Sir David Cuthbertson Medal Lecture

Metabolic cross talk between the colon and the periphery: implications for insulin sensitivity

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Until recently, a glance at a standard undergraduate textbook would have given the impression that the colon was merely a storage organ for faeces and maybe something about the absorption of electrolytes and water. In reality, the colon is a highly-metabolically active organ, the function of which has implications not only for the remainder of the digestive tract, but also for peripheral organs such as adipose tissue (AT), liver and skeletal muscle. The present review focuses on two distinct but complementary areas: (1) the metabolic adaptation that occurs following surgical removal of colonic tissue; (2) the effect of modulating the colon in situ in terms of postprandial metabolism, insulin sensitivity and disease risk. Work in these two areas points to the colon being important in modulating normal tissue insulin sensitivity. The role of fatty acids is central to the insulin sensitivity hypothesis. AT acts as a daily ‘buffer’ for fatty acids. However, following colonic resection there is an apparent change in AT function. There is an increase in the AT lipolysis rate, resulting in the release of excess fatty acids into the circulation and consequently the take up of excess fatty acids into skeletal muscle. This resultant increase in either storage of lipid or its oxidation would result in a reduction in insulin sensitivity. The insulin-sensitising effects of high fibre diets are also related to changes in AT function and fatty acid metabolism, but manipulating colonic tissue in situ allows the mechanisms to be elucidated. This research area is an exciting one, involving the potential role of SCFA (the absorbed by-products of colonic bacterial fermentation) acting directly on peripheral tissues, following the recent identification of G-protein-coupled receptors specific for these ligands.

‘I have finally come to the conclusion that a good reliable set of bowels is worth more to a man than any quantity of brains’ Henry Wheeler Shaw (1818–1885)

Obesity, insulin resistance and type 2 diabetes are predicted to become the epidemics of the 21st century. It would be too simplistic to assume that changing any one dietary constituent would provide a strategy for prevention. However, key elements of the diet have repeatedly been linked with a reduced risk of developing chronic diseases such as type 2 diabetes and CVD: decreased SFA; decreased trans-fatty acids; decreased glycaemic index of digestible carbohydrates; increased non-viscous cereal fibres, such as those normally found in whole grains (Baxter et al. 2006). The picture is changing, with emphasis now being placed firmly on the quality of carbohydrates in the diet. Unlike the glycaemic index concept, which is primarily involved with acute changes in glycaemia caused by manipulating the proportions of rapidly- and slowly-absorbed digestible carbohydrates, non-viscous fibres are resistant to small intestinal enzymic digestion. They have negligible effects on gastric emptying, macronutrient absorption from the gut, postprandial

Abbreviations: AT, adipose tissue; GI, gastrointestinal; GLP, glucagon-like peptide; GPR, G-protein-coupled receptors; TC, total colectomy. Corres ponding author: Dr Denise Robertson, fax +44 14863 686401, email m.robertson@surrey.ac.uk
glucose responses or blood lipids. However, increased consumption is linked to a reduced disease risk by a mechanism that because of the physico-chemical properties of the fibres themselves must involve colonic metabolism. For many years the colon has been overlooked by both physiologists and nutritionists; however, this oversight is now being addressed. The colon is intimately linked to the functioning of peripheral tissues distant from the gastrointestinal (GI) tract. The absence of colonic metabolism leads to insulin resistance through changes in adipose tissue (AT) metabolism; conversely, increasing colonic metabolism increases insulin sensitivity, potentially also through changes in AT metabolism. These research areas appear distinct, yet provide complementary information and an integrative approach to the investigation of the importance of the colon. This metabolic cross talk between the colon and peripheral tissues, especially AT, has the potential to provide a new interpretation for the health benefits of non-viscous fibres, in addition to providing novel insights into the role of the colon in both health and disease.

**Loss of normal colonic function**

Conventionally, surgical loss of colonic tissue, or total colectomy (TC), involves performing a loop-ileostomy following resection of the entire colon, with only minimal resection of the terminal ileum (<50 mm). This procedure leaves either a temporary (with follow-up surgery at a later date to reconstruct a continent ileal reservoir) or permanent stoma, which is formed from the small intestine through the abdominal wall. TC can be performed for ulcerative colitis, colon cancer, Hirschsprung’s disease, Crohn’s disease and familial adenomatous polyposis, which are diseases with very different aetiologies and progression. Quantitatively, the most common reason for this surgery is ulcerative colitis, a chronic inflammatory disease confined to the large intestine that currently affects three in 1000 of the population in the UK, with similar incidences in both Western Europe and the USA. Despite dramatic advances in both the genetic understanding of ulcerative colitis and improvements in medication, it is still estimated that ≥15% of patients will require TC at some point in their lives. Understanding the consequences for this surgery is not only an important issue for this substantial group of patients, but also gives an insight into the relationship between the colon and metabolic interactions involving other segments of the GI tract and more peripheral organs such as the liver, AT and muscle, and the disease risk that may be may posed.

**Gastrointestinal adaptation**

It is not surprising that surgical loss of an organ such as the colon would lead to adaptation in both the structure and function of the remaining GI tract. Multiple areas are affected: GI motility (Robertson & Mathers, 2000); bile acid metabolism (Teufel et al. 1988); composition of the intestinal microflora; absorption of both Na⁺ and water. Following surgery, the most consistent observation in both human and animal studies is a rapid change in stomal function. Immediately following resection, post-operative diarrhoea results in fluid losses of approximately 1–0–1·5 l/d. However, there is rapid ‘adaptation’ leading to a dramatic drop in fluid and Na⁺ loss from the stoma in a scale of days to weeks to months (Wright et al. 1969; Hill, 1976). This adaptation is an important initial step, without which there would be continuous and deleterious losses of electrolytes and water from the body. The initial step in adaptation following TC has been well described and involves stimulation of the adrenal cortex.

The characteristic response to the electrolyte and fluid loss is stimulation of the renin–angiotensin system and increased aldosterone production (Christl & Sceppach, 1997). Both renin and aldosterone levels have been reported to be elevated following TC (Robertson et al. 2005b), with plasma concentrations remaining elevated for several years following surgery, implying a more fundamental metabolic change. The GI tract is a well-characterised target tissue for aldosterone action, with the mineralocorticoid receptor found widely distributed (Fuller & Verity, 1990), including in the gastric parietal cells (Hall et al. 1999).

Increased levels of plasma aldosterone have the acute effect of activating receptors in both the GI tract and kidney tubule to enhance Na⁺ re-absorption and increase the net loss of K⁺ from the body. In both animals (Koyama et al. 1999) and man (Huber et al. 2001) TC results in secondary aldosteronism as a result of the subclinical state of mild dehydration and Na⁺ depletion that, despite metabolic adaptation, persists long term.

It has been established since the pioneering work of the 1960s and 1970s (Wright et al. 1969; Hill, 1976; Woo & Nygaard, 1978) that TC results in structural and functional changes within the remaining GI tract. More recently, the emergence of more molecular technologies has allowed a more detailed examination of the underlying mechanisms. The GI adaptation occurring following colonic resection, for simplicity, has been subdivided into two sections: (1) generalised hyperplasia of the gut; (2) specific or selective changes in levels or activities of transporters and enzymes.

**General hyperplasia**

During intestinal adaptation the residual bowel undergoes dilatation, muscle-wall hypertrophy and mucosal hypertrophy to compensate for the loss of the colon through surgery. There is an increased production of cells in the crypt, and migration of these cells within the crypt results in apparent enlargement of the villus size. The outcome is an increased potential absorptive capacity of the small intestine. Most of the work into intestinal adaptation has been undertaken following massive small-bowel resection. Although there are distinct differences between the loss of the large intestine compared with loss of the small intestine, some parallel mechanisms may exist. In animal studies colon resection leads to changes in the gastric mucosa (Hallonquist et al. 1998), with a generalised thickening and dilution of the mucosal surface and consequent up-regulation of the gastric acid-producing parietal cells.
Changes in the structure of the small intestine are also well documented, with an increased intestinal length and weight, mucosal thickness, villus length and villus cell count (Woo & Nygaard, 1978; Willis et al. 2002). The loss of colonic absorption is thus compensated by the increase in the ileal surface, with subsequent elevations in Na\textsuperscript{+} and water absorption. The ‘trigger’ for this gross and generalised change in structure is poorly understood. Peptide hormones and growth factors released either locally from the GI tract and from extra-GI sites may have trophic effects on the intestine. Neurotensin, a peptide derived from endocrine cells of the jejunum and duodenum, is elevated following colonic resection (Kennedy et al. 1982) and has been shown to enhance mucosal weight, in addition to increasing RNA and DNA content (Évers et al. 1992) and so promoting intestinal adaptation (Mata et al. 1997). Mediators found to be crucial following massive small-bowel resection, such as glucagon-like peptide (GLP)-2, are actually decreased following TC (Kennedy et al. 1982), and therefore do not provide an explanation. Although other factors such as the growth hormone–insulin-like growth factor 1 axis and epidermal growth factors have been implicated in small-bowel adaptation following massive small-bowel resection (Lukish et al. 1997), the effects on these mediators following TC is at present unknown.

Following colonic resection there is rapid entry into a ‘feed-forward loop’. Generalised hyperplasia of the upper small intestine leads to increased numbers of endocrine cells in this region, specifically cells secreting cholecystokinin (Buchler et al. 1988b), glucose-dependent insulinotropic polypeptide (Robertson et al. 1999) and neurotensin (Kennedy et al. 1982), resulting in elevated fasting and postprandial secretion of these hormones into the plasma. There is some discrepancy in the literature about whether some of these hormonal changes are in fact part of the underlying pathology of chronic inflammatory bowel disease (ulcerative colitis and Crohn’s disease), which is the case for both motilin (Greenberg et al. 1989) and glucose-dependent insulinotropic polypeptide (Besterman et al. 1983), and whether this level of adaptation occurs before colonic resection. Irrespective of the time course of endocrine up-regulation, changes in the plasma levels of these hormones lead to an adaptation of function. Hypersecretion of both cholecystokinin and glucose-dependent insulinotropic polypeptide leads to delayed motility, especially gastric motility, which may partially compensate for the loss of colonically-derived hormones such as peptide YY (Adrian et al. 1987) and GLP-1 (Robertson et al. 1999) that if left uncorrected would result in rapid intestinal transit and would potentially exaggerate the stomal losses following surgery. In addition to effects on motility, elevated glucose-dependent insulinotropic polypeptide secretion could stimulate pancreatic insulin secretion. Hyperinsulinaemia can have anabolic actions on the intestinal tract, with a demonstrated stimulation of ileal protein synthesis following ileostomy (Rittler et al. 2006) and specific reduction of urinary Na\textsuperscript{+} excretion (Quinones-Galvan & Ferrannini, 1997), so addressing the underlying issue of Na\textsuperscript{+} depletion. Thus, although the exact ‘trigger’ for intestinal adaptation remains to be determined, adaptation does indeed take place, enabling the remaining absorptive surface of the GI tract and transit time to increase, both of which enhance the process of absorption and Na–water balance.

Specific transporter adaptation

The most intriguing part of this overall adaptation is perhaps the ability of the remaining GI tract to selectively up regulate transporters and/or enzymes that deal with Na\textsuperscript{+} conservation. This selectivity is intimately related to Na\textsuperscript{+} depletion. There is selective up-regulation of the Na co-transporters, Na–K–2Cl co-transporter in the gastric mucosa (Hallonquist et al. 1998) and the electrogenic Na–glucose co-transporter 1 in the small intestine (Haneda et al. 2006), and molecular induction of all three subunits of the epithelial Na\textsuperscript{+} channel and its cofactor prostanin (Koyama et al. 1999), a novel serine protease that may, in conjunction with epithelial Na\textsuperscript{+} channel, accelerate Na\textsuperscript{+} absorption (Adachi et al. 2001). Aldosterone is known to increase expression of both Na–K–2Cl and Na\textsuperscript{+} channels in the kidney tubule, and so secondary aldosteronism is likely to be the prime candidate responsible for parallel up-regulation in the gut. In animal experiments aldosterone infused to reach a plasma concentration similar to that observed following colectomy has also been found to induce the mRNA of all three subunits of the epithelial Na\textsuperscript{+} channel in addition to prostanin. In contrast, however, up-regulation of Na–glucose co-transporter 1 cannot be explained simply by elevated aldosterone, or indeed by dietary Na\textsuperscript{+} depletion (Fukushima et al. 2005). Further examination of this finding using a microarray approach (Fukushima et al. 2006) has led to the characterisation of a total of 6109 intestinal genes by RT–PCR. Following TC in the rat eighty-two genes were found to be up regulated and ninety-one genes down regulated in the residual ileum. However, using a similar approach it has been found that aldosterone infusion modulates only twenty-one genes, and there is a definite interaction with dietary Na\textsuperscript{+} depletion. Thus, although Na\textsuperscript{+} depletion and hyper-aldosteronism provide a potential explanation for specific intestinal adaptation, it is also clear that the situation is still very complex.

TC not only leads to an increase in circulating aldosterone, but also up regulates GI expression of the mineralocorticoid receptor throughout the GI tract (Fukushima et al. 1994). In addition, it increases expression (mRNA and protein) of the enzyme 11β-hydroxysteroid dehydrogenase type 2 (Sato et al. 2005). This enzyme is important in the overall adaptation process, as it confers specificity to the non-selective mineralocorticoid receptor by converting local levels of glucocorticoids to their receptor-inactive metabolites (cortisol to cortisone), thus allowing the binding of aldosterone, which circulates at much lower concentrations. Increased expression of both mineralocorticoid receptor and 11β-hydroxysteroid dehydrogenase type 2 is required for full adaptation following TC. Thus, loss of colonic tissue leads to elevated aldosterone levels, the clinical effect of which is magnified by an increased number of mineralocorticoid receptors and increased levels of receptor binding as a result of increased...
enzymic degradation of the competing substrate. Increased stimulation by aldosterone may then be responsible for the increased expression of Na⁺ transporters such as epithelial Na⁺ channel. Of course, the situation is likely to be far more complex, with local changes within the GI lumen that are not explained by changes in aldosterone playing an important role.

**Peripheral adaptation; cause or consequence?**

For many years it was assumed that any long-term effects following TC would be entirely GI. However, work that was started in the 1990s and continues today consistently demonstrates otherwise. With what is now known about the normal functioning of the colon, effects of endocrine mediators such as GLP-1 and SCFA, in addition to the well-established links between colonic fermentation of dietary fibre and chronic diseases such as type 2 diabetes and CVD, it should not be surprising that complete loss of colonic tissue would have implications for peripheral metabolism. The most consistent finding following TC in both human and animal studies is an inappropriate insulin response, both as a fasting measurement and in response to a carbohydrate challenge. The age- and gender-matched human studies addressing this issue are summarised in Table 1. The key observation from these data is that it demonstrates otherwise. With what is now known about the normal functioning of the colon, effects of endocrine mediators such as GLP-1 and SCFA, in addition to the well-established links between colonic fermentation of dietary fibre and chronic diseases such as type 2 diabetes and CVD, it should not be surprising that complete loss of colonic tissue would have implications for peripheral metabolism. The most consistent finding following TC in both human and animal studies is an inappropriate insulin response, both as a fasting measurement and in response to a carbohydrate challenge. The age- and gender-matched human studies addressing this issue are summarised in Table 1. The key observation from these data is that it is apparent the loss of colonic tissue that is important, not the underlying pathology that led to surgery. In the earlier discussion of GI adaptation it was suggested that inflammatory bowel disease itself may be the ‘trigger’ for adaptation; certainly for gut endocrinology. However, in other conditions such as Hirschsprung’s disease and colon cancer, in which the underlying aetiology is different, a similar level of hyperinsulinaemia is observed. Indeed, in the single study in which glucose metabolism was assessed in patients with inactive ulcerative colitis no such dysregulation was reported (Capristo et al. 1999) and, of course, when TC is performed in animal models there is no underlying disease (Buchler et al. 1988a). Based on the current evidence, it is likely that any peripheral changes in metabolism, of which hyperinsulinaemia is the most prominent and easily measured, is directly related to the loss of functioning colonic tissue.

**Insulin resistance**

Despite the prevailing hyperinsulinaemia, there have been many reports of concomitant hyperglycaemia, which implies a level of tissue insulin resistance (Table 1). In the postprandial state glucose enters the body from the GI tract. The main tissue involved in buffering this influx of glucose is the liver, which absorbs the influx of glucose and switches off hepatic glucose production. Skeletal muscle plays a parallel role, taking up glucose under the influence of insulin. The glycaemia measured is the simultaneous balance of these mechanisms, and so more kinetic studies are required to tease apart the various aspects. In a previous study (Robertson et al. 2000) a double-isotope approach was employed, in which a [1³C]glucose isotope was fed to trace glucose uptake from the GI tract in combination with a D-[6,6³H₂]glucose infusion to trace hepatic glucose production. Despite the potential increase in Na–glucose co-transporter 1 reported in animal models following TC (Haneda et al. 2006), in the human model no increase was found in the level of glucose uptake by the gut. An explanation for this finding is that the

**Table 1. Glucose metabolism following surgical colonic resection**

<table>
<thead>
<tr>
<th>Underlying pathology</th>
<th>Subjects</th>
<th>Age range (years)</th>
<th>BMI range (kg/m²)</th>
<th>Methodology</th>
<th>Primary result (compared with control group)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD</td>
<td>16</td>
<td>16–26</td>
<td>20–37</td>
<td>MTT</td>
<td>Elevated fasting glucose and insulin</td>
<td>Medhus et al. (2001)</td>
</tr>
<tr>
<td>UC, CD, FAP</td>
<td>6</td>
<td>26–46</td>
<td>20–26</td>
<td>OGTT</td>
<td>Normal fasting glucose and insulin</td>
<td>Nauck et al. (1996)</td>
</tr>
<tr>
<td>UC</td>
<td>6</td>
<td>40–55</td>
<td>22–26</td>
<td>MTT</td>
<td>Hyperinsulinaemia and elevated C-peptide concentration during OGTT</td>
<td>Robertson &amp; Mathers (2000)</td>
</tr>
<tr>
<td>UC</td>
<td>10</td>
<td>40–60</td>
<td>20–30</td>
<td>MTT, hyperinsulinaemic–euglycaemic clamp</td>
<td>Elevated fasting insulin and C-peptide during MTT</td>
<td>Robertson et al. (2005b)</td>
</tr>
<tr>
<td>UC</td>
<td>11</td>
<td>22–54</td>
<td>Normal wt</td>
<td>OGTT</td>
<td>Elevated fasting insulin and C-peptide during OGTT</td>
<td>Palnaes Hansen et al. (1997)</td>
</tr>
</tbody>
</table>

HD, Hirschsprung’s disease; CD, Crohn’s disease; FAP, familial adenatous polyposis; UC, ulcerative colitis; M, male; F, female; MTT, meal tolerance test; OGTT, oral glucose tolerance test.

*All studies are age- and BMI-matched v. healthy controls.*
normal human gut already ‘efficiently’ absorbs lumen glucose and so absorption is not increased further by increased Na–glucose co-transporter 1 expression. Furthermore, no defect in the normal suppression of hepatic glucose output was demonstrated. The primary outcome was, however, that insulin-dependent glucose disposal in the cohort that had undergone ileostomy was only 28% that of the matched controls, an observation that was primarily a result of a reduced rate of oxidative glucose disposal (Robertson et al. 2000).

In elucidating a primary mechanism for this change, it is likely that the insulin resistance observed following TC reflects alterations in intermediary metabolism.

**Adipose tissue function following total colectomy**

The links between AT function, fatty acid metabolism and glucose uptake into insulin-sensitive tissues are now well established. Plasma NEFA concentrations are the balance between release (from the lipolysis in AT and intravascular lipolysis of dietary TAG) and uptake (re-esterified in AT and liver and oxidised in muscle heart and liver). It is now believed that abnormalities in fatty acid storage and lipolysis, with increased flux from AT to non-AT (skeletal muscle, liver, pancreas), are critical in the development of insulin resistance (McCarron, 2002).

There are several lines of evidence that suggest a direct link between TC and changes in intermediary metabolism: (1) lower levels of systemic SCFA (Scheppach et al. 1991) produced from colonic fermentation may modulate AT lipolysis (Crouse et al. 1968); (2) lower levels of GLP-1 released from the distal gut may also act directly to regulate clearance of TAG-rich lipoproteins (Beck, 1989); (3) there may be a direct or indirect relationship with secondary hyperaldosteronism or the resultant hypokalaemia (Catena et al. 2006).

The understanding of the metabolic consequences of TC has been enhanced by the use of arterio–venous balance techniques that can determine directly the metabolic flux across the tissue of interest (AT or skeletal muscle). TC results in dysregulation of fatty acid metabolism, resulting in an increased level of AT lipolysis (Fig. 1) and increased NEFA and glycerol efflux into the plasma (Robertson et al. 2005b).

Acetate, quantitatively the most important of the SCFA, has been shown in vivo to suppress AT lipolysis, resulting in a suppression of both NEFA and glycerol levels (Suokas et al. 1988; Akanji et al. 1989). It is well established that the colon is an important exogenous source of plasma acetate; plasma levels in subjects who have undergone ileostomy are 50% lower than those of controls (Scheppach et al. 1991). Thus, the first potential mechanism is simply that lipolysis is increased after TC because of lower circulating levels of acetate. The second potential mechanism involves GLP-1. In animal and in vitro studies GLP-1 has been shown to have potent effects on the expression of lipoprotein lipase and potentially also AT lipolysis. However, the results of many studies are often confounded by the interplay between GLP-1 and insulin, and many of the effects relating to AT lipolysis may actually be a result of increased insulin secretion. In a single human AT microdialysis study (Bertin et al. 2001) in which this possibility was actually assessed in vivo by infusing GLP-1 directly into subcutaneous AT, no direct effect on AT lipolysis was found. Although the GLP-1 concentration is reduced by 50% following TC (Robertson et al. 1999), it is unlikely to be a primary cause of the resultant insulin resistance. The third proposed mechanism is the result of the most fundamental change in metabolism following TC, the secondary aldosteronism. In a recent study (Catena et al. 2006) hyperinsulinaemia and insulin resistance were found in patients with primary aldosteronism unrelated to hypertension, which rapidly resolved following either surgery or treatment with aldosterone antagonists. It is possible therefore that aldosterone itself might be the primary cause of insulin resistance, although currently there is little evidence in the literature for a direct causal link. In animal studies aldosterone treatment has been found to increase plasma NEFA levels, consistent with an effect on AT lipolysis (Kirsten et al. 1977), and aldosterone added to human adipocytes in vitro reduces insulin-dependent glucose uptake by 30% (Kraus et al. 2005). The relationship between aldosterone and glucose metabolism is poorly understood, but in the light of recent findings linking both primary and secondary aldosteronism with insulin resistance and hyperinsulinaemia, more work to elucidate this metabolic link is warranted.

**Skeletal muscle metabolism**

Perhaps as a direct consequence of the increased flux of fatty acids from AT there is an increased uptake of fatty acids directly into skeletal muscle following TC (assessed by arterio–venous sampling). Uptake of fatty acids by

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**Fig. 1.** Increased net efflux of fatty acids and glycerol from subcutaneous adipose tissue (AT) as a measure of lipolysis in patients following total colectomy (□) and in matched control subjects (■). Values are means with their standard errors represented by vertical bars. Mean values were significantly different from those for the patients following total colectomy: for NEFA, $P = 0.019$; for glycerol, $P = 0.02$. (Data taken from Robertson et al. 2005b.)
muscle requires transfer across the membrane by proteins such as fatty acid transporter CD36. Following TC the increased uptake of fatty acids by muscle is further enhanced by an increased tissue expression of CD36 (Robertson et al. 2005b). Under resting conditions the delivery of fatty acids to the mitochondria for β-oxidation is regulated by their rate of tissue uptake (which is increased) and so the increased rate of fatty acid oxidation observed after TC is perhaps as expected (Robertson et al. 2000). It is widely accepted that fatty acid competition with glucose for substrate oxidation leads to the inhibition of pyruvate dehydrogenase, phosphofructokinase and hexokinase II (Randle et al. 1963) activity. The result is decreased glucose transport and phosphorylation, in addition to independent effects on insulin receptor signalling caused by accumulation of intramyocellular lipid metabolites, which impair insulin action despite prevailing hyperinsulinaemia (Morino et al. 2006; Fig. 2).

Vascular function, aldosterone and leptin

The uptake of a substrate and its efflux from a tissue is mediated primarily by the rate of blood flow through it, which serves to maintain the effective concentration gradient. TC results in an increase in both muscle and AT blood flow, measured using independent methodology (Robertson et al. 2005b). This peripheral change in vascular function may again be inter-related with Na⁺ depletion and elevated aldosterone levels. Aldosterone has been shown to elevate forearm (muscle) blood flow by increasing NO release from the vascular endothelium (Schmidt et al. 2003). The change in AT blood flow is perhaps more intriguing. Leptin levels are elevated following TC (Robertson et al. 2005b), and hyperleptinaemia has been linked to increased sympathetic outflow to many tissues including AT. An increased level of leptin-induced NO release from the vascular endothelium could potentially explain the increased AT blood flow following TC. The mechanism for elevated leptin in these patients is, however, unclear. Active inflammatory disease has been linked to both low (Karmiris et al. 2006) and elevated (Barbier et al. 2003) leptin concentrations and mRNA expression in AT. Aldosterone treatment has been shown to elevate leptin expression (by 5000%) in isolated adipocytes (Kraus et al. 2005), which may provide an underlying link. Alternatively, recent studies have demonstrated gastric production of leptin, which has historically been considered to be an adipokine produced by white AT. Gastric chief cells are capable of secreting leptin directly into the circulation (Cammisotto et al. 2005), although the precise contribution to circulating concentrations is unknown. As there is hyperproliferation of the gastric mucosa following TC, the gastric production of leptin may also be enhanced, which could partly contribute to the observed hyperleptinaemia.

Colon in situ?

If the hypothesis is correct, that having no colon is a risk factor of insulin resistance, then the contrary view would be that having an ‘active’ colon would actually be preventative. The colon contains an active microflora that can efficiently metabolise most substrates. However, both in terms of quantity and health benefits, carbohydrates are the most important of these substrates. The carbohydrates entering the colon are those that are resistant to small intestinal digestion, and in the colon they are fermented to produce SCFA. The observed pattern of SCFA production is the result of a complex process involving primary saccharolytic fermenters and secondary cross-feeders. Typically, acetate:propionate:butyrate is 60:20:20. However, the corresponding proportions reached within the post-hepatic circulation would be 90:10:0, with butyrate preferentially metabolised by colonocytes. The classification of carbohydrates and dietary fibre will not be addressed here, but an important factor to consider when discerning the metabolic effects of the so-called dietary fibres is the physiochemical properties they confer. Viscous fibres change the lumen environment and so have a beneficial effect on lumen glucose diffusion and subsequent absorption from the GI tract, and have a direct impact on the glycaemic index. Although there is increasing evidence for the importance of glycaemic index in determining disease risk (Aston, 2006), the strongest epidemiological data still exist for a link between the ingestion of non-viscous (no effect on glycaemic index) fibre and a lower incidence of both type 2 diabetes and CVD. In order to fully assess the relationship it is important to look at experimental data for which the effects of glycaemic index and colonic fermentation can be fully separated, and for which insulin sensitivity has been assessed using appropriate methodology. When these two criteria are taken into account, the situation becomes more evident (Table 2). In all recent studies that have used euglycaemic–hyperinsulinaemic
Although many studies have reported changes in NEFA concentration after feeding fermentable carbohydrate (Ferchaud-Roucher et al. 2005; Brighenti et al. 2006), Robertson et al. (2005a) were the first to demonstrate a direct effect on fatty acid and glycerol flux from subcutaneous AT using arterio–venous sampling across AT in human subjects. With current advances in technology, it is now known that both acetate and propionate circulate in measurable micromolar concentrations in plasma (Robertson et al. 2005a), and so direct metabolic effects on peripheral tissues must now be considered. Carbohydrate fermentation elevates the plasma levels of both these SCFA, with direct uptake into subcutaneous AT (Robertson et al. 2005a). It was previously considered that only acetate reaches the circulation beyond the liver.

**Table 2. Effects of cereal fibre ingestion on insulin sensitivity, assessed by euglycaemic–hyperinsulinaemic clamp**

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Design</th>
<th>Dietary intervention</th>
<th>Effect*</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seventeen, overweight or obese (all female)</td>
<td>Randomised cross-over, clamp at end of each intervention</td>
<td>31.2 g oat fibre/d for 3 d v. placebo</td>
<td>M value: 6:85 v. 6:06 for fibre compared with placebo</td>
<td>Weickert et al. (2006)</td>
</tr>
<tr>
<td>Ten, normal weight (six female)</td>
<td>Randomised cross-over, clamp at end of each intervention</td>
<td>30 g resistant starch/d for 4 weeks v. placebo</td>
<td>M value: 9:7 v. 8:5 for fibre compared with placebo</td>
<td>Robertson et al. (2005a)</td>
</tr>
<tr>
<td>Eleven, overweight or obese (six female)</td>
<td>Randomised cross-over, clamp at end of each intervention</td>
<td>Six to ten servings whole or refined grains per d for 6 weeks</td>
<td>M value: mean of 0:07 higher following whole-grain intervention</td>
<td>Pereira et al. (2002)</td>
</tr>
<tr>
<td>285, adolescents (130 female)</td>
<td>Epidemiological, clamps at age 13 and 15 years</td>
<td>127 FFQ, subjects split into tertiles of whole-grain intake</td>
<td>M value across tertiles of intake: 13:3 v. 12:3 v. 11:5 from highest to lowest</td>
<td>Steffen et al. (2003)</td>
</tr>
</tbody>
</table>

NGT, normal glucose tolerance; IGT, impaired glucose tolerance.
*M value is the glucose disposal rate during the final 20 min of a 180 min euglycaemic–hyperinsulinaemic clamp expressed in mg glucose/min per kg, with the exception of the Pereira et al. (2002) study, which is expressed as mmol glucose/min per kg.

**Colonic effects on fatty acid metabolism**

As stated previously, following TC changes in insulin sensitivity are likely to be mediated via changes in intermediary metabolism; specifically, by changes in AT function. There are several key areas that could be mediated via colonic fermentation: (1) a change in AT lipolysis, and the buffering capacity of AT; (2) a change in adipocyte size and differentiation; (3) a change in adipokine release. The concept of ectopic fat storage and its detrimental effects on insulin sensitivity is also now well established (Yki-Jarvinen, 2002). A hyperlipolytic state within subcutaneous AT will result in an increased flux of plasma fatty acids and TAG accumulation in other peripheral tissues such as the liver, muscle, pancreas and heart, directly affecting metabolic function (Fig. 3). Despite this association, insulin resistance cannot always be directly attributed to changes in ectopic fat (Goff et al. 2005), and so whether the insulin-sensitising effects of fermentable carbohydrate observed during each of the studies shown in Table 2 is directly or indirectly related to fat distribution is at present unknown. Thus, the outstanding questions in relation to carbohydrate fermentation and intermediary metabolism are: does colonic fermentation affect AT metabolism; does colonic fermentation affect fatty acid metabolism and TAG accumulation in other insulin-sensitive tissues.

**Effects of SCFA on adipose tissue**

Colonic carbohydrate fermentation and intermediary metabolism affect AT metabolic function (Fig. 3). Despite this association, insulin resistance cannot always be directly attributed to changes in ectopic fat (Goff et al. 2005), and so whether the insulin-sensitising effects of fermentable carbohydrate observed during each of the studies shown in Table 2 is directly or indirectly related to fat distribution is at present unknown. Thus, the outstanding questions in relation to carbohydrate fermentation and intermediary metabolism are: does colonic fermentation affect AT metabolism; does colonic fermentation affect fatty acid metabolism and TAG accumulation in other insulin-sensitive tissues.

![Fig. 3. Interaction between colonic fermentation and ectopic fat distribution. Colonically-produced acetate and propionate appears in the post-hepatic circulation, where there is direct interaction with adipose tissue (AT) to inhibit the rate of TAG lipolysis. An increased buffering capacity of AT would decrease the peripheral uptake of fatty acids (FA) into other insulin-sensitive tissues such as the liver, muscle and pancreas, with the potential to affect both ectopic fat storage and organ function.](https://example.com/fig3.png)
Adipogenesis and hormone-sensitive lipase phosphorylation of hormone-sensitive lipase (Hong et al. 2005).

SCFA also appear to stimulate fat accumulation in adipocytes, potentially by stimulating both PPARγ2 and the enzymes acetyl CoA carboxylase and fatty acid synthase (Lee & Hossner, 2002), which control the initial rate-limiting step in AT lipogenesis. If these findings are a true representation of what occurs in vivo in man, carbohydrate fermentation, via its effects on plasma levels of acetate and propionate, could increase fat deposition within AT and hence reduce ectopic fat depots. The physiological importance of these primarily animal-based in vitro studies remains to be determined, but it is clear that there is a need for more human-based investigation.

Effects of SCFA on body fat distribution

The role of ectopic fat distribution in the aetiology of insulin resistance is well accepted, and any factor that can affect the fatty acid-buffering capacity of AT could impact on TAG storage in non-adipose sites and hence body fat distribution. Despite the potential effects on the adipocyte mentioned previously, there is limited evidence for the effects of acetate or propionate on ectopic fat distribution. One reason is presumably the technological limitations in assessing fat depots in vivo. A number of animal studies have reported that feeding diets high in fermentable carbohydrate results in a change in body composition (Pawlak et al. 2004), with a decrease specifically in intra-hepatic lipid levels, as determined by magnetic resonance spectroscopy (PW So, WS Yu, AP Goldstone, JD Bell and GS Frost, unpublished results). However, these studies are confounded by changes in the relative glycaemic index of the test diets and so the results cannot be clearly interpreted as being a result only of fermentation or increased SCFA production.

Future directions

To the author’s knowledge, there have been no experiments designed specifically to assess the potential effects of carbohydrate fermentation on adipocyte size and fat distribution. As such, all the data currently available in this area are severely confounded by the effects of glycaemic index (Lerer-Metzger et al. 1996; Kabir et al. 1998a,b) on these variables. Well-designed studies, preferably in human subjects, are required to demonstrate definitively this link between the colon and AT metabolism in vivo.

Summary

There is a theoretical mechanism that could link the colon with insulin sensitivity via the production of SCFA. In simplistic terms, acetate and propionate have beneficial effects on AT metabolism, serving to lower plasma fatty acid release, increase fat deposition and, because of changes in adipogenesis, result in smaller adipocytes that release higher levels of leptin and adiponectin and lower levels of pro-inflammatory adipokines. The increased

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**Fig. 4.** Role of SCFA as ligands for adipocyte G-protein-coupled receptors (GPR) 41 and 43. AC, acetyl-CoA carboxylase.
buffering capacity of the subcutaneous AT results in less substrate competition with glucose, lower levels of fat oxidation and lower ectopic fat accumulation in tissues such as the liver, pancreas and muscle. Like all physiological systems, however, the specific interactions involved are far more complex. Unravelling these interactions will not only increase the understanding of the aetiology of insulin resistance itself, but in the future may allow the formulation of functional foods that could specifically change colonic fermentation, providing a potential strategy to decrease the risk or progression of chronic disease at a population level.

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