Electrolyte absorption from the colon

Though man has always displayed a considerable if somewhat morbid interest in the workings of his bowel little scientific investigation of human large bowel function was carried out until the last decade. It has become clear that a prime function of the colon is the absorption of salt and water, and recently attention has been focused on the capacity of the colon to handle electrolytes and on the underlying mechanisms involved\(^1\), \(^2\), \(^3\). This review summarizes recent advances in this field. Examples are given of disorders of electrolyte transport in the human colon to illustrate its clinical relevance.

Unfortunately none of the several approaches employed for investigation \textit{in vivo} in man are entirely satisfactory. Both measurement of the appearance in the blood stream of test substances introduced into the lumen of the colon\(^4\) and the disappearance from the colon of substances instilled into isolated segments at laparotomy\(^5\) have limitations. The measurement of absorptive function by perfusion techniques with the aid of nonabsorbable markers, although tedious and uncomfortable for the subject, has yielded more direct and informative results\(^6\), \(^6\), \(^7\). These techniques, together with the recent reports of measurement of electrical potential differences across colonic mucosa,\(^8\), \(^9\) are beginning to clarify the physiology and pathophysiology of colonic absorptive function in man.

Absorptive Capacity

An indirect assessment of the amounts of salt and water which the colon handles each day can be made by comparing the volume and composition of ileostomy discharge and of stool water\(^10\), \(^11\). Daily absorption rates of 400 to 500 ml of water, 70 m-equiv sodium, and 35 m-equiv chloride, and a secretion rate of 4 m-equiv/day of potassium are the usual calculated values\(^10\). The total daily loss in the stools is less than 5 m-equiv sodium, 9 m-equiv potassium, and 2 m-equiv chloride. This very low rate of excretion, which is unaffected by ingestion of ion exchange resins\(^12\), explains the ability of man to survive on a very low salt intake for long periods\(^18\), a facility which is severely impaired in patients with an ileostomy\(^14\). These calculations for absorptive rates are based on the assumption that ileostomy discharge is representative of the fluid which enters the normal caecum from a normal ileum. Giller and Phillips\(^15\) have suggested recently that the volume of normal ileal contents in intact man is greater than ileostomy discharge measurements would suggest and have calculated that sodium and water absorption rates by the colon may be as much as three times greater than formerly proposed.

That the colon is capable of absorbing much more salt and water than these values for average daily loads is evidenced by the results of perfusion studies of the entire colon \textit{in vivo}. Levitan and his coworkers\(^2\) calculated that the colon would absorb up to 2.5 l water and over 400 m-equiv sodium and 550 m-equiv chloride per day if it could be perfused with isotonic saline at a
constant rate of 10 ml/minute for 24 hours (ie, 14·4 l per day). These widely quoted figures cannot be used, however, out of the context of the conditions in which they were obtained. At slower perfusion rates, with solutions having an ionic composition nearer to that of colonic contents, absorptive capacity would be less since less solute would be presented to the mucosa for absorption. Diarrhoea may well occur at much slower rates of flow into the colon from the ileum than the figure of 2-5 l/day for colonic capacity for water absorption would suggest.

Transport Mechanisms

WATER
In common with other biological membranes the colonic mucosa transports water as an entirely passive consequence of the movement of solutes, and occurs mainly in response to osmotic pressure gradients set up by ion movement18, 17, 18. Few workers now support an active process for water transport9. Sodium absorption is the major determinant of water movement. Perfusion studies reveal isosmotic absorption of sodium and water in the colon as elsewhere in the alimentary tract17, 19. Theoretically, colonic contents should thus be isosmotic with plasma but the osmolality of stool water is higher than plasma, being about 370 m osmole/kg20. This is almost certainly due to rapid bacterial breakdown of substrates, mainly unabsorbed carbohydrate, into a number of smaller solutes in the lower bowel and voided stool, since stool water becomes isosmotic with plasma when bacterial growth is inhibited by intestinal antibiotics21.

SODIUM AND POTASSIUM
The concentration of sodium in stool water is about one quarter of the concentration in plasma20 and perfusion studies reveal absorption continuing until the luminal concentration falls to below 24 m-equiv/l16. The mucosal surface of the colon is electrically negative to the serosal surface8, 9, and thus absorption of sodium occurs against an electrical as well as a chemical concentration gradient, strong evidence for an active process underlying sodium transport. Experiments in vitro in animals suggest that the electrical potential developed across colonic mucosa is produced predominantly by active sodium transport18, 22 and it seems likely that this is equally true of the electrical potential in the human colon9.

The potassium concentration in stool water is much higher than in plasma and may exceed 100 m-equiv/l20. Contraction of the volume of colonic contents may account for some of the rise in concentration from that in ileal effluent but secretion of potassium across the colonic mucosa also occurs. Perfusion studies demonstrated that potassium is secreted into isotonic saline8, while the experiments of Devroede and Phillips17 showed that secretion occurred into solutions containing less than 15 m-equiv/l potassium and absorption when the concentration was greater than 15 m-equiv/l. This figure of 15 m-equiv/l may not represent the concentration above which potassium is normally absorbed, however, since these studies were performed with sodium omitted from the perfusate, a factor which may affect electrical potential differences across the mucosa23, 24 and thus modify potassium movement secondarily. The orientation of the electrical potential difference, lumen negative to serosa, will induce potassium to enter the lumen against a concentration gradient, but it is not clear whether the recorded potential difference of 30 to 40 mV is sufficiently large to account for the observed concentration
gradient. Animal experiments suggest that potassium secretion is an entirely passive consequence of the potential difference set up by active sodium absorption. However, on the basis of measurements of human rectal potential difference and stool electrolytes, Edmonds and Godfrey calculated that potassium secretion was greater than would be expected from simple passive diffusion down an electrochemical gradient and suggested that therefore potassium must be secreted actively. Simultaneous measurement of potassium transport and electrical potentials in man, necessary to resolve this question, have not yet been performed.

CHLORIDE AND BICARBONATE
Stool water contains only about 15 m-equiv/l chloride. Chloride is absorbed from the colon against a concentration gradient, absorption occurring during perfusion of the colon with solutions containing less than 25 m-equiv/l chloride. Since the serosal surface of the human colon is 30 to 40 mV positive to the lumen, this concentration gradient for chloride could be an entirely passive consequence of the potential difference, as in animals. However, simultaneous measurements of potential difference and chloride transport have not yet been made to prove this point in man.

Since secretion of bicarbonate occurs during chloride absorption in both animals and man, it has been suggested that chloride is absorbed by a process of reciprocal anion exchange for bicarbonate. Carbonic anhydrase, present in high concentrations in colonic mucosa, could catalyze the production of bicarbonate. In perfusion experiments bicarbonate secretion occurred when chloride was present in the lumen but was inhibited when it was absent, lending support to the anion exchange hypothesis. However, changes in potential difference in the colon will also influence bicarbonate movement, and it is not known whether altering the concentration of intraluminal sodium chloride affects potential difference and thus, indirectly, bicarbonate secretion. There is good evidence, however, that a directly linked exchange does occur in the human ileum. The concentration of bicarbonate in stool water in man is about 30 mM, but this value may be misleadingly low due to the dissipation of bicarbonate as CO₂ by organic acids formed by bacterial fermentation of unabsorbed carbohydrate.

MUCOSAL PERMEABILITY
Few studies have been made of the permeability of the mucosa in the human colon. Levitan and Billich suggested that the effective diameter of 'pores' in the mucous membrane of the colon was smaller than 2.3 A, on the basis of the relative rates of diffusion out of the lumen of molecules of different sizes. These pores are smaller than those thought to exist in the jejunum and ileum and the colon appears to be less permeable to water and small ions than the small bowel.

In the colon a regional variation in permeability to sodium may exist, the caecum and ascending colon being more permeable than the sigmoid colon and rectum. Although permeability measurements cannot be equated with absorptive capacity, absorption of sodium from the rectum was virtually absent in one study in which saline was retained there for 90 minutes. It is likely that most sodium is absorbed proximal to the sigmoid region. This may be a factor in the production of watery diarrhoea seen in some cases of right-sided colitis.

HORMONAL INFLUENCES
Mineralocorticoids have been shown to influence salt and water absorption
from the large bowel. Aldosterone increased sodium and water absorption from the whole colon\textsuperscript{34}, increased the potential difference across the rectosigmoid mucosa\textsuperscript{8}, and increased potassium secretion in isolated segments of human colon\textsuperscript{35}. Stool sodium concentrations were reduced and potassium concentrations increased in normal subjects given mineralocorticoids, an effect inhibited by spironolactone\textsuperscript{36}. The stools of patients with endogenous hyperaldosteronism showed similar changes in the concentration of sodium and potassium\textsuperscript{36, 37}. Though such evidence suggests that mineralocorticoids play a role in regulating salt and water absorption in the colon their physiological importance is uncertain. It might be that in chronic diarrhoea the resulting loss of salt and water would stimulate the production of endogenous aldosterone, which would alter the ionic composition of the stools secondarily as diarrhoea continued. This phenomenon of secondary hyperaldosteronism has been described in patients with chronic purgative addiction\textsuperscript{38, 39}, and may well be responsible for an excessive faecal and urinary loss of potassium leading on to the hypokalaemia so striking in these patients.

**AMMONIA**

The colon is a quantitatively important site for the production and absorption of ammonia\textsuperscript{40}. It is produced predominantly in the lumen by the action of bacterial ureases on urea\textsuperscript{40} and is probably absorbed by a process of passive non-ionic diffusion\textsuperscript{41}. Neomycin inhibits the production of ammonia by its effect on bacteria but does not influence ammonia absorption\textsuperscript{40}. Although ammonia is produced from urea in the stomach and small bowel by mucosal ureases, which are present in higher concentrations than is colonic mucosal urease, the colon is quantitatively more important in the production of high plasma ammonia levels in cirrhosis\textsuperscript{40}. The rationale for colonic irrigation and neomycin therapy in the management of hepatic encephalopathy is emphasized by these observations.

**Disturbances in Electrolyte Absorption from the Colon**

Although simple determinations of stool electrolyte concentrations can reveal much about disordered colonic function in diarrhoea, these measurements are rarely made, and reports in the literature are often sketchy. From a survey of the literature Fordtran and Dietschy\textsuperscript{16} pointed out that in a variety of different forms of diarrhoea there was a linear relationship between sodium and water losses in the stools. As diarrhoea increases in severity sodium concentrations tend to rise and potassium concentrations fall, so that in very severe diarrhoeic stool ion concentrations approach those in plasma. This relationship is present in diarrhoea of both small and large bowel origin. Presumably rapid transit through the colon limits the contact time between luminal contents and mucosa and thereby reduces the extent of the changes normally produced by colonic mucosa. It has been held that the diarrhoea of patients with a villous adenoma of the rectum is especially rich in potassium\textsuperscript{42} but stool potassium concentrations in these patients are no higher than in normal subjects. The relationship found between severity of diarrhoea and electrolyte losses in other forms of diarrhoea is also valid for villous adenomata, and there is no convincing evidence of a specific potassium secretory process in this disease. It is possible that a secondary hyperaldosteronism could increase potassium losses and cause hypokalaemia in these patients as in purgative addiction\textsuperscript{38}. The excessive fluid production is attributed to secretion predominantly of sodium and chloride by the tumour itself\textsuperscript{35}. The cellular origin of the villous adenoma is uncertain but if it arises from
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References


a secretory crypt cell this might explain some of its clinical characteristics.

Patients with ulcerative colitis and Crohn's disease of the colon absorb less sodium and water and secrete more potassium than normals 43, 44, 45, and the permeability of the rectosigmoid area is reduced in distal colitis46. These observations provide an insight into the mechanism of the diarrhoea of these patients.

A rare but fascinating disorder of intestinal electrolyte transport has been termed 'congenital chloridorrhoea'47. It is characterized by severe watery diarrhoea from birth, metabolic alkalosis, and an excessive loss of chloride in the stools, the concentration of chloride being higher than the sum of the sodium and potassium concentrations47. The basis of the defect is thought to lie in the malabsorption of chloride in the ileum and colon, probably due to absence or reversal of the normal chloride/bicarbonate exchange process48, for which good evidence in the ileum and suggestive evidence in the colon47 has been cited. A similar but acquired chloridorrhoea has been reported rarely in patients with hypokalaemia, itself usually the result of prolonged diarrhoea47. The high stool chloride concentration returns to normal when the hypokalaemia is corrected and it is possible that the chloride/bicarbonate exchange is depressed by hypokalaemia in these cases. Hypokalaemia itself may thus perpetuate diarrhoea by this mechanism. Although the incidence of this phenomenon is unknown it is clearly important to consider this possibility in patients with prolonged diarrhoea.

The cathartic action of bile salts is well recognized. Recently it has been suggested that bile salts may be responsible for the watery diarrhoea encountered in some patients after removal of the terminal ileum, the site at which bile salts are normally re-absorbed49. Hofmann49 suggested that sodium and water absorption in the colon is impaired by bile salts, a view supported by perfusion studies50, and some of these patients obtain relief from diarrhoea by the oral ingestion of cholestyramine, which binds bile salts51.

The importance of the study of colonic absorptive function is emphasized by these examples of disordered electrolyte transport. A greater understanding of the pathophysiology of all forms of diarrhoea may well emerge as the normal mechanisms for ion transport in the colon become more clearly defined. Much could be learnt from even simple determinations of stool electrolyte concentrations, but this investigation, which could be a valuable aid in the diagnosis of difficult cases of persistent diarrhoea, is as yet infrequently applied.
20Devroede, G. J. (1968). Transport of Water and Electrolytes in the Human Large Intestine. Thesis. Mayo Graduate School of Medicine (University of Minnesota), Rochester, Minnesota (quoted in ref. 33).
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