Faecal dry weight and potassium are related to faecal sodium and plasma aldosterone in rats chronically fed on varying amounts of sodium or potassium chlorides

BY RICHARD D. McCABE, MANIS J. SMITH JR AND TERRY M. DWYER

The Department of Physiology and Biophysics, The University of Mississippi Medical Center, 2500 North State Street, Jackson, Mississippi 39216-4505, USA

Recent studies have shown that faecal residue (dry weight) and Na and K increase with increasing levels of dietary fibre, an effect which may be related to unstirred layers that slow absorption and the flow rate of chyme through the gastrointestinal tract. Salts of Na are the primary osmotic components of chyme and influence both retention of fluid in the bowel and transit of fluid from the small to the large intestine. The present study examines the chronic effects of dietary Na and K intake on faecal Na, K and residue excretion. Male Sprague-Dawley rats were given 12–13 g feed/d (control (g/kg): Na 4, K 8·5) for 1 week, followed by a 4-week period where Na or K intake was altered (0·01–3 times control levels). These diets altered chronic (> 1 week) faecal residue excretion and affected Na and K excretion by 8-, 310- and 2100-fold respectively. Low dietary Na reduced faecal Na and residue; K excretion was doubled during week 1, but fell over weeks 2–4 despite a 4–5-fold increase in plasma aldosterone. Chronic high dietary Na increased faecal Na, residue and K despite a 60% decrease in plasma aldosterone. Chronic low dietary K decreased faecal Na, K and residue and plasma aldosterone. Chronic high dietary K did not alter faecal Na and K despite increased faecal residue and a 4–5-fold increase in plasma aldosterone. Faecal water was unchanged by diet, paralleling changes in faecal residue. Analyses of the results provide systematic models of chronic regulation of faecal Na, K and residue excretions. When plasma aldosterone is low (< 160 ng/l), weekly faecal residue excretion is equal to 3·6 g (fibre intake was 2·6–2·7 g/week) + 2·6 g/mmol Na, and K excretion is equal to 0·55 mmol/mmol Na. When plasma aldosterone is high (> 1500 ng/l) weekly faecal residue excretion is equal to 2·3 g + 2·6 g/mmol Na, and K excretion is equal to 0·7 mmol/week + 0·55 mmol/mmol Na.

Sodium: Potassium: Aldosterone: Faeces: Rat

Recent studies with dietary fibre provide indirect evidence of flow-dependent intestinal absorption. Dietary fibre increases faecal excretion of Na, K and a residue composed of the fibre itself, plus carbohydrates and lipids (Eastwood *et al.* 1980; Murray *et al.* 1980; Judd & Trusell, 1981; Spiller *et al.* 1986; Jeraci & Van Soest, 1990) in the proportions 7:3 (Brandaru, 1990). Fibre may increase non-fibrous residue excretion by forming a gel adjacent to the small intestinal epithelium which creates a watery barrier (Dietschey *et al.* 1971; Johnson & Gee, 1981; Fluorie *et al.* 1984; Fuse *et al.* 1989). Such 'unstirred layers' can slow the rate of diffusion between chyme and absorptive sites on the small intestinal epithelium so that absorption becomes self-limiting. Thus, a gradient is created where the concentration of nutrients may remain high in chyme but diminishes along the thickness of the unstirred layer, reaching a minimum at the absorptive site. Unstirred layers may permit nutrients to flow through the gastrointestinal tract without being absorbed.

Na has important roles in intestinal transport and fluid balance. Salts of Na are the chief osmotic constituents of chyme (Edmonds, 1967; Dietschey *et al.* 1971). The presence of Na

and its conjugate anions necessitates retention of water within the lumen since small intestinal absorption is isosmotic (Curran & Solomon, 1957; Fordtran et al. 1965; Fordtran & Locklear, 1966). And so, Na salts determine the amounts of fluid contained in the small intestine (Gotch et al. 1957) and transferred from the small to the large intestine (Phillips, 1969; Phillips & Giller, 1973; Debongie & Phillips, 1978). Fluid retained in the gastrointestinal tract with Na can dilute nutrients and limit their entry into unstirred layers, resulting in reduced absorption. This could reduce absorption and increase excretion.

Na also exerts an important influence on the large intestine's ability to secrete K. The lumen of the colon has a negative electrical potential which is established by active Na absorption and largely determines the rate of colonic K secretion (Frizzell et al. 1976). Intestinal Na absorption and K secretion are both dependent on plasma aldosterone. Plasma aldosterone increases Na entry across the apical membrane of intestinal epithelial cells (Frizzell & Schultz, 1978) and increases the electrochemical driving force for K exit from colonic epithelial cells (Sandle et al. 1985). In the present study we examine the effects of dietary NaCl and KCl on plasma aldosterone and faecal Na excretion and their relationship with faecal residue and K excretion.

EXPERIMENTAL METHODS
Animals

Male Sprague-Dawley rats (250–275 g) from a colony maintained by The University of Mississippi Medical Center were isolated in stainless-steel metabolism cages (Lab Products, Maywood, NJ, USA). The cages had a stainless-steel screen on the bottom through which excreta passed into a collection funnel which directed urine into a collection bottle. The funnel was modified by the addition of a fine stainless-steel mesh over the collection port to prevent faeces from entering the urine collection bottle. Drinking water was dispensed from a calibrated bottle (Lab Products) which the rat could operate. Measured amounts of feed were dispensed by a stainless-steel feeder (Lab Products). Procedures were approved by the Institutional Animal Care and Use Committee.

Diets

Five diets were used in the present study. Four of these diets (control, high Na, low Na and high K) were based on a commercial diet (4881C-B for control, high Na and high K, and 4881C for low Na) obtained from Ralston Purina (Richmond, IN, USA). The basal diet consisted of (g/kg): dextrin 427 (436·5 for the low-Na diet), casein (unpurified) 210, sucrose 150, maize oil 50, lard 50, Ralston Purina mineral mix without Na 50, solka floc 30, Ralston Purina vitamin mix 20, NaCl 9·5 (0 for the low-Na diet), choline chloride 2, DL-methionine 1·5. Purina was unable to provide a low-K diet as most of the dietary K came from components other than the mineral mix. Therefore, a low-K diet from ICN (904665; ICN, Cleveland, OH, USA) was substituted. The low-K diet contained: sucrose 419·8, maize starch 215·8, purified casein (high-N) 297, butter 34·6, $CaCO_3$ 12·9, NaCl 9·9, and ICN vitamin diet fortification mixture 10. The actual Na and K values of the diets were determined by chemical analysis (see p. 327) and were (g/kg): Na 4, K 8·5, for control and high-Na or -K diets; Na 0·3, K 8·5, for the low-Na diet; Na 4, K 0·06, for the low-K diet.

The animals were fed on the control diet for 2 weeks before receiving the test diets. The first week of this control period served to adapt the rats to the diet. Control excretion rates were established from collections made during the second week of the control period. The animals were then fed on one of the test diets for 4 weeks. Animals were allowed ad lib. access to either deionized water (control, low-Na and low-K groups), 150 mmol NaCl/l (high-Na diet) or 150 mmol KCl/l (high-K diet). Feed was limited to 12–13 g/d (weighed

to 1 mg), because the high-K group consumed no more than this in preliminary experiments. No unused food remained for any rat on any day of the excretion experiments reported here. Monitoring of consumption showed that changes in dietary Na did not alter K intake and changes in dietary K did not alter Na intake.

Analytical methods

All waste was collected, processed and analysed. Feed was also analysed for Na and K. Faeces were separated from non-faecal solid wastes, chiefly food crumbs, with a spatula and each pellet was brushed free of other solid waste using a sable brush. Pellets were counted and collected with non-faecal solid waste in separate crucibles that had been tared after drying. Crucibles were dried under partial vacuum (40 KPa) for 24 h at 90° and 1 h at 110°, allowed to cool, and reweighed to determine faecal dry weight (residue). Faecal residue was ashed for 24 h at approximately 430° and the contents of each crucible digested in 1 ml analytical grade HNO_3 (700 ml/l; J. T. Baker, Phillipsburg, NJ, USA). Samples of feed of known weight were ashed in a similar manner and resuspended in a known amount of HNO_3. The contents of each crucible were washed into a polycarbonate centrifuge tube and diluted with deionized water (5 ml per crucible for low-Na and -K diets and 50 ml per crucible for other diets; one crucible per week was needed for each rat on low-Na or low-K diets, while two to five crucibles per week were needed for each rat on other diets).

The Na and K contents of extracts of faeces and non-faecal solid waste and of centrifuged urine samples were determined by flame photometry using an Instrumentation Laboratories Model 343 (Lexington, MA, USA) flame photometer. The Na and K contents of non-faecal solid waste were subtracted from the corresponding Na and K contents of the feed to determine the actual Na and K intakes. There was no detectable background contamination in the crucibles or HNO_3.

Parallel studies were conducted to measure plasma aldosterone and electrolytes, muscle ion and water contents, faecal water content, and weight gain. In these studies one group of rats received the control diet for 4 weeks to serve as a time-control. The other groups received one of the test diets for 4 weeks. The adapted or time-control rats were then isolated in a cage containing gauze pads soaked in halothane. When anaesthesia was verified by the absence of the deep tendon reflex and slowing of the corneal reflex, 3–5 ml plasma was collected by cardiac puncture in 100 U ammonium heparin for analysis by flame photometry, by vapour pressure osmometry (Wescor Model 1710, Logan, UT, USA), and by specific radioimmunoassay for plasma aldosterone. The right *anterior tibialis* was then removed, trimmed to isolate the muscle body from ligaments and muscle sheath, placed in a 10 mm × 75 mm glass tube that had been tared after drying, weighed, dried for 24 h at 90° and 1 h at 110° under partial vacuum, as described previously for faeces, and reweighed. HNO_3 (1 ml) was added to each tube and the tubes were tightly sealed with a double layer of Teflon tape and allowed to digest overnight. The tubes were further diluted with 1 ml distilled water and contents analysed by flame photometry. Faecal water was determined from fresh faeces, to avoid water loss. After the 4-week adaptation period, animals were isolated and observed until they defaecated. The pellet was immediately collected into a tared vial and weighed and then dried, as described for other faecal samples, and reweighed.

Statistics

The statistical significance of changes in faecal Na, K and residue was determined using Dunnett's test for repeated measures (Dunnett, 1955). Plasma Na and K concentrations, osmolarity, packed cell volume and aldosterone, and muscle Na and K concentrations were compared using Dunnett's test for repeated measures. The effects of K on cumulative Na

and K excretion were evaluated using a paired-sample Student's t test. Relationships between faecal Na, K and residue excretion were analysed using simple linear regression. The 95% confidence intervals (CI) of the intercepts were calculated as the 95% confidence belts at the intercepts (Zar, 1974). All tests of significance employed the two-sided assumption; $P < 0.05$ was considered significant.

RESULTS

Under control conditions faecal excretion accounted for 20 (SE 1)% of Na and 10 (SE 1)% of K excretion. In previous studies with rats faecal excretion accounted for 16–23% of Na and 10–11% of K excretion (Sealey *et al.* 1970; Mohring & Mohring, 1972; Chabert *et al.* 1984).

Dietary Na

After 4 weeks on the high-Na diet there was a 1·6-fold increase in faecal Na excretion (Fig. 1); 4 weeks on the low-Na diet decreased faecal Na excretion by 99%. During the final week the high-Na group consumed 45·8 (SE 0·6) mmol Na and excreted 44·6 (SE 3·4) mmol Na, while the low-Na group consumed 0·15 (SE 0·00) mmol Na and excreted 0·20 (SE 0·10) mmol Na. Urinary Na excretion quadrupled on the high-Na diet and fell by 97% on the low-Na diet (Table 1). Faecal excretion accounted for 12 (SE 2)% of total Na excretion during Na repletion and 9 (SE 2)% during Na depletion.

Dietary Na also influenced K excretion. The high-Na diet caused sustained increases in both faecal K (Fig. 2) and urinary K (Table 1) excretion, although K intake was constant. We normalized these K excretion values by subtracting the control value for weekly excretion rate from the excretion rate during each experimental week and a cumulative value from the sum of values for the four experimental weeks was obtained. Results (Fig. 3) show that the high-Na diet caused a negative K balance. This K loss was primarily accounted for by a weight loss of 5 (SE 12) g compared with a weight gain of 60 (SE 8) g for the controls (Table 2). The 65 g difference accounts for 5·5–5·9 mmol K with tissue K values of 84–90 μmol/g (Table 2), 60% of the difference in K retention. The ability of high salt intake to reduce weight gain has been reported by Sealey *et al.* (1970). With their *ad lib.*-fed diets, Sealey *et al.* (1970) also observed weight loss with increased dietary K. In preliminary experiments we found that this effect resulted from reduced consumption and we limited the consumption of all groups to prevent it (see pp. 326–327).

The low-Na diet caused biphasic changes in faecal K excretion. Faecal K increased during the first week of Na depletion (Fig. 2) as observed in acute studies in rabbit (Chabert *et al.* 1984) and dog (Field *et al.* 1954). However, this acute effect was actually reversed during chronic Na depletion since faecal K excretion during weeks 2–4 fell below that for controls (Fig. 2). Low dietary Na also produced a kaliuresis (Table 2). Decreased faecal K excretion quantitatively offset the kaliuresis and K excretion over the entire study was as expected on the basis of the control values for K excretion rate (Fig. 3).

Dietary K

The high-K diet had no significant effect on faecal K excretion, but the low-K diet reduced faecal K excretion by 99·94% (Fig. 2). Urinary K excretion was tripled on the high-K diet and reduced by over 95% on the low-K diet (Table 1). During week 4 the high-K group consumed 42·5 (SE 0·3) mmol K and excreted 39·8 (SE 3·6) mmol K and the low-K group consumed 0·13 (SE 0·00) mmol K and excreted 0·65 (SE 0·08) mmol K. Faecal excretion accounted for 5 (SE 2)% of K excretion on the high-K diet and 2 (SE 2)% of K excretion on the low-K diet.
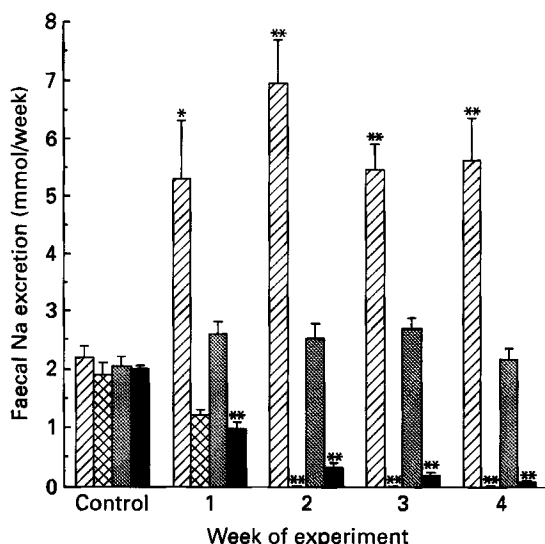
Fig. 1. The rate of faecal sodium excretion as a function of time before and after changing from normal (control) to high or low dietary KCl or NaCl: (▨), high Na; (▧), low Na; (▦), high K; (■), low K. Values are means with their standard errors, represented by vertical bars, for four groups of four rats each. Mean values were significantly different from those for the control week (two-sided Dunnett's test for repeated measures): *$P < 0.05$; **$P < 0.01$. For details of dietary regimen and procedures, see pp. 326–328.

Table 1. *Urinary excretion of minerals (mmol/week) by four groups of rats before and after changes in dietary sodium or potassium*†

(Mean values with their standard errors)

Diet...	High Na		Low Na		High K		Low K	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Control								
Na excretion	8·4	0·8	7·8	0·2	7·8	0·2	8·1	0·4
K excretion	12·8	0·6	12·2	0·4	12·6	0·6	12·4	0·7
Week 1								
Na excretion	27·2*	3·0	3·8**	0·9	8·9*	0·5	9·2	0·6
K excretion	10·6	0·7	11·1*	0·5	38·5**	4·4	2·2**	0·3
Week 2								
Na excretion	43·0**	8·0	0·7**	0·2	8·2	0·6	9·5*	0·3
K excretion	17·4*	1·3	13·4	2·4	39·4**	2·6	0·8**	0·3
Week 3								
Na excretion	38·7**	3·8	0·3**	0·1	7·4	0·7	10·4*	0·3
K excretion	15·7	1·7	13·1	1·4	36·5**	2·3	0·7**	0·1
Week 4								
Na excretion	32·9**	2·9	0·2**	0·1	7·9	0·6	10·4*	0·4
K excretion	13·1	2·3	13·4	1·0	35·1**	4·1	0·6**	0·1

Mean value was significantly different from that for the same group during the control week (two-sided Dunnett's test for repeated measures): *$P < 0.05$; **$P < 0.01$.
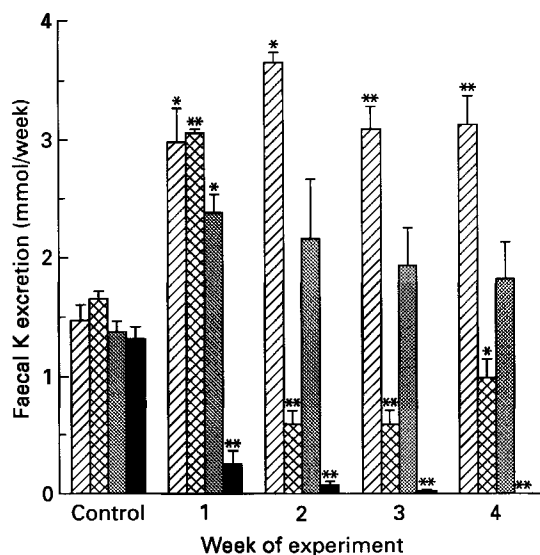† For details of dietary regimen and procedures, see pp. 326–328.

Fig. 2. The rate of faecal K excretion as a function of time before and after changing from normal (control) to high or low dietary KCl or NaCl: (▨), high Na; (▧), low Na; (▦), high K; (■), low K. Values are means with their standard errors, represented by vertical bars, for four groups of four rats each. Mean values were significantly different from those for the control week (two-sided Dunnett's test for repeated measures): $*P < 0.05$; $**P < 0.01$. For details of dietary regimen and procedures, see pp. 326–328.
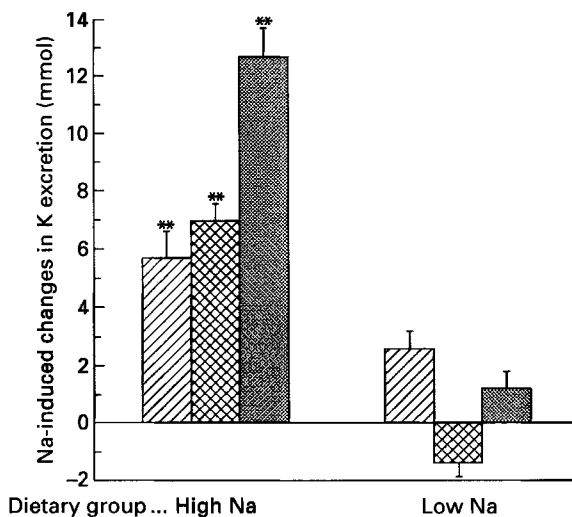

Fig. 3. The effects of dietary Na on K balance derived from the differences between control and experimental K excretion rates (sum of values for the 4-week course of the experimental period): (▨), Urinary K; (▧), faecal K; (▦), total K excretion. Values are means with their standard errors of the difference, represented by vertical bars, for two groups of four rats each. Mean values were significantly different from zero (two-sided, paired Student's t test): $**P < 0.01$. For details of dietary regimen and procedures, see pp. 326–328.

Changes in dietary K also caused changes in Na excretion. Urinary Na excretion was increased in the first week of high K intake (Table 1). Although faecal Na was not significantly increased during any particular week (Fig. 1) each rat excreted more faecal Na in 3 weeks of the 4 weeks of K repletion, resulting in an excess faecal Na excretion of 1·9

Table 2. *Plasma electrolytes and aldosterone, muscle electrolytes, faecal water content and weight gained by five groups of rats fed on differing diets for 4 weeks†*

(Mean values with their standard errors)

Diet…	Control		High Na		Low Na		High K		Low K	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Plasma										
Na (mmol/l)	145	2	146	2	147	31	144	5	147	4
K (mmol/l)	4·9	0·3	5·1	0·1	5·2	0·2	6·3	0·6**	3·4**	0·4
Osmolarity (mosm/kg)	308	3	309	5	305	7	306	5	307	4
Aldosterone (ng/l)	345	76	142**	16	1870**	640	1534**	416	158**	46
n	(5)		(7)		(7)		(3)		(6)	
Muscle										
Na (μmol/g)	27	1	28	3	19**	1	18**	0	25	1
K (μmol/g)	104	2	106	3	108	3	121**	1	98**	1
Water content (mg/g)	647	14	656	29	665	13	657	15	620	6
n	(8)		(6)		(6)		(7)		(4)	
Faeces										
Water content (mg/g)	556	35	511	36	515	24	493	45	460	30
n	(8)		(6)		(6)		(6)		(6)	
Wet gain (g)	75	8	−5*	12	66	10	59	11	62	10
n	(6)		(4)		(4)		(10)		(8)	

Mean value was significantly different from control group (two-sided Dunnett's test for repeated measures): *$P < 0.05$; **$P < 0.01$.

† For details of dietary regimen and procedures, see pp. 326–328.

(SE 0·6) mmol over 4 weeks (Fig. 4). This compares with a cumulative increase in urinary Na excretion of 1·2 (SE 0·6 mmol (Fig. 4) during the same period. A 7 μmol/g decrease in tissue Na (Table 2) accounts for most of this Na loss (over 2 mmol for rats weighing in excess of 300 g). The low-K diet decreased faecal Na excretion (Fig. 1), but also increased urinary Na excretion (Table 1) so that there was no cumulative change in total Na excretion during K restriction (Fig. 4).

Plasma electrolytes and aldosterone

The effects of diet on plasma electrolytes and aldosterone are presented in Table 2. Changes in dietary Na did not measurably alter plasma K and Na concentrations, osmolarity, or packed cell volume after 4 weeks. Increased dietary K increased plasma K concentrations, and decreased dietary K decreased plasma K concentrations (Table 2). Plasma aldosterone was strongly influenced by diet. Both low-Na and high-K diets increased plasma aldosterone by 4–5-fold, and both high-Na and low-K diets reduced plasma aldosterone by at least half (Table 2).

Faecal residue and water

Dietary Na and K also caused changes in faecal residue. These effects are presented in Fig. 5. The high-Na and high-K diets approximately doubled faecal residue, while the low-Na and low-K diets reduced faecal residue by over two-thirds (Fig. 5). Except for the low-K group, these changes were significant only after week 1 (Fig. 5). Since faecal water evaporates rapidly, we determined the faecal water contents (mg/g) of the various diets in
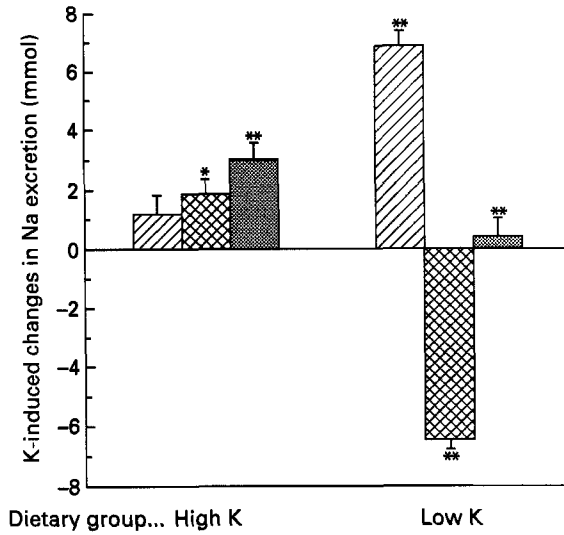
Fig. 4. The effects of dietary K on Na balance derived from the differences between control and experimental Na excretion rates (sum of values for the 4-week course of the experimental period): (▨), Urinary Na; (▩), faecal Na; (▨), total Na excretion. Values are means with their standard errors of the difference, represented by vertical bars, for two groups of four rats each. Mean values were significantly different from zero (two-sided, paired, Student's t-test): *$P < 0.05$; **$P < 0.01$. For details of dietary regimen and procedures, see pp. 326–328.
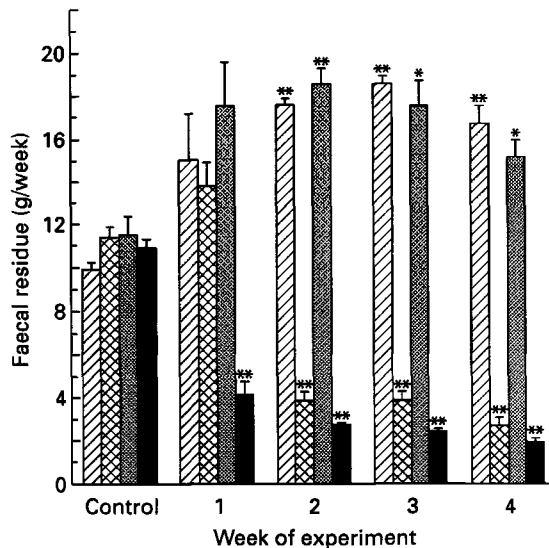

Fig. 5. The rate of faecal dry weight (residue) excretion as a function of time before and after changing from normal to high or low dietary KCl or NaCl: (▨), high Na; (▨), low Na; (▨), high K; (■), low K. Values are means with their standard errors, represented by vertical bars, for four groups of four rats. Mean values were significantly different from those during the control week (two-sided Dunnett's test for repeated measures): *$P < 0.05$; **$P < 0.01$. For details of dietary regimen and procedures, see pp. 326–328.

separate experiments. Fresh faecal wet weight (mg/g) was unaltered by diet (Table 2), indicating that changes in faecal water excretion paralleled the changes in faecal residue (Fig. 5).

DISCUSSION

Previous studies of the effects of dietary salts on faecal Na and K excretion focused primarily on the acute effects of these salts. We found important differences between the chronic and acute effects of changes in dietary salts. For example, acute Na restriction (1 week) was known to increase faecal K concentration or K:Na ratio which could result in increased faecal K excretion (Field *et al.* 1954; Edmonds, 1967; Charron *et al.* 1974). We also observed this response during the acute phase of adaptation (Fig. 2). However, the opposite result was seen during chronic adaptation (Fig. 2) because the volume of faeces was reduced, despite a high faecal K:Na ratio. In the present discussion we present models to account for the chronic effects of dietary Na and K on faecal excretion and as a basis for further studies.

Analysis of the results of the present study provide an initial model to account for chronic faecal residue excretion. According to this model faecal residue excretion is the sum of an intercept, representing primarily fibre intake, plus non-fibrous excretion which varies with faecal Na excretion and plasma aldosterone. The relationships for high ($\geqslant 1500$ ng/l) and low ($\leqslant 160$ ng/l) plasma aldosterone values are presented in Fig. 6. According to these relationships residue excretion is equal to 2·3 g/week (95 % CI 1·8, 2·7) plus 2·6 g/mmol Na (95 % CI 2·3, 2·7) when plasma aldosterone was low (Table 2) and 3·6 g/week (95 % CI 3·3, 3·9) plus 5·4 g/mmol Na (95 % CI 5·1, 5·6) when plasma aldosterone was high. The high-K and low-Na groups received 2·6–2·7 g solka floc/week, accounting for three-quarters of the high plasma aldosterone intercept. The residual portion of that intercept may result from other indigestible components within the semi-purified diet or from another factor.

The slope of the faecal residue *v.* Na relationship may result from the effects of Na salts on small intestinal fluid balance. The small intestine cannot establish a strong osmotic gradient (Field *et al.* 1954; Edmonds, 1967; Phillips, 1969; Phillips & Giller, 1973; Debongie & Phillips, 1978) so that Na and conjugate anions in transit cause fluid to be retained within the gastrointestinal tract (Gotch *et al.* 1957). The fluids retained can dilute nutrients, reducing their rate of entry into an unstirred layer which apparently limits intestinal absorption (Dietschey *et al.* 1971; Johnson & Gee, 1981; Fluorie *et al.* 1984; Fuse *et al.* 1989; Edwards, 1990). The colon absorbs most of the Na leaving the small intestine and concentrates the remaining osmotic particles (Edmonds, 1967; Phillips, 1969; Phillips & Giller, 1973; Debongie & Phillips, 1978), but does not participate materially in digestion or absorption of the carbohydrates and lipids that account gravimetrically for the substance of non-fibrous faecal residue (Bandrau, 1990). Other factors contributing to the faecal residue *v.* Na relationship may include dilution of digestive enzymes, micelles, or other constituents of chyme that aid in the overall digestive process. The effect of aldosterone on the faecal residue *v.* Na relationship could reflect colonic extraction of Na, since the colon primarily mediates the aldosterone-induced dilution of Na that occurs within the gastrointestinal tract (Edmonds, 1967).

Analysis of the data from the present study also yields the first quantitative model of chronic faecal K excretion. According to this model, faecal K excretion is related to faecal Na excretion and plasma aldosterone (Fig. 7). When plasma aldosterone is low, faecal K excretion is equal to 0·55 mmol K/mmol Na (95 % CI 0·54, 0·56). When plasma aldosterone is high the relationship between faecal K and Na excretion was 0·55 mmol K/mmol Na (95 % CI 0·48, 0·62). However, increased plasma aldosterone shifts the
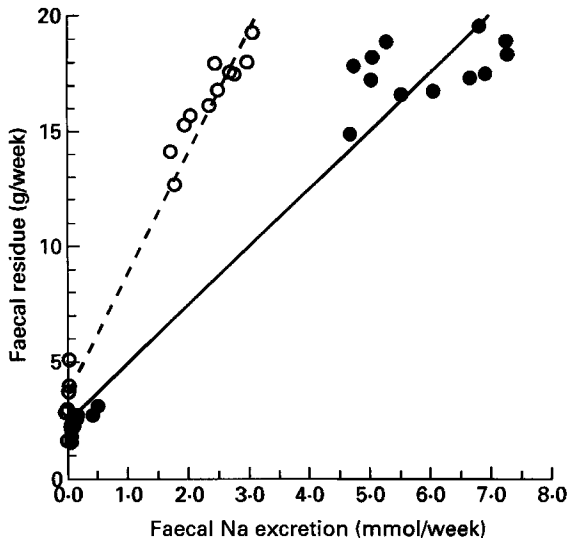
Fig. 6. The relationships between faecal Na excretion and residue (dry weight) when plasma aldosterone is low (○---○, high-Na and low-K diets) or high (●——●, low-Na and high-K diets). Values were obtained 2–4 weeks after the diet was changed and analysed by simple linear regression. The low-Na and low-K diets are those points where faecal residue is < 6 g/week. The high-Na and high-K diets are those points where faecal residue is > 12 g/week. For details of dietary regimen and procedures, see pp. 326–328.
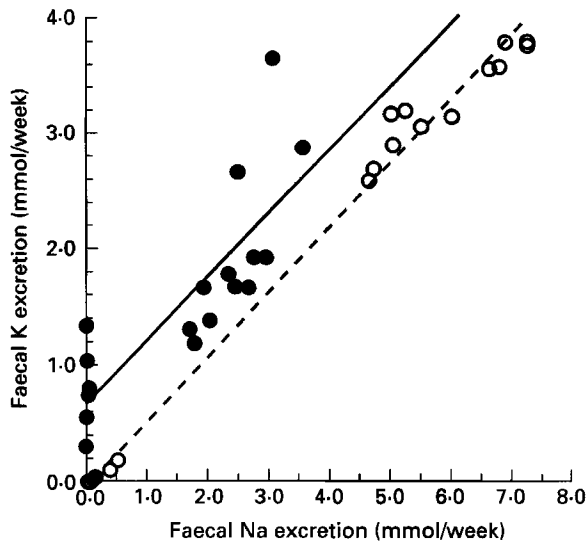

Fig. 7. The relationships between faecal K excretion and faecal Na excretion when plasma aldosterone is low (○---○, high-Na and low-K diets) or high (●——●, low-Na and high-K diets). Values were obtained 2–4 weeks after the diet was changed and analysed by simple linear regression. The low-Na and low-K diets are those points where faecal Na excretions is < 1 mmol/week. The high-Na and high-K diets are those points where faecal Na excretion is > 1 mmol/week. For details of dietary regimen and procedures, see pp. 326–328.

intercept of the faecal K v. Na relationship from 0·0 (95% CI −0·1, 0·0) to 0·7 (95% CI 0·54, 0·80) mmol K. Faecal K excretion, therefore, is accounted for by a constant faecal K:Na ratio with aldosterone increasing faecal K by a mechanism independent of that ratio.

The faecal K v. Na relationship may result from electrical coupling in the exchange of

Na and K in the colon (Wills & Biagi, 1982). The colon modulates faecal K losses by a combination of active K secretion and active K absorption (McCabe *et al.* 1982, 1984; Wills & Biagi, 1982; Foster *et al.* 1986). Colonic K secretion is strongly stimulated by the lumen negative transepithelial potential created by active Na absorption (Frizzell *et al.* 1976). This potential depolarizes the apical membrane and hyperpolarizes the basolateral membrane of colonic epithelial cells (Thompson *et al.* 1982), stimulating apical K exit and inhibiting basolateral K exit, which augments K secretion while retarding K absorption (McCabe *et al.* 1984). This proposed electrically coupled K–Na exchange could explain why plasma aldosterone, which stimulates colonic Na absorption (Frizzell & Schultz, 1978), does not entirely predict the chronic changes in faecal K excretion. Aldosterone-induced stimulation of colonic Na absorption can inhibit the K–Na exchange by reducing available Na. However, aldosterone also exerts a stimulatory effect on faecal K excretion independent of faecal Na excretion (i.e. the intercept). This effect is probably caused by aldosterone-mediated increases in the apical membrane K permeability and the intracellular K activity (Sandle *et al.* 1985) due to increased Na, K-ATPase (*EC* 3.6.1.37) activity (Charney *et al.* 1975) on the part of colonic epithelial cells.

The relationships we describe are specific for rat; we expect that the various constants will differ from species to species. In humans a small amount of bran chronically increases faecal Na excretion from 2·02 to 3·62 mmol/d, faecal K excretion from 10·70 to 18·66 mmol/d, and faecal residue from 26·1 to 42·5 g/d (Eastwood *et al.* 1980). If we correlate data from this human study, the faecal residue *v*. Na relationship is 12·9 g/mmol Na without bran and 11·7 g/mmol Na with a bran supplement. Thus, the results from humans are qualitatively similar to those of rats since there was a fairly constant relationship between faecal residue and Na, but these results differ quantitatively in that the constant relating them (the slope) is several times greater in humans than in rats. Similarly, human faecal K excretion was 5·30 mmol K/mmol Na without a fibre supplement and 5·15 mmol K/mmol Na with a dietary fibre supplement (Eastwood *et al.* 1980); constant within 3 %, but with a slope ten times that of the rat.

Species differences in the faecal K *v*. Na relationship reflect the lesser importance of faeces in Na excretion and the greater importance of faeces in K excretion in humans than in rats. Western humans eating self-selected diets excrete 15–16 % of their K intake but only 2 % of their Na intake in faeces (Holbrook *et al.* 1984). Rats excrete about 10 % of their K intake and 20 % of their Na intake in faeces (Sealey *et al.* 1970; Mohring & Mohring, 1972; Chabert *et al.* 1984). These differences may result from the greater length of the human colon, the paucity of fibre in Western diets or other factors. Another similarity is that hyperaldosteronism increases the human faecal K:Na ratio (Charron *et al.* 1974) as the model would predict. Thus, the fundamental concepts relating residue and K to Na appear to hold for humans in retrospective analysis of published data.

Important observations were also made concerning the effects of dietary K on Na balance. K repletion for 4 weeks increased Na excretion by 3·1 mmol, although Na intake remained constant (Fig. 4). Increased Na excretion and loss of tissue Na are both known effects of K adaptation (Blanchley *et al.* 1986; Rabelink *et al.* 1990). The present study illustrates the quantitative importance of this relationship since the 7 μmol/g wet weight difference in tissue Na content accounts for at least two-thirds of the Na loss in a rat weighing about 300 g by the end of the study. Thus, the present study demonstrates that K-induced 'natriuresis' chiefly results from loss of tissue Na. This may result from activation of Na, K-ATPase (Rabelink *et al.* 1990) which causes increased Na extrusion from the cells.

The second key finding about ionic balances is that changes in faecal excretion of Na and K did *not always* resemble the changes in urinary excretion in either direction or relative

magnitude. Although K depletion causes natriuresis (Table 1), no change occurs in Na balance (Fig. 4) because faecal Na excretion is markedly reduced (Figs. 2 and 4). The Na loss induced by K repletion (Fig. 4) was chiefly effected by increased faecal excretion. This contrasts with the fact that basal urinary Na excretion is four times the basal faecal Na excretion. These findings show that changes in ion excretion via a given route do not necessarily occur in proportion to the contribution of that route to basal excretion.

REFERENCES

Bandaru, S. R. (1990). Effect of types of dietary fiber on fecal mutagens and bacterial enzymes in relation to colon cancer. In *New Developments in Dietary Fiber*, pp. 159–166 [I. Furda and C. J. Brine, editors]. New York: Plenum Press.

Blanchley, J. D., Crider, B. P. & Johnson, J. H. (1986). Extrarenal potassium adaptation: role of skeletal muscle. *American Journal of Physiology* **251**, F313–F318.

Chabert, P. R., Guelpa-Decorzent, C., Riondel, A. M. & Vallotton, M. B. (1984). Effect of spironolactone on electrolytes, renin, ACTH and corticosteroids in the rat. *Journal of Steroid Biochemistry* **20**, 1253–1259.

Charney, A. N., Kinsley, D., Meyers, L., Giannella, R. A. & Gots, R. E. (1975). Na, K-activated adenosine triphosphate and intestinal electrolyte transport. *Journal of Clinical Investigation* **56**, 653–660.

Charron, R. C., Leme, C. E., Wilson, D. R., Ing, T. S. & Wrong, O. M. (1974). The effect of adrenal steroids on stool composition as revealed by in vitro dialysis of feces. *Clinical Science* **227**, 345–350.

Curran, P. F. & Solomon, A. K. (1957). Ions and water fluxes in the ileum of rats. *Journal of General Physiology* **41**, 143–168.

Debongie, J. C. & Phillips, S. F. (1978). Capacity of the human colon to absorb fluid. *Gastroenterology* **74**, 698–703.

Dietschey, J. M., Sallee, V. L. & Wilson, F. A. (1971). Unstirred water layers and absorption across intestinal mucosa. *Gastroenterology* **61**, 932–934.

Dunnett, C. W. (1955). A multiple procedure for comparing several treatments with a control. *Journal of the American Statistical Association* **50**, 1096–1121.

Eastwood, M. A., Mitchell, W. D. & Pritchard, J. L. (1980). The effect of bran on excretion of faecal cations. *Proceedings of the Nutrition Society* **35**, 78A–79A.

Edmonds, C. J. (1967). The gradient of electrical potential difference and sodium and potassium on the gut contents along the cecum and colon of normal and sodium-depleted rats. *Journal of Physiology* **193**, 571–588.

Edwards, C. (1990). Mechanism of action of dietary fiber on small intestinal absorption and motility. In *New Developments in Dietary Fiber*, pp. 95–104 [I. Furda and C. J. Brine, editors]. New York: Plenum Press.

Field, H., Dailey, R. E., Boyd, R. S. & Swell, L. (1954). Effect of restriction of dietary sodium on electrolyte composition of the contents of the terminal ileum. *American Journal of Physiology* **179**, 477–480.

Fluorie, B., Vidon, N., Florent, C. H. & Bernier, J. H. (1984). Effect of pectin on jejunal glucose absorption in normal man. *Gut* **25**, 936–941.

Fordtran, J. S. & Locklear, T. W. (1966). Ionic constituents and osmolarity of gastric and small intestinal fluids after eating. *American Journal of Digestive Diseases* **11**, 503–521.

Fordtran, J. S., Rector, F. C., Enton, M. F., Suter, N. & Kinney, J. (1965). Permeability characteristics of the human small intestine. *Journal of Clinical Investigation* **44**, 1935–1944.

Foster, E. S., Sandle, G. I., Hayslett, J. P. & Binder, H. J. (1986). Dietary potassium modulates active potassium absorption and secretion in rat distal colon. *American Journal of Physiology* **251**, G619–G626.

Frizzell, R. A., Koch, M. J. & Schultz, S. G. (1976). Ion transport by rabbit colon: I. Active and passive components. *Journal of Membrane Biology* **27**, 297–316.

Frizzell, R. A. & Schultz, S. G. (1978). Effects of aldosterone on ion transport by rabbit colon in-vitro. *Journal of Membrane Biology* **39**, 1–26.

Fuse, K., Bamba, T. & Hoso, S. (1989). Effects of pectin on fatty acid and glucose absorption and unstirred water layer in rat and human intestine. *Digestive Diseases and Sciences* **34**, 1109–1116.

Gotch, F., Nadell, J. & Edelman, I. S. (1957). Gastrointestinal water and electrolytes. IV. The equilibration of deuterium oxide (D_2O) in gastrointestinal contents and the proportion of total body water (TBW) in the gastrointestinal tract. *Journal of Clinical Investigation* **36**, 289–296.

Holbrook, J. T., Patterson, K. Y., Bodner, J. E., Douglas, L. W., Vellon, C., Kelsay, J. L., Mertz, W. & Smith, J. C. (1984). Sodium and potassium intake and balance in adults consuming self-selected diets. *American Journal of Clinical Nutrition* **40**, 786–793.

Jeraci, J. L. & Van Soest, P. J. (1990). Improved methods for analysis of biological characterization of fiber. In *New Developments in Dietary Fiber*, pp. 145–163 [I. Furda and C. J. Brine, editors]. New York: Plenum Press.

Johnson, I. T. & Gee, J. M. (1981). Effect of gel-forming food gums on the intestinal unstirred layer and sugar transport in-vitro. *Gut* **22**, 398–403.

Judd, P. A. & Trusell, S. A. (1981). The effect of rolled oats on blood lipids and fecal steroid excretion in man. *American Journal of Clinical Nutrition* **34**, 2061–2067.

McCabe, R. D., Cooke, H. J. & Sullivan, L. P. (1982). Potassium transport by rabbit descending colon. *American Journal of Physiology* **242**, C81–C86.

McCabe, R. D., Smith, P. L. & Sullivan, L. P. (1984). Ion transport by rabbit descending colon: mechanisms of transepithelial potassium transport. *American Journal of Physiology* **246**, G594–G602.

Mohring, J. & Mohring, B. (1972). Evaluation of sodium and potassium balance in rats. *Journal of Applied Physiology* **33**, 688–692.

Murray, D., Fleiszer, D., McArdle, A. H. & Brown, R. A. (1980). Effect of dietary fiber on intestinal mucosal sodium-potassium-activated ATPase. *Journal of Surgical Research* **29**, 135–140.

Phillips, S. F. (1969). Absorption and secretion by the colon. *Gastroenterology* **56**, 566–571.

Phillips, S. F. & Giller, J. (1973). The contributions of the colon to electrolyte and water conservation in man. *Journal of Laboratory and Clinical Medicine* **81**, 733–746.

Rabelink, T. J., Koomans, H. A., Hene, R. J. & Dorhout-Mees, E. J. (1990). Early and late adaptations to potassium loading in humans. *Kidney International* **38**, 942–947.

Sandle, G. I., Foster, E., Lewis, S., Binder, H. J. & Hayslett, J. P. (1985). The electrical basis of enhanced potassium secretion in rat distal colon during dietary potassium loading. *Pflügers Archives* **403**, 433–439.

Sealey, J. E., Clark, I., Bull, M. B. & Laragh, J. H. (1970). Potassium balance and the control of renin secretion. *Journal of Clinical Investigation* **49**, 2119–2127.

Spiller, G. A., Story, J. A., Wong, L. G., Nunes, J. D., Alton, M., Petro, M. S., Furomoto, J. D., Whittam, J. H. & Scala, J. (1986). Effect of increasing levels of hard wheat fiber on fecal weight, minerals, steroids and gastrointestinal transit time in healthy young women. *Journal of Nutrition* **116**, 778–785.

Thompson, S. M., Suzuki, Y. & Schultz, S. G. (1982). The electrophysiology of rabbit descending colon. II. Current-voltage relations of the apical membrane, the basolateral membrane and the parallel pathways. *Journal of Membrane Biology* **66**, 41–54.

Wills, N. K. & Biagi, B. (1982). Active potassium transport by rabbit descending colon. *Journal of Membrane Biology* **64**, 195–203.

Zar, J. H. (1974). Simple linear regression. In *Biostatistical Analysis*, pp. 198–227. Englewood Cliffs: Prentice-Hall.