Effect of carbohydrase supplementation of wheat- and canola-meal-based diets on growth performance and nutrient digestibility in group-housed weaned pigs

R. T. Zijlstra[1,3], S. Li[1,4], A. Owusu-Asiedu[1], P. H. Simmins[2], and J. F. Patience[1]

[1]*Prairie Swine Centre Inc., Saskatoon, Saskatchewan, Canada S7H 5N9; and*
[2]*Danisco Animal Nutrition, Marlborough, UK SN8 1AA.* *Received 16 December 2003, accepted 6 July 2004.*

Zijlstra, R. T., Li, S., Owusu-Asiedu, A., Simmins, P. H. and Patience, J. F. 2004. **Effect of carbohydrase supplementation of wheat- and canola-meal-based diets on growth performance and nutrient digestibility in group-housed weaned pigs.** Can. J. Anim. Sci. **84**: 689–695. Fibrous components in canola meal and wheat limit their effective use in diets for weaned pigs. Effects of supplementing a carbohydrase (845 and 327 Units g^{-1} xylanase and β-glucanase) to a wheat-canola meal diet on growth performance, small intestine nutrient digestibility and digesta viscosity were investigated. Ninety-six weaned pigs (7.2 ± 1.2 kg) had free access to control diet [65% wheat, 25% canola meal; 3.15 Mcal digestible energy (DE) kg^{-1}, 10.6 g digestible lysine kg^{-1}] or control diet supplemented with carbohydrase at three inclusion rates (1, 2, or 4 g kg^{-1}) for 28 d. Four pigs were housed per pen for six pens per diet. On days 19 to 21, six pigs per diet were euthanised to collect small intestine digesta. Carbohydrase increased average daily feed intake (ADFI) and average daily gain (ADG) quadratically ($P < 0.01$) for days 1 to 28, resulting in 16% higher ADFI and 13% higher ADG for 2 g kg^{-1} carbohydrase compared to control. Carbohydrase did not affect feed efficiency ($P > 0.10$). The ADG was positively correlated to ADFI ($r = 0.94$; $P < 0.01$), but not to feed efficiency ($P > 0.10$). Carbohydrase did not affect digestibility of dry matter (DM) and energy ($P > 0.10$). Carbohydrase at 4 g kg^{-1} only reduced digesta viscosity 30% in the distal small intestine compared to control ($P < 0.05$). Carbohydrase supplementation increased ADFI and thereby ADG, but not feed efficiency and nutrient digestibility, suggesting that reduction of dietary fibrous components using carbohydrase may stimulate voluntary feed intake of pigs fed diets limiting in DE.

Key words: Carbohydrase, canola meal, wheat, pig, feed intake, digestibility

Zijlstra, R. T., Li, S., Owusu-Asiedu, A., Simmins, P. H. et Patience, J. F. 2004. **Incidence d'un supplément de carbohydrase dans les rations à base de blé et de tourteau de canola sur la digestibilité des éléments nutritifs et sur la croissance des porcelets sevrés logés collectivement**. Can. J. Anim. Sci. **84**: 689–695. Les composants cellulosiques présents dans le tourteau de canola et le blé restreignent l'efficacité de ces derniers quand on s'en sert pour nourrir des porcelets sevrés. Les auteurs ont étudié l'incidence d'une ration de blé et de tourteau de canola enrichie de carbohydrase (845 ou 327 unités de xylanase et de β-glucanase par gramme) sur la croissance des animaux, la digestibilité des éléments nutritifs dans l'intestin grêle et la viscosité des digest. Pour cela, ils ont permis à 96 porcelets sevrés (7,2 ± 1,2 kg) de se nourrir à satiété de la ration témoin [65 % de blé, 25 % de tourteau de canola; 3,15 Mcal d'énergie digestible par kg, 10,6 g de lysine digestible par kg] pendant 28 jours. Chaque enclos contenait quatre porcs et on comptait six enclos par ration. Du 19^{e} au 21^{e} jour, on a euthanasié six sujets par ration afin de recueillir les digest de l'intestin grêle. La carbohydrase augmente la quantité quotidienne moyenne d'aliment ingérée (QMAI) et le gain quotidien moyen (GQM) de manière géométrique ($P < 0,01$) du 1er au 28^{e} jour, de sorte que l'addition de 2 g de carbohydrase par kg accroît la première de 16 % et le second de 13 %, comparativement aux témoins. La carbohydrase n'a aucune incidence sur l'indice de consommation ($P > 0,10$). Il existe une corrélation positive entre le GQM et la QMAI ($r = 0,94$; $P < 0,01$), mais pas avec l'indice de consommation ($P > 0,10$). La carbohydrase ne modifie pas la digestibilité de la matière sèche ni de l'énergie ($P > 0,10$). À 4 g par kg, elle ne fait que réduire la viscosité du bol alimentaire de 30 % dans la partie distale de l'intestin grêle, comparativement aux témoins ($P < 0,05$). Le supplément de carbohydrase augmente la QMAI, donc le GQM, mais pas l'indice de consommation ni la digestibilité des éléments nutritifs, signe que la réduction des composants cellulosiques dans la ration au moyen de cet enzyme pourrait stimuler l'ingestion volontaire d'aliments chez les porcs nourris avec une ration pauvre en énergie digestible.

Mots clés: Carbohydrase, tourteau de canola, blé, porc, ingestion d'aliments, digestibilité

Canola meal is superior in nutritional value compared to its predecessor, rapeseed meal (Bell 1993); however, the nutritional value of canola meal for pigs remains lower than soybean meal. Specifically, contents of DE, crude protein, and apparent digestible lysine are 18, 23, and 40% lower in canola meal than in soybean meal, respectively [National Research Council (NRC) 1998; Patience et al. 1995]; however, gross energy (GE) content of canola meal is similar to soybean meal (Barbour and Sim 1991). In canola meal, the content of fibre and fibrous components are up to three

[3]*To whom correspondence should be addressed (current address): Department of AFNS, University of Alberta, Edmonton, Alberta, Canada T6G 2P5 (e-mail: ruurd.zijlstra@ualberta.ca*
[4]*Present address: PT. Charoen Pokphand, Jawa Timur, Indonesia*

Abbreviations: **ADF,** acid detergent fibre; **ADG,** average daily gain; **ADFI,** average daily feed intake; **DE,** digestible energy; **DM,** dry matter; **GE,** gross energy; **NDF,** neutral detergent fibre; **NSP,** non-starch polysaccharide; **SEM,** standard error of the mean times higher than in soybean meal (Bell 1993), and cellulose and arabinoxylans are major non-starch polysaccharides (NSP) components (Slominski and Campbell 1990). The high content of fibrous components limits the digestibility of energy and other nutrients in canola meal (Bell 1993), similar to the reduced energy digestibility with increased fibre content observed for barley and wheat (Fairbairn et al. 1999; Zijlstra et al. 1999).

Carbohydrase supplementation has been recognized as a method to overcome the limitations of pigs to effectively utilize NSP such as arabinoxylans and β-glucans (Campbell and Bedford 1992). In pigs, apparent total-tract digestibility of NSP and nutrients entrapped by NSP is higher than ileal digestibility, due to microbial degradation in the hindgut (Li et al. 1996). However, energy and protein fractions digested in the large intestine have less nutritional value for pigs compared to nutrients digested and absorbed in the small intestine (Noblet et al. 1994). Therefore, carbohydrase supplementation may enhance ileal digestibility of NSP and entrapped nutrients, thereby improving efficiency of nutrient utilisation resulting in improved feed efficiency or ADG.

The objective of the present study was to evaluate the dose-response effects of carbohydrase supplementation of a wheat-canola meal diet on growth performance and apparent digestibility of nutrients in sequential segments of the small intestine of weaned pigs. Pigs had free access to diets limiting in DE, but with excess amino acids, so that improved energy digestibility or intake should be expressed by an increased ADG and that sole improved energy digestibility should be expressed by an increased feed efficiency.

MATERIALS AND METHODS

Animal and Diets

The animal protocol was approved by the University of Saskatchewan, University Committee on Animal Care and Supply, and followed principles established by the Canadian Council on Animal Care (1993). Ninety-six crossbreed pigs (Camborough 15 × Canabrid, Pig Improvement Canada, Acme, AB; 48 barrows and 48 gilts) were weaned at 3 wk of age and subsequently housed in an all-in-all-out nursery room containing 24 pens with fully-slotted floors. The room was equipped with automatic control of ventilation and temperature to maintain a thermo-neutral environment. Lights were on from 0700 to 1900. Pigs were assigned randomly within gender to pens containing either four barrows or gilts. Pigs were acclimatized to the room and weaning for 7 days while being fed a regular phase-1 diet. Pigs had free access to diet from a multi-space feeder and to water from a nipple-type drinker.

After acclimation, pigs with an initial body weight of 7.2 ± 1.2 kg (mean ± standard deviation) were used in a 28-d experiment. A control diet was formulated using 25% canola meal and 65% wheat (Table 1) to contain 3.15 Mcal DE kg^{-1}, 3.4 g digestible lysine Mcal^{-1} DE, and an ideal amino acid ratio (NRC 1998). The diet was formulated to be limiting in DE, but to contain excess amino acids (NRC 1998). Vitamins and minerals were supplemented to meet or exceed nutrient requirements (NRC 1998). Chromic oxide (0.3%) was included as an indigestible marker. A carbohydrase containing activities of xylanase and β-glucanase (845 and 327 Units g^{-1}, respectively; *Trichoderma longibrachiatum*; Danisco Animal Nutrition, Marlborough, UK) was added to the control diet at one of three doses to create four experimental diets [0 (control), 1, 2 and 4 g carbohydrase kg^{-1} diet]. Diet was provided in mash form. Six pens (three per gender) were assigned randomly to each of four dietary treatments, for a total of six pens per treatment.

Pigs were weighed individually at days 0, 7, 14, 21, and 28 of the experiment. Feed disappearance per pen was recorded every 7 days and used to measure feed intake. Feed efficiency (gain/feed) was calculated from measurements of ADG and ADFI. On each of days 19, 20 and 21 of the experiment, two pigs per treatment that were housed in separate pens were euthanised to collect small intestine digesta using the serial slaughter technique. In total, one pig per pen was euthanised thereby reaching six pigs per treatment. To balance the study statistically, the medium-weight pig was selected for euthanasia out of each pen, so that three pigs completed the 28-d experiment in each pen. To analyze per-

Table 1. Ingredient and nutrient composition of experimental diets[z]

Ingredient	%
Wheat	65.10
Canola meal	25.00
Casein	3.50
Limestone	1.34
Mono-dicalcium phosphate	1.20
Canola oil	1.00
Aureo SP 250[y]	0.70
PSC mineral premix[x]	0.50
PSC vitamin premix[w]	0.50
Salt	0.40
Chromic oxide	0.30
L-lysine-HCl	0.30
L-threonine	0.10
Choline chloride	0.05
L-tryptophan	0.01
Nutrients and fibre characteristics (calculated, as fed)	
DE (Mcal kg^{-1})	3.15
Digestible lysine (%)	1.06
Total lysine (%)	1.28
Crude protein (%)	21.70
Total phosphorus (%)	0.75
Calcium (%)	0.94
Crude fibre (%)	4.60
Acid detergent fibre (%)	6.60
Neutral detergent fibre (%)	15.70

[z]A carbohydrase (Danisco Animal Nutrition, Marlborough, UK) was added at three levels (1, 2, and 4 g kg^{-1}) to the control diet to create four experimental diets [0 g kg^{-1}, 0 and 0 Units kg^{-1} diet (control); 1 g kg^{-1}, 845 and 327 Units kg^{-1} diet; 2 g kg^{-1}, 1690 and 654 Units kg^{-1} diet; 4 g kg^{-1}, 3380 and 1308 Units kg^{-1} diet; respectively, for xylanase and β-glucanase; *Trichoderma longibrachiatum*].

[y]Provided per kilogram of diet: chlortetracycline hydrochloride, 308 mg; sulfamethazine 308 mg; penicillin (from procaine penicillin), 154 mg.

[x]Provided per kilogram of diet: Zn, 100 mg; Fe, 80 mg; Cu, 50 mg; Mn, 25 mg; I, 0.5 mg; Se, 100 μg.

[w]Provided per kilogram of diet: vitamin A, 8250 IU; vitamin D_3 825 IU; vitamin E, 40 IU; niacin, 35 mg; D-pantothenic acid, 15 mg; riboflavin, 5 mg; menadione, 4 mg; folic acid, 2 mg; thiamine, 1 mg; D-biotin, 200 μg; vitamin B_{12}, 25 μg.

formance data during days 14 to 21, all pigs were weighed and feed intake measured on the day of euthanasia for the specific pen, and pig-days per pen were used to calculate ADG and ADFI.

Sample Collection

Representative diet samples were collected and stored at 4°C. Digesta samples were collected from four small intestine segments according to the procedure described by Bedford et al. (1992). Pigs were euthanised by an intravenous injection of overdose sodium pentobarbital and the abdominal cavity was opened immediately. The small intestine was removed and clamped at the pyloric sphincter and ileo-caecal valve, dissected free from mesentery, and arranged to form four sequential segments of equal length (1, duodenum to 4, ileum) to study progress of nutrient digestion. Digesta in each of the four segments was collected by gravity into a container and mixed well. Immediately after collection, digesta pH was measured and digesta viscosity was measured using a digital viscosity-meter (Brookfield Engineering Laboratories Inc., Stoughton, MA). Digesta samples were frozen at –20°C and freeze-dried prior to analyses.

Chemical Analyses

Diets and freeze-dried digesta were ground though a 1-mm screen in a Retsch mill (Brinkman Instruments, Rexdale, ON). Diet and digesta were analyzed for DM [method 930.15; Association of Official Analytical Chemists (AOAC) 1990], acid detergent fibre (ADF; method 973.18; AOAC 1990), neutral detergent fibre (NDF; Van Soest et al. 1991), chromic oxide (Fenton and Fenton 1979), and GE using an adiabatic bomb calorimeter (model 1281, Parr Instrument Co., Moline, IL). Apparent digestibilities of DM, energy, ADF, and NDF were calculated using the chromic oxide concentration in diets and digesta, using the indicator method.

Statistical Analyses

Growth performance variables (feed intake, gain, feed efficiency, and body weight) were analyzed by repeated measures using the MIXED procedure of SAS (SAS Institute Inc. 1996) based on recent recommendations (Wang and Goonewardene 2004); body weight at day 0 was used as covariate. Linear and quadratic effects of carbohydrase supplementation were tested using orthogonal polynomials (Steel and Torrie 1980). Two pens were excluded from the analyses (one pen each for 1 and 2 g carbohydrase kg^{-1} diet), because feed intake and efficiency data were outside the range of mean ± 2 × SEM, probably due to excessive waste of feed out of the feeders.

Nutrient digestibility and digesta variables were analyzed by analysis of variance using the general linear model procedure of SAS (SAS Institute, Inc. 1996). Means were separated using the probability of difference.

For analyses of performance and digestibility variables, pen was considered the experimental unit, means were reported as least-square means, and $P < 0.05$ was considered significant to test the hypotheses. Trends ($0.05 < P < 0.10$) were reported and $P > 0.10$ was considered non-significant. The final statistical model included dietary treatment (carbohydrase supplementation) and gender.

Pearson correlation coefficients between performance for days 1 to 28 and digesta characteristics were analyzed using the correlation procedure of SAS (SAS Institute, Inc. 1996).

RESULTS

Feed Intake and Growth Performance

For the entire experiment (days 1 to 28), carbohydrase supplementation increased ADFI of pigs quadratically ($P < 0.001$; Table 2). Specifically, pigs fed diet supplemented with 2 g kg^{-1} carbohydrase had the highest ADFI, resulting in a 16% higher ADFI than pigs fed control diet. On a weekly basis, carbohydrase increased ADFI quadratically for days 8 to 14 ($P < 0.01$), and tended to increase ADFI quadratically for days 1 to 7 ($P < 0.10$) and linearly for days 22 to 28 ($P < 0.10$). Carbohydrase did not affect ADFI for days 15 to 21 ($P > 0.10$).

For the entire experiment (days 1 to 28), carbohydrase supplementation increased ADG of pigs quadratically ($P < 0.01$; Table 2). Specifically, pigs fed diet supplemented with 2 g kg^{-1} carbohydrase had the highest ADG, resulting in a 13% higher ADG than pigs fed control diet. On a weekly basis, carbohydrase increased ADG quadratically for days 8 to 14 ($P < 0.01$). Carbohydrase did not affect ADG for days 1 to 7, days 15 to 21 or days 22 to 28 ($P > 0.10$).

For the entire experiment (days 1 to 28), carbohydrase supplementation reduced feed efficiency of pigs linearly ($P < 0.05$; Table 2). Specifically for days 1 to 7, carbohydrase supplementation reduced feed efficiency of pigs linearly ($P < 0.05$), resulting in a 9% reduced feed efficiency for pigs fed diet supplemented with 4 g kg^{-1} carbohydrase than pigs fed control diet. Carbohydrase did not affect feed efficiency for days 8 to 14, days 15 to 21 or days 22 to 28 ($P > 0.10$).

Carbohydrase increased body weight quadratically by days 14 ($P < 0.01$; Table 2). The quadratic increase in bodyweight by carbohydrase was sustained until days 21 and days 28 ($P < 0.001$), Pigs fed diet supplemented with 2 g kg^{-1} carbohydrase were 1.37 kg or 7% heavier at day 28.

Nutrient Digestibility and Digesta Characteristics

Carbohydrase supplementation did not affect apparent digestibility of DM, energy, ADF, and NDF for each of the four segments of the small intestine ($P > 0.10$; Table 3). Apparent digestibility of DM was similar to digestibility of energy in segments 2 to 4, and both increased successively from segment 2 to 4. Apparent digestibility of NDF was lower than digestibility of DM and energy, especially for segments 3 and 4. Apparent digestibility for ADF was low and varied widely within dietary treatments and most means were negative values.

Overall, digesta pH increased from 6.1 for segment 1 to 6.7 for segment 4 (Table 4) and carbohydrase supplementation did not affect small intestine digesta pH ($P > 0.10$). The single trend observed was for segment 1: pigs fed diet supplemented with 2 g kg^{-1} carbohydrase had a 7% higher digesta pH than pigs fed control diet ($P < 0.10$); however,

Table 2. Effect of carbohydrase supplementation of wheat- and canola-meal-based diets on average daily feed intake, average daily gain and feed efficiency of weaned pigs

	Carbohydrase (g kg^{-1} diet)[z]				Pooled	*P* value for carbohydrase	
Variable	0	1	2	4	SEM	Linear	Quadratic
Average daily feed intake (g d^{-1})[y]							
Days 1 to 7	267	318	332	312	32	0.060	0.069
Days 8 to 14	543	611	639	560	32	0.387	0.004
Days 15 to 21	836	932	953	916	32	0.176	0.156
Days 22 to 28	966	1069	1097	1064	32	0.078	0.123
Days 1 to 28	653	732	755	713	17	0.004	0.001
Average daily gain (g d^{-1})							
Days 1 to 7	213	263	245	225	24	0.848	0.128
Days 8 to 14	353	390	413	345	24	0.993	0.005
Days 15 to 21	514	575	573	582	24	0.178	0.305
Days 22 to 28	562	605	625	586	24	0.410	0.246
Days 1 to 28	411	458	464	435	13	0.144	0.004
Feed efficiency							
Days 1 to 7	0.79	0.82	0.73	0.71	0.02	0.042	0.363
Days 8 to 14	0.65	0.64	0.65	0.62	0.02	0.446	0.941
Days 15 to 21	0.61	0.63	0.61	0.63	0.02	0.428	0.955
Days 22 to 28	0.59	0.56	0.57	0.56	0.02	0.270	0.653
Days 1 to 28	0.66	0.66	0.64	0.63	0.02	0.040	0.640
Body weight (kg)							
Days 7	8.58	9.10	8.94	8.66	0.30	0.848	0.128
Days 14	11.08	11.76	11.78	11.12	0.30	0.815	0.002
Days 21	14.72	15.72	15.73	15.23	0.30	0.336	0.001
Days 28	18.69	19.88	20.06	19.36	0.30	0.125	0.001

[z]Carbohydrase contained xylanase and β-glucanase.
[y]Means are least-square means. n = 6, 5, 5, and 6 for 0, 1, 2, and 4 g carbohydrase kg^{-1} diet, respectively.

carbohydrase supplementation at 1 and 4 g kg^{-1} did not affect digesta pH ($P > 0.10$).

Overall, digesta viscosity increased from 1.5 cPs for segment 1 to 2.7 cPs for segment 4 (Table 4) and carbohydrase supplementation did not affect small intestine digesta viscosity for segments 1, 2, and 3 ($P > 0.10$). The single difference observed was for segment 4: pigs fed diet supplemented with 4 g kg^{-1} carbohydrase had a 30% lower digesta viscosity than pigs fed control diet ($P < 0.05$); however, carbohydrase supplementation at 1 and 2 g kg^{-1} did not affect digesta viscosity ($P > 0.10$).

Correlation among Performance Variables

Among dietary treatments, ADG was strongly positively correlated with ADFI ($r = 0.94$; $P < 0.0001$; Table 5) and was weakly correlated with feed efficiency ($r = 0.40$; $P = 0.05$). Furthermore, ADG and ADFI were not correlated with DM and energy digestibility or to digesta pH or viscosity ($P > 0.10$).

DISCUSSION

Carbohydrase supplementation of a wheat-canola meal diet fed to weaned pigs increased ADFI and subsequently ADG for days 1 to 28 in the present study; however, feed efficiency and nutrient digestibility were not affected. These results combined therefore challenge the hypothesis that the beneficial effects of carbohydrase supplementation in diets for weaned pigs are mainly related to improved nutrient digestibility or feed efficiency (Bedford and Schulze 1998).

Studies with supplemental carbohydrase have not shown consistent patterns of improved performance variables. For example, carbohydrase supplementation did not improve ADG in weaned pigs fed rye-based diets , or grower-finisher pigs fed barley-based diets (Thacker et al. 1992; Baas and Thacker 1996). In contrast, carbohydrase supplementation improved ADG in weaned pigs fed barley-based diets (Bedford et al. 1992), wheat-based diets (Van Lunen and Schulze 1996), or hull-less barley-based diets (Baidoo et al. 1998). The positive responses to NSP-degrading enzymes may indicate partial or complete removal of the negative effects of the fibrous fractions in cereal ingredients that are of lesser nutritional value for the weaned pigs without supplemental carbohydrase. In previous studies, carbohydrase supplementation improved ADG as a result of improved ADFI (Baidoo et al. 1998; Van Lunen and Schulze 1996), improved feed efficiency (Bedford et al. 1992; Van Lunen and Schulze 1996), or a combination of improved ADFI and feed efficiency (Van Lunen and Schulze 1996). In the present study, carbohydrase supplementation improved ADG mostly as a result of increased ADFI, and not an increase in feed efficiency (or nutrient digestibility). Interestingly, ADG had a strong positive correlation with ADFI and a weak positive correlation with feed efficiency among dietary treatments, providing further support that improvements in ADG of weaned pigs fed a wheat and canola meal-

Table 3. Effect of carbohydrase supplementation of wheat- and canola-meal-based diets on apparent digestibility (%) of dry matter, energy, acid detergent fibre, and neutral detergent fibre in small intestine digesta collected from four sequential segments in weaned pigs

	Carbohydrase (g kg^{-1} diet)[z]			
Variable[y]	0	1	2	4
Segment 1[x]				
Dry matter	11.8 ± 6.0	–[w]	5.0 ± 6.8	14.5 ± 5.2
Energy	–	–	–	–4.4 ± 12.7
Acid detergent fibre	47.8 ± 35.6	–	–8.1 ± 35.7	18.3 ± 25.8
Neutral detergent fibre	30.8 ± 13.0	–	27.2 ± 23.0	47.4 ± 16.6
Segment 2				
Dry matter	22.0 ± 4.8	23.4 ± 4.8	26.5 ± 4.8	17.9 ± 4.8
Energy	22.7 ± 6.2	26.1 ± 5.5	28.4 ± 6.4	22.2 ± 5.5
Acid detergent fibre	–5.4 ± 14.1	–15.5 ± 15.6	10.4 ± 17.9	–4.8 ± 14.1
Neutral detergent fibre	19.8 ± 9.1	28.1 ± 10.0	37.6 ± 10.0	33.0 ± 9.1
Segment 3				
Dry matter	42.8 ± 4.8	46.4 ± 4.8	39.9 ± 4.8	39.7 ± 4.8
Energy	41.4 ± 5.6	45.1 ± 5.0	37.6 ± 5.0	40.4 ± 5.0
Acid detergent fibre	–2.7 ± 14.1	–3.6 ± 14.1	–24.0 ± 14.1	–14.4 ± 14.1
Neutral detergent fibre	28.4 ± 9.1	37.8 ± 9.1	22.9 ± 9.1	30.9 ± 9.1
Segment 4				
Dry matter	54.3 ± 4.8	57.1 ± 4.8	59.5 ± 4.8	57.1 ± 4.8
Energy	54.6 ± 5.0	58.3 ± 5.0	59.9 ± 5.0	58.6 ± 5.0
Acid detergent fibre	–17.4 ± 14.1	–14.0 ± 14.1	–1.9 ± 14.1	–17.7 ± 14.1
Neutral detergent fibre	19.3 ± 9.1	34.0 ± 9.1	36.1 ± 9.1	28.9 ± 9.1

[z]Carbohydrase contained xylanase and β-glucanase.
[y]Means are least squares means ± SEM. The SEM was reported for individual means for each variable, because SEM differed among dietary treatments for all variables in segments 1 and 2 and for energy digestibility in segment 3.
[x]Segments 1 to 4 (of equal length) represent sequentially the entire length of the small intestine.
[w]Indicates lack of sufficient sample to complete chemical analysis.

based diet limiting in DE were mostly achieved by an increased ADFI. The difficulty of consistently linking improved ADG caused by carbohydrase supplementation to improved feed efficiency suggests strongly that improved nutrient digestibility is not the sole mechanism of improved ADG following carbohydrase supplementation.

Supplemental carbohydrases in swine diets are mostly studied using a single dose recommended by the carbohydrase supplier. The present study indicates that a carbohydrase may have positive quadratic dose-response instead of a positive linear response on ADFI and ADG, suggesting that excess breakdown of arabinoxylans and β-glucans in the gastro-intestinal tract may directly or indirectly inhibit voluntary feed intake, e.g., due to resulting nutrient imbalances from entrapped nutrients that were released by the carbohydrase. Optimum doses of carbohydrase supplementation need further investigation in dose-response studies, and these studies might help explain the inconsistent results observed in other studies with carbohydrase supplementation at a single dose.

The effects of dietary NSP on voluntary feed intake can be investigated using three approaches: (1) the addition of purified NSP or NSP-containing ingredients to the diet, (2) collecting a set of ingredient samples with a range in NSP profile, or (3) the partial or complete removal of NSP or their effects using carbohydrase or other processing technology. Using ingredients widely differing in NSP, Kyriazakis and Emmans (1995) suggested that reductions of voluntary feed intake by NSP in pigs are mediated through water-holding capacity or viscosity of NSP. However, studies to associate alterations in intestinal viscosity to changes in passage rate or voluntary feed intake in pigs are scarce (Bedford and Schulze 1998). The digesta viscosity values of the present study fall within the range of 1.4 to 2.6 cPs reported previously for small intestine digesta of weaned pigs (Sudendey and Kamphues 1995). Supplementation of carbohydrase reduced digesta viscosity in the stomach, small intestine and large intestine of weaned pigs force-fed wheat- and barley-based diets and increased digesta passage rate from the stomach (Sudendey and Kamphues 1995); however, voluntary feed intake was, obviously, not measured. In the present study, carbohydrase supplementation reduced digesta viscosity at the highest dose in the distal small intestine, but not consistently through the small intestine, similar to Bedford et al. (1992); however, voluntary feed intake increased consistently. Following carbohydrase supplementation, an increased passage rate of digesta from the stomach and through the small intestine may be hypothesized to explain the increased voluntary feed intake in the present study by (partial) removal of inhibitory effects of NSP, specifically the soluble NSP arabinoxylans and β-glucans. Conversely, but in support of this mechanism, diets high in soluble NSP increased digesta viscosity in the stomach of pigs and reduced gastric emptying (Johansen et al. 1996) and therefore digesta passage rate (Wenk 2001). Supplementation of carbohydrase may thus increase digesta

Table 4. Effect of carbohydrase supplementation of wheat- and canola-meal-based diets on pH and viscosity of small intestine digesta collected from four sequential segments in weaned pigs

Variable[y]	Carbohydrase (g kg^{-1} diet)[z] 0	1	2	4	Pooled SEM
Segment 1[x]					
pH	6.1	5.9	6.5[†]	5.9	0.1
Viscosity (cPs)	1.5	1.3	1.2	1.3	0.3
Segment 2					
pH	6.2	6.0	6.3	6.2	0.1
Viscosity (cPs)	1.7	1.6	1.5	1.5	0.3
Segment 3					
pH	6.7	6.7	6.6	6.8	0.1
Viscosity (cPs)	1.6	1.7	1.6	1.6	0.3
Segment 4					
pH	6.7	6.8	7.0	6.8	0.1
Viscosity (cPs)	2.7	2.3	2.5	1.9[*]	0.3

[z]Carbohydrase contained xylanase and β-glucanase.
[y]Means are least squares means.
[x]Segments 1 to 4 (of equal length) represent sequentially the entire length of the small intestine.
[†,*] Different from 0 g carbohydrase kg^{-1} (control) diet ([†], $P = 0.07$; [*], $P = 0.04$).

Table 5. Correlations among average daily gain, average daily feed intake and feed efficiency for the entire experiment (days 1 to 28), and between average daily gain and feed intake and dry matter and energy digestibility and digesta characteristics for segment 4 of the small intestine in weaned pigs fed wheat and canola meal-based diets with or without supplemental carbohydrase

Variables	Correlation coefficient	*P* value
Average daily gain, and		
Average daily feed intake	0.94	< 0.0001
Feed conversion	0.40	0.05
Dry matter digestibility	–0.10	0.63
Energy digestibility	–0.16	0.45
Digesta pH	0.14	0.51
Digesta viscosity	–0.25	0.25
Average daily feed intake, and		
Feed conversion	0.05	0.81
Dry matter digestibility	–0.01	0.98
Energy digestibility	–0.05	0.83
Digesta pH	0.24	0.27
Digesta viscosity	–0.22	0.30

passage rate and thereby increase voluntary feed intake of the weaned pig.

Nutrient digestibility is commonly studied in pigs with equalized feed intake, because changes in feed intake will affect nutrient digestibility. In pigs with equalized feed intake, carbohydrase supplementation consistently increased apparent ileal or total-tract digestibility of nutrients (Graham et al. 1989; Li et al. 1994, 1996; Baidoo et al. 1998). In pigs provided with free access to feed, carbohydrase did not influence nutrient digestibility (Bedford et al. 1992; Baas and Thacker 1996), similar to the results in the present study. The expected improvement in nutrient digestibility caused by carbohydrase supplementation may have been negated by the expected reduction in nutrient digestibility with a higher level of feed intake following carbohydrase supplementation in the present study. An improved ileal or total-tract nutrient digestibility caused by carbohydrase supplementation may thus be less obvious under practical conditions. In addition, the lack of response in nutrient digestibility in the present study may be partly due to the technique used to collect digesta. A criticism of using the serial slaughter technique to study nutrient digestibility is that digesta is obtained only at one time point (Nyachoti et al. 1997), and that representative digesta samples are thus difficult to collect. Still, variation in DM and energy digestibility was minor in the present study, suggesting that results were sound and that carbohydrase supplementation did not affect nutrient digestibility.

The current paradigm is that soluble NSP, e.g., arabinoxylans and β-glucans, and not insoluble NSP, e.g., cellulose, primarily cause the negative effects of NSP on ileal digestibility of nutrients in non-ruminants . The negative, anti-nutritional effects of NSP seem to be associated with an increased viscosity of digesta. High viscosity could reduce the interaction between substrates and digestive enzymes and thereby reduce nutrient absorption in the small intestine (Bedford and Schulze 1998). Thus, supplementing diets fed to weaned pigs with a carbohydrase, i.e., an enzyme that degrades soluble NSP, should reduce digesta viscosity and subsequently enhance nutrient digestion and absorption. However, carbohydrase supplementation did not consistently reduce digesta viscosity or pH in the present study, similar to the lack of digesta viscosity and pH response to carbohydrase in hull-less barley-based and rye-based diets (Bedford et al. 1992). These results indicate that carbohydrase involvement in changing physical characteristics of digesta could not be ascertained, and are also consistent with the lack of improvement in nutrient digestibility following carbohydrase supplementation.

Experimental conditions of particular importance for nutrition experiments are feeding regime and diet formulation. Free access to feed might not allow separation of a feed intake response from a metabolic efficiency response (Baker 1984). Equalized (controlled) feed intake allows separation of these responses; however, unlimited access to feed is a critical performance variable in swine production in North America. The present study suggests that carbohydrase supplementation allowed young pigs to consume more of a diet with a low DE content based on wheat and canola meal. Feeding weaned pigs diets with low DE content and supplemental carbohydrase may allow for less expensive diet formulation without compromising digestible nutrient intake and therefore weight gain.

In summary, carbohydrase supplementation increased ADFI and thereby ADG for days 1 to 28, but not feed efficiency and nutrient digestibility of weaned pigs fed a wheat-canola meal diet limiting in DE. These results indicate that carbohydrase supplementation may reduce the negative effects that fibrous components included in wheat or canola meal may have on voluntary feed intake and therefore growth performance of weaned pigs.

ACKNOWLEDGEMENTS

Danisco Animal Nutrition, Canola Council of Canada, the Natural Sciences and Engineering Research Council of Canada, Saskatchewan Canola Development Commission, and the Program for Export Market Development are acknowledged for funding the project. Pork producers of Saskatchewan, Manitoba and Alberta and the Agriculture Development Fund of Saskatchewan Agriculture and Food are acknowledged for their strategic funding to Prairie Swine Centre Inc.

Association of Official Analytical Chemists. 1990. Official methods of analysis. 15th ed. AOAC, Arlington, VA.

Baas, T. C. and Thacker, P. A. 1996. Impact of gastric pH on dietary enzyme activity and survivability in swine fed β-glucanase supplemented diets. Can. J. Anim. Sci. **76**: 245–252.

Baidoo, S. K. and Liu, Y. G. 1998. Hull-less barley for swine: ileal and faecal digestibility of proximate nutrients, amino acids and non-starch polysaccharides. J. Sci. Food Agric. **76**: 397–403.

Baidoo, S. K., Liu, Y. G. and Yungblut, D. 1998. Effect of microbial enzyme supplementation on energy, amino acid digestibility and performance of pigs fed hulless barley based diets. Can. J. Anim. Sci. **78**: 625–631.

Baker, D. H. 1984. Equalized versus ad libitum feeding. Nutr. Rev. **42**: 269–273.

Barbour, G. W. and Sim, J. S. 1991. True metabolizable energy and amino acid availability in canola and flax products for poultry. Poultry Sci. **70**: 2154–2160.

Bedford, M. R., Patience, J. F., Classen, H. L. and Inborr, J. 1992. The effect of dietary enzyme supplementation of rye- and barley-based diets on digestion and subsequent performance in weanling pigs. Can. J. Anim. Sci. **72**: 97–105.

Bedford, M. R. and Schulze, H. 1998. Exogenous enzymes for pigs and poultry. Nutr. Res. Rev. **11**: 91–114.

Bell, J. M. 1993. Factors affecting the nutritional value of canola meal: a review. Can. J. Anim. Sci. **73**: 679–697.

Campbell, G. L. and Bedford, M. R. 1992. Enzyme application for monogastric feeds: a review. Can. J. Anim. Sci. **72**: 449–466.

Canadian Council on Animal Care. 1993. Guide to the care and use of experimental animals. Volume 1. 2nd ed. E. D. Olfert, B. M. Cross, and A. A. McWilliam, eds. CCAC, Ottawa, ON.

Fairbairn, S. L., Patience, J. F., Classen, H. L. and Zijlstra, R. T. 1999. The energy content of barley fed to growing pigs: characterizing the nature of its variability and developing prediction equations for its estimation. J. Anim. Sci. **77**: 1502–1512.

Fenton, T. W. and Fenton, M. 1979. An improved procedure for the determination of chromic oxide in feed and faeces. Can. J. Anim. Sci. **59**: 631–634.

Graham, H., Fadel, J. G., Newman, C. W. and Newman, R. K. 1989. Effect of pelleting and β-glucanase supplementation on the ileal and fecal digestibility of a barley-based diet in the pig. J. Anim. Sci. **67**: 1293–1298.

Johansen, H. N., Knudsen, K. E. B., Sandstrom, B. and Skjoth, F. 1996. Effects of varying content of soluble dietary fibre from wheat flour and oat milling fractions on gastric emptying in pigs. Br. J. Nutr. **75**: 339–351.

Kyriazakis, I. and Emmans, G. C. 1995. The voluntary feed intake of pigs given feeds based on wheat bran, dried citrus pulp and grass meal, in relation to measurements of feed bulk. Br. J. Nutr. **74**: 191–207.

Li, S., Sauer, W. C., Huang, S. X. and Gabert, V. M. 1996. Effect of β-glucanase supplementation to hulless barley- or wheat-soybean meal diets on the digestibilities of energy, protein, β-glucan, and amino acids in young pigs. J. Anim. Sci. **74**: 1649–1656.

Li, S., Sauer, W. C., Huang, S. X. and Mosenthin, R. 1994. Effect of cellulase supplementation to barley-based diet on the digestibilities of energy, β-glucans, crude protein and amino acids in early-weaned pigs. Pages 357–359 *in* W. B. Souffrant and H. Hagemeister, eds. Digestive physiology in pigs. FBN, Dummerstorf, Germany.

National Research Council. 1998. Nutrient requirements of swine. 10th ed. National Academy Press, Washington, DC.

Noblet, J., Fortune, H., Shi, X. S. and Dubois, S. 1994. Prediction of net energy value of feeds for growing pigs. J. Anim. Sci. **72**: 344–354.

Nyachoti, C. M., de Lange, C. F. M., McBride, B. W. and Schulze, H. 1997. Significance of endogenous gut nitrogen losses in nutrition of growing pigs: a review. Can. J. Anim. Sci. **77**: 149–163.

Patience, J. F., Thacker, P. A. and de Lange, C. F. M. 1995. Swine nutrition guide. 2nd ed. Prairie Swine Centre Inc., Saskatoon, SK.

SAS Institute, Inc. 1996. SAS/STAT user's guide. Release 6.12. SAS Institute, Inc., Cary, NC.

Slominski, B. A. and Campbell, L. D. 1990. Non-starch polysaccharides in canola meal: quantification, digestibility in poultry and potential benefit of dietary enzyme supplementation. J. Sci. Food Agric. **53**: 175–184.

Steel, R. G. D. and Torrie, J. H. 1980. Principles and procedures of statistics. 2nd ed. McGraw-Hill, New York, NY.

Sudendey, C. and Kamphues, J. 1995. Effect of enzymes (α-Amylase, Xylanase, β-Glucanase) as feed additive on digestive processes in the alimentary tract of piglets past forced feed intake. Proc. Soc. Nutr. Physiol. **3**: 88A (Abstr.).

Thacker, P. A., Campbell, G. L. and GrootWassink, J. 1992. The effect of organic acids and enzyme supplementation on the performance of pigs fed barley-based diets. Can. J. Anim. Sci. **72**: 395–402.

Van Lunen, T. A. and Schulze, H. 1996. Influence of *Trichoderma longibrachiatum* xylanase supplementation of wheat and corn based diets on growth performance of pigs. Can. J. Anim. Sci. **76**: 271–273.

Van Soest, P. J., Robertson, J. B. and Lewis, B. A. 1991. Methods for dietary fibre, neutral detergent fibre, and non-starch polysaccharides in relation to animal nutrition. J. Dairy Sci. **74**: 3583–3597.

Wang, Z. and Goonewardene, L. A. 2004. The use of MIXED models in the analysis of animal experiments with repeated measures data. Can. J. Anim. Sci. **84**: 1–11.

Wenk, C. 2001. The role of dietary fibre in the digestive physiology of the pig. Anim. Feed Sci. Technol. **90**: 21–33.

Zijlstra, R. T., de Lange, C. F. M. and Patience, J. F. 1999. Nutritional value of wheat for growing pigs: chemical composition and digestible energy content. Can. J. Anim. Sci. **79**: 187–194.