Glycaemic, gastrointestinal and appetite responses to breakfast porridges from ancient cereal grains: a MRI pilot study in healthy humans

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ABBREVIATIONS: FMP, finger millet porridge; PMP, pearl millet porridge; RP, rye porridge; SOP, Scottish oats porridge

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Abstract

Cereal grain based porridges are commonly consumed throughout the world. Whilst some data are available for varieties that are popular in the Western world such as oats and rye, other 'ancient' grains used in the East and in Africa such as millets are thought to have beneficial health effects, such as a suppression of post prandial hunger and circulating glucose levels. These grains, a sustainable food source due to their tolerance of extreme weather and growing conditions, are commonly found throughout Asia and Africa. However, knowledge of the physiological responses to these grain varieties is very limited. This study aimed to collect initial pilot data on the physiological and gastrointestinal responses to breakfast porridges made with two millet varieties and oats and rye grains. A total of n = 15 completed the oats and rye, n = 9 the finger millet n = 12 the pearl millet meals. MRI scans were undertaken at baseline, immediately after consumption and then hourly postprandially. Blood glucose was measured at baseline, immediately after consumption and then every 15 min until t = 80 min, then every 20 min until t = 120 min, followed on each occasion by completion of VAS. Seven participants completed the entire protocol and were included in the final analysis. A subgroup analysis with the n = 10 paired comparison between the same individuals that completed the oats, rye and pearl millet was also considered. The gastric volume AUC was higher for pearl millet than oats and rye (n = 10, $p<0.001$). The incremental area under the curve (iAUC) for blood glucose was not significantly different between the meals although this showed a trend to be lower for pearl millet. Hunger was lower for pearl millet compared to oats and rye (n = 10, $p = 0.01$). There was a significant correlation between total gastric volume AUC and average appetite AUC $r = -0.47$, $p < 0.010$. Isoenergetic breakfast porridges from 'ancient' varieties of millet grains showed physiological responses that were comparable with those from common Western varieties known to have beneficial health effects. Pearl millet appeared to induce lower postprandial blood glucose response and appetite scores though the differences were not conclusive compared with the other

porridges and further work is needed. Improved knowledge of the effects of different cereal grains could help direct dietary advice and ultimately improve health outcomes in the general population worldwide.

KEYWORDS: Magnetic resonance imaging, Blood glucose, Appetite, Gastric emptying, Breakfast porridges, Cereal grains .

1 Introduction

The increasing global prevalence of obesity is a growing public health problem. Obesity is associated with insulin resistance, a major risk factor for chronic non-communicable diseases such as type 2 diabetes and cardiovascular disease. (Kim et al., 2009; Kopelman, 2007; Meigs et al., 2007). Eating breakfast porridges based on whole cereal grains has been associated with a variety of health benefits including lower postprandial blood glucose levels, improved insulin responses, increased satiety and reduced long- term weight gain. (D. Jenkins et al., 1988; D. J. Jenkins et al., 2009; J. Slavin, 2004; J. L. Slavin, Martini, Jacobs, & Marquart, 1999; Who & Consultation, 2003) Cereal grains used at breakfast are a staple source of energy for many populations worldwide, with regional difference in consumption tending to reflect historical patterns of crop cultivation. Oats, for example, are more commonly consumed in the English-speaking countries; rye is favoured in the Scandinavian countries whilst millet is very common in Asia and Africa. (In, 1995; Kyro et al., 2012; Shobana et al., 2013). However nutritional value, potentially beneficially metabolic effects and other health effects may vary between different cereal grains, including insulinaemic responses and serum LDL cholesterol concentration. (Magnusdottir et al., 2014; Meynier, Goux, Atkinson, Brack, & Vinoy, 2015; Nilsson, Östman, Granfeldt, & Björck, 2008)This may be due to differences in the inter- relationships between digestion, gastric emptying and absorption. Subsequent differences may be seen in post prandial glycaemia and appetite (Koh-Banerjee et al., 2004; Liu, 2003; Liu et al., 2000; Liu et al., 1999; Meyer et al., 2000; Schlundt, Hill, Sbrocco, Pope-Cordle, & Sharp, 1992; J. Slavin, 2004); low glycaemic index (GI) diets produce a more gradual rise in blood sugar and insulin levels. Eating food with low GI may confer health advantages such as improving glycaemic control and insulin sensitivity in people with diabetes and reduced risk of chronic disorders. The rise in chronic non-communicable diseases in low and middle income countries such as India and China has been linked to a large shift from consumption of coarse grains such as millets to consumption of rice and wheat among the population (Popkin, Horton, Kim, Mahal, & Shuigao, 2001).

It has recently been suggested that different cereal grains, particularly millet grains, may have enhanced health benefits in terms of glucose and insulin metabolism (Helnaes et al., 2016; Nambiar, Dhaduk, Sareen, Shahu, & Desai, 2011; Shobana et al., 2013).

However, limited studies have been conducted to investigate the physiological and gastrointestinal responses to these grains, particularly the blood glucose and appetite responses to the millets.

Magnetic resonance imaging (MRI) provides a unique tool to investigate gastrointestinal handling of food (Alyami, Spiller, & Marciani, 2015). Furthermore, the small intestinal secretory and fluid response to breakfast porridges is unknown. After milling, intact particles can exert effects through mechanical stimulation of the small intestine, as we showed using bran and plastic particles (McIntyre, Vincent, Perkins, & Spiller, 1997), and MRI provides a non-invasive means to assess gastrointestinal fluid responses (Marciani et al., 2010).

This pilot study was therefore designed to collect initial data on postprandial glucose levels following consumption of isoenergetic breakfast porridges made from finger millet, pearl millet oats and rye. Secondly, the study aimed to compare postprandial gastric volumes, small bowel water content and subjective appetite for these meals. It also aimed to explore possible correlations between blood glucose levels, gastric volumes, and subjective appetite outcomes. We hypothesised that breakfast porridges made from different varieties of cereal grains would produce different postprandial glucose responses, gastric volumes and subjective appetite scores in healthy participants.

2 Material and methods

2.1 Study participants

Within the study period a total of 17 healthy participants were screened out of the planned 18. One did not attend screening so 16 healthy subjects (ten female and six male, 20.9 (SD 0.9) years old, BMI 22.1 (SD 2.9) kg/m^2 participated. A full dataset for all four meals was obtained for seven participants who were then included in subsequent analysis. This included four females and three males, aged 21 (SD 1.0) years old, and with a BMI of 21.8 (SD 2.1) kg/m^2. A subgroup analysis was also consideded for ten participants who consumed all of the SOP, RP and PMP meals. The remaining nine participants were excluded from the analysis either because they did not attend visits or because they were unable to consume all of the test meal on one or more visits (Fig. 1).

Participants were recruited from the student and staff population of the University of Nottingham via a poster advertisement. Those who expressed interest were invited to a screening session to establish whether they met the study inclusion criteria, namely: age 18 - 65 years, being healthy, BMI ≥ 18 and ≤30 kg/m^2 and able to give informed written consent. Exclusion criteria included: using medication which interferes with study measurements, participating in another nutritional or biomedical trial three months before the pre-study examination or during the study, not being a habitual breakfast consumer, not usually eating at least three meals a day, reporting participation in night shift (between midnight and 6.00 am), doing strenuous exercise for >10 h/week, consuming of ≥21 alcoholic drinks in a typical week, following a medically or self-prescribed diet during the two weeks prior to the pre-study examination and until the end of the study, contraindications for MRI scanning (e.g. presence of metal implants, infusion pumps and pacemakers) as assessed by standard MRI safety questionnaire, pregnancy, inability to lie flat and exceeding the scanner bed weight limit of 120kg.

The study was conducted at the Sir Peter Mansfield Imaging Centre at the University of Nottingham. Informed written consent was obtained from each participant before the trial. A site master file and case report forms were kept according to good clinical practice.

All procedures in this study involving human participants were approved by the University of Nottingham, Medical School Research Ethics Committee (F14072015). The study was registered within Clinical Trials.gov (NCT02653274). The trial registration name was 'Assessment of Millet, Oat and Rye Porridge Breakfasts Glucose and Gastric Emptying (AMORE)'.

2.2 Study design

This study was randomized, four way crossover design. Participants attended the laboratory on four separate days, approximately 1 week a part, in order to consume four different porridges in a randomized order. Participants consumed their habitual diet between each visit. Each visit lasted from 8:00 am until approximately 1:00 pm. The porridge meals differed in appearance and taste hence participants could not be blind although they were not informed which porridge they were consuming on each visit.

2.3 Screening

All potential participants attended a screening visit to establish that they met the study inclusion criteria for the study. Height and weight were measured and the Body Mass Index (BMI) was calculated as weight divided by the square of height.

2.4 Laboratory visit protocol and procedures

Fig. 2 shows the study day protocol. The participants were asked to fast overnight (for at least ten hours). A glass of water was permitted on waking. On arrival they completed the study eligibility check questionnaire to ensure adherence to the study day restrictions such as the overnight fasting. Baseline measurements (defined as t = 0 min) then were made which included fasting blood glucose, participant completion of paper based subjective visual analog appetite score (VAS, described below) and a MRI scan. The participants were then requested to eat the given porridge within a maximum time of 15 min. This was followed by an immediate postprandial (defined as t = 20 min) measurement of blood glucose, followed by VAS completion and a MRI scan. Blood glucose was subsequently measured every 15 min until t = 60 min, then every 20 min until t = 120 min, followed on each occasion by completion of VAS. MRI scans were undertaken hourly from t = 15 min up to t = 140 min. Participants were given a blank food diary and instructed to complete it over the remainder of the day.

2.5 Breakfast porridge intervention

Four breakfast porridges were made from Scottish oats (Asda, United Kingdom), rye (buywholefoodsonline.co.uk, Canterbury, United Kingdom), finger millet (Top-Op Foods Ltd., Stanmore, United Kingdom) and pearl millet (Herbs n Spice it, India). The oats and rye were steam rolled flakes. Rye flakes were larger than the oat flakes. The millets were plain dehulled grains ground to a flour using a spice grinder in our lab. The cooked products were analysed for macronutrient composition and total energy by Campden BRI, Chipping Campden, Gloucestershire, UK (Table 1) so that the four breakfast meals given to the participant could be made isoenergetic (220 kcal each). The grains were cooked in water in two separate aliquots using two microwaves (900 watts). The aim was to achieve an acceptable final product hence the grains were subjected to different cooking protocols. The oats were simply heated with water, the rye was soaked for half an hour in boiled water then heated; the millets were ground prior to cooking using a spice grinder for 30 s. The study meals were consumed with 240 ml of water in a glass and on each of the four occasions, the participants were asked to consume the entire portion with the water drink within 15 min. Other meal characteristics such as appearance, volume and weight necessarily differed between meals (SOP 400 g; RP 297 g; FMP 432 g; PMP 310 g).

2.6 *Gastrointestinal response measured by MRI*

Magnetic resonance imaging (MRI) was carried out on a research-dedicated 1.5 T Philips Achieva MRI scanner (Philips Healthcare, Best, The Netherlands). Participants were in the supine position with a 16 element receiver coil wrapped around their abdomen. Gastric volume was measured using a balanced turbo field echo (bTFE) sequence. A total of 25 axial images were acquired with the following sequence parameters: the field of view (FOV) 400 mm ×320 mm ×250 mm, acquired resolution 2.01 ×1 .76 mm^2, slice thickness 10 mm, repetition time (TR) 2.8 ms, echo time (TE) 1.4 ms, no slice gap, flip angle (FA) 80^o and one breath hold for 10 s. Gastric volume was measured manually by one operator using Analyze9 software (Mayo Foundation, Rochester, MN, USA).

The water content of the entire small bowel (SBWC) was measured using a single–shot, fast spin echo sequence (rapid acquisition with relaxation enhancement), which shows high intensity signals from areas with free mobile fluid and dark signals from other body tissues. A total of 24 coronal images were obtained using the following sequence parameters: FOV 400 mm × 400 mm, acquired resolution 0.78 × 0.78 mm^2, slice thickness 7 mm, TR 8000 ms, TE 320 ms, no slice gap, and one breath hold for 24 s.

The SBWC was assessed using in-house software which was previously validated (Hoad et al., 2007). Briefly, bright signals from organs other than small bowel water (e.g. stomach, gall bladder) were segmented out manually, and then integrating total volume over pixels with intensity values above the calculated threshold. The total AUC for gastric volume and for small bowel water were calculated.

2.7 *Glycaemic response*

The glycaemic response was measured in capillary blood samples (Freckmann et al., 2012) using the protocol described by Brouns et al. (2005) which is in line with techniques recommended by the World Health Organization (WHO) / Food and Agricultural Organization (FAO 1998). The capillary blood samples were collected by finger prick using single-use lancets (Unistix Owen Mumford, Oxfordshire, United Kingdom). The capillary blood glucose was measured using Accu-check (Roche Diagnostics, USA).

Participants were requested to warm their hands before the finger prick in order to increase the blood flow. To extract the blood, the fingertips were gently massaged from the base of the hand, moving towards the tips in order to minimise the plasma dilution. Incremental area under the glucose curve (iAUC) and peak blood glucose response to the test products were calculated according to Brouns et al. (2005); Wolever and Jenkins (1986). iAUC was obtained using the trapezoid rule and ignoring the area beneath the baseline.

2.8 Subjective appetite ratings

100 mm VAS were used to measure the subjective feelings of hunger, satisfaction, fullness, desire to eat and prospective food consumption.(Flint, Raben, Blundell, & Astrup, 2000) When outside the MRI scanner,the participants were requested to make a vertical mark on each scale at the point that best matched how they felt at that time. Each end of the line was anchored by statements expressing the extreme for the sensation. For example, ‘not hungry at all’ and ‘more hungry than have ever been’. To avoid bias from previous answers the participants were presented only with a new VAS sheet at each time point and this was removed immediately after completion. The VAS appetite ratings were determined by measuring (in millimetres) the distance from the left side of the line to the vertical mark.

The average Appetite score was calculated for each individual at each time of measurement, for each test meal, using the formula: Average appetite score = [hunger + (100 – satisfaction) + (100 – fullness) + desire to eat + prospective consumption]/5 (Anderson, Catherine, Woodend, & Wolever, 2002; Stubbs et al., 2007). The Average Appetite scores at each time point were used for the statistical analysis. The range for the appetite score was between 0 and 100; 0 representing the minimum appetite sensations and 100 representing the maximum appetite sensations. Total AUC for average appetite score were calculated (Blundell et al., 2010).

2.9 Food diaries

Food diaries were given to the participants before discharge. They were requested to provide a detailed record of food and beverages consumed over the remainder of the day, once they had left the unit. They were required to include information such as portion sizes, product brand names, and cooking and preparation methods. Furthermore, if the participants prepared composite dishes at home, then they were requested to provide the recipe and portion size.

Nutritics software (Nutritics Ltd , Dublin, Ireland) was used to analyse the food intake from the food diaries. Some food items were added manually to the database using the information on nutrition labels.

2.10 Sample size and statistical analysis

Descriptive and statistical analyses were undertaken using Prism version 6.07 (Graph Pad Software Inc., La Jolla, CA). All data are presented as mean±SE unless otherwise indicated. Data were assessed for normality using the Shapiro-Wilk 's test. Normally distributed data were analysed using parametric methods; non-normally distributed data were analysed using non-parametric methods.

This was a pilot study and we did not have own data to speculate on the sample size required. For an overall estimate, using data from Nilsson et al. (2008), a 33% change in blood glucose should be detectable with alpha=0.05 and a power of 80% using n=18.

Differences in glycaemic response, gastric volume, SBWC and appetite score were assessed using one-way repeated-measures analysis of variance followed by Tukey 's post hoc test.

Correlations between blood glucose, gastric volume and appetite scores were assessed using Pearson's correlation. Differences were considered significantly different at $p<0.05$.

3 Results

In this pilot study, the effects of different porridges on postprandial glycaemic response, gastrointestinal response (gastric volume and SBWC) and subjective appetite were measured.

Seven participants failed to consume all of the finger millet test meal hence they were excluded from the per protocol analysis. When asked, palatability was reported as the main problem. Two more subjects did not attend one of the study session hence were also excluded. The results presented are thus shown as per protocol analysis with n = 7 (four females and three males of normal weight) who consumed all of the four study meals (Table 2). Additionally, a subgroup analysis (n = 10 for SOP, RP and PMP) was consederd in this pilot study (Table 4)

3.1 Appearance of the gastric content and total gastric volumes

Fig. 3 shows the appearance of the gastric content for each of the porridges immediately after consumption (t = 20 min). With SOP, two layers can be seen, a bottom layer providing a lower signal (appearing darker in the figure) and a top layer providing higher signal (appearing brighter in the figure), whilst RP remains in a distributed form in the stomach. FMP and PMP produced multiple layers in the stomach.

There was no significant difference in fasting baseline gastric volumes between the test days as expected. Gastric volumes rose on consumption of the porridges and declined with time as shown in Fig. 4.

The immediate postprandial gastric volumes (t = 20 min) were significantly different between the four breakfast meals (p = 0.007) in keeping with the initial meal volume differences. Overall AUC 2 h gastric volumes showed a significant difference between the study meals (p = 0.003). There was a significant difference in gastric volume AUC between the RP and FMP (p = 0.04) and a difference in gastric volume AUC between the RP and the PMP (p = 0.002). The subgroup analysis (n = 10) also showed significant difference immediate postprandial gastric volumes (T = 20) and AUC gastric volum between the test meals as shown in Table 4.

3.2 Small bowel water content

SBWC data are shown in Fig. 5; the mean fasted SBWC was 23.1 ml (SD 6.4) for the four study porridges. All the meals induced an initial drop in SWBC after feeding followed by a rise at t = 80 min, but the differences were not statistically different.

3.3 Glycaemic response

The glycaemic responses to all the porridges were in the normal range for non-diabetic subjects. There were no differences in fasting glucose values, and the expected post consumption increase in blood glucose was seen in all cases. Fig. 6 shows the iAUC for all paricipants. The hightest mean peak glucose was following FMP at 7.8 mmol/ml compared with following SOP, RP and PMP at 7.1 mmol/ml, 6.8 mmol/ml and 6.9 mmol/ml. For the n = 7 analysis, glucose iAUC 0-2 h was also the lowest after PMP (109.6 mmol/l 120 min) compared with following SOP, RP and FMP (131.1 mmol/l

120 min, 119.5 mmol/l 120 min and 145.4 mmol/l 120 min respectively. These differences were not statistically significant.

The n = 10 subgroup analysis showed that PMP and RP had similar peak blood glucose level at 7.0 mmol/ml, wheras peak blood glucose of SOP was 7.1 mmol/ml. There was no siginificant difference in IAUC glocuse between the test meals (Table 4).

3.4 Subjective appetite ratings

The area under curves of the subjective appetite ratings are summarized in Table 3 and the impact of the four breakfast porridges on the scores for hunger, satisfaction and average appetite are shown in Fig. 7. As expected, for all interventions, the scores for hunger, desire to eat and prospective food consumption decreased after consuming the breakfast before returning to baseline, whilst fullness and satisfaction initially decreased and then increased again in all cases. AUC for the sense of hunger of the subgroup analysis showed a sigifnicant difference between the test meals ($p = 0.017$). The average appetite score was the lowest the after consuming the millet, but the AUC for this score was not significantly different between the three porridges (Table 5).

3.5 Food intake record

Four food diaries were not returned (1 for SOP, 2 for RP and 1 for FMP) so these data cannot be presented as per protocol. Data are presented as mean and standard errors of mean. The self-reported daily energy intake records following consumption of the SOP, RP, FMP and PMP were 1747 ± 158 kcal/d, 2332 ± 369 kcal/d, 1694 ± 100 kcal/d and 1754 ± 322 kcal/d respectively, the differences being not significant.

3.6 Correlations

There was a significant correlation between total gastric volume AUC and average appetite AUC $r = -0.47$ $p < 0.010$, but not between gastric volumes and iAUC glucose ($P < 0.3$). The subgroup analysis with n =10 showed also a similar significant negative correlation between total gastric volume AUC and average appetite AUC $r = -0.465$ $p < 0.01$.

4 Discussion

This is the first pilot, *in vivo* imaging study assessing the glycaemic, gastrointestinal and appetite responses to porridges made from different 'modern' and 'ancient' cereal grains in healthy, normal-weight participants. The pilot project is a small-scale study conducted to gain experience and allow appropriate sample size calculations for future studies (Thabane et al., 2010).

In this current study, some participants were unable to consume the meals in full particularly the FMP. Future studies need to review the way in which the product is prepared and consumed in order to ensure participants can adhere to the protocol. Exclusion of those participants who had not consumed all porridges reduced the sample size to n = 7. Ten subject completed oats, rye and pearl millet providing a second post-hoc analysis.

Among those who were able to consume all four porridges, isoenergetic breakfast porridges made from different grains induced different gastrointestinal and physiological responses, although for the sample size used in this pilot study only gastric volume were significantly different. After consumption of the pearl millet porridge, there was a trend for the glucose response to decrease, gastric volume to increase and appetite to increase compared with the other porridges some of which failed to reach significance potentially because of small numbers. The secondary analysis with n = 10 showed similar trends with some outcome differences reaching significance such as Hunger.

The immediate post prandial gastric volumes were significantly different as would be expected given that the isoenergetic portions had different volumes. Although the total energy of a meal has an effect on the gastric emptying, in this study the four breakfast meals were isoenergetic, suggesting that the gastric volume was affected by other factors such as particle size, viscosity and the meal volume, which is a key regulator of gastric emptying (Calbet & MacLean, 1997). Furthermore, separation of liquid and solid parts (known as sieving) could affect the gastric emptying rate as the liquid part would be absorbed quickly in the early phase (Marciani et al., 2012). In this study, SOP emptied faster compared with the other porridges, which may be due to the separation between liquid part and oat flakes as shown in Fig. 4. On the other hand, the liquid and solid phase were combined in the PMP and this may limit the sieving and delay emptying of the meal (M. Clegg, Ranawana, Shafat, & Henry, 2013). Although the volume of PMP porridge was lower than that of SOP and FMP, PMP emptied at a slower rate, which could account for the smaller rise in blood sugar of this millet (Horowitz, Edelbroek, Wishart, & Straathof, 1993).

The appearance of the SBWC resembles that reported previously (Hoad et al., 2007; Marciani et al., 2013). The postprandial SBWC initially fell during the 'gastric phase' after feeding and the rose during the 'intestinal phase'. The early decrease in the SBWC is possibly related to the absorption of the readily available nutrients in the liquid phase. The later rise of the SBWC is likely to be related to the increased pancreatobiliary and enterocyte secretion after a mixed liquid/ solid meal and possibly also the effect of particulates (Marciani et al., 2010; McIntyre et al., 1997; Murray et al., 2014).

All the grains had a relatively low glycaemic index (Gonzalez & Stevenson, 2012; Nambiar et al., 2011; Rosén, Östman, & Björck, 2011; Shobana et al., 2013). The present study is in agreement with many studies that have shown that rye is known to induce a low and prolonged blood glucose response (Rosén et al., 2011; Rosen et al., 2009). Although the rye grains were soaked in water before heating in the microwave in this study, which could have an effect on the gelatinisation of rye starch and as a result elevated the glucose response (Zhu, 2014). The glucose response after consuming the RP remained lower. The glucose response after consumption of oats was also in agreement with other studies. A study on rolled oats showed that after consumption a similar peak blood glucose value of 7 mmol/L, suggesting that our results are in line with the literature. (Gonzalez & Stevenson, 2012) However, the results in relation to the finger millet were inconsistent in terms of the higher blood glucose in comparison with other studies (Shobana et al., 2013; Shukla & Srivastava, 2014). However there is little information available about the physiological and gastrointestinal responses to millet grains, especially pearl millet, limiting our knowledge about their potential health benefits.

The differences in the glycaemic response seen between these grains could be due to the processing of cereals which alters the digestion of the cereal grains; this is a considered a major determinant of the glycaemic response (Heaton, Marcus, Emmett, & Bolton, 1988; Mackie et al., 2017) and also of the impact on appetite. (Isaksson et al., 2012). Oat and rye are steamed rolled flakes which can keep the endosperm intact and ultimately limit accessibility of amylase to the starch oats (Taylor, Emmambux, & Kruger, 2015). Our finger and pearl millet, on the other hand, were milled to flour which offers a higher surface area to digestion. This possible explanation is supported by a systematic review investigating the effects of different processing methods on glycaemic responses, in which it is shown that a smaller particle size caused greater gelatinisation and a heightened glycaemic response (Granfeldt, Eliasson, & Björck, 2000; Tosh & Chu, 2015). In addition, another study has found that different milling methods have effects on glycaemic response of foods made with finger millets flour (Jayasinghe, Ekanayake, & Nugegoda, 2013). The difference in the glucose response between the two millets could be due to the different amount of carbohydrate content which is potential an important determinant of the glucose response (Arvidsson-Lenner et al., 2004; Kang et al., 2013). In this study, FMP had the highest carbohydrate content (53.1 g) compared with PMP (45.6 g). This could explain the greater rise of FMP compared to the other porridges.

The current study indicated that the millet porridges may have prolonged satiating properties compared with the oats and the rye porridges. The increase in satiety following the millets could be related to the delay in decline of the gastric volume in these grains causing prolonged distension of the stomach and delayed delivery of nutrients into the small intestine (M. E. Clegg & Shafat, 2014; Kissileff, Carretta, Geliebter, & Pi-Sunyer, 2003; Mackie, Rafiee, Malcolm, Salt, & van Aken, 2013; Marciani et al., 2001). Furthermore, the reduced rate on gastric emptying following consumption of the PMP could account for the blunted glycaemic response of the pearl millet (Bornet, Jardy-Gennetier, Jacquet, & Stowell, 2007). This study did not measure duodenal motility hence it is not possible to comment on possible differences in motility between meals and the impact that this may have on gastric emptying. (Teramoto et al., 2012, 2014).

There were several limitations to the current study including the fact that the test meals were physically different, two were steam rolled flakes and two plain grains ground to a flour. The test meals were cooked slightly differently to obtain a more acceptable final product which may have altered the bioavailability of carbohydrates. Seven participants found the palatability of finger millet poor and could not finish all the test meal. The isoenergetic portions were of different volume. Use of capillary blood glucose does not represent arterial blood however it is a close approximation (Brouns et al., 2005). Also, future studies should measure insulin. Some food diaries were missed limiting our opportunity to assess the impact of the porridge consumed as a breakfast on 24 energy intake. Appetite ratings are a proxy measure for what people will actually eat. This leads us to suggest that this will be better assessed in future studies by providing lunch using ‘bottom less bowl’ thereby providing a more accurate and objective measure of actually food consumption at midday as week as more closely managing the return of diaries.

Although this pilot study did not demonstrate many significant differences in the physiological and gastrointestinal responses after consumption of the four breakfast meals, valuable experience has been gained in the implementation of the protocols and provided useful directions for further studies. Finally, the use of in vivo imaging can increase our knowledge of the behaviour of these meals in the gastrointestinal (GI) tract. This will facilitate an understanding of the interface between the input of a given feeding stimulus and various physiological and behavioural consequences. This will help us to improve our understanding of the effect of physical properties of food on digestion and appetite, engineer foods with the desired in vivo behaviour and develop more relevant in vitro / in vivo food digestion models.

5 Conclusion

Isoenergetic breakfast porridges from 'ancient' varieties of millet grains showed physiological responses that were comparable with those from common Western varieties known to have beneficial health effects. Pearl millet appeared to induce lower postprandial blood glucose response and appetite scores though small numbers did not allow conclusive inferences against other grains and further work is needed. Pearl millet is a popular 'ancient' and sustainable grain, and may represent a valid alternative to other cereal breakfasts. Improved knowledge of the effects of different cereal grains could help direct dietary advice. The breakfast porridge intervention is relatively cheap compared to other interventions and could help reduce the burden of obesity and related metabolic disorders worldwide.

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Authorship:

The authors' responsibilities were as follows: MAT, LM and JA designed the study with contribution from: RCS on gastroenterology, AAS on statistics, PAG on imaging, IAM on metabolic physiology and GPA on liver metabolism. CLH set up the MRI sequences and analysis. All authors read and approved the final manuscript.

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Table1

Macronutrient composition of the breakfast meals. The values are shown total for each cooked product as served

	SOP	RP	FMP	PMP
Weight (g)	400	297	432	311
Energy (kJ)	920.0	920.0	920.0	920.0
Energy (kcal)	220.0	220.0	220.0	220.0
Protein (kjeldahl, g)	7.2	4.2	3.5	5.3
Total carbohydrate (by difference, g)	42.0	49.3	53.1	45.6
Carbohydrate(Avail, g)	34.0	39.8	43.6	38.8
Total sugars (enzymic, g)	1.6	5.9	1.7	0.3
Fructose (enzymic, g)	0.4	0.3	0.4	0.3
Glucose (enzymic, g)	0.8	0.3	0.4	0.3
Maltose (enzymic, g)	0.4	0.3	0.4	0.3
Sucrose (enzymic, g)	0.8	5.9	1.7	0.3
Fat (Weibull-Stoldt, g)	4.4	2.7	1.3	3.1
Saturates (g)	0.8	0.6	0.4	0.6
MUFA (cis, g)	2.0	0.6	0.4	0.9
PUFA (cis)	1.2	1.2	0.4	1.2
Trans fatty acids (g)	0.4	0.3	0.4	0.3
Total fiber (AOAC, g)	8.0	6.5	13.8	6.8
Sodium(ICP-MS)	24.4	17.8	28.5	19.5
Moisture (Oven102°C)	345.2	240.0	372.4	255.6
Ash(@525C)	1.2	1.1	1.4	1.0
Protein N Factor	6.25	6.25	6.25	6.25
Equivalent Salt	0.4	0.3	0.4	0.3

SOP, Scottish Oats porridge; RP, Rye porridge; FMP, Finger millet porridge; PMP, Pearl millet porridge; AOAC, Association of Analytical Communities.

Table 2

Blood glucose, time to peak, gastric volumes, small bowel water content and average appetite sensations measured from n = 7 healthy participants who were fed four different breakfast porridges.

	SOP		RP		FMP		PMP		
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	1-ANOVA
IAUC glycaemic response mmol/l (over 120 min)	131	28	119	27	145	23	110	29	0.5
Glucose peak, mmol/l	7.2	0.3	7.2	0.5	7.7	0.4	6.7	0.3	0.2
Gastric volume at T = 20	505	26	384	22	548	48	532	23	0.007
AUC Gastric volume ml/min	50324	2696	41644	2892	56606	3832	58684	3339	0.003
AUC small bowel water content ml/min	1611	429	1303	360	735	259	2157	499	0.06

(Mean values with their standards errors) n = 7

Table 3

Participants’ (n = 7) area under the satiety curve from the visual analog scales for hunger, satisfaction ,fullness, desire to eat, prospective food consumption and average appetite score.

	SOP		RP		FMP		PMP		
Appetite sensations variables	Mean	SE	Mean	SE	Mean	SE	Mean	SE	1-ANOVA
Hunger (mm/min)	6325	461.9	7717	636.5	5378	1196	5465	1030	0.08
Satisfaction (mm/min)	6877	537	5920	716	8636	1164	7849	917	0.08
Fullness (mm/min)	6881	580	6149	754	8385	1117	8238	1102	0.3
Desire to eat (mm/min)	6776	526	7643	832	5549	1349	5992	1003	0.5
Prospective food consumption (mm/min)	7092	502	7984	788	5618	1359	5938	1067	0.3
Average appetite sensations	6887	463	7855	710	5505	1220	5862	991	0.5

(Mean values with their standards errors) n = 7

Table 4

Blood glucose, time to peak, gastric volumes, small bowel water content and average appetite sensations measured from n = 10 healthy participants who were fed four different breakfast porridges.

	SOP		RP		PMP		
	Mean	SE	Mean	SE	Mean	SE	1-ANOVA
IAUC glycemic response mmol/l (over 120 min)	134	27	102	21	107	21	0.6
Glucose peak, mmol/l	7.1	0.2	7.0	0.4	7.0	0.2	0.7
Gastric volume at T = 20	535	23	407	29	544	17	0.0008
AUC Gastric volume ml/min	41519	1978	34751	2249	59454	2499	0.0001
AUC small bowel water content ml/min	1302	255	1123	332	1713	275	0.18

(Mean values with their standards errors) n = 10

Table 5

Participants' (n = 10) area under the satiety curve from the visual analog scales for hunger, satisfaction ,fullness, desire to eat, prospective food consumption and average appetite score.

	SOP		RP		PMP		
Appetite sensations variables	Mean	SE	Mean	SE	Mean	SE	1-ANOVA
Hunger (mm/min)	5274	673.8	6606	770.5	4996	842.7	0.01
Satisfaction (mm/min)	7989	695	7062	785.9	8121	672.4	0.22
Fullness (mm/min)	7976	733.9	7235	799.6	8502	811.9	0.43
Desire to eat (mm/min)	5737	688.3	6535	829.5	5538	835	0.18
Prospective food consumption (mm/min)	6131	690.2	6836	833	5498	887.6	0.36
Average appetite sensations	5835	672.7	6736	786.6	5482	782.1	0.22

(Mean values with their standards errors) n = 10

Figure Legends

Fig. 1 Study participant flow diagram

Fig. 2 Diagram of the study day protocol

Fig. 3 Representative example of axial MRI images of the abdomen of a healthy participant fed with , Scottish oats porridge (SOP); Rye porridge (RP); Finger millet porridge (FMP); Pearl millet porridge (PMP) on four different occasions. Images were taken at t=20 min.

Fig. 4 Plot of the volume of the gastric contents for healthy participants after they consumed the four different study porridges. , Scottish oats porridge (SOP); , Rye porridge (RP); , Finger millet porridge (FMP); , Pearl millet porridge (PMP). Values are mean ± SE, n = 15 for SOP and RP, n = 9 for FMP and n = 12 for PMP. The arrow on the horizontal axis indicates the meal start time.

Fig. 5 Plot of the volume of the small bowel water content for healthy participants after they consumed the four different study porridges. , Scottish oats porridge (SOP); , Rye porridge (RP); , Finger millet porridge (FMP); , Pearl millet porridge (PMP). Values are mean ± SE, n = 15 for SOP and RP, n=9 for FMP and n = 12 for PMP. The arrow on the horizontal axis indicates the meal start time.

Fig. 6 Incremental area under the glucose curve (iAUC) for healthy participants after they consumed the four different study porridges., Scottish oats porridge (SOP); Rye porridge (RP); Finger millet porridge (FMP); Pearl millet porridge (PMP). Values are mean ± SE, n=15 for SOP and RP, n = 9 for FMP and n = 12 for PMP.

Fig. 7 Plot of the average appetite sensations for healthy participants after they consumed the four different study porridges. - ·▼ -, Scottish oats porridge (SOP); ···●···, Rye porridge (RP); —■—, Finger millet porridge (FMP); —△—, Pearl millet porridge (PMP). Values are mean ± SE, n = 15 for SOP and RP, n = 9 for FMP and n = 12 for PMP. The arrow on the horizontal axis indicates the meal start time.

Fig 1:

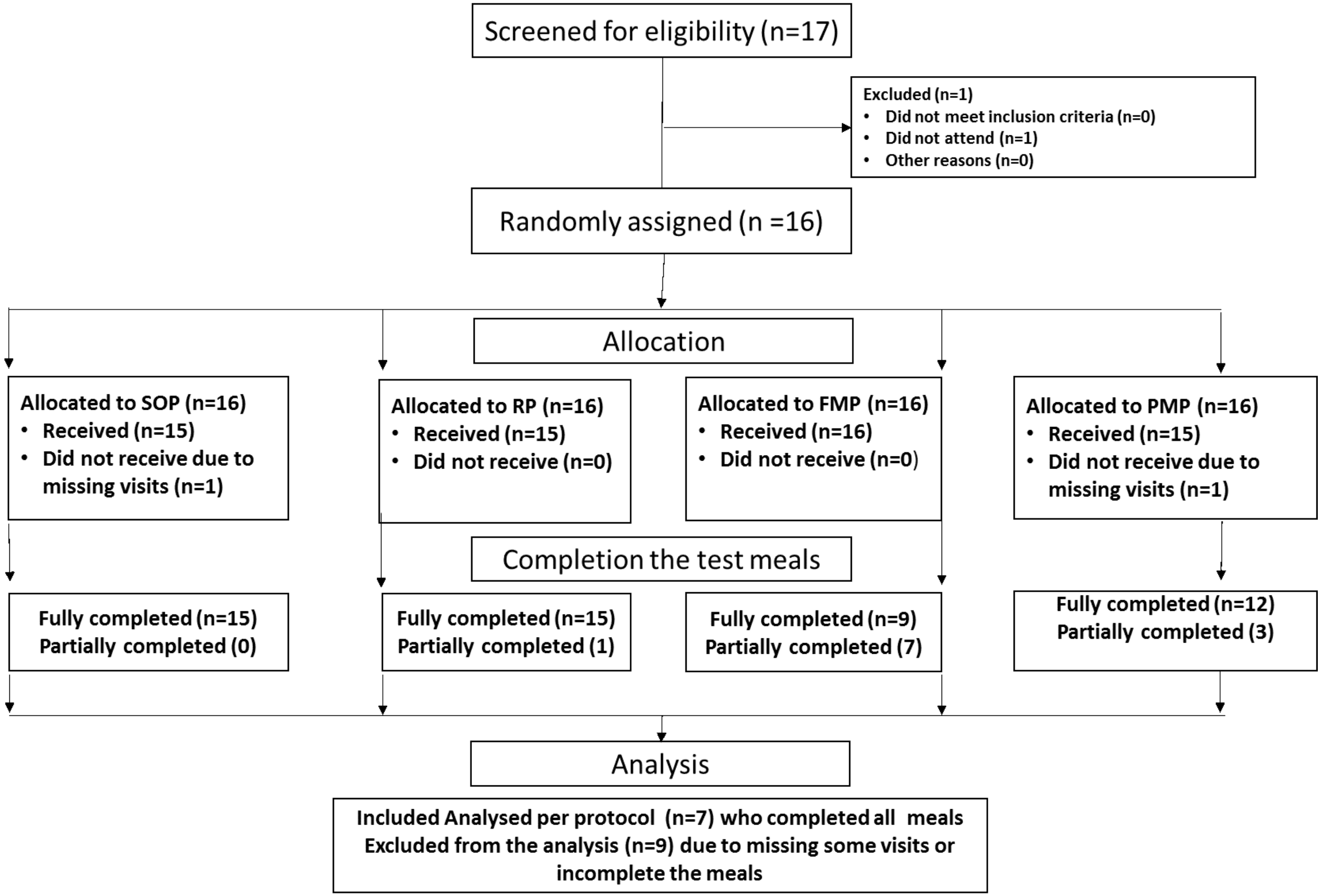

Screened for eligibility (n=17)
Excluded (n=1)
• Did not meet inclusion criteria (n=0)
• Did not attend (n=1)
• Other reasons (n=0)
Randomly assigned (n =16)
Allocation
Allocated to SOP (n=16)
• Received (n=15)
• Did not receive due to missing visits (n=1)
Allocated to RP (n=16)
• Received (n=15)
• Did not receive (n=0)
Allocated to FMP (n=16)
• Received (n=16)
• Did not receive (n=0)
Allocated to PMP (n=16)
• Received (n=15)
• Did not receive due to missing visits (n=1)
Completion the test meals
Fully completed (n=15)
Partially completed (0)
Fully completed (n=15)
Partially completed (1)
Fully completed (n=9)
Partially completed (7)
Fully completed (n=12)
Partially completed (3)
Analysis
Included Analysed per protocol (n=7) who completed all meals
Excluded from the analysis (n=9) due to missing some visits or incomplete the meals

Figure 2

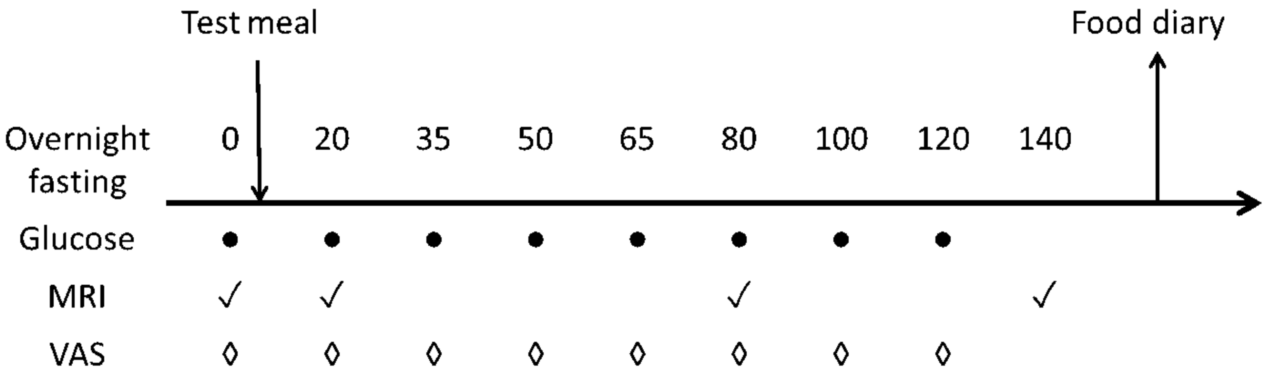

Test meal
Food diary
Overnight fasting
0
20
35
50
65
80
100
120
140
Glucose
MRI
VAS

Figure 3

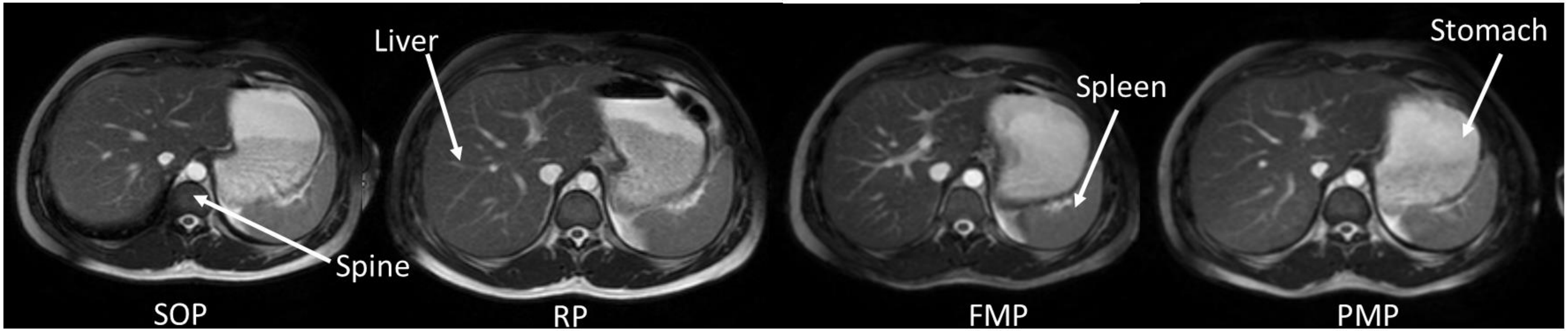


Figure 4

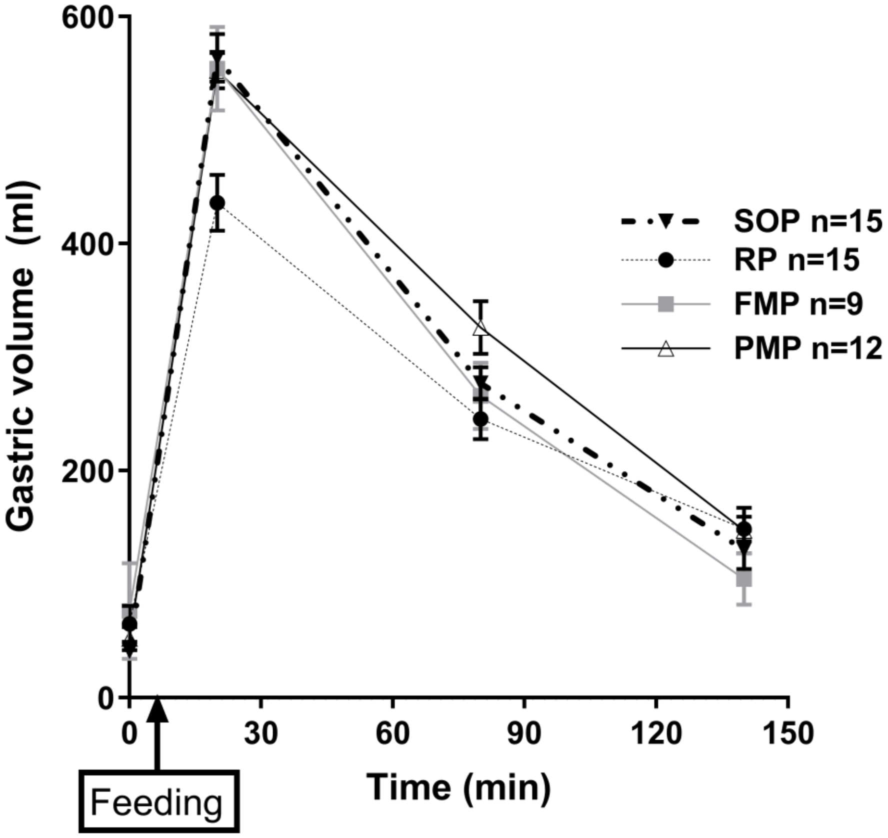

600
400
200
0
Gastric volume (ml)
0
30
60
90
120
150
Time (min)
Feeding
SOP n=15
RP n=15
FMP n=9
PMP n=12

Figure 5

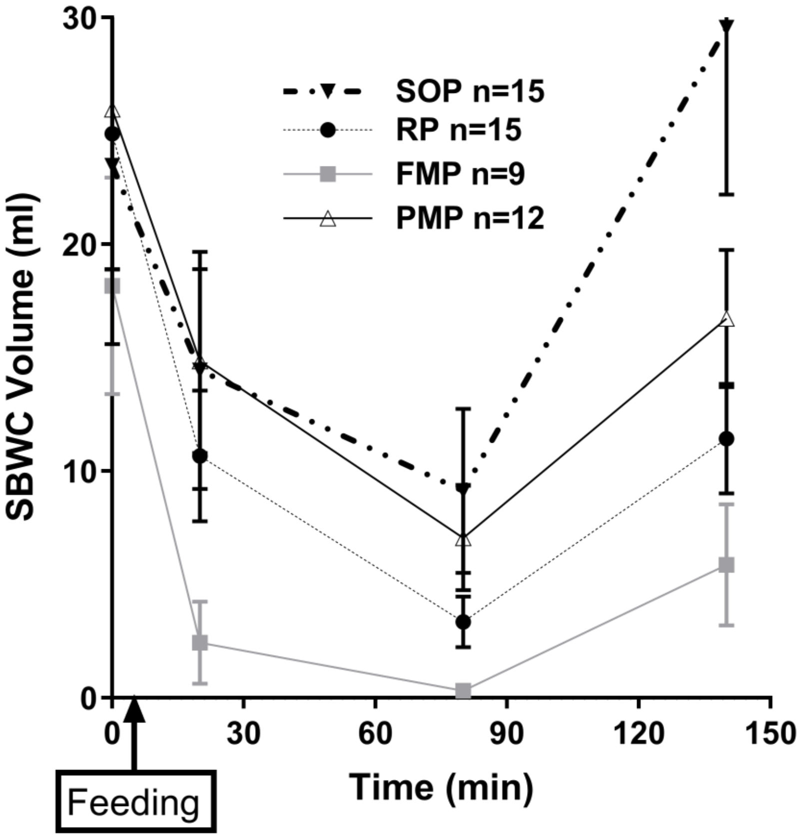

SOP n=15
RP n=15
FMP n=9
PMP n=12
SBWC Volume (ml)
30
20
10
0
0
30
60
90
120
150
Time (min)
Feeding

Figure 6

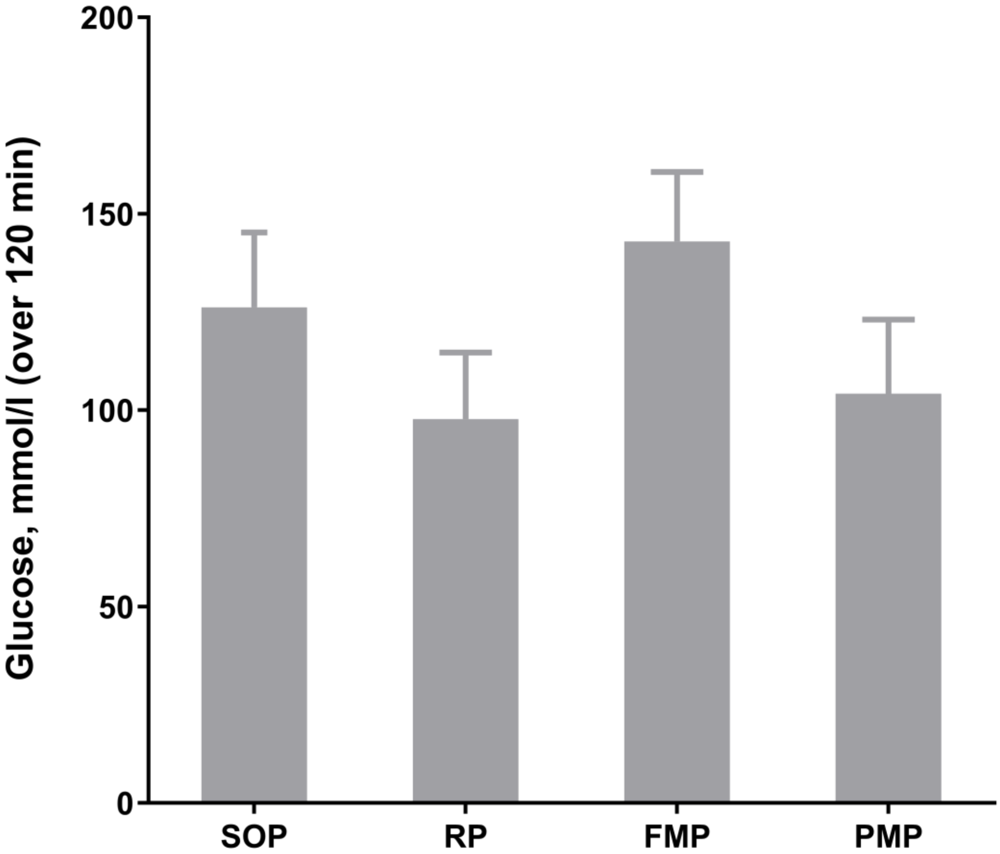
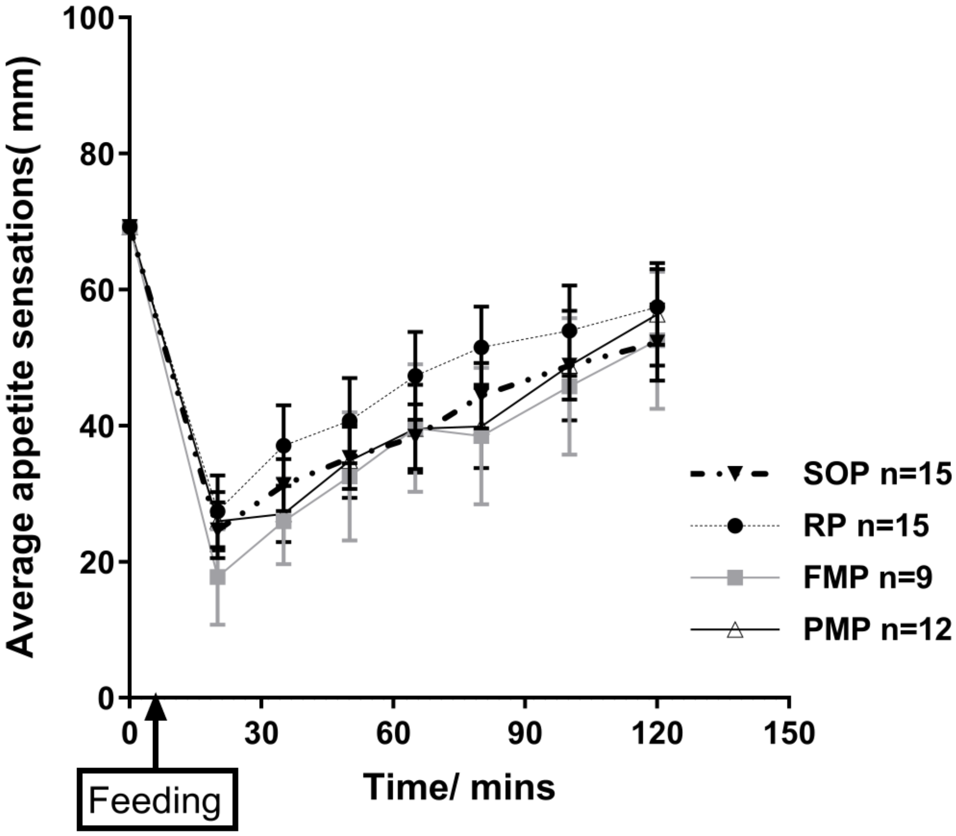


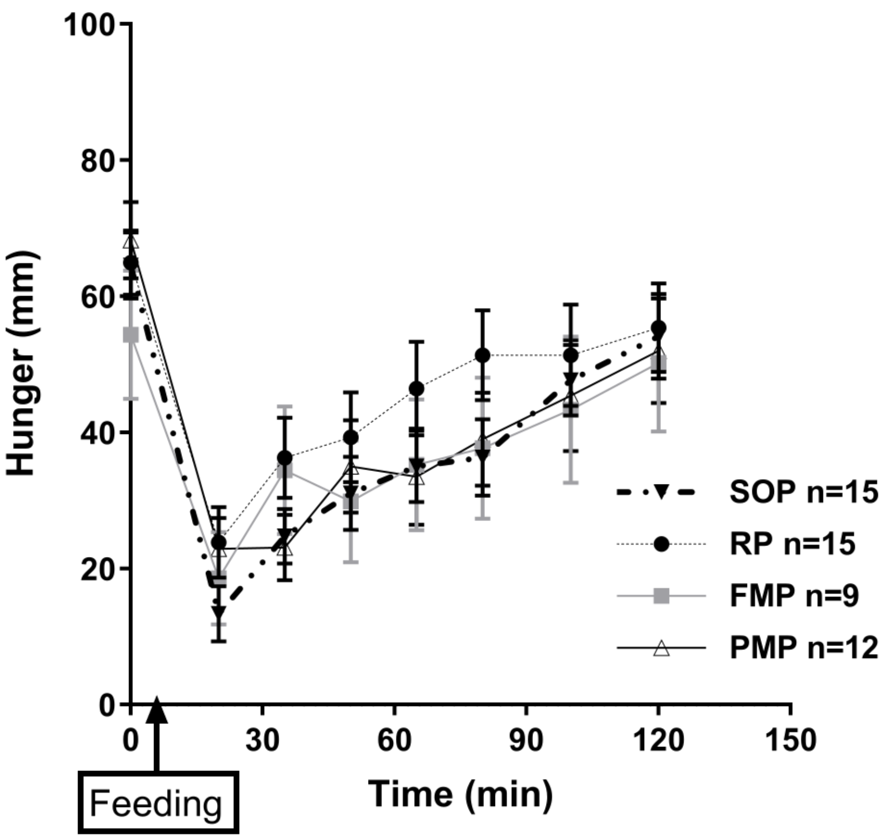
Figure 7



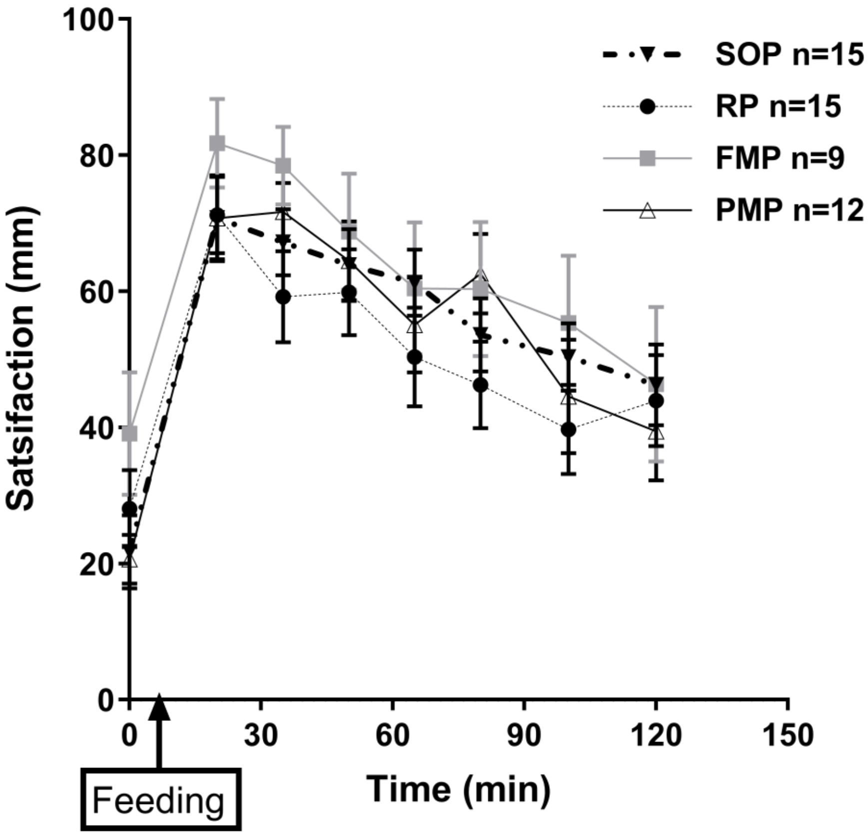
Average appetite sensations(mm)
100
80
60
40
20
0
0
30
60
90
120
150
Time/ mins
Feeding
SOP n=15
RP n=15
FMP n=9
PMP n=12

Supplementary material

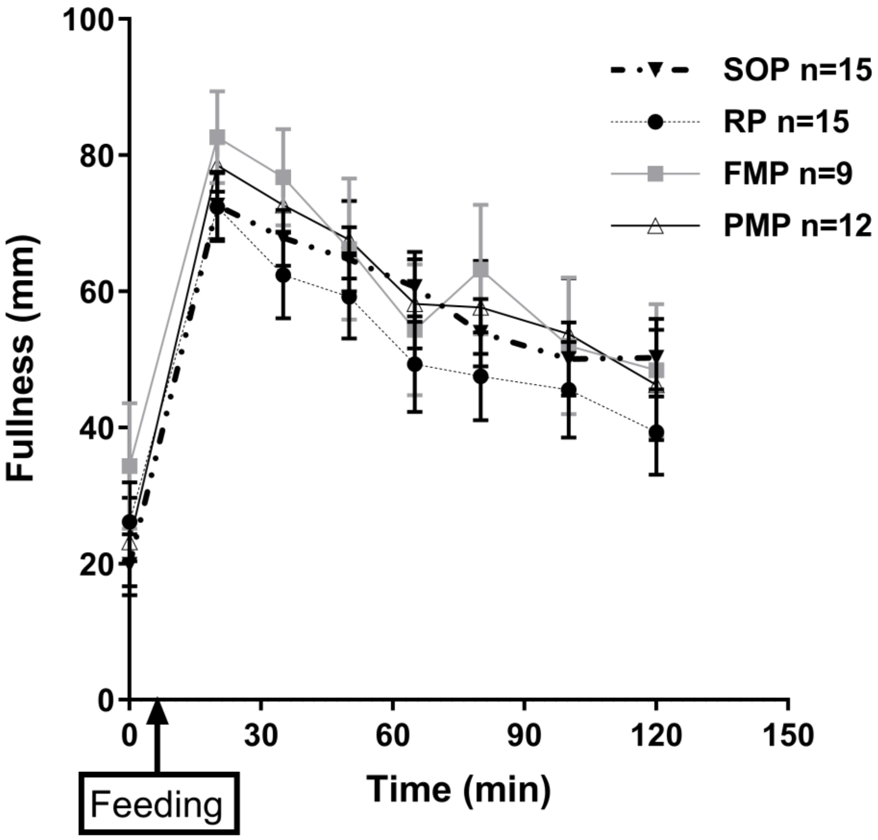
Supplementary Figure 1. Plot of hunger for healthy participants after they consumed the four different study porridges. , Scottish oats porridge (SOP); , Rye porridge (RP); , Finger millet porridge (FMP); , Pearl millet porridge (PMP). Values are mean ± SE, n=15 for SOP and RP, n=9 for FMP and n=12 for PMP. The arrow on the horizontal axis indicates the meal start time.



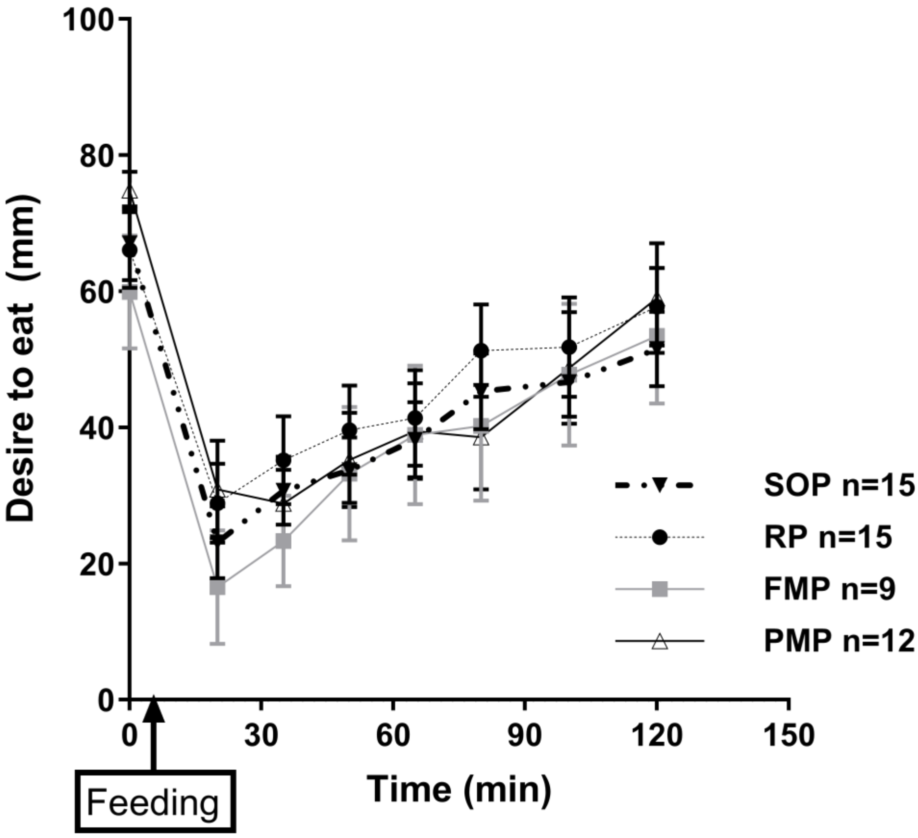
Supplementary Figure 2. Plot of satisfaction for healthy participants after they consumed the four different study porridges. - ·▼ -, Scottish oats porridge (SOP); ···●···, Rye porridge (RP); —■—, Finger millet porridge (FMP); —△—, Pearl millet porridge (PMP). Values are mean ± SE, n=15 for SOP and RP, n=9 for FMP and n=12 for PMP. The arrow on the horizontal axis indicates the meal start time.



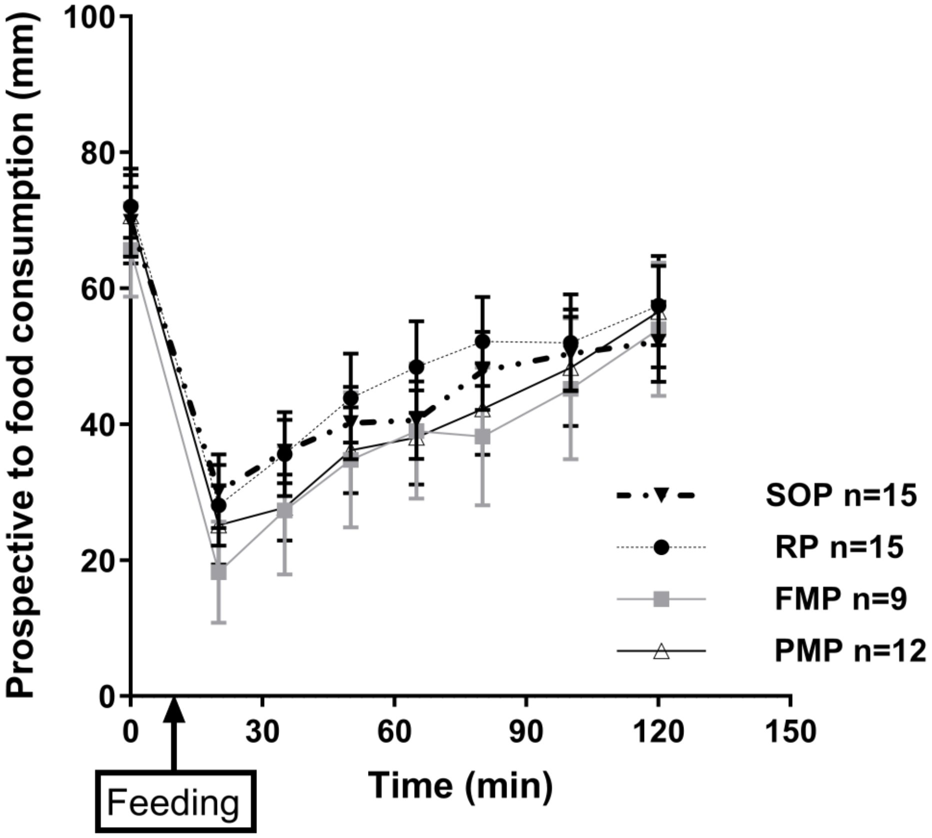
Supplementary Figure 3. Plot of fullness for healthy participants after they consumed the four different study porridges. , Scottish oats porridge (SOP); , Rye porridge (RP); , Finger millet porridge (FMP); , Pearl millet porridge (PMP). Values are mean ± SE, n=15 for SOP and RP, n=9 for FMP and n=12 for PMP. The arrow on the horizontal axis indicates the meal start time.



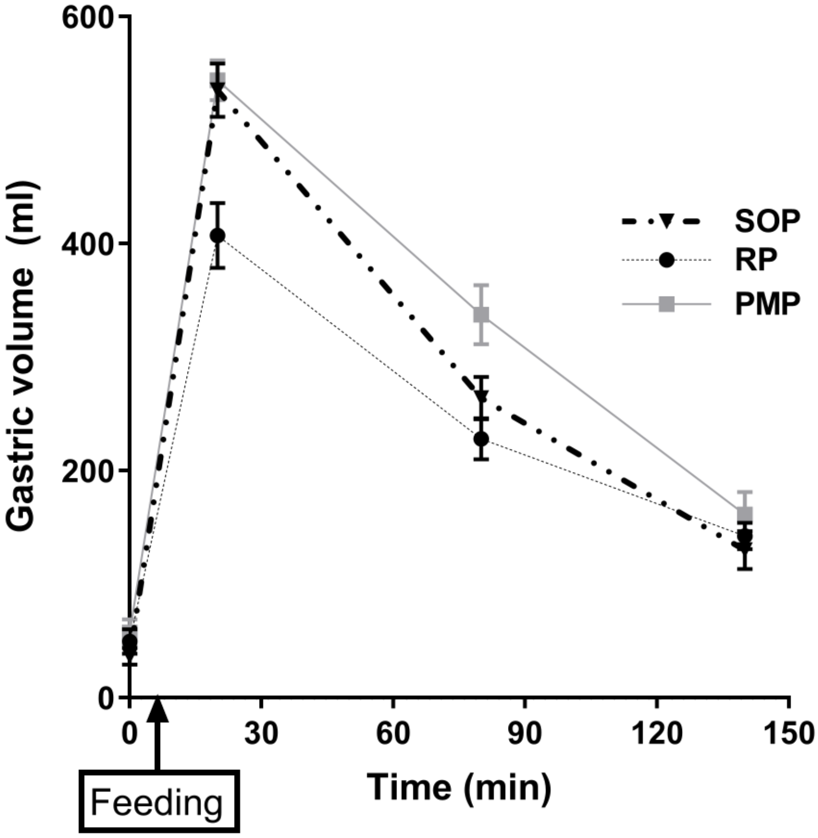
Supplementary Figure 4. Plot of desire to eat for healthy participants after they consumed the four different study porridges. ▼, Scottish oats porridge (SOP); ●, Rye porridge (RP); ■, Finger millet porridge (FMP); △, Pearl millet porridge (PMP). Values are mean ± SE, n=15 for SOP and RP, n=9 for FMP and n=12 for PMP. The arrow on the horizontal axis indicates the meal start time.



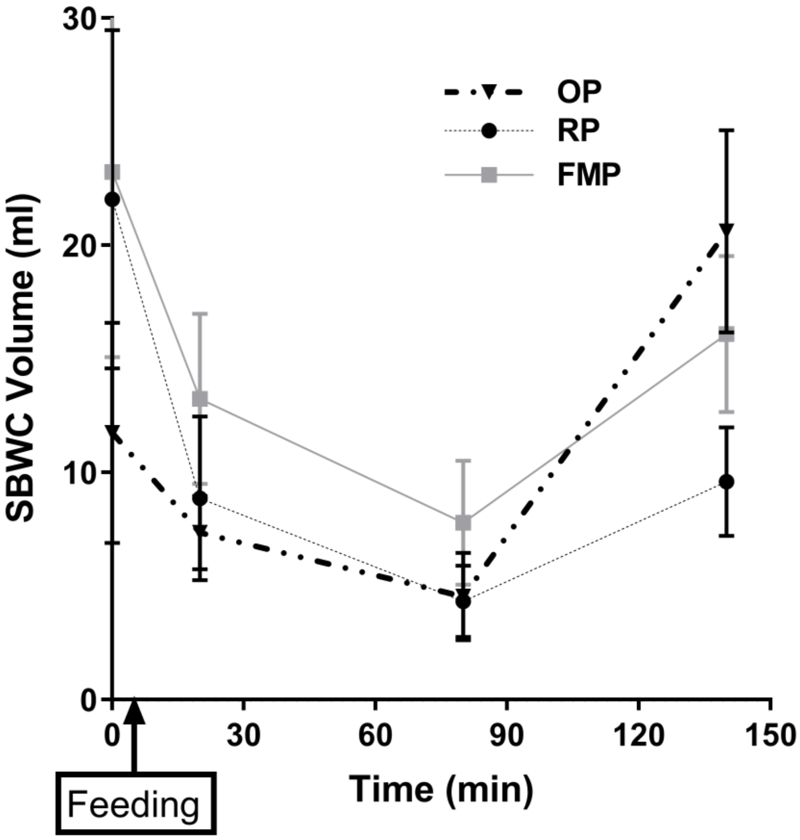
Supplementary Figure 5. Plot of prospective food consumption for healthy participants after they consumed the four different study porridges. , Scottish oats porridge (SOP); , Rye porridge (RP); , Finger millet porridge (FMP); , Pearl millet porridge (PMP). Values are mean ± SE, n=15 for SOP and RP, n=9 for FMP and n=12 for PMP. The arrow on the horizontal axis indicates the meal start time.



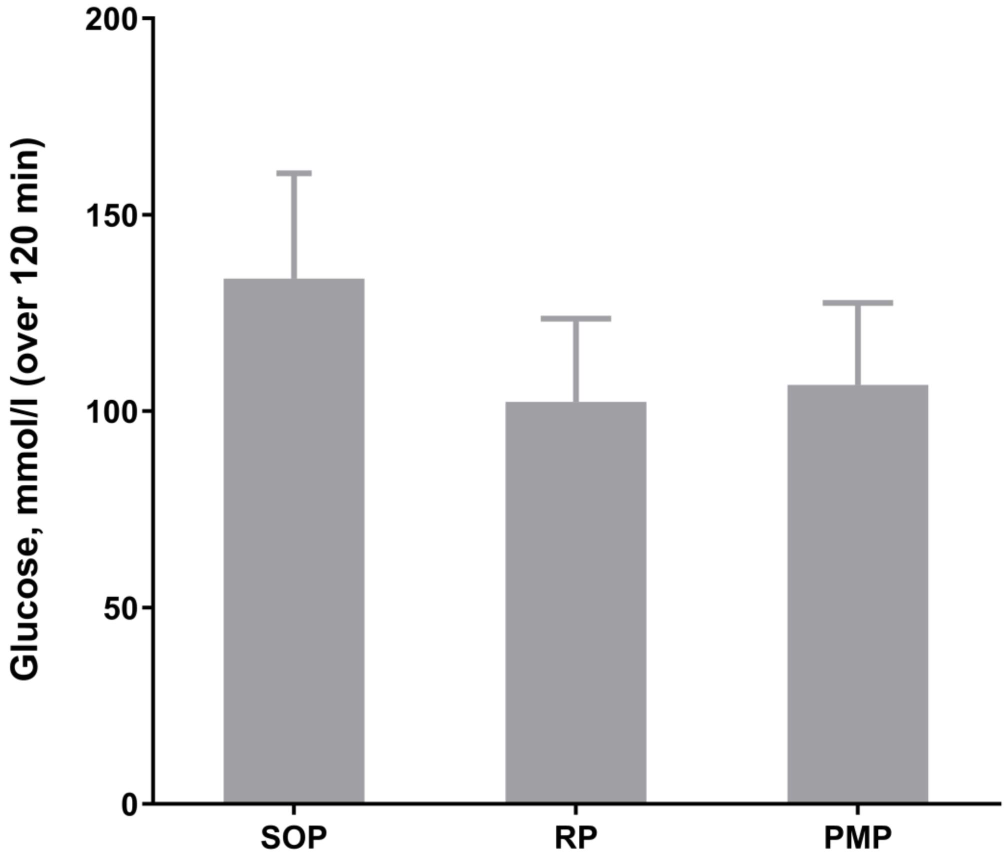
Supplementary Figure 6. Plot of the volume of the gastric contents for healthy participants after they consumed the three different study porridges. , Scottish oats porridge (SOP); , Rye porridge (RP); , Pearl millet porridge (PMP). Values are mean ± SE, n=10. The arrow on the horizontal axis indicates the meal start time.



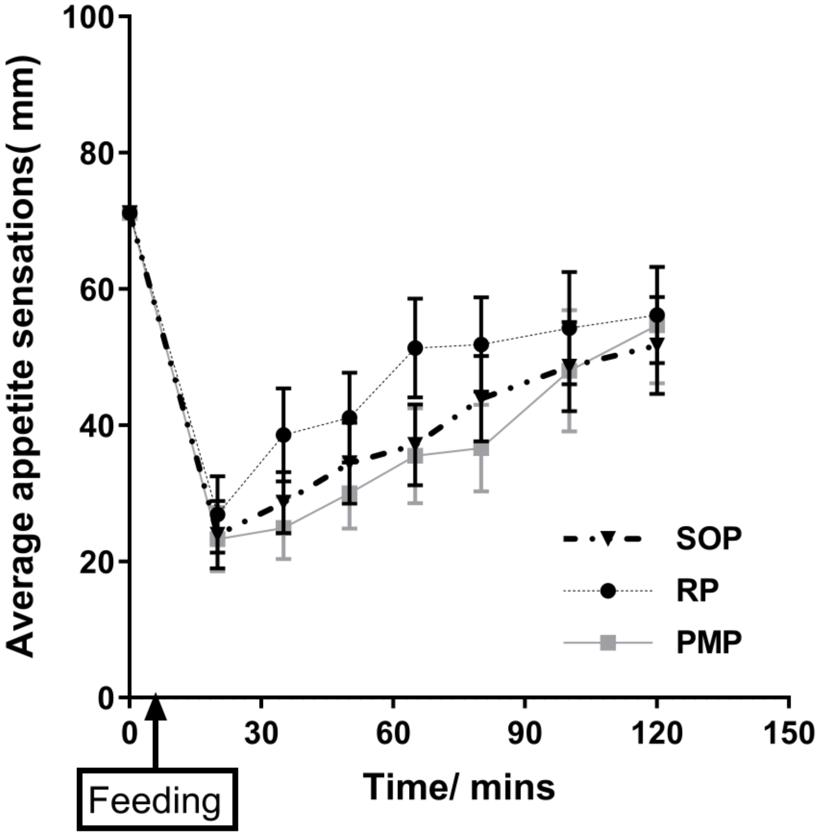
Supplementary Figure 7. Plot of the volume of the small bowel water content for healthy participants after they consumed the three different study porridges. - ·▼ -, Scottish oats porridge (SOP); ····●····, Rye porridge (RP); ——△——, Pearl millet porridge (PMP). Values are mean ± SE, n=10. The arrow on the horizontal axis indicates the meal start time.



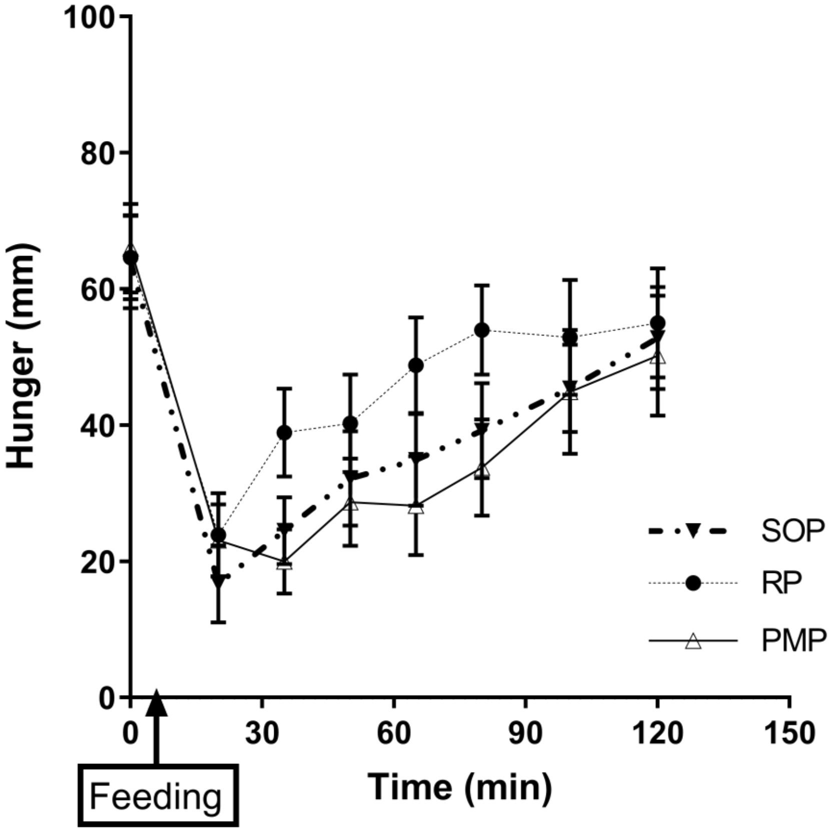
Supplementary Figure 8. Incremental area under the glucose curve (iAUC) for healthy participants after they consumed the three different study porridges., Scottish oats porridge (SOP); Rye porridge (RP); Pearl millet porridge (PMP). Values are mean ± SE, n=10



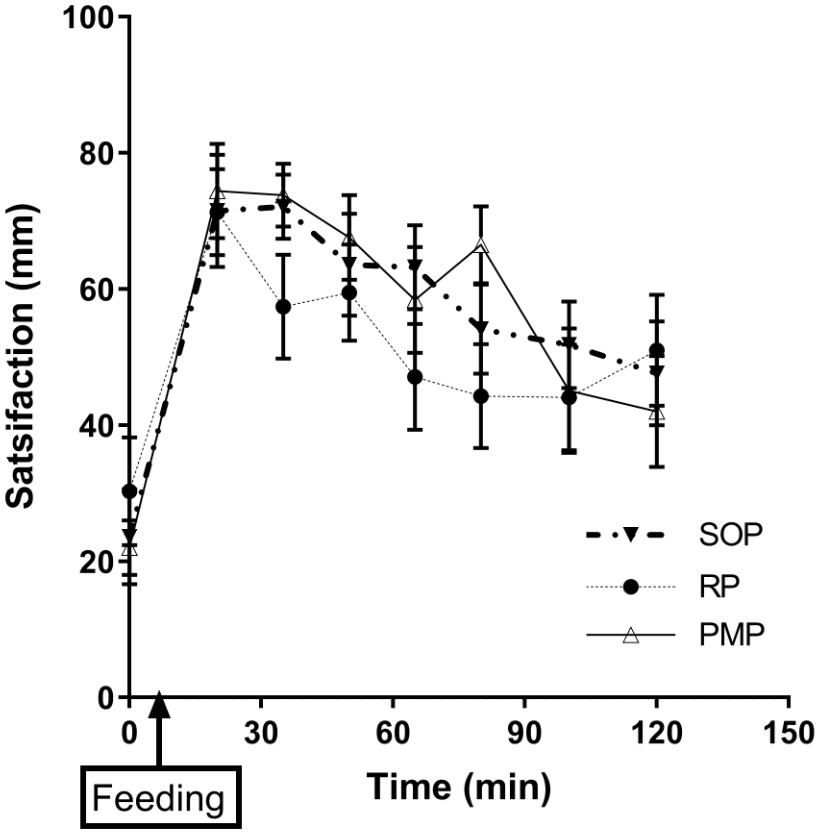
Supplementary Figure 9. Plot of the average appetite sensations for healthy participants after they consumed the three different study porridges. , Scottish oats porridge (SOP); , Rye porridge (RP); , Pearl millet porridge (PMP). Values are mean ± SE, n=10. The arrow on the horizontal axis indicates the meal start time.



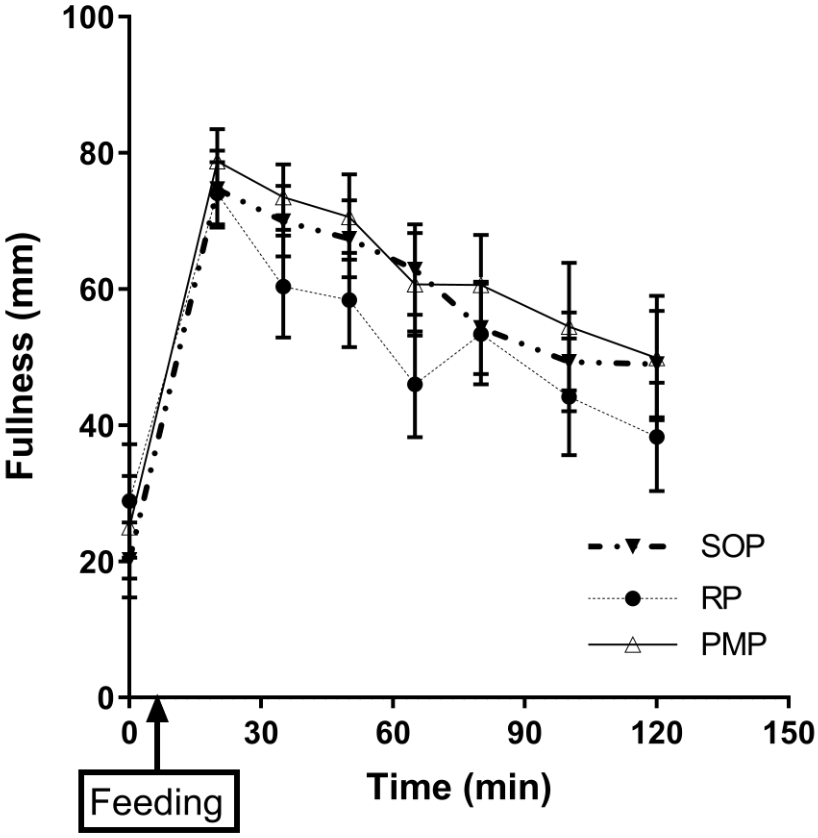
Supplementary Figure 10. Plot of hunger for healthy participants after they consumed the three different study porridges. , Scottish oats porridge (SOP); , Rye porridge (RP); , Pearl millet porridge (PMP). Values are mean ± SE, n=10. The arrow on the horizontal axis indicates the meal start time.



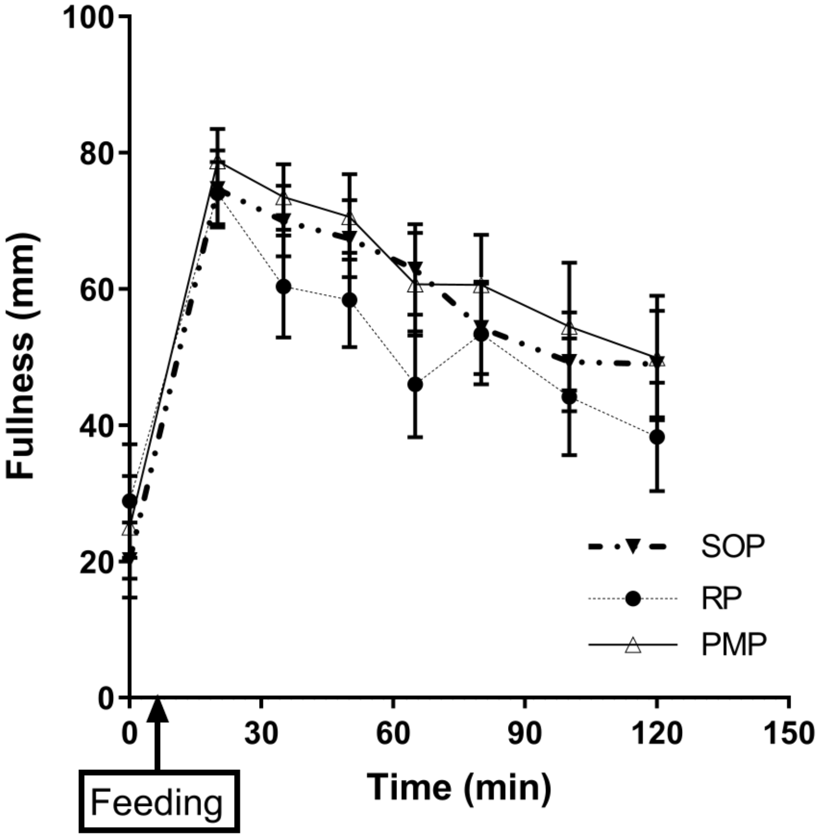
Supplementary Figure 11. Plot of satisfaction for healthy participants after they consumed the three different study porridges. ‑ ·▼‑, Scottish oats porridge (SOP); ·····●·····, Rye porridge (RP); —△—, Pearl millet porridge (PMP). Values are mean ± SE, n=10. The arrow on the horizontal axis indicates the meal start time.



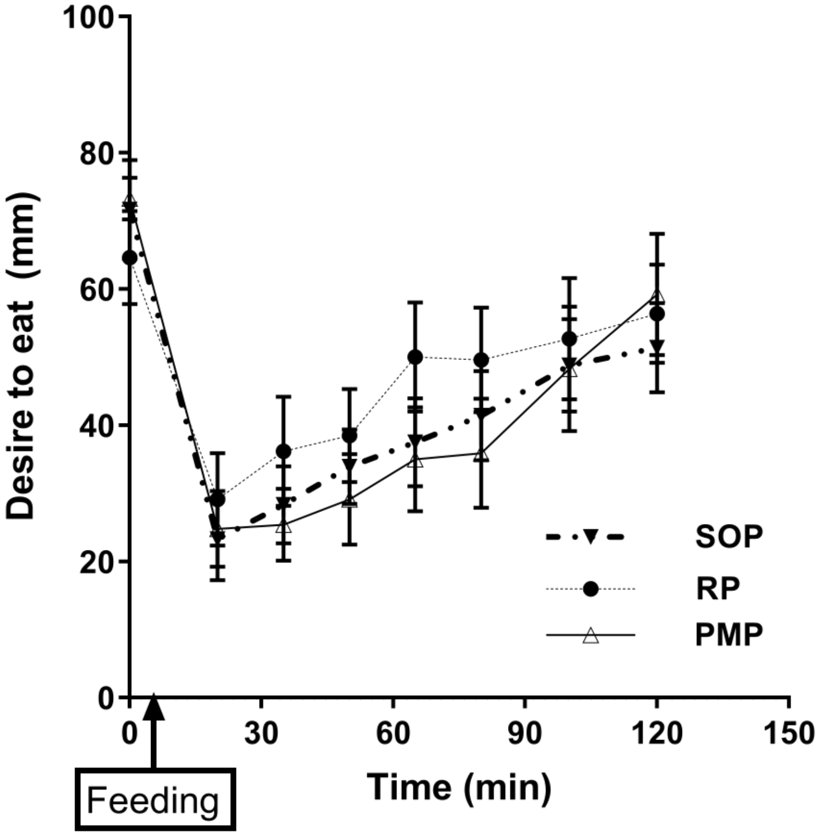
Supplementary Figure 12. Plot of fullness for healthy participants after they consumed the three different study porridges. , Scottish oats porridge (SOP); , Rye porridge (RP); , Pearl millet porridge (PMP). Values are mean ± SE, n=10. The arrow on the horizontal axis indicates the meal start time.



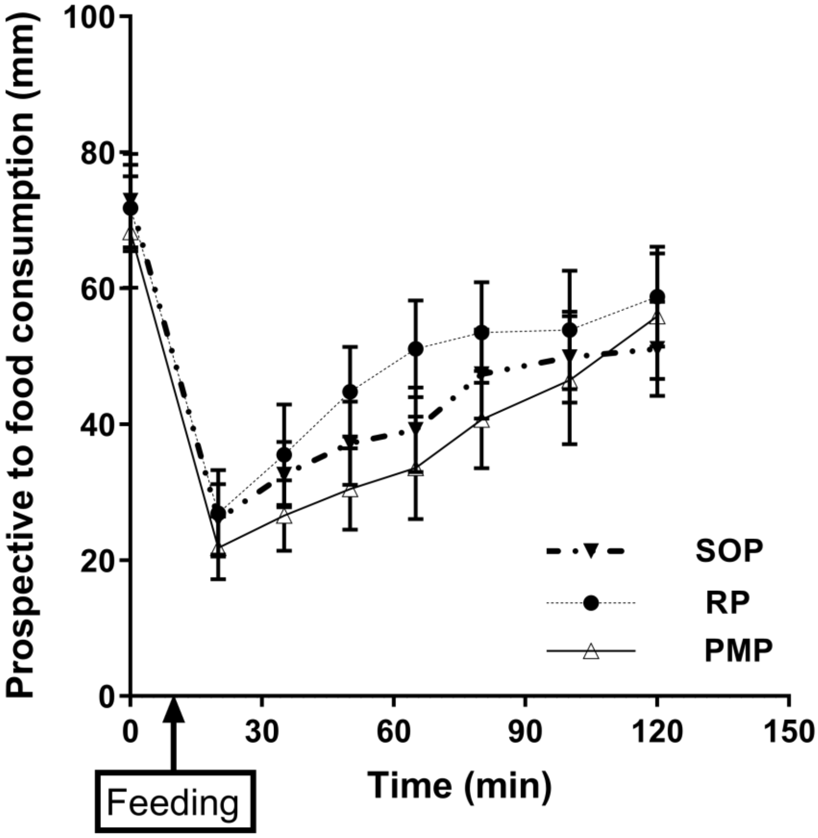
Supplementary Figure 12. Plot of fullness for healthy participants after they consumed the three different study porridges. , Scottish oats porridge (SOP); , Rye porridge (RP); , Pearl millet porridge (PMP). Values are mean ± SE, n=10. The arrow on the horizontal axis indicates the meal start time.



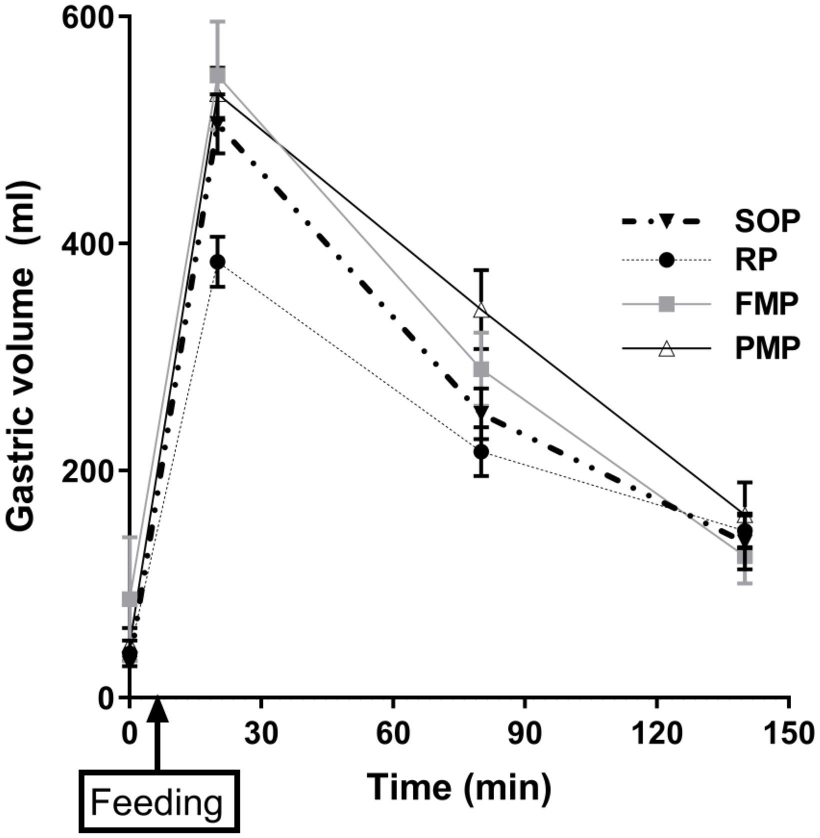
Supplementary Figure 13. Plot of desire to eat for healthy participants after they consumed the three different study porridges. - ·▼ -, Scottish oats porridge (SOP); ····●····, Rye porridge (RP), —△—, Pearl millet porridge (PMP). Values are mean ± SE, n=10. The arrow on the horizontal axis indicates the meal start time.



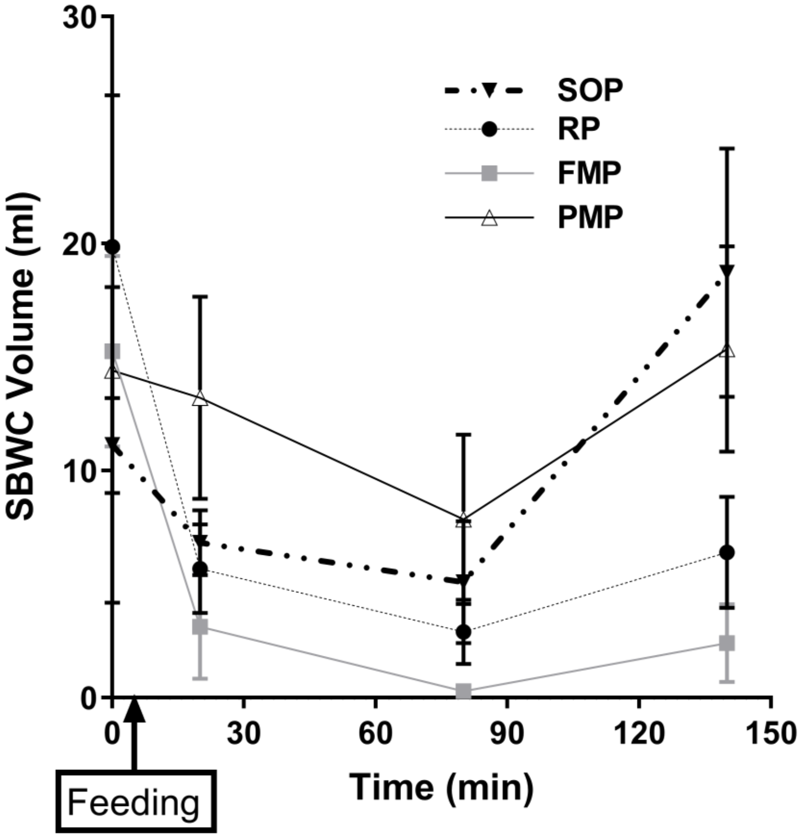
Supplementary Figure 14. Plot of prospective food consumption for healthy participants after they consumed the three different study porridges. , Scottish oats porridge (SOP); , Rye porridge (RP), , Pearl millet porridge (PMP). Values are mean ± SE, n=10. The arrow on the horizontal axis indicates the meal start time.



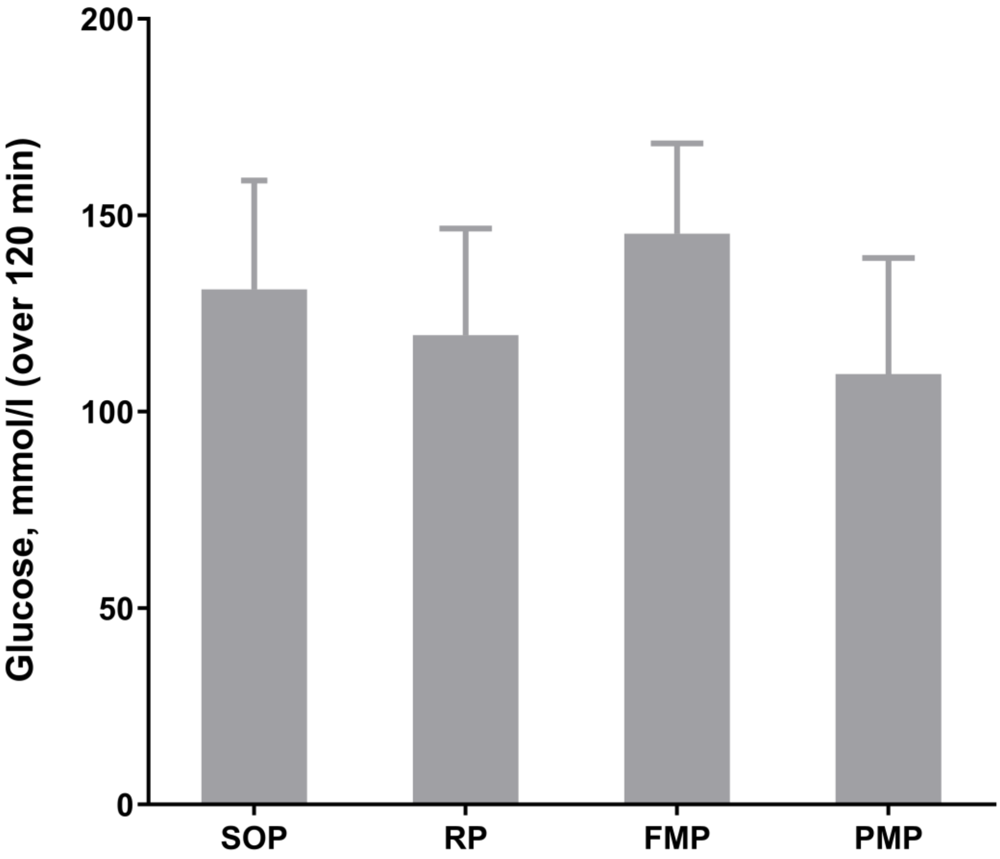
Supplementary Figure 15. Plot of the volume of the gastric contents for healthy participants after they consumed the four different study porridges. , Scottish oats porridge (SOP); , Rye porridge (RP); , Finger millet porridge (FMP); , Pearl millet porridge (PMP). Values are mean ± SE, n=7. The arrow on the horizontal axis indicates the meal start time.



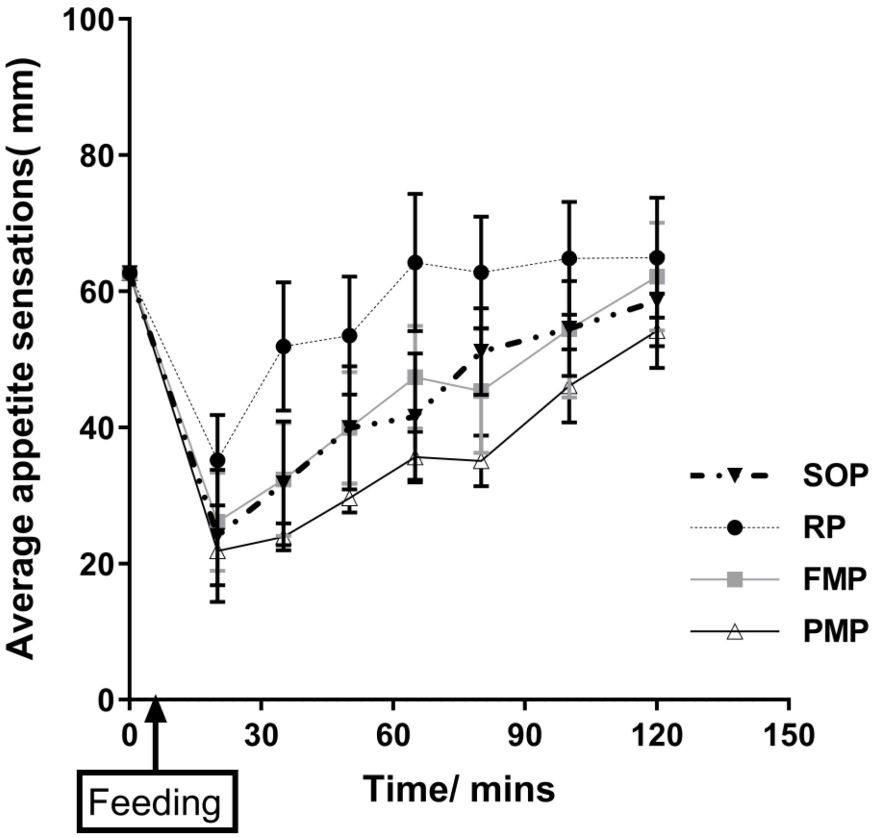
Supplementary Figure 16. Plot of the volume of the small bowel water content for healthy participants after they consumed the four different study porridges. , Scottish oats porridge (SOP); , Rye porridge (RP); , Finger millet porridge (FMP); , Pearl millet porridge (PMP). Values are mean ± SE, n=7. The arrow on the horizontal axis indicates the meal start time.



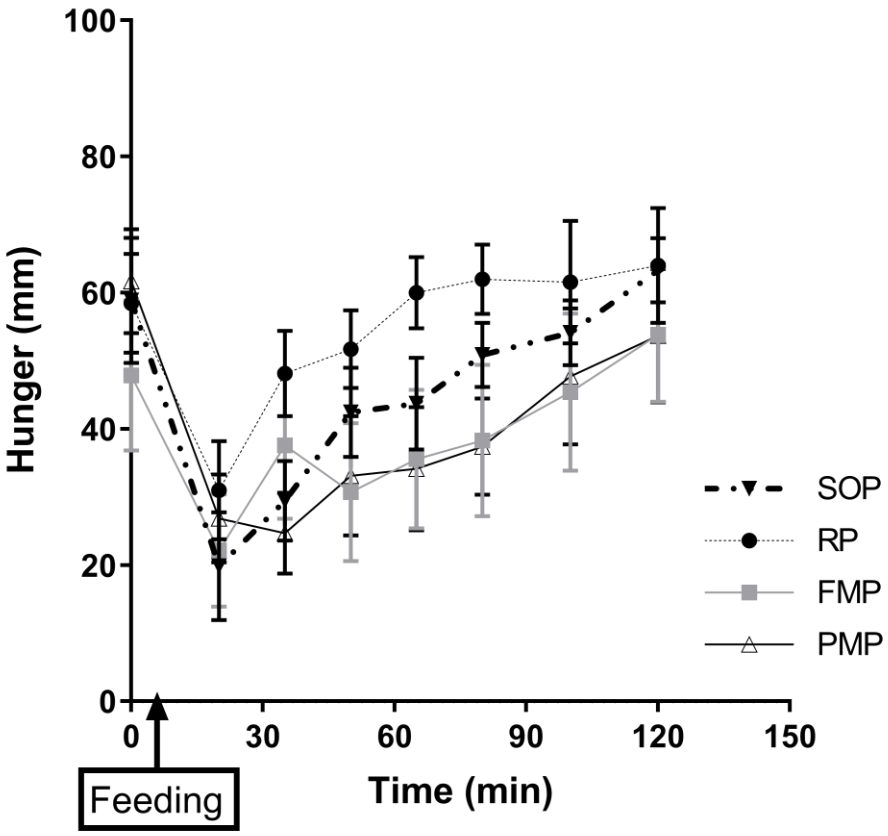
Supplementary Figure 17. Incremental area under the glucose curve (iAUC) for healthy participants after they consumed the four different study porridges., Scottish oats porridge (SOP); Rye porridge (RP); Finger millet porridge (FMP); Pearl millet porridge (PMP). Values are mean ± SE, n=7



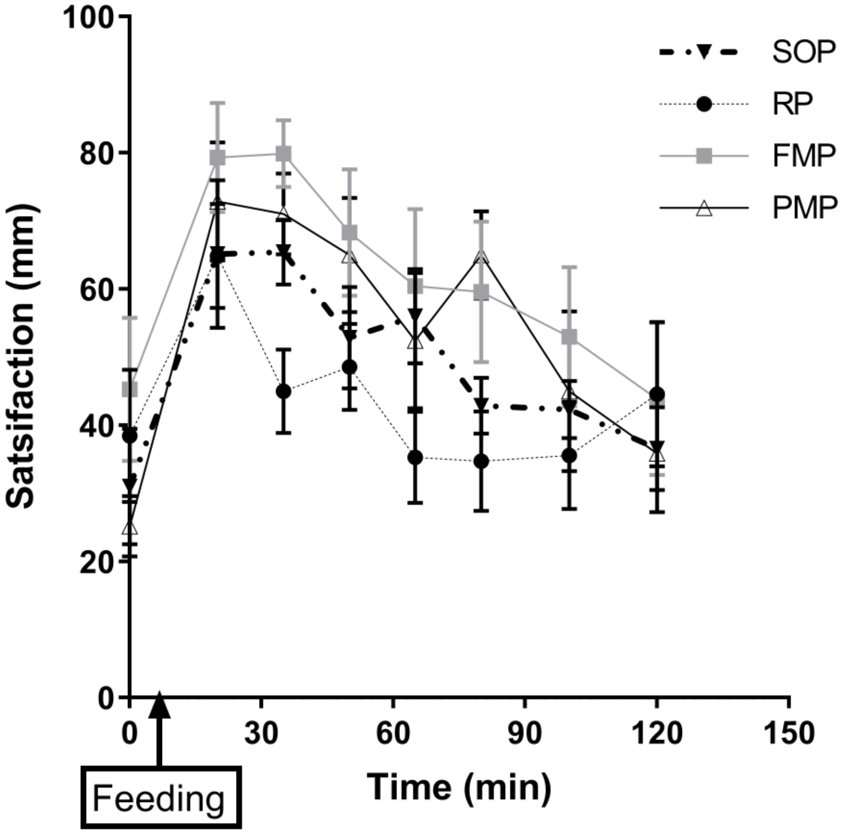
Supplementary Figure 18. Plot of the average appetite sensations for healthy participants after they consumed the four different study porridges. -·▼-, Scottish oats porridge (SOP); ···●···, Rye porridge (RP); —■—, Finger millet porridge (FMP); —△—, Pearl millet porridge (PMP). Values are mean ± SE, n=7. The arrow on the horizontal axis indicates the meal start time.



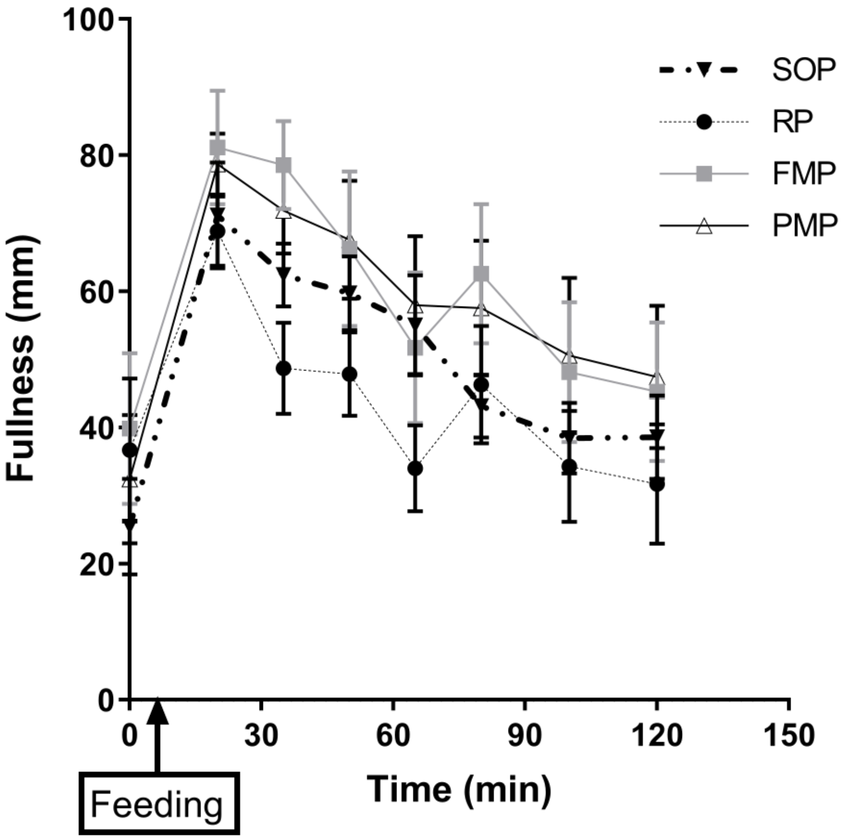
Supplementary Figure 19. Plot of the hunger for healthy participants after they consumed the four different study porridges. ▼, Scottish oatsporridge (SOP); ●, Rye porridge (RP); ■, Finger millet porridge (FMP); △, Pearl millet porridge (PMP). Values are mean ± SE, n=7. The arrow on the horizontal axis indicates the meal start time.



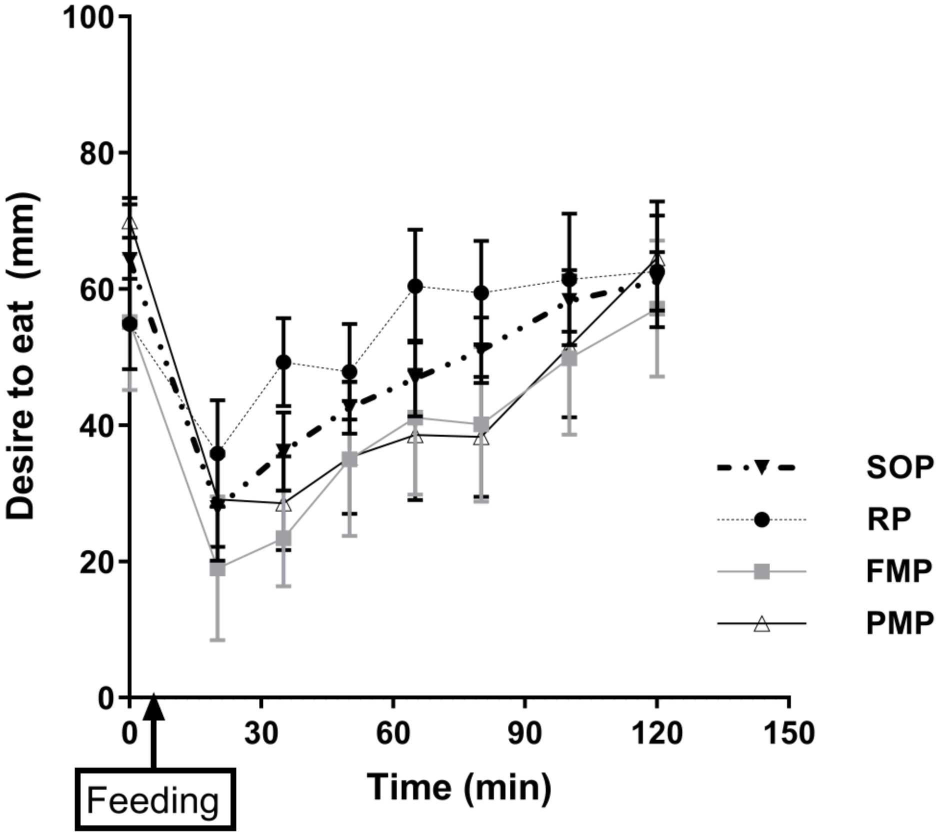
Supplementary Figure 20. Plot of the satisfaction for healthy participants after they consumed the four different study porridges. , Scottish oats porridge (SOP); , Rye porridge (RP); , Finger millet porridge (FMP); , Pearl millet porridge (PMP). Values are mean ± SE, n=7. The arrow on the horizontal axis indicates the meal start time.



Supplementary Figure 21. Plot of fullness for healthy participants after they consumed the four different study porridges. , Scottish oats porridge (SOP); , Rye porridge (RP); , Finger millet porridge (FMP); , Pearl millet porridge (PMP). Values are mean ± SE, n=7. The arrow on the horizontal axis indicates the meal start time.



Supplementary Figure 22. Plot of desire to eat for healthy participants after they consumed the four different study porridges. , Scottish oats porridge (SOP); , Rye porridge (RP); , Finger millet porridge (FMP); , Pearl millet porridge (PMP). Values are mean ± SE, n=7. The arrow on the horizontal axis indicates the meal start time.



Supplementary Figure 23. Plot of prospective food consumption for healthy participants after they consumed the four different study porridges. - ·▼ -, Sc Scottish oats porridge (SOP); ·····●·····, Rye porridge (RP); —■—, Finger millet porridge (FMP); —△—, Pearl millet porridge (PMP). Values are mean ± SE, n=7. The arrow on the horizontal axis indicates the meal start time.