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# Particle size of wheat, maize, and oat test meals: effects on plasma glucose and insulin responses and on the rate of starch digestion in vitro<sup>1-3</sup>

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**ABSTRACT** When normal volunteers ate isocaloric wheat-based meals, their plasma insulin responses (peak concentration and area under curve) increased stepwise: whole grains < cracked grains < coarse flour < fine flour. Insulin responses were also greater with fine maize meal than with whole or cracked maize grains but were similar with whole groats, rolled oats, and fine oatmeal. The peak-to-nadir swing of plasma glucose was greater with wheat flour than with cracked or whole grains. In vitro starch hydrolysis by pancreatic amylase was faster with decreasing particle size with all three cereals. Correlation with the in vivo data was imperfect. Oat-based meals evoked smaller glucose and insulin responses than wheat- or maize-based meals. Particle size influences the digestion rate and consequent metabolic effects of wheat and maize but not oats. The increased insulin response to finely ground flour may be relevant to the etiology of diseases associated with hyperinsulinemia and to the management of diabetes. *Am J Clin Nutr* 1988;47:675-82.

**KEY WORDS** Particle size, starch digestion, plasma glucose, plasma insulin, wheat, maize, oats

## Introduction

It might reasonably be expected that within the alimentary tract the more intact the structure of a cereal grain is, the more slowly the starch within will be digested. Larger food particles have a lower surface-to-volume ratio and this must reduce the access of enzymes to the interior of the particle as must the presence of intact cell walls. However, data to support these ideas are scanty. A meal of raw wheat flakes evoked a lower plasma glucose peak than one of whole-meal wheaten bread (1) but this may have been because raw starch is poorly digested (2, 3). When rice was ground into flour it evoked more glycemia and insulinemia than did the whole grains (4). This phenomenon has not been reported with any other cereal nor have comparisons been made of coarsely ground and finely milled flour. However, the in vitro studies of O'Dea et al (5, 6) suggest that particle size may be important with wheat, oats, and rye as well as rice.

The present study was designed to test the hypothesis stated above. A particular aim was to compare coarsely milled and finely milled wheat flour because bread and other wheat-flour products have long been staple foods but finely milled flour is a relatively recent invention (7, 8).

## Subjects and methods

### Test foods

The cereal products used for making the four wheat-based meals, the three maize-based meals, and the three oat-based meals were derived from the same batches of English wheat (*Triticum vulgare*, variety Avalon), mixed imported maize (*Zea mays*), and British oats (*Avena sativa*). They were milled at the Flour Milling and Baking Research Association (Chorleywood, Herts, UK) in October and November, 1984 and shipped to Bristol where they were stored at 4 °C until the test meals were prepared early in 1985.

The four grades of wheat were as follows: whole grains, cracked grains or kibbled wheat in which each grain was broken into six pieces on average, coarsely milled flour, and finely milled flour. Both flours were whole meal (ie, unsifted). The difference in particle size between the coarse and fine flour was considerable as shown by sieving analysis (Table 1). The fine flour was similar to the whole-meal flour sold for home baking in Britain. The coarse flour is not commercially available in

<sup>1</sup> From the University Department of Medicine, Bristol Royal Infirmary, Bristol, UK.

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<sup>3</sup> Reprints not available.

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TABLE 1

Sieving analysis of the flours and fine meals used in this study and, for comparison, a typical coarse Irish whole-wheat flour

Aperture $\mu\text{m}$	Percent retained on sieve of given aperture after sequential sieving				
	Wheat flour, fine	Wheat flour, coarse	Wheat flour, Irish	Maize meal, fine	Oatmeal, fine
2200	—	16.9	16.8	—	—
1350	—	15.6	15.8	—	—
1050	—	7.2	6.6	—	—
710	—	12.1	12.5	0.2	0.2
390	4.2	20.1	16.4	6.8*	9.6*
250	3.8	5.0	5.7	13.4	6.8
140	13.6	7.5	4.0	21.8	13.4
Percent not retained on any sieve	78.4	15.6	22.1	57.8	70.0

\* With maize and oats, Sieves of aperture 425 and 355  $\mu\text{m}$  were used; the percentages retained on the 425- $\mu\text{m}$  sieve were 2.8 and 2.2, respectively, and on the 355- $\mu\text{m}$  sieve were 4.0 and 7.4, respectively.

England but closely resembles the flour traditionally used for home baking in Ireland and still widely available there.

The three grades of maize were whole kernels, cracked grains (ie, kernels coarsely chopped up into 23 pieces on average), and flour (fine maize meal). The three grades of oats were whole groats; steamed, rolled oats (each flake weighing on average 6.7 mg compared with 17.8 mg for an average groat); and flour (fine oatmeal). For sieving analysis of the maize meal and oatmeal see Table 1.

The test meals were prepared in batches and frozen at  $-20^\circ\text{C}$ . Spare meals were prepared for use in the *in vitro* digestion study.

All test meals were designed to contain 50 g carbohydrate according to tables of food composition (9, 10). Thus, wheat-based meals contained 76 g wheat product, maize-based meals 68 g maize product, and oat-based 69 g oat product. The four batches of flour (coarse and fine wheat flour, fine oatmeal, and fine maize meal) were each made into scones by forming a dough with water, salt, baking powder and, to aid palatability, aspartame (Canderel, GD Searle, High Wycombe, UK) and baking at  $230^\circ\text{C}$  for 10–15 min. Each of the other six grain products was weighed into individual tin-foil containers, covered with 300 mL water, and baked at  $180^\circ\text{C}$  until it was judged to be cooked. The baking time was 4–5 h for whole grains and 2–3 h for cracked grains and rolled oats.

#### *In vivo plasma glucose and insulin responses*

Different but overlapping groups of 10 healthy volunteers (Table 2) ate in random order and at intervals of at least 48 h

TABLE 2

Sex, age, and body mass index ( $\text{kg}/\text{m}^2$ ) of the groups of volunteers who ate the three cereal-based meals

Cereal eaten	Subjects (M/F)	Mean age (range)	Body mass index (mean $\pm$ SEM)
	<i>n</i>	<i>y</i>	
Wheat	5/5	24 (21–37)	$21.9 \pm 0.63$
Oats	9/1	24 (21–27)	$23.0 \pm 0.59$
Maize	7/3	24 (21–40)	$22.2 \pm 0.48$

test breakfasts made from wheat (all four grades), maize (three grades), or oats (three grades). Studies in women were done during the first week of the menstrual cycle. The duration of the overnight fast was standardized for each subject. Meals were thawed overnight and warmed to  $40$ – $50^\circ\text{C}$  before being served. The meals were weighed so that their water content could be estimated by subtracting the weight of the raw ingredients. The water content of the breakfast was made up to 350 mL with decaffeinated coffee or weak tea. Meals were served with a sprinkling of aspartame, a few drops of lemon juice, powdered nutmeg, or powdered cinnamon as desired to increase palatability. All breakfasts commenced at the same time for a given subject and were consumed steadily under supervision over a 20-min period. No attempt was made to standardize the rate or amount of mastication. Subjects were comfortably seated in a quiet room throughout the study period.

Samples of venous blood were taken via an indwelling cannula during fasting and at 10, 20, 30, 40, 50, 60, 75, 90, 105, 120, 150, and 180 min from the beginning of the meal. Plasma samples were immediately separated by centrifugation and frozen until analyzed. Insulin was measured by a standard radioimmunoassay (11), all the samples from each subject's set of test meals being analyzed together. Blood glucose was measured on an autoanalyzer (AAI System, Technicon, Basingstoke, UK) by the glucose-oxidase method (12). The area under the plasma glucose and insulin curves was taken as the area above the zero-time or 10-min value, whichever was the lower.

This study was approved by the Bristol and Weston District Ethical Committee.

#### *In vitro rate of digestion of starch by pancreatic amylase*

Portions of food were incubated with pancreatin (dried pig pancreas) for differing periods of time to generate differing amounts of the digestion products glucose, maltose, maltotriose, and  $\alpha$ -limit dextrins (H Ghafari, unpublished observations, 1983). In a second incubation with the enzyme  $\alpha$ -glucosidase, the maltose and maltotriose were hydrolyzed to glucose (as was any starch that was solubilized). The glucose generated in the two incubations was measured and related to the estimated amount of starch in the original food to give a figure for percent digestion of starch at each time. In preliminary experiments with soluble potato starch, conditions for the *in vitro*



digestion study were established so that there was maximal yield of glucose. In these experiments the mean maximal yield of glucose was 68.5 mg/100 mg starch (68.5%).

Portions of thawed test meal were oven dried at 85 °C to constant weight to determine moisture content. Additional portions were then weighed out to contain ~360 mg dry solids (that is, ~250 mg starch assuming starch content of ~70%) (9). They were not warmed as the meals were before being eaten. These portions were mixed thoroughly with 5 mL 0.2 mmol/L phosphate buffer pH 6.5 containing 10 mmol/L sodium chloride (digest medium). At time zero, 20 mg grade VI pancreatin (Sigma Chemical Company, Poole, UK) in 5 mL digest medium was added to a series of tubes containing the food suspensions, and all but one of the tubes were incubated at 37 °C. After 5, 10, 15, 20, 30, 40, and 60 min incubation (in the case of the oat-based meals, 15, 30, 45, 60, 90, 120, and 180 min) one tube was placed on ice to stop the digestion and centrifuged at  $3500 \times g$  for 15 min at 4 °C. The unincubated tube was kept on ice and used as a blank. Enzyme-free blanks were used initially but were never found to generate glucose and were omitted thereafter. The supernatant was decanted and diluted 1 to 20 with digest medium containing 20 mmol/L disodium EDTA. One milliliter of this solution was incubated with two units  $\alpha$ -glucosidase (Sigma) in 1 mL digest medium at 25 °C for 2 h. Glucose produced was measured by the standard glucose-oxidase method with *o*-dianisidine (Sigma).

The mean between-assay coefficients of variations were as follows: fine-wheat flour, 11.0%; coarse-wheat flour, 10.5%; cracked wheat, 13.8%; whole-wheat grains, 34.9%; maize flour, 18.1%; cracked maize, 24.8%; whole maize, 113.8%; oat flour, 11.5%; rolled oats, 22.2%; and whole groats, 18.6%. (At each of the seven times,  $n = 5$  for wheat products and  $n = 6$  for all other products.) The large mean coefficients with whole grains of wheat and maize are due to the very low extent of digestion of these whole grains, which were clearly intact despite being thoroughly cooked.

#### Statistical methods

One-way analysis of variance and Student's *t* test for paired values were used to compare individual values for plasma glucose and insulin, the swing or descent of plasma glucose from peak to nadir, areas under plasma concentration curves, and glucose released by *in vitro* digestion.

## Results

### *In vivo* plasma glucose and insulin responses

With the wheat-based meals, plasma glucose tended to rise higher and fall lower after flour than after cracked or whole grains (Fig 1). Consequently, the mean swing of plasma glucose (descent from peak to nadir) was significantly greater after flour (Table 3). The area under the glucose curve tended to be higher after the two flours than after whole or cracked grains (Table 3) but the differences were not significant.

Plasma insulin rose significantly higher as the particle size of wheat decreased (Fig 2). This was reflected in stepwise increases in the peak plasma concentration and in the area under the curve (Table 4, Fig 3). The biggest difference was between coarse and fine flour, the area under the insulin curve being 38% higher after the fine flour ( $p = 0.0063$ ).

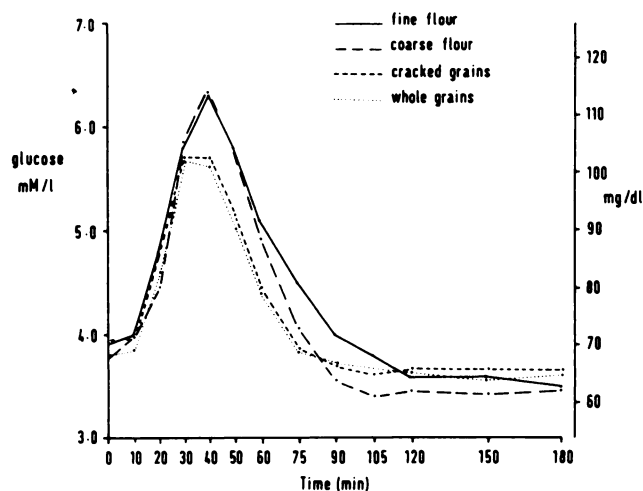


FIG 1. Mean plasma glucose concentration in 10 normal subjects after four isocaloric whole-wheat meals of different particle size.

With the maize-based meals there were no differences in plasma glucose responses. However, plasma insulin tended to rise more after maize flour than after cracked grains or whole maize (Fig 4) and the area under the insulin concentration curve was 60% higher after the flour than after cracked grains and 89% higher than after whole maize (Table 4).

With the oat-based meals, plasma glucose tended to rise higher with decreasing particle size but the areas under the glucose concentration curves were not significantly different (Table 3). Similarly, insulin values showed no relation to particle size (Table 4). Indeed, the peak insulin concentration and area under the curve were higher after rolled oats than after fine oatmeal flour although this difference did not reach statistical significance.

When the responses to all three oat-based test meals were combined and compared with the responses to all the maize-based and wheat-based meals, the rise in plasma glucose was substantially less with oats (mean maximum rise for all oat-based meals,  $1.6 \pm \text{SEM } 0.1$  mmol/L vs  $2.7 \pm 0.1$  for maize and  $2.6 \pm 0.1$  for wheat, both  $p < 0.001$  from unpaired *t* tests). The area under the glucose curve was substantially lower after the oat-based meals ( $55.2 \pm 6.4$  mmol/L min vs  $94.4 \pm 7.0$  with maize and  $95.0 \pm 6.3$  with wheat,  $p < 0.001$  from unpaired *t* tests). Furthermore, the area under the insulin curve after oat flour was only 57% of that after maize flour and 56% of that after fine wheat flour ( $p < 0.05$ ) although the particle size profile was similar for all three flours (Table 1). Different groups of subjects ate the three groups of meals but the subjects were similar in age, sex, and body mass index (except for a preponderance of males in the oats group) and had similar fasting values for plasma glucose (Table 3).

### *In vitro* digestion of starch

With all three cereals the rate of starch digestion was inversely related to particle size. Thus with wheat the or-

TABLE 3

Plasma glucose responses to meals of wheat, maize, and oats of different particle sizes (mean  $\pm$  SEM)

	Plasma glucose concentration				Area under concentration curve
	Fasting	Peak	Nadir	Swing	
	mmol/L	mmol/L	mmol/L	mmol/L	mmol/L min
<b>Wheat</b>					
Whole grains	3.8 $\pm$ 0.1	5.9 $\pm$ 0.2	3.3 $\pm$ 0.2	2.7 $\pm$ 0.2	80.5 $\pm$ 9.7
Cracked grains	3.9 $\pm$ 0.1	6.2 $\pm$ 0.2	3.3 $\pm$ 0.2	2.9 $\pm$ 0.2	86.3 $\pm$ 17.8
Coarse flour	3.8 $\pm$ 0.2	6.5 $\pm$ 0.2	3.1 $\pm$ 0.2	3.4 $\pm$ 0.2	108.2 $\pm$ 2.85
Fine flour*	3.9 $\pm$ 0.1	6.6 $\pm$ 0.2	3.2 $\pm$ 0.1	3.4 $\pm$ 0.3	106.2 $\pm$ 11.5
Significant differences	None	None	None	4 > 1† 3 > 1, 2‡	None
<b>Maize</b>					
Whole grains	4.0 $\pm$ 0.1	6.7 $\pm$ 0.3	3.2 $\pm$ 0.1	3.5 $\pm$ 0.4	102.6 $\pm$ 15.3
Cracked grains	4.1 $\pm$ 0.1	6.4 $\pm$ 0.2	3.2 $\pm$ 0.1	3.2 $\pm$ 0.2	81.4 $\pm$ 10.4
Flour	3.9 $\pm$ 0.1	6.5 $\pm$ 0.2	3.0 $\pm$ 0.2	3.4 $\pm$ 0.2	99.3 $\pm$ 10.0
Significant differences	None	None	None	None	None
<b>Oats</b>					
Whole grains	3.7 $\pm$ 0.1	5.0 $\pm$ 0.2	3.0 $\pm$ 0.2	2.0 $\pm$ 0.2	41.0 $\pm$ 7.9
Rolled oats	3.7 $\pm$ 0.1	5.3 $\pm$ 0.2	3.1 $\pm$ 0.2	2.2 $\pm$ 0.2	52.9 $\pm$ 7.8
Flour	3.7 $\pm$ 0.1	5.7 $\pm$ 0.3	3.1 $\pm$ 0.2	2.6 $\pm$ 0.4	71.6 $\pm$ 15.0
Significant differences	None	None	None	None	None

\* One subject's data excluded because of technical problems in assay of plasma glucose after this meal.

†  $p = 0.047$  using the unpaired  $t$  test.‡  $p = 0.022$  and  $0.040$ , respectively, using the unpaired  $t$  test.

der of digestion rates was whole grains < cracked grains < coarse flour < fine flour (Fig 5). There were obvious differences between whole and cracked grains and between cracked grains and coarse flour and a significant further increase in digestion rate with fine vs coarse flour. With maize and oats (Figs 6 and 7) there was also an inverse relationship between particle size and rate of di-

gestion. With maize the difference between whole and cracked grains was greater than that between cracked grains and fine maize meal (flour), at least from 20 min onwards.

As fine flour all three cereals were digested at a similar rate; at 30 min the conversion of starch to simple sugars was 46% for wheat, 42% for maize, and 41% for oats. However, as whole grains, oats were digested much faster than wheat or maize; at 30 min, the conversion of starch to sugars was 18% for oats vs 5% for wheat and 3% for maize (both  $p < 0.005$ ).

#### Correlation between in vitro and in vivo measurements

Among the wheat-based meals there was a significant correlation between in vitro digestibility of a meal (expressed as the mean percent of starch converted to sugars after 30 min incubation) and the mean rise in plasma glucose and between in vitro digestibility and the mean swing of plasma glucose after the same meal ( $r = 0.96$  and  $0.97$ , respectively,  $p < 0.05$  for both). The correlation was not significant with the area under the glucose concentration curve, with the peak plasma insulin, or with the area under the insulin concentration curve. Small numbers precluded looking for correlations among the oat-based and maize-based meals.

#### Discussion

When wheat and maize are milled before cooking, their contained starch is digested more rapidly in vitro

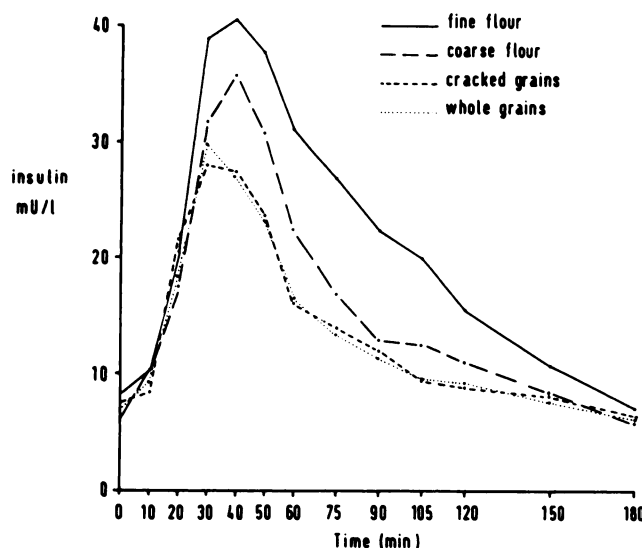


FIG 2. Mean plasma insulin concentration in 10 normal subjects after four isocaloric whole-wheat meals of different particle size. (1 mU/L = 7.175 pmol/L.)



TABLE 4

Plasma insulin responses to meals of wheat, maize, and oats of different particle sizes (mean  $\pm$  SEM)

	Plasma insulin concentration		
	Fasting	Peak	Area under curve
	mU/L (pmol/L)	mU/L (pmol/L)	mU/L min (pmol/L min)
Wheat			
Whole grains	7.2 $\pm$ 1.1 (52 $\pm$ 9)	31.4 $\pm$ 2.8 (225 $\pm$ 20)	1211 $\pm$ 165 (8689 $\pm$ 1184)
Cracked grains	7.5 $\pm$ 1.6 (54 $\pm$ 11)	34.2 $\pm$ 3.8 (245 $\pm$ 27)	1403 $\pm$ 267 (10067 $\pm$ 1916)
Coarse flour	6.3 $\pm$ 1.2 (45 $\pm$ 9)	37.7 $\pm$ 3.0 (270 $\pm$ 22)	1718 $\pm$ 160 (12327 $\pm$ 1148)
Fine flour	8.3 $\pm$ 1.6 (60 $\pm$ 11)	46.9 $\pm$ 4.3 (337 $\pm$ 31)	2366 $\pm$ 279 (16976 $\pm$ 2002)
Significant differences	None	4 > 1, 2, 3* 3 > 1†	4 > 1, 2, 3† 3 > 1§
Maize			
Whole grains	9.3 $\pm$ 1.5 (67 $\pm$ 11)	41.8 $\pm$ 5.2 (300 $\pm$ 37)	1238 $\pm$ 212 (8883 $\pm$ 1521)
Cracked grains	6.9 $\pm$ 1.3 (50 $\pm$ 9)	42.3 $\pm$ 5.5 (304 $\pm$ 39)	1461 $\pm$ 243 (10483 $\pm$ 1744)
Flour	8.0 $\pm$ 1.7 (57 $\pm$ 12)	48.7 $\pm$ 7.5 (349 $\pm$ 54)	2341 $\pm$ 459 (16797 $\pm$ 3293)
Significant differences	None	None	3 > 1, 2
Oats			
Whole grains	8.0 $\pm$ 1.0 (57 $\pm$ 7)	36.4 $\pm$ 3.9 (261 $\pm$ 28)	1111 $\pm$ 169 (7971 $\pm$ 1212)
Rolled oats	7.7 $\pm$ 1.6 (55 $\pm$ 11)	41.4 $\pm$ 4.8 (297 $\pm$ 34)	1701 $\pm$ 211 (12204 $\pm$ 1514)
Flour	7.9 $\pm$ 1.6 (57 $\pm$ 11)	36.4 $\pm$ 5.3 (261 $\pm$ 38)	1323 $\pm$ 182 (9492 $\pm$ 1306)
Significant differences	None	None	None

\*  $p < 0.001$ , 0.028, and 0.003, respectively.†  $p < 0.001$ , 0.019, and 0.017, respectively.‡  $p = 0.006$ .§  $p = 0.030$ .||  $p = 0.010$  and 0.012, respectively.

and evokes a greater plasma insulin response, indicating that the starch is digested and absorbed more rapidly in vivo as well as in vitro. Finely milled wheat flour is digested in vitro significantly faster than its coarsely milled equivalent and evokes a substantially greater insulin response.

Cooking conditions were not identical for all grades of cereal; all test meals were fully cooked in the everyday sense, but it is possible that some starch remained ungelatinized in the scones, which had brief baking times. This being so, our data underestimate the increase in digestibility that occurs when wheat and maize are ground into flour. Freezing the meals may have caused retrogradation of some starch. However, the freezing and reheating were identical for all meals so there should not have been any major differences in their content of resistant starch (13, 14).

Thus, with wheat and maize the findings were much as predicted. They indicate that grinding these grains into flour, especially fine flour, affects their digestibility profoundly, but simply breaking them into several small pieces has little or no effect.

These conclusions are essentially from the insulin responses. The glucose responses were not significantly different with the various grades of wheat and maize except that there were differences between the wheat-based meals for the swing of plasma glucose. Thus, it appears that measurements of plasma glucose are less sensitive than measurements of plasma insulin in detecting differences in the digestibility of starch (at least in nondi-

abetic subjects); our previous work suggests the same for the absorption of sugars from sugar-rich meals (11). On the other hand, both studies indicate that differences in the responses to foods that would otherwise be missed can be detected if the swing of plasma glucose is calculated.

The idea that the structural integrity of starchy foods determines their rate of digestion has been foreshadowed by studies showing that the plasma glucose and insulin response to rice and corn is less than that to potato (15–19) because when rice and corn are cooked, they retain their solidity and presumably their structure more than does potato. The traditional, coarsely milled wheat and rye products bulgur and pumpernickel were reported to evoke less glycemia (in diabetic subjects) than did ordi-

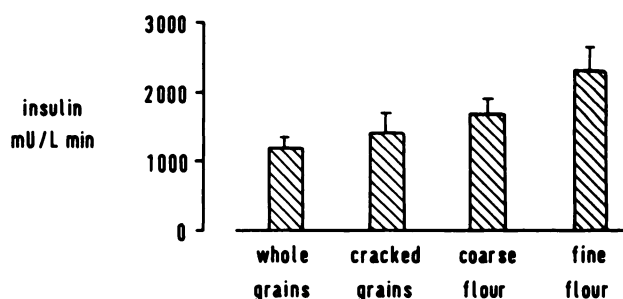


FIG 3. Area under plasma insulin concentration curve (mean  $\pm$  SEM) after four isocaloric whole-wheat meals. Significant differences as follows: fine flour > all others, coarse flour > whole grains.



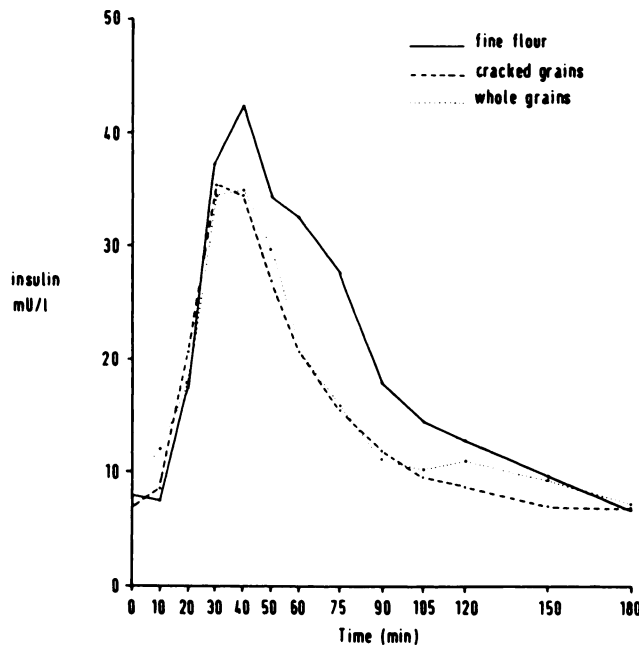


FIG 4. Mean plasma insulin concentration in 10 normal subjects after three isocaloric maize meals of different particle size. (1 mU/L = 7.175 pmol/L.)

nary wheat and rye bread (20), but in these studies the source of wheat and rye varied. When normal subjects swallowed rice, maize, or lumps of potato without chewing, the glycemic response was greatly reduced (21); unchewed potato can even be recovered from the feces (22). O'Dea et al (4, 5) compared the glucose and insulin responses of normal subjects to batches of white and brown rice in two forms, as whole grains and milled into flour, and found increased glycemia and insulinemia with the milled materials. They also found starch digestion by

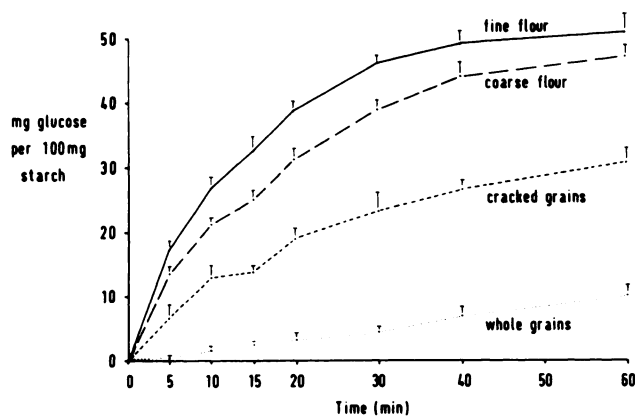


FIG 5. In vitro digestion of starch in four whole-wheat products of different particle size. Glucose and the glucose equivalent of maltose and maltotriose released at seven time points (mean  $\pm$  SEM of five different estimations). With 38 out of the 42 possible comparisons the mean values are significantly different from each other ( $p < 0.05$ ). (1 mg glucose = 5.551  $\mu$ mol.)

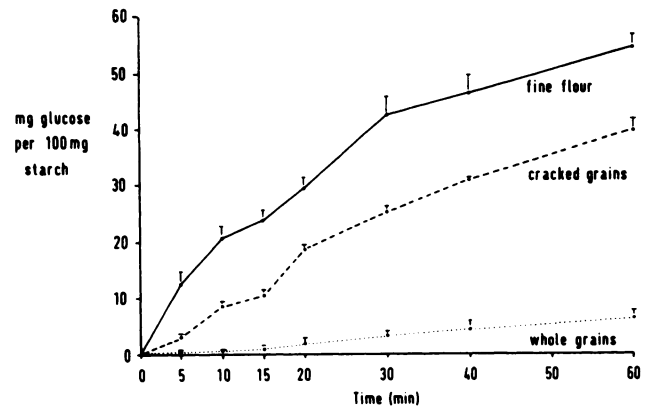


FIG 6. In vitro digestion of starch in three maize products of different particle size. Glucose and the glucose equivalent of maltose and maltotriose released at seven time points (mean  $\pm$  SEM of six different estimations). At every time point the three values are significantly different from each other ( $p < 0.05$ ). (1 mg glucose = 5.551  $\mu$ mol.)

amylase in vitro to be much faster with the ground rice and there were close correlations between the percent of starch digested in 30 min and the peak plasma glucose and insulin concentrations.

Correlations between in vitro and in vivo measures of wheat starch digestion could be demonstrated in this study but there were anomalies. Correlations existed with indices of glucose but not of insulin response, which is paradoxical in view of the greater sensitivity of insulin measurements. The difference between coarse and fine wheat flour was substantial in vivo (with indices of insulin release) but less impressive in vitro. The striking difference between whole and cracked maize in vitro had no counterpart at all in vivo. Of course, the in vitro incubation system is a very crude approximation of gastrointestinal events. In particular, it involves nothing equiva-

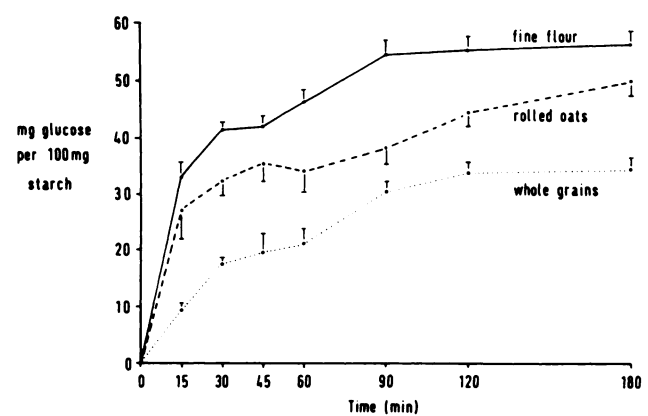


FIG 7. In vitro digestion of starch in three oats products of different particle size. Glucose and the glucose equivalent of maltose and maltotriose released at seven time points (mean  $\pm$  SEM of six different estimations). With 17 of the 21 possible comparisons the mean values are significantly different from each other ( $p < 0.05$ ). (1 mg glucose = 5.551  $\mu$ mol.)




lent to the chewing of food which, with whole grains especially, must reduce particle size and facilitate access of digestive enzymes. Also, there is no preliminary peptic digestion, which may leave some starch (at least in the unmilled and coarsely milled products) encapsulated within a protein matrix (23). Finally, gastric emptying is a determinant of the rate of digestion in vivo.

The more rapid digestion of rice, wheat, and maize when they are cracked or milled into flour is presumably due to the easier access of amylase to starch when the surface-to-volume ratio of food particles is increased and cell walls are mechanically disrupted. Loss of histological integrity has also been invoked to explain why the starch in beans, peas, and lentils is digested faster in vitro if the pulses are dry milled before cooking (24). An additional factor in vivo may be faster gastric emptying of small particles. However, with maize a 23-fold reduction in particle size that should have led to faster gastric emptying made no difference to the plasma insulin response.

With oats the in vitro findings were out of line with the in vivo findings. In vitro digestion rate increased as particle size decreased but in vivo the plasma glucose and insulin responses were not significantly different between the three oat-based meals. This implies that with oats there is a factor that strongly influences digestion or absorption in vivo but that was inoperative in the in vitro system. This factor could be the viscous properties of the soluble  $\beta$ -D-glucan that is the main component of dietary fiber in oats (25). This gummy material might create a viscous microclimate in the intestinal lumen and so impede the diffusion of amylase to starch or the diffusion of glucose and maltose towards the mucosa. These effects would have been minimized in the in vitro incubation because this involved constant mechanical shaking.

Another anomaly with oats was that the meals evoked relatively small glucose and insulin responses compared with the other two grains although the starch was digested in vitro equally fast; indeed, whole groats were more digestible than whole wheat and maize. Again, this can be explained by oats containing an unusually high proportion of soluble viscous fiber that limits the rate of digestion or absorption in vivo. Our findings are consistent with those of Jenkins et al (18) who reported the glycemic index after oat flakes to be only  $49 \pm 8$  compared with  $75 \pm 10$  after wheat flakes and  $80 \pm 6$  after corn flakes. A caveat is that the starch content of our oats meals may not have been identical with that of our maize and wheat meals because we used food-table values for starch and did not measure it directly.

In conclusion, this study demonstrates that wheat and maize, two of the major staple foods of mankind, are digested faster the more they are reduced in particle size. Finely milled wheat flour evokes substantially greater insulin responses than coarsely milled flour. Oat products do not behave in this way, possibly because of the different physical properties of oat fiber. Our finding of greater insulin secretion after finely milled flour raises the possibility that in susceptible genotypes regular consumption of such flour increases the risk of diseases in which hyper-

insulinemia has a possible etiological role, namely, obesity (26), diabetes (27), gallstones (28), and atherosclerosis (29). There may also be a practical consequence. Because the management of diabetes mellitus is aided by incorporating into the diet slow-release carbohydrates such as legume seeds (30), it may also be aided by the replacement of flour with whole or cracked grains or by the use of a coarsely milled flour. 

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