



Kiwifruit remnants from digestion *in vitro* have functional attributes of potential importance to health

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ABSTRACT

The physicochemical properties of plant cell walls in the gut are important in modulating processes that influence health. We investigated the physicochemical properties of kiwifruit cell walls digested under gastric and gastroileal conditions *in vitro*. Soluble and insoluble undigested polymer fractions were measured, the hydration properties of the digested pulp, and the capacity to retard diffusion and mixing in a simulated small intestinal segment. Undigested polymer (dietary fibre) fractions differed little between 'Hayward' ('Hayward') and 'Hort16A' (gold) kiwifruit cultivars in their relative proportions, although total dietary fibre was greater in 'Hayward' than in the 'Hort16A'. The polysaccharide composition of seed-free digestion-resistant polymer was similar in both cultivars and not affected by *in vitro* digestion. Indigestible remnants from kiwifruit had strong water retention and swelling capacities, also little affected by digesting, and retarded both glucose diffusion and mixing significantly, especially in the presence of low background viscosity. We conclude that the particulate cell wall remnants of digested kiwifruit retain substantial potential to influence the properties of gut contents.

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1. Introduction

Cell walls have important functional properties in fruits, and when the fruits are eaten many of these properties extend into the gut where they mediate a number of the health-related processes (Buttriss & Stokes, 2008). Fruit cell walls therefore have the potential to extend the direct benefits of consuming fruits for their nutrients to benefits derived from the impact of their digestion-resistant remnants on the digestion of co-consumed foods.

Soluble pectic polysaccharides are a large component of fruit cell walls, with well established rheological properties in solution (Dikeman & Fahey, 2006). Soluble polysaccharides are able to extend and interact by entanglement and formation of junction zones, to create friction and intermolecular adhesion that is manifested as viscosity and gelation (Ellis, Rayment, & Wang, 1996). However, soluble dietary fibres are not the only cell wall components that contribute to the rheological properties of gut contents. Insoluble particulate cell wall remnants have an important role in generating viscosity by interacting amongst themselves, with other particle types, and with polymers including pectin, in the aqueous phase of the matrix in which they are suspended (Lentle & Janssen,

2008; Rayment, Ross-Murphy, & Ellis, 2000; Takahashi & Sakata, 2005).

Kiwifruit contain about 2% dietary fibre on a fresh weight basis. However, in pigs fed diets containing kiwifruit, pectins and other cell wall polysaccharides become highly concentrated in the small intestine as available food components such as starch are digested and absorbed. Their effect on intestinal viscosity is, therefore, likely to be large enough to influence the rate of gut processes, such as nutrient transfer and absorption, that are able to influence health.

Viscosity in the upper small intestine is thought to retard glucose uptake, reducing glycaemic response, while viscosity at the terminal ileum is thought to retard bile acid uptake, leading to reduced plasma cholesterol when the plasma cholesterol is used as a biosynthetic substrate in replacement of bile acids lost to the colon (Dikeman & Fahey, 2006).

The key aim of the work described here was to determine the extent to which the non-starch polysaccharide fractions of the green 'Hayward' (*Actinidia deliciosa* 'Hayward') and gold (*A. chinensis* 'Hort16A') kiwifruit cultivars might possess properties that potentially contribute to the health attributes of kiwifruit. Using a valid *in vitro* digestion method (Monro & Mishra, 2010a) to simulate gut conditions, we measured the effects of digestion on soluble and insoluble dietary fibres and on their hydration properties. We also demonstrate the ability of the digested cell wall remnants to affect processes such as diffusion and mixing that determine rates of nutrient absorption from the gut lumen with numerous downstream physiological consequences of importance to health.

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2. Materials and methods

2.1. Samples

Fresh 'Hayward' and 'Hort16A' kiwifruit were delivered in a pre-ripe state and held for several days at room temperature until they had ripened to the point at which normally consumed as judged subjectively by the softness and palatability of similar fruit from the same batch. They were peeled, chopped and blended at low speed in a Waring laboratory blender for just enough time to form a puree (Carnachan, Bootten, Mishra, Monro, & Sims, 2012).

2.2. *In vitro* digestion

The freshly prepared kiwifruit pulp (10 g) was weighed into 70-ml specimen pots which were inserted to their full depth in a 15-place aluminium heating block placed on a 15-place magnetic stirrer and covered with an insulating sheet. The digestion consisted of a simulated gastric digestion for the gastric samples, and simulated gastric digestion followed by a small intestinal digestion for the gastric-ileal (GI) samples (Monro, Mishra, & Venn, 2010b). For the gastric phase, 20 ml of water and enough 1 M HCl (about 0.5 ml) to obtain a pH of 2.5 was added with mixing, followed by 1 ml of 10% pepsin dissolved in 0.05 M HCl, and the mixture stirred slowly (130 rpm) for 30 min at 37 °C to accomplish gastric digestion. The small intestinal phase was initiated by adding 1 M NaHCO₃ to a gastric digest to pH 6.5 and 5 ml of 1.0% pancreatin (Sigma P-7545) in 0.1 M maleate buffer pH 6, and the pots were immediately made to the 55-ml mark with distilled water and digestion continued for 120 min from the time of adding the pancreatin.

For extraction "as is" (water), the kiwifruit pulp was made up to the final digesta volume of 54 ml with water. For the gastric samples, the gastric digestion procedure was followed, but at the end of 30 min of gastric digestion, the volume was made to 54 ml with water rather than being neutralised with 1 M NaHCO₃. The ileal digestion was conducted as usual in a final volume of 54 ml.

2.3. Soluble (SUDP), insoluble (IUDP) and total (TUDP) undigested polymer

Digested contents of the digestion pots were transferred into 50-ml Falcon tubes and centrifuged (3000g). The supernatants were removed to a separate container and the residue resuspended in dilute HCl solution pH 2.5 for gastric, and water for ileal residues, and again centrifuged. The gastric supernatants and washings were combined, as were the ileal supernatants and washings, and 4 volumes of ethanol added, and after standing for at least 30 min, the precipitate (SUDP) was collected by centrifuging. The ethanolic precipitates and insoluble digestion residues (IUDP) were washed with 80% ethanol and again collected by centrifuging and the process repeated. Finally the precipitates (SUDP) and undigested residues (IUDP) were washed with acetone, air dried, and rehydrated before freeze drying to obtain a friable residue for further analysis. TUDP was prepared by adding the complete digestion pot contents after gastric and ileal digestion to four volumes of ethanol, mixing, and collecting the TUDP by centrifugation. Following 80% ethanol/acetone washes, the TUDP was hydrated and freeze dried.

2.4. Hydration properties: water retention and swelling

Hydration properties, water-retention capacity (WRC) and swelling (SW) were measured by the European Collaborative Study procedures (Robertson et al., 2000). WRC is the water that is bound tightly enough to a material to resist being separated by centrifug-

ing. SW is the volume a material occupies in water with no applied force, and is measured by allowing the material to settle passively. WRC, expressed as ml/g, was calculated from the weight of water retained by the centrifugation residue from kiwifruit pulp, while swelling was measured as the bed volume of the IUDP preparation allowed to settle overnight.

To measure WRC and SW, kiwifruit pulp samples were suspended in water ("as is"), digested *in vitro* under gastric conditions (as above), or digested in gastric followed by ileal conditions (as above). After digestion, the samples were centrifuged (3000 rpm), the supernatant was discarded and the residue re-suspended in added distilled water and again collected by centrifuging and the process repeated one more time to remove soluble sugars. For WRC determination, the washed residues were collected by centrifuging at 3000g for 10 min in pre-weighed Falcon tubes, the tube plus wet residue was weighed, and dried overnight in a vacuum oven at 60 °C before re-weighing to allow calculation of g water/g residue, which could be converted to g water/g starting pulp. For determination of SW, the washed residue was dispersed in 250 ml water in a measuring cylinder and allowed to settle overnight in a refrigerator.

The results for WR and SW per gram of IUDP allowed a solid volume fraction (Φ) for the settled bed to be estimated as:

$$\Phi = (\text{WR} + 1)/\text{SW}.$$

2.5. Mixing

Because the theory required to deal with the rheological complexity of fluid movements in the gut, involving turbulence, laminar flow, flexible particle interactions and background viscosity, is still developing (Lentle, Hemar, Hall, & Stafford, 2005), mixing was measured directly as a decrease in non-homogeneity when two initially separate 56-ml volumes of settled kiwifruit IUDP, one of which contained 1.0 g glucose, were mixed in a tube of internal length 26 cm and internal diameter 2.5 cm by a rolling ball of 1.5 cm diameter and 7.0 g weight traversing the tube length at a velocity of 5.0 cm sec⁻¹, or about 12 traverses per minute. The ball velocity and frequency of transit was set within the range of peristaltic and constrictive contractions in the ileum (Hasler, 2006). The glucose in samples removed from the sampling ports was measured using the p-hydroxybenzoic acid hydrazide (PAHBAH) method for reducing sugars (Blakeney & Mutton, 1980).

The contents of the tube were sampled by removing a small aliquot (100 μ l) from each of four equally spaced ports along the length of the tube. Mixing was measured by the decrease in standard deviation of measurements from the four ports as a result of ball transit, and was considered complete when the standard deviation had reached the standard deviation of samples from a pre-mixed solution containing 1.0 g glucose added to the tube.

An experiment was run using a solution of 0.5% guar gum to provide a small background viscosity, as a control, against which mixing retardation by settled kiwifruit made to 0.5% with guar was compared. Samples were removed every 16 traverses of the marble. Although the 0.5% guar alone only slightly reduced the marble falling time, the 0.5% guar in combination with the settled kiwifruit IUDP greatly reduced mixing. In further experiments the guar gum concentration was reduced to 0.25% and the experiment compared mixing in water, 0.25% guar, settled kiwifruit IUDP, and settled kiwifruit IUDP plus 0.25% guar.

2.6. Retardation of glucose diffusion

'Hayward' and 'Hort16A' kiwifruit pulp samples were digested as described above, after which the digests were transferred to 50-ml Falcon tubes, the residue collected by centrifuging, the

supernatant discarded, and the residue gently re-suspended in distilled water and again collected by centrifuging to wash. The washed residue (IUDP) was then thoroughly suspended in 250 ml of water, transferred to a measuring cylinder, and allowed to settle overnight. After settling, the bed volume was recorded, and the clear (fibre-free) top phase was removed by suction and discarded, while the settled volume containing the kiwifruit insoluble IUDP was made to 10% (v/v) in glucose. The IUDP/glucose solution was used to fill a 31-ml glass vial, and a dialysis sheet (MW 12,000 cut off) was stretched over the vial opening and secured with two rubber O rings. The vial was attached to a lead sinker with rubber bands and placed on its side in a beaker containing 400 ml of water stirred at 400 rpm. Two 1.0-ml aliquots of dialysate were removed at 0, 5, 10, 15 and 20 min, with the $T = 0$ aliquot being taken 1 min after adding the dialysis vial to the water. The experiment was also run using 10% glucose solution (reference) without kiwifruit IUDP. The difference between the rates of diffusion of glucose with and without kiwifruit IUDP was taken to provide a measure of the retardation of glucose diffusion. Glucose that had diffused into the dialysate was measured using the PAHBAH method (Blakeney & Mutton, 1980). Glucose retardation (GR) was calculated as:

$$\text{GR}(\%) = (\text{glucose OD} - \text{sample OD}) \times 100 / \text{glucose OD}.$$

3. Results

3.1. Soluble and insoluble UDP

Per equal weight of seedless pulp there was little difference in between 'Hayward' and 'Hort16A' kiwifruit in the yield of soluble undigested polymer (SUDP) and insoluble undigested polymer (IUDP) from them (Fig. 1). In all extracts from both 'Hort16A' and 'Hayward' kiwifruit, IUDP was present in greater amounts than the SUDP.

3.2. Hydration properties (Table 1)

Expressing the water retention results on a per 100 g pulp basis (Table 1) showed that about 30 ml of water was tightly enough bound to the kiwifruit fibre to resist centrifugation. That is, about 30% of the weight of kiwifruit can be regarded as bound water. Water, gastric and gastroileal conditions did not appear to affect the water binding differently, and the 'HAYWARD' and 'Hort16A' cultivars were similar in their water retention capacity. The kiwifruit pulp exhibited a large swelling capacity. Dispersion of the

pulp by crushing and digestion increased the volume occupied by cell wall material about three fold compared with the volume occupied in the intact fruit and it did not differ greatly between the 'Hayward' and 'Hort16A' cultivars. The water, gastric and gastroileal conditions did not differ markedly in their effect on swelling. The solid volume fractions calculated for the settled beds of swollen remnants from the 'Hayward' and 'Hort16A', with and without gastric and gastroileal digestion, all had a value close to 0.1. By expressing the results on a per 100 g kiwifruit pulp basis, an approximation of the water retention and swelling contributed by a single fruit was obtained, as the average weight of the fruit used was close to 100 g.

Comparison of the hydration properties of freeze dried kiwifruit IUDP with other forms of dried dietary fibre preparations showed kiwifruit IUDP fibre to have a relatively high WRC and SW, compared with commercial dietary fibres (Table 2).

3.3. Retardation of mixing

In the first experiment, in which kiwifruit IUDP was made to 0.5% with guar, a 94% reduction in the rate of mixing was attained relative to the reduction caused by 0.5% guar alone (Fig. 2). The relative resistances, measured as falling time compared with falling time in the empty tube (air), and with the resistance of water given a value of 1.0, were: water, 1.0; 5% guar, 1.63; 5% guar plus kiwifruit, 22.3.

Because of the large effect of the guar-kiwifruit interaction, the concentration of guar was halved to 0.25% and a comparison was made of mixing retardation in water, 0.25% guar, settled kiwifruit fibre (IUDP), and settled kiwifruit fibre plus guar (0.25%). Guar alone at a concentration of 0.25% caused a small retardation in mixing, kiwifruit IUDP a greater retardation, and 0.25% guar and kiwifruit combined, a yet greater retardation (Fig. 3). Furthermore, the sum of the individual retardations by guar and kiwifruit was less than the retardation by the two combined, indicating an interaction between the two (Fig. 4). The effect of the kiwifruit guar interaction had been reduced by halving the guar concentration from 0.5% to 0.25%, but nevertheless, adding kiwifruit IUDP to the 0.25% guar caused a 4.6-fold increase in resistance to mixing over that with guar alone.

3.4. Retardation of diffusion

The kiwifruit UDP preparations were able to retard glucose diffusion substantially, by 46.2% in the case of 'Hayward' kiwifruit and 35.7% in the case of 'Hort16A' kiwifruit (Fig. 5).

4. Discussion

In assessing the health-related properties of kiwifruit, and the differences between 'Hayward' and 'Hort16A' kiwifruit, it was relevant to determine the extent to which non-starch polysaccharides had entered solution at the end of gastric digestion, at the point where their influence on small intestinal events, such as digestion of available carbohydrates, commences. Also, as their influence is also extremely important at the terminal ileum, where the rate of re-absorption of bile acids may indirectly influence blood cholesterol concentrations (Dikeman & Fahey, 2006), analysis after the time required for gut transit was also relevant. Therefore, as the duration of small intestinal transit is 2–3 h (Yu & Amidon, 1998), we determined the proportions of soluble and insoluble undigested polymer after simulated gastric extraction for 30 min, and after a further 120 min of simulated ileal digestion *in vitro*. *In vitro* digestion using such timings has been shown to predict postprandial glycaemic responses with reasonable accuracy (Mon-

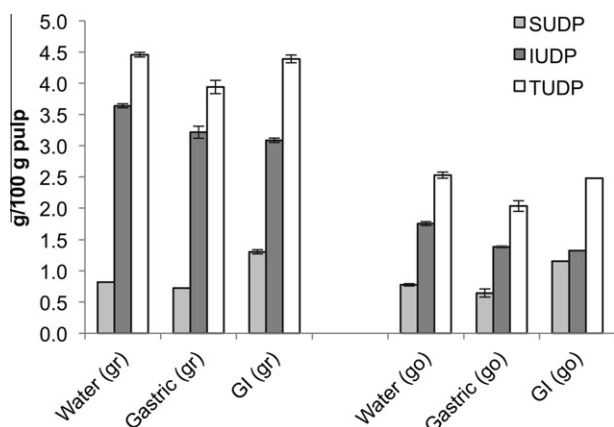


Fig. 1. Soluble (SUDP), insoluble (IUDP) and total (TUDP) undigested polymer fractions from 'Hayward' (gr) and 'Hort16A' (go) kiwifruit pulp after extracting with water, and gastric and and gastrointestinal (GI) conditions during *in vitro* digestion.

Table 1

Hydration properties: water retention, swelling and calculated solid volume fraction in the seed-free settled bed of 'Hayward' and 'Hort16A' kiwifruit digestion remnants expressed per gram of remnants and per 100 g fruit.

Sample	Water retention		Swelling		Solid volume fraction	
	Mean	SD	Mean	SD	Mean	SD
	(ml/g remnant dry matter)		(ml/g remnant dry matter)			
'Hayward'						
Water	12.8	±0.63	110	±5.9	0.12	±0.006
Gastric	12.6	±0.12	102	±8.1	0.13	±0.007
Ileal	12.0	±2.17	131	±5.4	0.10	±0.005
'Hort16A'						
Water	11.8	±0.65	123	±6.8	0.10	±0.005
Gastric	12.2	±0.28	110	±4.2	0.12	±0.006
Ileal	13.0	±0.25	145	±7.2	0.10	±0.005
(ml/100 g fruit)		(ml/100 g fruit)				
'Hayward'						
Water	34.3	±0.63	345	±11	–	–
Gastric	35.3	±0.70	299	±11	–	–
Ileal	32.8	±5.76	399	±13	–	–
'Hort16A'						
Water	30.3	±0.20	348	±11	–	–
Gastric	30.2	±0.10	297	±7.1	–	–
Ileal	29.9	±0.79	383	±19	–	–

Table 2

Hydration properties of freeze dried insoluble undigested polymer fraction from kiwifruit (IUDP) and several rehydrated dietary fibre preparations.

	Water retention (ml/g)		Swelling (ml/g)	
	Mean	SD	Mean	SD
Kiwifruit ('Hayward')	9.7	1.1	76	8.0
Swede fibre (in-house)	13.3	1.5	15.4	1.6
Sugar beet fibre (commercial)	4.8	0.55	7.6	0.8
Apple fibre (commercial)	5.3	0.61	9.1	0.9
Orange fibre (commercial)	6.6	0.76	7.7	0.8
Wheat bran	3.0	0.34	4.6	0.5

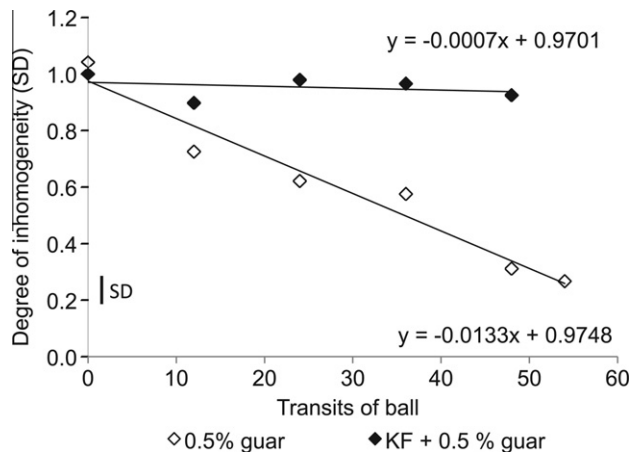


Fig. 2. Effect of insoluble undigested kiwifruit polymer (IUDP; dietary fibre) from *in vitro* digestion of 'Hayward' kiwifruit (KFgr), at settled bed density, on mixing of glucose in 0.5% guar gum as a function of transits of a 1.5-cm diameter ball in a 2.5-cm diameter tube containing the IUDP suspension. The degree of homogeneity is relative with unmixed given a value of 1.0. The mean inter-duplicate analytical range at each point is 0.05 units.

ro & Mishra, 2010a). Although we have referred to the residue from kiwifruit pulp after digestion as "undigested polymer", it is predominantly non-starch polysaccharide (dietary fibre) of cell wall origin, as kiwifruit contain little starch and protein (Athar, McLaughlin, Taylor, & Mishra, 2006), and after pepsin-HCl ("gastric") digestion will be depleted in protein and minerals.

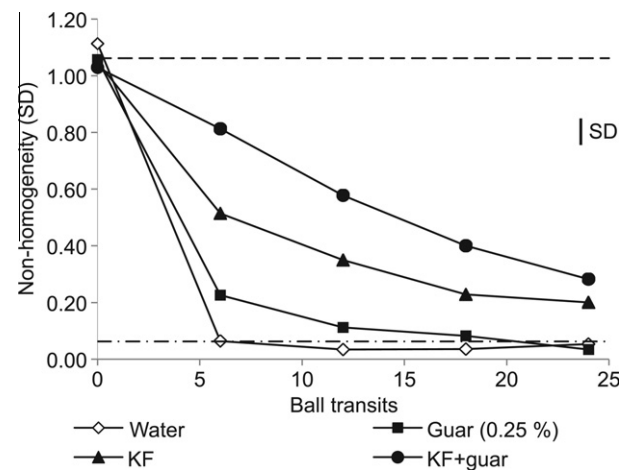


Fig. 3. Effect of 0.25% guar, 'Hayward' Kiwifruit insoluble undigested polymer fraction (IUDP), and the kiwifruit IUDP plus 0.25% guar on rate of mixing. Non-homogeneity is measured as the standard deviation of four equidistant samples taken from the mixing tube initially filled half with KF and half with KF + 10% glucose solution. Mixing is measured as the increase in homogeneity with transits of the mixing ball. The mean inter-duplicate analytical range at each point is 0.05 units.

The results showed that gastric and ileal conditions do not make a large difference either to the total quantity of dietary fibre, to its distribution between soluble and insoluble fractions, or to the gross composition of the polysaccharide fractions that comprised it. The stability of the undigested residue was consistent with the known properties of cell wall dietary fibre as a digestion-resistant food component (by definition) (Lee & Prosky, 1995), and the *in vitro* simulated digestion approach provided a valid analysis of soluble dietary fibre (Monro, 1993).

Using nutritionally valid digestive processing and analysis of the digestion-resistant residues was important in the present analysis because soluble pectin is the major component of fruit soluble polysaccharides, and has been shown in numerous studies to have beneficial physiological effects, such as reducing glycaemic response and blood cholesterol in human clinical studies (Plaami, 1997). Its efficacy, like that of many other soluble polysaccharides, appears to be due to its ability to increase the viscosity of intestinal

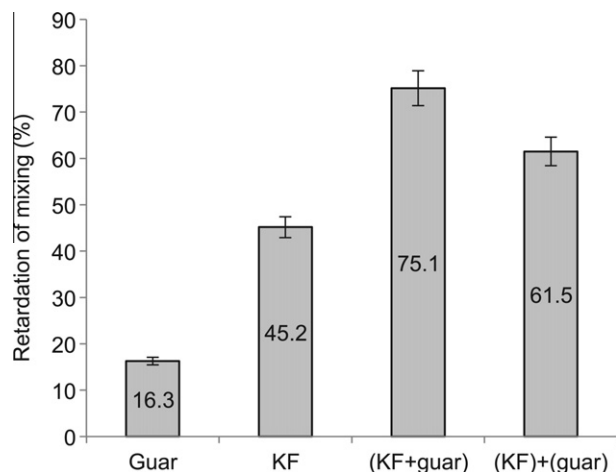


Fig. 4. Retardation of mixing (%) measured as the % non-homogeneity remaining after six transits of the mixing ball. Guar = 0.25% guar gum; KF = settled 'Hayward' kiwifruit insoluble undigested polymer fraction (IUDP); (KF + guar) = 0.25% guar gum in settled kiwifruit IUDP; (KF) + (guar) = sum of the separate values for KF and GG.

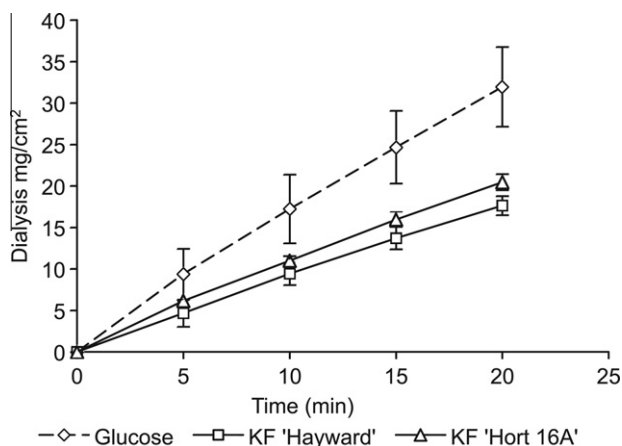


Fig. 5. Curves of glucose dialysis versus time showing the retarding effect the insoluble non-digested polymer fractions from 'Hayward' (KF 'Hayward') and 'Hort16A' (KF 'Hort16A') kiwifruit at settled bed density.

contents. But it is also labile and easily extracted and depolymerised by elevated temperatures at neutral pH, so it is important to adhere to gut-like conditions for *in vitro* analysis to provide a nutritionally valid preparation (Monro, 1991).

4.1. Hydration properties

The hydration properties, water-retention and swelling, are commonly measured properties of dietary fibres. In the kiwifruit cell walls, these properties appeared to be robust, as they were not greatly altered by exposure to gut conditions. They are important to measure because of their influence on the behaviour of gastric and intestinal contents. Water retention is important because the bulk that bound water contributes to hydrated cell wall remnants may affect gastric and intestinal filling, which affects transit rate and the distribution of nutrients in the intestine (Schneeman, 1998). The combined volume of particle mass and the volume of the water it retains contributes to the effective volume, or solid volume fraction, of the particles, which is a critical factor in the viscosity of particulate suspensions such as gut contents (Lentle & Janssen, 2011; Rayment, Ross-Murphy, & Ellis, 2000). Swelling is

more related to the relative volume of influence, the hydrodynamic volume, of particles dispersed in a liquid medium, such as in the gut. It is determined not only by the solid volume fraction, but by the irregular shape – polydispersity in length and size – of the particles that limits passive packing and ensures that the interstices within the settled bed contain a large proportion of suspending medium.

The higher WRC and SW values for kiwifruit dietary fibre compared with commercial preparations supplied as dried powders (Table 2) suggests that kiwifruit fibre retained its functionality relatively well because it had not been subjected to extensive processing and milling. In commercial dietary fibres depolymerisation of heat labile pectin remaining in the cell wall matrix will lead to a loss of hydration capacity. Milling of the product is likely to further diminish the hydration properties, because decreasing particle size will reduce the effective hydrodynamic volume. However, the relatively low WRC and SW of the minimally processed in-house swede fibre preparation suggests that differences in the native cell wall structure between pectin-rich ripe fruit parenchyma and the more cellulosic stem parenchyma such as that in swede also plays a role in determining WRC and SW.

The dietary fibre in fresh unprocessed kiwifruit may therefore be more functional in the upper bowel than the dry commercial fibres, because it is “natural” in the sense of being minimally processed, and is, therefore, likely to retain a greater proportion of intact pectic polymers than an equivalent weight of dry commercial fibre, such as the types typically used in bakery products, for example.

4.2. Mixing

Hydration properties of the digested kiwifruit fibre in the gut are related to their effects on diffusion and mixing, which were also measured in the present experiment. In a non-viscous medium, the generation of viscosity by IUDP particles from digested kiwifruit will depend solely on the interaction of the particles themselves – on their solid volume fraction. But when soluble polymers are included in the medium containing kiwifruit IUDP, they will allow transmission of force between particles and so can, in combination with the particles, lead to an increase in viscosity, and so to a decrease in mixing.

Mixing has a central role in bulk transfer of digesta to the intestinal wall for absorption (Lentle & Janssen, 2011). It is achieved by peristaltic and constrictive contractions which produce local points of pressure to propel gut contents by a combination of laminar flow and turbulence. As flow and turbulence are involved in intestinal mixing, factors that alter the fluidity of the intestinal matrix will influence mixing and therefore the rate of processes that depend on mixing, such as carbohydrate transfer and absorption and so too the blood glucose response. In view of the fact that intestinal contents contain a variety of molecules, such as endogenous mucous and polysaccharides of dietary origin, including soluble pectin, that would induce some viscosity, the ability of kiwifruit IUDP to enhance viscosity greatly in the presence of a low concentration of soluble polysaccharide, as demonstrated in the present work, therefore has important implications for health conditions that are affected by luminal mixing, such as postprandial hyperglycaemia and its long-term complications.

The results showed that the types of polydisperse cell wall and tissue fragments generated by digesting kiwifruit have the potential to greatly augment the viscogenic properties of polymers in the luminal fluid, and thereby to strongly modulate the rate of nutrient uptake by delaying mixing. Considering that the present results have shown that a single kiwifruit of about 100 ml volume gives digestion-resistant remnants with a settled bed volume of

about 300 ml, kiwifruit may potentially have a substantial ability to influence gut rheology.

Rheological factors, their interactions, and patterns of mixing forces applied by the small intestine are complex (Dikeman & Fahey, 2006; Lentle, Hemar, Hall, & Stafford, 2005). Even for the luminal contents, without the complexity of gut motility patterns, the rheology theory cannot deal adequately with polydispersity in size, irregular shapes and flexible particles, all of which are typical of the mixture of tissue, cell and cell wall remnants in digested kiwifruit. As detailed rheological analysis was beyond the scope of the present study we used a simple tubular system to generate the same types of forces and flows that lead to mixing in the duodenum, namely constriction, propulsion, laminar flow and turbulence, and to measure the net outcome, mixing, by moving a ball through a flexible tube containing the dietary fibre suspension. While the authors recognise that the admixture of influences acting is not characterised and will not have been exactly the same as in the living gut, the apparatus allowed a practical measurement of the comparative potential of kiwifruit fibre to modulate mixing. A simple tube has been used successfully by others to study the effect of viscosity on flow behaviour (Takahashi & Sakata, 2005).

We have shown here that digested remnants of kiwifruit in the disperse form of a settled bed, that is, at single solid volume fraction, and at a single shear rate, are capable of influencing mixing, especially in the presence of some background viscosity. Much more detailed research is now required to determine the interaction of parameters that coincide with *in vivo* gut conditions, and will involve varying the solid volume ratio, shear rate, viscosity of the fluid phase, presence of other food particles, and analysis of the dynamic changes that occur as the background of digestible particles, and polymers such as starch, are digested.

4.3. Retardation of diffusion

Diffusion is a much slower process for moving nutrients and enzymes within the gut lumen than is the mass transfer achieved by mixing (Edwards, Johnson, & Read, 1988; France, Thornley, Siddons, & Dhanoa, 1993). Nevertheless, within food fragments, and after digesta have been positioned adjacent to the gut wall by mixing, diffusion will become an important factor determining the net rate of ultimate transfer to the intestinal brush border interface for final depolymerisation and/or nutrient uptake. Both the rate of diffusion of digestive enzymes into food particles and rate of diffusion of the products of digestion from particles to the lumen and brush border and transfer to the portal system, will affect the rate of nutrient loading. Therefore, diffusion in concert with luminal mixing is likely to have an important modulating effect on physiological responses that depend on absorption rate, such as the glycaemic response.

The measurements of retarded glucose diffusion in the present work used IUDP particles swelled and at settled bed density, which contained a much higher water content than in the solid volume of the centrifuged residue used for measurement of water retention. The solid volume fraction estimated in the present work was 0.1. Diffusion within the settled bed will have been able to follow two paths – through the cell wall matrix of the particles, and through fluid in the interstices between particles. In both cases, the presence of particles and the presence of polysaccharides in the cell wall matrix will impair diffusion of small solute molecules by increasing the distance required to find a diffusion path through the material (Spalding, 1969). The reason 'Hayward' kiwifruit retarded diffusion more than 'Hort16A' was probably due to a greater density of cell walls in the settled bed of the 'Hayward' digestion remnants used in the diffusion experiments. This suggestion is supported by the data showing that 'Hort16A' swelled more than

'Hayward' (Table 1), while the amount of dietary fibre per gram of kiwifruit was greater in 'Hayward' than in 'Hort16A' (Fig. 1).

Given that much of the middle lamella of fruit cell walls consists of pectin, unencumbered by association with hemicellulose and cellulose microfibrils, much of the pectin that was soluble under physiological conditions in the present experiment may have originated from the middle lamella, while the cell wall matrix may have remained substantially intact, physically and functionally, with a capacity to retard solute movement through it. More research is required to link microscopic and molecular structure of digestion resistant remnants of kiwifruit to their ability to retard diffusion. Furthermore, while the present research has shown that a static bed of digestion-resistant remnants effectively retards glucose diffusion, their effectiveness and the contribution of diffusion retardation in concert with the retardation of mixing to the net retardation of nutrient uptake within a system of moving fluids, such as the gut, needs further research.

5. Conclusion

The dietary fibre component of kiwifruit is stable under foregut conditions, and passage through the stomach and small intestine does not greatly alter the solubility of the digestion-resistant polymers, or the proportions of polysaccharide fractions that constitute dietary fibre in kiwifruit. The stability of both 'Hayward' and 'Hort16A' kiwifruit dietary fibres under gastrointestinal conditions ensured retention of functional properties: high water retention and swelling capacities, and capacity to influence processes dependent on gut rheology.

Even in the absence of the soluble pectin fraction, digestion-resistant residues from kiwifruit had a substantial capacity to retard mixing and glucose diffusion. The ability of kiwifruit dietary fibre to reduce luminal mixing, and therefore mass transfer of digesta to gut wall, combined with its ability to reduce diffusion, suggests that it may have an important role to play in protecting against disorders related to absorption rate, such as the long-term consequences of elevated postprandial and/or chronic glucose, lipid, and cholesterol concentrations in the blood.

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