Satiating Effects of Rye Foods

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Abstract

The satiating capacity of foods and meals is affected by caloric content, but also varies with several aspects of food composition (*e.g.* macronutrient composition, energy density, fibre content and food structure). Rye is a cereal that possesses interesting characteristics with the potential to increase satiety. There are currently public health threats related to overweight and obesity, conditions that result from energy intake exceeding energy output. Excessive energy intake can be avoided by diets based on foods that prolong the feeling of fullness per calorie.

This work aimed to study the effects of rye foods on subjective appetite. Ratings of satiety, hunger and desire to eat were recorded during 8 h after intake of well-characterised rye foods, compared with iso-caloric refined wheat bread, served as parts of breakfast meals in cross-over design studies. The effect of rye processing (sifting and milling) on perceived appetite was investigated by comparing rye kernels and whole-grain rye flour in breads and porridges. The effect of regular consumption of whole-grain rye porridge compared with refined wheat bread was investigated during three weeks, along with self-reported food intake and oro-caecal transit-time. Apparent small intestine absorption of macronutrients in response to diets supplemented with high-fibre rye or with low fibre wheat bread was studied in an ileostomy model.

All rye products (whole-grain porridges made from flour, flakes or kernels and breads including whole-grain flour, kernels or milling fractions) improved satiety and decreased hunger for up to 8 h after intake, in contrast to refined wheat bread. Rye bran as bread ingredient resulted in improved satiety compared with other rye fractions. The effect of milling was demonstrated as rye kernel intake resulted in higher satiety ratings appearing 4 h after intake and remained at a higher level during the following 4 h, compared with bread with the same material milled to flour. At regular consumption of whole-grain rye porridge for three weeks, the post-meal satiety was constant and remained at a higher level compared with refined wheat bread. Replacement of low-fibre wheat bread with high-fibre rye bread in a standardised diet resulted in higher amounts of all macronutrients being excreted from the terminal ileum in ileostomy subjects, showing lowered small intestine absorption of the high-fibre diet. A range of rye products was shown to improve satiety up to 8 h after intake and inclusion of rye foods into a healthy diet may thereby potentially prevent body weight gain.

Keywords: rye foods, satiety, breakfast, dietary fibre, human, intervention, ileostomy

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Dedication

Till Syster

Ingenting är säkert

Too-ticki

Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Isaksson H, Sundberg B, Åman P, Fredriksson H & Olsson J (2008). Whole grain rye porridge breakfast improves satiety compared to refined wheat bread breakfast. *Food & Nutrition Research,* 52**.**

II Isaksson H, Fredriksson H, Andersson R, Olsson J & Åman P (2009). Effect of rye bread breakfasts on subjective hunger and satiety: a randomized controlled trial. *Nutrition Journal,* 8:39.

III Isaksson H, Rakha A, Andersson R, Fredriksson H, Olsson J & Åman P (2011). Rye kernel breakfast increases satiety in the afternoon – an effect of food structure. *Nutrition Journal,* 10:31.

IV Isaksson H, Tillander I, Andersson R, Olsson J, Fredriksson H, Webb D-L & Åman P (2011). Whole grain rye breakfast – sustained satiety during three weeks of regular consumption. *Physiology & Behavior*. In press.

V Isaksson H, Landberg R, Sundberg B, Lundin E, Hallmans G, Zhang J-X, Tidehag P, Knudsen KEB, Moazzami AA & Åman P (2011). High-fiber rye diet increases ileal excretion of energy and macronutrients compared with low-fiber wheat diet independent of meal frequency in humans with ileostomy (submitted).

Papers I–IV are reproduced with the permission of the publishers.

The contribution of Hanna Isaksson to the papers included in this thesis was as follows:

I Designed and planned the study in collaboration with supervisors, evaluated the results and had main responsibility for writing and revising the paper

II Designed and planned the study in collaboration with supervisors, developed the test products, recruited subjects, performed the study, evaluated the results and had main responsibility for writing and revising the paper

III Designed and planned the study in collaboration with supervisors, developed the test products, recruited subjects, performed the study, evaluated the results and had main responsibility for writing and revising the paper

IV Designed and planned the study in collaboration with supervisors, developed the test products and study diets, performed the study in collaboration with Good Food Practice AB, evaluated the results and had main responsibility for writing the paper

V Main responsibility for writing the paper

Abbreviations

ANOVA	Analysis of Variance
BMI	Body mass index (kg/m^2)
CCK	Cholecystokinin
CIAA	European Food and Drink Federation
EFSA	European Food Safety Authority
FAO	Food and Agriculture Organization
GLP-1	Glucagon-like peptide 1
ILSI	International Life Sciences Institute
KIS	Keep it simple
PASSCLAIM	Process for the Assessment of Scientific Support for Claims on Foods
PYY	Peptide tyrosine-tyrosine
WHO	World Health Organization

1 Introduction

Physical wellbeing is in many respects dependent on homeostasis or equilibrium in the body's internal environment despite changing external conditions, as first proposed by physiologist Claude Bernard (Tortora & Grabowsky, 2000). Maintenance of body weight is achieved by a balance between energy intake and energy expenditure (FAO, 1998). A body weight (in proportion to body length as Body Mass Index, BMI, kg/m^2) within the range of 20-25kg/m^2 is related to several health benefits (James, 1996). A BMI above this apparent optimum is a strong predictor of overall morbidity and mortality, mainly due to vascular disease (Whitlock *et al.*, 2009). A body weight below this range is also associated with increased mortality on a population level. In order to maintain a steady body weight, energy intake and energy output must be carefully matched, a process that to a large degree occurs below individual awareness (Cohen, 2008). The sensation of hunger/motivation to eat generally occurs when energy intake is lower than energy expenditure, while when food intake is sufficient a feeling of satiety and satisfaction usually takes place. These sensations to some extent respectively encourage or discourage food intake (Blundell, 2006) and are considered a crucial element in maintenance of energy balance in humans (Stubbs *et al.*, 2000). However, the current living conditions in the Western world differ greatly from those prevailing only a couple of generations back (Hill, 2006; Hill *et al.*, 2003). These changes have had a major influence on food intake as well as energy output. Through efficient food production, food availability has increased. Relatively cheap, palatable and often energy-dense foods are easily accessible nearly everywhere at any hour, factors known to promote energy intake (Erlanson-Albertsson, 2005; Hill & Peters, 1998). Simultaneously, modern infrastructure allows for extremely sedentary life-styles. In combination, these factors have the potential to overwhelm energy regulation and are likely to play a role in the current increase in overweight and obesity rates (Hill, 2006). For people living in this environment, it is highly relevant to understand how different types of foods and diets affect hunger, satiety, motivation to eat and thereby energy intake.

1.1 Appetite regulation

Hunger is described as a mental urge to eat and is an important component in determining when and how much to consume. When food is eaten, the feeling of fullness, or satiety, arises. This is a consequence of cognitive and physiological responses to food intake, taking place before, during and after a meal (Blundell *et al.*, 1988). Satiation is a term describing within-meal satiety and takes place during ingestion of food, restraining further eating and bringing an eating episode to an end. Satiation thereby influences meal size. When an eating episode is brought to an end, satiety (between-meals satiety) develops. It influences the timing of the next meal and possibly meal size on the following eating occasion. Appetite is often used as a collective term referring to all aspects of motivation/inhibition of eating.

Subjective experiences of hunger and satiety are collective terms including a range of physical sensations and cognitive perceptions, with large individual variation (Monello & Mayer, 1967). Hunger is typically described as an uncomfortable and irritating sensation mostly related to stomach growls and aches, weakness, headache, pain and dizziness. Cerebral sensations most commonly recognised as hunger identifiers include the: urge to eat and preoccupation with food, anxiety and loss of concentration. A study using a figurative measure (Friedman *et al.*, 1999) showed that just above 50% of subjects associated slight hunger with a physical sensation in the stomach region, extending to additional body sites with increasing hunger. Satiety is usually described with a smaller number of sensations and is mainly associated with gastric bulk, relaxation and calmness. The early identified sensations interpreted as hunger and satiety have been confirmed in later works (Murray & Vickers, 2009; Mattes & Friedman, 1993).

The underlying biological system of appetite sensation and motivation to eat is comprehensive. The physiological response to food intake involves afferent neural and endocrine hormonal signalling that informs the brain about the amount and type of foods ingested (Ritter, 2004). Signals originate from multiple sites along the gastrointestinal tract, including the stomach, duodenum and distal small intestine. Identified circulating hormones of particular interest, which are released following food intake and involved in metabolism and inhibition of further intake, are CCK, PYY and GLP-1 (Delzenne *et al.*, 2010; Cummings & Overduin, 2007). Ghrelin is the most studied appetite-stimulating hormone and has been shown to decrease with food intake and increase before meals (Cummings, 2006). There are also some indications of signals arising in the colon playing a role in appetite regulation. Release of PYY and GLP-1 from colonic cells in response to bacterial fermentation, suggests a potential explanation for the satiating effects of prebiotic dietary fibre (Roberfroid *et al.*, 2010).

1.2 Measuring hunger and satiety

Despite the large individual variety in the underlying sensations and identifiers of hunger and satiety (Murray & Vickers, 2009; Mattes & Friedman, 1993; Monello & Mayer, 1967), it seems that most people can relate to and identify variations in these feelings, enabling subjective assessments with a simple set of questions. Physiologists and clinicians have a long tradition of using subjective feelings in research and patient care (Stubbs *et al.*, 2000). Investigations of pain, quality of life and depression typically use rating scales for quantitative assessments. For the purpose of measuring appetite-related feelings, different types of scales have been used, the most common being the Visual Analogue Scale (Stubbs *et al.*, 2000). This is a 100 mm (sometimes 150 mm) horizontal line representing a continuum of the subjective feeling in question. Questions regarding feelings of hunger, fullness, satiety, desire to eat and prospective consumption are presented next to the line, the opposite ends of which represent extremes of the feeling, such as extremely hungry/not at all hungry. Stubbs *et al.* (2000) reviewed available data and reported a good degree of within-subject reliability and validity, concluding that subjective ratings are sensible to experimental manipulations. An electronic version, greatly simplifying data collection and handling, is now in use (Stubbs *et al.*, 2001; Stubbs *et al.*, 2000; Stratton *et al.*, 1998).

When measuring subjective satiety after intake of a certain meal or food, several methodological aspects have to be taken into consideration (Blundell *et al.*, 2010). Since appetite measurements are clearly subjective, they are of most value as within-subject comparisons, with test foods being assessed in the same subject. The composition and manipulations of test and control foods is dictated by the research question. Foods are usually compared on an iso-caloric basis, *i.e.* the foods are served in portions providing identical amounts of metabolisable energy. Since many aspects of food composition potentially affect appetite, characteristics such as appearance, taste, volume and macronutrient composition may be matched. Test and control foods are then usually tested in a randomised order, alone or in the context of a meal, by a group of subjects that function as their own control when the foods are tested in a cross-over design under standardised conditions. Test occasions should be scheduled a week apart in order to avoid any carry-over effects. Subjective measurements of appetite (hunger, desire to eat, fullness, etc.) are self-recorded before and at regular time intervals (usually every 30-60 min) after the test meal. The period used for appetite measurements is usually somewhere between 1 and 3 hours.

Subjective ratings of appetite are often followed by measurements of voluntary food intake in an *ad libitum* test meal. *Ad libitum* translates as 'at one's pleasure' and in this context it involves presenting the subject with a large amount of food, more than could be eaten on one occasion. The subject is instructed to eat until comfortably satisfied. It is important to consider that the amount eaten does not necessarily only reflect satiation. For instance, opportunistic eating or a learned behaviour of clearing one's plate may cause overeating beyond satiation. These problems may partly be overcome by excluding subjects with high scores of dietary restrain, uncontrolled or emotional eating (Cappelleri *et al.*, 2009; Stunkard & Messick, 1985). In order to avoid the influence of a social context on eating behaviour, the subjects should be seated separately.

The timing of an *ad libitum* meal is crucial when designing a study. The period left between a test food and the *ad libitum* meal varies widely between studies. The best chance of seeing an effect on energy intake is probably at the time when satiety ratings differ the most as a result of different treatments. However, the persistance of satiety after consumption of test foods or meals is rarely known at the planning stage. A commonly employed design is the 'preload' approach, involves serving different well-defined test foods (preloads) 5-30 min prior to a main meal served *ad libitum*, in order to investigate the influence of manipulations of different preloads on food intake at the following meal (Rolls *et al.*, 2004). An alternative to a fixed time point for the *ad libitum* meal is to measure the time from consumption of a test food until the subject is hungry again and requests a meal (Marmonier *et al.*, 2000).

Another important aspect of appetite studies is the nature of the participants. Different people can be expected to respond differently to a fixed meal (Gregersen *et al.*, 2011) and, more importantly, may be more or less sensitive to experimental manipulations. Gender, age, BMI, physical activity level, smoking and eating habits may influence appetite ratings. As an example, Rolls *et al.* (1994) showed that the satiating efficiency of fat was lower in overweight subjects and in restrained normal-weight subjects than in unrestrained normal-weight men. Lomenick *et al.* (2009) reported that overweight children experienced lower satiety and stronger feelings of hunger compared with normal-weight children after consumption of a standard breakfast meal that was high in sugar. However, both groups of children had a similar appetite response to breakfasts high in protein and fat. Thus the ability to experience post-meal satiety after a breakfast rich in protein or fat did not differ between the groups, but the ability of overweight children to experience satiety after a breakfast rich in sugar was lower than that for normal weight children. Furthermore, the elderly may have impaired ability to detect and compensate for energy-dense foods and thus over-eat such foods. The ability to accurately compensate for energy in preloads is reported to be less precise in old men (n=16, aged 60-84 years) than in young men (n=16, aged 18-35 years), resulting in a higher energy intake in the elderly (Rolls *et al.*, 1995). This is an advantage in preventing undereating in undernourished elderly. In women, menstrual cycle affects appetite (Gregersen *et al.*, 2011; Brennan *et al.*, 2009). Ratings of hunger were lower after intake of a fixed glucose drink during the follicular phase compared with the luteal phase. In addition, gastric emptying rate was slower and glucose, insulin, GLP-1 and energy intake lower at the following meal during the follicular phase. Similar results on variations in appetite according to menstrual phase have been reported by Gregersen *et al.* (2011). The fact that people react differently to a defined food implies that satiety studies are best done by within-subject comparisons. Different groups vary in their ability to detect differences between test foods, which suggests that conclusions from studies in one group of people may not translate to a different group of people.

In the European Union, work to define methods and relevant study design to substantiate the satiating effect of foods for food labelling started in the PASSCLAIM project (Riccardi *et al.*, 2004) and has been continued by the ILSI Europe Appetite Regulation Task Force that together with an expert group recently published two papers on methodological aspects (Blundell *et al.*, 2010) and physiological targets for appetite regulation such as stomach emptying, gastrointestinal passage time, rate of absorption and peptides involved in food metabolism (Delzenne *et al.*, 2010). A draft document released by the EFSA on 26 April (2011a) suggests the following:

> "Claims on changes in different appetite ratings after consumption of a food, including increased satiety and/or reduced sense of hunger/appetite, have been proposed. Different appetite ratings can be measured *in vivo* in humans using validated visual analogue scales (*i.e.* behavioral assessment). Changes in certain biochemical markers (*e.g.* CCK) can only be considered in the context of the behavioural assessment.
>
> The beneficial physiological effects of changing appetite ratings in response to food consumption may be a decrease in subsequent energy intake and/or a decrease in body weight. If the health benefit of changing appetite ratings is to

decrease subsequent energy intake, subsequent energy intake should be measured using appropriate methods, and the effect should be sustained over time, taking into account possible compensatory effects. If the health benefit of changing appetite ratings is to decrease body weight, body weight changes should be measured. Other beneficial physiological effects of changing appetite ratings in response to food consumption should be specifically indicated, substantiated, and considered on a case-by-case basis. In general terms, changes in appetite ratings after consumption of a "test" food should also be observed after chronic consumption of the food (*e.g.* after one month), and therefore tests performed on a single occasion would not be considered sufficient for substantiation.

Claims on changes in appetite ratings after food consumption are generally comparative claims (i.e. comparison of the "test" food with the "control" food). In this context, both the test and the control food should be sufficiently characterised for a scientific evaluation, and comparable with respect to other factors (*e.g.* energy) than the food/constituent responsible for the claimed effect."

Thus suggested method for measuring the satiating effect of a specific food is to: (1) Under standardised conditions, in a cross over design, compare subjective appetite ratings after intake of well-controlled and characterised test and control foods: (2) validate the appetite with subsequent changes in energy intake: and (3) verify that the effect remains after regular consumption for at least 4 weeks.

1.3 Food components affecting satiety

Perceived hunger and satiety following food intake is not solely dependent on the caloric content of the foods eaten. Thus two foods or meals of similar energy content can result in different intensity and duration of satiety, depending on composition. The main food characteristics that have been studied in relation to satiety include: the relative effects of the major energy-providing macronutrients (protein, fat and carbohydrates); energy density; dietary fibre and whole-grain content; and food structure.

1.3.1 Macronutrients

A central aspect of food composition, which can influence satiation, satiety and energy intake, is macronutrient composition. The relative satiating efficiency of equal amounts of energy from protein, carbohydrate and fat have been investigated in different settings. Such studies usually employ a cross-over design, serving test foods/snacks or meals in isocaloric portions as breakfast, lunch or snack and thereafter, under standardised conditions, measuring subjective ratings of appetite at regular intervals. In order to measure subsequent food intake, an *ad libitum* meal is often included in the study design, served at 30 min before (preload design) or several hours after the test meal. On an iso-caloric basis, high-protein meals and diets result in stronger suppression of hunger and/or lower energy intake at the following meal, than meals high in carbohydrate or fat (Lomenick *et al.*, 2009; Marmonier *et al.*, 2000; Latner & Schwartz, 1999; Porrini *et al.*, 1997; Johnstone *et al.*, 1996; Stubbs *et al.*, 1996; Barkeling *et al.*, 1990). Regarding the relative satiating efficiency of carbohydrate and fat, carbohydrate seems to be more effective, whereas fat exerts a weak satiating effect relative to its energy content (Green *et al.*, 2000; Holt *et al.*, 1999; Johnstone *et al.*, 1996; Green *et al.*, 1994; Blundell *et al.*, 1993). These studies all use whole foods, with the implication that food characteristics other than macronutrient composition vary, such as energy density, water content, texture, flavour and visual impression, etc. The conclusions from these studies therefore concern the macronutrient composition of whole foods, meals and diets and cannot be extrapolated to the macronutrients per se, but should be valid in the context of macronutrient composition of a mixed diet.

When visual and oral cues have been obscured, the relative satiating effects of macronutrients are less clear. For example, differences in satiety after intake of equicaloric loads of sucrose, corn oil and protein were minimised by suppressing olfaction with nose-clips and taste with topical anaesthesia of the mouth (Geliebter, 1979). When the relative influence of carbohydrate and fats was investigated independently of any visual or oral stimulation by infusing them directly into the stomach (Shide *et al.*, 1995), they had similar satiating effects. This indicates an important influence of the pre-ingestive cognitive cues and of the oral phase on the relative satiating effect of carbohydrate and fat. Furthermore, the low satiating value of fat may to a large degree be attributable to its high energy density, as equal satiating efficiency was reported after consumption of foods rich in either fat, carbohydrate or protein when test foods were manipulated to equal energy density (Raben *et al.*, 2003; de Graaf *et al.*, 1992). In addition, meals with varying protein content (10%, 15%, 20%, 25% or 30% energy) that were matched for energy density, fat content, palatability and appearance, exerted similar effect on hunger ratings and energy intake (Blatt *et al.*, 2011).

The mechanisms involved are complex and involve different patterns of appetite hormone secretion in response to fat, protein and carbohydrates (Lomenick *et al.*, 2009; Karhunen *et al.*, 2008). Diet-induced thermogenesis, which decreases in the order protein>carbohydrate>fat is suggested to be partly responsible (Raben *et al.*, 2003).

To conclude, when macronutrient composition has been altered by the use of whole foods and those have been ingested in a natural manner, *i.e.* allowing oro-sensory and cognitive aspects to influence the results, protein-rich meals seem to bring about stronger satiety than those rich in carbohydrate and the least satiating meals are those rich in fat. These results seem to depend on other properties that are related to foods naturally rich in a particular macronutrient, *e.g.* sensory characteristics and energy density, and not only macronutrient composition as such.

1.3.2 Energy density

Food energy density, generally expressed as kcal or kJ per gram, affects satiety and food intake (Rolls, 2009). Energy density is determined by food composition and varies between 0 and 9 kcal/g in drinks and foods. Since the average energy value of fat (9 kcal/g) is more than double that of protein and available carbohydrates (4 kcal/g), macronutrient composition affects energy density. Furthermore, when dietary fibre, on average providing 2 kcal/g (FAO, 2003; FAO, 1998), replaces other macronutrients, the result is a lower energy density. Water content of a food also strongly affects energy density by contributing to weight but not energy.

The effect of variations in energy density on energy intake was shown by varying the water content in nutritionally identical 500-kcal cold milk-based drinks (300, 450, 600 mL) (Rolls *et al.*, 1998). The drinks were consumed as preloads in random order on separate occasions by 20 normal-weight young men in a cross-over study. *Ad libitum* energy intake at a meal served 30 min after the drinks was lower after the 600 mL drink than after the 300 and 450 mL drinks. Intake at an *ad libitum* dinner 4 h later was equal for all treatments. Thus, despite identical energy and nutrient content, increasing the volume by increasing the water content resulted in a lower energy intake 30 min after the test meal and this reduction was not compensated for at the meal 4 h later. Another preload-type study showed a similar effect of warm food (Rolls *et al.*, 1999). In this, a casserole was served as a starter 17 min before an *ad libitum* test meal. When the volume of the casserole was increased by adding water, satiety increased and lunch intake was lowered by 26% compared with the casserole without added water. The same study showed the importance of incorporating the water into the food. Drinking the same amount of cold water on the side of the casserole did not contribute to increased satiety or decreased energy intake. Satiation was also improved when energy density was lowered by addition of low-fibre vegetables (tomato and zucchini) to a meal (Latner *et al.*, 2009). Taken together, a lower energy density resulting from a more voluminous diet, increases satiety and decreases spontaneous intake within 30 min. However, these short-term results do not provide evidence of a long-term effect and adaptation to a diet with low energy density may occur by increasing portion size to compensate for the lower energy value of the foods. On the other hand, some medium-term studies indicate that the lower energy intake caused by a lower energy density diet is consistent over time. By varying the energy density of diets consumed *ad libitum* for two consecutive days, Bell *et al.* (1998) showed that a consistent amount of food was eaten irrespective of energy content. Thus fewer calories were spontaneously consumed with a diet with lower energy value per weight. However, Children (3-6 yrs), adapted their daily food intake according to the energy density of experimental diets eaten *ad libitum* for three days (Kral *et al.*, 2007). Results from a one-year intervention suggest that low energy density snacks beneficially influence weight-loss (Rolls *et al.*, 2005). Overweight subjects (n=147) were provided with two iso-caloric snack foods daily, with high (dry snack) or low energy density (soup), together with weight loss counselling. After one year the soup group had lost 50% more weight than the dry snack group. These studies indicate that short term compensation do not occur according to the energy density of foods in normal weight and overweight adults. Rather, a constant amount of food is eaten, which results in a spontaneous increase in energy intake with high energy density diets and a lower energy intake with low energy density diets. Few controlled long-term trials have tested the adaptation to a change in energy density, but population-based studies indicate that energy density of the diet is associated with body weight (Rolls, 2009). The mechanisms behind the influence of variations in energy density caused by water content on eating behaviour are likely complex involving cognitive, sensory and physiological influences (Rolls, 2009).

1.3.3 Cereal dietary fibre and whole-grain

Dietary fibre content in foods and meals has shown great potential to increase the feeling of fullness during and between meals (Wanders *et al.*, 2011; Slavin & Green, 2007). The concept 'dietary fibre' includes a wide range of plant food polysaccharides with one defining characteristic, that they cannot be degraded by human digestive enzymes. Despite the large variability, there are some general characteristics of many dietary fibre types and dietary fibre rich foods that may influence hunger and satiety. Firstly, through providing less energy than other macronutrients, dietary fibre reduces the energy density of foods by providing bulk but a relatively low quantity of energy. A low energy density has the potential to decrease food intake, because, as discussed in the previous section, food intake is determined by amount of food to a larger extent than by energy content (Leahy *et al.*, 2008; Bell *et al.*, 1998). Furthermore, naturally occurring dietary fibre contributes to structure and texture and increases the chewiness, extending the time taken for ingestion (Haber *et al.*, 1977) and thus prolonging the time for sensory perception and related satiety signalling (Ruijschop *et al.*, 2008). The lower palatability of some whole-grain foods compared with their refined counterparts may also lessen appetite (Sørensen *et al.*, 2003). On entering the stomach, some dietary fibre types have been shown to affect stomach emptying rate, through their rheological properties, such as viscosity- or gel-formation (Juvonen *et al.*, 2009; Sanaka *et al.*, 2007; Darwiche *et al.*, 2003), and digestion and absorption of macronutrients in the small intestine (Wolever & Jenkins, 1993). These effects may prolong the time during which the digesta is present in the gastrointestinal tract, enabling the release of satiety signals (Delzenne *et al.*, 2010; Maljaars *et al.*, 2008). There is also a possible influence on satiety when fermentable dietary fibres are degraded by the microflora in the colon, producing short-chain fatty acids available as energy for the human host (Cani *et al.*, 2009; Zhou *et al.*, 2008). Studies in rats conclude that the most likely mechanism explaining increased levels of satiety-related hormones in response to high intakes of resistant starch is gut fermentation (Zhou *et al.*, 2008). Further increased plasma concentrations of leptin resulted from oral administration of SCFA propionate in rodents, although no effect on food intake was detected (Covington *et al.*, 2006).

A number of short-term intervention studies on the effects of dietary fibre rich foods on satiety have been conducted. A total of 25 papers reporting short-term post-meal satiety after intake of 60 different fibre-rich products based on cereals are listed in Tables 1-4 (oats, wheat, barley and rye, respectively). The studies use whole-grain, parts of the grain or dietary fibre from cereal sources in a wide variety of foods. All studies listed use a within-subject design and iso-caloric portions of the test and control foods. Control foods are low in dietary fibre and mostly wheat-based. The studies cover a large range of subject characteristics, including an age range from 18-65 yrs. Younger subjects (20-36 yrs) are represented to a larger extent than middle-aged or older. Most studies include both sexes and subjects are in most cases normal-weight to slightly overweight, with only one study including obese subjects (Kim *et al.*, 2006).

Overall, the majority of the studies listed report increased satiety, suppressed hunger and/or a decrease in subsequent energy intake after consumption of foods rich in dietary fibre or whole-grain compared with iso-caloric low-fibre control foods (Tables 1-4). A number of studies fail to show any difference between products. The lack of overall consensus concerning the satiating effects of fibre-rich foods may reflect differences in experimental methodology, including characteristics of the individuals being tested and their background diet, the types of foods used, the source of the dietary fibre, the food matrix and interactions with additional test foods. An important consideration is also that many of the studies are not primarily designed to measure satiety, with the implication that the study design may not be optimised for detecting differences in the satiating capacity of the foods. One such issue is study power. Despite methodological variations, only one of the 25 studies listed reports that fibre-rich cereal foods result in lower satiety compared with a iso-caloric low-fibre control (Delargy *et al.*, 1997).

Table 1. *Satiating effect of **oat** products*

Test and control foods, portion size tested and dietary fibre (df) content/portion[1]	Duration of period for appetite measurements	Number of subjects	Results for satiety[2] after test compared with control food	Reference
Rolled whole-grain oats, prepared as porridge (174 g, 14.1 g df) *Control: refined wheat bread (94 g, 3.3 g df)*	120 min	n = 11	Higher satiety during 120 min	(Holt *et al.*, 1995)
Extruded oat flakes of whole-grain oats (50 g, 4 g df) *Control: Cornflakes* *(50 g, 1.5 g df)*	120 min	n = 12	No difference between products	(Hlebowicz *et al.*, 2007)
Extruded oat bran cereal (24.5 g, 9 g df) *Control: Cornflakes* *(17.5 g, 0.5 g df)*	120 min	n = 12	No difference between products	(Hlebowicz *et al.*, 2008a)
Bread with 40% whole-grain oats (240 g, 13.7 g df) *Control: refined wheat bread (224 g, 7.8 g df)*	Immediately after test food intake	n = 15	Higher satiety	(Berti *et al.*, 2005)
Bread with 40% whole-grain oats (81 g, 4.6 g df) *Control: refined wheat bread (74 g, 2.6 g df)*	Immediately after test food intake	n = 15	Higher satiety	(Berti *et al.*, 2005)
Pasta with 40% oats (200 g, 0.8 g df) *Control: wheat pasta* *(200 g, 0 g df)*	Immediately after test food intake	n = 14	Higher satiety	(Berti *et al.*, 2005)
Pasta with 40% oats (400 g, 1.6 g df) *Control: wheat pasta* *(400 g, 0 g df)*	Immediately after test food intake	n = 14	Higher satiety	(Berti *et al.*, 2005)

Bread with 45% oat bran (157 g, 9.1 g df) *Control: refined wheat bread (101 g, 2.2 g df)*	180 min	n=10	Higher satiety at 15 min	(Holm & Björck, 1992)
Muffin with bleached dietary fibre from oats and barley β-glucan (96 g, 9.4 g df) *Control: Muffin with no added df (76 g, 1.6 g df)*	180 min	n=20	No difference between products	(Willis *et al.*, 2009)
Bread with oat fibre (10.6 g df) *Control: refined wheat bread (low-fiber)*	300 min	n = 14	No difference between products	(Weickert *et al.*, 2006)
Beverage with oat β-glucan (400 g, 10.5 g df) *Control: Beverage (400 g, 0 g df)*	120 min	n = 19	Increased fullness during 120 min	(Lyly *et al.*, 2009)

[1]Within each study, test and control meals were served in iso-caloric portions and together with identical additional foods if any, unless otherwise stated. [2]For uniformity the term satiety is used to denote reported increase in satiety or fullness, lower hunger, lessened motivation to eat or lower appetite. Satiety results for the entire period measured, unless otherwise stated.

Table 2. *Satiating effect of **wheat** products*

Test and control foods, portion size tested and dietary fibre (df) content/portion[1]	Duration of period for appetite measurements	Number of subjects	Results for satiety[2] after test compared with control food	Reference
Bread of whole-grain wheat (146 g, 11.7 g df) *Control: refined wheat bread (119g, 3.6 g df)*	180 min	n = 16	Increased satiety during 180 min	(Kristensen *et al.*, 2010)
Bread of whole-grain wheat (101 g, 6.6 g df) *Control: refined wheat bread (94 g, 3.3 g df)*	120 min	n = 13	No difference	(Holt *et al.*, 1995)
Bread with 80% whole-grain wheat kernels (145 g, 8.1 g df) *Control: refined wheat bread (101 g, 2.2 g df)*	180 min	n = 10	Increased satiety at 15 and 180 min	(Holm & Björck, 1992)
Bread with 80% whole-grain wheat kernels (133 g, 7.2 g df)	120 min	n = 15	Increased satiety during 120 min	(Hlebowicz *et al.*, 2008b)
Bread with 80% whole-grain wheat flour (108 g, 7.2 g df) *Control: refined wheat bread (106 g, 2.1 g df)*			No difference	
Pasta of whole-grain wheat (84 g, 5.0 g df) *Control: refined wheat pasta (72 g, 2.2 g df)*	180 min	n = 16	No difference	(Kristensen *et al.*, 2010)
Pasta of whole-grain wheat (cooked weight: 210 g, 10.9 g df) *Control: refined wheat bread (94 g, 3.3 g df)*	120 min	n = 13	Higher satiety	(Holt *et al.*, 1995)

Rolled wheat, whole-grain (50 g, 7.4 g df) prepared as a hot cereal	120 min	n =19 (overweight/ obese)	Increased satiety during 60 min (women, n = 10) Increased satiety at 30 min (men, n = 9)	(Kim *et al.*, 2006)
Rolled wheat and barley, whole-grain (50 g, 7.4 g df) prepared as a hot cereal *Control: Glucose (75 g, 0 g df)*			Increased satiety during 60 min (women, n = 10) Increased satiety at 15 min (men, n = 9)	
Rolled wheat, whole-grain (56 g, 5 g df) prepared as a hot cereal and whole-grain wheat snack mix (30 g, 2 g df) *Control: refined rice hot cereal (56 g, 1 g df) and refined wheat snack mix (30 g, 0 g df)*	210 min	n = 47	Higher satiety	(Schroeder *et al.*, 2009)
Extruded wheat bran cereal (50 g, 4 g df) *Control: Cornflakes (50 g, 1.5 g df)*	120 min	n = 12	No difference	(Hlebowicz *et al.*, 2007)
Extruded cereal with whole-grain wheat and corn bran (60 g, 28 g df) *Control: Cornflakes (60 g, 1.8 g df)*[3]	180 min	n = 32	Increased satiety during 180 min	(Hamedani *et al.*, 2009)
Extruded cereal with whole-grain wheat and corn bran (90 g, 41 g df) prepared as a hot cereal *Control: low-fiber wheat cereal (44 g, 1 g df) prepared as a hot cereal*[4]	I: 60 min II: 120 min	I: n = 17 II: n = 16	I: Higher satiety at 15 min II: No difference	(Freeland *et al.*, 2009)

Extruded cereal with whole-grain wheat and corn bran (71 g, 33 g df) *Control 1: Cornflakes (30 g, 1 g df)* *Control 2: refined wheat bread (76 g, 0 g df)*	I: 75 min II: 150 min (standardised meal was served at 75 min)	I: n = 16 II: n = 15	I: Increased satiety only compared with control 2. II: Increased satiety compared with both controls	(Samra & Anderson, 2007)
Wheat bran cereal (160 g, 21.9 g df) *Control: low-fiber cereal (140 g, 3.1 g df)*	90 min	n = 15	Lower satiety	(Delargy *et al.*, 1997)
Extruded wheat bran cereal (33 g, 9 g df)[5] **Extruded** cereal with whole-grain wheat and wheat bran (33 g, 5 g df) [5] *Control: habitual breakfast*	240 min	n = 24	Higher satiety during 240 min Higher satiety during 120 min	(Turconi *et al.*, 1995)
Extruded wheat bran cereal (174 g, 14.1 g df) *Control: refined wheat bread (94 g, 3.3 g df)*	120 min	n = 11	No difference	(Holt *et al.*, 1995)
Extruded cereal with whole-grain wheat and corn bran (57 g, 22.2 g df) **Extruded** wheat bran cereal (57 g, 20.0 g df) **Extruded** corn and wheat bran cereal (57 g, 10.3. g df) **Extruded** whole-grain wheat cereal (57 g, 6.3 g df) *Control: Cornflakes (57 g, 0 g df)*	270 min (only measured at one single time-point)	n = 14	No difference Increased satiety No difference No difference	(Levine *et al.*, 1989)

Bread with wheat fibre (10.5 g df) *Control: refined wheat bread (low-fiber)*	300 min	n = 14	No difference	(Weickert *et al.*, 2006)
Beverage with wheat bran (400 g, 10.5 g df) *Control: beverage (400 g, 0 g df)*	120 min	n = 19	No difference	(Lyly *et al.*, 2009)

[1]See footnote 1, Table 1, [2]See footnote 2. Table 1. [3]The cereals were not served in iso-caloric portions but the results are expressed as change in appetite per kilocalorie. [4]Additional ingredients were added to equalise weight, volume and macronutrient composition between test and control cereals. [5]Served in two energy levels, the lower one is given here.

Table 3. *Satiating effects of **barley** products*

Test and control foods, portion size tested and dietary fibre (df) content/portion[1]	Duration of period for appetite measurements	Number of subjects	Results for satiety[2] after test compared with control food	Reference
Breads with 90% whole-grain barley kernels, four types:	Test foods eaten in the evening and appetite measurements taken during 180 min after a standardised breakfast meal	n = 15	Increased satiety as a result of the high β-glucan barley evening meal.	(Nilsson *et al.*, 2008a)
- whole ordinary (161 g, 20.2 g df)			No difference between other test foods and control	
- cut ordinary (190 g, 19.4 g df)				
- high amylose (213 g, 38.1 g df)				
- high β-glucan (388 g, 81 g df)				
Bread with added barley fibre (182 g, 19.1 g df)				
Control: Refined wheat bread (117 g, 3.9 g df)				
Bread with 70% high-amylose whole-meal barley flour, three types:	4-7 h (not measured during the first 4 h)	n = 10		(Liljeberg *et al.*, 1999)
- ordinary baking (159 g, 11.4 g df)			No difference	
- baked for a long time at a low temperature (164 g, 16.1 g df)			Increased satiety (at 4.75 h)	
- baked for a long time at a low temperature and preboiled flour (212 g, 18.8 g df)			Increased satiety (at 4 and 5.5 h)	
Bread (115 g) and barley flakes (62 g, total df bread + flakes: 36.2 g)			Increased satiety (at 4, 4.75 and 5.5 h)	
Control: refined wheat bread (123 g, 2.1 g df)				
Bread with 10% whole-grain barley flour (5 g df)	120 min	n = 7	Higher satiety	(Urooj *et al.*, 1998)
Bread with 15% pearled barley flour (6 g df)			Higher satiety	
Control: refined wheat bread (0.1 g df)				

Barley **cereal** (30 g, 8 g df) for breakfast and barley **bread** (110 g, 9.2 g df) and barley **muffin** (90 g, 5.3 g df) Total 22.5 g df. *Control: Branflakes (30 g, 5 g df) for breakfast and wheat bread (110 g, 4.4 g df) and refined wheat muffin (90 g, 1.4 g df) Total 10.8 df*	180 min (first measurement 6 h after intake)	n = 14	No difference	(Keogh *et al.*, 2007)
Rolled barley, whole-grain (50 g, 7.4 g df) prepared as a hot cereal *Control: glucose (75 g, 0 g df)*	120 min	n =19 (overweight/ obese)	Increased satiety during 60 min (women, n = 10) Increased satiety at 30 min (men, n = 9)	(Kim *et al.*, 2006)
Kernels of whole-grain barley (four varieties, 76-91 g, 15-19 g df) **Flour** of whole-grain barley (two varieties, 79 g/90 g, 15 g /18 g df/100g dw). All products were prepared as porridges *Control: refined wheat bread (403 g)[3]*	180 min	n = 10	Increased satiety for two of the barley kernel varieties. Increased satiety for one of the barley flour varieties.	(Granfeldt *et al.*, 1994)
Bread with concentrated barley β-glucan extract (100 g, 4.4 g df) *Control: refined wheat bread (93 g, 1.4 g df)*	180 min	n = 14	Increased satiety (at 120 and 180 min)	(Vitaglione *et al.*, 2009)
Rolled whole-grain barley (56 g, 12 g df) prepared as a hot cereal and whole-grain barley snack (30 g, 6 g df) *Control: refined rice flakes (56 g, 1 g df) prepared as a hot cereal and refined wheat snack (30 g, 0 g df)*	210 min	n = 47	Increased satiety at 210 min	(Schroeder *et al.*, 2009)

[1]See footnote 1, Table 1 [2]See footnote 2, Table 1. [3]Portion size provides 50 g potentially available starch. The meals were also adjusted to contain similar amounts of protein 19.0 g (with cheese) and fat 8.4 g (with butter).

Table 4. *Satiating effects of* ***rye*** *products*

Test and control foods, portion size tested and dietary fibre (df) content/portion[1]	Duration of period for appetite measurements	Number of subjects	Results for satiety[2] after test compared with control food	Reference
Bread with 75% whole-grain rye flour (123 g, 9.6 g df)	180 min	n=12	No effect	(Rosén *et al.*, 2009)
Bread with 75% sifted rye flour (106 g, 6.7 g df)			No effect	
Bread with 35% rye bran (142 g, 12 g df)			Higher satiety	
Sifted rye flour (45 g, 6.5 g df) prepared as **porridge**			Higher satiety	
Flour of whole-grain rye (51.1 g, 10.1 g df) prepared as **porridge**			Higher satiety	
Control: refined wheat bread (101 g, 1.8 g df)				
Bread of whole-grain rye flour (163 g, 20 g df)	180 min	n=10	Higher satiety (0-60 min)	(Rosén *et al.*, 2011)
Bread of sifted rye flour (135 g, 11.9 g df)			Higher satiety (0-60 min)	
Kernels of whole-grain rye (107 g, 25 g df)			Higher satiety (0-270 min)	
Control: refined wheat bread (124 g, 4.4 g df)				

[1]See footnote 1, Table 1. [2]See footnote 2, Table 1.

A few of the studies summarised in Tables 1-4 also measured food intake at a following meal. Some report lowered energy intake as a result of the higher satiety after intake of dietary fibre-rich foods (Rosén *et al.*, 2011; Freeland *et al.*, 2009; Vitaglione *et al.*, 2009; Samra & Anderson, 2007; Holt *et al.*, 1995). However, despite improved satiety, test products high in dietary fibre did not result in altered energy intake in other studies (Kristensen *et al.*, 2010; Schroeder *et al.*, 2009; Kim *et al.*, 2006; Berti *et al.*, 2005; Delargy *et al.*, 1997; Levine *et al.*, 1989). One study (Keogh *et al.*, 2007) even measured a self-reported increase in energy intake following the high-fibre barley diet. The inconsistent relationship between perceived satiety and subsequent energy intake may relate to the timing of the test meals, which varies between 75-270 min after test food intake. An effect on energy intake is probably most likely to be observed during the time when satiety is affected, but the persistence of the effect is rarely known at the planning stage. For instance Kim *et al.* (2006) reported increased satiety during the first hour after intake of wheat and barley porridges compared with a low-fibre control. However when the test meal was served 2 h later, the satiety ratings were indistinguishable between products. This decreases the likelihood of any variability in energy intake and may explain the lack of effect on energy intake. Holt *et al.* (1995), comparing 37 different foods eaten for breakfast, reported that energy intake 2 h later was highly associated with the satiety scores on an individual level ($p<0.001$).

The concept that a diet rich in dietary fibre and whole-grain can increase the feeling of fullness and thereby spontaneously result in lowered energy intake, followed by a decreased risk for overweight, is supported by epidemiological data. Diets rich in dietary fibre are associated with a lower BMI and are protective against weight gain in different populations (Maskarinec *et al.*, 2006; Schulz *et al.*, 2005; Koh-Banerjee *et al.*, 2004; Liu *et al.*, 2003). Recent reviews conclude that body weight is inversely associated with the intake of high-fibre, whole-grain foods but not with the intake of refined grain foods (Williams *et al.*, 2008; Gaesser, 2007; Koh-Banerjee *et al.*, 2004). This protective effect of dietary fibre and whole-grain consumption may also be partly mediated by lowered digestibility of macronutrients and thereby lowered energy value of the diet (Baer *et al.*, 1997; Miles *et al.*, 1988; Southgate & Durnin, 1970). The evidence for a protective role of dietary fibre in preventing obesity has been classified as convincing by the WHO (2003).

In conclusion, fibre from different sources included in a variety of different foods eaten in a mixed diet protects against weight gain, most likely due to increased satiety. However, it is not certain that a fibre-rich food will increase satiety in all circumstances and an increased understanding of how different fibre sources, food matrixes and meal compositions affect the intensity and duration of satiety is of importance.

1.3.4 Food structure

Structure is another characteristic affecting the metabolism of foods. The botanical structure of cereal grains such as wheat, oats, and rye is maintained to varying degrees during food processing (Figure 1). The grains can be cracked, cut, rolled or milled before being used in a wide range of products, including breads, pasta and breakfast cereals. The breakdown of botanical structure by milling of whole-grain cereal result in an increase in the rate of digestion and absorption of macronutrients after consumption of wheat, rye, barley, oats, maize and rice (Heaton *et al.*, 1988; Jenkins *et al.*, 1988; Jenkins *et al.*, 1986; Odea *et al.*, 1980), as shown by altered postprandial changes in blood glucose.

Figure 1. Rye kernels, whole-grain rye flakes and whole-grain rye flour.

Furthermore, cereal grain structure influences postprandial levels of hunger and satiety. Previous meal studies (Table 5) investigating the effect of intact botanical structure of cereal kernels from rye, wheat and barley show that disruption of the structure can decrease the satiating capacity of cereal-based food products up to 4.5 h after intake. A significant decrease in subsequent *ad libitum* food intake has also been noted (Rosén *et al.*, 2011). Intake of rye kernels for breakfast resulted in a mean energy intake of 843 kcal 4.5 h later, which was significantly lower than for an iso-caloric refined wheat bread control that resulted in a mean intake of 1000 kcal. However milling of rye (whole-grain rye flour bread) resulted in an energy intake (983 kcal) similar to that of refined wheat bread (Rosén, 2011). Another interesting point is that intact structure of some fruits has been shown to improve satiety (Bolton *et al.*, 1981; Haber *et al.*, 1977), while solid carrots eaten with a mixed meal resulted in a lower spontaneous energy intake compared with the same amount of blended carrot (Moorhead *et al.*, 2006). Furthermore, solid apple was shown to enhance satiety more than puréed fruit or juice, and including the solid fruit into a meal reduced energy intake (Flood-Obbagy & Rolls, 2009).

The studies reviewed suggest a role of intact food structure in improving the satiating power of foods. The underlying physiological mechanism explaining this effect most likely involves several factors. Firstly, a prolonged period of ingestion (Haber *et al.*, 1977) will stimulate early cephalic satiety signals (Ruijschop *et al.*, 2008). Furthermore gastric distension, gastric emptying rate and hormonal effects relating to variations in digestion and absorption are likely to play an important role. An intact botanical structure of cereal grains can also lower the digestibility (Nitrayova *et al.*, 2009; Pettersson & Åman, 1989) and result in more material being available for colonic fermentation, suggested to influence satiety (Cani *et al.*, 2009; Zhou *et al.*, 2008).

Table 5. *Satiating effects of intact cereal grains compared with milled whole-grain cereal*

Test foods and portion size[1]	Duration of period for appetite measurements, number of subjects	Results for appetite compared with control (for the entire period measured unless otherwise stated)	Reference
Rye kernels, boiled, 227 g Bread made from 100% whole-grain rye flour, 163 g	270 min n = 10	Increased fullness (120-270 min) after intake of rye kernels compared with the whole-grain rye flour bread	(Rosén *et al.*, 2011)
Bread with 80% **wheat** kernels, 133 g Bread with 80% whole-grain wheat flour, 108 g	120 min n = 13	Increased satiety (120 min) after intake of the bread with wheat kernels compared with the bread with whole-grain wheat flour	(Hlebowicz *et al.*, 2008b)
Wheat: - whole-kernel, 78 g - cracked, 78 g - coarse flour, 78 g - fine flour, 78 g The cereals were covered in water and oven-baked	120 min n = 10	120 min satiety AUC: kernel 293 ± 82 cracked 305 ± 51 coarse flour 243 ± 38 fine flour 231 ± 32 (NS, p<0.05)	(Holt & Miller, 1994)
Barley (ordinary, covered)[2]: - kernels, 76 g - flour, 79 g Barley (high-amylose, covered) - kernels, 88 g - flour, 90 g All products were prepared as porridges	180 min n = 10	180 min satiety AUC: Barley (ordinary): kernels 484 ± 134 flour 382 ± 98 Barley (high-amylose) kernels 432 ± 87 flour 580 ± 145 (NS, p<0.05)	(Granfeldt *et al.*, 1994)
Bread with 80% whole-kernel **barley**, 160 g Bread with 80% cut-kernel barley, 190 g	120 min[3] n = 15	Appetite ratings similar between products	(Nilsson *et al.*, 2008b)

[1]Within each study, test and control meals were served in iso-caloric portions and together with identical additional foods if any, unless otherwise stated. [2]Each test portion provided 50 g of available carbohydrate and was served with varying amounts of cheese and butter to adjust for variation in protein and fat content. [3]Test meals served as evening meals and appetite measurements were made within 120 min of a standardised breakfast. NS = not significant, AUC = Area under the curve.

1.4 Definitions of whole-grain and dietary fibre

Cereal whole-grain is defined by the American Association of Cereal Chemists (AACC, 1999) as:

> "Whole grains shall consist of the intact, ground, cracked or flaked caryopsis, whose principal anatomical components - the starchy endosperm, germ and bran - are present in the same relative proportions as they exist in the intact caryopsis."

The main cereals consumed as whole-grain in the Western world are wheat, corn, rice, oats, barley and rye. U.S. Food and Drug Administration (2006) suggests that types of cereal grains may also include amaranth, buckwheat, corn (including popcorn), millet, quinoa, sorghum, teff, triticale and wild rice. A recent definition suggested by the European Union project HEALTHGRAIN (Healthgrain Consortium, 2010) agreed on inclusion of cereals and pseudocereals and allowed removal of as much as 10% of the bran. There is currently no universal agreement on the exact definition with questions remaining regarding processing and range of cereals to be included. Whole-grain foods are an important source of dietary fibre, defined by the European Commission (2008) as:

> "carbohydrate polymers with three or more monomeric units, which are neither digested nor absorbed in the human small intestine and belong to the following categories:
>
> - edible carbohydrate polymers naturally occurring in the food as consumed;
> - edible carbohydrate polymers which have been obtained from food raw material by physical, enzymatic or chemical means and which have a beneficial physiological effect demonstrated by generally accepted scientific evidence;
> - edible synthetic carbohydrate polymers which have a beneficial physiological effect demonstrated by generally accepted scientific evidence."

This definition is nearly identical to the Codex Alimentarus definition (Phillips & Cui, 2011), except that according to Codex, the inclusion of oligosaccharides is not mandatory, but is open for decision by individual nations.

1.5 Rye

Rye (*Secale cereale* L.) is a cereal especially high in dietary fibre and is traditionally consumed as whole-grain (Åman *et al.*, 2010).

1.5.1 Production and consumption

The European Union produces 7-10 million tons of rye yearly, of which 3 million tons are used in food for humans (FAO, Faostat). For comparison, the amount of wheat used for food is 17 times higher. Globally, rye constitutes as little as 0.5% of total cereal production. Rye is cold-resistant and most production takes place in temperate climates. The Russian Federation, Germany, Poland, Ukraine and Belarus produced 80% of the total world production in 2009, while Sweden produced around 1%. Rye is mainly consumed in the Northern and Eastern European countries, which all exceed the European average of 7 kg/yr (2007; Figure 2). Within the EU, Poland is at the top, with a mean annual rye consumption of 30 kg/person (2000-2007). This equates to 80 g rye per day, indicating that rye products constitute a substantial part of the diet. Rye consumption per capita has decreased by 65% over the last 50 years (Figure 2). Bread is by far the most common rye product, including sour dough breads, loaf bread based on sifted rye flour and crisp bread, followed by rye flakes, used for baking, porridge and breakfast cereals.

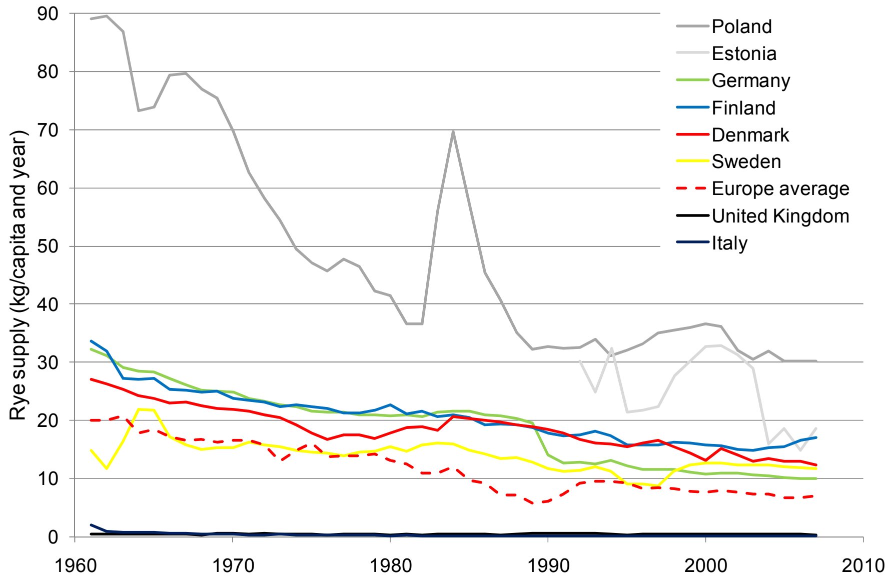

Figure 2. Yearly supply of rye for human consumption, kg per capita 1961-2007 (FAO, Faostat).

The use of rye in feed for monogastric animals is limited due to its anti-nutritional properties, which have mainly been linked to the high amounts of soluble arabinoxylans. Good proof of this concept is that supplementation with arabinoxylan-degrading enzymes largely eliminates the anti-nutritional effect of rye feed (Frigård *et al.*, 1994). In humans these properties of rye may be beneficial, giving rise to a lower digestibility of macronutrients and more material for colonic fermentation.

1.5.2 Composition

Analysis of 10 European varieties of rye demonstrated a macronutrient composition of (% of dry matter): protein 11.5-16.0, lipids 2.5-3.0, digestible starch and free sugars 57-62 (Nyström *et al.*, 2008). The composition is similar to that of wheat (Gebruers *et al.*, 2010) and barley (Andersson *et al.*, 2008), whereas oats has higher lipid content and is lower in starch (Andersson *et al.*, 2008).

The dietary fibre content of rye is high, ranging between 18-22% (Andersson *et al.*, 2009) of which about a third is extractable. The main dietary fibre components of rye are arabinoxylan, ranging from (8-12%) of dry matter, fructan (4.5-6.4%), β-glucan (1.3-2.2%) and cellulose (1.0-1.7%) (Hansen *et al.*, 2003). Small amounts of Klason lignin (0.9-1.4%) and arabinogalactan are also present (Andersson *et al.*, 2009). Changes in dietary fibre characteristics such as molecular weight distribution and extractability due to processing and preparation of foods are considerable (Andersson *et al.*, 2009) and may affect physiological effects after rye consumption.

Rye is also a rich source of vitamins and minerals. A daily intake of 100 g whole-grain rye provides 20-50% of the recommended daily intakes of several vitamins and minerals (Table 6). A 100 g portion of whole-grain rye would comprise a substantial part of the diet, but is still realistic. A standard portion of porridge represents between 35 and 55 g, and along with one to two slices of whole-grain rye bread the 100 g level is easily reached. However, 100 g whole-grain rye only contributes about 15% of the average daily energy requirement,

Table 6. *Contribution to Recommended Daily Intake (RDI) of some vitamins and minerals present in whole-grain rye*

Nutrient	Content in 100 g whole-grain rye[1]	RDI[2]	% of RDI in 100 g whole-grain rye
Thiamine (B1)	0.2 mg	1.1 mg	18%
Vitamin B6	0.35 mg	1.4 mg	25%
Folic acid	50 µg	200 µg	25%
Phosphorus	350 mg	700 mg	50%
Magnesium	110 mg	375 mg	29%
Iron	2.8 mg	14 mg	20%
Zinc	2.5 mg	10 mg	25%

[1]National Food Administration, www.slv.se. [2]European Commission (2008).

making whole-grain rye an excellent way to increase the nutritional quality of the diet. However, it should be noted that by binding to phytic acid present in the aleurone layer of rye bran, the availability of some minerals can decrease (Idouraine *et al.*, 1996; Sandberg *et al.*, 1982).

Other bioactive compounds present in rye include plant sterols, phenolic acids, alkylresorcinols and lignans (Nyström *et al.*, 2008). The content of some of these compounds and vitamins is affected by processing of rye foods (Liukkonen *et al.*, 2003).

1.5.3 Rye foods

The processing of rye to produce food products involves the main steps: cleaning, heat treatment and removal of the husk, which can be followed by peeling, cutting, flaking, milling and sifting. Before rolling of rye to make flakes, the grains are steamed to increase the water content and soften the grain so they remain whole through the rolling process, when flakes are formed. Rye flakes can be produced from whole rye kernels, or cut kernels can be used to decrease the cooking time. The thickness of the flakes also influences the cooking time. An intact rye kernel that has not been rolled requires about 40 min of boiling before the consistency is soft enough to chew. Cracking the kernels by rolling to 1.8 mm shortens the cooking time to 12-16 min. Flakes used for porridge are usually between 0.5-0.9 mm thick and require a boiling time of between 3 and 10 min. Thin flakes can also be eaten uncooked and used in muesli. Rye flour is used as an ingredient in a large variety of foods. The main use is in bread, but it is also used in extrusion of cereal flakes, muffins, pastries and other flour-based foods. Milling of rye kernels makes whole-grain rye flour (extraction rate 100%) or different milling fractions of varying composition can be obtained. In Sweden, rye flour with an extraction rate of about 80% is commonly used in breads to improve baking quality and to create softer breads that are lighter in colour and milder in flavour than whole-grain rye breads. The use of sifted rye rather than whole-grain rye lowers the dietary fibre content and other substances associated with the bran fraction. However, sifted rye still contains more dietary fibre than sifted wheat flour due to high dietary fibre content throughout the rye kernel.

1.5.4 Health effects

Health outcomes investigated in intervention studies in relation to rye consumption include: blood cholesterol levels (Lundin *et al.*, 2004; Leinonen *et al.*, 2000), cholesterol absorption (Hallikainen *et al.*, 2006), improved insulin and glucose metabolism (Laaksonen *et al.*, 2005; Lundin *et al.*, 2004; Juntunen *et al.*, 2003; McIntosh *et al.*, 2003; Nygren *et al.*, 1984), inhibition of prostate cancer progression (Landberg *et al.*, 2010; Bylund *et al.*, 2003) and improved bowel function and easing of constipation (Holma *et al.*, 2010; Gråsten *et al.*, 2007; Hongisto *et al.*, 2006; McIntosh *et al.*, 2003; Gråsten *et al.*, 2000). Regarding the development of type 2 diabetes, epidemiological reports indicate a protective association of whole-grain consumption (Priebe *et al.*, 2008). In a Finnish population, where rye intake is high, reported an inverse association between intake of whole-grain and the risk of type 2 diabetes (Montonen *et al.*, 2003). Given the nutritional profile and several promising indications for positive health effects, especially those against major threats to human health such as obesity and vascular disease, increased use of rye for human consumption would be beneficial, with great potential for health improvement.

2 Objectives

The overall aim of this thesis was to investigate the effects of rye foods on subjective hunger and satiety.

Specific aims of this work were to study:

- The effect of rye products (breads and porridges) compared with iso-caloric reference bread served as parts of standardised breakfast meals on perceived appetite during 8 h after intake (Paper I-IV).

- The effect of rye milling fractions used as ingredients in breads served as parts of standardised breakfast meals on perceived appetite during 8 h after intake (Paper II).

- The effect of milling by including rye kernels and whole-grain rye flour in breads and porridges, served as parts of standardised breakfast meals, on perceived appetite during 8 h after intake (Paper III).

- The effect of regular consumption of whole-grain rye porridge or refined wheat bread breakfasts for three weeks on perceived appetite during 8 h after intake. A secondary aim was to measure oro-caecal transit-time and self-reported energy intake (Paper IV).

- The effect of replacing low-fibre wheat bread with high-fibre rye bread in a standardised diet, on 24 h ileal excretion of nutrients (fat, protein, amylase-available starch and dietary fibre) in an ileostomy model (Paper V).

3 Materials and methods

3.1 Designing the studies

As described earlier, there are several options available when designing appetite studies. We assessed subjective appetite by the use of electronic rating scales (Stubbs *et al.*, 2001; Stratton *et al.*, 1998) before and during 8 h after intake of breakfast meals (Paper I-IV; Figure 3). Test foods were evaluated in the same subjects in a cross-over design, under the same conditions. Test occasions were separated by 1-2 weeks. General aspects that were considered when planning the design used in Paper I-V are described below.

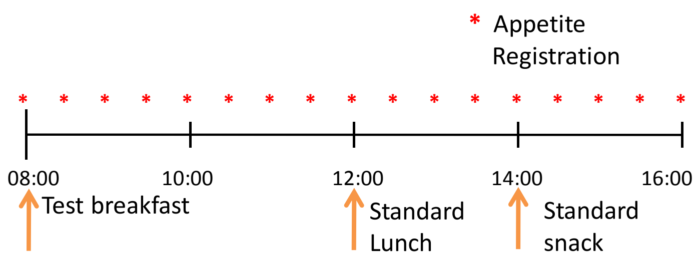

Figure 3. Study design for the test days in Paper I-IV

When planning the composition and timing of the test meal and standardised diet, the primary aim was to match a realistic meal and meal pattern as closely as possible as regards caloric content of the meals, macronutrient composition, choice of test foods and additional foods and timing of the meals. In the first stage, we were interested in how different breakfast products, served in portions with identical energy content, would influence satiety and hunger during the morning hours before lunch. A realistic period between breakfast and lunch was assumed to be at least 4 h and therefore the lunch meal was served 4 h after the start of the breakfast. The test products were served in a portion size that together with additional breakfast foods, standardised in terms of type and amount (Figure 4), provided energy corresponding to national recommendations (National Food Administration, 2005). The alternative to serve the test foods alone, with no additional foods, was not an option, primarily because the caloric content of the breakfast would be low, with the risk of reaching high levels of hunger towards lunch and potentially lowering the chances of seeing differences between foods. Another option, serving the test food in a large enough portion to provide sufficient energy to last until lunch, was ruled out on the basis that the results would then be dependent on an unrealistic portion size. A secondary consideration was that eating the test foods alone would lower the applicability of the results, since these types of foods (cereal-based breads and porridges) are rarely eaten by themselves in real life but mostly in the context of a meal. The additional breakfast foods used were intended to be as representative and general as possible (Becker & Pearson, 1999). For Papers I, III and IV, which compared rye porridges with refined wheat bread, the test foods were served along with margarine (eaten on the bread or stirred into the porridge), jam, milk (on the porridge or in a glass on the side) and coffee or tea.

In addition to comparisons of breakfast meals, Paper I examined different test meals for lunch and appetite measurements were continued during the afternoon. This study showed no effect of lunch manipulation (whole-grain vs. refined wheat pasta) on appetite ratings in the afternoon. On the other hand, the breakfast meal (whole-grain rye porridge) resulted in a long-lasting effect over the whole 8-h period of measurement. Therefore, in the following studies (II-IV), appetite was measured in an 8-h perspective under standar-

Figure 4. Test breakfast with rye bran bread served with standardised additional breakfast foods.

dised conditions.

Appetite measurements are often validated by measuring food intake at a following meal (Blundell *et al.*, 2010) using an *ad libitum* test meal. This meal is preferably offered at a point in time when appetite ratings differ the most. Flint *et al.* (2000) measured lower differences 4 h after a meal than directly following the meal. In our case, the 8-h standardised period ruled out the option of an *ad libitum* meal in the most relevant time period and this was therefore not included except in the first study (Paper I), in which an *ad libitum* meal was served at 8 h after the test breakfast.

Another aspect of interest regarding study design is standardisation of the day prior to the test. Flint *et al.* (2000) reported no or negligible benefit of a standardised diet for two days prior to the test day compared with allowing the subjects to keep to their habitual diet. In our studies, we chose to instruct subjects carefully regarding food and drink intake as well as physical activity on the day prior to the test. During the test day, subjects stayed at the study centre for the entire period of measurement (Paper I) or were allowed to return to their sedentary daily activities after intake of the test breakfast (Papers II-IV).

Furthermore, we chose to keep the full focus on appetite measurements and not include physiological measurements that have been suggested to relate to satiety. This prioritisation was made to keep the full focus on the subjective satiety measurements in order to optimise the quality of these and avoid the risk of disturbing the subjects with simultaneous blood measurements. The central role for subjective appetite measurements in the assessment of hunger and satiety has also recently been stressed by both the ILSI Appetite Regulation Task Force (Blundell *et al.* 2010) and the EFSA (2011a).

In order to investigate the satiating effect of rye porridge at regular consumption, a three-week study was performed (Paper IV). Subjects (n=24) were randomly assigned to daily consumption of iso-caloric standardised breakfast meals with whole-grain rye porridge and refined wheat bread for two 3-wk phases, separated by a wash-out period of 3-4 weeks. Each intervention phase had three scheduled visit days (days 1, 8 and 22) when appetite ratings were recorded according to the same procedure as for the short-term studies (Paper I-III). In Paper IV, the period for measurements and standardised conditions was extended until bedtime. Physiological measurements of oro-caecal transit-time and gut fermentation were made in a subgroup (n=16) on day 8 of both treatments. Day 8 was chosen to avoid the risk of disturbing or shifting the focus from the subjective satiety measurements on the most important test days, namely the first and last day. An intervention period of three weeks was considered to be long enough for possible adaptations but not long enough to risk potential changes in body weight.

Both dietary fibre content and type can influence the physiological response of a diet. High-fibre diets can lower the small intestine digestibility of the diet and thus lower the metabolisable energy value of the diet or/and alter the site for energy uptake by resulting in unabsorbed material entering the colon and becoming available for fermentation by the colonic flora. To examine the effect of high-fibre rye diets on apparent small intestine digestibility, a 2 x 2-week intervention study was performed on ileostomy subjects (Paper V). Ten ileostomy subjects consumed a standardised iso-caloric diet including low-fibre wheat bread (20 g dietary fibre/day) for two weeks, followed by high-fibre rye bread (52 g dietary fibre/day) for two weeks. The study also examined the effect of meal frequency on apparent small intestine absorption of energy. Therefore, both diets were consumed as 3 meals/day and 7 meals/day. Meal frequency was arranged in a cross-over design and changed in the middle of the two-week periods. Ileal effluent was collected over 24 h at the third day of each of the four dietary periods and analysed for energy and nutrient contents. The bags were changed every 2 h and the contents immediately frozen in order to minimise the effect of bacterial degradation of the contents (Sandberg *et al.*, 1981).

3.2 Appetite measurements

As described earlier, individuals describe the physical and cognitive sensations referred to as hunger and satiety in diverse ways, with no single traits characterising the sensations. Thus, the terms refer to categories of subjective experiences that differ between individuals. Therefore, underlying sensations that are interpreted, identified and described by individuals as hunger, satiety *etc*. are not relevant for investigation, but the most reliable outcome is achieved when hunger and satiety are asked for and the content or definition of those remains open for individual interpretation (Blundell, 1979).

Appetite measurements were registered on subjective rating scales at regular intervals, every 30 min. Unipolar unmarked scales including three questions presented one at a time (Figure 5) were used in all studies (Papers I-IV). The data were collected using a programme designed for hand-held computers (Stubbs *et al.*, 2001; Stratton *et al.*, 1998). The model used (model Palm z22, Palm Inc, Sunnyvale, USA) is operated by tapping on the screen with a rubber pen and it mimics the use of pen and paper (Figure 6). Like the conventional 100-mm visual analogue scale, the computerised system translates a mark along the scale to a number between 0 and 100, starting from the left. The electronic rating scales, also referred to as the electronic appetite rating system (EARS), was developed to overcome potential errors and inadequacies of the paper visual analogue questionnaires. Electronic rating scales have been found to be sensitive and reliable for the collection of appetite data (Stubbs *et al.*, 2001; Stratton *et al.*, 1998).

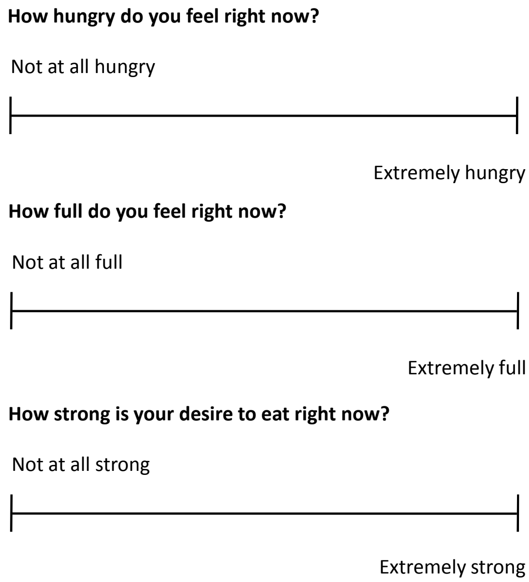

Figure 5. Scales and questions used to assess subjective appetite (Papers I-IV).

Figure 6. Electronic appetite rating system on a hand-held computer.

3.3 Recruiting the subjects

Normal to slightly overweight (BMI 18-27 kg/m^2) men and women aged between 18 and 60 years were invited to participate (Papers I-IV). Recruited individuals had regular eating habits in terms of daily consumption of breakfast, lunch and dinner and no eating disorders (self-reported in Papers I-III and assessed by a questionnaire in Paper IV). Papers I-IV used the following criteria for exclusion: intake of medicine likely to affect appetite or food intake; any medical condition involving the gastrointestinal tract; eating disorder; smoking; consumption of more than three cups of coffee per day; change in body weight of more than 10% in the three months prior to screening; consumption of any restricted diet such as vegan, gluten-free, slimming, *etc*.; and pregnancy, lactation or wish to become pregnant during the study period. Blood samples were also taken to ensure normal metabolism, including measurements of fasting glucose, thyroid and liver function, as well as haemoglobin. Paper IV also assessed physical activity level (Johansson & Westerterp, 2008), cognitive and behavioural components of eating, and energy intake as reported by a 3-day weighed food diary. Subjects were not included if they had high levels of cognitive restraint, uncontrolled eating or emotional eating (Stunkard & Messick, 1985), or reported below or above a mean of 1750-2750 kcal daily energy intake based on a 3-day weighed food diary completed during screening.

Recruitment of subjects was done in different groups for Papers I-IV: advertising in a local paper, Uppsala, Sweden (I), internal e-mail to employees in a private company (II), internal e-mail to university students and employees (III) and advertising in a local newspaper and on the website of the clinic where the study was performed (Paper IV). Potential subjects were interviewed over the telephone or in person before being booked in for a screening visit including health control with measurements of height and weight for BMI calculations and blood measurements. Flint *et al.* (2000) investigated the number of test participants needed to provide sufficient enough power to detect differences in sensations of hunger, satiety, fullness and appreciation of prospective consumption using the visual analogue scale. They measured mean values during 4.5 h and concluded that with a paired design, between 9 and 34 individuals are needed to detect a product induced difference in satiety of between 5 and 10 mm at a power of 90%. We aimed for a sample size of around 20 subjects (Paper I). Papers II-IV included between 16 and 24 subjects. To study the effect of high-fibre rye bread diet on apparent small intestine absorption of macronutrients (Paper V), 10 ileostomy subjects were recruited. All subjects were proctocolectomised for ulcerative colitis 8-29 yrs before the study.

3.4 Choosing the study products

A variety of rye-based breads and porridge products (Table 8) were studied in Papers I-IV. Bread made from refined wheat flour, served to provide an equal amount of calories as the test product within the comparison, was used as reference product in all studies.

Figure 7. Porridge made from whole-grain rye flakes served with lingon berry jam.

The aim in Paper I was to identify and test a food product that by its composition and characteristics would have the potential to provide a high satiating capacity, when compared on an iso-caloric basis with a relevant reference product. With the background information regarding the satiating efficiency of food components, the cereal rye was an interesting food raw material for several reasons. Firstly, the dietary fibre content of rye is higher than that of many cereals. When fructan is included in total dietary fibre, whole-grain rye contains around 20% of dietary fibre (Andersson *et al.*, 2009). Secondly, rye is an affordable and safe food, with a long tradition of consumption and is easily accessible to people. In order to further increase the potential for improved satiety, there is the possibility to prepare rye as porridge (Figure 7). Porridge has a large volume and a low energy density due to its high water content, a food property with potential to increase within-meal satiety and decrease food intake, as discussed earlier. The most common form of rye used for porridge is rolled whole-grain flakes, which is interesting because processing of rye kernels into flakes retains some original botanical structure. Food structure, as discussed earlier, is a food property that has been shown to alter metabolism of cereal grains, including satiety. As the reference product, refined wheat bread was considered appropriate because bread is a typical breakfast food in Sweden, and in a real-life setting is a relevant alternative for an individual when deciding a main breakfast food. Clearly, with the use of this reference, many aspects of food composition differed between test and reference, and the results depended on a combination of these factors. However, importantly, macronutrient composition and energy content were kept constant between test and reference foods and they were consumed with identical additional breakfast foods.

A comparison was also made between whole-grain pasta and refined wheat pasta, served for lunch (Paper I). Combinations of the breakfast and lunch meals were given on three separate occasions to enable comparisons between breakfast meals and lunch meals independently. In the following studies (Papers II-IV), only the breakfast meals were manipulated and the lunch meal was standardised between test days.

Within the cereal kernel, the quality and quantity of dietary fibre and other compounds varies (Rakha *et al.*, 2009). When rye is milled, a number of milling fractions can be produced. For Paper II, three different rye milling fractions were chosen, representing a large compositional variation (Table 7).

Table 7. *Macronutrient contents (g/100g) in rye milling fractions and refined wheat flour used as bread ingredients in Paper II*

	Rye bran	Inner rye bran	Sifted rye flour	Refined wheat flour
Protein	16	13	8.1	11
Available carbohydrates	33	54	69	68
Fat	4.4	2.9	1.7	2
Dietary fibre[1]	32.2	16.4	8	2.5
- of which extractable	5.2	7.2	3.5	0.7

[1]Fructan and fructo-oligosaccharides were not included.

Rye bran (20% by weight of the total grain), an inner rye bran fraction and sifted rye flour (80% of the total grain) were used as ingredients in breads. To reduce the possible effects of structure/particle size, the rye bran was milled to a fine flour, similar to that of the intermediate rye fraction and sifted rye flour. Breads that were made using the three rye milling fractions, as well as the refined wheat bread used as reference, varied in appearance and volume (Figure 8).

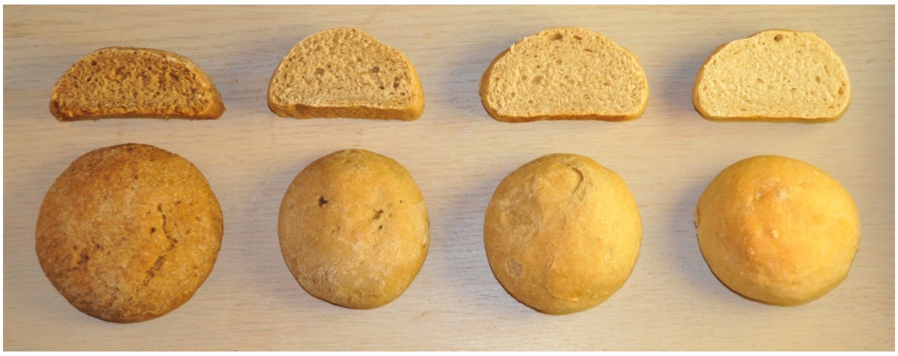

Figure 8. Breads baked with rye fractions (rye bran, inner rye bran and sifted rye flour) and refined wheat bread (to the right) evaluated in Paper III.

The effect of rye grain structure was investigated by grinding whole rye kernels to fine whole-grain rye flour (Paper III). Kernels and flour were used in breads and porridges. Porridge made from rye is a traditional Nordic breakfast food. Boiled rye kernels are not traditionally consumed as breakfast, other than in bread, but could be used as a rice replacer, similar to oats, barley and wheat kernels available on the market.

Rye porridge made from whole-grain rye flakes was chosen for the study of satiety at regular consumption (Paper IV). The food is the most interesting of all rye products included in that it provided high dietary fibre content, retained macrostructure and microstructure and high volume per calorie, combined with an aspect of practical importance: this product is a familiar food that is quick and easy to prepare at home, which lowers the risk of non-compliance.

In the study of ileal excretion in response to a high-fibre rye diet compared with a low-fibre wheat bread diet (Paper V), the rye products selected were whole-grain rye crisp bread and soft bread with rye bran. The corresponding wheat products were refined wheat crisp bread and refined wheat soft bread in standardised amounts. The total daily fibre intake from the low and high fibre diet in this study was 20 and 52 g, respectively.

Table 8. *Rye foods investigated in Papers I-IV*

Test product and rye ingredient used in rye porridges (g/portion) and breads (% of total flour)	Serving size (g)	Caloric content (kcal/portion)	Dietary fibre (g/portion)	Publication
Porridge of whole-grain rye flakes, cut and rolled to 0.6 mm (62 g)	250	190	9.0	Paper I
Porridge of whole-grain rye flakes, cut rolled to 0.6 mm (55 g)	340	190	10.8	Paper IV
Porridge of whole-grain rye flour (66 g)	350	239	12	Paper III
Porridge of rye kernels, slightly cracked by rolling to 2 mm (66 g)	137	215	11	Paper III
Bread with sifted rye flour (50%)	100	260	3.5	Paper II, part I
Bread with inner rye bran (53%)	120	260	6.5	
Bread with rye bran (58%)	133	260	15	
Bread with inner rye bran (74%)	126	260	8.5	Paper II, part II
Bread with inner rye bran (48%)	123	260	6.0	
Bread with rye bran (37%)	121	260	9.0	
Bread with rye bran (25%)	114	260	6.0	
Bread with whole-grain rye flour (50%)	158	395	13	Paper III
Bread with rye kernels, steamed and rolled to 1.8 mm (50%)	156	380	11	

Chemical characterisation

In Paper I, manufacturers' data was used for nutritional values of the test products. In Paper II, the rye material and wheat flour were analysed in duplicate for contents of water, protein, fat, ash and total dietary fibre (not including fructan) and available carbohydrate was calculated by difference. The information was used together with manufacturers' data for the additional bread ingredients to calculate the nutritional composition of the breads. In Paper III, in addition to the analysis described for Paper II, detailed determinations were carried out of dietary fibre content and composition in all rye and wheat products. Fructan and fructo-oligosaccharides were also analysed and included in total dietary fibre. In Paper IV, rye and wheat products were analysed as described for Paper II, and additional total dietary fibre analysis including fructan determination was performed. In all studies, caloric content of the foods was calculated according to the standard food energy conversion factors for protein, available carbohydrate and fat: 4 kcal/g, 4 kcal/g, 9 kcal/g, respectively (FAO 2003). In Papers III-IV, total dietary fibre was calculated to provide 2 kcal/g as recommended by the European Commission (2008).

3.5 Oro-caecal transit-time and gut fermentation

In order to optimise metabolism and nutrient uptake, passage time through the stomach and small intestine is adjusted by nerve and hormonal signalling (GLP-1 and PYY) in a feedback loop, from the distal to proximal intestine and stomach (Maljaars *et al.*, 2008). Stomach emptying rate and passage time through the small intestine can decrease in response to macronutrients in the duodenum, jejunum and ileum and possibly also the colon. Signals originating from the ileum are perhaps the most powerful. Infusions of fat, protein and carbohydrates induce this brake mechanism, with decreased passage time as a result, as well as increased satiety and decreased energy intake.

Oro-caecal transit-time refers to the time frame from consumption of a food until unabsorbed digesta reaches the proximal colon (caecum). We measured the time from ingestion of breakfast (whole-grain rye porridge or refined wheat bread breakfast) until arrival of unabsorbed material in the caecum by use of the salicylazosulphapyridine/sulphapyridine-method. Subjects were given tablets containing 500 mg salicylazosulphapyridine with half a glass of water, 30 min after the start of the breakfast. The majority of the substance passes undigested and unabsorbed through the stomach and small intestine. Upon reaching the caecum the azo bond of the molecule is rapidly cleaved during bacterial fermentation, liberating sulphapyridine, which is rapidly absorbed and can be measured in the blood as an indicator of oro-caecal transit-time (Gramatte & Terhaag, 1991; Kellow *et al.*, 1986; Kennedy *et al.*, 1979). Blood samples to be analysed for sulphapyridine were taken before breakfast (0) and at 2, 4, 5, 6, 7 and 8 h on day 8 of each treatment. Breath hydrogen as an indicator of colonic fermentation (Rumessen, 1992) was measured at the same day and time intervals.

3.6 Statistical analysis

Statistical analyses were performed using SPSS (version 14, LEAD Technologies, Inc., USA) in Paper I and Minitab (version 15 and 16, Minitab Inc., USA) in Papers II-V. The level of significance was set at $p<0.05$. Paired t-tests were performed for comparisons of appetite ratings (hunger, satiety and desire to eat) at single time points (Paper I). In Papers II-IV, appetite ratings were evaluated by ANOVA performed using subject as random effect and type of breakfast and time point as fixed effects. Separate analyses were performed for morning (08:30-12:00) and afternoon ratings (12:30-16:00). Differences between breakfasts were evaluated by Tukey comparisons. In Paper IV the differences in ratings after breakfasts on the 3 days were compared according to the procedure described above, thus porridge breakfast on days 1, 8 and 22 and bread breakfast on days 1, 8 and 22 were all compared for morning and afternoon ratings, separately.

4 Results

4.1 Compliance

Subjects generally complied well with the study procedures; the dropout rate was 0-10% (Paper I-IV). Study products were well liked, portion sizes were accepted and all meals were finished within the given time-frame (Figure 9).

Figure 9. Study participants consuming test breakfasts, Swedish University of Agricultural Sciences (Paper III).

On arrival in the morning, the participants rated high feelings of hunger and desire to eat, along with low feelings of satiety. After the breakfast meal, satiety ratings were increased, while hunger and desire to eat were rated lower. During the time period towards lunch, a gradual decrease in satiety was accompanied by increasing hunger and desire to eat. A similar pattern was observed in response to the lunch meal. In cases where test meals differed in effects, all three appetite-related concepts (hunger, satiety and desire to eat) generally gave the same indication, *i.e.* when a product resulted in higher satiety, then hunger and desire to eat were lower during the same period. Only satiety is presented and discussed here.

4.2 Satiety

4.2.1 Rye porridges

Intake of porridges made from a variety of whole-grain rye ingredients consistently resulted in increased satiety and decreased hunger during 4 h after intake, compared with iso-caloric refined wheat bread, served with identical additional breakfast foods within the study (Papers I, III and IV). The effect was apparent after intake of porridges made of rye flakes (Figures 10 and 11), rye flour and rye kernels (Figure 12). Further, satiety was rated higher up to 8 h after intake of the rye porridges (Figures 10 and 12), thus also during the 4 h after the standardised lunch meals.

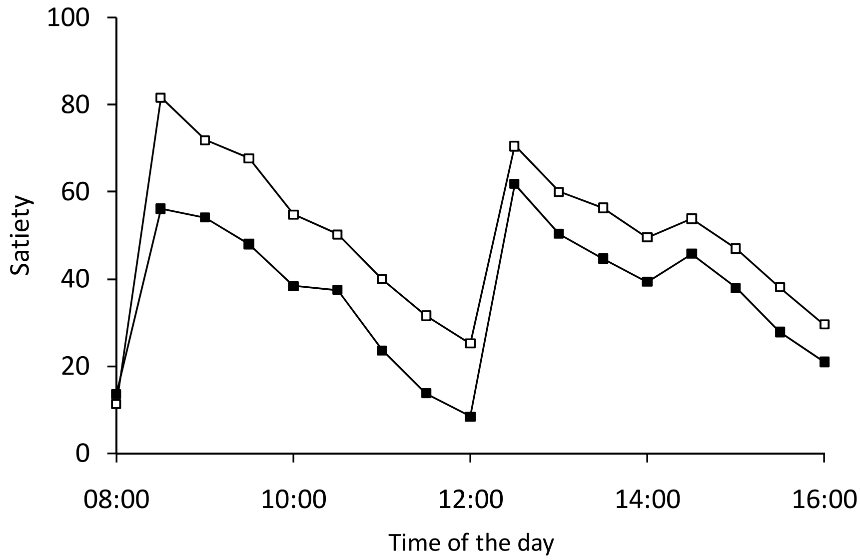

Figure 10. Mean satiety ratings (n = 22) significantly different (8:30-16:00) after iso-caloric breakfasts including whole-grain rye flake porridge (-□-) or refined wheat bread (-■-), Paper I. Significantly different between breakfast from 8:30-16:00.

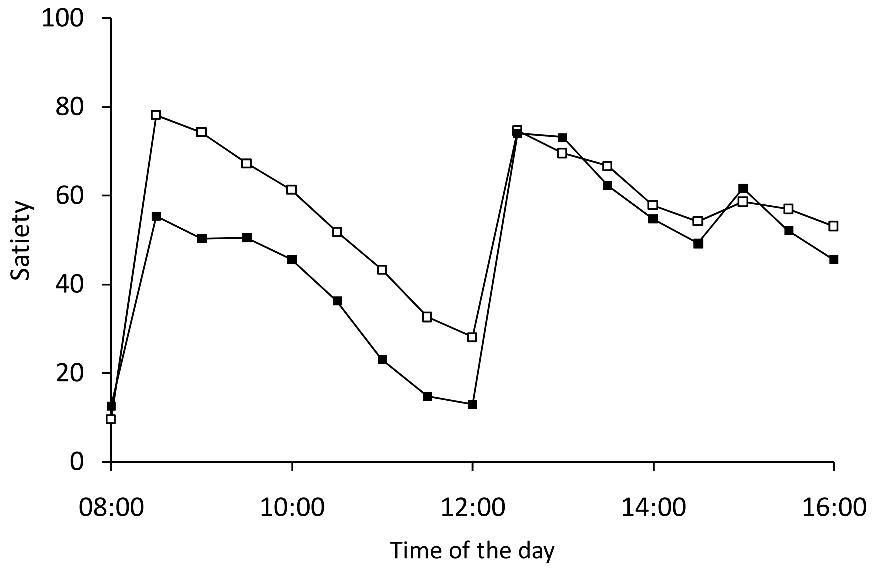

Figure 11. Mean satiety ratings (n = 24) significantly different (8:30-12:00) after iso-caloric breakfasts including whole-grain rye flake porridge (-□-) or refined wheat bread (-■-), Paper IV.

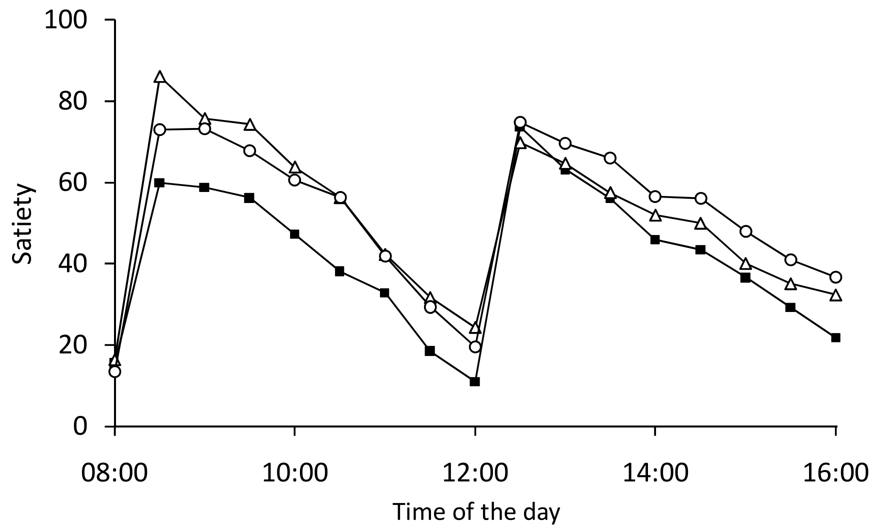

Figure 12. Mean satiety ratings (n = 20) after iso-caloric breakfasts including porridge of whole-grain rye flour (-Δ-), rye kernels (-○-) or refined wheat bread (-■-), Paper III.

4.2.2 Processing of rye ingredients

In comparisons of breads containing different rye milling fractions, the bread that included rye bran resulted in higher satiety ratings than the inner rye bran bread and sifted rye flour bread. All rye breads including rye milling fractions resulted in higher satiety ratings than the refined wheat bread (mean 4 h ratings). Thus, sifted rye, which contained more dietary fibre than sifted wheat, resulted in higher satiety ratings when used in breads (50% of the total flour from sifted rye) than refined wheat (Paper II). Rye bran included in breads by replacing from 25% up to 60% of total wheat flour resulted in increased satiety 4 h post-consumption.

Paper III demonstrated significantly higher satiety after consumption of the rye breads with 50% whole-grain rye of total flour, compared with refined wheat bread (Figure 13). The effect was similar between rye breads using rye kernels and whole-grain rye flour and lasted for the 8 h of measurements for both rye products.

Likewise, rye kernels or whole-grain rye flour prepared as porridges resulted in higher satiety ratings for 8 h compared with refined wheat bread breakfast (Figures 12 and 13). In addition, an effect of rye grain structure appeared in the afternoon. When the rye kernels had been consumed for breakfast, higher satiety ratings were recorded in the afternoon (4.5-8 h after breakfast) compared with the whole-grain rye flour porridge breakfast, suggesting that grain structure was beneficial for increased satiety several hours after intake. Detailed chemical characterisation of the dietary fibre components demonstrated that disintegration of the rye kernel did not result in any changes in the quality and quantity of dietary fibre during processing and preparation of the porridges and thus the effect was not a result of changes in dietary fibre composition.

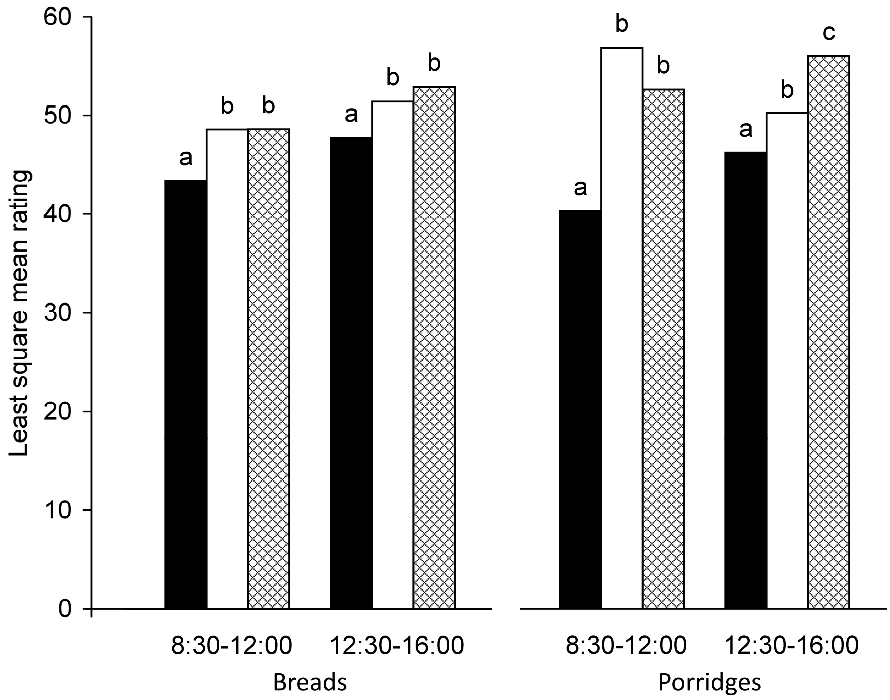

Figure 13. Mean satiety ratings after test breakfast meals (served at 8:00) and a standardised lunch meal (12:00). Refined wheat bread (black), whole-grain rye flour (white) and rye kernels (checked) included in breads and porridges, and served in iso-caloric portions with standardised additional foods within both studies. Different letter within study and time period indicate statistically significant differences ($p<0.05$). Modified from Paper III.

The thorough characterisation of dietary fibre components demonstrated that milling of the rye kernel resulted in minor variations in breads and porridges (Paper III). Total dietary fibre content differed slightly, with the products including whole-grain rye flour having a slightly higher content than their kernel counterparts, probably as an effect of higher formation of resistant starch (type III, retrograded amylose) when whole-grain rye flour was used. Amount of arabinoxylan, arabinogalactan, β-glucan, fructan and Klason lignin was unaffected by milling in both breads, as well as in porridges. In the breads, milling of rye resulted in lower molecular weight (number-average molecular weight and weight-average molecular weight) of extractable arabinoxylan, as well as lower β-glucan average molecular weight and higher β-glucan solubility. Disappearance of fructan with a low degree of polymerisation was also indicated. Thus, with more intact structure of the rye kernel, the composition of those dietary fibre components remained stable throughout the baking process to a larger extent than when rye flour was used. In the porridge products, on the other hand, milling of rye did not significantly affect these parameters.

4.3 Regular consumption

When porridge made from whole-grain rye flakes was consumed daily for three weeks as part of a standardised breakfast meal, satiety measured under standardised conditions was similar on the first day, after one week (day 8) and on the last day (day 22, Figure 14). Thus, regular consumption of this food did not alter the 8-h profile of mean satiety ratings over the three-week period.

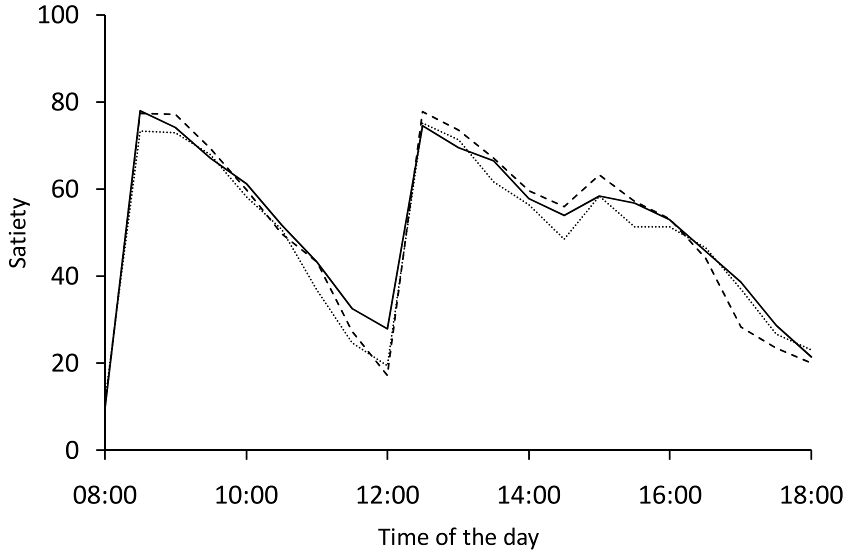

Figure 14. Mean satiety ratings (n=24) after rye porridge breakfast (served at 8:00), a standardised lunch meal (12:00), and a snack (14:30) under similar conditions on day 1 (—), day 8 (···) and day 22 (---), during a 3-wk period of daily consumption, Paper IV. Satiety ratings remained similar between days.

The rye porridge breakfast increased satiety compared with the iso-caloric refined wheat bread breakfast on all three test occasions (day 1, 8 and 22), during the first 4 h preceding the standard lunch. In the afternoon, however, unlike the previous studies, satiety ratings were unaffected by breakfast type. With one exception, on the first day, desire to eat was lower during the afternoon as a result of the rye porridge breakfast compared with the refined wheat bread breakfast.

Satiety response after intake of the refined wheat bread breakfast remained consistently lower than for rye porridge throughout the study and similar between day 1 and day 8. However, on the last day participants responded with increased satiety after intake of the refined wheat bread compared with day 1 and day 8, although did not reach the satiety levels provided by the whole-grain rye porridge.

In the analysis of oro-caecal transit-times of rye porridge and refined wheat bread breakfasts, total serum sulphapyridine levels were found to be elevated between 5 and 6 hrs after intake of both breakfasts, indicating arrival of the ingested substance to the caecum. There were no detectable differences between arrival times of the breakfasts in this setting. However arrival time is of interest because it indicates that the satiating effect of rye porridge seen in the afternoon in Papers I and III could be mediated by colonic events. Gut fermentation as indicated by much higher breath hydrogen increased at 4 h after consumption of the rye porridge breakfast, peaking at 5 h.

4.4 Small intestinal digestibility of a rye diet

As measured in ileostomy subjects (Paper V), daily intake of a diet supplemented with high-fibre rye bread caused an increase in ileal excretion of energy and macronutrients compared with low-fibre refined wheat. More dry matter, ash, protein, fat, amylase-available starch and dietary fibre were excreted when the diet was supplemented with rye bread (Table 9). Apparent small intestine digestibility and absorption, calculated as percentage of intake, was also found to be higher for dry matter, ash, protein, fat, amylase-available starch and dietary fibre with high-fibre rye bread intake (Table 10). The implication of the results for humans with an intact gastrointestinal tract is that as a result of high-fibre rye bread intake, more substrates of different types escape digestion in the small intestine. These are delivered to the colon and become available for fermentation by the microflora. This in turn can potentially trigger the ileal brake mechanism by release of gut peptides (Maljaars *et al.*, 2008) and may be a possible explanation why the late (>4 h after intake) satiating effect of rye is mediated.

Interestingly, meal frequency had no effect on apparent digestibility of macronutrients. Thus similar total amounts and proportions of macronutrients were excreted when identical diets were divided into three large or seven smaller daily meals.

Table 9. Dietary intake (g/24 h) and ileal excretion (g/24 h), in ileostomy subjects (n=10), Paper V.

	Low-fibre wheat bread diet[1]	High-fibre rye bread diet[1]
Protein		
Intake	133	139
Excretion	17	24
Fat		
Intake	88	89
Excretion	5.5	7.2
Amylase-available starch		
Intake	178	171
Excretion	2.0	3.2
Dietary fibre		
Intake	20	52
Excretion	16	44
Dry matter		
Intake	595	638
Excretion	68	124
Ash		
Intake	24	28
Excretion	9.9	14

[1]Results presented as means of two eating frequencies: three or seven meals/day

Table 10. Apparent small intestine digestibility and absorption (%) in ileostomy subjects (n=10), Paper V.

	Low-fibre wheat bread diet[1]	High-fibre rye bread diet[1]
Protein	87	83
Fat	94	92
Amylase available starch	99	98
Dietary fibre	21	15
Dry matter	89	81
Ash	59	50

[1]Results presented as means of two eating frequencies: three or seven meals/day

5 Discussion

5.1 Satiating characteristics of rye

A variety of rye materials, whole-grain as well as milling fractions rich in dietary fibre, used in a range of breads and porridges consumed as parts of breakfast meals resulted in increased satiety compared with iso-caloric refined wheat bread breakfast. This demonstrates that inclusion of rye in different forms is an efficient way of enhancing the satiating capacity of meals and diets. The caloric content and composition was similar between test meals within every comparison and differences in macronutrient composition were minor. The main potentially satiety-altering characteristics in rye foods include a high content of dietary fibre, low energy density and the fact that rye is often consumed with intact grain structure. Thus, the satiating capacity of rye foods most likely results from a combined effect of these characteristics.

5.1.1 Dietary fibre

The dietary fibre content of rye is higher than in most other cereal grains and many studies support the potential of dietary fibre as a satiety-enhancing component (Wanders *et al.*, 2011; Slavin & Green, 2007). Thus, the high dietary fibre content of rye is probably one of the key factors behind the satiating effects of rye products, as also indicated by the fact that it constitutes the main compositional difference between rye test foods and refined wheat-based reference. The studies described in Papers I-IV included rye foods providing around 10 g of dietary fibre per portion in porridges and between 4 and 10 grams per bread portion. Investigations of satiety and physiological effects of dietary fibre similar to those present in rye, but from other cereal sources, are discussed below.

Arabinoxylan

Arabinoxylan is the dominant dietary fibre type in whole-grain rye and constitutes 8-9% of dry weight (Vinkx & Delcour, 1996). Wheat arabinoxylan was found to lower blood glucose concentration (2 h, n=14) in a dose-dependent manner when 0, 6 and 12 g were included in breads (Lu *et al.*, 2000). Effects on the hunger-related hormone ghrelin have been studied in response to wheat arabinoxylan intake. When 15 g/day of wheat arabinoxylan was consumed during a 6-wks period by participants with impaired glucose tolerance (n=15), total plasma ghrelin concentrations (4 h postprandial) were lowered in response to a standardised test meal by the end of the period (Garcia *et al.*, 2007). Contradictory results were found after consumption of a wheat arabinoxylan-enriched (6 g) breakfast meal (Möhlig *et al.*, 2005). Plasma ghrelin concentrations were significantly higher at 2 h after intake compared with a low-fibre control (n=15). However, 2 h is a relatively short period for ghrelin measurements and a postprandial time frame of 3-4.5 h, approaching the following meal, would probably be of higher interest (Rosén *et al.*, 2011). Subjective feelings of appetite were not examined in those studies.

β-Glucan

Significant amounts of β-glucan (1.5-2% of dry weight) are present in rye. β-Glucan from other sources has been shown to increase satiety. When 5 or 10 g of oat fibre (50% β-glucan) were added to a beverage, satiety was increased and hunger decreased compared with no-fibre control beverage (Lyly *et al.*, 2009). The influence of viscous properties of oat β-glucan on gastric emptying and circulating levels of gut peptides (CCK, GLP-1 and PYY) were clearly demonstrated by Juvonen *et al.* (2009). In another recent study (Vitaglione *et al.*, 2009), enrichment of breakfast breads with barley β-glucan (4.4 g) increased subjective satiety ratings at 2 and 3 h after consumption compared with an iso-caloric low-fibre wheat bread control. The increase in satiety was accompanied by lower ghrelin levels at the same points in time and higher total PYY response (only at 3 h) and followed by a 19% lower *ad libitum* lunch intake at 3 h. An overnight effect was shown by Nilsson *et al.* (2008b). In that study, an evening meal including a barley variety with elevated amounts of β-glucan increased fasting and postprandial satiety ratings (n=15) on the next morning after a standardised meal compared with other cereal-based evening meals.

Resistant starch

Starch can resist small intestine digestion and absorption for different reasons, be delivered to the colon and thus fall under the definition of dietary fibre.

Consumption of boiled rye kernels provides high amounts of resistant starch type 1 (RS1) caused by physical encapsulation (Rosén *et al.*, 2011). Rye kernels (107 g) boiled for 35 min contained as much as 7.5 g RS1 per portion. A satiating effect of resistant starch type 3 (RS3) from maize (Hi-maize) was reported when 8 g RS3 was added to a muffin, resulting in suppressed hunger for a longer period than with a low-fibre control muffin (Willis *et al.*, 2009). In Paper II, the increase in RS3 formation that occurred in bread made with whole-grain rye flour compared with bread including rye kernels did not affect satiety. However, RS1 was most likely higher in the bread with rye kernels and total amount of resistant starch may have been similar between the two rye breads.

Cellulose and fructan

Whole-grain rye can contains 1-2% cellulose. A breakfast cereal (Fiber One) with a high content (33 g/portion) of insoluble wheat dietary fibre, including cellulose, lowered appetite compared with a low-fibre wheat bread reference during 75 min post-consumption in 16 healthy men (Samra & Anderson, 2007). It is relatively recently that fructan and fructo-oligosaccharides were included into the dietary fibre definition. A rather high amount (4-6% of dry weight) is found in whole-grain rye. A compound with similar characteristics, oligofructose, has been studied with regard to its satiating enhancing properties (Cani *et al.*, 2009). Daily ingestion of as much as 16 g over a period of two weeks resulted in a decrease in hunger ratings. The effect was suggested to be mediated via colonic fermentation of the dietary fibres.

Overall, these studies show potential for the different components of dietary fibre present in rye to alter hormonal and satiating response. However, the specific effect of rye dietary fibre components remains to be studied.

5.1.2 Processing

In addition to dietary fibre, processing of the rye grain was shown to influence satiety (Papers II and III). The study of rye milling fractions in breads was designed to record appetite ratings during 8 h of standardised conditions. The results showed that during the first 4 h after the start of breakfast intake, satiety ratings were affected by bread type. The more fibre-rich rye milling fraction (rye bran) had a stronger affect on satiety than those with less fibre (inner rye bran and sifted rye flour). During the afternoon, unlike the rye porridge made from whole-grain rye flakes, ratings were only marginally affected by the rye bread breakfasts. We speculated that this was an effect of milling, since rye flakes used in the porridge retained some original integrity of the rye grain, whereas the rye milling fractions used in the breads were finely ground. The following study (Paper III) was therefore designed to specifically investigate the effect of rye grain structure.

Rye kernels and whole-grain rye flour (milled rye kernels) were included in breads and porridges. Rye kernel structure (kernels vs. flour) had no effect on satiety in breads, but the porridge made of rye kernels resulted in an increased satiety 4-8 h after consumption, *i.e.* in the afternoon after the standardised lunch meal, compared with the porridge made of whole-grain rye flour. The lack of effect of rye kernel structure in the breads could be a result of the lower overall level of rye in those, 45 g per portion. Bread baking diluted the rye concentration in the breakfast by inclusion of additional bread ingredients, mainly wheat flour, whereas the porridges were made from pure whole-grain rye and contained 66 g rye per portion.

Food processing affects the chemical composition of cereal grains. Whole-grain rye is composed of a large number of macronutrients, micronutrients and other bioactive compounds. Of special interest is the content and composition of dietary fibre, since it is well known that processing affects these parameters and that this in turn may influence physiological effects and health outcomes. Therefore, in the studies comparing products with rye kernels and whole-grain rye flour, characterisation of dietary fibre content and composition was emphasised. The small differences that were demonstrated between breads with rye kernels or whole-grain rye flour were not reflected in any variation in appetite ratings. On the other hand, the two porridge products were very similar in all dietary fibre parameters measured. Therefore, the differences in appetite that the porridges resulted in could be ascribed to food structure and not to any differences in dietary fibre composition.

5.1.3 Food volume and energy density

In addition to a high content of dietary fibre and maintained grain structure, rye porridge has a low energy density due its to high water-binding capacity. To provide the same amount of energy as refined wheat bread, porridge was therefore served in larger portion sizes. Low energy density is a food property that increases within-meal satiety (Latner *et al.*, 2009; Lappalainen *et al.*, 1993). Food volume of a standardised starter, increased by incorporation of water, was shown to lower food intake at the main meal served *ad libitum* 17 min later (Rolls *et al.*, 1999). Water intake during a meal has also been shown to increase satiation (within-meal satiety) (Lappalainen *et al.*, 1993). The effect is probably the combined result of visual impression of a larger meal size and in some cases a prolonged time for ingestion, as well as increased gastric filling (Rolls, 2009). Paper III showed that the effect of high water content is short-term and disappears within the first hour after consumption. The weight of the rye porridge made with rye kernels (137 g/portion) was only 40% of that made from whole-grain rye flour (350 g/portion) and the latter provided higher satiety ratings at 30 min after start of the breakfasts, presumably as a result of the large volume resulting in high gastric filling, as well as the visual impression of a large meal. However, already at 60 min after both porridge meals the satiety ratings were similar, indicating that the effect of water incorporated into a food is short-term. The effect seen on appetite ratings several hours after intake of rye porridges in comparison with refined wheat bread is most likely not explained by the large volume of porridge.

5.2 Duration of altered satiety

In Papers I and III, rye porridge resulted in increased satiety, not only during the first 4 h after consumption, but also in the afternoon (4-8 h) after the standardised lunch meal. However, although the satiating effect of rye porridge seen in the morning (4 h) was confirmed in Paper IV, appetite response in the afternoon was not significantly different than for the refined wheat bread breakfast. This was unexpected, since Paper IV had a similar design to Paper I. Two changes had been made. Firstly, the wheat bread was coloured to mimic darker whole-grain bread, with no change in composition or taste. However, the impression of the coloured refined wheat bread did not affect the ratings directly after consumption and would be less likely to explain the lack of effect in the afternoon. Secondly, to ease compliance at regular consumption, the portion size was lowered from 62 g, used in the first study, to 55 g of rye flakes. The amount of rye may be important, as bread breakfasts with lower amounts of rye resulted in weak and inconsistent satiating effects in the afternoon.

5.3 Energy intake

In order for the increased satiety to prevent unwanted weight gain, energy intake must be lowered. Papers I-IV were primarily designed to measure satiety at 8 h under standardised conditions regarding timing and amount of food intake. Therefore amount and timing of food intake was standardised between 08:00 and 16:00 and did not allow for measurements of voluntary energy intake during this period. At the *ad libitum* meal (Paper I), the amount eaten was similar and not affected by the type of breakfast served 8 h earlier. In a real-life situation, where the availability of food is often unlimited, food intake would possibly be affected as a result of higher satiety during this period. Another aspect of interest is *ad libitum* intake of the test foods themselves. The high satiating capacity of the rye porridge in relation to the refined wheat bread may result in lower energy intake from porridge, and yet result in similar levels of satiety. Effects on spontaneous food intake were investigated in Paper IV by self-reported weighed 3-day food diaries, completed during intake of an iso-caloric rye porridge breakfast and a refined wheat bread breakfast. However this study was unable to show any effect on energy intake, as similar mean energy intakes were reported independently of breakfast. This method was chosen to reflect energy intake in a real-life situation, but is probably too imprecise to reveal differences in energy intake. Significant underreporting of respondents is a commonly known bias (Gibson, 2005) and even with the carefully performed individual instructions, underreporting and/or under-eating probably occurred. This implies that no conclusion regarding the effect of breakfast type on energy intake can be drawn from these results. Thus complementary studies, specifically designed to measure energy intake, are necessary to evaluate the impact of satiating rye products on food and energy intake.

Consumption of 100 fewer kcal daily is a highly relevant amount of energy with regard to weight maintenance (Hill, 2006). The differences in mean satiety ratings between test rye foods and refined wheat bread ranged from 10% to 25%. A theoretically idea of the practical importance of such a difference, we can use the following example. Breakfast meals providing different levels of energy levels were served in a randomised cross-over design and satiety was measured for the following 4 h (de Graaf *et al.*, 1992). An increase from 250 kcal to 400 kcal resulted in an approx. 10% increase in satiety ratings between 1.75 h and 2.75 h after consumption. This suggests that a breakfast food that increases satiety by 10% compared with an iso-caloric reference food would require consumption of 150 kcal more of the reference food in order to reach the same level of fullness.

5.4 Physiological mechanisms

Rye grain chemical composition is highly complex, with additional disparity resulting from processing and preparation of rye foods. In addition, satiety is a result of highly complex interactions between a number of physiological stages in food intake and metabolism. Thus it is clear that a discussion regarding the underlying mechanism explaining the satiating effects of rye foods will be extensive. Some aspects of interest relating to the measurements made within this project are discussed below.

Dietary fibre and intact botanical structure of cereal grains can act as physical barriers to digestion and small intestine absorption (Al-Rabadi *et al.*, 2009; Wolever & Jenkins, 1993), resulting in altered blood concentration profiles of nutrients and signalling peptides. Furthermore, lowered food digestibility by addition of intact cereal structure and dietary fibre may result in macronutrients such as fat, protein and starch reaching the terminal ileum to a larger extent. Investigations have shown that perfusion of these macronutrients into the ileum triggers the ileal brake mechanism involving slower small intestine transit-time and gastric emptying rate, as well as lower food intake in humans (Maljaars *et al.*, 2008). The regulation of small intestine transit and stomach emptying rate involve release of GLP-1. However, there are conflicting reports regarding plasma levels of GLP-1 after intake of rye breads (Juntunen *et al.*, 2002) and dietary fibres (Adam & Westerterp-Plantenga, 2005). Results from the study in ileostomy subjects (Paper V) showed that a diet high in rye dietary fibre does in fact result in lowered small intestine apparent digestibility. It was found that increased amounts of nutrients (protein, fat and amylase-available starch) in ileal excreta as a result of replacing low-fibre wheat bread with a high-fibre rye bread in an otherwise identical diet. Rye bread intake has also been shown to lower the digestibility of macronutrients in a pig model (Le Gall *et al.*, 2009). Thus a diet rich in dietary fibre that leads to macronutrients being present in the lower part of the small intestine may provoke satiety signals as well as slow passage time. However, the small amount of ingested macronutrients that reaches the terminal ileum after a regular meal may not be enough to evoke strong signals and this may explain why the current study (Paper IV) did not show any difference in mouth to caecum transit-time between the two breakfasts (rye and wheat). More frequent blood sampling might have allowed detection of more precise caecum arrival times. The fact that salicylazosulphapyridine is not chemically bound to the food molecules introduces uncertainty regarding the timing of the passage of the digesta in relation to the substance. Salicylazosulphapyridine is water-soluble and is likely to accompany the liquid part of the meal, such as the hot drink, milk and water in the porridge. A liquid phase is known to empty from the stomach earlier than a solid food (Mishima *et al.*, 2009) and if the various food components of the meal travel at different rates, it may well be that the impact of the rye and wheat material is not reflected in the appearance of sulphapyridine in the blood.

Another proposed mechanism of interest is colonic fermentation, which has been suggested to play a role in the satiating effects of fermentable dietary fibre. Increased fermentation measured by breath hydrogen has been correlated with increased satiety (Rosén *et al.*, 2011; Cani *et al.*, 2009; Nilsson *et al.*, 2008a). Suggested mechanisms are stimulated release of satiety hormones (GLP-1, PYY) in response to fermentation to by L-cells in the colon (Zhou *et al.*,

2008) and altered gastric and small intestinal motility (Cherbut, 2003). Rye induces especially high fermentation 4-8 h after consumption, as shown in Paper IV. Rye kernels also result in higher breath hydrogen 4-6 h after consumption, compared with oat and wheat kernels (Nilsson *et al.*, 2008a), suggesting that rye provides more material for bacterial fermentation than other whole-grains cereals. Fermentation and related events may at least partly explain increased satiety levels several hours after a test meal, when the unabsorbed digesta has reached the proximal colon.

5.5 Applicability

Rye is unique in its dietary fibre composition and quantity, providing more dietary fibre than most other cereal grains. In combination with intact botanical structure of the cereal grain and low energy density, rye provides several potential satiety-enhancing properties. Rye products are convenient, safe and easily affordable foods that when processed and prepared in traditional ways such as bread and porridge naturally provide a combination of those satiating characteristics. Due to the design of the diets, the results presented in this thesis are applicable without much modification of the amounts or types of foods. The portion sizes of rye products tested can be incorporated into a healthy diet compatible with dietary recommendations. Some people experience uncomfortable bowel symptoms on including rye breads and rye porridges into their diet. However, rye has been shown to promote bowel health. Studies on bowel function at high intakes of rye breads, providing from 17 up to 37 g of dietary fibre from rye daily, consistently report improved bowel health, measured as increased faecal weight, increased defecation frequency, eased defecation and increased passage time (Holma *et al.*, 2010; Gråsten *et al.*, 2007; Hongisto *et al.*, 2006; McIntosh *et al.*, 2003; Gråsten *et al.*, 2000). This is further stressed by the positive opinion regarding bowel health for dietary fibre-rich rye products made by the EFSA (2011b). Concerns that should be mentioned as regards to high intakes of whole-grain and especially bran relate to the presence of cadmium (EFSA, 2009; Eriksson, 2009), mycotoxins (Fredlund *et al.*, 2009) and acrylamide (CIAA, 2009). Heavy metals and mycotoxin producing organisms can be minimised by removing the most outer parts of the bran, and allowing 10% removal of the bran or 2% of the total grain is suggested for whole-grain (Healthgrain Consortium, 2010). The formation of acrylamide is mainly dependent on processing conditions and varies considerably between foods (CIAA, 2009). Overall, whole-grain intake is related to positive health effects and, as shown in epidemiological studies, protect against type 2 diabetes, cardio-vascular disease and some cancers

(Fardet, 2010). The replacement of refined grain with whole-grain products is recommended for public health reasons and whole-grain rye is an excellent choice in many regards.

5.5.1 Rye for a healthy body weight?

Several studies in monogastric animals report that the energy in rye is less available and/or energy intake is lower, as shown by a lower growth, lower body weight and reduced adiposity (Andersson *et al.*, 2010; Nitrayova *et al.*, 2009; Pettersson & Åman, 1989; Pettersson & Åman, 1988). The results presented in this thesis showed that a diet with high-fibre rye breads increased the amounts of macronutrients and energy reaching the terminal ileum. This is in line with several previous studies reporting a lower metabolisable energy value of diets rich in dietary fibre. Lower apparent availability for small intestine digestion and absorption, and thus possibly lower energy utilisation from a rye-based diet, could be expected to result in an increased desire to eat to compensate for the lower energy availability. However, Papers I-IV and other supporting literature show that rye foods result in lower hunger and increase post-meal satiety. Thus, by lowering the energy utilization of the diet and providing a high satiating value, inclusion of rye foods into the daily diet could provide a two-pronged tool for preventing body weight gain.

6 Main findings

- All rye products (porridge of whole-grain flakes, porridge of whole-grain flour, boiled kernels, bread with kernels, bread with whole-grain flour and breads with 3 rye milling fractions in different levels) served as part of breakfast meals, resulted in higher satiety ratings, compared with the iso-caloric refined wheat bread breakfast during 4 h after intake and in some cases during 8 h.
- Rye bran bread resulted in higher satiety than breads including other rye fractions during 4 h after intake.
- Rye kernels and whole-grain rye flour used as bread ingredients resulted in similar satiety ratings.
- Rye kernels and whole-grain rye flour prepared as porridge resulted in similar satiety ratings during the first 4 h after intake. Between 4-8 h after intake, rye kernels resulted in higher satiety ratings than the same material in milled form.
- At regular consumption of whole-grain rye porridge breakfast for three weeks, the satiating effect remained the same and was consistently higher compared with refined wheat bread breakfast. In this study, however, no difference in self-reported energy intake or oro-caecal transit-time (5-6 h) between breakfasts could be detected.
- Inclusion of high-fibre rye bread into a standardised diet resulted in higher proportions of nutrients (fat, protein and amylase-available starch) escaping small intestine absorption and being excreted from the terminal ileum, compared with a low-fibre wheat bread diet.

7 Future prospects

To further investigate and verify the potential for rye products to affect satiety, energy intake and body weight, the following investigations would be of interest:

- The effect on hunger and satiety of further rye products such as muesli, crisp bread, extruded products etc.
- Further evaluation of the specific effects on hunger and satiety in relation to rye composition, processing and food preparation.
- The dose-response effect of rye food ingredients in order to establish how intakes at different levels influence the intensity and duration of hunger and satiety during the following 24 h at standardised conditions.
- Individual variation in appetite sensations to rye test foods assessed *e.g.* in groups with variations in BMI, age, background diet, gender, age, microflora etc.
- Satiation (within-meal satiety) of rye foods served in excess and eaten *ad libitum.*
- Validation of post-meal hunger-suppressing effects of rye foods by measuring *ad libitum* food intake at the following meal and energy intake over a period of time during intake of a diet high in rye.
- Effect on body weight over a longer period of time (1-2 years) of rye-supplemented diets. It would be of interest to carry out such a study on slightly overweight subjects.
- Another interesting option would be to observe body weight in relation to rye intake, independently of other potentially confounding variables, in a free-living population, not subjected to an intervention.

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