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The effects of bulking, viscous and gel-forming dietary fibres on satiation

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Abstract

The objective was to determine the effects of dietary fibre with bulking, viscous and gel-forming properties on satiation, and to identify the underlying mechanisms. We conducted a randomised crossover study with 121 men and women. Subjects were healthy, non-restrained eaters, aged 18–50 years and with normal BMI (18·5–25 kg/m^2). Test products were cookies containing either: no added fibre (control), cellulose (bulking, 5 g/100 g), guar gum (viscous, 1·25 g/100 g and 2·5 g/100 g) or alginate (gel forming, 2·5 g/100 g and 5 g/100 g). Physico-chemical properties of the test products were confirmed in simulated upper gastrointestinal conditions. In a cinema setting, *ad libitum* intake of the test products was measured concurrently with oral exposure time per cookie by video recording. In a separate study with ten subjects, 4 h gastric emptying rate of a fixed amount of test products was assessed by ^{13}C breath tests. *Ad libitum* energy intake was 22 % lower for the product with 5 g/100 g alginate (3·1 (SD 1·6) MJ) compared to control (4·0 (SD 2·2) MJ, $P<0·001$). Intake of the other four products did not differ from control. Oral exposure time for the product with 5 g/100 g alginate (2·3 (SD 1·9) min) was 48 % longer than for control (1·6 (SD 0·9) min, $P=0·01$). Gastric emptying of the 5 g/100 g alginate product was faster compared to control ($P<0·05$). We concluded that the addition of 5 g/100 g alginate (i.e. gel-forming fibre) to a low-fibre cookie results in earlier satiation. This effect might be due to an increased oral exposure time.

Key words: Dietary fibre: Meal termination: Eating time: Physico-chemical properties

The consumption of dietary fibre has been associated with increased satiety and reduced energy intake[1–5]. Satiety and satiation are part of a complex system of appetite control, including cognitive factors, sensory sensations and post-ingestive feedback mechanisms[6]. Satiety is defined as the inhibition of appetite and occurs as a consequence of eating. Satiation is defined as the satisfaction of appetite that develops during the course of a meal, and results in meal termination. Numerous studies have been carried out to clarify the effects of dietary fibre on satiety[4,5,7]. Studies on the effects of fibre on satiation are, however, limited and show inconsistent results. For example, Grimes & Gordon[8] found that the satiating capacity of wholemeal bread was higher than that for white bread. Opposing to this, Burley *et al.*[9] did not find differences in *ad libitum* intake between a meal containing a meat replacer with chitin and insoluble β-glucan and a similar low-fibre meal. Odunsi *et al.*[10] also did not find differences in *ad libitum* intake after ingestion of capsules with cellulose and alginate compared to placebo capsules.

Dietary fibre is a term that reflects a heterogeneous group of compounds that differ in their chemical structure and physico-chemical properties. Dietary fibres may affect satiation via diverse related mechanisms[7,11]. First, the metabolisable energy content of fibre is less than that for other nutrients[12] and, as meal intake volume is relatively constant[13], the inclusion of fibre in foods decreases total energy intake. Second, adding fibre to a meal can increase chewing activity or oral exposure time to foods, which may result in earlier satiation[14–16]. Third, the addition of fibre can increase viscosity and water-holding capacity of digesta and induce formation of gels in the stomach[11,17]. These properties can slow down gastric emptying and concurrently increase stomach distension. Stomach distension, or fullness, is seen as a causal factor in the chain of events leading to satiation[18,19]. In response to the mechanical and physico-chemical properties of the ingested foods, a series of neural and humoral signals develop from the gut, which can result in satiation[20].

The aim of the present research was to determine the effects of three distinctive dietary fibres with different physico-chemical properties on satiation. Hence, we selected cellulose, a bulking fibre; guar gum, a viscous fibre; and alginate, a gel-forming fibre, and added the selected fibres

Abbreviation: AUC, area under the curve.

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to test products. Two dosages of guar gum and alginate were included to be able to study effects of high-fibre, but less palatable products. Physico-chemical properties of the test products were characterised in simulated upper gastrointestinal conditions. Satiation was determined by measuring *ad libitum* intake of the test products in a real-life setting. Furthermore, oral exposure time and gastric emptying rate were measured.

Subjects and methods

Two short-term intervention studies were conducted. Satiation and oral exposure time were determined in study one, and gastric emptying rate was assessed in study two. In both studies, the subjects participated in six test sessions with six different test products.

Subjects

For both studies, men and women, aged 18–50 years, were recruited in Wageningen and Ede, The Netherlands. Subjects had to have a normal BMI (18·5–25·0 kg/m^2), and had to be healthy. Subjects were excluded if they were restrained eaters according to the Dutch Eating Behaviour Questionnaire (DEBQ) (score: men >2·89; women >3·39)[21]. They were also excluded if they used an energy-restricted diet or lost or gained more than 5 kg body weight during the last 2 months, if they had a lack of appetite, had diabetes, gastrointestinal problems or were hypersensitive for any ingredient in the test products. The present study was conducted according to the guidelines laid down in the Declaration of Helsinki, and all procedures involving human subjects were approved by the Medical Ethics Committee of Wageningen University (registration no. NL 26 703.081.09). Written informed consent was obtained from all subjects. The study was registered in the National Institutes of Health clinical trial database (ClinicalTrials.gov no. NCT00904124).

Out of the 124 subjects in study one, three dropped out due to reasons unrelated to the intervention. We included 121 subjects in data analysis, of which 112 participated in six sessions, seven in five sessions and two in four sessions. The missed sessions were due to illness or problems with planning. The study population for study one consisted of forty-five men and seventy-six women, aged 25 (SD 7) years, with a BMI of 22·0 (SD 1·9) kg/m^2 and a DEBQ score of 2·1 (SD 0·6.). The number of women in the menstrual phase did not differ (P=0·79) between treatments.

A total of ten subjects, six men and four women, participated in study two. All subjects were included in data analysis, of which nine participated in six sessions and one in five sessions. The missed session was due to problems with planning. Mean age of the participants was 21 (SD 3) years, mean BMI 21·8 (SD 1·9) kg/m^2 and mean DEBQ score 1·8 (SD 0·7).

Test products

The six test products were one-bite-sized (6·8 (SD 0·3) g) chocolate cookies. The basic recipe of the cookies contained 36 % white flour, 27 % butter, 18 % sugar, 14 % chocolate chips, 4 % egg, 2 % cacao powder and 0·1 % salt. Flour was exchanged for dietary fibre. Cellulose (Vitacel L 00, Rettenmaier & Söhne) was given in a dose of 5 %; guar gum (Viscogum™ MP 41 230, Cargill; molecular weight 60–1000 kDa) in doses of 1·25 and 2·5 % and alginate (Protanal LF 5/60, FMC BioPolymer; molecular weight 17–710 kDa; guluronic acid:mannuronic acid ratio of 1·9) in doses of 2·5 and 5 %. A professional bakery manufactured the cookies freshly on each test day.

Duplicate portions of the products were collected on each test day and stored at −20°C pending measurements for macronutrients and physico-chemical properties. Before measurements, a homogenised mixture of cookies was ground until it passed a 2 mm sieve. Protein, total fat, total dietary fibre, moisture and ash were measured according to methods previously described[22]. Available carbohydrate was estimated by subtracting moisture, ash, protein, fat and fibre from total weight. Atwater factors were used to calculate available energy: fat 37 kJ/g and protein and carbohydrate 17 kJ/g. For fibre, 0 kJ/g was used because of uncertainty about the availability of energy[12]. This may have underestimated the available energy content. Macronutrient composition is shown in Table 1.

Physico-chemical properties were measured only for the high-dose products and the control. These properties included viscosity and water-holding capacity using three conditions to simulate the mouth, stomach and small intestine.

Table 1. Available energy and macronutrient composition of the test products (per 100 g)

	Control		Cellulose 5 %		Guar gum 1·25 %		Guar gum 2·5 %		Alginate 2·5 %		Alginate 5 %	
Component	g	En%	g	En%	g	En%	g	En%	g	En%	g	En%
Available energy (kJ)*	2241		2087		2204		2171		2180		2122	
Fat	33·3	55	32·2	57	33·3	56	33·2	57	33·2	56	33·2	58
Protein	6·4	5	5·9	5	6·3	5	6·2	5	6·5	5	5·8	5
Available carbohydrates	53·1	40	46·7	38	51·0	39	49·3	39	49·6	39	46·8	38
Dietary fibre	3·6		10·6		5·6		6·9		6·0		9·0	

En%, percentage of energy, as derived from the specific nutrient compared to the total calculated energy content of the test product.
* Available energy was calculated based on chemical analysis of the macronutrient composition. Energy conversion factors used: fat 37 kJ/g, protein and carbohydrate 17 kJ/g. Energy content of fibre was set at 0 kJ/g.

Measurements were performed according to methods described by Turnbull *et al.*[23], with modifications for the amount of samples and types of reagents. Reagents used included α-amylase from porcine pancreas (1.16.312.0001, Merck), pepsin from porcine gastric mucosa (P6887, Sigma-Aldrich), pancreatin from porcine pancreas (P1625, Sigma-Aldrich) and bile extract (B8631, Sigma-Aldrich). The amount of sample was increased by 4-fold, to compensate for lower fibre levels. Furthermore, the volume for each simulation was set to 30 ml, and amounts of sample and reagents were adjusted comparatively. In addition, amounts of enzymes were adjusted to obtain similar activity. Bile was increased by 4-fold to ensure good emulsification of fat. After each simulation, samples were centrifuged at 4250 ***g*** for 20 min. The supernatant was decanted and used for viscosity measurements. The tube with the remaining pellet was inverted to remove excess water. The pellet that contained insoluble material was weighed and the DM was measured. Water-holding capacity was expressed as the amount of water held after centrifugation by the insoluble material from 1 g of cookie.

The viscosity of the supernatant was measured at 37°C, using a rheometer (MCR 501, Anton Paar) with double gap geometry. A shear sweep was performed at 1–1000/s in logarithmic scale during 5 min. The data obtained at shear rate of 100/s were used to compare between samples.

Experimental procedure: study one

Ad libitum intake was measured in a randomised single-blind cross-over study with six test sessions, separated by at least 2 d. *Ad libitum* intake was calculated from the weight of the test products before and after consumption. Products were weighed in duplicate on a digital scale, with a precision of 0·1 g. Subjects were not aware that the primary outcome was *ad libitum* intake, as this could have affected the outcome of the study.

The study was performed in a cinema (Cinemec) to create a real-life setting aimed to distract subjects from visual and weight cues[24]. During each test session, subjects watched a movie in the genres romance or comedy. On each test day, the subjects arrived at 18.00 hours. At 18.45 hours, they were seated in the theatre. Just before entering the theatre, 400 g of test product was served in a white carton box and a bottle with 500 ml water was provided. The subjects were instructed to eat as little or as much of the test product as they wanted until they felt comfortably full. The movie was divided in two parts of 45 min, with a 15 min break. During the break, subjects left the theatre and handed in the box with test product. At the restart, they received a new box with 400 g of test product. The participants were instructed to finish the bottle of water before the end of the movie.

Before and after *ad libitum* intake, subjects rated five appetite questions on 100 mm visual analogue scales. Scales were anchored from 'not at all' to 'very much' and included feelings of hunger, fullness, desire to eat, prospective food consumption and thirst. Before *ad libitum* intake, the participants were also asked to rate palatability, expected satiation and sensory attributes (sweetness, bitterness, chocolate taste, freshness, dryness, stickiness and difficulty to swallow) of the test product on 100 mm visual analogue scales.

To standardise the individual state of satiety, subjects were instructed to eat the same breakfast and lunch at all six test days and to record this in a diary. Individual state of satiety was further standardised by consuming a preload at 18.00 hours. The preload provided approximately 18 % of the daily energy requirements. This was chosen to correspond to half the energy content of a normal Dutch dinner[25]. Individual energy requirements were calculated by the Schofield equation[26], and subjects were divided into one of three preload groups. Group one (estimated energy need ≤ 10 MJ, n 63) received 0·5 pizza, group two (10–14 MJ, n 56) received 0·75 pizza and group three (≥ 14 MJ, n 2) received 1·0 pizza.

Oral exposure time

Oral exposure time of the test products was measured by means of video recording a random subgroup of eleven men and twenty-five women. To record eating time, five video cameras were used (Sony Handycam DCR-HC51/DCR-SR55E; Sony). These were set at night shot mode and supported by two separate IR lights. Video analysis on oral exposure time over the first 45 min of the movie was done through The Observer®XT9 (Noldus). Oral exposure time was measured in seconds and defined as time spent on chewing, swallowing, cleaning the mouth and teeth with tongue or fingers. Breaks were considered as not eating. Two researchers coded the video recordings. Reliability analysis was carried out regularly, which resulted in an inter-observer agreement of $\kappa = 0{\cdot}75$ ($P < 0{\cdot}01$). Due to varying reasons (e.g. view blocked, poor quality of light) videos of twenty-one to twenty-seven subjects per test product were suitable for quantifying oral exposure time.

Experimental procedure: study two

In a second randomised single-blind crossover trial, gastric emptying rate and appetite sensations were measured in six test sessions, separated by at least 7 d. Subjects consumed a fixed amount of the test products, which corresponded to approximately 20 % of daily energy requirements[25]. This resulted in dosages varying from 80 to 100 g. Each portion was supplemented with 87·4 mg [1-^{13}C]octanoic acid (Campro Scientific GmbH). Breath samples were collected by breathing into a 10 ml Exetainer tube (Labco) via a drinking straw and then closing the tube with a cap. Samples were stored at room temperature and were analysed for ^{13}C enrichment in CO_2 on a Finnigan Delta C continuous-flow isotope ratio mass spectrometer (Finnigan MAT).

Subjects arrived at our research centre between 07.30 and 08.00 hours after a 10 h overnight fast. They were asked to consume a low-fibre meal on evenings before test sessions. In addition, they should avoid unusual vigorous physical activity and consuming products naturally enriched in ^{13}C (maize, millet, sorghum and cane sugar). Before ingestion of the test product, within 10 min together with 300 ml water, two baseline breath samples were taken. Subsequent breath

samples were taken after exactly 15, 30, 45, 60, 75, 90, 105, 120, 150, 180, 210 and 240 min. Appetite sensations were rated on 100 mm visual analogue scales, as described for study one, and measured at baseline and after 30, 60, 90, 120, 150, 180, 210 and 240 min. Subjects were seated at a desk and allowed to do light desk work during the session.

Statistical analysis

Data are presented as means and standard deviations. Statistical analyses were performed with SAS (version 9.2; SAS Institute, Inc.). Significance was set at $P<0{\cdot}05$. One-way ANOVA was used to analyse differences between physico-chemical properties of the cookies. For study one, treatment effects on sensory ratings, palatability ratings, *ad libitum* intakes and eating time were analysed by means of a mixed-model ANOVA (proc mixed). Treatment, day and treatment × day interaction (= order) were included as fixed factors and subject was included as a random factor. For dose–response effects, orthogonal contrasts among control, low- and high-dose fibres were calculated. If the treatment effect was statistically significant, Dunnett's procedure was used to compare the fibre treatments with the control treatment, to control for multiple testing. The appetite ratings were analysed according to a similar procedure, with the addition of time (before and after *ad libitum* intake) and treatment × time as fixed factors in the model. Additionally, to control for differences in appetite ratings at baseline, baseline values were added to the model as a covariate. For study two, treatment effects were analysed according to a similar procedure, after calculation of total area under the curve (AUC) for appetite ratings and gastric emptying rate (proc expand). Time-to-peak data were not normally distributed and were therefore log-transformed for analysis and presented as back-transformed geometric means (±95% CI). Pearson's partial correlation coefficient, controlled for subject, was calculated to assess relations among sensory properties, palatability and *ad libitum* intake for the treatments separately and together.

Results

Physico-chemical properties

Physico-chemical properties of the test products in simulated upper gastrointestinal conditions are presented in Table 2. Under mouth-like conditions, high-dose guar gum increased viscosity up to 24-fold compared to control ($P<0{\cdot}001$). The increased viscosity for high-dose guar gum persisted under simulated conditions for stomach and small intestine ($P<0{\cdot}001$). High-dose alginate increased water-holding capacity up to 3-fold in the stomach-like conditions compared to control ($P<0{\cdot}001$).

Study one

Palatability and sensory ratings of test products. Mean palatability and sensory ratings of the test products are given in Table 3. Products with cellulose ($P<0{\cdot}001$), high-dose guar gum ($P=0{\cdot}001$) and high-dose alginate ($P=0{\cdot}023$) were rated lower on palatability than control. Expected satiation was rated similar for all test products compared to control. All fibre-enriched products changed in texture ratings compared to the control product. The products with cellulose, high-dose guar gum and both dosages of alginate were rated to be more sticky ($P<0{\cdot}001$) than control.

Appetite ratings. After *ad libitum* intake, ratings for hunger, desire to eat and prospective consumption decreased ($P<0{\cdot}001$) and ratings for fullness increased ($P<0{\cdot}001$) for all test products compared to before *ad libitum* intake. The change in ratings compared to baseline did not differ between test products (data not shown).

Ad libitum *intake*. Fig. 1 shows the total *ad libitum* intake of the test products. Before the break, at 45 min, *ad libitum* intake represented 67–70% of total intake for all test products. Intake of the products containing cellulose, both dosages of guar gum and the low-dose alginate did not change compared to the control product, regardless of the dimension used (i.e. g or MJ). Compared to the control product, high-dose alginate reduced *ad libitum* intake in grams by 17%

Table 2. Viscosity and water-holding capacity of the test products in simulated upper gastrointestinal conditions (Mean values and standard deviations)

	Control		Cellulose 5%		Guar gum 2·5%		Alginate 5%		
Properties	Mean	SD	Mean	SD	Mean	SD	Mean	SD	*P*†
Viscosity (mPa s)‡									
Mouth	1·4	0·2	1·3	0·3	34·5***	9·4	5·9	0·7	<0·001
Stomach	1·2	0·3	1·0	0·1	8·4***	1·8	1·7	0·4	<0·001
Small intestine	2·5	1·3	3·5	1·1	5·6***	0·9	4·1*	0·8	<0·001
Water-holding capacity (g water/g cookie)§									
Mouth	0·41	0·02	0·47	0·06	0·70***	0·02	0·37	0·01	<0·001
Stomach	0·47	0·06	0·53	0·06	0·48	0·02	1·51***	0·12	<0·001
Small intestine	0·28	0·06	0·46	0·07	0·37	0·06	0·33	0·12	0·052

Mean values were significantly different from control: * $P<0{\cdot}05$, *** $P<0{\cdot}001$.
† *P*-value from one-way ANOVA, subsequently all fibre treatments were compared to control with Dunnett's procedure.
‡ Viscosity in mPa s at shear rate 100/s; mean of six measurements.
§ The amount of water held by the insoluble material from 1 g of cookie; mean of four measurements.

Table 3. Palatability ratings, expected satiation and analytical attributes† by test products, before *ad libitum* intake
(Mean values and standard deviations)

	Control		Cellulose 5 %		Guar gum 1·25 %		Guar gum 2·5 %		Alginate 2·5 %		Alginate 5 %		
Attribute	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	*P*‡
Palatability	66	17	51***	21	62	17	59**	17	63	17	61*	18	<0·001
Expected satiation	52	19	53	18	49	18	51	17	52	18	55	16	0·022
Sweetness	58	18	50***	20	55	19	48***	21	52*	19	55	18	<0·001
Bitterness	30	20	29	21	32	21	31	21	30	21	28	20	0·082
Chocolate taste	64	17	57**	18	58*	19	53***	20	60	17	59*	19	<0·001
Freshness	68	20	41***	22	64	19	56***	20	64	20	63*	19	<0·001
Dryness	45	22	58***	23	50	21	52	22	50	23	53**	23	<0·001
Stickiness	40	23	49**	23	47	24	55***	24	57***	23	71***	16	<0·001
Difficulty to swallow	31	21	42***	26	37	22	41***	24	42***	25	51***	25	<0·001

Mean values were significantly different from control: * $P<0·05$, ** $P<0·01$, *** $P<0·001$.
† Values were measured on a 100 mm visual analogue scale anchored from 'not at all' to 'very much' (0 to 100). Measured in 121 subjects.
‡ *P*-value from mixed-model ANOVA, subsequently all fibre treatments were compared to control with Dunnett's procedure.

($P<0·001$), which corresponded to a reduction in MJ of 22 % ($P<0·001$). In addition, a dose–response effect of alginate was found; increasing fibre dose reduced *ad libitum* intake ($P<0·05$).

Palatability scores were positively correlated with *ad libitum* intake (r 0·17; $P<0·001$). For the individual products, this correlation was only found for test products containing cellulose (r 0·18; $P=0·045$), low-dose guar gum (r 0·40; $P<0·001$) and high-dose guar gum (r 0·19; $P=0·041$). Scores for stickiness were inversely correlated with *ad libitum* intake (r −0·10; $P=0·008$), but this was not found for the individual test products. Adjusting the results of *ad libitum* intake for palatability and stickiness of the test products, by including these variables as covariates in the model did not change the findings.

Oral exposure time. In the subgroup for video analysis (n 36), *ad libitum* intake of test products did not differ from the intake in the complete group. Although there was an effect of treatment on total oral exposure time ($P=0·045$), this effect could not be localised to specific test products compared to control (Table 4). Oral exposure time per cookie was only longer for the high-dose alginate, compared to control ($P=0·01$).

Study two

Table 5 shows the AUC and time to peak for gastric emptying. Compared to control, AUC for gastric emptying was larger after consumption of the products with cellulose ($P=0·048$), low-dose alginate ($P=0·027$) and high-dose alginate ($P=0·004$). Additionally, time to reach the peak percentage dose recovery of ^{13}C per h was 27 % shorter for high-dose alginate compared to control ($P=0·03$). AUC for 4 h ratings of hunger, fullness, desire to eat and prospective consumption did not differ between the test products and control (data not shown).

Discussion

In the present study, we found that cookies supplemented with 5 % alginate (i.e. gel-forming fibre) reduced *ad libitum* intake in energy by 22 %, compared to cookies without added fibre. Addition of guar gum (i.e. viscous fibre) and cellulose (i.e. bulking fibre) did not affect *ad libitum* intake.

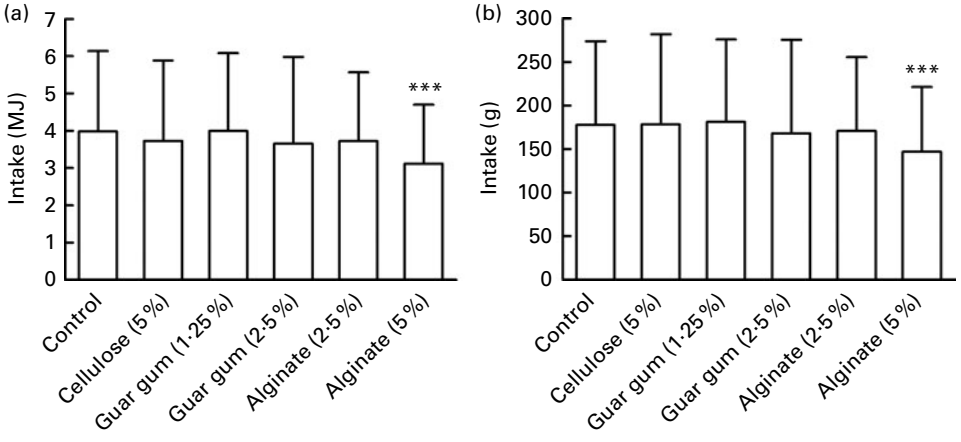

Fig. 1. *Ad libitum* intake of the test products in (a) MJ (SD) (n 121) and (b) g (SD) (n 121). Analysis with mixed-model ANOVA resulted in $P<0·001$, subsequently all fibre treatments were compared to control with Dunnett's procedure. Orthogonal contrasts among control, low- and high-dose guar gum and alginate showed a dose–response effect of alginate ($P<0·05$). ***Values were significantly different from control ($P<0·001$).

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Table 4. Total oral exposure time and oral exposure time† of the test products measured by video observation
(Mean values and standard deviations)

	Control		Cellulose 5 %		Guar gum 1·25 %		Guar gum 2·5 %		Alginate 2·5 %		Alginate 5 %		
	n 26		*n* 25		*n* 27		*n* 22		*n* 24		*n* 21		
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	*P*‡
Total oral exposure time (min)†	20·2	8·9	20·2	10·6	24·9	11·7	24·1	14·0	22·3	9·5	22·9	12·5	0·045
Oral exposure time per cookie (min)	1·6	0·9	1·7	1·5	1·7	1·3	2·0	1·6	1·7	0·8	2·3**	1·9	0·043
Oral exposure time/MJ (min)	9·4	4·9	10·7	8·1	10·2	7·0	11·8	9·1	10·1	4·5	13·1**	8·3	0·031

Mean values were significantly different from control: ** $P<0·01$.
† Total oral exposure time and oral exposure time per cookie are reported in minutes over the first 45 min of a test day. Measured in a subgroup of thirty-six subjects.
‡ *P*-value from mixed-model ANOVA, subsequently all fibre treatments were compared to control with Dunnett's procedure.

Cookies with 5 % alginate increased oral exposure time by 48 %, but also increased the rate of gastric emptying. The present study was performed in a real-life setting to distract subjects from visual and weight cues. We included two different dosages of guar gum and alginate to be able to study effects of high-fibre, but less palatable products.

Selection of the types of fibre for the present study was based on anticipated working mechanisms of bulking, viscous and gelling fibres on satiation. By definition, all fibres have bulking properties, as inclusion of dietary fibre in food products reduces energy density[12]. In the present study, *ad libitum* intake in weight remained unchanged after inclusion of cellulose compared to the control product without added fibre. The change in energy content after inclusion of cellulose was, however, not large enough to lead to significant decreases in energy intake.

In addition to weight or volume of foods, palatability is an important determinant of meal size[27]. A very pleasant-tasting meal may result in higher *ad libitum* intake. In the present study, palatability ratings for the high-dose fibre products were lower than that for the control product. However, adjusting for palatability did not explain the difference in *ad libitum* intake between high-dose alginate and control products.

We hypothesised that addition of guar gum would reduce *ad libitum* intake[14,28] by increasing oral exposure time[16,29]. The measurements of physico-chemical properties confirmed that guar gum was highly viscous in mouth conditions. However, in the satiation study, we showed that guar gum neither reduced *ad libitum* intake nor increased oral exposure time. Although there were texture differences, we speculate that these were not large enough to prolong oral exposure time[30]. Previous studies showing effects on oral exposure time used liquid and semi-liquid test products with large differences in texture[14,28].

While no effect of guar gum was observed, oral exposure time increased after high-dose alginate supplementation, although viscosity in the simulated mouth condition did not differ from control. Alginate forms a gel either at a low pH or in the presence of divalent cations (e.g. Ca^{2+} or Mg^{2+})[31]. We postulate that alginate already started forming a gel in the oral cavity due to the presence of water and divalent cations from saliva[32]. This is also in agreement with the sensory ratings, as alginate was rated the most sticky and difficult to swallow.

We further hypothesised that increased viscosity of digesta as well as formation of gels would reduce gastric emptying rate, and as a result reduce *ad libitum* intake[11,17,19]. The measurements of physico-chemical properties confirmed that guar gum increased viscosity in all three upper gastrointestinal conditions, and that alginate increased water-holding capacity in stomach conditions. In the gastric emptying study, we found, however, that none of the test products reduced gastric

Table 5. Gastric emptying rate by test product expressed as area under the curve (AUC) and time to peak†
(Mean values and 95 % confidence intervals)

	Control		Cellulose 5 %		Guar gum 1·25 %		Guar gum 2·5 %		Alginate 2·5 %		Alginate 5 %		
	n 10		*n* 9		*n* 10		*n* 10		*n* 10		*n* 10		
	Mean	95 % CI	Mean	95 % CI	Mean	95 % CI	Mean	95 % CI	Mean	95 % CI	Mean	95 % CI	*P*‡
AUC	1780	1513, 2047	2045*	1769, 2321	1918	1650, 2185	1864	1579, 2149	2126*	1860, 2392	2145**	1877, 2412	0·007
Time to peak (min)	83	56, 123	64	41, 102	81	59, 110	99	67, 148	66	44, 99	61*	45, 83	0·006

Mean values were significantly different from control: * $P<0·05$, ** $P<0·01$.
† Gastric emptying was measured as percentage dose recovery of ^{13}C per h after ingestion of a fixed amount of test product. Total AUC over 240 min was calculated according to the trapezoid method. An increase in AUC reflects an increased amount of test product that is emptied into the duodenum over 240 min. Data on time to peak were log-transformed for analysis and are presented as back-transformed geometric means (± 95 % CI).
‡ *P*-value from mixed model ANOVA, and subsequently all fibre treatments were compared to control with Dunnett's procedure.

emptying rate. Gastric emptying rate even increased for alginate. Previous findings on the effects of viscous fibre[29,33,34] and gelling fibre[10,17] on gastric emptying have also been inconclusive. Despite this, increased viscosity as well as gel formation in digesta generally results in prolonged presence of nutrients in the small intestine, which in turn inhibits the absorption of glucose in blood and affects appetite-regulating peptides[35]. This process may have contributed to the reduced intake of high-dose alginate cookies in the present study.

The initial hypotheses on oral exposure time, gastric emptying rate and *ad libitum* intake could not be confirmed. This may be explained by the rate of hydration. When mixed with liquids (e.g. saliva and gastric secretion), viscous and gelling fibres are expected to be hydrated and induce thickening or form a gel. The thickening of a fibre depends not only on factors such as structure, dose and molecular weight, but also on the rate of hydration[35–37]. For gelling fibre, factors such as dose, pH, presence of Ca^{2+} and rate of hydration are crucial[31]. In the simulation study, the test product was finely ground and the incubation time in mouth, stomach and small-intestinal conditions were relatively long, respectively, 10, 60 and 180 min[23]. In real life, oro-gastric transit time may be faster, so fibres may not have been fully hydrated before arriving in the stomach and therefore not behave according to the anticipated working mechanisms.

In the present study, we showed that physico-chemical properties of fibres can affect food intake and satiation-related mechanisms in the upper gastrointestinal tract. Apart from the physico-chemical properties, as determined in simulated conditions, it should be realised that intraluminal conditions in the upper gastrointestinal tract, such as interactions with the digesta matrix, pH, hydration status and passage rate, have an impact on fibre properties and post-meal effects *in vivo*.

It is important to note that fibre properties associated with satiation (i.e. gel-forming in the present study) may not automatically be associated with a reduced energy intake or sustained satiety after repeated exposure. We previously showed that in the short term, viscous fibre increased satiety more than non-viscous fibre, whereas in the longer term, effects on energy intake and body weight were independent of viscosity[7]. Other mechanisms related to specific fibre properties, such as secretion of appetite-regulating peptides, inhibited absorption of nutrients from the lumen, enhanced insulin sensitivity and enhanced prebiotic activity, may interplay and affect energy intake or sustained satiety[38,39].

Conclusion

Addition of 5 g/100 g alginate (i.e. gel-forming fibre) to a low-fibre cookie resulted in earlier satiation in a real-life setting. This effect may be mediated by an increased oral exposure time. Guar gum (i.e. viscous fibre) and cellulose (i.e. bulking fibre) did not affect *ad libitum* intake. Fibre properties can% change after interaction with the food matrix and the environment in the upper gastrointestinal tract, and as a result this can change the effect on satiation.

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