Influence of Feed Intake, Forage Physical Form, and Forage Fiber Content on Particle Size of Masticated Forage, Ruminal Digesta, and Feces of Dairy Cows

R. D. SHAVER, A. J. NYTES, L. D. SATTER, and N. A. JORGENSEN
US Dairy Forage Research Center, USDA-ARS
and
Department of Dairy Science
University of Wisconsin
Madison 53706

ABSTRACT
Two trials were conducted to determine particle size of masticates, ruminal digesta, and feces of dairy cows. In Trial 1, three Holstein cows with ruminal cannulae were fed prebloom alfalfa hay in long, chopped, or pelleted form in a Latin square design (21-d periods) conducted in early lactation (wk 3 to 11) and again during the dry period to attain high (3.75) and low (1.95% of BW) feed consumption. In trial 2, prebloom, midbloom, and full bloom alfalfa hay, mature bromegrass hay, and corn silage were fed to early lactation (wk 5 to 15) Holsteins in a 5 × 5 Latin square design (15-d periods). All diets (Trials 1 and 2) were formulated to 17% CP and contained forage:grain in a 60:40 ratio (DM basis). Similar particle distributions of digesta from long and chopped hay diets suggest little influence of chopping forage on particle size reduction when high quality forage is fed. The large proportion of DM in the small particle (<.6 mm) pool in the rumen in both trials suggests that rate of escape of small particles from the rumen is an important factor influencing ruminal retention time. Increased proportion of coarse (>2.36-mm screen) fecal particles at high intake and with fine grinding appears related to a reduction in chewing per unit feed consumed. Soluble DM and particulate matter passing a .063-mm screen made up a significant portion (30 to 50%) of the total DM sieved from all sampling sites in both trials.

INTRODUCTION
Rumen fill can physically limit intake in dairy cows fed high forage diets. Feed residue must escape the rumen by either digestion or passage for further intake to occur. Effects of rate of particle size reduction on ruminal retention time and fill are not well-established.

Hungate (8) suggested that the rumen consists of a rumination pool of large particles that cannot pass through the reticulo-omasal orifice and a pool of small particles eligible for escape from the rumen. Poppi et al. (10) proposed a critical size theory based on analysis of fecal particle distributions, which suggests that particles above a certain size cannot leave the rumen whereas particles below the critical size have a similar ease of passage. Each concept has been interpreted to suggest that particle size reduction is rate limiting for particulate passage. The small particle pool may contain 60% of the total DM (4, 10, 19). With such a large proportion of the digesta in the small particle pool, particle size reduction may not be the limiting step in passage of undigested feed residue from the rumen.
Information about particle size distributions at various sites within the reticulorumen, abomasum, and intestines is limited. It has been observed that coarse particles are more concentrated in the dorsal than ventral rumen and that the proportion of coarse particles declines with time after feeding (6). Mean particle size decreased in the progression of feed, rumen digesta, and feces (9). Other workers (10, 15) concluded that little particle size reduction occurs postruminally. Limited information is available concerning particle size reduction of feed and digesta in high producing dairy cows. Objectives of this study were 1) to determine particle size distributions of masticated forage, ruminal digesta, and feces of dairy cows and 2) to evaluate effects of forage physical form, feed intake, and forage fiber content on particle size reduction.

MATERIALS AND METHODS

Particle size was determined on digesta samples collected in two digestion trials (13, 14). In Trial 1, three Holstein cows were fed prebloom alfalfa hay in long (LH), chopped (CH), and pelleted (PH) form in a 3 x 3 Latin square design (21-d periods) conducted in early lactation (wk 3 to 11) and during the dry period to attain high (H) and low (L) feed intake. Average intakes of DM for H and L were 3.75 and 1.95% of body weight. Digestion, passage, and production data have been reported, as well as the method of preparation of CH and PH hays (14). Chewing activities were visually noted for individual cows every 5 min over 24 h during each 7-d collection period. It was assumed that the eating, ruminating, or resting activity observed at 5-min intervals occurred for the entire 5 min preceding the observation. Total eating, ruminating, or resting activity represented the sum of 5-min intervals for each activity. In Trial 2, pre-(AE), mid-(AM), and full-(AL) bloom alfalfa hay, mature bromegrass (BR) hay, and corn silage (CS) were fed to early lactation (wk 5 to 15) Holstein cows in a 5 x 5 Latin square design with 15-d periods. Intake, digestion, passage, and production data have been presented (13). All diets (Trials 1 and 2) contained forage:concentrate in a 60:40 ratio (DM basis). Forage and concentrate were fed 4x daily at 0400, 1000, 1600, and 2200 h in Trial 1 and at 0500, 1100, 1700, and 2200 h in Trial 2. Chemical composition of forages and total diets appear in Table 1.

In Trial 1, samples of masticated forage were collected as boluses of ingested hay passed from the esophagus to the rumen at 1000 h on the last day of each period when the rumen was empty during determination of rumen fill. Samples of masticated forage were composite of three boluses collected after each treatment hay was consumed for 3 to 5 min. Rumen and fecal samples were collected at 1400 h on d 19.

<table>
<thead>
<tr>
<th>Chemical analysis (dry matter basis)</th>
<th>Trial 1</th>
<th>Trial 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tr>
<tr>
<td>Alfalfa hay</td>
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<tr>
<td>Organic matter, %</td>
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</tr>
<tr>
<td>Crude protein, %</td>
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<td>23.2</td>
</tr>
<tr>
<td>Neutral detergent fiber, %</td>
<td>41.3</td>
<td>42.2</td>
</tr>
<tr>
<td>Acid detergent fiber, %</td>
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<td>32.6</td>
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<tr>
<td>Total diet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Organic matter, %</td>
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</tr>
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<td>Crude protein, %</td>
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<td>17.4</td>
</tr>
<tr>
<td>Neutral detergent fiber, %</td>
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<td>30.8</td>
</tr>
<tr>
<td>Acid detergent fiber, %</td>
<td>19.9</td>
<td>21.1</td>
</tr>
</tbody>
</table>

1 Prebloom (AE), midbloom (AM), and full (AL) bloom alfalfa hay, mature bromegrass (BR) hay, and corn silage (CS).

2 Forage:concentrate ratio, 60:40 (DM basis).
Figure 1. Particle size distribution of chopped hay separated by wet sieving analysis.

Figure 2. Particle size distribution of ground hay separated by wet sieving analysis.

and 20 of each period. Dorsal rumen samples were a composite of four grab samples obtained from the caudal and cranial dorsal rumen. Reticulum and ventral rumen samples were obtained by passing a capped 400-ml wide mouth plastic bottle into the sampling site twice to collect 800 ml. Digesta from the reticulum and ventral rumen contained sufficient liquid to allow digesta to flow freely into the bottle so that a representative sample could be obtained. Daily samples from each site were composited by hand on a weight basis. Samples from the ventral rumen and reticulum were composited using a subsampler described by Combs (4). Daily samples from each site were composited by period and stored at -20°C.

Data were analyzed with analysis of variance for Latin square designs (16) using the General Linear Models procedure of the Statistical Analysis System (12). In Trial 1, effects due to intake x forage physical form were included in the model. Individual mean differences were by Fisher's least significant difference method (16) after a significant F-test.

RESULTS AND DISCUSSION

Chewing activity data (Trial 1) appear in Table 2. All chewing activity parameters were similar for LH and CH. Feeding pelleted hay reduced total chewing activity per unit of feed consumed and rumination activity per unit of NDF consumed. Time spent eating and ruminating declined as feed consumption declined. Total chewing activity per unit of intake was lower at high feed consumption. Rumination activity per unit of NDF intake was lower at
TABLE 2. Influence of forage physical form and amount of feed consumption on chewing activity (Trial 1).

<table>
<thead>
<tr>
<th>Item</th>
<th>Form of hay</th>
<th>Feed consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Long</td>
<td>Chopped</td>
</tr>
<tr>
<td>Eating, min/d</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ruminating min/d</td>
<td>383a</td>
<td>398a</td>
</tr>
<tr>
<td>min/kg NDF Intake</td>
<td>64.1a</td>
<td>64.4a</td>
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<tr>
<td>Total chewing min/d</td>
<td>579a</td>
<td>572a</td>
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<tr>
<td>min/kg DM Intake</td>
<td>29.2a</td>
<td>28.6a</td>
</tr>
</tbody>
</table>

a,b Means in the same row within measures with different superscripts differ (P<.001).

High feed consumption. This is an agreement with observations of Bae et al. (1). However, in the study of Bae et al. (1), different amounts of feed consumption were obtained by restricting intakes, whereas cows were fed ad libitum diets in early lactation and the dry period to obtain high and low feed consumption in our study. Whether the same mechanism is responsible for the relationship between rumination activity per unit NDF intake and feed consumption in both studies cannot be determined from these data.

Dry matter content of masticated forage, rumen digesta, and fecal samples (Trial 1) is in Table 3. Dry matter content of masticated hay, ventral rumen, and reticulum samples was highest for PH. This may reflect reduced chewing activity (Table 2) and consequent reduction in saliva flow (3). This was most apparent in the relationship between eating time and DM content of the hay masticate for PH when compared with those for LH and CH. Sample DM contents were similar for LH and CH at all sampling sites. Amount of consumption did not influence sample DM content. Sample DM content was greater for the dorsal rumen than the ventral rumen or reticulum. This is in agreement with the findings of Evans et al. (6).

Particle size distribution of hay masticates, ruminal digesta, and feces (Trial 1) are in Table 4. Hay masticates for LH and CH were of a similar particle size. Although the forage differed in particle length (14), size distribution of DM entering the rumen was similar due to mastication during initial consumption of forage. Mastication during the initial consumption of alfalfa reduced the proportion of coarse particles (>1 mm) by 50% in sheep (11). Uylatt (17) suggested that food is chewed during eating to a common end point so that the bolus

TABLE 3. Influence of forage physical form and amount of feed consumption on sample dry matter content (Trial 1).

<table>
<thead>
<tr>
<th>Item</th>
<th>Form of hay</th>
<th>Feed consumption</th>
</tr>
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<tr>
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<td>Hay masticate</td>
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<td>22.7b</td>
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<tr>
<td>Dorsal rumen</td>
<td>16.4</td>
<td>15.6</td>
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<td>Ventral rumen</td>
<td>5.3b</td>
<td>6.8b</td>
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<tr>
<td>Reticulum</td>
<td>6.2b</td>
<td>5.9b</td>
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<tr>
<td>Feces</td>
<td>17.9</td>
<td>17.2</td>
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</table>

a,b Means in the same row within measures with different superscripts differ (P<.05).
may be swallowed easily. That this occurred with little change in time spent eating (Table 2) was probably related to the low fiber content of the forage (Table 1).

Particle size of ruminal digesta and feces was similar for LH and CH. The largest proportion of coarse (>2.36-mm screen) DM was observed in the dorsal rumen for LH and CH, and this agrees with the observations of Evans et al. (6). The proportion of coarse (>2.36-mm screen) DM was higher for PH than for LH or CH in the ventral rumen. Higher DM content and proportion of coarse DM in the ventral rumen for PH indicate effects of physical form on digesta stratification. When sampling from the rumen it appeared that the integrity of the fibrous mat in the rumen was diminished for PH compared with that of LH and CH. Lack of a fibrous mat may have influenced the normal stratification of particles within the rumen. Little difference

<table>
<thead>
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<td>Masticate</td>
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</tr>
<tr>
<td>&gt;2.36</td>
<td>50.9 &lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>&gt;1.18</td>
<td>58.7 &lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>&gt; .6</td>
<td>64.2 &lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>&lt; .6</td>
<td>35.8 &lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
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<td>Dorsal rumen</td>
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<td>Long</td>
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<td>30.6 &lt;sup&gt;b&lt;/sup&gt;</td>
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<td>39.7 &lt;sup&gt;b&lt;/sup&gt;</td>
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<tr>
<td>&lt; .6</td>
<td>60.3 &lt;sup&gt;a&lt;/sup&gt;</td>
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<td>&lt; .063</td>
<td>47.1 &lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Feces</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Long</td>
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<td>&gt;1.18</td>
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<td>&lt; .6</td>
<td>62.9</td>
</tr>
<tr>
<td>&lt; .3</td>
<td>54.4 &lt;sup&gt;ab&lt;/sup&gt;</td>
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<tr>
<td>&lt; .063</td>
<td>47.4 &lt;sup&gt;ab&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a,b</sup> Means in the same row within measures with different superscripts differ (P<.05).
was observed between samples from the ventral rumen and reticulum. Particle size distributions were similar for samples from the reticulum and feces, suggesting little size reduction postruminally. This agrees with observations of others (10, 15).

The fine DM pool (<.6-mm screen) comprised nearly 60% of the ventral rumen and reticulum DM and 40% of the dorsal rumen DM for LH and CH. Thus, a large portion of rumen DM can theoretically pass through the reticulo-omasal orifice based on fecal particle distributions. Others (4, 10, 19) have made similar observations.

Although not statistically significant, coarse fecal DM tended to increase with fine grinding and at high feed intake. This is in agreement with other work (18) and was possibly related to the reduction in chewing per unit feed consumed. Dry matter passing the .063-mm screen comprised nearly 40 to 50% of the DM in the ventral rumen, reticulum, and feces. Soluble DM, very fine particulate DM, or microbial matter comprise this fraction. No attempt was made to determine the relative contribution of each of these to the <.063-mm fraction. Cardoza (2) observed that 40 to 50% of the fecal DM passed through a .037-mm screen in studies with dairy cattle.

Particle size distributions of rumen and fecal samples (Trial 2) are in Table 5. Percent coarse (>2.36-mm screen) rumen DM was lowest for AM, AL, and BR. Although chewing activities were not measured, this may have been related to an increase in rumination time per unit fiber intake for the high fiber diets (2, 18). Percent coarse fecal DM was also lowest for the high fiber diets. This is in agreement with work by Cardoza (2). A large portion of the rumen DM could theoretically pass from the rumen since 39 to 46% of rumen DM passed through a .6-mm screen. Retention of whole corn kernels on coarse screens may partially account for the high proportion of DM retained on screens >.6 mm in size for diet CS.

Poppi et al. (10) suggested a critical size of 1.18 mm for escape of particles from the rumen. Critical size for escape of particles from the rumen in cattle appears greater than 1.18 mm since 20 to 25% and 24 to 36% of fecal DM in trials 1 and 2, respectively, were retained on screens >1.18 mm in size as opposed to 1 to 2% retention reported by Poppi et al. (10) with sheep. Cardoza (2) suggested a critical size of 3.6 mm for dairy cattle. This is in closer agreement with our data since only 4 to 5% of fecal DM was retained on screens >4.75 mm in size. Thus, in both trials reported here and in the

<table>
<thead>
<tr>
<th>Site</th>
<th>AE</th>
<th>AM</th>
<th>AL</th>
<th>BR</th>
<th>CS</th>
<th>SE</th>
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<tr>
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<td></td>
<td></td>
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<tr>
<td>&gt;2.36</td>
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<td>Feces screen size, mm</td>
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</table>

Means in the same row with different superscripts differ (P<.05).

1 Prebloom (AE), midbloom (AM), and full (AL) bloom alfalfa hay, mature bromegrass (BR) hay, and corn silage (CS).
study of Cardoza (2), dairy cows passed coarser DM from the rumen than has previously been reported for sheep (10). Percent of DM passing a .063-mm screen ranged from 28 to 36% in the rumen to 33 to 44% in the feces.

Similar particle distributions for LH and CH suggest little influence of chopping forage on particle size reduction when low fiber forage is fed. The large proportion of rumen DM contained in the small particle pool coupled with small differences in chewing activity for LH and CH raises the question of what role particle size reduction has as a rate limiting step in particulate passage from the rumen. The large proportion of small particles in the lumen for low and high fiber forages suggests that rate of escape of small particles from the rumen is an important factor influencing ruminal retention time. Particle specific gravity influences escape of small particles from the lumen (5). The effect that larger particles have on average retention time of DM in the rumen may be through their effect on rumen mat formation, and subsequent entrapment of small particles, as opposed to longer retention time of the large particle itself.

Soluble DM or particulate matter passing a .063-mm screen comprised a significant portion (30 to 50%) of the total DM sieved from all sampling sites. This raises questions about current concepts of flow rates of solids and liquid from the rumen (7). It is widely held that the rumen consists of particulate and liquid phases, which differ in their rate of passage from the rumen. However, our data suggest that a large portion of the rumen DM is either very fine or soluble and potentially flows with the liquid phase.

ACKNOWLEDGMENTS

The authors thank Ralph Lance at UW-Madison and the farm staff at US Dairy Forage Research Center for care of the animals. Appreciation goes to Beth Jones for assistance with sample collection.

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