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SUMMARY

Feed intake has been associated with hydration and density of the diet in several studies. Methods used for evaluating these factors are surveyed and their effect on feed intake reviewed. Filtration, centrifugation, sorption isotherm, capillary suction, dialysis, freezing point depression, and pulsed nuclear magnetic resonance methods of measuring water holding capacity are discussed. Additional data must be gathered before a method for measuring water holding capacity can be chosen which best explains the effect of hydration on feed intake of ruminants. However, analysis by pulsed nuclear magnetic resonance appears promising. Various measurements of diet density which have been shown to affect intake are examined. Unit density (functional sp. gr., the density of particles with air or gas pockets intact) of digesta in the reticulorumen is considered the parameter most likely to have the greatest biological relevance in controlling feed intake, although this hypothesis has not been studied.

Introduction

Hydration and density of feedstuffs have been recognized as important determinants of their consumption by ruminants for some time (2, 7). Proliferation of methods, diversity of applications, and confusion of terminology have occurred, making it difficult to integrate data already gathered. Our objectives were: to survey methods used for evaluating hydration and density; to review the effects of these factors on feed intake; and to recommend areas needing further study.

Hydration

A negative relationship between water content of grasses or silage and feed intake is often observed (7). The water contained in plant material acts more like water in balloons than free water; i.e., the volume of digesta dry matter (DM) that can be packed into the reticulorumen is reduced. Staples et al. (27) recently reported that dry matter intake (DMI) of lactating cows decreased as DM content of the diet decreased. Their results were based on diets in which wet corn gluten feed had been substituted for ground corn and soybean meal. The experiment was not designed to specifically examine effects of varying diet DM content; composition of DM changed along with DM content, confounding their effects. Therefore, this research shares a problem common to many studies, especially those in which hydration of silages has been compared.

A different approach was taken by Conrad and Rogers (5) who fed 20% of diet DM as brewers grains in either dry, wet, or rewet (to 80% water) form to 24 cows in early and late lactation. Milk production did not differ between diets; however, DMI was depressed 23% (from 22.4 to 17.3 kg) when brewers grains were fed in the wet or rewet form. The DMI of wet and rewetted grains were similar; therefore, it is unlikely previous drying of the rewetted grains affected their consumption. A similar study, in which cows in late lactation were fed brewers grains at 40% of diet DM, reported a 10% decrease (from 13.3 to 12.0 kg) in DMI when wet or rewetted grains were fed instead of dried grains (17). In contrast, Thomas et al. (32) found that addition of water to change wilted alfalfa silage from 45 to 22% DM did not affect DMI of heifers. Additionally, intraruminal water administration did not affect DMI of hay fed heifers.

Decreased DMI after addition of water to feeds may be due to the way water is being held by these feeds. One technique which has been found suitable for determining the amount of free and bound water in feeds is pulsed nuclear magnetic resonance analysis (6). Relaxation times of water (T_2) for dry, wet and rewetted brewers grains measured using this method were 11.8 ± 1.0 , $18.9 \pm .4$, and $18.4 \pm .3$ msec, respectively (M. R. Murphy, unpublished data). Longer relaxation times indicate the presence of more free water. Comparable values for wet and rewetted grains indicate that they hold water in a similar manner. Based on their water content, 7 to 8 times that of dried grains, wet and rewetted grains would be expected to have much longer relaxation times; however, only a 58% increase was observed. This indicates additional water in wet and rewetted grains was rather tightly bound, without much free water.

More common methods of measuring water holding (or binding, or hydration) capacity include: filtration, centrifugation, sorption, isotherm, capillary suction, dialysis, and freezing point depression. The filtration method involves soaking the feed (or a fraction of it), filtering, weighing, drying, reweighing, and calculating water held by difference (13, 22, 23, 24, 26, 29, 34). Soaking times, temperatures and solutions vary. Cheesecloth, glass wool or paper filters have been used and material has been oven or freeze dried. Methods employing centrifugation have been the most popular (1, 4, 9, 16, 19, 21, 22, 23, 24, 25, 28). Feed or a fraction of it, is soaked, centrifuged, drained (decanted or otherwise separated), weighed, dried, and reweighed. Soaking solutions and times vary, as do time and force of centrifugation, and drying method. In the sorption isotherm technique, moisture content of a sample is determined 10 to 12 wk after being placed over saturated salt slurries with water activities in the range of 0 to 0.98 (4, 36). Water activity (a_w) is a physicochemical parameter food microbiologists prefer to use instead of water content (8). It is the ratio of water vapor pressure over a feed to that over pure water, or the relative humidity (percent) of the atmosphere in equilibrium with the sample divided by 100. Because it measures the amount of 'available' water, which varies considerably depending on the solute, water activity is much better than water content for defining the growth of microorganisms. Water holding capacity at $a_w = .98$, the highest possible a_w avoiding errors due to microbial growth, has been used for comparison with other methods; however, capacity by capillary suction involves placing a small amount of sample on a filter in a small chamber (3, 4, 36). Rate of water uptake and an equilibrium value are then determined by following water movement through a calibrated capillary

attached to the base of the filter. Measuring water content of samples at equilibrium with solutions of known osmotic potential across a dialysis membrane is another technique for estimating water holding capacity (13, 22, 28). Finally, osmolalities of low concentration slurries (.1 to 3%) have been analyzed by freezing point depression and water holding capacity from extrapolation of the resulting regression to 280 mOsm ($.995 a_w$).

Two techniques for measuring water hydration capacity have been approved by the American Association of Cereal Chemists (1). Method 56-20 involved soaking samples in excess water, centrifugation, and decanting. It is not considered suitable for products containing over 25% water soluble material. In method 88-04 only enough water is added to saturate the sample. Since there is no liquid phase, the estimate is not affected by solubility of the material.

Physical form and chemical composition of a feedstuff are probably the two most important factors affecting its water holding capacity. Conflicting data are available concerning the effect of the former. McConnell et al. (16), using a centrifugation method, found that ground bran, corn and cabbage fibers held less water than intact fibers. Stephen and Cummings (28) reported that 75 to 150 μ m isogel, wheat bran, carrot and cabbage fibers held 28% more water, using the dialysis technique, than 710 to 1000 μ m fibers did. Mongeau and Brassard (18) showed water holding capacity per gram of neutral detergent fiber was closely correlated ($r = .85, P < .01$) with mean particle size of wheat breakfast cereals, using a centrifugation method. Ground corn has also been reported to hold more water than whole corn, using a filtration technique (29). In summary, the effect of particle size on water holding capacity is not at all clear.

Negative correlations ($r = -.99, P < .01$ and $r = -.80, P < .05$) between water holding capacity (ml/g DM) of ground samples, as measured by centrifugation, and dry matter intake (g/kg^{.75}) of chopped hays by sheep have been observed (25, 26). The possibility that water holding capacity of a feed, as opposed to DM content of a diet, may affect DMI for other diets and in other species has apparently not been examined.

Potential problems with methods of estimating water holding capacity include types of water being measured and lack of agreement between methods. Lack of correlation between estimates by capillary suction, centrifugation, sorption isotherm, and freezing point depression for various fibers was interpreted by Chen et al. (4) to indicate that different mechanisms of water binding occur in different method/sample combinations. Another potential problem is that water holding capacity is often measured on ground or extracted samples, not the intact feed or digesta. Also, none of the methods evaluate effects of swelling on hydration (35) which, as discussed below, may affect DMI.

DENSITY

Density terminology has been adapted from the scheme suggested by McNulty and Kennedy (18), Figure 1. Baile and Pfander (2) found that a definable relationship apparently existed between intake by sheep and diet bulk density. The relationship was developed with few data and these tended to be concentrated towards the ends of the spectrum;

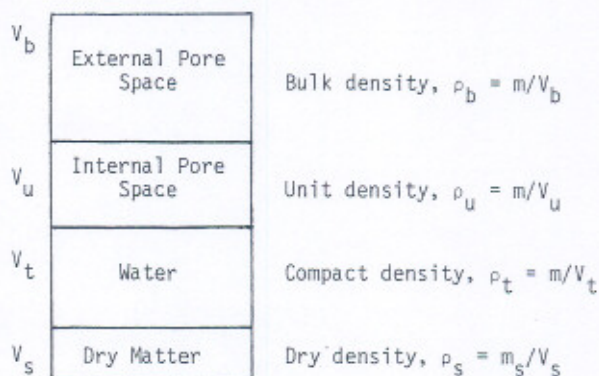


Figure 1. Density terminology: M_s = mass of solid or dry matter, m = mass of dry matter plus water (mass of the gaseous phase is assumed to be negligible), V = volume. Adapted from McNulty and Kennedy (1982).

however, others have also concluded the space filling characteristics of roughages are perhaps more important in determining intake than some of the other factors usually considered (29).

Seoane et al. (25, 26) showed that packed volume (measured two different ways and somewhere between bulk and unit density) was negatively correlated ($r = -.99, P < .01$ and $r = -.97, P < .01$, respectively) with intake ($\text{g/kg}^{.75}$) of chopped forages by sheep. Although all forages were ground through the same size screen, particle size differences in the ground dietary materials may have confounded results to some extent; however, this possibility was not examined. In an experiment in which physical characteristics other than density were controlled, Tetlow and Wilkins (26) concluded that intake of forage wafers may be influenced by their density. Laredo and Minson (14) also found that voluntary intake ($\text{g/kg}^{.75}$) of 30 forage fractions (5 chopped grasses, 3 maturities, leaf or stem) by sheep was negatively correlated with bulk density ($r = -.70, P < .001$).

Several methods have been used to measure density of feeds. Tapping graduated cylinders containing sample until no further reduction in volume occurred has been used to estimate bulk density (2, 14, 33). It has also been measured by repeatedly swirling and refilling a cylinder (20). Compaction by centrifugation (25, 26) or added weight (26) reduced external pore space and approaches a measure of unit density. Package density has been determined by coating wafers of feed with paraffin and measuring water displacement in specific gravity jars (30, 31). Toluene displacement and air comparison pycnometry have been used to estimate compact density (18). Depending on the degree to which internal pore space is filled (or at equilibrium for air comparison pycnometry) with the displacing medium, a density intermediate between the compact and unit densities will be measured. Intake studies using the latter two methods have not been reported.

Of the density measures available, unit density of particles being digested in the reticulorumen is most likely to have the greatest biological relevance in the control of feed intake. The animal, by chewing during eating and rumination, would presumably alter the bulk and package densities of feeds. In addition, microbial fermentation should change digesta particle density. With this view it is remarkable that bulk density of the intact or ground feeds themselves has been closely correlated with intake. A method to overcome these philosophical objections has recently been proposed by Hooper and Welch (10, 11, 12). Their technique allows changes in unit density (or functional sp.gr., the density of the particle with air or gas pockets intact) of digesta particles to be followed over time. Further study of the dynamics of this process, in association with measures of intake, digestion and passage may provide a more detailed explanation of the control of feed intake in ruminants.

Needed are: a method for measuring water holding capacity with demonstrated physiological significance across diets; more detailed examination of possible effects of water holding capacity on feed intake; resolution of the effects of processing on water holding capacity and density; and a study of the potential relationship between unit density (functional sp.gr.) of digesta and feed intake.

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Discussion of Paper by Dr. Murphy; Chaired by Dr. Paterson

Q: With calves grazing wheat pasture forage, could water content of the forage limit forage intake or is water flowing through the gut so fast that it will not limit intake?

Murphy: I don't know how tightly that water is held. I would like to put some wheat forage through NMR analysis. We have only done this with wet brewer's grains. Thomas et al. (32) showed that adding water to reduce dry matter content of wilted alfalfa silage from 45 to 22% failed to reduce intake. It is possible that water in fresh forage may be more tightly bound and more likely to affect intake.

M. Gill: Why do feeds differing in hydration produce different intakes? Is it due to the volume that material occupies in the rumen, on movement from the rumen, on the rate of attachment and digestion or what?

Murphy: It must have something to do with the swelling and the binding as well. Just adding free water to the rumen doesn't seem to alter intake. It must have something to do with the degree that it is bound and also to the physical action of swelling. If water is held tightly, it acts as a physical barrier; it has to move with that material; it can't move separately. So it seems to be a combination of the two factors. There is another problem here. If there is short term regulation of intake and an animal eats dry food, water must be taken up very quickly. Usually within 20 minutes, foods are up to 70 to 80% water, at least for the feeds I have looked at. So if the animal's meal lasts 25 minutes to 2 hours, there is plenty of time for water uptake and for that to regulate food intake. Yet with dry feeds, dried brewer's grains especially, animals were able to eat very large quantities even though that should hydrate in the rumen and go up to that level of water. It didn't inhibit intake, so there has to be more than water uptake involved in intake regulation.

Comment: Plant materials with a lot of polysaccharide material may alter intestinal motility. Amorphous cellulose is able to take on a tremendous amount of water. Whether cellulose is amorphous or crystalline will markedly influence water uptake. We rarely measure ratio of amorphous to crystalline cellulose though that ratio may be important to regulate bulk fill and feed intake.