Influences of dietary adaption and source of resistant starch on short-chain fatty acids in the hindgut of rats.

Henningsson, Åsa; Nyman, Margareta; Björck, Inger

Published in:
British Journal of Nutrition

DOI:
10.1079/BJN2003782

2003

Link to publication

Citation for published version (APA):

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal

Take down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.
Influences of dietary adaptation and source of resistant starch on short-chain fatty acids in the hindgut of rats

Åsa M. Henningsson*, E. Margareta, G. L. Nyman and Inger M. E. Björck

Applied Nutrition and Food Chemistry, Center for Chemistry and Chemical Engineering, Lund University, P.O. Box 124, SE-221 00 Lund, Sweden

(Received 10 January 2002 – Revised 23 September 2002 – Accepted 17 October 2002)

The effect of adaptation time on the concentration and pattern of short-chain fatty acids (SCFA) formed in the hindgut of rats given resistant starch (RS) in the form of raw potato starch (RPS) or high-amylose maize starch (HAS) was evaluated. Each starchy material was tested in diets containing 100 g indigestible carbohydrates/kg DM, and fed for 13, 28 and 42 d. At the end of each period, the content of SCFA was determined in caecum, distal colon and faeces. The caecal concentration of total and individual SCFA increased for both diets with increasing adaptation time. The concentration of butyric acid was higher in the group fed RPS than in that fed HAS at all adaptation times. The caecal proportion of butyric acid was low both in rats fed RPS and HAS (6 and 4 %, respectively) following 13 d of adaptation. However, after 28 d of adaptation, the proportion of butyric acid had increased to 19 % in rats given RPS. A longer adaptation period (42 d) did not increase the proportion of butyric acid further. With HAS, there was also a significant (P<0.01) increase in the proportion of butyric acid with longer adaptation time. However, the increase was much slower and the proportion of butyric acid reached 6 and 8 % after 28 and 42 d respectively. It is concluded that the pattern of SCFA formed from RS in rats is dependent on adaptation time. It cannot be excluded that the different patterns of SCFA reported in the literature for RS may be due to the time of adaptation.

Resistant starch: Fermentation: Short-chain fatty acids: Butyric acid: Rats

Short-chain fatty acids (SCFA; mainly acetic, propionic and butyric acid) are formed during microbial fermentation of carbohydrates in the colon. There is increasing evidence that SCFA, especially butyric acid, play an essential role in the maintenance of the colonic mucosa. Butyric acid is the main energy substrate for the colonocytes (Roediger, 1982) and has been suggested to play a role in the prevention and treatment of diseases of the colonic mucosa, such as distal ulcerative colitis (Cummings, 1997) and cancer (Scheppach et al. 1995). A diminished oxidation of butyrate in the colonocytes has been suggested to contribute to the genesis of ulcerative colitis (Roediger, 1980) and enemas with butyric acid have been associated with reduced symptoms in patients with ulcerative colitis (Scheppach et al. 1992). Although butyric acid serves as the primary energy source for the normal colonic epithelium and stimulates growth of colonic mucosa, the growth of colon tumour cell lines has been reported to be obstructed by butyrate (Whitehead et al. 1986). Butyrate also appears to induce cell differentiation (Barnard & Warwick, 1993) and to stimulate apoptosis (Hague et al. 1995) in tumour cell lines.

Starches have been shown to produce high proportions of butyric acid by in vitro fermentation in human faecal inocula (Englyst et al. 1987; Weaver et al. 1992; Bradburn et al. 1993; Casterline et al. 1997). Starch that reaches the colon has also been shown to increase the faecal concentration of butyric acid in human subjects. Thus, administration of an α-amylase inhibitor, acarbose, resulted in a specific increase in faecal concentrations of butyric acid in normal subjects (Scheppach et al. 1988; Weaver et al. 1997). Further, when adding the resistant starch (RS) source high-amylose maize starch (HAS) to the diet, the faecal concentration (Phillips et al. 1995; Noakes et al. 1996) or daily excretion (van Munster et al. 1994) of butyric acid increased. However, of these studies, only the study by Noakes et al. (1996) showed an increase in the faecal proportion of butyric acid. In another study, different sources of RS, such as raw starch from potatoes and bananas and retrograded starch from wheat and maize, were given to normal subjects (Cummings et al. 1996). Of these substrates, only raw potato starch (RPS) gave an increased faecal proportion of butyric acid. However,
et al. (1995), whereas retrograded HAS required a longer intervention period (1 month; Brunsgaard et al. 1995), whereas retrograded HS has required a longer intervention period (1 month; Brunsgaard et al. 1995). Concerning the effect of adaptation time on the profiles of SCFA from RS, differing results have been obtained in rats. In rats fed RPS, the proportion of butyric acid in the caecum increased with time, from 13 to 28% following 0.5 and 6-0 months adaptation, respectively (Le Blay et al. 1999). In another study, however, no change in faecal patterns of SCFA was found in rats fed RPS or retrograded potato starch over a 5-month period (Kleessen et al. 1997).

Another factor that might influence fermentation characteristics is the adaptation time. With respect to dietary fibre, e.g. wheat bran, pectin, cellulose and guar gum, even a short adaptation time (between 5 and 7 d) appears to yield stable fermentation in rats as judged from determination of extent of fermentation (Nyman & Asp, 1985; Brunsgaard et al. 1995), whereas retrograded HS has required a longer intervention period (1 month; Brunsgaard et al. 1995). Concerning the effect of adaptation time on the profiles of SCFA from RS, differing results have been obtained in rats. In rats fed RPS, the proportion of butyric acid in the caecum increased with time, from 13 to 28% following 0.5 and 6-0 months adaptation, respectively (Le Blay et al. 1999). In another study, however, no change in faecal patterns of SCFA was found in rats fed RPS or retrograded potato starch over a 5-month period (Kleessen et al. 1997).

The aim of the present investigation was to study the pattern of SCFA formed during fermentation of two types of RS using a rat experimental model. The pattern of SCFA was measured at different sites along the hindgut, and the possible influence of the adaptation time was investigated. Ungelatinised crystalline starches rich in RS 2, RPS and HASg were chosen as substrates.

Materials and methods

Diets and animals

RPS (Lyckeby Stärkelsen AB, Kristianstad, Sweden) or HAS (Hi-maize®; Penford Australia, Lane Cove, New South Wales, Australia) was included into diets at a level of 100 g indigestible carbohydrates/kg DM. The composition of the test diets is listed in Table 1. The DM content of the diets was adjusted with wheat starch, a starch source that has been shown to be completely digested and absorbed in the small bowel of rats, and thus does not contribute to hindgut fermentation (Björck et al. 1987).

Males of Wistar rats (B&K Universal, Stockholm, Sweden) with an initial weight of 72 (SD 7) g were randomly divided into groups of seven. Rats used for the first 13 d of the study were housed individually in metabolism cages (Berggren et al. 1993). After 7 d of adaptation to the diet, a 5 d balance experiment followed when faeces were collected daily for determination of fermentation of RS and faecal dry weight. Faeces were kept at −20°C and then freeze-dried and milled before analysis of starch. The experimental diets were fed to the rats for another 24 h, and during this time fresh faeces were collected on dry ice for determination of the faecal excretion of SCFA (‘13 d’ in Tables 2, 3–5). Rats used for studying SCFA following 28 and 42 d of ingestion were kept singly in cages with wire-mesh floors. Faeces were collected the last 5 h of the experiment, frozen at −80°C and saved for analysis of the concentration of SCFA. To facilitate determination of fermentability, the feed intake was restricted to 12 g DM/d during the first 13 d. The feed during the longer adaptation was given to the rats ad libitum and found to be between 15 and 17 g DM/d (Table 2). At the end of the various adaptation periods, the animals were killed using CO2. The caecum and colon were removed immediately and the colon divided into a proximal and a distal part and then kept frozen (−80°C) until analysed for SCFA. The protocol of the animal experiment

Table 1. Composition of test diets (g/kg)

<table>
<thead>
<tr>
<th>Ingredient*</th>
<th>RPS</th>
<th>HAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPS</td>
<td>157</td>
<td>168</td>
</tr>
<tr>
<td>Wheat starch</td>
<td>515</td>
<td>504</td>
</tr>
<tr>
<td>Casein</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Sucrose</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Maize oil</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Mineral mixture†</td>
<td>48</td>
<td>48</td>
</tr>
<tr>
<td>Vitamin mixture†</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Choline chloride</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>DL-Methionine</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

* RS (Lyckeby Stärkelsen AB, Kristianstad, Sweden), HAS (Hi-maize®; Penford Australia, Lane Cove, New South Wales, Australia), wheat starch (Ceressta, Krefeld, Germany), casein (Sigma Chemical Company, St Louis, MO, USA), sucrose (Danisco Sugar, Malmö, Sweden), maize oil (Mazola; Bestfoods Nordic A/S, Copenhagen, Denmark), mineral mixture (Apoteket, Malmö, Sweden), vitamin mixture (Apoteket, Malmö, Sweden), choline chloride (Aldrich-Chemie, Steinheim, Germany), DL-methionine (Sigma Chemical Company).  
† Containing (g/kg): CuSO4·5H2O 0.37, ZnSO4·7H2O 1.40, KH2PO4 332.10, NaH2PO4·2H2O 171.80, CaCO3 324.40, KI 0.068, MgSO4 57.20, FeSO4·7H2O 7.70, MnSO4·H2O 3.40, CoCl2·6H2O 0.020, NaCl 101.70.  
‡ Containing (g/kg): menadione 0.00375, retinyl palmitate 0.0000375, retinyl palmitate 0.187, calciferol 0.00015, α-tocopherol acetate 25.00, maize starch 941.25.
was approved by the Ethics Committee for Animal Studies at Lund University.

**Analysis of starch**

An *in vitro* model (Åkerberg *et al.* 1998) was used for determination of RS in the test materials. Six human subjects performed simulated mastication using glass beads for 15 s and then rinsed their mouths with 5 ml water, and thereafter the saliva was pooled. Pooled saliva (5 ml) was transferred to a beaker containing the test product and water. The pH was adjusted to 1·5 and pepsin (Merck, Darmstadt, Germany) was added. Thereafter, the samples were incubated at 37°C for 30 min. The pH was adjusted to 5·0 after addition of pancreatin (Sigma Chemical Company, St Louis, MO, USA) and amyloglucosidase (Boehringer Mannheim, Mannheim, Germany). The suspension was incubated for 16 h at 40°C. Undigested starch was precipitated with ethanolic and adjusted to 1·5 and pepsin (Merck, Darmstadt, Germany) was added. Thereafter, the samples were incubated at 37°C for 30 min. The pH was adjusted to 5·0 after addition of pancreatin (Sigma Chemical Company, St Louis, MO, USA) and amyloglucosidase (Boehringer Mannheim, Mannheim, Germany). The suspension was incubated for 16 h at 40°C. Undigested starch was precipitated with ethano-

**Determination of short-chain fatty acids**

The amount of SCFA (acetic, propionic, isobutyric, butyric, isovaleric, valeric, caproic and heptanoic acid) and succinic acid in caecum and colon contents were analysed by a GLC method (Richardson *et al.* 1989). The intestine content was homogenised (Polytron®, Kinematica, Luzern, Switzerland) with 2-ethylbutyric acid (internal standard). HCl was added to protonise the SCFA, which were then extracted with diethyl ether and silylated with N-(tert-butyldimethylsi-
l)-N-methyl trifluoroacetamide (Sigma Chemical Company). The samples were allowed to stand for 48 h to complete derivatisation. Samples were analysed using GLC (HP 6890; Hewlett-Packard, Wilmington, DE, USA) equipped with an HP-5 column (Hewlett-Packard), and integrated by Chem Station software (Hewlett-Packard).

**Calculations and statistical evaluation**

The faecal excretion of RS (%) was calculated as the amount of starch found in faeces divided with the ingested amount of RS and multiplied by 100. The caecal pool of SCFA was calculated by multiplication of the concentration of SCFA in the caecum (mmol/kg) by the total weight of the caecal contents (kg). The faecal excretion of SCFA was calculated by multiplication of the concentration of SCFA in the faeces (mmol/kg) by the weight of faeces (kg) excreted during the last 24 h of the experiment (‘13 d’ in Tables 2, 4–5).

The proportion of butyric acid was calculated as the proportion of butyric acid of the three major SCFA (i.e. acetic, propionic and butyric acid) and this was calculated for each rat before statistical evaluation.

---

**Table 2. Feed intake, body-weight gain and caecal wet content in rats fed either raw potato starch (RPS) or high-amylose maize starch (HAS)**

(Mean values with their standard errors for seven rats per group)†

<table>
<thead>
<tr>
<th></th>
<th>RPS</th>
<th>HAS</th>
<th>RPS</th>
<th>HAS</th>
<th>RPS</th>
<th>HAS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean SEM</td>
<td>Mean SEM</td>
<td>Mean SEM</td>
<td>Mean SEM</td>
<td>Mean SEM</td>
<td>Mean SEM</td>
</tr>
<tr>
<td>Feed intake (g/d)</td>
<td>12·0 0·0</td>
<td>11·9 0·1</td>
<td>15·7 0·4</td>
<td>15·0 0·3</td>
<td>16·9 0·4</td>
<td>16·8 0·7</td>
</tr>
<tr>
<td>Body-weight gain (g/d)</td>
<td>3·5 0·1</td>
<td>3·7 0·1</td>
<td>5·5 0·2</td>
<td>5·3 0·2</td>
<td>5·1 0·2</td>
<td>5·2 0·3</td>
</tr>
<tr>
<td>Caecal wet content (g)</td>
<td>2·9*** 0·2</td>
<td>1·7 0·1</td>
<td>6·1* 0·6</td>
<td>4·7 0·3</td>
<td>7·1 0·5</td>
<td>6·5 0·5</td>
</tr>
</tbody>
</table>

Mean values were significantly different from those in the HAS group (one-way ANOVA): *P<0·05, ***P<0·001.
† For details of diets and procedures, see Table 1 and p. 320.

**Table 3. Faecal dry weight and fermentability of resistant starch (RS) in rats fed either raw potato starch (RPS) or high-amylose maize starch (HAS) following 12 d of ingestion**

(Mean values with their standard errors for seven rats per group)

<table>
<thead>
<tr>
<th></th>
<th>RPS</th>
<th>HAS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean SEM</td>
<td>Mean SEM</td>
</tr>
<tr>
<td>Faecal dry weight (g/d)</td>
<td>1·0*** 0·1</td>
<td>0·5 0·0</td>
</tr>
<tr>
<td>Fermentability of RS (%)</td>
<td>54·5*** 6·4</td>
<td>97·4 0·7</td>
</tr>
</tbody>
</table>

Mean values were significantly different from those in the HAS group (one-way ANOVA): ***P<0·001.
† For details of diets and procedures, see Table 1 and p. 320.
Table 4. Concentration (mmol/kg) of short-chain fatty acids in caecum, distal colon and faeces of rats fed a diet containing raw potato starch (RPS) or high-amylose maize starch (HAS) for 13, 28 or 42 d†

(Mean values with their standard errors for seven rats per group)

<table>
<thead>
<tr>
<th></th>
<th>13 d</th>
<th>28 d</th>
<th>42 d</th>
<th>Statistical significance of effect: P</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RPS</td>
<td>HAS</td>
<td>RPS</td>
<td>HAS</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>SEM</td>
<td>Mean</td>
<td>SEM</td>
</tr>
<tr>
<td>Caecum</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acetic</td>
<td>72.2</td>
<td>3.3</td>
<td>69.5</td>
<td>6.3</td>
</tr>
<tr>
<td>Propionic</td>
<td>12.6</td>
<td>1.4</td>
<td>12.6</td>
<td>1.2</td>
</tr>
<tr>
<td>Butyric</td>
<td>5.2**</td>
<td>0.2</td>
<td>3.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Total</td>
<td>102.8</td>
<td>4.1</td>
<td>95.1</td>
<td>7.3</td>
</tr>
<tr>
<td>Distal colon</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acetic</td>
<td>49.2</td>
<td>3.1</td>
<td>57.3</td>
<td>5.4</td>
</tr>
<tr>
<td>Propionic</td>
<td>6.8</td>
<td>1.2</td>
<td>7.4</td>
<td>1.2</td>
</tr>
<tr>
<td>Butyric</td>
<td>3.7</td>
<td>0.5</td>
<td>3.9</td>
<td>0.5</td>
</tr>
<tr>
<td>Total</td>
<td>69.8</td>
<td>3.5</td>
<td>80.3</td>
<td>6.5</td>
</tr>
<tr>
<td>Faeces</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acetic</td>
<td>48.9</td>
<td>2.6</td>
<td>57.3</td>
<td>5.2</td>
</tr>
<tr>
<td>Propionic</td>
<td>7.1</td>
<td>0.8</td>
<td>5.5</td>
<td>0.8</td>
</tr>
<tr>
<td>Butyric</td>
<td>4.0</td>
<td>0.7</td>
<td>3.2</td>
<td>0.5</td>
</tr>
<tr>
<td>Total</td>
<td>67.9</td>
<td>3.7</td>
<td>74.1</td>
<td>7.8</td>
</tr>
</tbody>
</table>

Mean values were significantly different from those in the HAS group (one-way ANOVA): *P<0.05, **P<0.01, ***P<0.001.
† For details of diets and procedures, see Table 1 and p. 320.
‡ Two-way ANOVA could not be performed, as some rats did not defecate during the sampling time.
All statistical analyses were performed with the Mini-
tab Statistical Software package (version 13.0; Minitab Inc., State College, PA, USA). In Tables 2 and 3, mean
values were analysed by one-way ANOVA using the Gen-
eral Linear Model procedure according to Minitab. In
Tables 4 and 5, mean values were analysed by two-way
ANOVA to assess the effects of diet, adaptation time and
interactions between the diet and time on the concentration
of SCFA in caecum and distal colon. The analysis was not
performed on faecal data because some values were miss-
ing. When significant differences were found, individual
means were analysed by one-way ANOVA to assess the
effects of diet at each adaptation time. The level of signifi-
cance was $P < 0.05$.

Results

RPS contained a higher amount of RS (640 g/kg DM) than
HAS (591 g/kg DM). Only HAS contained a measurable
amount of NSP (14 g/kg DM).

The rats tolerated both diets well and there was no
difference in feed intake or body weight gain between
the two diets during any of the intervention periods
(Table 2). However, ingestion of the RPS diet gave a
higher caecum wet weight than the HAS diet following
13 and 28 d of adaptation ($P < 0.05$). Further, the faecal
dry weight measured during the balance experiment was
twice as high for rats fed RPS than for those fed HAS
($P < 0.001$, Table 3). The two starches were fermented to
various extents. RS in HAS was almost completely fermen-
ted during the balance experiment, and only about 3.0%
of the ingested amount appeared in faeces. RS in RPS, on
the other hand, was considerably more resistant and 45.5%
appeared in faeces ($P < 0.001$).

The caecal concentration of SCFA increased with adap-
tation time in rats fed both substrates (Table 4). Further,
the concentration of SCFA was higher in caecum than in
distal colon or faeces, and this difference increased with
prolongation of the adaptation time. The two substrates
gave similar caecal concentrations of total SCFA, as well
as of acetic and propionic acid after all adaptation periods.
Butyric acid formation was, however, dependent on the
diet, and the caecal concentration was significantly higher
($P < 0.05$) in rats fed RPS than HAS during the entire
experiment. In the distal colon and faeces, the concen-
tration of total SCFA also generally increased with time.

Table 5. Total caecal pool and daily faecal excretion of short-chain fatty acids (SCFA) in rats fed a diet containing raw potato starch (RPS) or high-amylose maize starch (HAS) for 13, 28 or 42 d†

<table>
<thead>
<tr>
<th></th>
<th>13 d</th>
<th>28 d</th>
<th>42 d</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean SEM</td>
<td>Mean SEM</td>
<td>Mean SEM</td>
</tr>
<tr>
<td></td>
<td>RPS HAS</td>
<td>RPS HAS</td>
<td>RPS HAS</td>
</tr>
<tr>
<td><strong>Acetic</strong></td>
<td>207.3 18.0</td>
<td>119.8 13.2</td>
<td>952.0 106.0</td>
</tr>
<tr>
<td><strong>Propionic</strong></td>
<td>36.6 5.3</td>
<td>21.5 2.2</td>
<td>146.3 18.7</td>
</tr>
<tr>
<td><strong>Butyric</strong></td>
<td>15.6 1.5</td>
<td>18.6 2.2</td>
<td>201.5 21.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>295.0 24.1</td>
<td>163.6 15.5</td>
<td>1380.0 143.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>13 d</th>
<th>28 d</th>
<th>42 d</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean SEM</td>
<td>Mean SEM</td>
<td>Mean SEM</td>
</tr>
<tr>
<td><strong>Acetic</strong></td>
<td>199.0 10.2</td>
<td>59.4 8</td>
<td>–‡</td>
</tr>
<tr>
<td><strong>Propionic</strong></td>
<td>14.6 2.4</td>
<td>5.7 0.9</td>
<td>–‡</td>
</tr>
<tr>
<td><strong>Butyric</strong></td>
<td>8.4 1.8</td>
<td>3.4 0.7</td>
<td>–‡</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>137.8 14.8</td>
<td>76.7 10</td>
<td>–‡</td>
</tr>
</tbody>
</table>

Mean values were significantly different from those in the HAS group (one-way ANOVA): *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.
†For details of diets and procedures, see Table 1 and p. 320.
‡Faecal SCFA excretions were not measured after 28 and 42 d.

Resistant starch and short-chain fatty acids
The molar proportion of butyric acid in the caecum was low with both RPS (6%) and HAS (4%) after 13 d of adaptation (Fig 1). In rats given RPS, the proportion of butyric acid increased significantly to 19% after 28 d of adaptation ($P=0.0017$). A longer adaptation (42 d) did not affect this proportion further. The pattern of SCFA formed in rats fed HAS was also affected by adaptation time, but the increase in the proportion of butyric acid was slower and reached 8% after 42 d ($P=0.0023$). Similar trends were found also for the proportion of butyric acid in distal colon and faeces (Fig. 1).

**Discussion**

Two sources of native RS were used to study the potential effect of adaptation time on the concentration and pattern of SCFA in the hindgut of rats. The rat model used has been shown to correlate well with human experiments with respect to total fermentation of dietary fibre (Nyman et al. 1986). Concerning the formation of SCFA, *in vitro* incubations with human and rat faeces have been found to give similar profiles from both dietary fibre (Lupton & Villalba, 1988; Barry et al. 1995) and starch (Wyatt & Horn, 1988) and the rat therefore seems to be useful for comparisons of patterns of SCFA formed from different carbohydrate substrates. However, previous studies on rats have indicated that the pattern of SCFA formed from RS may vary due to the length of the feeding time (Le Blay et al. 1999). This is important from a methodological point of view, to enable valid comparisons of potential differences in the formation of SCFA from various carbohydrate substrates.

The fermentation of the RS in HAS was very high and of the same magnitude as in previous studies in rats (Schulz et al. 1993; De Schrijver et al. 1999). RPS was more resistant to fermentation, which has been demonstrated previously (Berggren et al. 1995). Accordingly, the faecal dry weight was higher for rats fed RPS than those given HAS. In spite of higher fermentation of HAS, the rats fed this substrate generally had lower caecal pools of SCFA and lower faecal excretions of SCFA than those fed RPS. Similarly, others have reported lower caecal pools of SCFA in combination with lower faecal weights in rats fed HAS, than rats fed RPS (de Dekere et al. 1995; Ferguson et al. 2000). In these studies, the analysed RS in the substrates were of the same magnitude as in the present investigation (618–650 and 650–670 g/kg for HAS and RPS respectively) and RS was added to yield a level of about 140 (de Dekere et al. 1995) or about 222 (Ferguson et al. 2000) g/kg in the diet. These results suggest that RS may differ in fermentation characteristics and SCFA production depending on origin. The *in vitro* model for RS determination, used in the present study, has been demonstrated to yield RS contents in agreement with literature results obtained in the ileostomy model for several food products (Akerberg et al. 1998). However, it cannot be excluded that the differences in SCFA formation from fermentation of HAS and RPS respectively may have emanated from erroneous estimation of the true amount of starch delivered to the rat hindgut.

After a short adaptation (13 d), both starch sources gave similar patterns of SCFA, with low caecal and faecal proportions of butyric acid. The proportion of butyric acid increased with prolongation of the adaptation time with both substrates. However, the increase in the proportion of butyric acid was faster in rats given RPS than in those given HAS and after 28 and 42 d of adaptation, the butyric acid formation was shown to be promoted by RPS. This result is in agreement with previous studies by Le Blay et al. (1999), where the caecal proportion of butyric acid increased with adaptation time in rats fed RPS. It is noteworthy that RPS also caused bloating in the colon.

**Fig. 1.** Proportion of butyric acid (%) in caecum (●), distal colon (■) and faeces (▲) of rats given raw potato starch and in caecum (○), distal colon (□) and faeces (▲) of rats given high-amylose maize starch (HAS), following different adaptation times. For details of diets and procedures, see Table 1 and p. 320. Values are means for seven rats per group with standard errors shown by vertical bars. Mean values were significantly different from those in the HAS group at the same adaptation time (one-way ANOVA): *P<0.05, **P<0.01, ***P<0.001.
following 28 and 42 d of adaptation, a phenomenon that not could be seen with HAS or with RPS after 13 d of adaptation. Bloating is caused by production of H₂ and CO₂ during fermentation by some specific bacterial strains. Interestingly, studies in human subjects have shown that RPS may produce higher amounts of breath H₂ than HAS (Olesen et al. 1992). Various bacterial species are known to use different fermentation pathways (Moore & Holdeman, 1974; Holdeman et al. 1977), and an explanation of the differences in the pattern of SCFA formed and gas production between starches could be that different micro-organisms are involved during the fermentation. Different bacterial strains have also been shown to be involved in the degradation of amylopectin and amylose in in vitro studies (Wang et al. 1999). The two starches differ regarding the granule structure and amylose:amylopectin ratio. Potato starch in its native form exists as relatively large spherical or ellipsoid granules (Gallant et al. 1992) and has a low amylose:amylopectin ratio (0.25). Instead, HAS granules are small and can be both polyhedral and irregular with a higher amylose:amylopectin ratio (4.00). Possibly these differences in physico-chemical properties affect the type of micro-organisms involved in fermentation and in the production of SCFA.

With HAS, the increase in the proportion of butyric acid with adaptation time was less significant. However, it cannot be excluded that the butyric acid formation with the two substrates would be similar if adaptation were prolonged. Thus, the discrepancy in literature regarding butyric acid formation from RS in rat models (Mallett et al. 1988; Gee et al. 1991; Berggren et al. 1995; Monsma & Marlett, 1995) might be explained partly by the fact that various starches, when fed as individual substrates, are affected differently by the length of the adaptation time. It may be hypothesised that the length of the intervention period may influence the pattern of SCFA formed from RS also in studies on human subjects. Another factor that has been reported to affect the pattern of SCFA formed from RS is the level of RS in the diet (Mathers et al. 1997).

As butyric acid has been shown to inhibit growth of colon cancer cells in vitro (Whitehead et al. 1996) and stimulate apoptosis (Hague et al. 1995), RS (by its ability to promote butyric acid production) has been suggested to protect against colon cancer (Hylla et al. 1998). Further, epidemiological studies have shown a strong correlation between a high intake of dietary starch and a low incidence of colo-rectal cancer, whereas no significant relationship has been found between NSP and colon cancer (Cassidy et al. 1994). However, in studies investigating the effect of RS and cancer prevention using rodent models, varying results have been obtained. Thus, when intestinal cancer was induced by azoxymethane in rats, both HAS (Caderni et al. 1994) and RPS (Thorup et al. 1995) were observed to be protective. In contrast with these results, RPS enhanced tumourogenesis (Young et al. 1996), whereas no effect of this starch was noted in the investigation by Sakamoto et al. (1996). Of the reports mentioned earlier, only the study by Sakamoto et al. (1996) specified the SCFA produced from RS. In that study, the butyric acid concentration in the distal part of the colon did not differ from the basal group. Recently, Perrin et al. (2001) found that only dietary fibres promoting a high and stable butyric acid production in the rat hindgut decreased the rate of aberrant crypt foci in rats. It thus appears as if evaluation of butyric acid formation from various starches is important in relation to colon diseases. In this context, it is interesting to note that RPS generally gave higher concentrations of butyric acid.

In conclusion, the present study shows that the proportion of butyric acid formed in rats fed RS, in the form of RPS and HAS, increases with increasing length of adaptation time. However, the increase in the proportion of butyric acid with RPS was faster than with HAS. The impact of adaptation time may explain the different patterns of SCFA for RS reported in the literature. More studies are needed in order to establish steady-state conditions with respect to patterns of SCFA formed from different RS substrates. Potential differences in butyric acid production between different RS sources are important to evaluate, as butyric acid has been suggested to protect against diseases of the colon mucosa, such as distal ulcerative colitis and cancer.

Acknowledgements

This work was made possible by financial support from the Swedish Foundation for Strategic Research through the LiFT Programme.

References


