmers & Squires, 1953). However, because sodium and water excretion normally represents only a small percentage of the filtered load, considerable changes in urinary excretion might result from small changes in G.F.R. In the present experiments an attempt to minimize possible changes in G.F.R. was made by allowing sufficient muscular movement while the subjects were standing to avoid subjective syncopal sensations, and by prolonging the observations, when any acute changes in G.F.R. might be expected to have become stabilized. Under these circumstances the alterations in absolute outputs of ammonium and bicarbonate and the changes in urinary pH and ionic pattern become more significant and indicate an alteration in the magnitude of tubular hydrion secretion.

On current theory the renal production of titratable acid and ammonium and part, at least, of the tubular reabsorption of bicarbonate are functionally related by being manifestations of the distal tubular ion exchange of sodium for hydrion (Gilman & Brazeau, 1953). The present demonstration of alteration in hydrion excretion (Fig. 4) provides strong evidence of the participation of the $Na^+ \rightleftharpoons H^+$ exchange mechanism in the renal response to change of posture. Standing appears to increase the magnitude of this exchange, with a decrease in sodium excretion and an increase in hydrion excretion, as manifested by increased ammonium and titratable acid excretion and a decrease in urinary pH and in bicarbonate output. Lying down depresses the magnitude of this exchange.

The contribution of this change in ion exchange to the total alteration in sodium excretion was variable, but usually at least 50% of the change in sodium excretion could be attributed to this mechanism. In many periods

the alteration in sodium excretion could be entirely accounted for by change in hydrion excretion. Some of the quantitative variation between experiments is presumably related to the varying change in G.F.R. that may occur after change of posture. In some experiments the percentage of the change in sodium output attributable to the change in hydrion output progressively increased, from the early periods when change in G.F.R. might be maximal to the later periods when the altered posture had been maintained for some hours.

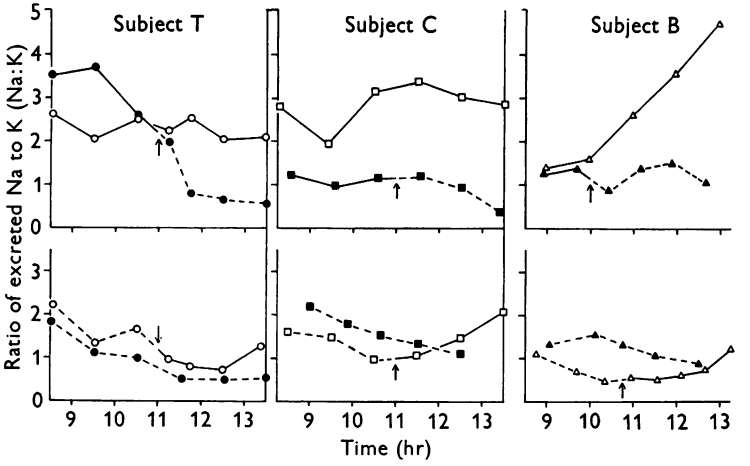

Fig. 5. Ratio of excreted Na to excreted K (Na:K): top, in expts. on subjects B, C and T in which they remained recumbent (B, △—△; C, □—□; T, ○—○) compared with expts. in which they changed from lying to standing (B, ▲- - -▲; C, ■- - -■; T, ●- - -●); and below, in expts. in which they remained standing (B, ▲- - -▲; C, ■- - -■; T, ●- - -●) compared with expts. in which they changed from standing to lying (B, △- - -△; C, □- - -□; T, ○- - -○.)

There was little evidence in the present experiments to indicate any competition between secreted H^+ and K^+ for available Na^+ (Berliner, Kennedy & Orloff, 1951), since any early changes in potassium outputs were usually small and transient. In the two experiments where standing up was followed by small increases in potassium excretion in the later periods, an increase in $Na^+ \rightleftharpoons K^+$ exchange presumably occurred in the presence of increased $Na^+ \rightleftharpoons H^+$ exchange.

More suggestive evidence of an alteration in the magnitude of $Na^+ \rightleftharpoons K^+$ exchange, in the same direction as change in $Na^+ \rightleftharpoons H^+$ exchange, is provided by consideration of the ratio of excreted sodium to potassium (Na:K). Fig. 5 illustrates experiments on all three subjects, and shows that standing up compared with continued recumbency progressively decreased Na:K, and that lying down compared with continued standing progressively increased Na:K, though more slowly.

Standing, therefore, seems to have caused a specific tubular retention of sodium, in addition to any retention secondary to change in G.F.R. This tubular retention of sodium seems to have been effected by increase in the magnitude of $Na^+ \rightleftharpoons H^+$ exchange, but an increased $Na^+ \rightleftharpoons K^+$ exchange may also have been involved. If the need for sodium conservation during standing is enhanced, as during a sulphate diuresis, the presence of an increase in $Na^+ \rightleftharpoons K^+$, as well as in $Na^+ \rightleftharpoons H^+$, exchange may become more obvious (Epstein, Kleeman, Lamdin & Rubini, 1956).

Surtshin & White (1956) have emphasized alterations in proximal, rather than distal, reabsorption of sodium in renal postural responses. This conclusion depended on several assumptions, including that of complete suppression of antidiuretic hormone (ADH) secretion under conditions of maximal water diuresis in both the standing and recumbent positions. However, it is possible that the reduced flows of urine in the standing position, even in maximally hydrated subjects, may be partly related to ADH secretion (McCance, 1951; Rosenbaum *et al.* 1953; Pearce & Newman, 1954).

The present experiments give no direct evidence as to the nature of the stimulus which caused such variations in tubular ion-exchange processes, but it appears unlikely that alterations in the acid–base balance of body fluids account for the altered bicarbonate excretion. There is a tendency for alveolar partial pressure of carbon dioxide (pCO_2) to increase in recumbency (Higgins, 1914), while Main (1937) reported a small but significant rise of 0·03–0·06 in blood pH on standing. The increased bicarbonate excretion after lying down is therefore in the opposite direction to that expected from any direct effect of plasma pCO_2 on tubular reabsorption of bicarbonate (Brazeau & Gilman, 1953; Dorman, Sullivan & Pitts, 1954).

Change of posture is well known to be one of the circumstances leading to an alteration in the dynamic distribution of extracellular fluid between the intravascular and extravascular compartments (Asmussen, Christensen & Nielsen, 1940), and such effects persist for many hours, as indicated by alterations in blood composition (Widdowson & McCance, 1951). There is considerable evidence for the existence of some 'volume receptor' mechanism, responsive to changes either in the total volume, or some related function, of the extracellular fluid (Wrong, 1957), and variations in aldosterone secretion may be involved in this mechanism (Bartter, 1956). Although it is unlikely that changes in aldosterone secretion could account for the immediate alterations in sodium excretion after change of posture, it seems more probable that such changes in hormone output could explain the prolonged alterations found in the present experiments. In particular, the progressive effects on (*a*) urinary pH and the outputs of sodium, bicarbonate, ammonium and titratable acid, (*b*) ionic pattern, (*c*) the proportion of the change in sodium output attributable to change in hydrion excretion, and (*d*) the Na:K ex-

cretory ratio, all suggest a hormonal mechanism rather than effects secondary to any change in G.F.R., which would be expected to be maximal immediately after the change of posture. Such progressive alterations are compatible with variations in adrenocorticoid secretion since adrenocorticoids appear to influence tubular transport of sodium (Roemmelt, Sartorius & Pitts, 1949), potassium (Ingbar, Kass, Burnett, Relman, Burrows & Sisson, 1951), ammonium and titratable acid (Sartorius, Calhoun & Pitts, 1953) and tubular reabsorption of bicarbonate (Giebisch & Macleod, 1955).

Rosenbaum, Papper & Ashley (1955) concluded that postural changes in sodium excretion, while dependent on the presence of adrenal hormone, were independent of alteration in hormone activity. They assumed that the administration of exogenous cortisone in their patients with Addison's disease would completely suppress any endogenous activity, but there are reports that cortisone administration does not suppress endogenous aldosterone secretion (Liddle, Bartter, Duncan, Barber & Delea, 1955; Farrell, Banks & Koletsky, 1956).

The present results, therefore, seem consistent with the view that change of posture may affect some extracellular fluid volume receptor mechanism which, via an adrenal cortical hormone, presumably aldosterone, varies sodium reabsorption in the renal tubules by influencing the magnitude of ion-exchange processes, particularly $Na^+ \rightleftharpoons H^+$ exchange.

SUMMARY

1. In morning experiments on three subjects, urinary pH and flow and the outputs of sodium, potassium, chloride, ammonium, bicarbonate and phosphate were determined for several hours after change of posture from lying to standing, and from standing to lying, and compared with control experiments in which the initial posture was maintained.

2. Standing up was followed by prolonged reductions in urine flow and in sodium and chloride outputs, and lying down by the opposite changes.

3. Changes in potassium and phosphate outputs were usually absent, or small and transient, and diurnal rhythmic variations were hardly affected. In two experiments small increases in potassium output occurred in the third hour after standing up.

4. Standing up was consistently followed by a decrease in urine pH and bicarbonate output and an increase in ammonium and titratable acid outputs; lying down was followed by the opposite changes. These changes in urine acid–base balance became more pronounced or prolonged maintenance of the new posture.

5. After standing up the percentage of urinary anion (A) covered by sodium ($Na:A$) decreased, while $K:A$ and $NH_4:A$ increased; the percentage of excreted cation (B) covered by bicarbonate ($HCO_3:B$) decreased, and $Cl:B$

showed small inconstant increases. The opposite changes occurred after lying down.

6. Standing up was followed by an increased, and lying down by a decreased, hydrion excretion; the percentage of the change in sodium output attributable to the opposite change in hydrion output was variable, but often progressively rose on maintenance of the new posture.

7. It is concluded that part, at least, of the sodium retention caused by standing and of the increased sodium excretion after lying down is attributable to an altered tubular $Na^+ \rightleftharpoons H^+$ exchange.

8. These results are considered to be consistent with a view that change of posture causes a specific alteration of tubular ion-exchange processes, possibly by a hormonal mechanism.

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REFERENCES

ASMUSSEN, E., CHRISTENSEN, E. H. & NEILSEN, M. (1940). The regulation of circulation in different postures. *Surgery*, **8**, 604–616.

BACHMAN, D. M. & YOUMANS, W. B. (1953). Effects of posture on renal excretion of sodium and chloride in orthstatic hypotension. *Circulation*, **7**, 413–421.

BARTTER, F. C. (1956). The role of aldosterone in normal homeostasis and in certain disease states. *Metabolism*, **5**, 369–383.

BAZETT, H. C., THURLOW, S., CROWELL, C. & STEWART, W. (1924). Studies on the effects of baths on man. II. The diuresis caused by warm baths, together with some observations on urinary tides. *Amer. J. Physiol.* **70**, 430–452.

BERLINER, R. W., KENNEDY, T. J., JR. & ORLOFF, J. (1951). Relationship between acidification of the urine and potassium metabolism. *Amer. J. Med.* **11**, 274–282.

BONSNES, R. W. & TAUSSKY, H. H. (1945). On the colorimetric determination of creatinine by the Jaffe reaction. *J. biol. Chem.* **158**, 581–591.

BRAZEAU, P. & GILMAN, A. (1953). Effects of plasma CO_2 tension on renal tubular reabsorption of bicarbonate. *Amer. J. Physiol.* **175**, 33–38.

CHALMERS, T. M. & SQUIRES, R. D. (1953). Renal response to motionless standing. *J. Physiol.* **122**, 58*P*.

COLLINS, G. C. & POLKINHORNE, H. (1952). An investigation of anionic interference in the determination of small quantities of potassium and sodium with a new flame photometer. *Analyst*, **77**, 430–436.

DORMAN, P. J., SULLIVAN, W. J. & PITTS, R. F. (1954). The renal response to acute respiratory acidosis. *J. clin. Invest.* **33**, 82–90.

EPSTEIN, F. H., GOODYER, A. V. N., LAWRASON, F. D. & RELMAN, A. S. (1951). Studies of the antidiuresis of quiet standing: the importance of changes in plasma volume and glomerular filtration rate. *J. clin. Invest.* **30**, 63–72.

EPSTEIN, F. H., KLEEMAN, C. R., LAMDIN, E. & RUBINI, M. E. (1956). Studies of the antidiuresis of quiet standing: observations upon electrolyte and acid-base excretion during sulfate diuresis. *J. clin. Invest.* **35**, 308–313.

FARRELL, G. L., BANKS, R. C. & KOLETSKY, S. (1956). The effect of corticosteroid injection on aldosterone secretion. *Endocrinology*, **58**, 104–108.

FISKE, C. H. & SUBBAROW, Y. (1925). The colorimetric determination of phosphorus. *J. biol. Chem.* **66**, 375–400.

GIEBISCH, G. & MACLEOD, M. B. (1955). Effects of adrenal steroids, ACTH and potassium depletion on renal tubular reabsorption of bicarbonate. *Fed. Proc.* **14**, 57.

GILMAN, A. & BRAZEAU, P. (1953). The role of the kidney in the regulation of acid-base metabolism. *Amer. J. Med.* **15**, 765–770.

GOODYER, A. V. N. & SELDIN, D. W. (1953). The effects of quiet standing on solute diuresis. *J. clin. Invest.* **32**, 242–250.

HAWK, P. B., OSER, B. L. & SUMMERSON, W. H. (1947). *Practical Physiological Chemistry*, 12 ed., p. 828. London: Churchill.

HIGGINS, H. L. (1914). The influence of food, posture, and other factors on the alveolar carbon dioxide tension in man. *Amer. J. Physiol.* **34**, 114–126.

HOLLAND, B. C. & STEAD, E. A., JR. (1954). Electrolyte excretion after single doses of ACTH, cortisone, desoxycorticosterone glucoside and motionless standing. *J. clin. Invest.* **33**, 132–135.

INGBAR, S. H., KASS, E. H., BURNETT, C. H., RELMAN, A. S., BURROWS, B. A. & SISSON, J. H. (1951). The effects of ACTH and cortisone on the renal tubular transport of uric acid, phosphorus, and electrolytes in patients with normal renal and adrenal function. *J. Lab. clin. Med.* **38**, 533–541.

KATTUS, A. A., SINCLAIR-SMITH, B., GENEST, J. & NEWMAN, E. V. (1949). The effect of exercise on the renal mechanism of electrolyte excretion in normal subjects. *Johns Hopk. Hosp. Bull.* **84**, 344–368.

KELSER, G. A., JR., IZBAR, H. L., ESTES, E. H., JR. & WARREN, J. V. (1955). Renal sodium regulation: a comparison of the effect of recumbency and neck compression. *Amer. J. Med.* **19**, 144–145.

LEWIS, J. M., JR., BUIE, R. M., SEVIER, S. M. & HARRISON, T. R. (1950). The effect of posture and of congestion of the head on sodium excretion in normal subjects. *Circulation*, **2**, 822–827.

LIDDLE, G. W., BARTTER, F. C., DUNCAN, L. E., JR., BARBER, J. K. & DELEA, C. (1955). Mechanisms relating aldosterone production in man. *J. clin. Invest.* **34**, 949.

LONGSON, D. & MILLS, J. N. (1953). The failure of the kidney to respond to respiratory acidosis. *J. Physiol.* **122**, 81–92.

MAIN, R. J. (1937). Alterations of alveolar CO_2 in man accompanying postural change. *Amer. J. Physiol.* **118**, 435–440.

MARSHALL, E. K., JR. (1922). The effect of loss of carbon dioxide on the hydrogen ion concentration of urine. *J. biol. Chem.* **51**, 3–10.

MCCANCE, R. A. (1951). Studies of undernutrition, Wuppertal 1946–9. X. Aspects of renal function and water metabolism. *Spec. Rep. Ser. med. Res. Coun., Lond.*, no. 275, pp. 175–192.

MCGEE, L. C. & HASTINGS, A. B. (1942). The carbon dioxide tension and acid-base balance of jejunal secretions in man. *J. biol. Chem.* **142**, 893–904.

MILLS, J. N. & STANBURY, S. W. (1952). Persistent 24-hour renal excretory rhythm on a 12-hour cycle of activity. *J. Physiol.* **117**, 22–37.

NETRAVISESH, V. (1953). Effects of posture and of neck compression on outputs of water, sodium and creatinine. *J. appl. Physiol.* **5**, 544–548.

PEARCE, M. L. & NEWMAN, E. V. (1954). Some postural adjustments of salt and water excretion. *J. clin. Invest.* **33**, 1089–1094.

PEARCE, M. L. & SIMMONS, D. H. (1954). Effects of water diuresis and postural and pitressin antidiuresis on urine composition. *Fed. Proc.* **13**, 109.

ROEMMELT, J. C., SARTORIUS, O. W. & PITTS, R. F. (1949). Excretion and reabsorption of sodium and water in the adrenalectomised dog. *Amer. J. Physiol.* **159**, 124–136.

ROSENBAUM, J. D., FERGUSON, B. C., DAVIS, R. K. & ROSSMEISL, E. C. (1952). The influence of cortisone upon the diurnal rhythm of renal excretory function. *J. clin. Invest.* **31**, 507–520.

ROSENBAUM, J. D., NELSON, W. P., III., STRAUSS, M. B., DAVIS, R. K. & ROSSMEISL, E. C. (1953). Variation in the diuretic response to ingested water related to the renal excretion of solutes. *J. clin. Invest.* **32**, 394–404.

ROSENBAUM, J. D., PAPPER, S. M. & ASHLEY, M. M. (1955). Variations in renal excretion of sodium independent of change in adrenocortical hormone dosage in patients with Addison's disease. *J. clin. Endocrin.* **15**, 1459–1474.

SANDERSON, P. H. (1952). Potentiometric determination of chloride in biological fluids. *Biochem. J.* **52**, 502–505.

SARTORIUS, O. W., CALHOUN, D. & PITTS, R. F. (1953). Studies on the interrelation of the adrenal cortex and renal ammonia excretion by the rat. *Endocrinology*, **52**, 256–265.

SJÖSTRAND, T. (1953). Volume and distribution of blood and their significance in regulating circulation. *Physiol. Rev.* **33**, 202–228.

SMITH, H. W. (1951). *The Kidney Structure and Function in Health and Disease*, pp. 432–435. New York: Oxford University Press.

STANBURY, S. W. & THOMSON, A. E. (1951). Diurnal variations in electrolyte excretion. *Clin. Sci.* **10**, 267–293.

SURTSHIN, A. & WHITE, H. L. (1956). Postural effects on renal tubular activity. *J. clin. Invest.* **35**, 267–271.

THOMAS, S. (1956). Renal adjustments to change in posture. *J. Physiol.* **132**, 61–62*P*.

VAN SLYKE, D. D. & NEILL, J. M. (1924). The determination of gases in blood and other solutions by vacuum extraction and manometric measurement. *J. biol. Chem.* **61**, 523–573.

VIAR, W. N., OLIVER, B. B., EISENBERG, S., WILLIS, K., LOMBARDO, T. A. & HARRISON, T. R. (1951). The effect of posture and of compression of the neck on excretion of electrolytes and glomerular filtration; further studies. *Circulation*, **3**, 105–115.

VIERSMA & TEN HOLT, quoted by BORST, J. G. G. & DE VRIES, L. A. (1950). Three types of 'Natural Diuresis'. *Lancet*, **259**, 1–6.

WHITE, H. L. & ROLF, D. (1948). Effects of exercise and of some other influences on the renal circulation in man. *Amer. J. Physiol.* **152**, 505–516.

WHITE, H. L., ROSEN, I. T., FISCHER, S. S. & WOOD, G. H. (1926). The influence of posture on renal activity. *Amer. J. Physiol.* **78**, 185–200.

WIDDOWSON, E. M. & MCCANCE, R. A. (1951). Studies of undernutrition, Wuppertal 1946–9. IX. The effect of undernutrition and of posture on the volume and composition of the body fluids. *Spec. Rep. Ser. med. Res. Coun., Lond.*, no. 275, pp. 165–174.

WRONG, O. (1957). The volume control of body fluids. *Brit. med. Bull.* **13**, 10–14.