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RENAL EXCRETION OF SODIUM AND POTASSIUM IN RATS

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Renal excretion of potassium has been investigated in man (Griffon, 1936; Cutler, Power & Wilder, 1938; Hall & Langley, 1940), in the dog (Winkler & Smith, 1942) and in the cat (Wirz, 1945), but opinions as to its mechanism are divergent. It is not clear from these papers whether the amount of potassium excreted is related to the rate of glomerular filtration. It was, therefore, decided to investigate the mechanism of potassium excretion in rats and to compare it with that of chloride and of sodium.

METHODS

Experimental animals. Male adult albino rats were used. The animals, before being used, were on a standard diet for several weeks.

Experimental procedures. Inulin was injected subcutaneously and 5% of the body weight of tap water was given by stomach tube. The routine procedure for determining the clearances conformed with that described previously (Dicker & Heller, 1945).

Analytical methods. Inulin in plasma and in urine was determined by the method of Smith, Goldring & Chasis (1938). Chloride in plasma was determined by Whitehorn's (1921) method, and in urine by that of Volhard (1878). Sodium in plasma and in urine was determined by the method of McCance & Shipp (1931), and potassium in plasma and in urine by Kramer & Tisdall's method as modified by McCance & Shipp (1933); the empirical factor used in the calculation being that proposed by McCance & Shipp, i.e. 0·12. The inulin preparation used was Inulin (Kerfoot & Co.).

Method of calculation. The following formula was used to calculate the tubular reabsorption rate of electrolytes (T_E):

$$C_{In} \times E_p - U \times E_u = T,$$

where C_{In} = inulin clearance/min./100 g. = glomerular filtration rate (G.F.R.), E_p = concentration of the ion E per 100 c.c. plasma, U = urinary volume/min./100 g. body weight and E_u = concentration of the ion E per 100 c.c. urine. To allow for possible variations of the glomerular filtration rate, T was expressed as percentage of the amount of ion E filtered thus:

$$T_E = \frac{T}{C_{In} \times E_p} \times 100.$$

Statistical treatment of results. A 'small sample' method was used throughout for the estimation of the significance of means (Fisher, 1944). As the population of the samples was small, the standard deviation was multiplied by $\sqrt{(n/n-1)}$ (Bradford Hill, 1942). Correlation coefficients (r) were calculated according to Mainland (1938). The values for the probability (P) of r and of t were obtained from the Fisher & Yates (1943) tables.

RESULTS

Renal excretion of chloride, sodium and potassium during a water diuresis. It has been shown (Dicker & Heller, 1945) that the G.F.R. of rats does not change significantly during a water diuresis. The mean value for G.F.R. in the present series amounted to $0{\cdot}39 \pm 0{\cdot}024$ c.c./100 g. rat/min. (S.E. of mean of twelve observations). The mean values for the concentration of chloride, sodium and potassium in the plasma were:

$$274{\cdot}4 \pm 8{\cdot}4\ (9),\ 283{\cdot}5 \pm 13{\cdot}0\ (9)\ \text{and}\ 24{\cdot}2 \pm 0{\cdot}3\ (12)\ \text{mg./100 c.c.},$$

respectively. The mean amount of the three ions filtered through the glomeruli was therefore: 1·08 mg./100 g./min. for chloride, 1·12 mg./100 g./min. for sodium and 0·09 mg./100 g./min. for potassium. It will be seen from Fig. 1 that the reabsorption of chloride and that of sodium, expressed as percentages of the amount of chloride and of sodium filtered, remained unchanged with variations of urine flow ranging from 0·0046 to 0·0650 c.c./100 g./min.; in other words the rates of chloride and of sodium reabsorption (T_{Cl} and T_{Na}) remained practically constant at the very low and at the very high rates of urine formation encountered in the experiments. They were independent of the amount of chloride and sodium filtered and of the rate of water reabsorption. The reabsorption of chloride, expressed as percentage of chloride filtered (T_{Cl}) amounted to $96{\cdot}0 \pm 0{\cdot}9\%$ (9) and that of sodium (T_{Na}) to $97{\cdot}4 \pm 0{\cdot}6\%$ (9) (Table 1). It will be noted that the rate of tubular reabsorption of chloride was significantly different from that of sodium ($t = 3{\cdot}070$, $P < 0{\cdot}02$).

The rate of potassium reabsorption was quite different from that of sodium and of chloride. It was high at low rates of urine flow and low at high rates of urine formation (Fig. 1, A, I). The mean rate of potassium reabsorption, expressed as percentage of the amount of potassium filtered (T_K), was $68{\cdot}0 \pm 3{\cdot}27\%$; it was found to be related (*a*) to the amount of potassium filtered, $r = -0{\cdot}940$, $P < 0{\cdot}001$ (coefficient of regression, $b = -5{\cdot}31$); (*b*) to the rate of water reabsorption (T_W), $r = +0{\cdot}757$, $P < 0{\cdot}01$; and (*c*) to the urine flow, $r = -0{\cdot}887$, $P < 0{\cdot}001$ (Table 1).

It is thus clear that in rats during a normal water diuresis, the rates of chloride and of sodium reabsorption are independent of the rate of water reabsorption and the rate of urine flow, but that the rate of potassium reabsorption varies with the rate of water reabsorption and, therefore, with the urinary output.

Renal excretion of chloride, sodium and potassium after injection of potassium chloride. To determine how an increase of plasma potassium affects potassium excretion, rats were injected subcutaneously with 0·1 c.c./100 g. body weight of a 3·0% KCl solution. Inulin, chloride, sodium and potassium clearances were estimated in the usual way.

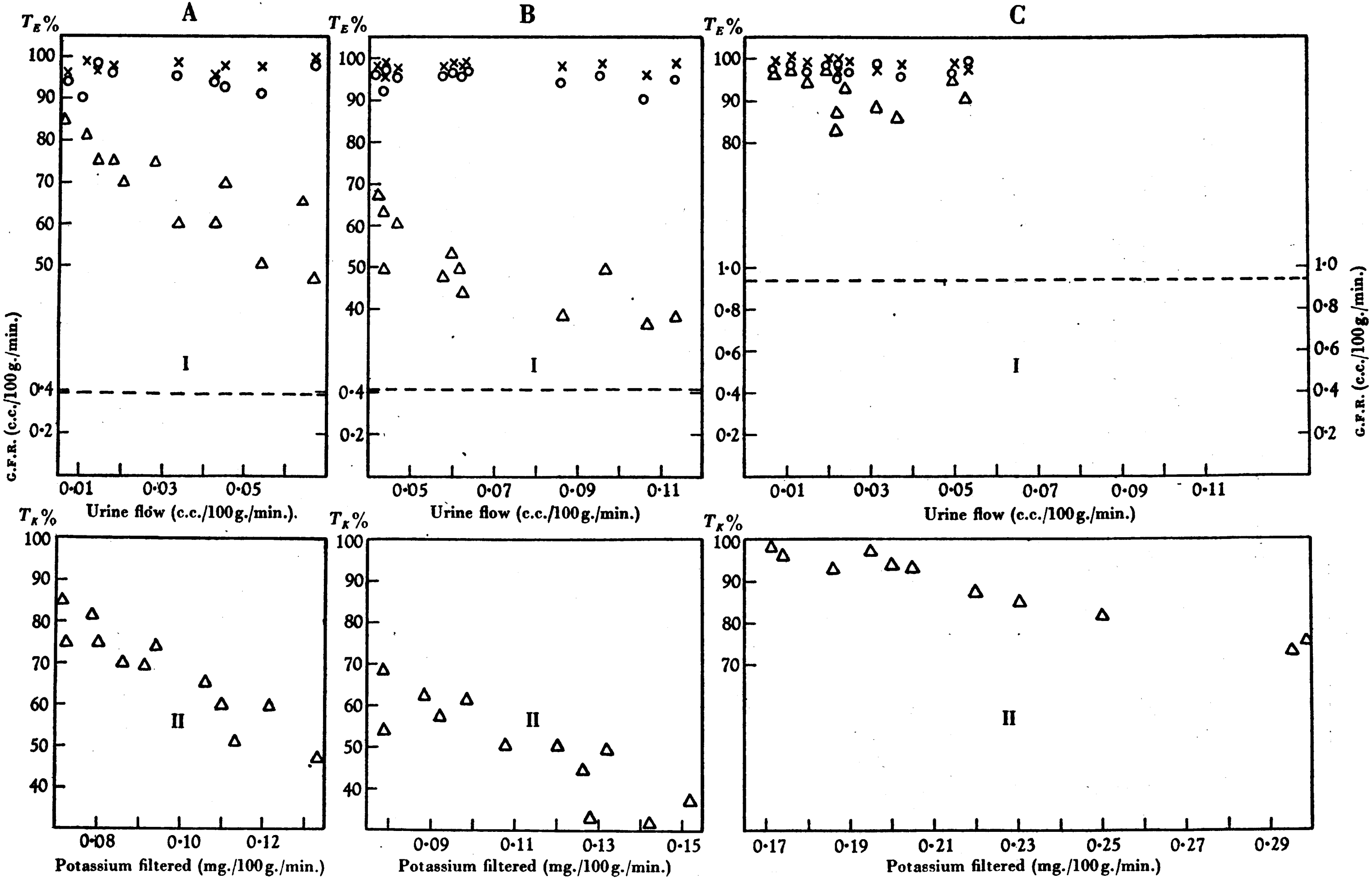

Fig. 1. Electrolyte reabsorption per min./100 g. rat expressed as percentage of the amount of electrolyte filtered (T_E): A, during a normal diuresis; B, after injection of 0·1 c.c. of a 3·0% KCl solution; C, after administration of 5·0 c.c. of an 85 mM solution of NaCl per 100 g. rat. In I, the electrolyte reabsorption (T_E) is plotted against the rate of urine flow, expressed as c.c./100 g./min. In II, potassium reabsorption (T_K) is plotted against the amount of potassium filtered, expressed as mg./100 g./min. × = chloride; ○ = sodium; △ = potassium. The broken line indicates the mean value obtained for the G.F.R.

TABLE 1

	G.F.R. (c.c./100 g./min.)	Cl filtered (mg./100 g./min.)	Na filtered (mg./100 g./min.)	K filtered (mg./100 g./min.)
Water diuresis	0·39 ±0·024 (12)	1·08 ±0·165 (9)	1·12 ±0·047 (9)	0·09 ±0·006 (12)
After injection of 0·1 c.c./100 g. of a 3·0% KCl solution	0·41 ±0·042 (12)	1·39 ±0·282 (12)	1·21 ±0·263 (12)	0·11 ±0·007 (12)
After administration of 5·0 c.c./100 g. of 85 mM solution of NaCl	0·94 ±0·049 (11)	3·01 ±0·163 (11)	3·04 ±0·134 (11)	0·22 ±0·013 (11)

	T_{Cl} (%)	T_{Na} (%)	T_K (%)	r between T_K and T_W	r between T_K and K filtered	r between rate of urine flow and T_W
Water diuresis	96·0 ±0·96 (9)	97·4 ±0·62 (9)	68·0 ±3·27 (12)	+0·757 —	−0·940 —	−0·995 —
After injection of 0·1 c.c./100 g. of a 3·0% KCl solution	97·4 ±0·57 (12)	98·3 ±0·28 (12)	48·4 ±3·22 (12)	+0·660 —	−0·950 —	−0·977 —
After administration of 5·0 c.c./100 g. of 85 mM solution of NaCl	97·8 ±0·32 (11)	98·6 ±0·14 (11)	91·7 ±2·51 (11)	+0·365 —	−0·955 —	−0·909 —

The figures are mean results with standard errors; r = correlation coefficient between the values indicated.

Number of experiments in brackets.

Such an injection resulted in an increase of potassium and of chloride in the plasma, and had a pronounced diuretic effect. The mean value for the G.F.R. was 0·41 ± 0·042 (12) c.c./100 g./min., a value which is comparable to that observed during a normal water diuresis. The mean plasma chloride amounted to 339·9 ± 6·42 (12) mg./100 g., and the plasma potassium was 27·2 ± 0·71 (12) mg./100 c.c., compared with 24·2 ± 0·28 in normal rats. However, the plasma sodium remained normal (293·5 ± 7·09 (12) mg./100 c.c.). The increase in the plasma concentration of chloride and of potassium resulted necessarily in an increase in the amount of these ions filtered. After injection of the KCl solution the mean amount of chloride filtered per 100 g. body weight per min. was 1·39 mg., that of potassium 0·11 mg. and that of sodium 1·21 mg. (Table 1). The mean value for the rate of chloride reabsorption, expressed as percentage of the amount of chloride filtered was $T_{Cl} = 97{\cdot}4 \pm 0{\cdot}57\,\%$ (12), a figure which is significantly different from that obtained during a normal water diuresis ($t = 2{\cdot}258$, $P < 0{\cdot}05$). The mean value for the rate of sodium reabsorption was $T_{Na} = 98{\cdot}3 \pm 0{\cdot}28$ (12). The difference between the rate of chloride and of sodium reabsorption remained significant, $t = 2{\cdot}806$, $P < 0{\cdot}02$. It is thus clear that both chloride and sodium were reabsorbed at higher rates than during a normal water diuresis, but that, just as in control rats, the two rates were not the same. The rates of chloride and of sodium reabsorption, expressed as percentages of the amounts filtered (T_{Cl} and T_{Na}) were unaffected by the rate of water reabsorption and that of urine flow, i.e. they remained practically constant at all rates of urine flow encountered.

In contrast to the rate of chloride and of sodium reabsorption, the rate of potassium reabsorption, expressed in percentage of the amount of potassium filtered (T_K) was found to be significantly correlated with the amount of potassium filtered $r = -0{\cdot}950$, $P < 0{\cdot}001$ (coefficient of regression, $b = 5{\cdot}27$) and with the rate of water reabsorption, $r = +0{\cdot}660$, $P < 0{\cdot}02$ (Table 1). A comparison with the data obtained during a normal water diuresis shows that the relationship between T_K and T_W was no longer the same ($r = +0{\cdot}660$ instead of $r = +0{\cdot}757$), but that the degree of relation between the amount of potassium filtered and the rate of potassium reabsorbed remained unaltered ($r = -0{\cdot}950$ and $r = -0{\cdot}940$).

Renal excretion of chloride, sodium and potassium after the administration of 85 mM *solution of* NaCl. Inulin, chloride, sodium and potassium clearances were estimated as usual. The weight of 85 mM solution of NaCl given by stomach tube was 5% of the rat's body weight. This caused a rise in the rate of water reabsorption and ultimately a decrease in the rate of urine flow (Dicker, 1946). The plasma chloride and sodium levels increased without affecting that of potassium.

The mean G.F.R. amounted to $0{\cdot}94 \pm 0{\cdot}05$ (11) c.c./100 g./min. The plasma chloride concentration was $322{\cdot}6 \pm 8{\cdot}30$ (11) mg./100 c.c., a figure which is comparable with that found in rats injected with KCl ($t = 1{\cdot}124$, $P > 0{\cdot}2$) and the plasma sodium level rose to $323{\cdot}2 \pm 7{\cdot}13$ (11) mg./100 c.c. The plasma potassium concentration was almost the same as that in rats during a water diuresis 23·4 mg./100 c.c. ($t = 0{\cdot}745$, $P > 0{\cdot}4$). The mean amount of chloride filtered per min. per 100 g. rat was 3·01 mg., that of sodium was 3·04 mg. and that of potassium 0·22 mg. (Table 1).

The rates of chloride and of sodium reabsorption expressed as percentages of the amount of chloride and of sodium filtered (T_{Cl} and T_{Na}) did not change with changes of urine flow and were independent of the rate of water reabsorption (T_W). The mean value for T_{Cl} was $97{\cdot}8 + 0{\cdot}32$% (11) and that for T_{Na} $98{\cdot}6 + 0{\cdot}14$% (11). These values do not differ significantly from those for T_{Cl} and T_{Na} in rats given KCl solution ($t = 0{\cdot}560$, $P > 0{\cdot}6$ and $t = 1{\cdot}869$, $P > 0{\cdot}05$, respectively) though the amounts of chloride and of sodium filtered were significantly higher (Table 1).

The rate of potassium reabsorption (T_K) was no longer significantly correlated with the rate of water reabsorption $r = +0{\cdot}365$, $P > 0{\cdot}1$. The amounts of potassium reabsorbed were much higher than in the other two series but remained closely correlated with the amount of potassium filtered $r = -0{\cdot}955$, $P < 0{\cdot}001$ (coefficient of regression, $b = -4{\cdot}89$) (Table 1).

DISCUSSION

The mechanism of renal excretion of potassium in rats has been found to be the same as that observed in dogs by Winkler & Smith (1942). During a normal water diuresis the amount of potassium reabsorbed proved to be closely correlated with the amount of potassium filtered. This correlation persisted when the amount of potassium filtered was raised either by increasing the level of potassium in the plasma or by increasing the glomerular filtration rate —as after administration of a 85 mM solution of NaCl. The mechanism of renal potassium excretion in rats stands thus in complete contrast to the mechanism of renal excretion of other ions like chloride and sodium.

SUMMARY

1. The renal excretion of chloride, sodium and potassium in rats was investigated with the aid of inulin clearances: (*a*) during a water diuresis, (*b*) after injection of 0·1 c.c./100 g. body weight of a 3·0% KCl solution, and (*c*) after administration of 5·0 c.c./100 g. body weight of a 85 mM solution of NaCl.

2. The rates of chloride and of sodium reabsorption were significantly different, and independent of the urine flow and of the rate of water reabsorption. No correlation could be found between the rate of chloride and of sodium reabsorption by the tubules and the amount of chloride and of sodium filtered.

3. During a water diuresis the rate of potassium reabsorption was correlated with the amount of potassium filtered per unit time. This correlation persisted when the amount of potassium filtered was raised either by increasing the level of potassium in the plasma or by increasing the glomerular filtration rate.

4. The reabsorption of potassium does not passively follow that of water.

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