Effect of Twin-Screw Extrusion on the Nutritional Quality of Wheat, Barley, and Oats[1]

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ABSTRACT

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Rat weight gains and feed efficiencies from diets of extruded oats (with husks), barley (with husks), or wheat were no different than those from raw grain diets. Animals that were fed extruded grains had lower serum and liver cholesterol levels than those fed the raw grain and control (casein-based) diets. Of the raw grain diets, only the barley diet had a hypocholesterolemic effect when compared to the control diet. Rats fed extruded barley had lower serum and liver cholesterol than any other grain-fed group. Factors contributing to the greater hypocholesterolemic effects of barley diets could be the higher total and soluble β-glucan contents and higher viscosities of the barley diets versus the oat, wheat, and control diets. Diet viscosity was negatively correlated with serum ($r = -0.7906$, $P = 0.0013$) and liver ($r = -0.7937$, $P = 0.0015$) cholesterol. Data support the hypothesis that dietary fibers may exert their cholesterol-lowering effect by increasing the viscosity of material in the digestive tract.

Nutritional effects of extrusion processing are not well documented and depend on many factors, including type of extruder, screw configuration, and processing conditions. Some effort has been devoted to studying the effects of extrusion cooking on nutritional or chemical properties of wheat (Bjorck et al 1984a,b; Phillips 1988); wheat bran (Aoe et al 1989, Ralet et al 1990); and corn (Peri et al 1983, Bhattacharya and Hanna 1988), but few studies report the effects of extrusion on oats and barley. Presently, whole oats and barley are not consumed as food by humans. Hulls, comprising about 25% of oats and 15% of barley, are commonly fed to animals or used in industrial applications. However, with the current governmental and health agency emphasis on increasing dietary fiber intake in the general population, very high fiber ingredients may find an assortment of food applications. Wang and Klopfenstein (1993) and others (Aoe et al 1989, Ralet et al 1990) have shown significantly increased soluble dietary fiber (SDF) in extruded wheat bran. Oats and barley contain a high proportion of SDF, particularly $(1\rightarrow3),(1\rightarrow4)$-$\beta$-D-glucan, which has been shown to be hypocholesterolemic (Shinnick et al 1988; Welch et al 1988; Newman et al 1989, 1992). Effects of extrusion on the hypocholesterolemic properties of those grains have not been established. The first objective of this study was to evaluate the effects of extrusion processing, using Wenger TX-52 equipment, (Wenger Mfg., Sabetha, KS) at three different screw speeds, on nutritional properties (including hypocholesterolemic effect) of whole grain oats (with husks), barley (with husks), and wheat. The second objective was to relate nutritional changes to changes in physical properties of the grains.

MATERIALS AND METHODS

Whole grain oats and barley (both with husks) and hard red winter wheat were obtained from a local elevator in Manhattan, KS. Grains were first ground through the 1/8-in. (3.2-mm) screen of a Fitz mill (Fitzpatrick Co., Elmhurst, IL) and then extruded using a Wenger TX-52 corotating twin-screw extruder as previously described (Wang and Klopfenstein 1993). Dry extrudates were ground through the 1/8-in. (3.2-mm) screen of the Fitz mill to produce products more similar in particle size to those of the raw (unextruded) materials and to aid in further analyses. Both the raw and extruded products were stored at room temperature for a few days until needed for mixing in rat diets.

Rat-Feeding Study

Thirteen groups of 10 male Wistar rats each (Charles River Breeding Laboratory, Wilmington, MA) were fed diets containing raw or extruded grains or a casein-based control diet with no cereal. All diets were formulated to contain the same amount of total dietary fiber (TDF), protein, and fat, using Mixit-2+ least-cost ration-balancing software, version 1.0 (Agricultural Software Consultants, Inc., Kingsville, TX). The compositions and proximate analyses of diets are shown in Tables I and II. Mean initial weights of animals in all groups were statistically the same and averaged 136 g. Animals were individually housed in stainless steel cages in an environmentally controlled room (23°C with a 12-hr light-dark cycle). Diets and water were fed ad libitum. Animals were weighed weekly. Feed consumption records were kept, and feed efficiencies were calculated.

Serum Total Cholesterol Analysis

At the end of weeks 3 and 6, rat blood samples were taken by cardiac puncture from fasting (12-hr), ether-anesthetized rats. The clot was removed after centrifugation at 12,000 × *g* for 15 min. Serum total cholesterol concentrations were assayed using the enzymatic method of diagnostic kit 352 (Sigma Chemical Co., St Louis, MO).

Liver Cholesterol

After six weeks of feeding, the animals were sacrificed in an ether atmosphere. The livers were quickly removed, rinsed under cold tap water, blotted dry, and stored frozen until analysis for cholesterol. Lipids were extracted from liver homogenates with chloroform-methanol (Klopfenstein and Clegg 1980). An aliquot of the chloroform extract was evaporated to dryness under nitrogen. The lipid residue was redissolved in absolute ethanol and used for determination of total liver cholesterol (Rosenthal et al 1957).

TABLE I
Percent Composition of Rat Diets[a]

Ingredients	Oats Diets 1–4	Barley Diets 5–8	Wheat Diets 9–12	No Cereal Diet 13
Grains	25.2	53.2	50.0	0
Casein (vitamin-free)[b]	18.7	14.0	14.6	21.8
Corn starch[b]	40.5	17.2	15.5	52.2
Cellulose[c]	...	...	4.38	8.65
Soybean oil[d]	3.59	3.57	3.52	5.35
Sucrose	5.00	5.00	5.00	5.00
Vitamin mix 2[e]	2.00	2.00	2.00	2.00
Mineral mix (salt mixture XVII)[e]	4.00	4.00	4.00	4.00
Cholesterol[b]	1.00	1.00	1.00	1.00

[a] Diets 1, 5, and 9 contained the raw grains; diets 2, 6, and 10 contained grains extruded at low screw speed (200 rpm); diets 3, 7, and 11 contained grains extruded at medium screw speed (300 rpm); and diets 4, 8, and 12 had grains extruded at high screw speed (400 rpm).
[b] Sigma Chemical Co., St. Louis, MO.
[c] Alphacel, ICN Nutritional Biochemicals, Clevland, OH.
[d] Food Club Brand, Dillons, Inc., Manhattan, KS.
[e] ICN Nutritional Biochemicals, Cleveland, OH.

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TABLE II

Percent Dietary Fiber and Proximate Contents of Rat Diets (dry basis)

Diet	Type[a]	TDF[b]	IDF[b]	SDF[b]	Moisture[c]	Protein[d]	EE[e]	Ash[f]
1	Oats-R	12.10	9.88	2.22	9.34	21.7	4.90	4.65
2	Oats-L	12.53	9.63	2.90	7.87	21.9	5.98	4.58
3	Oats-M	12.75	10.83	1.92	7.69	22.1	5.60	4.64
4	Oats-H	12.69	10.28	2.41	7.68	22.5	5.62	4.46
5	Barley-R	13.84	11.25	2.69	8.46	21.5	5.40	4.92
6	Barley-L	13.51	12.31	1.20	6.13	21.7	5.17	5.18
7	Barley-M	12.70	10.62	2.08	6.01	21.7	4.94	5.02
8	Barley-H	12.99	10.41	2.58	7.03	21.6	5.15	4.88
9	Wheat-R	12.90	10.80	2.10	8.43	22.1	4.99	4.51
10	Wheat-L	12.89	10.24	2.65	6.89	22.3	5.17	4.59
11	Wheat-M	12.49	10.92	1.57	6.23	21.8	5.40	4.60
12	Wheat-H	12.59	10.54	2.05	6.47	21.8	5.04	4.74
13	No Cereal	13.34	12.59	0.75	7.51	22.2	5.54	3.57

[a] R = raw (unextruded), L = extruded low, M = extruded medium, and H = extruded high.

[b] TDF = total dietary fiber; IDF = insoluble dietary fiber; SDF = soluble dietary fiber. Determined using AACC method 32-07.

[c] AACC method 44-40.

[d] AACC method 46-16.

[e] EE = petroleum ether extract. Determined using AACC method 30-25.

[f] AACC method 08-01.

Viscosity

A Rapid Visco Analyzer (RVA-3C, Newport Scientific Pty. Ltd., NSW, Australia) was used to measure the viscosities of aqueous suspensions of the rat diets. To determine the viscosity at physiological temperature, diet suspensions (25% solids) were stirred at 37°C, and the viscosity values at 12 min were recorded.

Statistical Analysis

The data were statistically evaluated by the one-way analysis of variance procedure with the least significant difference test using the statistical analysis system at Kansas State University, Manhattan (SAS 1985).

RESULTS AND DISCUSSION

Effects of Raw and Extruded Grain Diets on Rat Weight Gains and Feed Efficiencies

Weight gains of animals fed all of the grain diets were similar and all gained more weight than animals fed the control (no cereal) diet (Table III). Weight gains of animals fed the extruded cereals did not differ from those of rats fed the raw grain diets. Feed efficiencies for the raw oats, wheat, and barley were not statistically different, nor did extrusion processing of each grain change its efficiency with respect to the raw grain (Table III). However, barley was a more efficient feed than oats when both were extruded at high screw speed conditions. Feed efficiencies were significantly higher for the raw and extruded grain diets than they were for the control (no cereal) diet. Rats appeared to prefer the grain diets to the control diet. Spillage was less for those diets, and feed intake (and, therefore, feed efficiency) values were more accurate for the grain diets. In addition, the control diet tended to stick to the animals' faces and forepaws, making diet wastage difficult to estimate. TDF was similar in all diets, but soluble fiber was lower in the control diets than in the other diets (Table II). According to Olson et al (1987), many components of SDF can be fermented by colonic bacteria to volatile fatty acids that can be absorbed by the body and metabolized for energy. The main source of dietary fiber in the no-cereal diet was cellulose, which has essentially no soluble and fermentable fiber and is considered to be noncaloric. The correlation between SDF and weight gains was $r = 0.6598$ ($P = 0.010$). The correlation between SDF and feed efficiencies was $r = 0.7222$ ($P = 0.005$). Although the diets were formulated to be isocaloric (350–360 Kcal), the data indicate that the SDF may have increased the caloric value of the grain diets, thereby increasing rat weight gains and feed efficiencies somewhat.

TABLE III

Cumulative Weight Gains, Feed Intakes, and Feed Efficiencies of Rats Fed Raw or Extruded Grain or No-Cereal Diets for Six Weeks[a]

Diet	Type[b]	Weight Gain (g)	Feed Intake (g)	Feed Efficiency[b]
1	Oats-R[c]	201 b	1,017 de	0.198 abc
2	Oats-L	211 ab	1,008 e	0.210 ab
3	Oats-M	203 b	1,020 cde	0.199 abc
4	Oats-H	199 b	1,028 bcde	0.193 c
5	Barley-R	210 ab	1,049 abcd	0.200 abc
6	Barley-L	210 ab	1,060 ab	0.198 abc
7	Barley-M	212 ab	1,068 a	0.198 abc
8	Barley-H	223 a	1,060 ab	0.211 a
9	Wheat-R	203 ab	1,057 abc	0.192 c
10	Wheat-L	204 ab	1,039 abcde	0.196 abc
11	Wheat-M	206 ab	1,054 abcd	0.195 bc
12	Wheat-H	208 ab	1,059 ab	0.196 abc
13	No cereal (control)	128 c	945 f	0.134 d
LSD[d]		18	38	0.015

[a] Means in the same column not followed by the same letter are significantly different at $P < 0.05$.

[b] Feed efficiency = grams gained per grams of feed consumed.

[c] R = raw (unextruded), L = extruded low, M = extruded medium, and H = extruded high.

[d] Least significant difference.

Effects of Raw and Extruded Grains on Rat Serum and Liver Cholesterol Levels

Rats fed raw barley and oats had lower serum cholesterol concentrations than those fed raw wheat after three weeks of feeding (Table IV). Although the barley and wheat diets contained similar amounts of grain, the oat diets contained only about half as much grain as the wheat diets (Table I). After six weeks, serum cholesterol levels were significantly lower in the animals fed raw barley than they were in animals fed the other raw cereals or control diet. Raw wheat and oat diets did not produce a cholesterol-lowering effect in comparison to the control diet.

Extrusion processing had a dramatic effect on the grains' cholesterol-lowering potential. At both sampling times, total serum cholesterol concentrations were lower in all the animals fed extruded cereal diets than they were in animals fed raw cereal or control diets (Table IV). Rats fed extruded barley diets had the lowest serum cholesterol levels.

Liver cholesterol concentrations (Table IV) were positively correlated with serum total cholesterol levels ($r = 0.855$, $P = 0.0002$); animals fed the extruded grains had lower concentrations than those fed the raw grains. Animals fed raw and extruded grains, with the exception of those fed raw oats, had lower liver cholesterol concentrations than animals fed the control (no cereal) diet.

Different types of fiber are distinguished by physiological properties and systemic effects. The soluble component of dietary fiber is thought to be the primary hypocholesterolemic agent in humans and animals (Anderson et al 1990). Anderson et al (1984) reported that β-glucan-rich oats lowered serum total and low-density lipoprotein cholesterol while it increased high-density lipoprotein cholesterol in humans and rats. When Shinnick et al (1988) conducted a study to determine the effect of extrusion processing (low and high pressure) on the ability of oat bran and high-fiber oat flour (Quaker Oats, Barrington, IL) to lower plasma and liver cholesterol concentrations in rats, results showed that all of the oat products significantly lowered plasma and liver cholesterol without depressing food intake or weight gain. However, no hypocholesterolemic effect was observed for processed oat hull products (Lopez-Guisa et al 1988). That result supports the earlier reports of studies with Japanese quail (Rogel and Vohra 1983) and hens (Weiss and Scott 1979), in which up to 20% unprocessed oat hull in the diet had no effect on plasma or yolk cholesterol levels. Certain β-glucan-rich barley cultivars also lower serum cholesterol in chicks and rats (Newman et al 1989, 1992). In a study on humans, daily consumption of 1.2, 2.0, and 2.4 g of β-glucan resulted in 5.8, 4.7, and 3.5% reductions in low-density lipoprotein cholesterol, respectively (Davidson et al 1991). Whole oats, containing about 25% hulls that are rich in cellulose and xylans, were used in the present study. Total and soluble β-glucan concentrations in the oat diets were about half those in the barley diets (Table V). That probably explains why the barley diets were more hypocholesterolemic than the oat diets.

TABLE IV
Mean Serum and Liver Cholesterol Levels in Rats Fed Raw or Extruded Grain or No-Cereal Diets[a]

Diet	Type[b]	Total Serum Cholesterol (mg/dL) Week 3	Week 6	Liver Cholesterol (mg/g liver)
1	Oats-R	102.6 bc	123.3 a	18.8 a
2	Oats-L	84.4 de	93.4	9.6 d
3	Oats-M	92.4 cd	92.1	14.3 b
4	Oats-H	88.9 de	91.7 c	11.7 c
5	Barley-R	92.7 cd	107.9 b	11.2 cd
6	Barley-L	66.5 f	68.5 d	7.1 e
7	Barley-M	65.6 f	66.9 d	7.5 e
8	Barley-H	79.6 e	74.8 d	7.3 e
9	Wheat-R	121.0 a	124.0 a	14.8 b
10	Wheat-L	89.2 de	89.2 c	10.9 cd
11	Wheat-M	78.9 e	94.2 c	7.2 e
12	Wheat-H	78.2 e	88.6 c	9.8 cd
13	No cereal (control)	106.9 b	122.6 a	17.4 a
LSD[c]		11.7	13.7	1.9

[a] Means in the same column not followed by the same letter are significantly different at $P < 0.05$.

[b] R = raw (unextruded), L = extruded low, M = extruded medium, and H = extruded high.

[c] Least significant difference.

The effect of wheat diets on serum cholesterol is still controversial. Fisher and Griminger (1967) induced a significant decrease in plasma cholesterol levels in chickens with wheat, whereas other laboratories have found wheat to be an ineffective hypocholesterolemic agent (Anderson and Chen 1979, Kay and Truswell 1980, Kies 1985).

When dietary SDF levels were calculated from grain values (Table V), the negative correlation with serum cholesterol was significant ($r = -0.649$, $P = 0.05$). Dietary fiber values obtained by diet analysis tended to be higher than values calculated using only the grain contribution to TDF, especially for the oats and no-cereal diets, which contained 40 and 52% corn starch, respectively. Incompletely hydrolyzed nonfiber residue may have remained in the diet samples, giving higher TDF values.

Effect of Diet Viscosities on Rat Cholesterol Levels

Viscosity may play a role in mediating several of the physiological effects of dietary fiber (Jenkins et al 1978). Vahouny et al (1981) provided a theory of the hypocholesterolemic mechanism that relates to modification of lipid absorption from increased viscosity created by soluble fibers. Works of Fadel et al (1987) and Newman et al (1987) suggest that high viscosity caused by the degree of polymerization is the major factor in the hypocholesterolemic effect of β-glucans.

Our results showed that viscosities were significantly higher for slurries of all extruded grain diets than for those of raw grain and no-cereal diets, with the exception of oats extruded at low screw speed conditions (Table V). Slurries of extruded barley diet had the highest viscosities, followed by slurries of extruded wheat diets; slurries of extruded oats diets had the lowest viscosities. Slurries of all medium-speed extruded grain diets had the highest viscosities. Although slurries of extruded oat diets had lower viscosities than extruded wheat diets, they had similar cholesterol-lowering effects. However, diet slurry viscosity was negatively correlated with serum cholesterol ($r = -0.7906$, $P = 0.0013$) and liver cholesterol ($r = -0.7937$, $P = 0.0015$).

In addition to differences in SDF, percent of the various grain starches and corn starch added to diets were different (Table I). Starch type, as well as concentration and condition, might have played an important role in viscosity in this experiment. Diet viscosity appears to be an important factor affecting cholesterol values. It would be interesting to test diet viscosities using the RVA system, but with the addition of α-amylase to the slurries to get a more representative indication of the contributions of starch and enzyme-susceptible starch to viscosity under in vivo conditions.

TABLE V
Percentages of Calculated Dietary Fiber, (1→3), (1→4) β-Glucan Content, and Viscosities (cP) of Rat Diets

Diet	Type[a]	TDF[b]	IDF[b]	SDF[b]	TGLN[c]	SGLN[d]	Viscosity[e,f]
1	Oats-R	11.47	10.62	0.85	0.88	0.61	50 h
2	Oats-L	10.12	8.91	1.21	1.03	0.66	50 h
3	Oats-M	10.27	8.71	1.56	1.06	0.74	145 g
4	Oats-H	9.83	8.54	1.29	0.99	0.60	140 g
5	Barley-R	14.09	11.39	2.70	2.02	1.19	60 h
6	Barley-L	13.33	10.38	2.95	2.19	1.32	2,880 b
7	Barley-M	13.21	10.46	2.75	2.08	1.10	2,975 a
8	Barley-H	12.91	10.59	2.32	2.13	1.29	2,775 c
9	Wheat-R	12.37	11.69	0.68	...	...	60 h
10	Wheat-L	11.86	10.80	1.06	...	...	1,850 f
11	Wheat-M	11.78	10.73	1.05	...	...	2,455 d
12	Wheat-H	11.93	10.76	1.17	...	...	2,305 e
13	No cereal (control)	9.32	9.12	0.20	...	...	60 h

[a] R = raw (unextruded), L = extruded low, M = extruded medium, and H = extruded high.

[b] TDF = total dietary fiber, IDF = insoluble dietary fiber, SDF = soluble dietary fiber.

[c] Total (1→3), (1→4)-linked β-D-glucan, calculated from the amount in the raw and extruded grains analyzed in triplicate by the method of McCleary and Glennie-Holmes (1985).

[d] Soluble β-glucan, calculated from the amount in the grains using the method of McCleary and Glennie-Holmes (1985) after extraction of the grains by the method of Aman and Graham (1987).

[e] Diet slurry viscosities at 37°C after 12 min (25% solids).

[f] Means in the same column not followed by the same letter are significantly different at $P < 0.05$.

CONCLUSIONS

Extrusion processing of grains did not affect rat weight gains or feed efficiencies. Extrusion enhanced the grains' cholesterol-lowering potential. Factors contributing to the greater hypocholesterolemic effects of barley diets appear to be their higher total and soluble β-glucan contents and higher viscosities compared to the oat, wheat, and control diets; SDF may also be a factor. The data support the hypothesis that dietary fibers may exert their cholesterol-lowering effect, at least partly, through their viscosity-raising properties.

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