Effects of different grinding methods and particle size of barley and wheat on pig performance and digestibility

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Abstract

The effect of grinding method of barley and wheat on total tract digestibility of barley–soyabean meal and wheat–soyabean meal diet, N-balance (experiments 1 and 2) and pig performance (experiments 3 and 4) was studied. Cereals were ground by four mill types and there were two degrees of grinding fineness within each mill type. Mill types were a hammer mill (HM, sieve size 3 and 5 mm), a crimping roller mill (RM1, gap between rolls 0.5 and 0.8 mm), a flattening roller mill (RM2, gap between rolls 0.15 and 0.35 mm) and a triple roller mill (RM3, gap between the 1st and 2nd roll 0.2 and 0.65 mm, gap between the 2nd and 3rd roll was fixed at 0.65 mm). Data were analysed in a nested design, mill type as the main treatment (all 4 mill types in experiments 1, 3 and 4, mill types HM, RM1 and RM2 in Experiment 2) and fineness of grinding (fine and coarse) as the subtreatment within each mill type.

Digestibility and N-balance experiment with barley was conducted with eight castrated male pigs (25.9–91.9 kg) in a 8 × 6 cyclic change-over design (Experiment 1) and with wheat, using 12 castrated male pigs (31.2–83.8 kg) in two 6 × 6 Latin square design (Experiment 2). A growth experiment was conducted with 160 growing-finishing pigs (25.2–101.5 kg) housed per pair (one female and one castrated male per pen, 10 pens per treatment) with barley (Experiment 3) and an other 160 pigs (25.2–100.3 kg) with wheat using the same procedure (Experiment 4).

RM1 depressed digestibility of crude protein \((p < 0.05\) and \(p < 0.10\), with barley and wheat) and ether extract \((p < 0.01\) and \(p < 0.05\), with barley and wheat) in both cereals and improved

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digestibility of NDF ($p < 0.01$) and crude carbohydrates, which were defined as total organic matter − (ether extract + crude protein) ($p < 0.05$) in barley compared to the other mill types. Coarse grinding within RM1 decreased all measured digestibilities ($p < 0.05$) in both cereals, except for NDF in barley, compared to fine grinding. The mill type had no effect on N retention g/day, but the proportion of faecal N excretion was increased with RM1 and RM3 barley ($p < 0.05$) and with RM1 and RM2 wheat compared to hammer milling ($p < 0.10$). Coarse grinding within RM1 increased the proportion of faecal N excretion with both cereals compared to fine grinding.

RM1 increased the total feed consumption with barley and depressed the daily gain and feed conversion ratio ($p < 0.10$) compared to the other mill types. The coarse grinding within RM1 and RM3 increased barley based feed consumption ($p < 0.10$) and depressed daily gain and feed conversion ratio ($p < 0.05$), but neither mill type nor fineness of grinding had any effect on carcass quality with barley. The mill type had no effect on feed intake, pig performance or carcass quality with wheat.

It was concluded that mill type had no effect on dry matter and gross energy digestibility in barley and wheat. Also, pig performance with rolled barley and wheat was equal to that obtained with hammer milled cereals, if the total feed consumption was not influenced by the grinding method. © 2000 Elsevier Science B.V. All rights reserved.

**Keywords:** Pigs; Barley; Wheat; Milling; Fineness; Digestibility; Nitrogen retention; Pig performance

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### 1. Introduction

Finely ground cereals are dusty and may induce respiratory diseases. Small grist size is one of the main causes of gastric lesions in growing pigs. Coarse grinding by a roller mill or by using a larger sieve in the hammer mill decreases the risk of gastric lesions (Potkins et al., 1989; Alaviuhkola et al., 1993). However, coarse grinding may also impair digestibility of nutrients and pig performance (Potkins et al., 1989; Bach Knudsen and Johansen, 1995).

In earlier studies, pig performance or digestibility of nutrients were equal from rolled or hammer milled barley (Simonsson, 1978b; Mortensen et al., 1981; Näsi, 1992; Alaviuhkola et al., 1993). Pig performance on rolled wheat has been equal (Ivan et al., 1974) or slightly better than that on hammer milled wheat (Seerley et al., 1988). However, roller mills differing in grinding technique have not been compared.

The aim of these four experiments was to compare a hammer mill and three different roller mills in grinding barley and wheat for growing pigs. In addition to mill type, the effects of fineness of grinding within each mill type were studied on digestibility, nitrogen utilisation (experiments 1 and 2), performance and carcass quality of growing-finishing pigs (experiments 3 and 4).

### 2. Material and methods

#### 2.1. Grinding methods

Barley and wheat were ground using the same grinding adjustments for both cereals by the hammer mill (HM, Pehrsson 50/SM, Lindkoski, Finland, 3850 rpm, mill diameter
500 mm) and three different roller mills and there were two fineness of grindings within each mill type. The crimping roller mill (RM1, Automatic 200, Automatic equipment MFG, Pender, Nebrasca, USA) had two grooved rolls (3.9 corrugations per centimetre) rotating at different speeds, 600 and 900 rpm. The diameter of both rolls was 152 mm. The flattening roller mill (RM2, Rivakka VAM F 128, Nipere, Teuva, Finland) had two dot-corrugated rolls (5 dot lines per centimetre) rotating at the same speed, 210 rpm. The diameter of both rolls was 250 mm. The triple roller mill (RM3, Rivakka VAM F 138, Nipere, Teuva, Finland) had three dot-corrugated rolls, rotating at different (rolls 1 and 2, 120 and 150 rpm) and the same speed (rolls 2 and 3, both 150 rpm). The diameter of all the rolls was 250 mm. The sieve sizes of the hammer mill were 3 and 5 mm. Roller mills were adjusted according to the instructions of their manufacturers for fine and coarse grindings. The gap between rolls of crimping roller mill, flattening roller mill and triple roller mill was 0.5 and 0.8 mm, 0.15 and 0.35 mm, 0.2 and 0.65 mm during fine and coarse grinding, respectively. The gap between rolls 2 and 3 of the triple roller mill was fixed on 0.6 mm. Initially, the volume weight of barley was 66.3 kg h\(^{-1}\) and the proportion of grains smaller than 2.2 mm was 11.6%. Wheat was soft type and its volume weight was 79.9 kg h\(^{-1}\).

2.2. Diets

Eight experimental diets (4 mill types, 2 fineness of grinding on each mill type) were formulated for both cereals using soyabean meal as a protein supplement. Minerals and vitamins were added to meet the requirements of growing pigs (Tuori et al., 1995). The diets were fortified with 1.5 and 2.2 g/kg L-lysine–HCl in the growth experiment with barley and wheat (Table 1).

2.3. Animals and experimental procedure

2.3.1. Digestibility and N-balance experiment with barley (Experiment 1)

Digestibility and protein utilisation experiment with barley was conducted as an 8 × 6 cyclic change-over design with eight castrated male pigs to obtain six replications for each treatment. Five of the pigs were of the Finnish Landrace × Yorkshire crossbreedings and three pigs were Yorkshire. The average initial weight of the pigs was 25.9 (±2.13) kg and the final weight 91.9 (±2.32) kg. The pigs were kept individually in metabolism cages (0.68 m × 1.52 m) with adjustable walls throughout the trial. Each experimental period lasted 12 days: seven days of adjustment and five days of collection. After the 3rd period, the pigs developed health problems and lost their appetite and the 4th period was repeated at the end of the trial.

The daily ration was 1450 g barley–soyabean mixture per pig per day on the first period and ration was increased by 240 g/day in the end of each period. Feed was given in two equal portions at 7.00 and 19.00 h and mixed with water immediately before feeding. The pigs were given water ad libitum after feeding. The wasted feed was collected and weighed during the collection periods. Urine was collected with the addition of 40 ml 10 N H\(_2\)SO\(_4\), sampled daily and frozen at −20°C. All faeces were collected and 0.30 of faeces at every collection time was stored frozen for chemical
2.3.2. Digestibility and N-balance experiment with wheat (Experiment 2)

Triple roller mill was not included in the digestibility trial of wheat. Twelve castrated male pigs were used in a 6 × 6 Latin square experiment to obtain six replications for each treatment in two complete randomised blocks (metabolism cage and metabolism pen). The pigs were randomly divided into the blocks. Eight of the pigs were Landrace × Yorkshire and the remaining four pigs were Yorkshire. The average initial weight of the pigs was 31.2 (±2.70) kg and the final weight was 83.8 (±10.62) kg. The daily ration was 1450 g wheat–soyabean meal mixture per pig per day on the first period and ration was increased by 240 g/day in the end of each period. Six pigs in the individual metabolism cages (0.68 × 1.52 m) were prevented from turning around during the collection period by adjusting the walls of the cages. Faeces were collected from a rubber sheet at the back of the cage. The other six pigs were kept in individual pens (1.43 × 1.23 m, fixed walls) and faeces were collected using plastic bags attached around their anuses with glued adhesive tape and snap-fasteners (Van Kleef et al., 1994). Urine was collected into 40 ml of 10 N H₂SO₄, sampled daily and stored at −20°C in both

\[
\begin{array}{lcccccc}
\text{Composition and calculated nutrient analysis of the experimental diets (g/kg) in the digestibility (experiments 1 and 2) and the growth trials (experiments 3 and 4)} \\
\hline
\text{} & \text{Digestibility trials} & \text{} & \text{Growth trials} & \text{} & \text{} \\
\text{} & \text{Experiment 1} & \text{Experiment 2} & \text{Experiment 3} & \text{Experiment 4} & \text{} & \text{} \\
\text{Barley} & 823 & \text{–} & 845 & \text{–} & 822 & \text{} & \text{} \\
\text{Wheat} & \text{–} & 822 & \text{–} & \text{–} & \text{–} & \text{} & \text{} \\
\text{Soyabean meal} & 150 & 130 & 150 & 150 & \text{} & \text{} & \text{} \\
\text{Ground limestone} & 5.6 & 7.5 & 5.6 & 8.3 & \text{} & \text{} & \text{} \\
\text{Monocalcium phosphate} & 7.5 & 4.0 & 7.5 & 4.5 & \text{} & \text{} & \text{} \\
\text{Vitamin–mineral premix}^a & 13.0 & 13.0 & 13.0 & 13.0 & \text{} & \text{} & \text{} \\
\text{NaCl} & 0.9 & 0.5 & \text{–} & \text{–} & \text{–} & \text{} & \text{} \\
\text{Lysine} & \text{–} & \text{–} & 1.5 & 2.2 & \text{} & \text{} & \text{} \\
\hline
\text{Calculated nutrient analysis}^b (g kg}^{-1} \text{)} & \text{} & \text{} & \text{} & \text{} & \text{} & \text{} & \text{} \\
\text{Crude protein} & 140 & 149 & 140 & 155 & \text{} & \text{} & \text{} \\
\text{NDF-fibre} & 169 & 99 & 168 & 98 & \text{} & \text{} & \text{} \\
\text{ADF-fibre} & 41 & 23 & 41 & 24 & \text{} & \text{} & \text{} \\
\text{Ileal digestible lysine} & 5.3 & 4.9 & 6.8 & 7.5 & \text{} & \text{} & \text{} \\
\text{Ileal digestible threonine} & 5.2 & 5.0 & 5.2 & 5.3 & \text{} & \text{} & \text{} \\
\text{Ileal digestible methionine + cystine} & 4.8 & 5.2 & 4.8 & 5.4 & \text{} & \text{} & \text{} \\
\text{NE (MJ kg}^{-1} \text{)} & 9.1 & 9.6 & 9.1 & 9.5 & \text{} & \text{} & \text{} \\
\hline
\end{array}
\]

\(^a\) Supplied per kg diet: Ca 2.3 g, digestible P 0.7 g, Mg 0.5 g, NaCl 3.3 g, Fe 103.2 mg, Cu 22.4 mg, Se 0.28 mg, Zn 90.6 mg, Mn 23.4 mg, I 0.22 mg, vitamin A 5174 IU, vitamin D 517 IU, vitamin E 50 mg, menadione 1.9 mg, thiamin 1.9 mg, riboflavin 4.7 mg, pyridoxine 2.8 mg, cyanocobalamin 20 μg, biotin 199 μg, pantothenic acid 14 mg, niacin 20 mg, folic acid 3.3 mg.

\(^b\) Calculated according to chemical analysis of barley, wheat and soyabean meal. Ileal digestible lysine, threonine, methionine and cystine calculated according to Tuori et al., 1995. NE, net energy, according to CVB, 1991.
procedures. The total length of the period was 12 days, which constituted of 6.5 days adjustment, 5 days collection of faeces and urine and 0.5 day for blood sampling. The blood samples were taken 4 h after morning feeding on the following day of the sampling period for the determination of plasma urea nitrogen. The plasma urea results and the comparison between cage and pen will be presented in another paper.

2.3.3. Growth trials with barley (Experiment 3) and wheat (Experiment 4)

Growth experiments with barley and wheat were conducted with 160 and 160 Finnish Landrace (58 and 49%), Yorkshire (16 and 23%) and cross bred (26 and 28%) pigs. One gilt and one castrated male from different litters were randomly assigned into each pen. The pens were randomly allotted to the eight treatments, 10 pens for each treatment in both experiments. The initial weight of the pigs was 25.2 (±1.18) and 25.2 (±1.45) kg in experiments 3 and 4. They were slaughtered in a commercial abattoir at an average live weight of 100 kg (±2.21 and ±2.98 in experiments 3 and 4).

The daily ration was from 1350 to 3050 and from 1300 to 2900 g of barley–soyabean and wheat–soyabean mixture per pig per day in the experiments 3 and 4 (Table 2). Pigs were dry fed twice a day and water was available ad libitum. If pigs did not eat their ration, feed refusal was removed from troughs daily and weighed, but feed on the floor of the pen was considered consumed.

2.4. Analytical procedure

The particle size distribution and modulus of fineness (MOF) of ground barley was determined by a series of sieves (ASAE, 1956). Sieve sizes were 4.0, 2.0, 1.0, 0.5, 0.25, 0.125 and 0.0625 mm. The degree of fineness was also evaluated by water absorption index (WAI) and by decrease in volume weight (DVW). WAI was determined according to the formula of König and Bernhard (1967): WAI = (weight of absorbed water by 100 g sample in 10 min)/(dry matter (DM) weight of the sample). DVW was calculated by the

<table>
<thead>
<tr>
<th>Experimental week</th>
<th>Barley–soyabean meal mixture</th>
<th>Wheat–soyabean meal mixture</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1350</td>
<td>1300</td>
</tr>
<tr>
<td>2</td>
<td>1550</td>
<td>1500</td>
</tr>
<tr>
<td>3</td>
<td>1800</td>
<td>1700</td>
</tr>
<tr>
<td>4</td>
<td>2000</td>
<td>1900</td>
</tr>
<tr>
<td>5</td>
<td>2200</td>
<td>2100</td>
</tr>
<tr>
<td>6</td>
<td>2400</td>
<td>2350</td>
</tr>
<tr>
<td>7</td>
<td>2650</td>
<td>2500</td>
</tr>
<tr>
<td>8</td>
<td>2750</td>
<td>2600</td>
</tr>
<tr>
<td>9</td>
<td>2850</td>
<td>2700</td>
</tr>
<tr>
<td>10</td>
<td>2950</td>
<td>2800</td>
</tr>
<tr>
<td>11 and thereafter</td>
<td>3050</td>
<td>2900</td>
</tr>
</tbody>
</table>
formula: \( DVW = \frac{(\text{volume weight of unground grain} - \text{volume weight of ground grain})}{(\text{volume weight of unground grain})} \times 100. \)

The proximate composition of feed and faeces was performed by the methods of AOAC (1984). Ether extract (EE) was determined after hydrolysis in 4 N HCl. Crude carbohydrates (CCH) was counted as organic matter minus crude protein (CP) and EE. Neutral and acid detergent fibre (NDF and ADF) was analysed according to Robertson and van Soest (1981). Gross energy (GE) was determined by the adiabatic bomb calorimeter. The percentage of lean in a carcass was evaluated with Hennessy GP equipment (Hennessy Grading Probe GP4, Hennessy Grading Systems, Auckland, New Zealand).

2.5. Statistics

The data were analysed as a nested design, mill type as the main treatment and within each mill type, fineness of grinding as the subtreatment (Snedecor and Cochran, 1980) by using the general linear model procedure of SAS, version 6.08 (SAS, 1990). The effects of the grinding method on the digestibility of barley and N-balance (Experiment 1) were analysed with the model:

\[
Y_{ijklm} = \mu + A_i + P_j + M_k + F_l(M)_k + e_{ijklm}
\]

where \( Y \) is the analyzed variable, \( \mu \) the overall mean, \( A \) the effects of the animal \( (i = 1.8) \), \( P \) is the effect of the period \( (j = 1 \ldots 6) \), \( M \) the effect of mill type \( (k = 1 \ldots 4) \), \( F(M) \) the effect of the fineness within the mill type \( (l = 1 \ldots 2) \) and \( e \) the residual error. The \( F(M) \) was used as the error term for testing the effect of mill type.

In the digestibility of wheat and N-balance experiment (Experiment 2), data was analysed using the model:

\[
Y = \mu + P_i + B_j + A_m(B_j) + (PB)_{ij} + (MB)_{jk} + M_k + F_l(M)_k + \varepsilon_{ijklm}
\]

where \( \mu \) is the overall mean, \( P \) the effect of period \( (i = 1 \ldots 6) \), \( B \) the effect of block \( (j = 1 \ldots 2) \), \( A_m(B_j) \) the effect of animal in the block \( (m = 1 \ldots 6) \), \( PB \) the interaction of period and block, \( MB \) the interaction of mill type and block, \( M_k \) the effect of mill type \( (k = 1 \ldots 3) \), \( F(M)_k \) the effect of fineness within the mill type \( (l = 1 \ldots 2) \) and \( \varepsilon_{ijklm} \) the residual error. The \( F(M) \) was used as the error term for testing the effect of mill type.

The daily gain, feed conversion ratio and carcass quality data from the growth experiments (experiments 3 and 4) were analysed on a pen basis with the model:

\[
Y_{klmn} = \mu + M_k + F_l(M)_k + \varepsilon_{klmn}
\]

where \( Y \), \( \mu \), \( M \), \( F(M) \) and \( e \) were as in the Experiment 1. The \( F(M) \) was used as the error term for testing the effect of mill type.

The effects of fineness within each mill were analysed by the following orthogonal contrasts in all experiments: \( C1 = H; \) fine vs. coarse, \( C2 = R1 \); fine vs. coarse, \( C3 = R2 \), fine vs. coarse, \( C4 = R3 \), fine vs. coarse. The tabulated values are least square means.
3. Results

3.1. Particle size

Using visual estimation, barley was ground into thin easily broken flakes by flattening roller mill, while crimping roller mill produced hard pieces of kernels. Hammer milled barley and wheat had the lowest modulus of fineness and decrease in volume weight, but water absorption index of hammer milled wheat was higher than that on the other mill types (Tables 3 and 4). Water absorption index of both cereals ground by crimping roller mill was the lowest. Enlarging the gap between the rolls and increasing the sieve size had a coarsening effect as illustrated by particle size distribution and by all fineness parameters.

3.2. Digestibility of barley and N-balance (Experiment 1)

Digestibilities of NDF \( (p < 0.01) \) and CCH \( (p < 0.05) \) were higher and digestibilities of CP \( (p < 0.05) \) and EE \( (p < 0.01) \) were lower in barley ground by the RM1 than those in barley ground by the other mill types (Table 5). The mill type had no effect on N retention, but pigs excreted less N via urine and more N via faeces with the diets ground by the crushing roller mills (RM1 and RM3) than by the other mill types \( (p < 0.05) \).

Fine grinding within RM1 improved digestibility of DM \( (p < 0.01) \), GE, CP, EE and CCH \( (p < 0.05) \) in barley compared to coarse grinding by RM1. Fine grinding had no effect on N retention of intake within any mill type, although fine grinding within RM1 and RM2 improved feed intake and N retention g/day \( (p < 0.10) \). Coarse grinding by RM1 shifted N excretion from urine to faeces compared to fine grinding by RM1 \( (p < 0.10) \).

Table 3
Particle size distribution (% on weight basis) and fineness parameters of ground barley

<table>
<thead>
<tr>
<th>Particle size (mm)</th>
<th>Hammer mill</th>
<th>Crimping roller mill</th>
<th>Flattening roller mill</th>
<th>Triple roller mill</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fine</td>
<td>Coarse</td>
<td>Fine</td>
<td>Coarse</td>
</tr>
<tr>
<td>4.0&lt;</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.1</td>
</tr>
<tr>
<td>2.0–4.0</td>
<td>0.1</td>
<td>2.3</td>
<td>19.9</td>
<td>62.6</td>
</tr>
<tr>
<td>1.0–2.0</td>
<td>10.3</td>
<td>23.3</td>
<td>61.3</td>
<td>32.3</td>
</tr>
<tr>
<td>0.5–1.0</td>
<td>31.6</td>
<td>32.9</td>
<td>11.4</td>
<td>2.9</td>
</tr>
<tr>
<td>0.25–0.5</td>
<td>28.2</td>
<td>21.5</td>
<td>4.0</td>
<td>1.0</td>
</tr>
<tr>
<td>0.125–0.5</td>
<td>14.5</td>
<td>10.6</td>
<td>1.5</td>
<td>0.4</td>
</tr>
<tr>
<td>0.0625–0.125</td>
<td>5.9</td>
<td>3.7</td>
<td>0.6</td>
<td>0.1</td>
</tr>
<tr>
<td>&lt;0.0625</td>
<td>8.5</td>
<td>4.4</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>Modulus of fineness</td>
<td>2.1</td>
<td>2.6</td>
<td>3.8</td>
<td>4.5</td>
</tr>
<tr>
<td>Decrease in volume weight (%)</td>
<td>8.2</td>
<td>4.9</td>
<td>32.0</td>
<td>29.3</td>
</tr>
<tr>
<td>Water absorption index</td>
<td>1.6</td>
<td>1.6</td>
<td>1.1</td>
<td>0.8</td>
</tr>
</tbody>
</table>
3.3. Digestibility of wheat and N-balance (Experiment 2)

The digestibility of CP ($p < 0.10$) and EE ($p < 0.05$) in wheat ground by the RM1 was lower than those in the diets ground by the other mill types (Table 6). Mill type had no effect on N retention g/day although RM2 had a higher N retention of intake ($p < 0.10$) compared to HM and RM1 mill. The proportion of faecal N excretion was higher with rolled than hammer milled wheat ($p < 0.10$).

Coarse grinding within RM1 and RM2 reduced feed intake. Fine grinding within RM1 improved all measured digestibilities of nutrients and GE ($p < 0.05$) compared to coarse grinding. The proportion of faecal N excretion ($p < 0.01$) and N retention of intake ($p < 0.10$) was increased by coarse grinding within RM1.

3.4. Growth experiment with barley (Experiment 3)

One pig on finely hammer milled barley died suddenly (necropsy was not performed) and one pig was removed from finely ground barley by RM2 due to leg injuries during the growth experiment. The daily gain and feed conversion ratio ($p < 0.10$) with RM1 barley was inferior to those with the other mill types (Table 7). Compared to coarse grinding, daily gain and feed conversion ratio was improved by fine grinding within RM1 ($p < 0.10$ and $p < 0.01$) and RM3 ($p < 0.05$). Also, the number of the weeks in experiment ($p < 0.01$) were reduced for the treatment fine grinding within RM3.

3.5. Growth experiment with wheat (Experiment 4)

The mill type had no effect on the pig performance and the carcass quality with wheat based diets (Table 8). Fine grinding within hammer milling and triple rolling slightly decreased the loss at slaughter ($p < 0.10$). Also, pig performance was improved by fine grinding within RM3 ($p < 0.10$) compared to coarse grinding.
Table 5
Feed intake, digestibility coefficients of the differently ground barley diets and nitrogen balance (Experiment 1)

<table>
<thead>
<tr>
<th></th>
<th>Hammer mill</th>
<th></th>
<th>Crimping RM&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Flattening RM</th>
<th></th>
<th>Triple RM</th>
<th></th>
<th>SEM&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Mill type</th>
<th>Fineness within mill</th>
<th>Contrast&lt;sup&gt;c&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fine</td>
<td>Coarse</td>
<td>Fine</td>
<td>Coarse</td>
<td>Fine</td>
<td>Coarse</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed intake (DM g/day)</td>
<td>1919</td>
<td>1925</td>
<td>1924</td>
<td>1839</td>
<td>1876</td>
<td>1773</td>
<td>1906</td>
<td>1862</td>
<td>30.7</td>
<td>NS&lt;sup&gt;d&lt;/sup&gt;</td>
<td>o&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td>Dry matter</td>
<td>0.822</td>
<td>0.818</td>
<td>0.833</td>
<td>0.807</td>
<td>0.819</td>
<td>0.814</td>
<td>0.785</td>
<td>0.797</td>
<td>0.006</td>
<td>NS</td>
<td>*</td>
</tr>
<tr>
<td>Gross energy</td>
<td>0.796</td>
<td>0.803</td>
<td>0.809</td>
<td>0.782</td>
<td>0.802</td>
<td>0.795</td>
<td>0.769</td>
<td>0.775</td>
<td>0.008</td>
<td>NS</td>
<td>NS&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
<tr>
<td>Crude protein</td>
<td>0.787</td>
<td>0.783</td>
<td>0.747</td>
<td>0.711</td>
<td>0.790</td>
<td>0.782</td>
<td>0.763</td>
<td>0.756</td>
<td>0.010</td>
<td>*</td>
<td>NS&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
<tr>
<td>Ether extract</td>
<td>0.542</td>
<td>0.518</td>
<td>0.409</td>
<td>0.362</td>
<td>0.491</td>
<td>0.480</td>
<td>0.456</td>
<td>0.435</td>
<td>0.015</td>
<td>**</td>
<td>NS&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
<tr>
<td>NDF-fibre</td>
<td>0.497</td>
<td>0.512</td>
<td>0.577</td>
<td>0.571</td>
<td>0.500</td>
<td>0.493</td>
<td>0.444</td>
<td>0.472</td>
<td>0.018</td>
<td>**</td>
<td>NS&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
<tr>
<td>Crude carbohydrates</td>
<td>0.856</td>
<td>0.853</td>
<td>0.885</td>
<td>0.863</td>
<td>0.855</td>
<td>0.850</td>
<td>0.819</td>
<td>0.835</td>
<td>0.006</td>
<td>*</td>
<td>NS&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

N-balance

|                  |               |                  |                         |               |                  |                   |                   |                   |           |                      |                   |
| N intake (g/day) | 48.4          | 48.5             | 49.0                     | 46.6          | 47.9             | 45.5             | 49.0              | 48.1             | 0.79      | NS                   | o<sup>e</sup>      |
| N in faeces (g/day) | 10.1        | 10.4             | 12.1                     | 13.5          | 9.7              | 9.8              | 11.5              | 11.6             | 0.47      | *                    | NS<sup>f</sup>     |
| N in urine (g/day) | 16.9          | 16.3             | 14.9                     | 13.2          | 15.7             | 15.5             | 14.5              | 14.6             | 0.52      | o<sup>e</sup>         | NS<sup>f</sup>     |
| N retained (g/day) | 21.4          | 21.8             | 22.0                     | 20.0          | 22.5             | 20.2             | 22.9              | 21.9             | 0.82      | NS                   | o<sup>e</sup>      |
| N retained, proportion of intake | 0.449 | 0.456 | 0.453 | 0.433 | 0.473 | 0.449 | 0.472 | 0.455 | 0.0118 | NS<sup>e</sup> | NS<sup>f</sup> |
| Faecal N, proportion of total N excretion | 0.389 | 0.402 | 0.466 | 0.509 | 0.399 | 0.399 | 0.451 | 0.448 | 0.0157 | * <sup>e</sup> | NS<sup>f</sup> |

<sup>a</sup> RM, roller mill.
<sup>b</sup> Standard error of mean.
<sup>c</sup> C1, hammer milling, coarse vs. fine; C2, crimping roller mill, coarse vs. fine; C3, flattening roller mill, coarse vs. fine; C4, triple roller mill, coarse vs. fine.
<sup>d</sup> Not significant.
<sup>e</sup> <i>p</i> < 0.10.
<sup>f</sup> <i>p</i> < 0.05; ** <i>p</i> < 0.01.
<table>
<thead>
<tr>
<th></th>
<th>Hammer mill</th>
<th>Crimping RM&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Flattening RM</th>
<th>SEM&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Mill type</th>
<th>Fineness within mill</th>
<th>Contrast&lt;sup&gt;c&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fine</td>
<td>Coarse</td>
<td>Fine</td>
<td>Coarse</td>
<td>Fine</td>
<td>Coarse</td>
<td></td>
</tr>
<tr>
<td>Feed intake (DM g/day)</td>
<td>1766</td>
<td>1725</td>
<td>1681</td>
<td>1744</td>
<td>1776</td>
<td>1709</td>
<td>24.9</td>
</tr>
<tr>
<td>Dry matter</td>
<td>0.887</td>
<td>0.885</td>
<td>0.879</td>
<td>0.870</td>
<td>0.881</td>
<td>0.876</td>
<td>0.0026</td>
</tr>
<tr>
<td>Gross energy</td>
<td>0.874</td>
<td>0.873</td>
<td>0.865</td>
<td>0.854</td>
<td>0.865</td>
<td>0.858</td>
<td>0.0031</td>
</tr>
<tr>
<td>Crude protein</td>
<td>0.878</td>
<td>0.873</td>
<td>0.855</td>
<td>0.841</td>
<td>0.870</td>
<td>0.861</td>
<td>0.0036</td>
</tr>
<tr>
<td>Ether extract</td>
<td>0.542</td>
<td>0.512</td>
<td>0.407</td>
<td>0.374</td>
<td>0.507</td>
<td>0.495</td>
<td>0.0106</td>
</tr>
<tr>
<td>NDF-fibre</td>
<td>0.523</td>
<td>0.501</td>
<td>0.522</td>
<td>0.487</td>
<td>0.517</td>
<td>0.532</td>
<td>0.0117</td>
</tr>
<tr>
<td>Crude carbohydrates</td>
<td>0.917</td>
<td>0.917</td>
<td>0.918</td>
<td>0.909</td>
<td>0.911</td>
<td>0.907</td>
<td>0.0023</td>
</tr>
</tbody>
</table>

*p < 0.10.
**p < 0.05; **p < 0.01.

<sup>a</sup> RM, roller mill.
<sup>b</sup> Standard error of mean.
<sup>c</sup> C1, hammer milling, coarse vs. fine; C2, crimping roller mill, coarse vs. fine; C3, flattening roller mill, coarse vs. fine.
<sup>d</sup> Not significant.
<sup>e</sup> p < 0.10.
Table 7
Effects of grinding method of barley on pig performance and carcass quality (Experiment 3)

<table>
<thead>
<tr>
<th></th>
<th>Hammer mill</th>
<th>Crimping RM&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Flattening RM</th>
<th>Triple RM</th>
<th>SEM&lt;sup&gt;c&lt;/sup&gt;</th>
<th>Mill type within the mill</th>
<th>Fineness Contrast&lt;sup&gt;d&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fine</td>
<td>Coarse</td>
<td>Fine</td>
<td>Coarse</td>
<td>Fine</td>
<td>Coarse</td>
<td></td>
</tr>
<tr>
<td>Total feed consumption</td>
<td>357</td>
<td>364</td>
<td>364</td>
<td>410</td>
<td>342</td>
<td>354</td>
<td>346</td>
</tr>
<tr>
<td>(kg DM/pen of two pigs)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>FS</td>
<td></td>
</tr>
<tr>
<td>Daily weight gain (g)</td>
<td>911</td>
<td>895</td>
<td>848</td>
<td>813</td>
<td>888</td>
<td>901</td>
<td>932</td>
</tr>
<tr>
<td>FCR&lt;sup&gt;a&lt;/sup&gt; (kg DM/kg gain)</td>
<td>2.34</td>
<td>2.37</td>
<td>2.52</td>
<td>2.70</td>
<td>2.35</td>
<td>2.35</td>
<td>2.27</td>
</tr>
<tr>
<td>Weeks in experiment</td>
<td>12.1</td>
<td>12.3</td>
<td>12.9</td>
<td>13.4</td>
<td>12.3</td>
<td>12.0</td>
<td>11.7</td>
</tr>
<tr>
<td>Carcass lean</td>
<td>0.622</td>
<td>0.615</td>
<td>0.614</td>
<td>0.617</td>
<td>0.616</td>
<td>0.619</td>
<td>0.617</td>
</tr>
<tr>
<td>Loss at slaughter of live weight</td>
<td>0.265</td>
<td>0.263</td>
<td>0.267</td>
<td>0.262</td>
<td>0.264</td>
<td>0.264</td>
<td>0.268</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>FS</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> Feed conversion ratio.
<sup>b</sup> RM, roller mill.
<sup>c</sup> Standard error of mean.
<sup>d</sup> C1, hammer milling, coarse vs. fine; C2, crimping roller mill, coarse vs. fine; C3, flattening roller mill, coarse vs. fine; C4, triple roller mill, coarse vs. fine.
<sup>e</sup> Not significant.
<sup>f</sup> **p < 0.01**.
Table 8
Effects of grinding method of wheat on pig performance and the carcass quality (Experiment 4)

<table>
<thead>
<tr>
<th></th>
<th>Hammer mill</th>
<th>Crimping RM</th>
<th>Flattening RM</th>
<th>Triple RM</th>
<th>SEMc</th>
<th>Mill type</th>
<th>Fineness within the mill</th>
<th>Contrastd</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fine</td>
<td>Coarse</td>
<td>Fine</td>
<td>Coarse</td>
<td>Fine</td>
<td>Coarse</td>
<td>Fine</td>
<td>Coarse</td>
</tr>
<tr>
<td>Total feed consumption</td>
<td>331</td>
<td>329</td>
<td>333</td>
<td>338</td>
<td>333</td>
<td>317</td>
<td>339</td>
<td>330</td>
</tr>
<tr>
<td>(kg DM/pen of two pigs)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daily gain (g/day)</td>
<td>908</td>
<td>930</td>
<td>909</td>
<td>890</td>
<td>912</td>
<td>915</td>
<td>880</td>
<td>922</td>
</tr>
<tr>
<td>FCRa (kg DM/kg)</td>
<td>2.22</td>
<td>2.17</td>
<td>2.21</td>
<td>2.27</td>
<td>2.20</td>
<td>2.21</td>
<td>2.27</td>
<td>2.18</td>
</tr>
<tr>
<td>Weeks in experiment</td>
<td>11.7</td>
<td>11.7</td>
<td>11.9</td>
<td>12.0</td>
<td>11.9</td>
<td>11.8</td>
<td>12.2</td>
<td>11.8</td>
</tr>
<tr>
<td>Carcass lean</td>
<td>0.610</td>
<td>0.610</td>
<td>0.613</td>
<td>0.615</td>
<td>0.616</td>
<td>0.613</td>
<td>0.616</td>
<td>0.613</td>
</tr>
<tr>
<td>Loss at slaughter of live weight</td>
<td>0.252</td>
<td>0.262</td>
<td>0.255</td>
<td>0.263</td>
<td>0.257</td>
<td>0.262</td>
<td>0.257</td>
<td>0.266</td>
</tr>
</tbody>
</table>

a Feed conversion ratio.

b RM, roller mill.

c Standard error of mean.

d C1, hammer milling, coarse vs. fine; C2, crimping roller mill, coarse vs. fine; C3, flattening roller mill, coarse vs. fine; C4, triple roller mill, coarse vs. fine.

e Not significant.

f $p < 0.10$.

* $p < 0.05$; ** $p < 0.01$.  

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4. Discussion

4.1. Particle size distribution

Particles larger than 1.0 mm constituted ca. 75 and 70% of the rolled barley and wheat on weight basis. Especially, crimping roller mill produced large particles and ca. 90% of ground cereals consisted in particles larger than 1.0 mm. However, it was impossible to assess, if the differences in the particle size distributions were caused by the rolling method, because the gaps between the rolls were confounded with the mill type. The coarsening effect of enlargement of the gap between rolls was illustrated by the increased proportion of the 2.0–4.0 mm particles within all the roller mills.

4.2. Nutrient digestibilities

Despite large particles of rolled feed, the mill type had only a tendency \( p = 0.11 \) to affect the digestibility of DM and GE in barley and no effect on digestibility of wheat based diets. These results are consistent with the earlier results with barley (Simonsson, 1978b; Näsi, 1992) and wheat (Ivan et al., 1974). Roller mills and especially triple roller mill left some barley unground (whole kernels 0.3, 0.8 and 2.0% on a weight basis of RM1, RM2 and RM3 barley, respectively), which was probably the main reason for a slightly lowered digestibility of triple rolled barley. The crimping roller mill increased the mean retention time of barley diets in the gastrointestinal tract by 5.2 h (Laurinen et al., 1997), which was the most likely reason for improved NDF digestibility (Van Soest et al., 1983). Näsi (1992) found slightly higher digestibility of NDF in hammer milled than in rolled barley. This is consistent with our results concerning only the triple rolled barley. The mean retention time of the wheat based diet and NDF digestibility in wheat was not affected by grinding method. Crimping roller mill decreased CP and EE digestibility in both cereals. In earlier experiments CP digestibility in hammer milled barley has been slightly higher (Simonsson, 1978b) and lower (Näsi, 1992) than that in rolled barley and mill type has had no effect on CP digestibility in wheat (Ivan et al., 1974).

Coarse grinding impaired digestibilities only within the crimping roller mill. In earlier studies, the screen size under 5.25 and 6.0 mm has had no effect on digestibility of DM in barley (Simonsson, 1978a) and wheat (Sauer et al., 1977).

4.3. Nitrogen balances

The flattening roller mill improved N retention with wheat, but mill type did not affect N retention with barley. This indicates that particle size per se may not have an effect on ileal digestibility of CP. In the previous experiment, rolling has improved N utilisation compared to hammer milled barley (Näsi, 1992). In our experiment, coarse grinding within the crimping roller mill with wheat improved N utilisation compared to fine grinding, which was surprising. According to Sauer et al. (1977) coarse grinding decreases the ileal digestibility of amino acids which depresses N utilisation.

Rolling, especially by the crimping roller mill, shifted N excretion from urine to faeces thus decreasing CP digestibility without depressing N utilisation with both cereals. The
increased NDF digestibility in barley and repartition of N excretion with both cereals suggests that microbial fermentation and protein synthesis have increased in the hindgut, thus impairing the total tract digestibility of CP (Kirchgessner et al., 1989; Tetens et al., 1996). Decreased ileal CP digestibility is also a possible explanation for decreased total tract digestibility, but that would also lead to impaired N utilisation.

4.4. Growth experiments

Pigs were very reluctant to eat coarsely rolled barley by the crimping roller mill and threw some feed on the floor of the pen and into the manure channel. That wasted feed, being mixed with manure, was impossible to measure or refeed to the pigs. Because this kind of wastage occurred only with the crimping roller mill and wasting is part of the total feed consumption from the economical point of view, the wasted feed was included in calculations. Due to wastage of feed, pig performance was impaired with barley ground by the crimping roller mill, despite nearly the same GE digestibility and equal N utilisation, compared to the other mill types. In several earlier experiments, pig performance has been equal on hammer milled and rolled barley, and no information on feeding problems have been reported (Cole et al., 1975; Simonsson, 1978b; Alaviuhkola et al., 1993). Also, in our experiment with wheat, mill type had no effect on pig performance and no feed intake problems occurred. Seerley et al. (1988) found that rolling slightly improved pig performance in the 55–100 kg weight range compared to hammer milled wheat. Similar to our study, carcass quality has been the same on hammer milled and rolled barley in the studies of Simonsson (1978a) and Alaviuhkola et al. (1993).

Increasing sieve size from 1.25 to 5.25 mm with barley (Simonsson, 1978a) and from 3.18 to 6.35 mm with wheat (Seerley et al., 1988) has not affected daily gain and feed conversion ratio. Also, in our experiment increasing sieve size from 3.0 to 5.0 mm did not affect pig performance. However, increasing the sieve size from 6.4 to 12.7 mm and lowering operating speed of the hammer mill from 2500 to 2000 rpm, has improved feed conversion ratio with wheat (Hale and Thompson, 1986).

4.5. Different fineness illustrated by grinding parameters vs. digestibility and pig performance

Particle size and area have affected digestibility rate (Löwgren et al., 1989) and ileal digestibility (Sauer et al., 1977; Bach Knudsen and Johansen, 1995) thereby having a great possibility to affect pig performance. However, despite large variation of the particle size distribution, modulus of fineness, water absorption index and decrease in volume weight, total tract digestibilities were almost the same on all grinding methods with barley. In addition, pig performance was almost the same on all grinding methods with wheat. Particle size distribution and modulus of fineness do not take into account the shape of the particles. That is why those parameters have been discarded as the predictors of pig performance and digestibility for comparing hammer milled and rolled cereals (Lawrence, 1970; Simonsson, 1978b; Näsi, 1992; Alaviuhkola et al., 1993). Water
absorption index takes into account the particle area, but it was also a poor indicator of digestibility and pig performance for comparing different mill types.

5. Conclusions

Mill type had no effect on DM and GE digestibility of barley or wheat based diets, if all the kernels were ground. Rolling, especially crimping roller mill, shifted some of the N excretion from urine to faeces. Flattening roller mill improved N utilisation with wheat, but with barley, mill type did not affect N utilisation. Daily gain, feed conversion ratio and carcass quality were very little affected by the mill type or fineness of grinding within the mill types, if the grinding method did not induce any feeding problems. The measured fineness of grinding parameters poorly predicted digestibilities and pig performance.

References


