Effects of Soluble Dietary Fibers on Lipid Metabolism and Activities of Intestinal Disaccharidases in Rats

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(Received December 17, 1998)

Summary The present study was aimed to investigate the effects of indigestible dextrin and polydextrose, soluble dietary fibers with low molecular weight, on lipid metabolism and disaccharidase activities of intestinal mucosa in rats fed a high sucrose diet. Their effects were compared with those of well-known soluble fibers, pectin, and guar gum, and also with an insoluble fiber, cellulose. Dietary fibers added to diets at the 5% (w/w) level were α-cellulose, pectin, guar gum, indigestible dextrin, and polydextrose. Male Sprague-Dawley rats were given free access to test diets for 6 weeks. Body weight gain was the lowest in rats fed guar gum, the highest in rats fed cellulose, and in-between in rats fed other diets. Although guar gum, pectin, and indigestible feeding dextrin had lower plasma lipid values than cellulose feeding did, the differences were statistically insignificant. Liver triglyceride of the guar gum-fed group was about a third that of the cellulose-fed group, but although those of rats fed polydextrose, indigestible dextrin, and pectin were lower than that of cellulose, the differences were insignificant. Liver cholesterol and phospholipid concentrations were similar among groups. Daily fecal excretion of total lipid, cholesterol, and bile acids were highest in rats fed guar gum, followed by pectin-fed and cellulose-fed rats, and the lowest in rats fed indigestible dextrin and polydextrose. Jejunal sucrase activity was low in the order of guar-gum, polydextrose, indigestible dextrin, pectin, and cellulose. The results indicate that the hypolipidemic effect of soluble dietary fibers would be lessened with reduction in molecular weight, but that the lower sucrase activity by soluble fibers with low molecular weight might be beneficial for hypoglycemic effect.

Key Words dietary fiber, hypolipidemic effect, bile acid, disaccharidase

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Numerous studies indicated hypolipidemic functions of soluble dietary fibers (1). The suggested mechanisms of actions were as follows: Their ability to elevate the viscosity in the small intestine, thus depressing lipid absorption, and their bile acid binding capacity, which increases the catabolism of cholesterol through conversion to bile acids in the liver. Moreover, soluble fibers are fermented by microflora in the large intestine, and propionate, one of the fermented products, may inhibit the synthesis of cholesterol in the liver (2, 3). Dietary fibers may also affect the lipid metabolism in the liver and peripheral tissues by modifying the secretion of gastrointestinal hormones, insulin, and glucagon, as suggested by Albrink et al (4).

Soluble dietary fibers act like a sponge, binding water, nutrients, bile acids, and carcinogens as they pass along the gastrointestinal tract, which is their primary site of action. However, simply characterizing dietary fibers as soluble or insoluble in water is not sufficient to explain their physiological effects (5). Other physicochemical properties of dietary fibers affect their various physiological functions. Properties such as viscosity, water-holding capacity, bile acid binding ability, particle size, and microbial degradation are better predictors of physiological function (5, 6). The water-holding capacity of dietary fibers is influenced by the particle size, chemical composition, and structure of the fibers (6, 7). A reduction of particle size to 180 μm, from 800 μm, decreased the water-holding capacity of wheat bran fiber by 41% (7). For a polysaccharide to become viscous in the gut, it must have a high solubility and water-holding capacity (5). The viscosity generated by soluble polysaccharides in solution is dependent on the number of disordered coils and their sizes. Roughly, the doubling of either the concentration or the molecular weight will increase viscosity by about a factor of 10 (8).

Pectin (mol. wt. 20,000–400,000) and guar gum (mol. wt. 220,000), which are gel-forming or viscous fibers, act like ion exchangers and can adsorb bile acids and increase fecal bile salt excretion. They are very effective in decreasing total serum cholesterol levels, as reflected from 77 human studies (1). Polydextrose and indigestible dextrin, which can be used as a low-energy bulking agent, have low molecular weights, about 1,500 and 1,600, respectively. Although they are used extensively for dietary fiber beverages because of high solubility and relatively low viscosity in water, their hypolipidemic effects are not fully confirmed (9–12).

The present study was aimed to investigate the effects of soluble dietary fibers with low molecular weight on lipid metabolism and the disaccharidase activities of intestinal mucosa in rats fed a high-sucrose diet. Their effects were compared with those of well-known soluble fibers such as pectin and guar gum, and also with an insoluble fiber, cellulose.

MATERIALS AND METHODS

Male Sprague-Dawley rats (Experimental Animal Management Division, National Institute of Health, Seoul, Korea) weighing about 150 g were acclimated...
Table 1. Composition of diets (%).

| Ingredients         | CC  | PT  | GG  | ID  | PD  |
|---------------------|-----|-----|-----|-----|-----|
| Casein              | 20  | 20  | 20  | 20  | 20  |
| dL-Methionine       | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| Sucrose             | 40.5| 40.5| 40.5| 40.5| 40.5|
| Cornstarch          | 10  | 10  | 10  | 10  | 10  |
| Lard                | 9.5 | 9.5 | 9.5 | 9.5 | 9.5 |
| Soybean oil         | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 |
| AIN mineral mix     | 3.5 | 3.5 | 3.5 | 3.5 | 3.5 |
| AIN vitamin mix     | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Choline bitartarate | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Dextrin             | 5   | 5   | 5   | 3.8 | 4.5 |
| Fiber\(^1\)         | 5   | 5   | 5   | 6.2 | 5.5 |

CC: α-cellulose; PT: pectin; GG: guar gum; ID: indigestible dextrin; PD: polydextrose.

\(^1\) Amounts of fiber ingredients were adjusted for 5% (w/w) fiber.

to the facility for 1 week. The 50 rats were grouped by stratified allocation based on body weight, and they were given free access to test diets and water for 6 weeks. Food intake was measured daily and body weight once a week; feces were collected daily during the last 2 weeks and kept frozen at \(-20^\circ\text{C}\). The experiment was done appropriately under the guidelines of animal experiments provided by Taegu University.

Diets. Table 1 represents the composition of test diets, which is based on AIN-76 diet \((13)\). The diets consisted of 55.5% carbohydrate, including 40.5% sucrose; 14.5% fat (30% of total energy); and 20% casein by weight. Dietary fibers added to diets at the 5% (w/w) level were α-cellulose, pectin, guar gum, indigestible dextrin, and polydextrose. Cellulose, pectin, and guar gum were purchased from Sigma Chemical (St. Louis, Mo., USA), indigestible dextrin from Matsutani Chemical Industry (Japan), and polydextrose from A. E. Staley Manufacturing (Ill., USA). Casein and vitamin and mineral mixtures were purchased from Teklad Test Diets (Madison, WI, USA), and dL-methionine, dextrin, and choline bitartrate were obtained from Sigma Chemical.

Tissue sampling. After fasting overnight, the rats were anesthetized by inhaling diethyl ether, and blood was withdrawn by heart puncture into a syringe containing heparin solution. The abdomen was opened, the liver excised, and the small bowel stripped away from its mesentry from the ligament of Treitz to the ileocecal valve. A proximal 5 cm segment of jejunum was resected from a 1/3 point of total length of the bowel. The segment was washed with cold saline and blotted with tissue, the mucosa was scraped between two slide glasses, and the mucosa was weighed and
stored at −60°C.

*Measurements of lipids and bile acid.* Plasma cholesterol was measured by using a cholesterol esterase-cholesterol oxidase assay (Iatron Lab, Japan), and HDL cholesterol was measured the same as total cholesterol after precipitation of LDL and VLDL by phosphotungstate and Mg$^{2+}$. Plasma triglyceride was determined by hydrolyzing triglycerides measuring the released glycerol (Iatron Lab). Hepatic lipids were extracted by the method of Folch et al (14). Cholesterol (15) and phospholipid (16) were measured colorimetrically, and triglyceride was measured by using the enzymatic kit (Iatron Lab) by the aid of a detergent, triton x-100 (17). Lipids were extracted from dry feces by Folch et al (14), the extract was filtered through a 0.45 μm filter (Millipore), and the solvent was dried and the residue weighed. Bile acid from feces was extracted by the method of Crowell and Macdonald (18) and determined by using the enzymatic kit (Sigma).

*Assay of intestinal disaccharidase activities.* Disaccharidases were assayed within 3 months after storage. Mucosa was thawed and homogenized with 20 times volume of distilled water. An aliquot of mucosa homogenate was assayed by the method of Dahlqvist (19). Activities of maltase and sucrase were assayed by using maltose and sucrose as substrates. One micromole of glucose produced per minute was 1 unit of disaccharidase activity, and the activity was expressed as units/cm intestine and units/g protein (specific activity). Protein was determined by the Lowry method (20), using bovine serum albumin as a standard.

*Statistical analysis.* Group means were compared by the Duncan’s multiple range test after the preliminary analysis of variance (ANOVA), and the differences were considered statistically significant at $p<0.05$.

**RESULTS AND DISCUSSION**

*Effects of diets on animals*

As shown in Table 2, body weight gain was the lowest in rats fed guar gum,

Table 2. Body weight gain, feed efficiency, and relative liver weight.

|                      | Initial body weight (g) | Body weight gain (g/6 weeks) | Feed efficiency (g/100 g diet) | Relative liver weight (g/100 body weight) |
|----------------------|-------------------------|------------------------------|---------------------------------|------------------------------------------|
| Cellulose            | 225 ± 26                | 223 ± 34*                   | 24.2 ± 1.10                     | 2.65 ± 0.24                              |
| Pectin               | 221 ± 20                | 202 ± 30*                   | 22.6 ± 3.40                     | 2.65 ± 0.29                              |
| Guar gum             | 229 ± 25                | 173 ± 50*                   | 20.5 ± 5.26                     | 2.79 ± 0.27                              |
| Indigestible dextrin | 220 ± 26                | 209 ± 51*                   | 23.0 ± 4.05                     | 2.65 ± 0.22                              |
| Polydextrose         | 226 ± 20                | 191 ± 63*                   | 20.8 ± 5.78                     | 2.80 ± 0.19                              |

Mean ± SD of 8–10 rats per group.

Values in the same column not sharing common superscript letters were significantly different at $p<0.05$ by Duncan’s multiple-range test.

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Table 3. Plasma total cholesterol, triglyceride, and HDL cholesterol.

|                  | Total cholesterol (mmol/L) | Triglyceride | HDL cholesterol |
|------------------|----------------------------|--------------|-----------------|
| Cellulose        | 1.33 ± 0.34<sup>ab</sup>   | 0.85 ± 0.30<sup>ab</sup> | 0.68 ± 0.20     |
| Pectin           | 1.26 ± 0.25<sup>ab</sup>   | 0.73 ± 0.25<sup>ab</sup> | 0.70 ± 0.16     |
| Guar gum         | 1.11 ± 0.27<sup>b</sup>    | 0.57 ± 0.13<sup>b</sup> | 0.63 ± 0.12     |
| Indigestible dextrin | 1.23 ± 0.21<sup>ab</sup> | 0.65 ± 0.18<sup>ab</sup> | 0.68 ± 0.18     |
| Polydextrose     | 1.44 ± 0.43<sup>a</sup>    | 0.89 ± 0.43<sup>a</sup> | 0.64 ± 0.24     |

Mean ± SD of 8–10 rats per group.
Values in the same column not sharing common superscript letters were significantly different at p < 0.05 by Duncan’s multiple-range test.

the highest in rats fed cellulose diet, and in-between in rats fed other diets. Feed efficiency was low in rats fed guar gum and polydextrose, but the differences were not significant. Liver weights divided by body weights were not significantly different among groups.

Rats fed indigestible dextrin and polydextrose at the 5% (w/w) of diet experienced rather soft feces through a 6-week experimental period, and it was more pronounced with polydextrose. This phenomenon was supported by the observation reported by Oku et al, where a diet containing 5% polydextrose induced diarrhea in rats (12).

**Effects of diets on plasma and liver lipids**

The exact mechanism by which water-soluble fibers exert hypocholesterolemic effects have not been elucidated. Dietary fiber may retard the absorption of lipids by the enhancement of digest viscosity or physical trapping with particles or by sequestering either the bile acids necessary for the formation of lipid micelles or the micelles themselves (8). The molecular weight of dietary fiber is closely related with the viscosity of dietary fiber (8). The average molecular weight and viscosity of indigestible dextrin and polydextrose are lower than those of pectin and guar gum. Therefore the effects on the intestinal absorption of triglyceride and cholesterol and consequently on plasma and liver lipids would differ because of fiber sources.

As shown in Table 3, although rats fed polydextrose and indigestible dextrin had higher plasma total cholesterol and triglyceride than guar gum-fed rats did, no difference was found between them and cellulose-fed rats. There was no difference in HDL levels among groups. Hepatic lipid concentrations are shown in Table 4. Liver cholesterol and phospholipid concentrations were not significantly different among groups. The hepatic level of triglyceride of guar gum was about a third that of the cellulose group. Although the triglyceride levels of rats fed polydextrose, indigestible dextrin, and pectin were lower than those of the cellulose group, the differences were not statistically significant. Our results showed trends similar to
Table 4. Hepatic concentrations of cholesterol, triglyceride, and phospholipid.

|                | Cholesterol (μmol/g liver) | Triglyceride (μmol/g liver) | Phospholipid (μmol/g liver) |
|----------------|---------------------------|----------------------------|-----------------------------|
| Cellulose      | 62.5 ± 17.6               | 10.1 ± 9.8a                | 47.4 ± 14.5                 |
| Pectin         | 51.2 ± 35.9               | 6.20 ± 6.37aβ             | 47.7 ± 12.7                 |
| Guar gum       | 51.5 ± 33.4               | 3.03 ± 1.94b              | 46.1 ± 11.6                 |
| Indigestible dextrin | 60.8 ± 34.4          | 4.98 ± 3.34ab             | 48.3 ± 11.4                 |
| Polydextrose   | 61.0 ± 29.2               | 4.90 ± 5.42ab             | 48.9 ± 7.1                  |

Mean ± SD of 8–10 rats per group.
Values in the same column not sharing common superscript letters were significantly different at p < 0.05 by Duncan’s multiple-range test.

Table 5. Daily excretion of fecal lipids and bile acids.

|                | Total lipids (mg/d) | Cholesterol (mg/d) | Bile acids (mg/d) |
|----------------|---------------------|---------------------|-------------------|
| Cellulose      | 73.3 ± 32.5bc       | 3.55 ± 1.42b        | 39.1 ± 25.2a      |
| Pectin         | 99.7 ± 32.8b        | 4.20 ± 2.18ab       | 49.2 ± 26.2a      |
| Guar gum       | 161 ± 20.8a         | 4.97 ± 1.50a        | 64.4 ± 39.1a      |
| Indigestible dextrin | 55.0 ± 43.5cd     | 2.09 ± 0.92c        | 13.4 ± 4.9b       |
| Polydextrose   | 41.1 ± 23.0d        | 1.51 ± 0.57c        | 7.1 ± 2.5b        |

Mean ± SD of 8–10 rats per group.
Values in the same column not sharing common superscript letters were significantly different at p < 0.05 by Duncan’s multiple-range test.

those reported by others (11, 12). In a previous study, indigestible dextrin had a lower serum total cholesterol and HDL-cholesterol in comparison with corn fiber and a similar level in comparison with pectin (11). Another study showed no difference on serum lipids between polydextrose and other dietary fibers such as pectin and cellulose (12).

Effects of diets on fecal excretions of lipids and bile acids

As shown in Table 5, the daily excreted amounts of total lipids, cholesterol, and bile acids in feces were in the order of guar gum, pectin, cellulose, indigestible dextrin, and polydextrose. Although soluble fibers with high molecular weight seem to be more effective in fecal excretion of lipids and bile acid than cellulose does, soluble fibers with low molecular weight were less effective than cellulose. According to the report by Kishimoto et al (11), the daily excretion of bile acid in rats fed indigestible dextrin was lower than in those fed corn fiber.

Cellulose, an insoluble fiber, stimulates the motor activities of alimentary tracts and reduces the transit time of meals; it has a bulking effect on feces. On the other
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Table 6. Disaccharidase activities of small intestinal mucosa.

|                | Maltase (units/cm) | Maltase (units/g protein) | Sucrase (units/cm) | Sucrase (units/g protein) |
|----------------|-------------------|--------------------------|--------------------|--------------------------|
| Cellulose      | 2.27 ± 0.42<sup>ab</sup> | 405 ± 231               | 4.68 ± 1.12<sup>a</sup> | 769 ± 220<sup>a</sup>   |
| Pectin         | 2.58 ± 0.57<sup>ab</sup> | 399 ± 105               | 4.17 ± 1.33<sup>ab</sup> | 630 ± 186<sup>ab</sup>   |
| Guar gum       | 2.83 ± 0.93<sup>a</sup>  | 365 ± 163               | 3.18 ± 0.85<sup>b</sup>  | 410 ± 145<sup>c</sup>   |
| Indigestible dextrin | 2.16 ± 0.53<sup>b</sup>  | 316 ± 103               | 3.68 ± 1.03<sup>ab</sup>  | 531 ± 156<sup>bc</sup>   |
| Polydextrose   | 2.24 ± 0.32<sup>ab</sup>  | 371 ± 142               | 3.31 ± 1.00<sup>b</sup>  | 530 ± 188<sup>bc</sup>   |

Mean ± SD of 8–10 rats per group.

Values in the same column not sharing common superscript letters were significantly different at p < 0.05 by Duncan’s multiple-range test.

hand, soluble fibers such as pectin and guar gum with high water-holding capacity result in an increased viscosity of gastrointestinal contents and an increased binding of bile acids. In turn, they slow gastric emptying and the digestion and absorption of nutrients, and they influence the microbial breakdown of fiber. All these effects are known to give hypoglycemic and hypolipidemic effects of soluble fibers (21). Therefore it is concluded that the hypolipidemic effects of soluble fibers with low molecular weight such as indigestible dextrin and polydextrose were not as effective as guar gum or pectin were, probably a result of low viscosity.

Effects of diets on the activities of maltase and sucrase of intestinal mucosa

Table 6 shows total activity (units/cm jejunal intestines) and specific activity (units/g protein) of maltase and sucrase of intestinal mucosa. Sucrase activity, which was greater than maltase activity, could be due to the induction of sucrase because rats were fed sucrose at the level of 40.5% of their diet. The feeding of specific carbohydrates or carbohydrate-rich diets increases the amount of disaccharidases in the brush border, and in some cases even the specific activity of the enzyme. Thus the feeding of increased amounts of sucrose increases sucrase activity by de novo synthesis (22). In humans, high dietary intakes of sucrose and fructose, but not glucose, increase sucrase and maltase activities, but not lactase activity (23).

Jejunal maltase activity (units/cm intestine) of rats fed cellulose, indigestible dextrin, and polydextrose was relatively lower than in rats fed pectin and guar gum. However, the specific activity of maltase was not significantly different among groups. Jejunal sucrase activity (units/cm intestine) was significantly lower in the groups of guar gum and polydextrose than in the cellulose group, and it tended to be low in the groups of indigestible dextrin and pectin in comparison with the cellulose group. The specific activity of sucrase was lowest in the guar gum group, followed by the groups of indigestible dextrin and polydextrose. Wakabayashi et al (24) also observed a lower sucrase activity in small intestines of rats fed indigestible
dextrin than in rats fed no fiber, pectin, or corn fiber.

Oku et al (12) reported that polydextrose did not affect the activity of sucrase, maltase, or isomaltase in the in vitro assay system. That means the decreased activity was not due to polydextrose itself, but rather to the long-term effect of dietary fiber on intestinal mucosal cells. It was suggested by Yoshioka et al (25) that dietary polydextrose and guar gum acutely lowered the absorptive function in the small intestine before adaptation to the diet occurred. They observed that polydextrose and guar gum affected passive or active carrier-mediated transport rate acutely in comparison with cellulose, but long-term feeding of these dietary fibers negated the difference.

Maltase and sucrase serve as villus cell marker enzymes (26). Some studies have indicated that insoluble dietary fibers such as cellulose and bran have no effect on brush-border enzymes, and the effects of soluble dietary fibers such as pectin are less straightforward and often contradictory (27). According to the work of Calvert et al (28), the total and specific activities of sucrase in the proximal small intestine were similar among cellulose, pectin, and guar gum. Farness and Schneeman (29) evaluated the effect of oat bran and cellulose (20% of the diet) and pectin (5% of the diet) on sucrase activity in the rat small intestine mucosa and found that neither pectin nor cellulose altered sucrase activity. Thomsen and Tasman-Jones (30) investigated the effect of pectin (5%) and cellulose (10%) on jejunal lactase, sucrase, and maltase and found that pectin decreased lactase and sucrase activities, but that cellulose had no effect. In the present study, we observed that the total and specific activities of sucrase of the pectin group were similar to those of the cellulose group and somewhat higher than those of other dietary fiber groups.

In consideration of lowered sucrase activities as a result of the subjects being fed guar gum, indigestible dextrin, and polydextrose in comparison with cellulose feeding, it is possible that sucrose would be hydrolyzed at a slower rate, which may contribute to lower postprandial serum glucose and insulin concentration.

We thank the Hyundai Pharmaceutical Company, Korea, for its support in the accomplishment of this study.

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