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The influence of food preparation methods on the in-vitro digestibility of starch in potatoes

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For nutritional purposes, starch may be divided into rapidly digestible starch (RDS), slowly digestible starch (SDS) and resistant starch (RS). These fractions can be determined *in vitro* by a new analytical technique. Using this classification and technique the digestibility of starch from potatoes processed in various ways has been assessed. Potato starch was highly resistant to hydrolysis by amylase when raw but was rendered rapidly digestible by all conventional cooking techniques. After cooling, cooked potato contained a small proportion of RS formed as the result of processing. Isolated potato starch was rapidly digestible when cooked with water but, when made into biscuits cooked under dry conditions, much of the resistance was retained. Further analysis of the RS showed that, in raw potato and in potato biscuits cooked under dry conditions, resistance to digestion was due to the structure of the starch granules whereas, after cooking with water and cooling, the resistance was mainly attributable to retrogradation of starch.

INTRODUCTION

The rate at which a starchy food is digested in the small intestine depends largely on its physical form (Hermansen *et al.*, 1986; Heaton *et al.*, 1988). Enzymic degradation of starch to glucose relies on pancreatic amylase coming into contact with its substrate, and anything that inhibits this process will also inhibit the rate of starch hydrolysis, or even prevent its complete hydrolysis in the small intestine. Starch hydrolysis is inhibited by cell walls (Snow & O'Dea, 1981; Wursch *et al.* 1986; Tovar *et al.*, 1990, 1991), dense packing structures (Colonna *et al.*, 1990) and certain crystalline forms of starch that have a reduced susceptibility to alpha amylase (Fuwa *et al.*, 1980; Englyst *et al.*, 1982). Starch that escapes hydrolysis in the small intestine as a result of such inhibiting factors, and enters the colon for fermentation, is known as resistant starch (Englyst & Kingman, 1990).

The digestibility of starch in a particular food may be described in terms of the starch classification shown in Table 1. According to this system, starch may belong to one of three categories, depending on the rate at which it is likely to be digested and absorbed *in vivo*. These categories are rapidly digestible starch (RDS), slowly digestible starch (SDS) and resistant starch (RS). Most starchy foods will contain starch belonging to at least two of these categories, if not all three, but the proportions of starch in each of the categories will vary according to the origin, physical form and processing conditions of the food, and will describe the rate at which the starch is digested. To accompany this classification, we have developed an *in-vitro* technique for measuring the amounts of RDS, SDS and RS present in a starchy food cooked under specified conditions (Englyst *et al.*, 1992*a*). Using the values generated in this technique, two further useful indices of starch digestion may be calculated. The starch digestion rate index (SDRI) is rapidly digestible starch expressed as a percentage of the total starch in the food, and gives an indication of the ease with which the starch in a food is hydrolysed. Thus an easily hydrolysed starchy food such as bread, having gelatinised starch and an open structure, will have an SDRI of close to 100, whereas a starchy food that is more dense, and more difficult to hydrolyse, such as pasta, will have an SDI of 50 or less. The other useful index that can be calculated using values from this method is rapidly available glucose (RAG). The RAG value represents the total amount of glucose that is likely to be liberated into the bloodstream from a certain portion of food in the form in which it is eaten, and includes contributions from free sugars. This value is dependent upon the starch and sugar contents of the food, its water content and the digestibility of the starch component. It gives a more realistic measure of a food's glycaemic potential for those who need to monitor blood glucose carefully.

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Table 1. In-vitro nutritional classification of starch

Type of starch	Example of occurrence	Probable digestion in small intestine
Rapidly Digestible Starch (RDS)	Freshly cooked starchy food	Rapid
Slowly Digestible Starch (SDS)	Most raw cereals	Slow but complete
Resistant starch (RS)		
1. Physically inaccessible starch	Partly milled grains and seeds	Resistant
2. Resistant starch granules	Raw potato and banana	Resistant
3. Retrograded starch	Cooled, cooked potato, bread, and cornflakes	Resistant

From: Englyst & Kingman (1990).

The subcategories of RS shown in Table 1 are a means of discriminating between different causes of resistance. RS_1, or physically inaccessible starch, represents starch that is entrapped within a cellular or multi-cellular structure which prevents the access of amylase, for example the starch trapped in a whole cereal grain. RS_2 represents starch that is not hydrolysed because of its crystal structure within a starch granule. Raw starch granules from potato and banana have the B crystalline structure which is particularly resistant to hydrolysis (Katz, 1934). RS_3 describes starch that has formed into a resistant crystalline structure during cooling of gelatinised starch. It is known as retrograded starch, and consists mainly of retrograded amylose. These RS fractions can be measured using our *in-vitro* technique (Englyst *et al.*, 1992*a*).

The aim of this study is to demonstrate the use of the *in-vitro* technique for measuring starch digestibility, and to show how the digestibility of starch from a single source can vary according to the method by which it is processed. Values are presented for a single variety of potato processed in different ways, for commercially available pre-cooked and/or frozen potato products, and for isolated potato starch after various treatments.

MATERIALS AND METHODS

Potatoes

Marfona, Maris Piper, Belle de Fontenay and Desiree potatoes were obtained locally and processed in the laboratory. Commercially prepared potato products were purchased in local supermarkets and cooked in the laboratory according to the instructions, where appropriate. Isolated potato starch (99–100% pure), prepared commercially from raw potatoes, was obtained from the local health food store. Biscuits made from this and non-starch polysaccharide (NSP)-free wheat starch were prepared in the unit's diet kitchen.

Food processing techniques

Boiling
Potatoes were peeled and cut into chunks of approximately 2 in cubes, then placed in cold water and brought to the boil on a domestic hot plate. The boiling time was taken as the time from the point of reaching the boil to achieving acceptable softness (11–14 min). After draining, the potatoes were either analysed immediately ('hot') or cooled and chilled overnight in a refrigerator ('cold'). Mashed potatoes were mashed with a fork when hot and analysed immediately or cooled as described above. Re-heating was achieved by microwaving on full power for 2 min.

Baking
Potatoes were washed and the skin pierced to prevent bursting. Oven-baked potatoes were placed in a domestic oven at 200°C for 50 min; microwave-baked potatoes were wrapped in kitchen paper and cooked on full power for 7 min. In each case the flesh was scooped out from the skin before analysis. Cold baked potatoes were cooled in their skins and chilled overnight in a refrigerator.

Slow cooking
Potatoes were peeled, cut into 1 in cubes and brought to the boil in a saucepan. The contents of the pan were then transferred to a Tower 'slow-cooker' and cooked overnight, drained and analysed immediately.

Frying
Cold, boiled potatoes were sliced into thin slices (approx. 0·5 cm) and shallow-fried in hot fat at setting 4 on the domestic hot plate for 5–10 min until golden brown on each side. They were drained on absorbent paper before analysis.

Potato biscuits
Potato starch biscuits were prepared by mixing together 75 g potato starch, 37·5 g Echo margarine, 9 g icing sugar and a pinch of salt in a food processor (but no water). The resulting dough was rolled to a thickness of approximately 0·5 cm, biscuits were cut from this and baked at 200°C for 20 min, until golden. Potato and wheat starch biscuits were prepared from the same recipe but with half the potato starch replaced by NSP-free wheat starch (Tenstar).

Analytical

Total starch, RDS, SDS, RS and resistant starch fractions were measured by the method of Englyst *et al.*

(1992*a*) which is based on, and agrees favourably with, the physiological assessments of starch digestibility (Veenstra & Englyst, unpublished; Englyst *et al.*, 1992*b*). The method is described in brief below.

The food was prepared as described and passed once through a domestic mincer. Samples of the food (3–5 replicates), estimated to contain 0·4–1·0 g of starch, were incubated with pancreatin, invertase and amyloglucosidase in a shaking water bath at 37°C and pH 5·2. After 20 and 120 min incubation, 0·5 ml samples of the hydrolysate were removed and placed into 66% ethanol to halt the reaction. Following removal of the second sample the hydrolysates were boiled for 30 min to gelatinise any granular starch. The hydrolysates were then chilled in ice water, and potassium hydroxide added to give a 2 M solution which was agitated for 30 min. A portion of this alkaline solution was then taken into 0·5 M acetic acid and incubated at 70°C with amyloglucosidase before dilution. A separate sample of the food was incubated with invertase alone to correct for free sugars. The values obtained (using a glucose oxidase kit) for glucose released after 20 min and 120 min enzyme incubation, and after treatment with heat and alkali (corrected for free sugars) were used to calculate total, rapidly digestible, slowly digestible and resistant starch fractions.

Using the same system, physically inaccessible starch (RS_2) was determined as the difference between glucose released from a finely milled or homogenised sample and that released from a minced sample after 120 min enzyme incubation. The resistant starch granule fraction (RS_2) was determined as the difference between glucose released from a finely milled or homogenised sample and a similar sample that had been boiled for 30 min, after 120 min enzyme incubation.

The retrograded starch fraction (RS_3) was determined as the starch remaining in a finely milled and boiled sample after exhaustive hydrolysis with pancreatin and pullulanase. The residue was washed in ethanol and acetone, and the RS_3 was measured directly in the residue after dispersion in 2 M KOH and hydrolysis with amyloglucosidase.

RESULTS

Marfona potatoes

Table 2 shows the effect of various common food processing treatments on the digestibility of starch in a single variety of potato, Marfona (a white potato recommended for baking). Raw Marfona potato starch was highly resistant to hydrolysis, having a SDRI of 3 and a RAG value of less than 1 g/100 g. Only 11% of the raw starch was hydrolysed within 2 h, leaving 89% measuring as RS. This high degree of resistance was virtually eliminated by all of the cooking methods. Baking, microwaving, boiling and slow cooking all resulted in SDRI values of 94–99 when the potato was analysed hot, with only 1–3% of the starch measuring as SDS or RS. In each case, chilling the cooked potato overnight led to a reduction in the SDRI to between 80 and 90, with a concomitant increase in the SDS and RS fractions. After one heating and cooling cycle the content of RS did not exceed 5% of the total starch. Reheating chilled mashed potato restored its digestibility to some extent, but on further cooling more resistant starch was formed. This pattern was seen for successive heating and cooling cycles, so that after cooling for the third time, nearly 8% of the starch was resistant to hydrolysis.

Table 2. Effect of cooking method on the digestibility of starch in a single variety of potato (RDS = rapidly digestible starch, SDS = slowly digestible starch, RS = resistant starch, TS = total starch)

	Dry matter (%)	g/100 g DM				Starch digestion rate index	Rapidly available glucose (g/100 g)
		RDS	SDS	RS	TS		
Marfona potato							
Raw	22·2	2	7	70	79	3	<1
Baked (oven, hot)	24·9	71	2	2	75	95	20
Baked (oven, cold)	29·7	63	7	4	73	86	21
Baked (microwave, hot)	24·2	73	1	2	76	96	20
Baked (microwave, cold)	32·1	61	11	4	76	80	22
Slow cooked (hot)	16·2	79	3	2	84	94	14
Mashed (freshly cooked)	20·2	77	t	1	78	99	18
Mashed (cooled)	20·1	70	5	3	78	90	16
Mashed (reheated × 1, hot)	20·1	73	2	2	78	94	17
Mashed (reheated × 1, cold)	20·7	67	9	5	80	84	16
Mashed (reheated × 2, hot)	20·7	72	4	3	78	92	17
Mashed (reheated × 2, cold)	21·0	67	5	6	78	86	16
Mashed (reheated × 3, hot)	21·0	73	2	5	79	92	17
Boiled (freshly cooked)	25·9	71	1	1	74	96	21
Boiled (cooled)	23·6	66	9	5	79	83	17
Boiled, refried in lard (hot)	40·3	58	3	5	65	89	26
Boiled, refried in oil (hot)	48·6	58	3	5	66	88	32
Boiled, refried in butter (hot)	39·8	58	1	5	63	91	26

The starch in boiled potato that had been cooled and re-fried in lard, vegetable oil or butter, was digested more rapidly than that in cold boiled potato but less rapidly than that in freshly boiled potato. Frying also led to a small increase in the proportion of starch measuring as RS compared with cold boiled potato (8% versus 6%), despite the potatoes being analysed hot. Starch digestibility was not affected by the type of fat used for frying.

Other potato varieties

Three other varieties of potato, Maris Piper, Belle de Fontenay and Desiree, were also analysed after boiling and cooling (Table 3). The total starch in all of the varieties was similar, ranging from 72% for Belle de Fontenay to 77% for Maris Piper. Belle de Fontenay potatoes contained significantly greater amounts of free sugars than the other varieties (data not shown).

All of the varieties were rapidly digested when freshly cooked and contained only small amounts of RS (0–1% of dry matter), consistent with the results for the Marfona variety. On cooling, the starch digestion rate was reduced, and SDS and RS fractions increased slightly. This was most noticeable for the Belle de Fontenay potatoes which had a closer texture than the other varieties and did not become 'floury' on cooking.

Commercially available potato products

Table 4 shows the digestibility of starch in a range of commercially available potato products. In general, these were readily digestible (mean SDRI 88), but tended to contain a slightly greater proportion of RS than freshly cooked potato (mean 7% of total starch). The least well digested products were the canned potatoes, especially those not specifically designated as new potatoes. When analysed cold (straight from the can) these contained 12% RS on a dry matter basis, equivalent to 16% of the total starch content. The starch that was hydrolysed was also digested more slowly (SDRI 57, SDS 26% of total starch). Canned new potatoes and commercially prepared potato salad were also more resistant to hydrolysis than freshly cooked potato. In contrast, dried instant potato was rapidly digestible, as were freeze-cook products such as oven chips, potato waffles and potato croquettes.

Whilst freshly cooked potatoes and most commercially available potato products were rapidly digested, their RAG values were low because of their very high water content (mean RAG 20). The highest RAG value of 51 was seen for potato crisps which had 98% dry matter.

Isolated potato starch

The in-vitro hydrolysis of isolated potato starch pro-

Table 3. Comparison of the digestibility of starch in three varieties of potato after boiling (RDS = rapidly digestible starch, SDS = slowly digestible starch, RS = resistant starch, TS = total starch)

	Dry matter (%)	g/100 g DM				Starch digestion rate index	Rapidly available glucose (g/100 g)
		RDS	SDS	RS	TS		
Maris Piper, hot	22·1	71	5	1	77	92	18
Maris Piper, cold	25·1	66	8	2	76	87	18
Belle de Fontenay, hot	19·4	71	2	1	74	96	16
Belle de Fontenay, cold	21·2	58	10	4	72	80	14
Desiree, hot	22·3	72	3	0	75	96	18
Desiree, cold	21·5	69	5	1	76	91	16

Table 4. The digestibility of starch on some commercially available potato products (RDS = rapidly digestible starch, SDS = slowly digestible starch, RS = resistant starch, TS = total starch)

	Dry matter (%)	g/100 g DM				Starch digestion rate index	Rapidly available glucose (g/100 g)
		RDS	SDS	RS	TS		
Potato salad	25·0	23	8	4	35	66	7
Canned old potato (hot)	16·1	62	2	8	72	86	11
Canned old potato (cold)	16·1	41	19	12	72	57	7
Canned new potato (hot)	16·0	70	4	1	74	95	13
Canned new potato (cold)	16·0	56	13	5	74	76	10
Instant potato	16·7	72	1	1	73	98	13
Potato crisps	98·0	46	0	3	49	95	51
Long-life potato rosti (hot)	28·1	58	1	4	63	92	18
Oven chips (hot)	45·1	56	5	3	63	89	29
Potato waffles (hot)	51·1	48	1	4	54	89	28
Potato scones	47·0	66	2	3	71	93	35
Potato croquettes (hot)	43·0	56	1	3	60	93	27

Table 5. Effect of wet and dry cooking processes on the digestibility of isolated raw potato starch (RDS = rapidly digestible starch, SDS = slowly digestible starch, RS = resistant starch, TS = total starch)

	Dry matter (%)	g/100 g DM				Starch digestion rate index	Rapidly available glucose (g/100 g)
		RDS	SDS	RS	TS		
Raw	81·8	6	19	75	99	6	5
Boiled	3·3	98	1	1	99	98	3
Boiled and cooled	3·3	91	4	6	100	91	3
Potato starch biscuits	99·0	12	18	30	60	20	18
Potato + wheat starch biscuits	94·9	23	17	15	55	42	30

cessed in various ways is described in Table 5. The raw starch was highly resistant to enzyme attack but less so than that in the raw, fresh potato in which the protective cell structure was still present. Of the isolated starch, 25% was hydrolysed after 120 min enzyme incubation, leaving 75% RS. On boiling with a large excess of water the starch became rapidly digestible and was virtually all converted to glucose within 20 min of enzyme incubation. However, on cooling, 6% of RS was present. In contrast, cooking the potato starch under dry conditions to make a biscuit, did not render it rapidly available for hydrolysis. Even after baking for 20 min, 50% of the starch remained unhydrolysed during 120 min enzyme incubation.

Resistant starch fractions

Table 6 shows that the RS present in the potato biscuits was in the same form as that in the raw potato flour (resistant starch granules), suggesting that in the absence of moisture the granular structure and resistance of the raw starch was retained during heat treatment. This was also the case for biscuits made with potato flour and NSP-free wheat starch. These products contained negligible amounts of retrograded starch in comparison with samples that had been cooked under moist conditions and then cooled, where retrograded starch accounted for up to 3% of the dry matter (Table 6).

Canned potatoes, potato salad and potato crisps contained RS from all three of the RS fractions. For canned old potatoes the largest RS fraction was RS_2.

Table 6. Resistant starch fractions in various potato products

	Dry matter (%)	g/100 g DM		
		RS1	RS2	RS3
Raw potato starch	81·8	—	75·7	0·1
Potato starch biscuits	99·0	—	29·6	t
Potato + wheat starch biscuits	94·9	—	15·2	0·2
Potato salad	25·0	0·7	0·6	1·1
Canned old potato (cold)	16·1	3·4	6·4	3·1
Canned new potato (cold)	16·0	—	1·9	2·1
Mashed Marfona potato (cold)	18·6	—	—	2·3
Instant potato	16·7	—	0·5	1·8
Potato crisps	98·0	0·9	0·6	0·3

DISCUSSION

The starch in raw potatoes is in a form that is highly resistant to digestion by pancreatic amylase. Isolated raw potato starch is slightly better digested than that in the intact potato, possibly due to the removal of cellular barriers or to damage sustained by the starch granules during processing. Mechanical damage to raw potato starch during analysis has been shown to increase its digestibility (Englyst *et al.*, 1992*a*). The lack of suitability of unprocessed potatoes as food has been recognised in all the societies where they are a regular part of the diet, in that they are seldom eaten raw. However, all of the common techniques used to prepare potatoes for consumption in the domestic situation are highly effective at rendering the starch available for hydrolysis. In the natural state, potato tubers contain sufficient water to allow full gelatinisation of their starch content during heat treatment, as demonstrated by the digestibility of potatoes baked in the conventional oven or microwave oven. Thus it is unlikely that potatoes cooked by customary domestic techniques would retain any resistant starch granules.

In general the starch in fully cooked potatoes is rapidly digestible, and only a small residue remains unhydrolysed after 20 min incubation with pancreatin and amyloglucosidase. In this study, the digestibility profile of the potato differed only slightly according to the method of food processing. This was probably because the form and texture of the cooked potato was very similar whether the tuber was baked, boiled or microwaved. The rapid expansion of the starch as it gelatinises in the presence of excess water, loosens the cellular architecture to give the familiar 'floury' texture that is characteristic of most potato products, and which allows easy access for starch-degrading enzymes. Unlike wheat flour, potatoes are not usually used to make products as diverse in form and texture as bread and pasta.

The digestibility of the starch in cooked potatoes was influenced most greatly by the process of cooling and chilling overnight. This consistently resulted in a reduced rate of starch digestion and an increase in the proportion of RS. During cooling, gelatinised starch recrystallises into a more ordered solid state less susceptible to the action of pancreatic amylase. Most of the crystallised starch chains are re-dispersed by reheating, leading to restoration of digestibility, but a small fraction of mainly retrograded amylose (RS_3) remains resistant (Englyst *et al.*, 1982). During each reheating and cooling cycle a bit more RS_3 is formed. Thus the amount of RS in moist potato products is increased by successive heating and cooling cycles.

The effect of heating and cooling is enhanced by elevated processing temperatures such as those used in canning. In this study, canning had a greater depressive effect on the digestibility of potato starch than normal cooking and cooling, and this was only partially ameliorated by reheating. In cold, canned potatoes the digestibility profile was shifted markedly away from RDS and towards SDS and RS. Only part of the increase in RS was in the form of RS_3, the remainder being RS_2. In view of the extensive heat treatment that the potatoes had received it is unlikely that this was the same fraction represented in the raw potato starch and potato biscuits. The result probably indicates that some starch has retrograded to a form which, like the potato granules, can be reversed to a more digestible form by reheating.

In a study in man using ileostomy subjects it was shown that the starch in freshly cooked potatoes was well digested, only 2·4 g/100 g dry weight being recovered in the ileostomy effluent. For cooked, cooled potatoes, 9 g/100 g dry weight escaped digestion in the small intestine. Reheated potatoes were digested better than the cooled, but not as well as the freshly cooked (Englyst & Cummings, 1987). The digestibility of potato starch granules fed in the form of potato and wheat starch biscuits has also been assessed in ileostomates (Englyst *et al.*, 1992*b*). The mean recovery of starch in effluent following a meal of 100 g biscuits (containing 11·7 g RS measured by the in-vitro method) was 13·7 g (range 12·7–15·7).

Overall the digestibilities of potato products measured *in vitro* are reflected in in-vivo studies. The amount of starch recovered in the ileostomy studies is slightly higher than the mean RS value obtained by the in vitro technique, but a very substantial variation is seen between the individual ileostomy subjects (Englyst *et al.*, 1992*b*). The values obtained by the in-vitro technique depend only on the starchy foods themselves and not on factors such as the individual chewing habits, variation in amylase concentration in the gut or transit time. The in-vitro technique therefore represents a reproducible measure by which starchy foods can be classified and compared according to their potential digestibility in man.

Depending on the type of processing, the amount of RS entering the colon from potato may be very small, or substantial. An average portion of boiled potato of 150 g, with a dry matter content of 25%, would account for only 0·7–1·1 g of starch entering the colon, and a similar portion of cold, canned potatoes would provide less than 3 g. However, using isolated raw potato starch it is possible to prepare palatable products that contain very high levels of resistant starch. The biscuits made in our laboratory from potato starch were palatable and contained 30% RS, so that a manageable portion of 50 g (about three biscuits) could provide 15 g of fermentable substrate to the colon, or more than the mean NSP intake in the UK. The available starch in such biscuits is digested slowly, with a SDRI value of only 20. The physiological effects of potato and other biscuits high in RS have been addressed in a series of studies in man (Cummings *et al.*, 1992).

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