Insulin and glycemic responses in healthy humans to native starches processed in different ways : correlation with in vitro alpha-amylase hydrolysis

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Insulin and glycemic responses in healthy humans to native starches processed in different ways: correlation with in vitro α-amylase hydrolysis[1-3]

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ABSTRACT The aim of the study was to elucidate how extracted starches submitted to food processing (or not) can influence plasma insulin and glucose responses in healthy subjects. Native starches from wheat, manihot, smooth peas, or mung beans were tested either raw, as starch gels (boiled and cooled), or cooked and cooled after a preliminary industrial processing: extrusion cooking for wheat, tapioca for manihot, and noodles for mung beans. Eighteen healthy subjects randomly assigned received three different starches under one form of conditioning. All products were submitted to in vitro α-amylolysis. Raw manihot starch produced the lowest ($p < 0.05$) metabolic responses. Cooking significantly ($p < 0.01$) increased plasma responses. However, cooked mung bean noodles gave metabolic responses similar to those of raw products. Close correlations were found between percentages of in vitro starch hydrolysis at 30 min and mean areas under the glycemic curves and the insulinemic curves ($r = 0.95$, $p < 0.001$). *Am J Clin Nutr* 1989;50:315–23.

KEY WORDS Starch, legume starch, amylose, starch food processings, α-amylolysis, glycemic responses, insulinemic responses, normal subjects

Introduction

The effects of starchy foods on blood glucose and insulin responses may vary considerably (1–3). The reasons for this variation are numerous; some effects are intrinsic to the raw material and others are environmental, such as the carbohydrate content of the meal (4), the coingestion of other carbohydrates (5), protein (6, 7), fat (8), and dietary fiber (9, 10) in mixed meals, and the way the starch has been transformed (11–14) and ingested (15–18). Similar variability (for similar reasons) is observed when starchy foods are submitted to α-amylase in vitro (11–14, 19).

In a recent study (20) we showed that six starch-rich foods (bread, potato, rice, spaghetti, beans, and lentils), when taken alone or as part of a isoglucosidic-isolipidic-isoproteinic mixed meal, presented different glycemic and insulinemic responses. These results suggested that the differences observed could be attributed not only to the fiber content of the food (particularly with legumes) but also to the type of food processing used (bread vs pasta) and to the botanical origin of the starch. To evaluate this suggestion we studied in normal subjects the metabolic effects of extracted native starches, free from the other intrinsic food constituents (protein, fiber, lipid, etc), processed in different ways. We also studied the in vitro α-amylase susceptibility of the tested starches.

Methods

Starches

Native starches extracted from four sources were tested: from wheat (Roquette Frères SA, Lestrem, France), from manihot (Tipiak, Nantes, France), from the smooth pea (Woodstone Foods Co, Portage la Prairie, Canada), and from the mung bean (mung bean noodles manufactured in the Republic of China; chemical analysis of mung bean noodles confirmed that they are almost exclusively made of pure starch) (**Table 1**). Dry matter was determined after drying at 103 °C over 12 h.

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TABLE 1
Chemical composition of the native starches used

Starch	Percent of starch in dry matter	Protein	Lipid	Amylose
	%	*g/100 g**	*g/100 g**	%*
Wheat	97.5	0.33	1.12	27
Manihot	99.7	0.10	0.10	17
Smooth pea	95.3	0.19	0.18	35
Mung bean	97.6	0.10	0.10	32

* Percent of dry weight of starch.

The percentage of starch in dry matter was determined by an enzymatic method (21). Protein was assessed according to the Kjeldahl method and lipids were extracted by an isopropanol-water solution (3:1) at 90 °C according to Drapron (22). The amylose content was measured on defatted starches by the amperometric method described by Larson et al (23).

Processing

Starches were tested in three forms:

1) Raw: starches extracted from wheat, manihot, and the smooth pea. They were slurried in 350 mL 0.5% salted Evian® mineral water (BSN Co, Evian, France).

2) Gelled: starches extracted from wheat, manihot, and the smooth pea cooked in 0.5% salted Evian® water for 20 min from 20 to 96 °C in a round-bottom vessel. Stirring was achieved by an anchor-shaped blade rotating at 200 rpm. Starch concentration in the final product was 9% (wt:wt), determined by drying aliquots at 103 °C for 12 h. Immediately after the starch paste was boiled, it was flavored with vanilla and aspartame and kept at room temperature for 24 h to produce a gel.

3) Pasted after preliminary industrial processing: method varied for each native starch. (Smooth pea as noodles was not tested; mung bean and smooth pea starches are similar.) Wheat starch was extruded through a twin-screw CLEXTRAL® extruder (BC 45; CLEXTRAL Co, Firminy, France) with 500-mm screws as previously described (24). The temperature was 180 °C; the feed rate for starch was 47 kg/h, for water, 16 kg/h; screw speed was 270 rpm. The product thus extruded was ground and sieved to achieve a granularity < 3 mm. It was cooked in 0.5% salted Evian® water raised from 20 °C to 96 °C in 10 min, stirred at 200 rpm for 15 s every minute, then flavored, sweetened with aspartame, and stored for 24 h at room temperature.

Tapioca® (Tipiak, Nantes, France) was manufactured from manihot starch; a paste made of manihot starch and water (55% dry matter) was cooked on a hot plate at 100 °C for 6–7 min. After it was dried, ground, and sieved, the fraction tested had a granularity of 0.53–0.90 mm. This fraction (called tapioca) was cooked in 0.5% salted Evian® water under the same conditions as for extruded wheat, flavored, sweetened, and cooled. Mung bean noodles are traditionally manufactured from pure mung bean starch, as described elsewhere (25). Noodles were cooked under the same conditions as extruded wheat and tapioca. After noodles were cooked, the soaking water was discarded and the noodles were cooled. Because their palatibility was adequate when cooked in salted water, flavoring and sweetening were avoided.

Experimental procedures

In vivo study. Eighteen healthy, young subjects participated in the study (**Table 2**). They were informed volunteers for this study, which received approval from the Hotel Dieu Hospital's Ethical Committee and which was in full accord with the guidelines for human experimentation of the Helsinki Declaration of 1975 as revised in 1983.

Subjects were randomly assigned to three subgroups according to a three-factor experimental design. Each subject was tested on three consecutive days with three starches under one form of conditioning (ie, one group ingested only raw starches, one ingested the starch gels, and one ingested the industrially precooked starches). Each test meal, which contained 35 g (dry basis) starch, was ingested at 0800 after an overnight fast. The meals weighed 385 g for raw starch suspensions; 400–410 g for starch gels; and 380 g for the extruded wheat meal, 420 g for the tapioca meal, and 220 g for the noodle meal.

Blood samples were taken at 0730 and every 30 min after the start of the meal for 180 min. Plasma glucose was immediately assayed by a glucose oxidase method (Beckman Autoanalyser II®, Beckman Instruments Co, Fullerton, CA; intraassay reproductibility, 2%). Plasma aliquots were frozen at −20 °C for subsequent insulin radioimmunoassay (with antiinsulin antibody, Novo Industri, Copenhagen, Denmark) by a charcoal separation (intraassay reproductibility, 6%).

In vitro study. The four starches were tested in vitro in their different states of conditioning (raw, gel, industrial) to investigate their susceptibility to α-amylase. An aliquot (containing 18 g starch) of each of these products was submitted, after 1-mm sieving, to α-amylase hydrolysis with 3000 U hog pancreatic α-amylase (art: 16312, Merck, Darmstadt, FRG) under constant stirring (30 rpm) in 200 mL phosphate buffer (0.005 mol/L, pH 6.9–7.0) for 3 h at 37 °C. Every 5 min a 0.90-mL

TABLE 2
Characteristics of subjects

Subject	Sex	Age	Body mass index	Fasting plasma glucose	Fasting plasma insulin
		y	*kg/m²*	*mmol/L*	*pmol/L*
1	M	24	20.5	5.2	93
2	F	25	19.1	4.5	129
3	F	23	19.3	4.7	93
4	F	27	24.9	4.7	72
5	F	25	21.1	4.7	86
6	F	24	17.5	4.7	93
7	M	22	19.7	4.9	144
8	F	23	22.1	4.8	100
9	M	25	21.1	4.8	108
10	M	20	18.6	5.6	129
11	M	20	23.3	5.2	86
12	M	26	20.0	5.1	100
13	F	24	19.5	4.6	79
14	F	23	20.6	4.9	100
15	F	25	19.8	4.4	129
16	F	26	20.4	4.6	108
17	M	24	22.8	5.0	72
18	M	24	20.0	4.8	93
$\bar{x} \pm$ SEM		23.9 ± 0.4	20.6 ± 0.4	4.8 ± 0.1	100 ± 5

TABLE 3
Ingestion time of starch test meals*

	Time
	min
Raw starches	
Wheat	6.0 ± 1.9
Manihot	4.0 ± 1.5
Smooth pea	4.0 ± 1.0
Starch gels	
Wheat	15.2 ± 3.4
Manihot	13.2 ± 2.9
Smooth pea	19.0 ± 3.3
Industrially processed starches	
Extruded wheat	10.5 ± 1.7
Tapioca	10.0 ± 1.9
Mung bean noodles	12.3 ± 1.8

* $\bar{x} \pm$ SEM. Ingestion times for raw starches as a group were significantly different from times for the starch-gel and processed-starch groups ($p < 0.05$). All other differences were NS.

sample was mixed in 4.5 mL ethanol (95%) and acetic acid (1.5%) and stored overnight at 4 °C. Samples were then centrifuged (9000 × g) for 10 min. The polysaccharide content was thereafter assayed in the supernatant by a sulfuric orcinol automatic method (26). Intraassay reproductibility was 15% at 30 min and 4% at 180 min.

Statistical analysis

We designed a three-way experimental design (6 × 3 × 2) with one case observation per cell. We used analysis of variance (27) to test the effect of the following factors: type of starch, type of processing, interaction between type of starch, type of processing, and subject (which is nested within the type of the processing factor). Multiple comparisons were made using the method of Newman-Keuls (27). To simplify the expression of the results, only significant differences were systematically recorded in the text and tables. Thus, in the absence of explicit indications, comparisons should be considered not significantly different. A possible association between in vivo and in vitro data was tested using a correlation analysis (27).

Results

In vivo

Meal durations were unequal. **Table 3** gives the mean values for ingestion time and shows that raw products were ingested significantly more rapidly than cooked starches (starch gels and industrially processed starches) ($p < 0.05$).

Figure 1 shows the incremental plasma glucose variations after the meals. The mean peak values for plasma glucose are given in **Table 4;** raw starches presented a lower peak than cooked starches ($p < 0.01$) except for the mung bean noodles, which behaved like the raw starches. Maximal plasma glucose values were observed between 35 and 65 min (Table 4). There was no significant difference for this variable either between starches of different origins or between the starch preparation procedures tested (intra- and intergroup comparisons, NS).

The mean areas under the incremental plasma glucose curves between 0 and 180 min were significantly lower with the raw than with cooked products ($p < 0.01$). Raw manihot was significantly less hyperglycemic than both

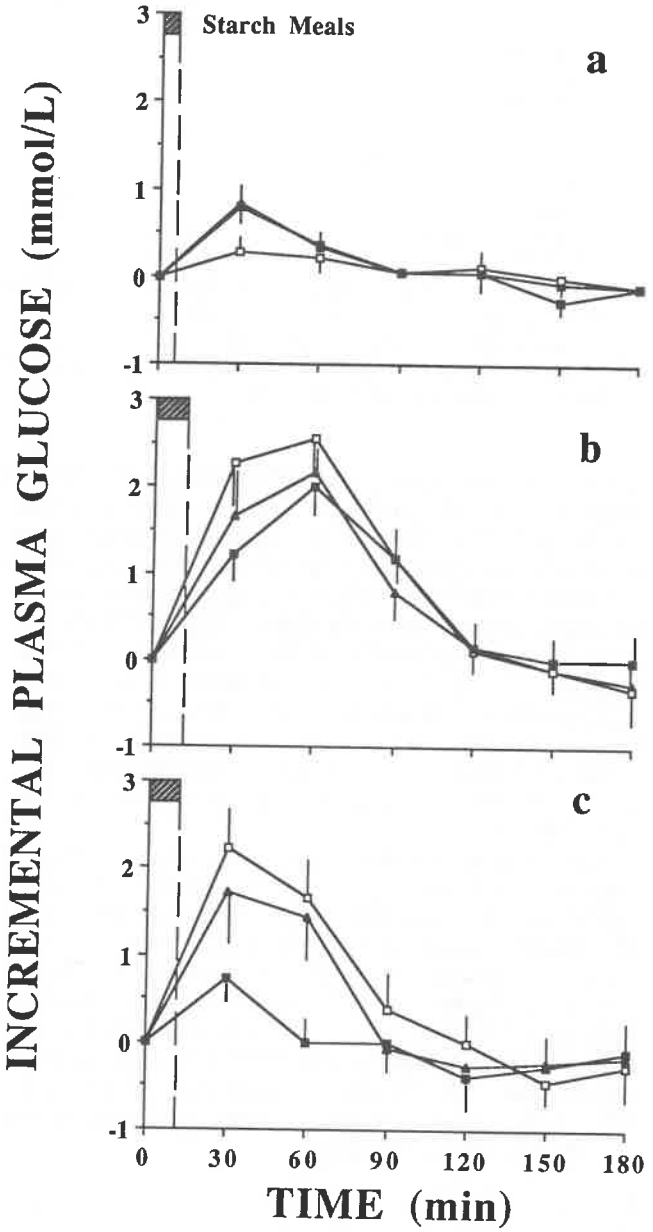

FIG 1. Incremental plasma glucose variations observed within 180 min. (a) Raw starches from wheat (▲), manihot (□), and smooth peas (■); (b) starch gels from wheat (▲), manihot (□), and smooth peas (■); (c) industrially processed starches: extruded wheat (▲), tapioca (□), and mung bean noodles (■). Shaded rectangular areas represent the mean time for ingestion of starch meals. ($\bar{x} \pm$ SEM.)

TABLE 4
Characteristics of plasma glucose variation within the first 180 min of testing*

	Plasma glucose levels		Peaking time	Area under curve for 0–180 min
	Fasting	ΔPeak†		
	mmol/L		*min*	$mmol \cdot L^{-1} \cdot min^{-1}$
Raw starches				
Wheat	4.8 ± 0.1	1.1 ± 0.2	65 ± 18	53 ± 11
Manihot	5.0 ± 0.2	0.4 ± 0.1	65 ± 18	27 ± 7
Smooth pea	4.8 ± 0.1	0.9 ± 0.4‡	35 ± 5	49 ± 19‡
Starch gels				
Wheat	4.8 ± 0.1	2.4 ± 0.4	50 ± 7	159 ± 42
Manihot	4.8 ± 0.1	3.2 ± 0.9	60 ± 14	213 ± 65
Smooth pea	4.9 ± 0.2	2.3 ± 0.4§	50 ± 7	143 ± 29§
Industrially processed starches				
Extruded wheat	4.9 ± 0.2	2.0 ± 0.3	35 ± 5	109 ± 31
Tapioca	4.8 ± 0.1	2.5 ± 0.6	40 ± 7	148 ± 41
Mung bean noodles	4.9 ± 0.2	0.8 ± 0.3‡	35 ± 5	28 ± 10‖

* $\bar{x} \pm$ SEM. Intra- and intergroup ANOVA tests were NS except when otherwise indicated.
† Maximal incremental value above basal value.
‡ Significant intragroup difference, $p < 0.05$.
§ Values for starch gels as a group significantly different from values for the raw-starch group ($p < 0.01$).
‖ Significant intragroup difference, $p < 0.01$.

of the other raw starches ($p < 0.05$). Among the cooked starches no significant differences were observed except for the mung bean noodles, which gave rise to lower glycemic areas ($p < 0.01$), similar to those of raw starches.

Figure 2 shows the incremental postprandial plasma variations for insulin in the three groups of foods. The mean peak plasma insulin values are given **Table 5.** Raw manihot elicited the lowest insulinemic peak value ($p < 0.05$), as it did for plasma glucose. Mung bean noodles behaved more as a raw starch than a cooked one in terms of plasma insulin increment. These maximal values were observed between 40 and 70 min and were not statistically different.

Table 5 gives the mean area under the incremental plasma insulin curves between 0 and 180 min. Raw products gave significantly lower insulin responses than did cooked starches ($p < 0.05$); manihot starch was the weakest stimulant ($p < 0.05$). Among the cooked starches mung bean noodles gave the lowest insulin release ($p < 0.01$). In the gel group small differences (approaching significance [$p = 0.05$]) between the products were noted. The lowest response was observed for smooth pea starch; the intermediate, for wheat starch; and the highest, for manihot.

In vitro

Figure 3 shows the kinetics of in vitro susceptibility of the different starches submitted to α-amylolysis. The amount of soluble oligosaccharides formed increased rapidly in the first 30 min and a maximal plateau level was progressively reached after 60 min. There were wide between-product variations in α-amylase susceptibility, from the lowest, for raw manihot starch (2% at 180 min), to the highest, for manihot starch gel (70% at 180 min). Raw starches were less susceptible to α-amylolysis than were cooked products, with manihot the most resistant. Among cooked products, the starches deriving from legumes (smooth pea and mung bean noodles) were the least susceptible.

Correlation between in vivo and in vitro data

Figure 4 shows the correlation between the area under the 0–180-min incremental plasma glucose and insulin curves and the percentage of starch hydrolyzed in 30 min. There was a close correlation between in vivo responses and in vitro starch digestibility in terms of plasma glucose ($r = 0.88$, $p < 0.01$) and in terms of insulin response ($r = 0.95$, $p < 0.001$).

Figure 5 shows the variation of the coefficient of correlation between the area under the 0–180-min incremental plasma insulin curves and percentage of starch hydrolyzed vs time intervals of 5 and 30 min for the first 30 min and the next 150 min of hydrolysis, respectively. During the first hour of in vitro starch hydrolysis, the level of correlation was highest. Nevertheless, at time 180 min the level of correlation remained significant ($r = 0.88$, $p < 0.01$).

Discussion

Carbohydrate foods lead to different glycemic and insulinemic responses according to numerous factors. The influential factors that have been best identified and

most extensively studied are the carbohydrate content of a meal (4, 15), its dietary fiber content (9, 10), and the physical form and the processing of the foods (11–14). Very few studies in humans have focused attention on the botanical origin of the starch food and therefore on the physical structure of the starch molecule itself. Some differences (eg, between bread and lentils [19, 20]) can be attributed to variable fiber content but other differences (eg, between rice and potatoes or bread and pasta [20, 28]) cannot.

The design of this study, which used starches in the form of native granules free from any other constituents, allowed us to better delimit, in a multifactorial and complex process, two main determinants of physiological responses: the botanical origin of the starches and the impact of food processing. Native starches were from industrial sources. Their granular integrity was checked by the absence of any swelling or solubilization in water at room temperature and the absence of any gelatinization endotherms, determined by differential scanning calorimetry (not reported).

Our study clearly confirms that starches give weaker metabolic responses when raw than when cooked. Similar results were reported in vivo by Collings et al (29) and in vitro by Dreher et al (30). In practice very few starches are consumed raw; the banana is consumed raw and, when it is not overripe, it contains a considerable amount of indigestible starch (31).

The types of processing used in our study were pastification, extrusion cooking, and tapioca processing, followed in all cases by further boiling (as usually used for tapioca and mung bean noodles) and cooling (to test industrially processed starches at the same temperature as starch gels). We did not observe any clear-cut difference in plasma glucose or insulin variation with the type of food processing, with the exception of the mung bean noodles. Cooking time however can be very influential (32, 33). The tapioca and the extruded wheat were cooked for half the time needed for starch gels. The apparent lack of effect of food processing and cooking in this study is probably the result of a pregelatinization of the considered starch by the industrial processing techniques, which are in fact precooking processes (24, 34). The severe extrusion-cooking conditions used by Colonna et al (24) led to a macromolecular degradation of amylose and amylopectin, as seen in a high starch solubility. In similarly severe extrusion-cooking conditions Björck et al (35) showed that extruded white flour gives a higher increase in glucose and insulin plasma responses than does boiled white flour.

More original is our observation that metabolic effects and the in vitro susceptibility of starch to α-amylase depend on the botanical origin, thus probably the structure, of the starch. Our results in normal subjects show that raw manihot behaved differently from raw wheat and smooth pea starches and elicits almost flat plasma glucose and insulin responses. This same raw starch food is considered highly digestible in animals (30). Our in vitro

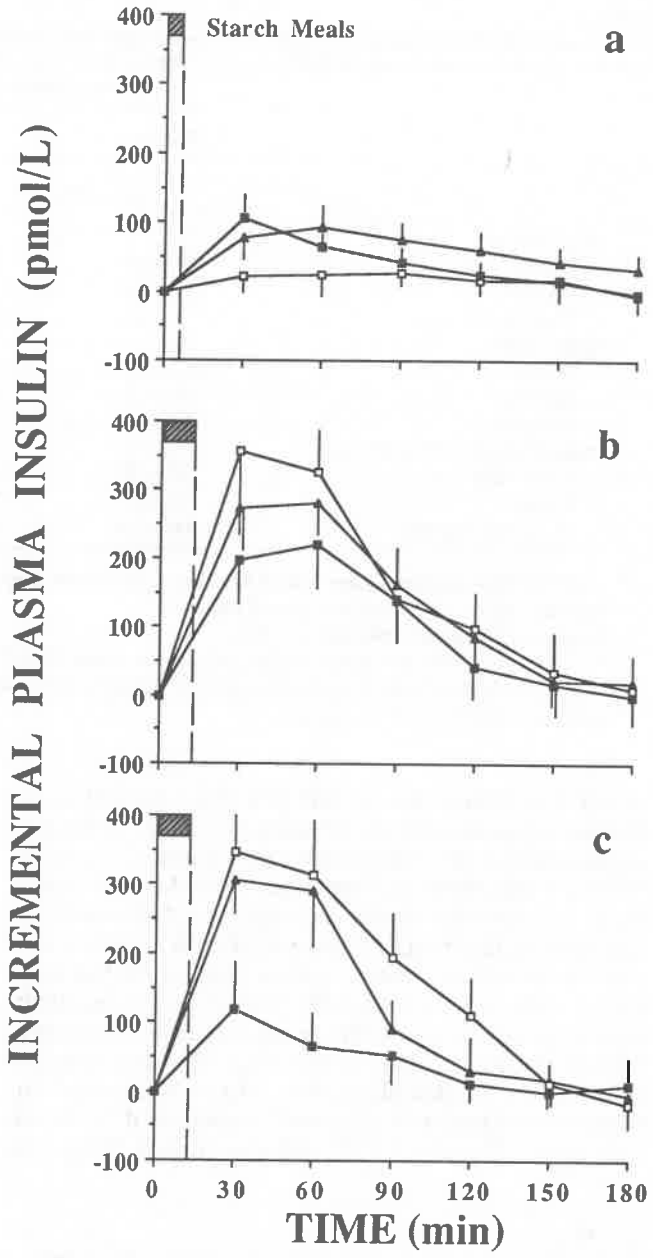

FIG 2. Incremental plasma insulin variations observed within 180 min. (a) Raw starches from wheat (▲), manihot (□), smooth peas (■); (b) starch gels from wheat (▲), manihot (□), smooth peas (■); (c) industrially processed starches: extruded wheat (▲), tapioca (□), and mung bean noodles (■). Shaded rectangular areas represent the mean time for ingestion of starch meals. ($\bar{x} \pm$ SEM.)

study shows that raw manihot is very slowly hydrolyzed by α-amylase. Sandstedt et al (36) also showed that raw manihot is less digestible than raw wheat starch.

There was some moderate difference among starch gels in terms of insulin response. Manihot seemed to give the highest rise, followed by wheat, then by smooth peas; the difference was almost significant ($p = 0.058$). The

TABLE 5
Characteristics of plasma insulin variation within the first 180 min of testing*

	Plasma insulin levels		Peaking time	Area under curve for 0–180 min
	Fasting	ΔPeak†		
	pmol/L		*min*	$nmol \cdot L^{-1} \cdot min^{-1}$
Raw starches				
Wheat	108 ± 14	136 ± 36	75 ± 23	11.0 ± 2.1
Manihot	93 ± 14	36 ± 14	45 ± 10	3.4 ± 1.4
Smooth pea	79 ± 22	129 ± 29‡	55 ± 14	8.0 ± 1.2‡
Starch gels				
Wheat	100 ± 7	301 ± 57	50 ± 10	24.8 ± 4.2
Manihot	93 ± 14	416 ± 93	45 ± 7	29.2 ± 4.8
Smooth pea	108 ± 22	258 ± 43§	50 ± 7	19.1 ± 4.1‖
Industrially processed starches				
Extruded wheat	115 ± 22	373 ± 79	45 ± 7	22.5 ± 3.7
Tapioca	86 ± 14	402 ± 100	40 ± 7	29.5 ± 8.6
Mung bean noodles	100 ± 14	122 ± 36‡	40 ± 7	8.0 ± 1.3¶

* $\bar{x} \pm$ SEM. Intra- and intergroup ANOVA tests were NS except when otherwise indicated.
† Maximal incremental value above basal value.
‡ Significant intragroup difference, $p < 0.05$.
§ Values for starch gels as a group significantly different from values for the raw-starch group ($p < 0.01$).
‖ Values for starch gels significantly different from values for the raw-starch group ($p < 0.05$).
¶ Significant intragroup difference, $p < 0.01$.

slower digestion of the smooth pea starch cannot be attributed to an incomplete swelling of the starch because swelling temperature is known to be between 49 and 67 °C (37), much below the temperature used in our experiment. Nor can the slower digestion be attributed to an entrapment in fibrous, thick-walled cells, which could prevent complete swelling during cooking as has been shown with legume seeds (38). Rather, it can be attributed to a beginning of amylose reorganization (retrogradation) during cooling. In our study the metabolic responses and in vitro digestibility of starch gels were inversely correlated with the amylose content of the starch (manihot, 17%; wheat, 27%; and smooth pea, 35%). The role of amylose content as a factor influencing the glycemic response to starch was emphasized by Goddard et al (39), who tested rices of differing amylose content (0%, 14–17%, and 25%) and found that the rices with the highest amylose content elicited the lowest glycemic and insulinemic responses. These authors assigned the observed effects to the formation during cooking of amylose complexes, based on constitutive lipids. Amylose-lipid complexes were reported to be resistant to α-amylase in vitro (40) as well as in vivo (41). In our study the lack of starch lipids in legumes backs up the hypothesis that other mechanisms may be involved, such as the retrogradation phenomenon that occurs during cooling and that is most pronounced with high-amylose starches (42).

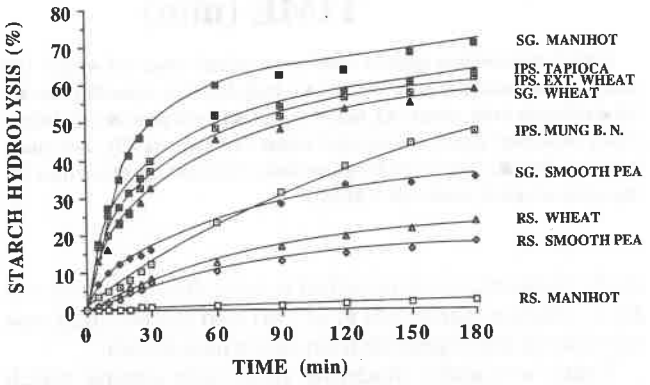

FIG 3. In vitro starch hydrolysis kinetics using 3000 U hog pancreatic α-amylase within 180 min at 37 °C. RS, raw starches; SG, starch gels; IPS, industrially processed starches.

For normal genotypes (manioc, wheat, and smooth pea) amylose content is not a discriminant indicator of α-amylase susceptibility of native starch granules. However, after gelatinization during cooking, amylose is far more able to gel and retrograde than is amylopectin. Therefore, when describing the processing conditions of a starchy food, the cooling step after the thermal gelatinization must be taken into account. Once a starchy food has been processed, amylose content becomes an important factor in determining α-amylase susceptibility.

Biliaderis et al (43, 44) showed that legume starches (smooth pea, mung bean, red kidney bean, fava bean, and green lentil) of normal genotypes are characterized by relatively high amylose content (32–35%), a C-type crystalline structure, and low gelatinization temperatures (60–70 °C). Therefore mung bean starch can be

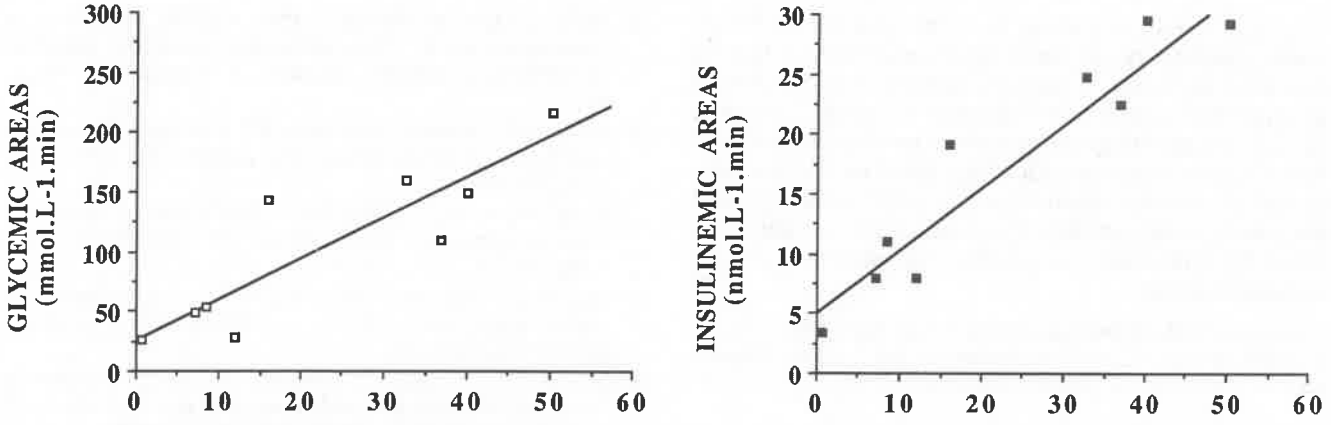

FIG 4. Correlations between ratio of in vitro starch hydrolysis within 30 min and mean areas ($mmol \cdot L^{-1} \cdot min^{-1}$) under the 0–180-min plasma glucose variations (□) ($y = 3.4x + 26.7$; $r = 0.88$, $p < 0.01$) and mean areas under the 0–180-min plasma insulin variations (■) ($y = 0.54x + 5.1$; $r = 0.95$, $p < 0.001$).

considered equivalent to smooth pea starch. Mung bean noodles were different from the rest of the starches studied. They exhibited low plasma responses, similar to those of raw products. In this study nausea was never noticed when test foods were ingested. A gastric stasis induced by very poor palatability was then very unlikely with mung bean noodles. These noodles do not contain proteins, as does durum-wheat pasta; their cohesion during cooking is due to an amylose-retrograded network that is heat-resistant and α-amylolysis-resisting (45). The presence of this network, caused by high amylose content and processing techniques (25, 45; I Sin, unpublished observation, 1974), is the structural cause for the low in vitro hydrolysis rate and low glucose and insulin plasma responses encountered. Englyst and Cummings (46) recently showed that digestion and absorption of cooked potato starch from the small intestine is reduced by cooling and correlates with the formation of α-amylase-resistant starch. Mung bean noodles hydrolyzed quickly whereas all other starchy samples hydrolyzed slowly for the second period (60 min after start of α-amylolysis). This feature should be explained by the slow diffusion of α-amylase inside the particle gel (47); macromolecular network is the limiting factor.

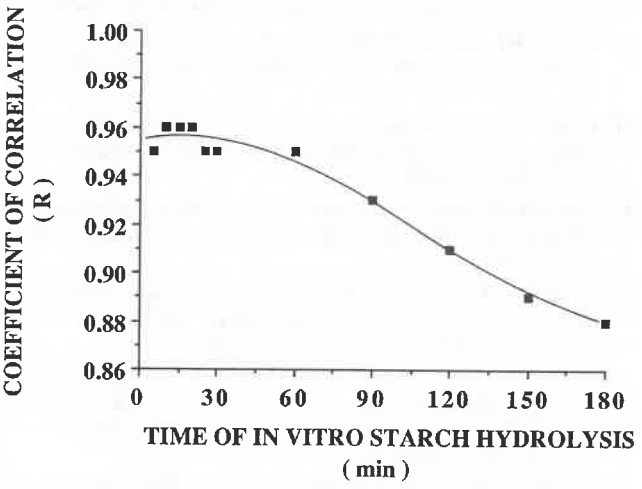

FIG 5. Variation of the coefficient of correlation (R) between the area under the 0–180-min incremental plasma insulin curves and percentage of starch hydrolyzed at several times: every 5 min for the first 30 min and every 30 min for the next 150 min after start of α-amylolysis.

Gastric emptying is certainly an important physiological regulating factor of plasma responses (48). However it cannot explain the differences observed in our study. Indeed the identified factors increasing this transit time are *1*) the time taken to eat the meal (16) (in our study this was shorter with the raw products); *2*) the viscosity of the ingested food (49–51) (the raw products were less viscous); and *3*) the osmolarity of the gastric content (52–54) (it was probably lower with the raw products). Gastric emptying in pigs on a diet with raw potato starch (one of the most α-amylase-resisting raw starches) was initially more rapid than in pigs on a diet with extruded potato starch (gelatinized starch) (55).

Our work with pure starches shows that in vitro digestibility for 30 min or even 5 min is highly correlated with plasma responses in normal subjects. These results were also found by O'Dea et al (11) and Jenkins et al (19). When particle-size effect is discarded by screening as in our study, the first period of starch hydrolysis is assimilated into a period of easily hydrolyzed starch fraction, which depends on botanical origin and on degree of damage, grinding, and thermal processing. The presence of an easily hydrolyzed starch fraction seems therefore to determine the metabolic responses to starchy food.

In conclusion, this study indicates that *1*) the starch origin and the way the starch is processed are two factors that need to be taken into consideration in predicting glycemic and insulinemic responses to starch; *2*) in vitro studies can advantageously replace in vivo studies; and *3*) the legume starches with a high amylose content processed as noodles (heat-resisting amylose-retrograded network) provide an important source of slow carbohydrates for modulation of postprandial glucose and insulin plasma levels.

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