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Composition and Digestion in the Pig Gastrointestinal Tract of Jerusalem Artichoke Tubers

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ABSTRACT

The digestion in the pig gastrointestinal tract of fructans from Jerusalem artichoke (Helianthus tuberosus *L.*) *tubers was investigated. The tuber sample, and duodenal and ileal digesta and faeces from pigs fed the tubers, were analysed for chemical composition, and the gel filtration profiles of fructans from tubers and duodenal and ileal digesta examined.*

The tuber sample contained, on a dry matter basis, 60 g kg^{-1} ash, 122 g kg^{-1} crude protein, 7 g kg^{-1} crude fat, 654 g kg^{-1} soluble sugars (glucose, fructose, sucrose and fructans), 6 g kg^{-1} starch, 6 g kg^{-1} permanganate lignin and 147 g kg^{-1} non-fructans, non-starch polysaccharides. Sucrose (319 g kg^{-1}) and fructans (288 g kg^{-1}) were the main components.

About 50% of the fructans were degraded anterior to the duodenum, but little further degradation occurred during passage through the small intestine. The gel filtration profiles established that the molecular weight of the fructans did not significantly change between the diet and terminal ileum.

INTRODUCTION

Fructose polymers (fructans) are storage polysaccharides in a number of plants and are present in many foods (MacLeod & Preece, 1954; Smith, 1973). These polysaccharides are composed of homologous series

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of fructofuranosyl units linked β-2,1 (inulin type) or β-2,6 (levan type) with a glucopyranosyl unit linked 1,2 at the non-reducing end, i.e. the terminal disaccharide residue is sucrose. The degree of polymerisation can vary from 3 (inulobiose) to over 100 (in levans from *Dactylis glomerata*; Pollock *et al.*, 1979). As mammals do not produce β-fructosidases, fructans can be included in the dietary fibre fraction (Trowell *et al.*, 1976). However, the polymer is easily hydrolysed by acid (Dahlqvist & Nilsson, 1984) and could thus be degraded in the stomach, although experimental evidence for this has not been presented. In the present study the chemical composition of Jerusalem artichoke tubers, an inulin-rich product (Kosaric *et al.*, 1984), was studied and included in the diet of pigs fitted with intestinal cannulas to determine the fate of fructans in the gastrointestinal tract.

MATERIALS AND METHODS

Jerusalem artichokes

Jerusalem artichoke tubers were obtained from a commercial source and minced through a 5 mm screen prior to feeding. Samples for analysis were minced, frozen immediately and freeze-dried.

Digestibility experiments

Digestibility experiments were carried out with two 7-month-old cross-bred female pigs weighing 70–90 kg. Both pigs were fitted with steel, replaceable T-cannulas (Björnhag & Jonsson, 1984) about 150 mm before the ileo-caecal junction, and in the duodenum, just distal to the pancreatic and bile ducts. The pigs were fed a cereal-based basal diet alone (1·1 kg dry weight daily) or with Jerusalem artichoke tubers included (0·9 kg basal diet and 0·123 kg tubers dry weight daily). All diets contained 5 g kg^{-1} Cr_2O_3 as marker. For details of composition and digestion of basal diet, and of digesta collection methods, see Graham *et al.* (1986).

Chemical analysis

Samples were freeze-dried and ground to pass a 1 mm screen prior to analysis. Dry matter, ash and crude protein (Kjeldahl N × 6·25) were estimated by standard methods (AOAC, 1980), while crude fat was

extracted with diethyl ether after acid hydrolysis (Anon, 1971). Content of Cr_2O_3 was determined by atomic absorption spectrophotometry (Williams *et al.*, 1962), and permanganate lignin by the method of Robertson & Van Soest (1981). Soluble sugars—glucose, fructose, sucrose and fructans—were extracted with acetate buffer (0·05M, pH 5, 65°C) and determined enzymatically (Larsson & Bengtsson, 1983). 80% aqueous ethanol-extracted samples were analysed for starch by an enzymatic method (Åman & Hesselman, 1984), neutral non-starch polysaccharide (NSP) residues, excluding fructose, as alditol acetates by GC (Theander & Åman, 1979) and uronic acid residues by decarboxylation (Theander & Åman, 1979).

All results were calculated on a dry matter basis. The content of polysaccharide residues was calculated as anhydrosugars, and all digestibilities were calculated relative to the Cr_2O_3 content. Digestibility of Jerusalem artichoke tuber components was calculated by difference, i.e. by subtracting the contribution of the basal diet.

Gel filtration

Samples were extracted with 95% aqueous ethanol (100°C, 1 h) to remove enzyme activity and low molecular-weight sugars, the residues recovered by centrifugation (2000 *g*, 10 min) and further extracted with water (60°C, 1 h). The aqueous extract of fructans obtained on centrifugation was applied directly to a 2·5 × 90 cm column of Sephadex G-25, thermostated at 35°C. Elution (14 ml h^{-1}) was carried out with water, and 2·5 ml fractions were collected. The total hexose content in fractions was determined by the anthrone method (Scott & Melvin, 1953), while fructose residues were assayed by the carbazole method (Dische & Borenfreund, 1951). The column was calibrated with inulin (Jerusalem artichoke; BDH, Poole) and sucrose. Partial acid hydrolysis of the extracted fructans was carried out in 0·05M HCl at 39°C for 4 h. Samples were neutralised (0·5M NaOH) before application on the column.

RESULTS

Composition and digestion

The dry matter content of the tubers was 250 g kg^{-1}, with sucrose (319 g kg^{-1}) and fructans (288 g kg^{-1}) as the major components of the

TABLE 1
Chemical Composition of Jerusalem Artichoke Tubers

Component	Content ($g\,kg^{-1}$ DM)	Component	Content ($g\,kg^{-1}$ DM)
Glucose	18·0	NSP[a] residues	
Fructose	28·9	rhamnose	4·4
Sucrose	319·4	arabinose	21·4
Fructans	287·7	xylose	2·7
Starch	6·0	mannose	5·5
Ash	60·1	galactose	11·9
Crude protein (N × 6·25)	122·3	glucose	55·1
Crude fat	7·4	uronic acids	46·2
Permanganate lignin	6·1	total	147·2

[a] Non-starch polysaccharides insoluble in 80% aqueous ethanol, not including fructose residues.

dry matter (Table 1). Crude protein ($122\,g\,kg^{-1}$), ash ($60\,g\,kg^{-1}$) and NSP ($147\,g\,kg^{-1}$) were the other main constituents. Glucose, uronic acids, arabinose and galactose were the predominant NSP residues.

When included in the pig diet ($120\,g\,kg^{-1}$), the tubers contributed over 90% of dietary fructans, 75% of soluble sugars and 12% of NSP, but less than 10% of other constituents. About 40% of tuber dry matter was apparently digested prior to the terminal ileum, while a further

TABLE 2
Apparent Digestibility, Determined by Difference, at the Duodenum and Terminal Ileum of Fructose, Sucrose and Fructans from Jerusalem Artichoke Tubers[a,b]

Component	Apparent digestibility (%)	
	Duodenum	Terminal ileum
Fructose	−51 ± 4	92 ± 1
Sucrose	48 ± 13	60 ± 9
Fructans	48 ± 2	51 ± 2
Total	28 ± 5	58 ± 5

[a] Jerusalem artichoke tubers included ($120\,g\,kg^{-1}$) in basal diet.
[b] Mean of two pigs (±SD).

50% was digested in the large intestine. Approximately 56% of NSP was degraded in the gastrointestinal tract, with arabinose (100% degraded) and uronic acids (97% degraded) residues particularly susceptible to breakdown and glucose (19% degraded) relatively resistant. Soluble sugars were completely degraded and thus were not detected in faeces. The content, and apparent digestibility, of individual soluble sugars varied considerably with sampling site (Table 2). An increase in fructose content from the feed to the duodenum resulted in a negative apparent digestibility, but this sugar was relatively well absorbed before the terminal ileum. Sucrose was digested in both the stomach and small intestine, while about 50% of the fructans were recovered in both duodenal and ileal digesta.

Gel filtration

Pre-extraction of samples with hot 95% aqueous ethanol removed low molecular-weight sugars with an elution volume greater than 140 ml but

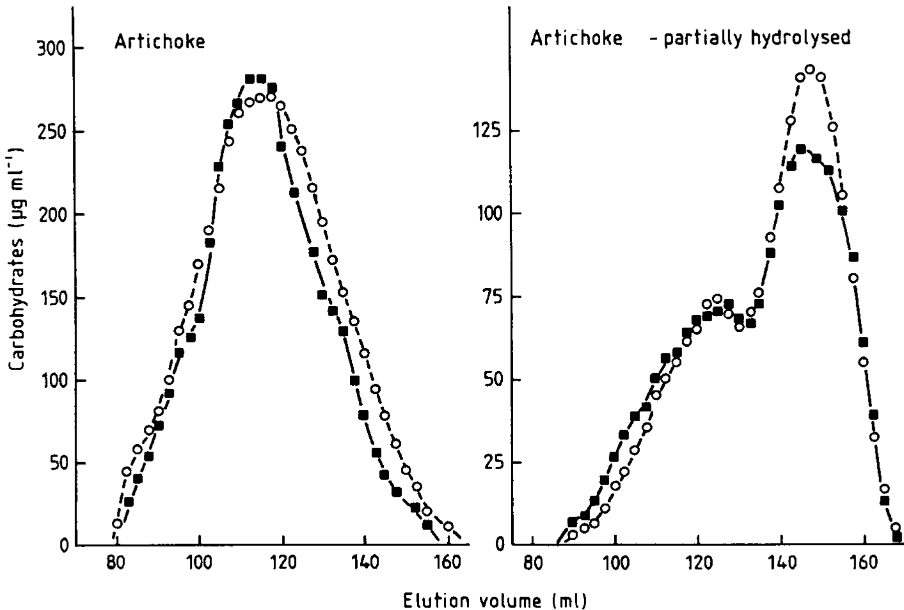

Fig. 1. Gel filtration profiles of a fructan preparation and partially hydrolysed (0·05M HCl, 39°C, 4 h) fructan preparation from Jerusalem artichoke tubers (○---○, total hexose residues, ■—■, fructose residues).

did not influence either the yield or elution profile of longer-chain fructans relative to absolute ethanol pre-extraction.

Gel filtration of hot-water extracts from the Jerusalem artichoke tuber sample (Fig. 1) demonstrated that the fructans gave a broad elution profile with a peak at 115 ml. The inulin standard had an elution peak at 87·5 ml (Fig. 2) and a glucose content, determined as alditol acetates

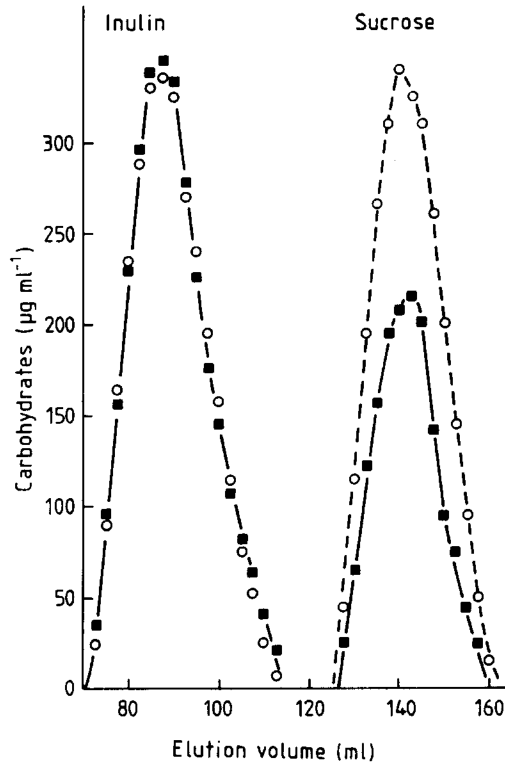

Fig. 2. Gel filtration profile of inulin standard and sucrose (○---○, total hexose residues; ■—■, fructose residues).

by GC after acid hydrolysis, of 33 mg g^{-1}. As the contents and elution profiles of fructans from digesta were similar for both pigs, data in Fig. 3 are averages of values from these two pigs. Fructans were a minor fraction of the carbohydrates present in the duodenal extracts and had a wide elution profile, with peaks at about 110 and 135 ml (Fig. 3). However, fructose-containing polymers were predominant in the ileal extracts (Fig. 3) and had an elution peak at about 110 ml, with indications

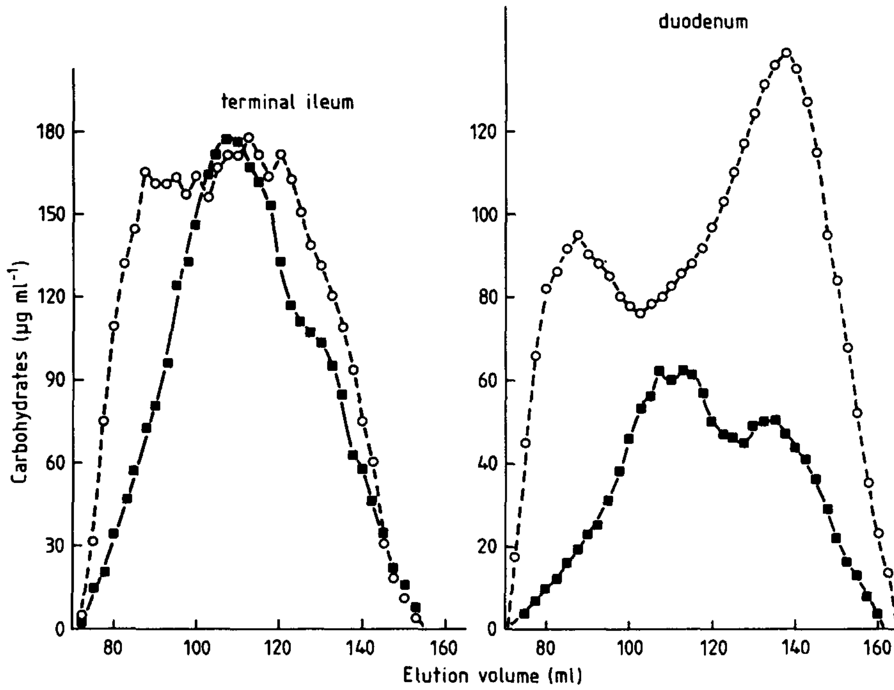

Fig. 3. Gel filtration profiles of fructan preparations from terminal ileal and duodenal digesta of pigs fed diets including Jerusalem artichoke tubers (○---○, total hexose residues; ■—■, fructose residues).

of a shoulder at 135 ml. Partially acid-hydrolysed fructans from the tubers gave elution profiles with two peaks at 125 and 145 ml (Fig. 1).

DISCUSSION

The dry matter, ash, crude protein, crude fat and permanganate lignin contents of the tuber sample were similar to those in the literature (Chubey & Dorrell, 1974; Kosaric *et al.*, 1984). Little relevant quantitative data are available on the non-fructan polysaccharides. The tubers examined had a low starch content. The non-starch polysaccharides detected in the present study (*ca.* 150 g kg^{-1}) were made up mostly of pectic residues (uronic acids, arabinose and galactose) and glucose residues, probably mostly cellulose (Kosaric *et al.*, 1984). This will include terminal glucose residues from the longer chain fructans which

are insoluble in 80% aqueous ethanol. Sugar analysis of the inulin standard as alditol acetates by GC gave an apparent mannose content of 12 mg g^{-1}, suggesting that some fructose survived the acid hydrolysis procedure employed. Such fructose would, on reduction, yield either mannitol or glucitol, and thus contribute to the NSP mannose and glucose residue contents of the artichokes. Likewise, the determined glucose residue content of the inulin standard (33 mg g^{-1}) may be higher than the actual content.

The tubers in the present study had higher sucrose and fructose contents and lower fructan contents than those normally found (Chubey & Dorrell, 1974; Kosaric *et al.*, 1984). However, as the sample was obtained in April, about 5 months post harvest, this was probably the result of the action of endogenous hydrolases and isomerases which are active in harvested tubers, producing inulins of shorter chain-length, sucrose and fructose (Edelman & Jefford, 1968; Kosaric *et al.*, 1984).

The gel filtration profiles show that the artichoke tuber fructans (Fig. 1) have, as previously reported (Pollock *et al.*, 1979), a wide range of molecular sizes, with a mean molecular weight less than that of the inulin standard. The standard sample had a mean degree of polymerisation, calculated from glucose residue content as determined by GC, of 30, but, as discussed previously, this may be an underestimate and the figure of 33–34 reported earlier (Pollock *et al.*, 1979) may be more correct.

Although Jerusalem artichoke tubers are reported to have a high feeding value for domestic animals (Kosaric *et al.*, 1984), no comparable digestibility studies in pigs are known. The apparent ileal digestibility of the tubers investigated—40%—was mainly due to the partial degradation and absorption of fructans and sucrose. Bacterial activity and/or absorption in the caecum-colon resulted in complete disappearance of fructans, sucrose, glucose and fructose, and extensive degradation of pectic residues. Non-starch glucose residues were partially degraded, but this would, to some extent, be due to the disappearance of terminal glucose groups of the fructans.

Hydrolysis of fructans in the stomach led to a doubling in fructose content, but the content of sucrose, the other product of acid or enzyme hydrolysis (Edelman & Jefford, 1968; Kosaric *et al.*, 1984), decreased between the diet and duodenum. An apparent digestibility of 28% for the fructans group of compounds (fructans, sucrose plus fructose) indicated the absorption or further degradation of this fraction before

the duodenum. The shorter chain fructans (elution at 135 ml, Fig. 3) present in duodenal digesta were almost completely degraded before the terminal ileum. This, and the fact that the molecular weight of the major fructans fraction did not appreciably decrease between the diet and ileal digesta, indicated that the shorter-chain polymers were more susceptible to degradation.

Although only one diet and two pigs were employed in this investigation, the results obtained clearly demonstrate that fructans are degraded in the stomach. Three processes could lead to this degradation—acid hydrolysis at stomach pH, tuber endogenous enzyme activity and degradation by bacteria found in this part of the gastrointestinal tract (Kidder & Manners, 1978). Incubation of extracted fructans in simulated stomach conditions (0·05M HCl, 4 h, 39°C, Kidder & Manners, 1978) established that partial acid hydrolysis could occur, reducing fructan chain-length and producing low molecular-weight sugars (Fig. 1). Endogenous enzyme activity and bacterial degradation are also likely, particularly in the upper regions of the stomach where pH is relatively high (Kidder & Manners, 1978).

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REFERENCES

Åman, P. & Hesselman, K. (1984). Analysis of starch and other main constituents of cereal grains. *Swedish J. Agric. Res.*, **14**, 135–9.

Anon. (1971). Determination of crude oils and fats. *Off. J. Eur. Comm.*, **L297**, 995–7.

Association of Official Analytical Chemists (AOAC) (1980). *Official methods of analysis*, AOAC, Washington, DC.

Björnhag, G. & Jonsson, E. (1984). Replaceable gastro-intestinal cannulas for small ruminants and pigs. *Livest. Prod. Sci.*, **11**, 179–84.

Chubey, B. B. & Dorrell, D. G. (1974). Jerusalem artichoke, a potential fructose crop for the prairies. *Can. Inst. Food Sci. Technol. J.*, **7**, 98–100.

Dahlqvist, A. & Nilsson, U. (1984). Cereal fructosans: Part 1—Isolation and characterization of fructosans from wheat flour. *Food Chem.*, **14**, 103–12.
Dische, Z. & Borenfreund, E. (1951). A new spectrophotometric method for the detection and determination of keto sugars and trioses. *J. Biol. Chem.*, **192**, 583–7.
Edelman, J. & Jefford, T. G. (1968). The mechanism of fructosan metabolism in higher plants as exemplified in *Helianthus tuberosus* L. *New Phytologist*, **67**, 517–32.
Graham, H., Hesselman, K. & Åman, P. (1986). The influence of wheat bran and sugar-beet pulp on the digestibility of dietary components in a cereal-based pig diet. *J. Nutr.*, **116**, 242–51.
Kidder, D. E. & Manners, M. J. (1978). *Digestion in the pig*, Kingston Press, Bath.
Kosaric, N., Cosentino, G. P., Wieczorek, A. & Duvnjak, Z. (1984). The Jerusalem artichoke as an agricultural crop. *Biomass*, **5**, 1–36.
Larsson, K. & Bengtsson, S. (1983). *Determination of low molecular-weight carbohydrates in plant material.* Methods report 22, National Laboratory of Agricultural Chemistry, Uppsala, Sweden.
MacLeod, A. M. & Preece, A. A. (1954). Studies on the free sugars of the barley grain. V. Comparison of sugars and fructosans with those of other cereals. *J. Inst. Brew.*, **60**, 46–55.
Pollock, C. J., Hall, M. A. & Roberts, D. P. (1979). Structural analysis of fructose polymers by gas–liquid chromatography and gel filtration. *J. Chromatogr.*, **171**, 411–15.
Robertson, J. & Van Soest, P. J. (1981). The detergent system of analysis and its application to human foods. In: *The analysis of dietary fiber in foods.* (James, W. P. T. & Theander, O. (Eds)), Marcel Dekker, New York, 123–58.
Scott, T. A. & Melvin, E. H. (1953). Determination of dextran with anthrone. *Anal. Chem.*, **25**, 1656–61.
Smith, D. (1973). The nonstructural carbohydrates. In: *Chemistry and biochemistry of herbage*, Vol I. (Butler, G. W. & Bailey, R. W. (Eds)), Academic Press, New York, 105–55.
Theander, O. & Åman, P. (1979). Studies on dietary fibre. 1. Analysis and chemical characterization of water-soluble and water-insoluble dietary fibres. *Swedish J. Agric. Res.*, **9**, 97–106.
Trowell, H., Southgate, D. A. T., Wolever, T. M. S., Leeds, A. R., Gasull, M. A. & Jenkins, D. A. (1976). Dietary fibre redefined. *Lancet*, **i**, 967.
Williams, C. H., David, D. J. & Iismaa, O. (1962). The determination of chromic oxide in feces samples by atomic absorption spectrophotometry. *J. Agric. Sci., Camb.*, **59**, 381–5.