Original Article

Faecal bulking index: A physiological basis for dietary management of bulk in the distal colon

John A Monro BSc(Hons), PhD, MA

Food Industry Science Centre, New Zealand Institute for Crop and Food Research, Palmerston North, New Zealand

Bulk in the distal colon provides protection against a range of large bowel disorders, but a simple standardized measure of the relative bulking efficacy of foods, for use in dietary management of distal colonic bulk, has not been available. This paper describes a faecal bulking index (FBI) for standardized measurement of the relative colonic bulking efficacy of foods relative to a reference material. Faecal bulking index is defined as the mass of fully rehydrated faecal matter accumulated by the distal colon per gram of a food consumed, as a percentage of the matter accumulated from the same weight of a reference food. The FBI of foods was measured after feeding adult rats at moderate levels by partially or completely replacing sucrose in a baseline diet already containing mixed dietary fiber. Faeces were collected, dried, weighed, allowed to imbibe water until fully rehydrated, reweighed and their mass and water holding capacity measured. The FBI was calculated as the increase over baseline in rehydrated faecal mass induced by a test food as a percentage of the increase due to wheat bran (reference). The FBI values were measured for 69 diets including breakfast cereals, breads and other bakery products, fruits, vegetables, food ingredients and polysaccharides. Values for most foods ranged between almost zero for some starch-based foods to about 50 for wheat bran-enriched breakfast cereals, but laxatives based on fermentation-resistant hydrated polysaccharide had FBI values well in excess of 100 (FBI for psyllium = 500). The FBI values allow foods to be ranked according to their faecal bulking efficacy on an equal edible weight basis. They can also be used to calculate the bulking action of any amount of food in terms of equivalents to a reference material such as wheat bran. Wheat bran equivalents allow the cumulative intake of potential distal colonic bulk to be monitored for single foods or mixed meals, and shortfalls to be quantified for dietary modification or supplementation. Measures such as FBI or wheat bran equivalents would prove more useful than dietary fiber in controlling 'functional foods' promoted as effective bulking agents.

Key words: distal colon, faecal bulk, water-holding capacity, wheat bran equivalents.

Introduction

Bulk in the distal colon is generally accepted as essential to maintenance of large bowel health.[1,2] It has a number of direct positive effects including distribution of intracolonic pressure, stimulation of defecation, dilution of toxins and other indirect benefits from the fermentation that such bulk usually supports when it is derived from plant material in the diet.[3] Low stool weights are correlated with constipation, diverticulosis and increase in a range of risk factors for colorectal cancer.[4,5] Faecal bulk has been shown to be a potent index of colon cancer risk in the Australian population.[6] It is one of the most important factors preventing constipation, which is widespread in the fiber-depleted, sedentary and ageing populations typical of most developed countries today, and for this reason alone the development of data sets for managing colonic bulk deserve attention

Despite the importance of bulking efficacy of foods, a standardized measure of it for use in food selection has not been available. Most previous work on colonic bulk has focused on the role and effects of dietary fiber on faecal bulk.[7] Dietary fiber content is at present the only indicator available to guide consumer choice of foods for faecal bulk, but it cannot do so with any reliability because fibers vary in their resistance to fermentation and in their water-holding capacity,[4,5] and large quantities of material other than dietary fiber enter the colon.[8,9] Dietary fiber is seldom eaten apart from the food matrix in which is immersed, and it varies in quantity and characteristics from food to food, making it difficult for consumers to use as a basis for predicting effects of a food on their large bowel contents, especially when they must deal with whole foods and in everyday quantities such as cups and spoons.

With the development and marketing of foods containing so-called functional ingredients, there is an increasing need for manufacturers and consumers to be able to assess the degree to which properties of foods such as bulking capacity are expressed, because quantity of a component is often a poor indicator of the amount of *in vivo* effect that it will induce. A measure of the relative capacity of foods to contribute bulk to the distal colon would allow direct comparison of whole foods against a familiar standard, and would be far more useful in dietary management of colonic bulk than fiber content.

The relative impact of foods on colonic bulk would be best measured using a standardized *in vivo* model that can economically mimic the complexity of the human colon, in which the effects of a food on its contents are influenced by

Correspondence address: Dr John A Monro, Nutrition and Health Team, New Zealand Institute for Crop & Food Research, Private Bag 11 600, Palmerston North, New Zealand.
Tel: 64 6356 8300; Fax: 64 6351 7050
Email: monroj@crop.cri.nz
Accepted 29 February 2000

the overall composition of the diet, rather than by a single food component such as dietary fiber. Distal colonic bulk is an emergent property of whole foods interacting with the gut, and is the net result of many interdependent processes including digestion, endogenous secretion, fermentation of non-digested food residues and endogenous secretions, bacterial growth, secretion and absorption by the hind gut, water holding by the residue, and others, all of which would be difficult to reproduce in the appropriate combination *in vitro.*

In this paper a faecal bulking index (FBI) of the relative bulking efficacy of human foods after conversion to faecal matter in the monogastric gut, is described. The FBI is defined as the weight of fully rehydrated faecal mass accumulated per unit of edible weight of food consumed, as a percentage of the amount accumulated per unit of edible weight of a reference food consumed, and it uses the laboratory rat as an animal model system.

Materials and methods

Animals

Male Sprague Dawley rats were raised on a standard pelleted diet until they weighed 300 ± 50 g. They were housed individually in hanging wire bottomed cages in a rack containing 30 cages per side, in a controlled environment room (light, 12 h; dark, 12 h; temperature, 21°C; humidity 50–60%). Water was provided *ad libitum*.

Materials

Hard wheat bran was obtained from Champion Flour Mills, Palmerston North, New Zealand. All cereal products and fruit and vegetables were bought from a local supermarket. All dry products such as breakfast cereals were fed without further drying. Baked foods such as bread were air dried in a convection oven at 50°C. Fruit and vegetables were freeze-dried. All were passed through a mill with a 1 mm sieve plate and stored in plastic bags at about –20°C until made up into the diets. Sucrose as castor sugar and corn oil were bought from

Table 1. Composition of trial diets

	Component weight (g/kg diet base)
Diet base	
Casein	200
Mineral mix	50
Vitamin mix	50
Fiber mix	50
Corn oil	50
Wheat starch	100
Diets	
Baseline:	400 g sucrose + 400 g diet base
Reference (wheat bran):	200 g wheat bran + 200 g sucrose + 400 g diet base
Test (Test mixes in Table 2):	400 g test mix + 400 g diet base

Minerals (Diet concentration, units/kg provided by mineral mix): Ca, 6.29 g; Cl, 7.79 g; Mg, 1.06 g; P, 4.86 g; K, 5.24 g; Na, 1.97 g; Cr, 1.97 mg; Cu, 10.7 mg; Fe, 424 mg; Mn, 78 mg; Zn, 48,2 mg; Co, 29.0 µg; I, 151 µg; Mo, 152 µg; Se, 151 µg
Vitamins (Diet concentration, units/kg provided by vitamin mix): Retinol, 5 mg; ergocalciferol, 25 µg; dL-–tocopherol acetate, 200 mg; 4.0; menadione, 3.0 mg; thiamin hydrochloride, 5 mg; riboflavin, 7.0 mg; pyridoxine hydrochloride, 8.0 mg; D-pantothenic acid, 20 mg; folic acid, 2.0 mg; nicotinic acid, 20 mg; cyanocobalamin, 50 µg; D-biotin, 1.0 mg; myo-inositol, 200 mg; choline chloride, 1500 mg.
Fiber mix: Wheat bran: Pectin (4 : 1).

Table 2. Composition of test mixes (400 g) added to 400 g of diet base to make trial diets

Trial diets	Test mix components (g/400g)		
Baseline and reference formulations	Wheat bran	Starch	Sucrose
1 Sucrose	—	—	400
2 Starch:sucrose (1:3)	—	100	300
3 Starch:sucrose (1:1)	—	200	200
4 Starch:sucrose (3:1)	—	300	100
5 Starch	—	400	—
6 Wheat bran:sucrose (1:3)	100	—	300
7 Wheat bran:sucrose (1:1)	200	—	200
8 Wheat bran:sucrose (3:1)	300	—	100
9 Wheat bran	400	—	—
10 Wheat bran:starch (1:3)	100	300	—
11 Wheat bran:starch (1:1)	200	200	—
12 Wheat bran:starch (3:1)	300	100	—
Breakfast cereals and Bakery products	Test food		
13–32*	400	—	400
Fruit and vegetables			
33 Pear, dried	150	—	250
34 Apricot, dried	250	—	150
35 Prune, stewed	200	—	200
36 Cabbage, steamed;			
37 Carrot boiled	100	—	300
38 Pumpkin, boiled	150	—	250
39 Spinach, cooked	35	—	365
40 Haricot beans, boiled	200	—	200
41 Lentils, boiled	400	—	—
42 Green peas, boiled	150	—	250
Ingredients			
43 Starch; 44 Rye flour;			
45 Pea flour; 46 Soy flour;	400	—	—
47 Cornmeal coarse, raw;			
48 Ground linseed, raw	400	—	—
49 Wheat germ, raw;			
50 Lactic casein	200	—	200
Polysaccharides	Polysaccharide source.	Wheat bran	Sucrose
51 Mucilax (48.6% psyllium; 7.5% psyllium in diet)	123.5	—	276.5
52 Mucilax:wheat bran (60 psyllium:200 bran)	123.5	200	76.5
53 Isogel (90% ispaghula gum; 7.5% ispaghula in diet)	66.7	—	333.3
54 Isogel:Wheat bran (60 ispaghula:200 bran)	66.7	200	133.3
55 Guar gum	60	—	340
56 Guar gum:Wheat bran	60	200	140
57 Pectin	60	—	340
58 Pectin:wheat bran	60	200	140
Wheat bran(reference diets)			
59, 60, 61	—	400	—
62, 63, 64	—	200	200
Sucrose (baseline diets)			
65, 66, 67, 68, 69	—		400

*13, All bran; 14, Bran flakes; 15, Kornies; 16, Corn flakes; 17, Puffed wheat; 18, Puffed rice; 19, Rolled oats; 20, Oat bran; 21, Miniwheats; 22, Vita crunch; 23, White bread; 24, 'Fiber White'bread; 25, Wheatmeal bread; 26, Wholemeal bread; 27, Burgen mixed grain bread; 28, Molenberg Swiss Bake bread; 29, Burgen mixed fruit loaf; 30, Anzac biscuit; 31, Digestive biscuit, plain; 32, 'Ryvita' crispbread.

a local food retailer. All of the vitamins and minerals used in the rat diets were of high quality.

Diets

The composition of the experimental diets is shown in Table 1. All diets contained a basal level of about 4% mixed non-starch polysaccharide provided by hard wheat bran (0.25 mm):apple pectin (Mexpectin™; Grinsted Products, Denmark) (4:1; 50 g/kg diet) plus 9.3 g cellulose/kg diet added in the mineral mix, to ensure that even with test foods of very low fiber content there was sufficient non-digestible and non-fermentable throughput to ensure normal gut function, an abundant and diverse hind gut flora and rapid replacement of gut contents upon changing diets. A new diet was almost always apparent in the faeces within 24 h.

Trial diets were based on the baseline diet, which contained 50% sucrose. Test and reference diets were the baseline diet in which sucrose was replaced with a test food mix or with the wheat bran reference material to a maximum level of 50% of the diet (Table 2), so that all groups had the same starch loading from the standard food ingredients. A bulk quantity of complete diet without the sucrose was made and the trial diets were formulated by adding sucrose for the baseline, wheat bran/sucrose for the reference and test food or test food/sucrose for the test diets. Each set of trials always included a baseline and a reference group in addition to the test diets.

The inclusion rate of test foods varied (Table 2) and was related to the recommended daily intakes of food groups in the human diet on a dry weight basis. Most starchy foods such as breakfast cereals and bakery products were included at 50% of the diet, fully replacing the sucrose. Fruit and leafy vegetables were included at a lower level which was never sufficient to cause diarrhoea.

Feeding

The feeding trials used groups of either five or six rats per group in batches of 60; either six groups with five rats per group or 10 groups with six rats per group. All groups were initially fed the baseline diet until accustomed to the powdered diet and their intakes had stabilized.

The sets of trials were conducted in a 7-day rotation. For the first 2 days all groups were fed the baseline diet. In the following 5 days one group continued the baseline diet, one was fed the reference diet and the remaining groups were fed a selection of the test food diets. During the 5-day period in which the test diets were fed, the first 2 days were treated as a clean out period and the last 3 days (days 5, 6, 7) as providing intakes for a balance period with faeces collected on the morning of days 6, 7 and 8. The eighth day was the first day of a new set of trials starting with the introduction of baseline diet in the afternoon. Before commencing a new trial the rats were redistributed so that each rat in a new group had come from a different group in the previous round. The protocol is summarized in Fig. 1.

Day	1 (8)	2	3	4	5	6	7	8(1)
Diet	Baseline		Test, baseline, and reference diet groups					Baseline
Period	Reset		Clean out	Balance – feed in				
				Balance – faeces out				

Figure 1. Feeding and faecal collection protocol.

Feed intakes were measured daily over the 7-day trial period. The daily feed ration was restricted to 25 g/rat weighed into glass pots placed in the cages in fixed pot holders at 16.30 h. The pots were removed at 09.00 h the following morning and reweighed.

Faecal collections

Faeces were collected beneath the wire mesh cages on a double thickness of blotting paper to ensure rapid dispersal of urine, and each morning of the collection period were separated from any diet spillage and placed in open jars to air dry. Diet spillage was retained and weighed at the end of the trial and taken into account when calculating dietary intakes.

Faeces from each rat that were collected over the 3-day balance period were pooled and the air dry faeces freeze-dried to obtain a value for dry matter output.

Faecal water-holding capacity

Ten dry faecal pellets were taken at random from the collection from each rat and weighed. To rehydrate them they were placed on a 3×10 cm blotting paper strip covering the lid of a 50 mL plastic pot in a tray. The pot and lid were preweighed. The faeces and lid were covered by the inverted pot and water was added to the tray. The blotting paper strip acted as a wick through which the pellets rehydrated while the inverted pot maintained a humid atmosphere. After 24 h rehydration the pots were removed one at a time, wiped dry of any condensation, the rehydrated pellets were tapped into the pot, and the lid was wiped and screwed on tightly before the pot plus lid and rehydrated pellets were reweighed to enable rehydrated faecal mass to be determined. Water-holding capacity (WHC) was calculated from the difference between dry and rehydrated weights.

Rehydrated faecal volume was determined by removing the rehydrated faecal pellets to a preweighed 10 mL graduated centrifuge tube and a known volume of water added (usually 5 mL). The faecal pellet was fragmented to ensure that all air bubbles were removed and the rehydrated faecal volume in the tube measured as total volume minus the volume of added water.

Calculations

Faecal dry matter output was calculated per 100 g dry feed intake to eliminate effects of different feed intakes. To compare colonic bulking effects the amount of moist faecal mass accumulating in the lower large bowel is expressed per unit weight of food consumed.

The FBI values were calculated to obtain a relative measure of the effects of diets on the bulk of colon contents before dehydration. The FBI is defined as the mass of fully rehydrated faecal output per unit weight of food consumed, as a percentage of the rehydrated faecal output per unit weight of a reference material consumed:

$$\text{FBI} = \frac{\text{Increase over baseline in mass of rehydrated faeces per g of test food}}{\text{Increase over baseline in mass of rehydrated faeces per g of reference food}} \times 100.$$

FBI is calculated using the following formula:

$$FBI = (T - B/R - B) \times (Pr/Pf) \times \%DM.$$

For the above equation:
FBI = faecal bulking index
T = mass of rehydrated faeces/100 g feed intake for test diet
B = mass of rehydrated faeces/100 g feed intake for baseline diet
R = mass of rehydrated faeces/100 g feed intake for reference diet
Pr = proportion of reference material in reference diet
Pf = proportion of test food in test diet
%DM = dry matter percentage in test food

Data analysis

Calculations and statistical analyses were carried out using MINITAB (Release 12) software (Minitab Inc., PA, USA).

Results

The various diets influenced both the dry matter output per unit weight of food and the water held per unit of dry faecal matter (WHC; Table 3). The effect on faecal dry matter was, in the case of most foods, more pronounced than the effect on water-holding capacity. The difference between diets inducing the smallest versus the largest absolute increase in faecal dry matter output was about fivefold, whereas the water-holding capacities of foods varied over a twofold range, except for the non-fermentable gums psylium and ispaghula (diets 51–58) which more markedly increased the WHC of the faeces. Faecal dry matter outputs were increased most by foods containing wheat bran, whereas starch-based low-fiber foods had very little influence on either faecal dry matter output or WHC. Products with added bran, such as All Bran (diet 13), bran flakes (diet 14), wholemeal bread (diet 26), Anzac biscuits (diet 30) and those containing bran because they were whole wheat products, such as whole wheat biscuits (Kornies; diet 15), puffed wheat (diet 17) and miniwheats (diet 21), had relatively high FBI. In contrast, bran-free cereal products such as cornflakes (diet 16), puffed rice (diet 18), white (diet 23) and Fiber White™ (diet 24) breads added little to colonic bulk. The ability of brans in cereals other than wheat to augment faecal bulk was evident in the case of rolled oats (diet 19), oat bran (diet 20) and rye flour (diet 44).

Fruit and vegetables (diets 33–42) in general had very low FBI. Dried pears (diet 33) were an exception, perhaps due to the presence of highly lignified stone cells in their flesh and because they were dehydrated and therefore had a high dry matter content in edible form. Ground linseed (diet 48) very effectively increased faecal bulk, no doubt because linseed is a small seed with a large proportion of fermentation-resistant seed coat.

Diets containing polysaccharides showed extreme differences in faecal bulking, pectin (diet 57) had an FBI of 3.6 compared with a value of 441 for isogel (diet 53; 90% ispaghula gum), a more than 100-fold difference.

The data in Table 4 for baseline and wheat bran diets indicate that the procedure for measuring FBI is reasonably reliable and robust within the range of bran concentrations used here. Wheat bran test mixes provided several levels of wheat bran in the diet: 50% (diets 9 and 59–61); 25% (diets 7, 11, and 62–64); 12.5% (diets 6 and 10); and 37.5% (diets 8 and

Table 3. Faecal dry matter output and faecal water-holding capacity (WHC) for rats fed the experimental diets listed in Table 2

Diet		Dry Matter output (g/100g diet)			WHC (g/g faecal DM)	
		n	Mean	SEM	Mean	SEM
1	Sucrose	5	6.2	0.2	1.6	0.3
2	Starch:sucrose (1 : 3)	5	6.7	0.3	1.9	0.2
3	Starch:sucrose (1 : 1)	5	6.8	0.3	1.7	0.2
4	Starch:sucrose (3 : 1)	5	6.4	0.2	2.0	0.2
5	Starch	5	6.5	0.2	1.7	0.2
6	Wheat bran:sucrose (1 : 3)	5	11.9	0.5	3.2	0.4
7	Wheat bran:sucrose (1 : 1)	5	16.9	0.7	2.9	0.1
8	Wheat bran:sucrose (3 : 1)	5	22.8	0.6	2.8	0.1
9	Wheat bran	5	25.5	1.7	2.8	0.2
10	Wheat bran:starch (1 : 3)	5	12.9	0.3	2.7	0.1
11	Wheat bran:starch (1 : 1)	5	18.4	0.6	2.4	0.3
12	Wheat bran:starch (3 : 1)	5	22.7	0.6	2.6	0.1
13	All bran	6	20.8	0.8	3.1	0.2
14	Bran flakes	6	14.6	0.4	2.9	0.3
15	Kornies	6	10.9	1.0	2.3	0.1
16	Corn flakes	6	7.1	0.2	1.4	0.2
17	Puffed wheat	6	9.8	0.3	2.3	0.2
18	Puffed rice	6	7.1	0.4	1.7	0.2
19	Rolled oats	6	10.9	0.8	2.2	0.2
20	Oat bran	6	10.4	0.3	2.2	0.2
21	Miniwheats	6	11.2	0.2	2.4	0.2
22	Vita crunch	6	8.8	0.7	2.7	0.1
23	White bread	6	6.5	0.2	2.5	0.1
24	'Fiber White' bread	6	8.0	0.2	2.5	0.3
25	Wheatmeal bread	6	10.4	0.9	3.3	0.3
26	Wholemeal bread	6	10.6	0.4	3.2	0.2
27	Mixed grain bread	6	8.1	0.5	3.2	0.2
28	Swiss Bake bread	6	8.6	0.2	2.3	0.2
29	Burgen mixed fruit loaf	6	8.2	0.3	2.5	0.2
30	Anzac biscuit	6	8.5	0.3	2.7	0.2
31	Digestive biscuit, plain	6	8.1	0.3	2.4	0.2
32	'Ryvita' crispbread	6	11.6	0.4	3.3	0.1
33	Pear, dried	5	10.0	0.2	3.0	0.4
34	Apricot, dried	5	8.3	1.1	2.2	0.3
35	Prune, dry	5	8.8	0.5	2.6	0.3
36	Cabbage, boiled	5	8.0	0.3	1.9	0.2
37	Carrot, boiled	5	7.2	0.2	2.7	0.3
38	Pumpkin, boiled	5	7.4	0.2	2.6	0.2
39	Spinach, cooked	5	6.9	0.2	2.3	0.1
40	Haricot beans, boiled	5	8.7	0.3	3.3	0.4
41	Lentils, boiled	5	12.6	0.3	3.7	0.2
42	Green peas, boiled	5	8.9	0.3	3.1	0.3
43	Starch	6	6.5	0.2	1.7	0.2
44	Rye flour	6	11.5	0.4	3.1	0.3
45	Pea flour	5	11.4	0.7	3.4	0.2
46	Soy flour	5	8.1	0.1	2.8	0.2
47	Cornmeal coarse, raw	6	6.3	0.2	2.7	0.2
48	Ground linseed, raw	6	21.9	0.3	2.2	0.4
49	Wheat germ, raw	6	9.7	0.2	3.2	0.2
50	Lactic casein	5	5.8	0.3	2.5	0.3
51	Mucilax	5	12.6	0.6	6.8	0.3
52	Mucilax:wheat bran	5	28.8	0.6	8.5	0.4
53	Isogel	5	16.1	0.1	6.0	0.6
54	Isogel:Wheat bran	5	27.6	0.9	6.0	0.5
55	Guar gum	5	8.4	0.2	1.9	0.3
56	Guar gum:Wheat bran	5	18.7	0.7	3.3	0.4
57	Pectin	5	7.6	0.12.1	0.1	
58	Pectin:wheat bran	5	17.4	0.6	3.3	0.04

Table 4. Faecal bulking indices (FBI) based on mass of rehydrated rat pellets from rats fed diets containing test mixes shown in Table 2

Diet		FBI	
		Mean	SEM
1	Sucrose	– 1.7	1.5
2	Starch:sucrose (1:3)	1.0	1.7
3	Starch:sucrose (1:1)	0.2	2.3
4	Starch:sucrose (3:1)	– 7.2	3.2
5	Starch	– 0.3	1.1
6	Wh bran:sucrose (1:3)	96.1	8.1
7	Wh bran:sucrose (1:1)	88.9	6.0
8	Wh bran:sucrose (3:1)	88.3	4.0
9	Wh bran	87.3	9.1
10	Wh bran:starch (1:3)	98.1	7.3
11	Wh bran:starch (1:1)	96.8	7.1
12	Wh bran:starch (3:1)	86.3	2.9
13	All bran	56.6	3.0
14	Bran flakes	30.7	1.2
15	Kornies	16.7	3.5
16	Corn flakes	3.2	0.8
17	Puffed wheat	13.2	1.1
18	Puffed rice	1.9	1.3
19	Rolled oats	14.6	2.7
20	Oat bran	13.1	1.2
21	Miniwheats	20.4	2.4
22	Vita crunch	9.6	2.3
23	White bread	1.4	0.5
24	'Fiber White' bread	3.8	0.6
25	Wheatmeal bread	11.6	2.4
26	Wholemeal bread	12.6	0.9
27	Mixed grain bread	4.1	1.1
28	Swiss Bake bread	6.5	0.5
29	Burgen mixed fruit loaf	5.2	2.9
30	Anzac biscuit	10.5	1.3
31	Digestive biscuit, plain	7.8	1.3
32	'Ryvita' crispbread	23.0	1.3
33	Pear, dried	26.5	2.0
34	Apricot, dried	3.1	4.1
35	Prune, dry	8.2	2.0
36	Cabbage,boiled	4.0	0.6
37	Carrot,boiled	2.8	0.4
38	Pumpkin, boiled	1.5	0.3
39	Spinach, cooked	5.9	1.6
40	Haricot beans,boiled	7.9	0.5
41	Lentils,boiled	8.5	0.6
42	Green peas, boiled	6.5	0.9
43	Starch	– 0.3	1.1
44	Rye flour	20.8	1.2
45	Pea flour	10.5	2.1
46	Soy flour	8.5	1.0
47	Cornmeal coarse, raw	1.9	0.7
48	Ground linseed, raw	33.1	3.7
49	Wheat germ, raw	36.8	5.9
50	Lactic casein	– 0.3	1.5
51	Mucilax	277.6	23.7
52	Mucilax:wheat bran	166.5	4.2
53	Isogel	441.0	43.9
54	Isogel:Wheat bran	195.7	8.4
55	Guar gum	16.1	14.4
56	Guar gum:Wheat bran	76.2	3.2
57	Pectin	3.6	3.0
58	Pectin:wheat bran	83.7	5.1

12); yet after adjusting for the level of wheat bran, all had reasonably similar FBI. Reliability in measurement of the FBI for baseline diets containing caster sugar was similarly high for both weight-and volume-based indices.

A very crude estimate of error was obtained from foods with FBI values between 10 and 50, which had a mean FBI of 19.9 with a standard error of 2.9, giving an approximate overall coefficient of variation of 15%.

The application of FBI values to the ranking of foods on a fresh weight basis is shown in Fig. 2. Wheat bran-containing foods tended to be highest in the ranking, and low fiber starch-based foods and fruit and vegetables had rather low indices.

Discussion

The research on FBI presented here differs from previous studies of the effects of dietary fiber on faecal bulk in that it is focused on the effects of entire foods, and the results have been expressed relative to the effects of a wheat bran reference. In the procedure described here FBI is based on mass rather than bulk, but as the faeces were about 70% moisture after rehydrating and the density of plant cell wall material is close to one, mass will have been an adequate basis for calculating FBI.

The results are consistent with reports of the effects of the dietary fiber in foods on faecal bulk and output, which have consistently shown that cereal fibers such as wheat bran increase faecal output, while the dietary fiber from fruit and vegetables is extensively fermented, and contributes much less to faecal bulk.[4] The comparison of pectin with ispaghula gum, showing a 400-fold difference is a clear demonstration that levels of dietary fiber in foods are not able to predict the different faecal bulking effects that the foods might have, particularly where the types of fiber involved differ. Food labels showing the dietary fiber content of foods that contain polysaccharides such as psyllium and ispaghula will not be able to inform consumers of the faecal bulking effects that they may experience. Some measure of effectiveness of foods is required.

The aim of the present study was to design an economical and standardized *in vivo* method for predicting the relative bulking capacity of foods in the distal colon. Achieving this aim clearly requires the use of small animal models, which afford a high degree of experimental control at low cost. A central question, then, is whether or not the rat model used in the present study can adequately represent humans. In fact, the rat model has been able to predict faecal output in humans with a high degree of accuracy even when the effects of dietary fibers rather than foods have been the focus, and when the effects of adding dietary fiber to diets were measured against fiber-free controls.[10] Digestion of fiber in the rat and man was shown to be quite similar in short-term studies.[11] More recently fiber fermentation has been shown to be less complete in the rat than in the human, but nonetheless, differences in fiber fermentation due to changing human diets were paralleled in the rat.[12]

An *in vivo* model using whole foods for measuring FBI has several advantages over *in vitro* systems focused on dietary fiber. It enables FBI to be based on the digestibility of the whole food and fermentability of the food residue within a physiological environment that is buffered from the effects

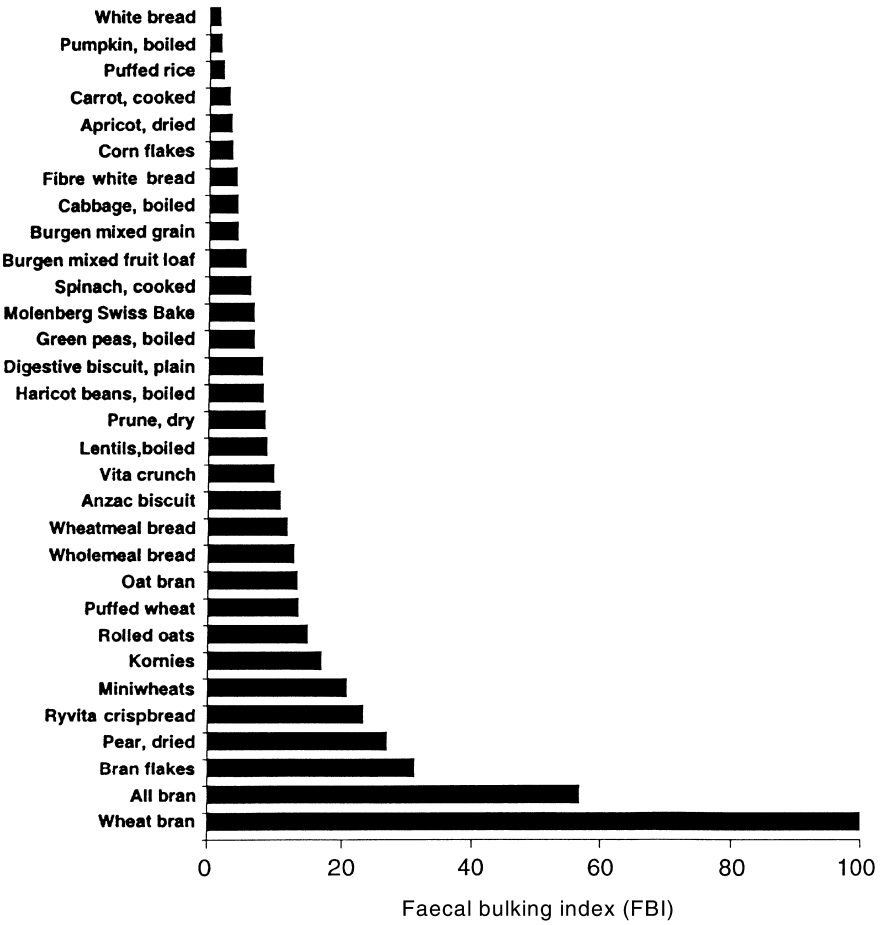

Figure 2. Ranking of foods by FBI against a hard wheat bran reference (FBI = 100).

of end product accumulation, pH changes and so on. The effects of all non-digested components in addition to non-starch polysaccharide, such as protein[8] and starch,[9] which may enter the large bowel and have significant effects,[13,14] are included. It also allows for endogenous secretions such as mucin, which has been shown to be differentially stimulated by fiber.[15,16] Another important advantage of *in vivo* over *in vitro* measurement of fermentation-resistant residues is that the contribution of all soluble components, such as non-fermentable soluble fiber, can be included because the colon confines it to within the faecal mass where it can contribute to the properties of the mass, which is not possible in liquid culture.

As FBI is a measurement of net effects of digestion, fermentation and water holding in the laboratory rat as used in the proposed procedure should be an appropriate indicative model. The assay depends on mixed bacterial fermentation of moderate amounts of undigested residues, from foods provided at realistic levels to a pre-adapted monogastric gut containing a flora already accustomed to a mixed fiber substrate. The precise composition of the gut flora probably does not matter; if there is material present that is susceptible to bacterial attack a population of microbes will exist to exploit the resource. All diets contained a base level of mixed non-starch polysaccharides so a substantial mixed population of bacteria would have always been present to utilize a range of fermentable food polysaccharides. Furthermore, the FBI is not intended to predict absolute amounts of faecal matter produced, but rather, to provide a comparative measure of the net impact of a food on colonic bulk after digestion and fermentation of food added to a diet already containing fiber.

Using rehydrated rather than fresh faecal mass in the measurement of FBI helps to overcome two problems. First, rat faecal pellets are far more dehydrated than human stools, and even though they have often been used to measure effects of fiber on faecal moisture they are not a suitable model. Second, large variations in water content between individuals and within a single faecal evacuation due to factors affecting the final degree of dehydration achieved at the point of evacuation are overcome. Bulk then becomes an independent property of the faecal mass determined by the amount of faecal dry matter and its water-holding capacity and should give a measure of the internal bulking capacity of distal colonic contents immediately before being dehydrated during formation of faeces.

It is assumed in the FBI procedure described that rehydrated faecal mass is a valid representation of distal colonic mass. The transformation from ileal digesta to faecal mass is a constant process with no set end-point. But final dehydration of the distal faecal mass into a faecal plug is a relatively acute change from its prior state in the distal colon. Rehydrated faeces will certainly equate to the colonic contents at some point late in their transition into a faecal mass although where that point occurs may differ between foods. Edwards *et al.*[10] showed that residues from *in vitro* fermentation could be used to predict faecal bulking in humans if water-holding capacity was included in the prediction, which suggests that using rehydrated faecal matter in the measurement of FBI is a physiologically valid approach to predicting distal colonic bulk in humans.

Based on moisture content, rehydrated rat pellets provide a model for human faeces. Fresh pellets of rats fed the base-

line diet typically contain only about 46% moisture compared with human faeces, which contain 64–79% moisture.[6,7] But after rehydration in the present study faeces from the baseline diet contained 61% moisture and those from the wheat bran reference diets contained 75% moisture, which is close to the range observed in numerous human studies. The data suggest that the intrinsic capacity of the gut-fermented residues to hold water was not greatly influenced by the host; rat versus human. The FBI thus appears to have a firm basis as an indicator of the tendency of a food to promote bulking in the distal colon.

The aim of making FBI a rapid procedure meant that the possibility of the rats completely adapting to the diets, which can take many weeks to complete, was excluded. To overcome the need for an adaptation period, mixed fiber was included at baseline levels in all diets, so that the gut was already pre-adapted to fiber. Furthermore, the present research addressed the impact of whole foods on faecal properties, so variations in fiber intakes were seldom as extreme as in most experiments that have focused specifically on dietary fiber and used dietary fiber preparations. As the FBI is a relative measure of the impact of foods at normal levels in a mixed and varying diet, a completely stabilized, fully adapted animal model is not necessary; the human diet is not constant and adaptation to a single food is not the norm. The FBI is designed to indicate the effect of introducing foods into a mixed diet at moderate fiber levels, is not designed to cope with the effects of extraordinarily high intakes of individual food components, and does not involve transition from a no-fiber to high-fiber diet. But even under the extreme conditions of such a transition, acute adaptation to high fiber diets in the rat has been shown to be quite rapid, with most of the caecal content having adapted in 2 days to change from a fiber-free to 15% fiber diet.[17] In similar studies, when 10% resistant starch was added to a fiber- and starch-free diet in rats most of the adaptation of hind gut fermentation was complete within a few days.[18,19]

The lack of impact of large changes in fiber intake on FBI when feeding the wheat bran diets suggests that measurement of FBI is quite robust, at least with material that is intrinsically resistant to fermentation. This conclusion is supported by recent research on the effects of level of fiber intake on fiber digestion, which showed that the differences between rat and man were quite similar at both high and low fiber intakes.[12]

The main purpose of the present study was to describe a basic protocol for measuring the distal colonic bulking efficacy of foods. The results to date indicate that the procedure would benefit from some modification to reduce variability, and that the 7-day trial period used in the present study is probably the minimum. The procedure would benefit from a larger number of rats per group and longer clean out and collection periods; for instance, a 14-day routine involving a 5-day baseline, 4-day prebalance and a 5-day balance period. The method would not be appropriate for foods that are consumed as large particles which remain intact during passage through the entire gut, but is limited by the ability of the rats to swallow large food particles.

The FBI can be used to provide an immediate indication of the relative bulking efficacy of foods on a weight-for-weight basis, as shown in Fig. 2. Ratios of FBI values can be used to calculate quantities of foods that are equivalent in bulking impact, and if such a ratio is used to compare all foods with a reference material, such as wheat bran, the bulking efficacy of any quantity of a food for which there is an FBI value can be expressed in bran equivalents. Then, if the daily requirement for bulk is known in bran equivalents, dietary management of colonic bulk becomes a simple matter of adding the bran equivalents, delivered in the diet, and calculating the shortfall that can be made up with an appropriate dietary source. The application of FBI to dietary management of colonic bulk will be discussed in detail elsewhere.

Dietary management of colonic bulk requires that daily requirements for bulk are determined. The requirements will no doubt be influenced by a large range of factors such as age, health, activity, and body size. Furthermore, the interaction of other properties such as abrasiveness, fermentive activity, and pH with faecal bulk in determining laxation requires further definition. The applicability to humans of FBI determined with rats would benefit from clinical validations in which the rats are fed a range of human diets in parallel with human subjects. Meanwhile, given that intakes of bulking matter are generally insufficient and that dietary fiber is an excessively crude basis for selecting diets for bulk, it is justifiable to propose that FBI, even in its present crude form, would be an improved basis for managing colonic bulk.

Acknowledgements. The author thanks Justine Shoemark and Margaret Scott for their assistance with maintaining the experimental animals and Meili Chiang for carrying out faecal rehydrations.

References

1. Trowell HC, Burkitt DP. Western diseases, their emergence and prevention. London: Edward Arnold, 1981.
2. Eastwood M. Diet, fiber and colorectal disease: A critical appraisal. In: Philips SF, Pemberton JH, Shorter RG, eds. The Large Intestine: Physiology, Pathophysiology, and Disease. New York: Raven Press Ltd, 1991; 209–222.
3. Davidson MH, McDonald A. Fiber: Form and function. Nutr Res 1998; 18: 617–624.
4. Cummings JH, Bingham SA, Heaton VW, Eastwood MA. Fecal weight, colon cancer risk and dietary intake of non-starch polysaccharides (dietary fiber). Gasteroenterol 1992; 103: 1783–1789.
5. Schneeman BO. Dietary fiber and gastrointestinal function. Nutr Res 1998; 18: 625–632.
6. Burkett AM, Jones GP, de Silva AM, Young GP, Muir JG. Dietary intake and faecal excretion of carbohydrate by Australians: Importance of achieving stool weights greater than 150 g to improve faecal markers relevant to colon cancer risk. Euro J Clin Nutr 1997; 51: 625–632.
7. Cummings JH. The effect of dietary fiber on faecal weight and composition. In: Spiller GA, ed. CRC handbook of dietary fiber in human nutrition. Boca Raton: CRC press, 1993; 263–349.
8. Chacko A, Cummings JH. Nitrogen losses from the human small bowel: obligatory losses and the effect of physical form of food. Gut 1988; 29: 809–815.
9. Muir JG, Birkett A, Brown I, Jones G, O'Dea K. Food processing and maize variety affects amounts of starch escaping digestion in the small intestine. Am J Clin Nutr 1995; 61: 82–89.
10. Edwards CA, Adiotomre J, Eastwood MA. Dietary fiber: the use of in vitro and rat models to predict action on stool output in man. J Sci Food Agric 1992; 59: 257–260.
11. Nyman M, Asp N-G. Dietary fiber fermentation in the rat intestinal tract: effect of adaptation period, protein and fiber levels, and particle size. Br J Nutr 1985; 54: 635–643.

12. Bach Knudsen KE, Wisker E, Daniel M, Feldheim W, Eggum BO. Digestibility of energy, protein, fat and non-starch polysaccharides in mixed diets: Comparative studies between man and the rat. Br J Nutr 1994; 71: 471–487.
13. Annison G, Topping DL. Nutritional role of resistant starch: chemical structure vs physiological function. Ann Rev Nutr 1994; 14: 297–320.
14. Philips J, Muir JG, Birkett A, Lu Z, Jones GP, O'Dea K, Young GP. Effect of resistant starch on fecal bulk and fermentation-dependent events in humans. Am J Clin Nutr 1995; 62: 121–130.
15. Vahouny GV, Le T, Ifrim I, Satchithanandam S, Cassidy MM. Stimulation of intestinal cytokinetics and mucin turnover in rats fed wheat bran or cellulose. Am J Clin Nutr 1985; 41: 895–900.
16. Satchithanandam S, Klurfeld DM, Calvert RJ, Cassidy MM. Effects of dietary fibers on gastrointestinal mucin in rats. Nutrition Res 1996; 16: 1163–1177.
17. Tulung B, Rémésy C, Demigné C. Specific effects of guar gum or gum arabic on adaptation of cecal digestion to high fiber diets in the rat. J Nutr 1987; 117: 1556–1561.
18. Faulks RM, Southon S, Livesey G, Utilization of α-amylase (EC 3.2.1.1) resistant maize and pea (*Pisum sativum*) starch in the rat. Br J Nutr 1989; 61: 291–300.
19. Gee JM, Faulks RM, Johnson IT. Physiological effects of retrograded α-amylase-resistant cornstarch in rats. J Nutr 1991; 121: 44–49.