Effects of Neutral Detergent Fiber Concentration and Particle Size of the Diet on Chewing Activities of Dairy Cows

Y. H. Moon, S. C. Lee[1] and Sung S. Lee*

Department of Animal Science & Biotechnology, RAIRC, Jinju National University, Jinju, 660-758, Korea

ABSTRACT : Six dry Holstein cows were used to evaluate the effect of dietary neutral detergent fiber (NDF) concentration and particle size (PS) on chewing activity. Treatments were arranged in a 3×3 factorial design; total mixed rations contained three NDF concentrations (26, 32, 38%) and three PS (1.0, 1.5, 2.0 cm). NDF levels and particle sizes of diets were adjusted by formulating rate and cutting length of alfalfa hay and rice straw. Cows were fed twice daily at 90% of *ad libitum* feed intake throughout the experiment. Chewing activity was positively associated with NDF concentration, but not significantly affected by PS of diet. Eating time per unit of NDF intake was affected by PS rather than NDF concentration of diet. Time spent ruminating per unit DM or NDF intake increased with increasing NDF concentration of diet, but was not affected by PS. As the PS of diet increased, the eating time per day increased, but the rumination time decreased. In addition, as the number of rumination bolues decreased the rumination duration increased as well as the chews per bolus. The regression equation induced from relationships of NDF concentrations (NDF, %) and particle sizes (PS, cm) of diet on roughage value index (RVI, min of chewing time/kg DMI) was as follows. RVI=-19.672+1.44×NDF+5.196×PS, (r^2=0.81). ***(Asian-Aust. J. Anim. Sci. 2004. Vol 17, No. 11 : 1535-1540)***

Key Words : Chewing Activity, NDF, Particle Size, Roughage Index Value, Dairy Cow

INTRODUCTION

Although the increased chewing time did not increase total daily saliva secretion because increased eating and ruminating saliva was associated with decreased resting saliva (Maekawa et al., 2002), time spent chewing and the number of chews during eating and rumination are primary factors that determine the rate of saliva secretion (Balch, 1958). Saliva buffers products of fermentation within the rumen and enhances cellulolysis. Consequently, chewing is also the primary mode of particle size (PS) reduction of ingested roughage, enabling digesta to leave the reticulorumen (Ulyatt et al., 1986), and influences the extent, rate, and site of digestion (Beauchemin and Buchanan-Sminth, 1989).

Chewing activity is the animal response associated with physical effectiveness of the neutral detergent fiber (NDF) fraction (Mertens, 1997) and especially, rumination activity is influenced highly by the source and nature of the feed (Moon et al., 2002), physiological state of cow (Campling, 1966), forage to concentrate ratio and forage intake (Sudweeks et al., 1979; Beauchemin and Buchanan-Smith, 1989), NDF content of diet (Beauchemin and Buchanan-Smith, 1989), feed PS (Woodford et al., 1986), specific gravity of diet (Welch, 1986), and amount of feed intake (Luginbuhl et al., 1989). Chewing time is highly influenced by NDF content, and the PS of forage (Beachemin, 1991) is a very accurate estimator of effective forage intake, therefore it may be a useful indicator of dietary effective fiber (Mertens, 1997). Taking this into consideration, the ability to quantify eating and ruminating activities of cattle is desirable to provide greater understanding of the effects and significance of chewing on feed utilization and animal performance. Balch (1971) proposed using time spent chewing per kilogram DM intake as an index of “fibrousness” of feedstuffs. Sudweeks et al. (1981) extended this concept and developed the roughage value index (RVI) displayed as chewing time (minute) spent for eating and ruminating per kilogram of DM intake. The RVI could be used to define animal roughage requirements and, thus to make feed formulation, particularly for total mixed rations for ruminants.

The objective of this study is to evaluate the chewing activity to predict the RVI by NDF concentrations and PS in total mixed ration of dairy cow.

* Corresponding Author: Sung S. Lee. Major in Dairy Science, Division of Applied Life Science, Gyeongsang National University, Jinju 660-701, Korea. Tel: +82-55-751-5411, Fax: +82-55-751-5410, E-mail: lss@nongae.gsnu.ac.kr

[1] Division of Applied Life Science, Gyeongsang National University, Jinju 660-701, Korea.

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MATERIALS AND METHODS

Animals and diets

Six dry Holstein cows weighed an average of 550 kg were used to evaluate chewing activity. Treatments were arranged in a 3×3 factorial design; three feed particle sizes (PS; 1.0, 1.5, 2.0 cm) in the total mixed rations of three NDF concentrations (26, 32, 38%). The experiment was composed of three periods of 26 d; 10 d of preliminary for the start of period, 2 d for data collection, and 5 d of

Table 1. Compositions of experimental diets

Composition	NDF 26%				NDF 32%				NDF 38%			
	%	Particle size, cm			%	Particle size, cm			%	Particle size, cm		
		1.0	1.5	2.0		1.0	1.5	2.0		1.0	1.5	2.0
In gradients, % as fed basis												
Yellow corn	39.32	1.26	1.26	1.26	37.38	1.26	1.26	1.26	32.98	1.26	1.26	1.26
Wheat meal	-	-	-	-	8.57	0.84	0.84	0.84	16.25	0.84	0.84	0.84
Sunflower meal	15.00	1.09	1.09	1.09	10.00	1.09	1.09	1.09	-	-	-	-
Tapioca	15.00	0.63	0.63	0.63	3.15	0.63	0.63	0.63	-	-	-	-
Molasses	2.60	0.00	0.00	0.00	2.00	0.00	0.00	0.00	-	-	-	-
Urea	0.77	0.00	0.00	0.00	0.30	0.00	0.00	0.00	0.50	0.00	0.00	0.00
Limestone	0.20	0.00	0.00	0.00	0.20	0.00	0.00	0.00	-	-	-	-
$CaHPO_4$	0.66	0.00	0.00	0.00	0.40	0.00	0.00	0.00	0.17	0.00	0.00	0.00
NaCl	0.50	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.50	0.00	0.00	0.00
Vitamin-mineral premix[2]	0.50	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.50	0.00	0.00	0.00
Corn cob	4.95	1.52	1.52	1.52	4.50	1.52	1.52	1.52	5.00	1.52	1.52	1.52
Alfalfa hay	14.35	1.00	1.00	6.00	22.75	1.00	3.00	3.00	30.87	1.00	2.00	3.00
Rice straw	6.15	1.00	1.00	6.00	9.75	1.00	1.00	6.00	13.23	1.00	2.00	3.50
Total	100.00	1.03	1.52	2.06	100.00	1.07	1.52	2.01	100.00	1.07	1.51	2.02
Chimical composition, %DM												
Dry matter	86.92				87.20				88.40			
Crude protein	12.39				12.00				12.00			
NDF	26.40				32.40				38.14			
ADF	16.03				18.09				19.75			
Ca	0.60				0.59				0.51			
P	0.42				0.41				0.35			
TDN[3]	62.20				61.20				61.00			
Roughage NDF[4]	57.70				65.60				74.00			

[1] Mean particle size of ingredients adjusted by the size of alfalfa hay and rice straw.
[2] Provided the following per kilogram of the complete diet: vitamin A: 166,700 IU; vitamin D3: 20,850 IU; vitamin E: 200 IU; Mg: 5.5 g; K: 9.0 g; Zn: 8.9 g; Mn: 6.75 g; Cu: 1.63 g; Se: 28.7 mg.
[3] Estimated (NRC, 1988).
[4] Roughage (corn cob+alfalfa hay+rice straw) NDF/total NDF×100.

preliminary between PS. Each period contained a specific PS and the three levels of NDF were administered within each period. During each period the experiment was a 3×3 Latin square arrangement with three groups of cows in each of the three PS (blocks). A group was composed of two cows, therefore each data of chewing activity was obtained from the results of six cows.

Composition of experimental diets was given in Table 1. NDF level and PS of diets were adjusted by formulating rate and cutting length of rice straw and alfalfa hay. In order to get precise PS roughages were cut by a cutter equipped with a scale. Mean PS of ingredients determined on a vibrational sieve shaker as described by Waldo et al. (1971) were 1.26, 1.09, 0.84, 0.63 and 1.52 cm for yellow corn, sunflower meal, wheat meal, tapioca and corn cob, respectively. For adjusting the PS of diet, alfalfa hay and rice straw cut to the lengths of 1.0, 2.0, 3.0, 3.5 and 6.0 cm were used for formulating total mixed rations. Total mixed rations were contained about 62% TDN and 12% crude protein. The ratio of NDF supplied from roughage including corncob ranged from 58 to 74% of total intake. Cows were forcibly dried off before a week of the experimental period fed at 90% of their respective *ad libitum* feed intake throughout the experiment with free access to water and a trace mineral salt block. *Ad libitum* intake for each cow was determined prior to the experiment. Diet was allocated in equal portions daily at 0800 and 1800 h. Afternoon feed refusals were offered during the morning feeding in addition to the regular feed portion. Feed refusals were weighed after the morning feeding in order to calculate daily feed intake. DM intake was averaged 12.3 kg/d throughout the experiment. Cows were housed in individual stanchion barn with rubber mats to prevent the consumption additional fiber, and fitted with halters equipped with strain gauge (EA-06-125AD-120, Intertechnology Ltd., Toronto, Ont., Canada) transducers to record chewing activities on a chart recorder (056, Hitachi Co.). Transducer that measure voltage changes occurring in proportion to jaw movement consisted of magnet sewn to an elastic band and amplifier. And the sensing unit was located around the lower part of the muzzle of cow. Cows were gradually adjusted to the experimental diet during preliminary trial and were equipped with halter throughout the entire experimental period. Cows were exercised in an outside yard for 2 h daily, except on days when chewing was measured.

Table 2. Effects of dietary NDF concentration and particle size on chewing time

Chewing activity	NDF 26%			NDF 32%			NDF 38%			SEM[1]	Significance[2]		
	1.0	1.5	2.0	1.0	1.5	2.0	1.0	1.5	2.0		NDF	PS	INT
Chewing time, min/d													
Eating	89.9	161.6	169.3	121.5	175.2	195.7	183.2	190.8	200.2	12.27	**	*	NS
Ruminating	168.6	151.5	140.8	261.7	248.7	251.9	353.1	339.7	355.6	28.42	**	NS	**
Total	258.5	313.1	310.1	383.2	423.9	447.6	536.3	530.5	555.9	36.49	**	NS	*
Chewing time, min/kg DM intake													
Eating	7.4	12.3	13.9	10.0	13.4	16.0	14.8	15.4	18.9	1.12	*	*	NS
Ruminating	12.6	12.5	11.6	21.4	20.4	20.6	26.5	27.5	30.2	2.31	**	NS	*
Total[3]	20.0	25.8	25.5	31.4	34.8	36.7	41.3	42.9	49.1	3.14	**	NS	NS
Ruminating/total, %	63.0	48.4	45.5	68.2	58.6	56.1	64.2	64.1	61.5	2.54	*	*	NS
Chewing time, min/kg NDF intake													
Eating	28.0	50.3	52.7	30.8	30.8	49.6	38.8	40.4	45.6	2.98	NS	**	NS
Ruminating	52.5	47.2	43.8	66.4	66.4	63.8	74.8	72.0	78.2	4.11	**	NS	**
Total	80.5	97.5	96.5	97.2	97.2	113.5	113.6	112.4	123.8	4.56	**	NS	*

[1] Standard error of the mean.
[2] NDF=main effect of dietary NDF concentration; PS=main effect of particle size of diet; INT=interaction of NDF and PS.
[3] Roughage value index (RVI). ** p<0.01, * p<0.05, NS: Not significant.

Table 3. Effects of dietary NDF concentration and particle size on chewing number

Chewing activity	NDF 26%			NDF 32%			NDF 38%			SEM[1]	Significance[2]		
	1.0	1.5	2.0	1.0	1.5	2.0	1.0	1.5	2.0		NDF	PS	INT
Day ($\times 10^2$)													
Eating	69.1	115.8	130.7	84.8	125.2	149.6	148.6	142.3	150.5	9.83	*	*	*
Ruminating	91.8	87.6	76.0	157.0	146.2	151.2	178.0	183.0	185.9	14.44	**	NS	**
Total	160.9	203.4	206.7	241.8	271.4	300.8	326.6	325.3	336.4	21.21	**	NS	NS
Chews/min. rumination	54.4	57.9	55.0	60.0	58.9	60.1	50.4	53.9	52.3	1.47	**	NS	NS
Chews/kg DM intake													
Eating	568	952	1,074	694	1026	1,226	1,201	1,150	1,303	82.5	**	*	*
Ruminating	755	720	709	1,286	1197	1,238	1,438	1,479	1,507	110.7	**	NS	*
Total	1,322	1,671	1,783	1,980	2,222	2,464	2,639	2,628	2,809	170.7	**	NS	NS
Chew/kg NDF intake													
Eating	2,150	3,605	4,068	1,856	1,950	2,237	2,879	3,014	3,108	256.6	**	NS	NS
Ruminating	2,859	2,726	2,365	3,982	3,707	3,835	3,771	3,876	3,954	207.1	**	NS	*
Total	5,009	6,330	6,433	5,838	5,657	6,072	6,651	6,890	7,052	215.3	**	NS	*

[1] Standard error of the mean.
[2] NDF=main effect of dietary NDF concentration; PS=main effect of particle size of diet; INT=interaction of NDF and PS.
** p<0.01, * p<0.05, NS: Not significant.

Analysis

Feed ingredients were ground through a Wiley mill equipped with a 1 mm screen, and subsequently analyzed for dry matter (105°C), crude protein (Kjeldahl N×6.25), acid detergent fiber (ADF) and NDF (Goering and Van Soest, 1970). Feed PS was determined with 50 g samples of feed in duplicate, using a vibrational sieve shaker equipped with dry sieve as described by Waldo et al. (1971). Data were analyzed using the general linear models procedure of Statistical Analysis System (1985) for ANOVA and relationship among parameters (RVI, NDF, PS) was analyzed by regression.

RESULTS AND DISCUSSIONS

The results on time spent chewing (eating and ruminating), the number of chews, and the rumination bolus of cows fed the diets having different NDF concentration and PS are presented in Table 2, Table 3 and Table 4, respectively. During each experimental period, chewing activities of individual cows were recorded on average for 2 d. Because feed PS was only adjusted by roughage source included in total mixed ration, different cutting lengths of roughage ingredients could influence feed intake pattern. This influence is a reason of significant interactions between NDF concentration and PS in chewing activity.

Eating

Time spent eating increased as NDF concentration ($p<0.01$) and PS ($p<0.05$) of diet increased; concurrently there was a corresponding increase in the number of chews. Mean eating time increased from 11.5 to 16.4 min/kg of DM intake (Table 2) and mean eating chews from 864 to 1,218 chews/kg of DM intake (Table 3) as NDF concentration increased from 26 to 38%, indicating that more time and more chews were required to masticate higher NDF diets. Although time spent ruminating was not significantly ($p>0.05$) affected by feed PS in this experiment, eating characteristics were altered. As the PS of diet increased, the eating time per day increased but the rumination time decreased. The time spent eating per NDF intake (Table 2) is rather longer in the diets of NDF 26% (1.5 and 2.0 cm of PS) than the diets containing higher NDF. According to visual observation, cows spent more time to eat by choice intake when fed the diet formulated by lower level of roughages (alfalfa hay and rice straw) with relatively long cutting length (Table 1). Total chewing time per NDF intake increased with increasing NDF concentration of diet. Expressed per unit of NDF intake, eating time was not affected by NDF concentration, but was remarkably ($p<0.01$) greater in 1.5 and 2.0 cm than 1.0 cm in PS. Therefore, eating time per unit of NDF intake was rather affected by PS than NDF concentration of diet. Furthermore, time spent eating remained constant but ruminating increased as concentration of NDF in diet increased. These results are not consistent with observations that dairy cattle fed diets containing NDF ranging from 21 to 30% NDF (Woodford et al., 1986) and from 26 to 34% (Beauchemin and Buchanan-Smith, 1989) maintained a relatively constant rumination time per unit of NDF intake when offered a given amount of feed. Eating chews per unit of NDF intake (Table 3) is greater in the diets of NDF 26% (1.5 and 2.0 cm of PS) than the diets containing higher NDF.

Ruminating

The mean of the time spent ruminating increased by 65% when NDF concentration of the diet increased from 26% to 32% (from 154 to 254 min/d), and increased by 38% when NDF concentration of the diet increased from 32% to 38% (from 254 to 350 min/d). Time spent ruminating per DM or NDF intake was increased with increasing NDF concentration of diet, however was not affected by PS of diet. Krause et al. (2002) reported that an increase of forage PS (2.8 to 3.0 vs. 6.0 to 6.3 mm) resulted in increase of time spent ruminating, which was caused by an increase in number of rumination periods per day and a trend towards an increase ($p=0.07$) in duration of each rumination period. In this study, time spent ruminating per NDF intake was affected by time spent eating, and the longer eating times resulted in spending less rumination time relatively. Beauchemin and Buchanan-Smith (1989) reported that time spent ruminating increased by 20% when fiber content of the diet increased from 26 to 30%, but did not increase when fiber was increased from 30 to 34% (413 and 414 min/d), and that rumination time and rumination chews were similar, regardless of NDF concentration of diet and supplementation of forage. Other researchers have reported that rumination time increases as PS of forage increases (Woodford et al., 1986), rumination time per gram of DM and NDF decreases as DM intake increases (Sudweeks et al., 1980), and rumination time per unit of NDF intake is relatively constant in dairy cattle fed diets containing from 21 to 30% NDF when offered a given amount of feed (Woodford et al., 1986). The ratio of rumination to total chewing time was higher with decreasing the PS, which was due to the increased time spent eating for swallowing when cows fed the diets with larger particles. When the cows fed the diets of NDF 26% with 1.5 or 2.0 cm in PS, time spent ruminating was rather less than that of eating. Chews per minute of rumination are greatest in cows fed the diets of 32% NDF irrespective to feed PS. Robinson and McQueen (1997) induced the regression equation from means NDF intake of dairy cow fed silages as ruminating chews per day ($\times 10^3$)=12.04+ [2.364×NDF intake(kg/d)], $r^2=0.56$. When applying NDF intake of this study to the above equation, the result of ruminating chews was much greater than that of this study.

Total chewing time

Mean of total chewing time increased ($p<0.01$) from 294 min/d for diets of 26% NDF to 418 and 541 min/d for diets of 32 and 38% NDF respectively. This result was very low compared to the result of Beauchemin and Buchanan-Smith (1989) which reported that total chewing time was 558, 651, 674 min/d for dairy cows fed the diets of 26, 30, 34% NDF with alfalfa silage and/or long alfalfa hay respectively. This difference may due to the feeding conditions as feed intake (12 vs. 18kg/d), type of diet (TMR vs. concentrate and long hay or silage), and animal condition (dry vs. lactating). Relating chewing time to intake revealed that as the concentration of NDF in the diet increased, total chewing time per kilogram of DM intake (RVI) increased ($p<0.01$). But RVIs were not significantly ($p>0.05$) affected by PS of diet. Shaver et al. (1986) reported that hay chopped to 0.78 cm mean particle length was as effective as long hay for maintaining chewing activity and rumen fermentation, and RVI was 29.2, 28.6 and 9.8 when cows fed alfalfa hay in long, chopped, and pelleted form (60:40 hay:grain ratio), respectively. In this study, RVIs for the diets of 26, 32 and 38% NDF were 23.8, 34.3, and 44.4, respectively. Beauchemin and Buchanan-Smith (1989) reported that the RVIs for the diets of 26, 30, 34% NDF were 30.6, 36.1 and 38.1, respectively. RVI in this experiment was relatively low in the lower NDF of diet compared to those previously reported. Beauchemin and Buchanan-Smith (1989) concluded that as feed particle length increased (or supplementation of long hay), chewing time also increased, however cows spent less time chewing per unit of adjusted intake as particle length increased. In contrast, this experiment chewing time was expressed per units of DM or NDF intake, was not affected by feed PS. Application of RVI to predict milk fat production by dairy

Table 4. Effects of dietary NDF concentration and particle size on rumination boli

Chewing activity	NDF 26%			NDF 32%			NDF 38%			SEM[1]	Significance[2]		
	1.0	1.5	2.0	1.0	1.5	2.0	1.0	1.5	2.0		NDF	PS	INT
Rumination boli													
Boli/day	267.3	228.3	171.7	353.7	297.0	322.0	394.3	425.7	435.3	30.00	**	NS	**
Boli/kg DM intake	22.0	18.8	14.1	29.0	24.3	27.2	31.9	34.4	30.7	2.20	**	NS	**
Boli/kg NDF intake	83.2	71.1	52.7	89.7	75.3	84.2	83.5	90.2	80.7	3.86	*	NS	**
Bolus duration, sec.	37.7	39.8	48.7	44.4	51.7	45.7	56.6	46.8	43.4	1.93	**	NS	**
Chews/bolus	34.4	38.3	43.5	44.4	50.8	45.5	45.2	43.3	39.2	1.60	**	NS	**

[1] Standard error of the mean.
[2] NDF=main effect of dietary NDF concentration; PS=main effect of particle size of diet; INT=interaction of NDF and PS.
** p<0.01, * p<0.05, NS: Not significant.

cows indicated that 21.4, 32.4 and 44.8 were needed to maintain milk fat percentages of 3.2, 3.5 and 3.9%, respectively, by cows producing 17.9 to 20.0 kg milk/d (Sudweeks et al., 1981). These levels of RVI are similar with our results (23.8, 34.3 and 44.4) by NDF concentrations (26, 32 and 38%) of diets. The regression equation produced from the relationships of NDF concentrations (NDF, %) and particle sizes (PS, cm) of diet on RVI (min/kg DM intake) in this study was as follows.

$$RVI=-19.672+1.44\times NDF+5.196\times PS, (r=0.81)$$

Woodford and Murphy (1988) also reported that RVI was 28.2, 24.1 and 20.0 when lactating cows fed the total mixed rations with concentrate:alfalfa haylage:alfalfa pellets ratio of 60:40:0, 60:28:12, and 60:12:28 on a DM basis, and induced the regression equation on total chewing time (Y) by haylage intake (X); Y (min/d)=26.7X (kg/d)+ 375, (r^2=0.44); Y (min/kg X)=-0.83X (kg/d)+31.8, (r^2=0.82). Murphy et al. (1983) reported that the equation describing effect of cell wall content (CWC) on total rumination time (Y) in sheep was Y=57.95+732.23CWC, (r=0.657). The regression of RVI or rumination time on NDF or CWC concentrations and PS of diet indicates that they are in positive relationship.

Rumination bolus

As the feed NDF concentration increased, rumination boli and bolus duration increased. Chews per bolus were greatest in cows fed the diet of NDF 32%. The characteristics of rumination bolus shown in this experiment (Table 4) were that less number of rumination bolus induced to prolong the rumination duration and to increase the chews per bolus. Jaster and Murphy (1983) reported that animals fed forages of longer PS were more efficiently chewed than forages of shorter PS. Cows consuming long hay spent less time chewing each bolus, resulting in more boli per minute of rumination, although total rumination time per day was similar. Additionally, Beauchemin and Buchanan-Smith (1989) reported that chews per bolus (52.8 vs. 50.6, p<0.01) and chews per min (59.0 vs. 57.9, p<0.05) were less when cows fed the diet formulated by substituting 15% of the alfalfa silage DM with an equivalent amount of long alfalfa grass hay compared with cows fed silage as the sole source of forage. This means that cows consuming long forage chewed more efficiently than those of chopped silage. In this experiment, the rumination bolus was not affected by the PS and was significant (p<0.01) interactions between NDF concentration and PS of diet.

CONCLUSION

The particle size of forage in TMR diets based on either a1falfa hay and rice straw had no significant effect on chewing activity and time spent ruminating per DM or NDF intake without eating time per unit of NDF intake. However, there was a trend that increasing forage particle size in TMR diets increased the eating time per day, but decreased the rumination time. Chewing activity including eating and ruminating times, and time spent ruminating per DM or NDF intake increased linearly as the concentration of dietary NDF in TMR increased from 26 to 38%. RVI for the diets of 26, 32 and 38% NDF was calculated 23.8, 34.3 and 44.4, respectively. This result indicates that rumen parameters including pH, microbial populations and VFA concentrations, and so forth could be influenced by NDF concentrations rather than particle size of forage in TMR diets.

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REFERENCES

Balch, C. C. 1958. Observation on the act of eating in cattle. Br. J. Nutr. 12:330.

Balch, C. C. 1971. Proposal to use time spent chewing as an index of the extent to which diets for ruminants possess the physical property of fibrousness characteristic of roughages. Br. J. Nutr. 26:383.

Beauchemin, K. A. 1991. Effects of dietary neutral detergent fiber concentration and alfalfa hay quality on chewing, rumen function, and milk production of dairy cows. J. Dairy Sci. 74:3140.

Beauchemin, K. A. and J. G. Buchanan-Smith. 1989. Effects of dietary neutral detergent fiber concentration and supplementary long hay on chewing activities and milk production of dairy cows. J. Dairy Sci. 72:2288.

Campling, R. C. 1966. The intake of hay and silage by cows. J. Br. Grassl. Soc. 21:41.

Goering, H. K. and P. J. Van Soest. 1970. Forage fiber Analysis. Agric. Handbook No. 379, US Dept. Agric., Washington, DC, p. 20.

Jaster, E. H. and M. R. Murphy. 1983. Effects of varying particle size of forage on digestion and chewing behavior of dairy heifers. J. Dairy Sci. 66:802.

Krause, K. M., D. K. Combs and K. A. Beauchemin. 2002. Effects of forage particle size and grain fermentability in midlactation cows. II. Ruminal pH and chewing activity. 85:1947.

Luginbuhl, J. M., K. R. Pond, J. C. Burns and J. C. Russ. 1989. Eating and ruminating behavior of steers fed coastal bermudagrass hay at four levels. J. Anim. Sci. 67:3410.

Maekawa, M., K. A. Beauchemin and D. A. Christensen. 2002. Effect of concentrate level and feeding management on chewing activities, saliva production, and ruminal pH of lactating dairy cows. J. Dairy Sci. 85:1165.

Mertens, D. R. 1997. Creating a system for meeting the fiber requirements of dairy cows. J. Dairy Sci. 80:1463.

Moon, Y. H., S. C. Lee and S. S. Lee. 2002. Chewing activities of selected roughages and concentrates by dairy steers. Asian-Aust. J. Anim. Sci. 15:968.

Robinson, P. H. and R. E. McQueen. 1997. Influence of level of concentrate allocation and fermentability of forage fiber on chewing behavior and production of dairy cows. J. Dairy Sci. 80:681.

SAS. 1985. SAS User's Guide: Statistics. SAS Inst. Inc., Cary, NC.

Shaver, R. D., A. J. Nytes, L. D. Satter and N. A. Jorgensen. 1986. Influence of amount of feed intake and forage physical form on digestion and passage of prebloom alfalfa hay in dairy cows. J. Dairy Sci. 69:1545.

Sudweeks, E. M., L. O. Ely and L. R. Sisk. 1980. Effect of intake on chewing activity of steers. J. Dairy Sci. 63:152.

Sudweeks, E. M., L. O. Ely, D. R. Mertens and L. R. Sisk. 1981. Assessing minimum amounts and form of roughages in ruminant diets: Roughage value index system. J. Anim. Sci. 53:406.

Sudweeks, E. M., S. E. Law, L. O. Ely, M. E. McCullough and L. R. Sisk. 1979. Development and application of a roughage value index for formulating dairy rations. Univ. Georgia Coll. Agric. Exp. Stn. Res. Bull. 238.

Ulyatt, M. J., D. W. Dellow, A. John, C. S. W. Reid and G. C. Waghorn. 1986. Contribution of chewing during eating and rumination to the clearance of digesta from the ruminoreticulum. In: Control of Digestion and Metabolism in Ruminants. (Ed. L. P. Milligan, W. L. Glovum and A. Dobson). Reston Publ. Co., Reston, VA., pp. 498-515.

Waldo, D. R., L. W. Smith, E. L. Cox, B. T. Weinland and H. L. Lucas, Jr. 1971. Logarithmic normal distribution for description of sieved forage materials. J. Dairy Sci. 54:1465.

Welch, J. G. 1986. Physical parameters of fiber affecting passage from the rumen. J. Dairy Sci. 69:2750.

Woodford, J. A., N. A. Jorgensen and G. P. Barrington. 1986. Impact of dietary fiber and physical form on performance of lactating dairy cows. J. Dairy Sci. 69:1036.

Woodford, S. T. and M. R. Murphy. 1988. Dietary alteration of particle breakdown and passage from the rumen in lactating dairy cattle. J. Dairy Sci. 71:687.