DCAD: It's Not Just for Dry Cows

Rich Erdman[1] and Marie Iwaniuk
Department of Animal and Avian Sciences, University of Maryland

Introduction

For more than 20 years, dairy producers have been using low DCAD diets in their dry cow feeding programs to prevent milk fever and subclinical hypocalcemia during the transition period. The use of low DCAD diets in dry cows has virtually eliminated the incidence of milk fever in most dairy herds. While dairy producers are well aware of the importance of proper DCAD concentrations in the dry period, relatively little attention has been paid to the effect of DCAD in lactating cows. We will review the principles of the strong ions in physiology and calculating and formulating for DCAD and then highlight the responses of lactating cows to DCAD.

What is DCAD?

The term **DCAD** stands for Dietary Cation Anion Difference. DCAD is an index of the relative balance between the principle cations (potassium, K and sodium, Na) and the principle anions (chloride, Cl and sometimes sulfur, S) in the cow's diet. Sodium, potassium, and chloride fall into a class of dietary minerals that are sometimes referred to as the "osmoregulators" because of the critical role that they play in maintaining osmotic balance in various body tissues (**Table 1**). In blood, Na is the primary cation and Cl (and to a lesser extent, bicarbonate ion) are the primary anions. In the cell, K is the principal cation while amino acids and proteins with a negative charge serve as the principle anions. Finally, in ruminal fluid, a combination of Na and K are the principal cations whereas volatile fatty acids (**VFA**) that are produced during ruminal fermentation serve as the primary anions. These minerals are absorbed from the diet with nearly 100% efficiency and can readily move across the intestinal wall, blood, and cell membranes. Their relative content in these tissues is maintain by a Na-K-ATP pump. They are also important for maintaining osmotic balance in milk and the relatively consistent moisture content (85%) of feces in the cow. Finally, any excess of these ions is excreted in the urine. Sodium and potassium are the primary drivers of urine output and thus added intake will also increase water intake in the cow.

There are two important principles with respect to the cations and anions: 1) the sum of the cations and anions (equivalent weight basis) should add up to about 300 to maintain a consistent osmotic pressure and maintain water balance between tissues; and 2) the sum of the cations should equal the sum of the anions to maintain neutral electrical charge. These two principles are important in understanding the role of DCAD in acid-base balance and urinary excretion of these minerals.

[1] Contact: Department of Animal and Avian Sciences, University of Maryland, Bldg. 142. College Park, MD 20742. (301) 405-4243. Email: erdman@umd.edu

Table 1. Principle cations and anions (mEq/L) in bodily fluids.

Ion$^{(charge)}$	Blood	Intracellular	Ruminal fluid
Sodium (Na^+)	145	12	84
Potassium (K^+)	4	139	27
Chloride (Cl^-)	116	4	8
Bicarbonate (HCO_3^-)	29	12	6
Amino acids & proteins$^-$	9	138	(VFA's) 105
Magnesium (Mg++)	1.5	0.8	4.2[1]
Calcium (Ca++)	1.8	< 0.0002	3.5[1]
Milliosmoles/L	290	290	315[1]

[1] From Bennink et al. (1978).

The Strong Ion Theory

Sodium, potassium, and chloride are also referred to as the "Strong Ions" because they are absorbed from the diet with nearly 100% efficiency, they remain completely dissociated in solution, and physiologically, any surplus intake from the diet above an animal's needs will be excreted in the urine. The "Strong Ion Theory of Acid-Base Balance," first proposed by Peter Stewart, a Canadian physiologist (Stewart, 1978) applies to virtually every mammal including humans. Stewart (1978) referred to the sum of the strong cations minus the sum of the anions as the Strong Ion Difference (**SID**):

$$SID = Na^+ + K^+ - Cl^-$$

The SID equation is in fact identical to the simplest DCAD equation that was first developed for poultry and swine that is also referred to as the Mongin (1981) equation. Excretion of strong ion secretion in the urine can be summarized by the following equation where the sum of the cations (Na^+, K^+, H^+) must equal the sum of the anions (Cl^-, OH^-) to maintain electrochemical neutrality:

$$Na^+ + K^+ + H^+ = Cl^- + OH^-$$

If an animal consumes a diet that is high in cations in relation to anions (SID or DCAD is positive), its urine must contain additional anions to maintain electrochemical neutrality. Cattle routinely consume diets that are high in K. The additional base (anion) excreted in the urine is usually the bicarbonate ion. In contrast, cattle consuming diets that are high in Cl relative to K and Na (DCAD or SID is negative), additional cations such as ammonium (NH_4^+) and other titratable acids are needed to balance the negative charge of Cl. Because of this relationship, animals such as cattle which are typically fed diets high in cations will have an alkaline urine (pH > 7) whereas animals that are fed diets that are low in cations will have acid urine (pH < 7). This concept is illustrated in **Table 2** that compares lactating sows and dairy cows. Pigs, because they consume a low K diet, have an acidic urine whereas cows that consume a high K diet have an alkaline urine.

Table 2. Comparison of strong ion requirements for lactating dairy cows and sows using the 2001 Dairy NRC and 2012 Swine NRC.

Mineral	Lactating sow requirement % of diet, as-fed	Lactating cow requirement % of dietary DM
Na	0.20	0.23
K	0.20	1.06
Cl	0.16	0.24
DCAD, mEq/kg	93	303
Expected urine pH	6.5	7.5 to 8.0

How Does DCAD Work in Preventing Milk Fever?

The initial work on use of DCAD was based on the observation by Scandinavian researchers that cows fed diets that were low in ash content resulted in reduced incidence of milk fever (Ender et al.,1971; Dishington et al., 1975). Since K is a major factor that affects ash content (low ash diets were also low in K), it was found that diets with low DCAD (low K and Na relative to Cl) reduced not only milk fever but also subclinical hypocalcemia. Since excess dietary Cl is excreted in urine, it requires a corresponding cation to maintain a neutral charge. Low K diets stimulated hydrogen ion (low pH) secretion and the "spilling of calcium" (Ca^{++}) in the urine. In turn, increased loss of Ca in the urine also increased the cow's metabolic mechanisms for increased resorption of Ca from bone and increased intestinal absorption of Ca from the diet such that the cow was able to regulate blood Ca more effectively when the increased demand for Ca in milk production kicked in at the time of calving.

These observations stimulated numerous studies on the use of DCAD to prevent milk fever by Elliott Block at McGill University in Canada, Jesse Goff and Ron Horst at the USDA Animal Disease Laboratory in Iowa, and several others. The key points from their work were the following: 1) Diets that were negative in DCAD were effective in preventing milk fever and subclinical hypocalcemia; 2) Selection of feeds that were low in K and Na along with addition of Cl and sulfate salts were required to achieve low or negative DCAD diets; and 3) Low urine pH was a very useful indicator of the cow's DCAD status. Probably the most pivotal experiment was a study using Jersey cows by Goff and Horst (1997) in which cows were fed diets containing 1.1, 2.1, or 3.1% K with either 0.5 or 1.5% Ca during the dry period. The DCAD across Ca levels was increased from -75 to +430 mEq/kg of dietary DM with increasing K. Incidence of milk fever increased from 0% in the 1.1% K, 0.5% Ca diet to 80% in the 3.1% K with either 0.5 or 1.5% Ca. It was clear that the low DCAD (low K) diets had a profound effect on milk fever. Subsequent work looked at the effectiveness of various Cl and sulfate salts to reduce urine pH and it was determined that dietary sulfur was about 60% as effective as Cl in reducing urine pH and preventing hypocalcemia (Goff et al., 2004).

The DCAD Equations

The simplest calculation of DCAD is referred to as the Mongin (1981) equation that was originally developed for formulating poultry and swine diets. The formula includes the Na, K, and Cl content of the diet. An example of DCAD calculations for a diet that meets the minimum (NRC, 2001) requirements for K, Na, and Cl in lactating dairy cows is illustrated in **Table 3**. The DCAD is most frequently expressed as either mEq/kg of mEq/100 g of feed DM. The difference in magnitude is a factor of 10.

Table 3. Calculation of DCAD for a lactating dairy cow diet containing the minimum concentrations of K, Na, and Cl (NRC, 2001).

Element	% of DM	g/kg	Atomic Wt., g	Eq./kg	mEq/kg
K	1.06	12	39.1	0.271	271
Na	0.23	2.3	23.0	0.100	100
Cl	0.24	2.5	35.5	0.067	67

$$\begin{aligned} \text{DCAD} &= \text{mEq K} + \text{mEq Na} - \text{mEq Cl} \\ \text{DCAD} &= 271 \quad + \quad 100 \quad - \quad 67 \\ \text{DCAD} &= 304 \text{ mEq per kg of DM} \\ &= 30.4 \text{ mEq per 100 g of DM} \end{aligned}$$

Table 4 shows the various DCAD equations that have been used by dairy nutritionists in diet formulation programs. Each equation is very similar in that they all account for the strong ion (K, Na, and Cl) content of the diet. The first equation suggested for use in formulating dry cow diets was proposed by Ender (1971). This equation includes dietary sulfur (S) which has a +2 valence; therefore, in this equation, the S content divided by the atomic weight is multiplied by 2. The inclusion of S in the DCAD formula is only important when dietary S varies. Typically, this is not an issue unless distillers grains (**DDGS**) are a major component of the cow's diet. As stated earlier, the Mongin equation is the simplest equation and is equally effective as long as dietary S does not vary substantially. The NRC (2001) equation is perhaps the most precise and is based on the relative absorption rate of each of the minerals in the equation. However, very few nutritionists utilize that equation. Finally the Goff et al (2004) equation with a 0.6 coefficient for S is based on the relative effectiveness of sulfate salts in reducing urine pH compared to Cl salts. In my opinion, this is probably the most precise of all of the DCAD equations. However, the Ender (1971) DCAD equation still remains the most commonly used one in spite of the fact that it probably overemphasizes the role of dietary S.

Table 4. Examples of various DCAD equations used in dairy cattle feeding programs.

Equation	Elements Included:	DCAD, mEq/kg of DM
Ender (1971)	Na + K - Cl - S	179
Mongin (1981)	Na + K - Cl	304
2001 Dairy NRC	(Na + K + 0.15 Ca + 0.15 Mg) − (Cl + 0.6 S + 0.5 P)	284
Goff et al. (2004)	Na + K - Cl - 0.6S	228

DCAD in Lactating Dairy Cow Diets

Although negative DCAD diets have been fed to dry cows for many years, relatively little work was done on the effect of DCAD in lactating dairy cow diets until the late 1980's and early 1990's. Work by Tucker et al. (1988) demonstrated that, in contrast to dry cows, negative DCAD diets should not be fed to lactating cows because negative DCAD diets resulted in reduced feed intake and milk production. A series of experiments at Georgia (West et al., 1992) and Florida (Sanchez and Beede, 1996) examined the effects DCAD during heat stress. They suggested that increasing DCAD improved feed intake, milk production, and milk fat concentration during heat stress. The importance of DCAD was extensively discussed in the 2001 NRC publication but no minimal DCAD requirement was established. There simply had not been enough experiments conducted with varying DCAD concentrations to establish a requirement at the time publication. If one were to feed diets at the minimal requirements for K, Na, Cl, and S, the implied requirement would be around 179 mEq/kg of DM using the Ender (1971) equation that includes dietary S or about 304 mEq/kg of DM using the Mongin (1981) equation that does not include S in the formula.

The first meta-analysis of DCAD studies in lactating dairy cows was published by Hu and Murphy (2004) in which the results of 12 papers involving 17 experiments and 54 treatment means were summarized. Hu and Murphy (2004) estimated that maximum feed intake, milk production, and 4% fat-corrected milk (**FCM**) production occurred at DCAD's of 40, 34, and 49 mEq/100 g of feed DM, respectively using the Mongin (1981) equation to calculate DCAD. This study conclusively demonstrated the importance of feeding positive DCAD diets to lactating cows. However, the number of experiments and treatment means available for the analysis were limited. Further, many of the diets in that summary were DCAD negative with more than 50% of the treatment means from cows fed diets containing less than 304 mEq/kg of DM, the theoretical requirement for cows fed diets with the minimum requirements for K, Na, and Cl. Because Hu and Murphy (2004) had chosen to use a quadratic equation to explain the data, only a maximal response to DCAD rather than an optimal response could be determined.

Dietary buffers containing bicarbonate and carbonate salts of K and Na will increase DCAD and they have been a common feed additive in dairy cow diets for more than 50 years. We reasoned that the numerous feeding studies on the use of buffers in the transition period and to increase milk fat in low forage diets (Erdman, 1988) along with studies published since 2004 could be used to augment the dataset of Hu and Murphy (2004). Although some of the older publications did not have complete mineral analysis to calculate DCAD, we were able to show that book values from the 2001 NRC software could be used to fill in the missing mineral concentrations and accurately predict DCAD (Iwaniuk and Erdman, 2015). The calculated DCAD from those publications were the basis for our recent meta-analysis of DCAD effects on lactating dairy cows (Iwaniuk and Erdman, 2015). A total of 43 articles published between 1965 and 2011 that included 196 treatment means and 89 DCAD treatment comparisons were included in the analysis. The range in DCAD was from −68 to +811 mEq/kg of dietary DM (Ender equation), but the vast majority of diets contained between 0 and 500 mEq/kg of dietary DM, which we considered to be the practical range of inference. Figure 1 (A to D) shows a summary of the dry matter intake (**DMI**), milk production, and milk composition responses to DCAD from that analysis that were fitted to curvilinear and linear response equations. For DMI (**Figure 1A**), the maximum response was 1.92 kg/d (4.2 lb/d); 66% and 80% of the maximum DMI responses were achieved at DCAD concentrations of 290 and 425 concentrations, respectively. Maximum milk production responses (**Figure 1B**) were small (1.1 kg/d; 2.4 lb/d) with very little response to DCAD above 300 mEq/kg of dietary DM. For milk fat percentage and yield (**Figures 1C and 1D**, respectively), the responses were linear. Every 100 mEq/kg increase in DCAD resulted in a 1 point (0.1 percentage unit) increase in milk fat percent and a 38 g/d (0.08 lb/d) increase in milk fat yield. This suggests that fat yield will be the primary economic response to DCAD. Consequently, the 3.5% FCM response was much greater than for milk production alone and that the 66% and 80% of the maximum FCM response (4.8 kg/d, 10.8 lb/d) occurred at DCAD concentrations of 450 and 675 mEq/kg of DM, respectively. We consider the 675 mEq/kg of dietary DM DCAD value to be outside of the range of inference of this data set. There were no effects of DCAD on milk protein percent or yield (data not shown). In summary, clearly there are intake, milk production, and milk composition responses to DCAD and these effects need to be accounted for in diet formulation for lactating dairy cows.

We also looked at the effects of DCAD on ruminal fluid pH (data not shown). A 100 mEq/kg of dietary DM increase in DCAD resulted in a linear 0.003 unit increase in ruminal fluid pH such that increasing DCAD from 0 to 500 mEq/kg of dietary DM was projected to increase mean ruminal fluid pH from 6.31 to 6.46. These results are very consistent with earlier studies on the use of buffers to increase ruminal fluid pH and correspond to changes in milk fat percent (Iwaniuk and Erdman, 2015).

With respect to digestibility, increasing DCAD from 0 to 500 mEq/kg of dietary DM resulted in a 3.5 percentage unit increase in DM digestibility and a 7.5 percentage unit increase in NDF digestibility (**Figures 2A & B**). About two thirds of the increase in DM digestibility was due to increased NDF digestibility. Changes in NDF digestibility of this magnitude are huge and exceed those expected with substitution of brown midrib corn silage for traditional corn silage. Oba and Allen (1999) suggested that a 1-percentage unit increase in NDF digestibility resulted in a 0.17 and 0.25 kg/d increases in DMI and 4.0% FCM, respectively. Using Oba and Allen (1999) coefficients and assuming a 7.5-percentage-unit increase in NDF digestibility by increasing DCAD from 0 to 500 mEq/kg, the expected increase in DMI and 3.5% FCM would be 1.3 and 1.9 kg/d, respectively and would account for 75% of the expected increase in DMI and 55% of the expected increase in 3.5% FCM. We concluded that one of the primary modes of action of DCAD is the increase in ruminal fluid pH and NDF digestibility.

Figure 1. Dry matter intake (A), milk production (B), milk fat percent (C), and milk fat yield (D) responses to increasing DCAD.

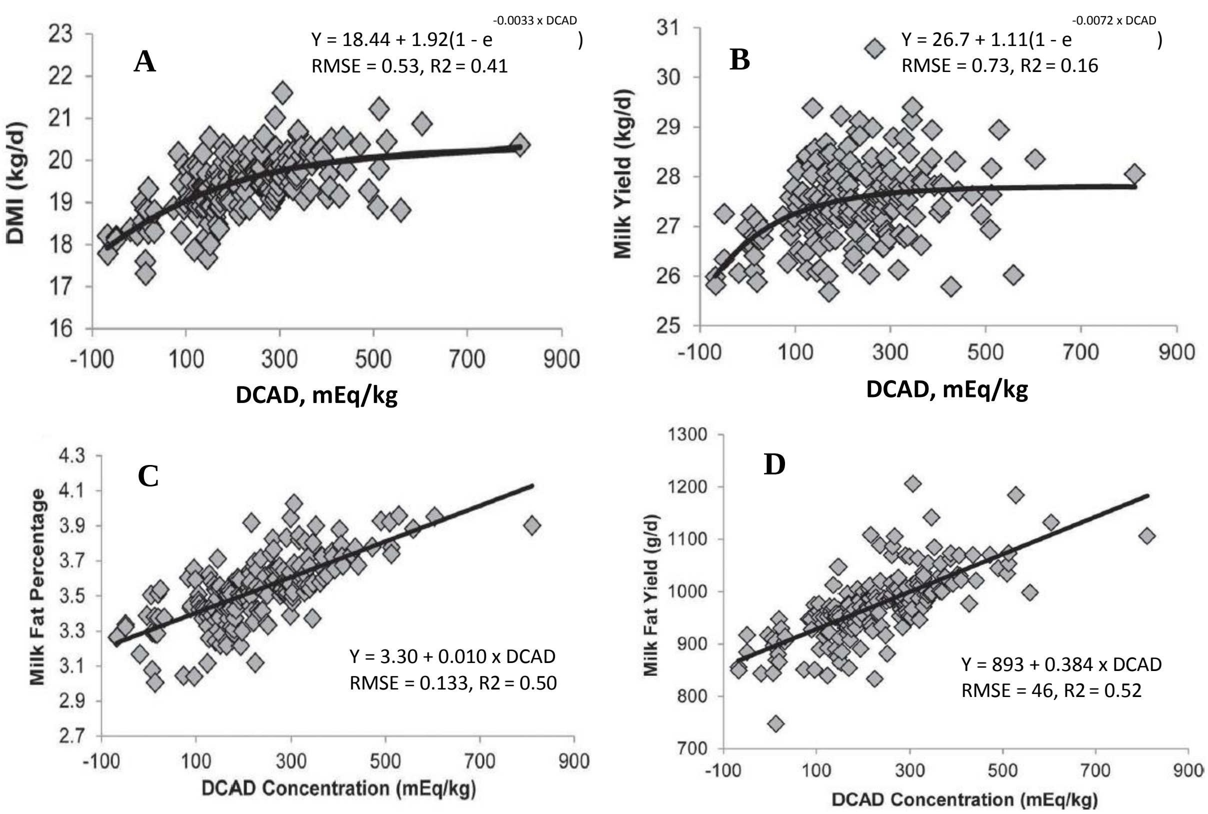
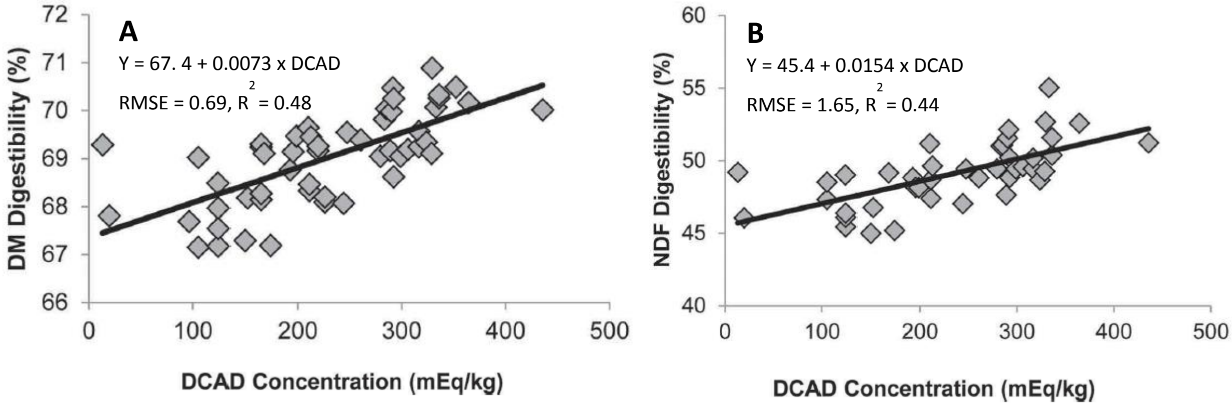


Figure 2. Effect of DCAD on digestibility of dry matter (DM) and NDF.



What is the Optimal DCAD for Lactating Dairy Cows?

As stated earlier, there is no NRC requirement for DCAD but feeding at the minimal requirements for Na, K, Cl, and S would result in a DCAD of 304 and 179 mEq/kg of dietary DM, respectively using the Mongin (1981) and Ender (1971) equations that differ by the incorporation of S in the DCAD calculation. **Table 5** shows a comparison of the maximum DMI, milk production, and FCM production responses from our summary (Iwaniuk and Erdman, 2015) and the earlier analysis of Hu and Murphy (2004). First, the primary economic response is milk fat yield which, in combination with a slight increase in milk production, drives increased FCM. Secondly, an optimal DCAD concentration is not necessarily the concentration at the maximal response. We prefer to look at DCAD concentrations somewhat below maximum because there is a cost in terms of added feed intake and addition of mineral supplements to increase DCAD. We view a practical minimum as a DCAD of 300 mEq/kg of dietary DM. This corresponds to two-thirds of the maximum response in DMI, will garner nearly all the added milk production, and achieve the majority of the increase in FCM production. After that point, the decision to feed higher DCAD with depend on the cost of supplementation and the added value of the extra milk fat produced.

Table 5. Comparisons of maximum responses to DCAD (Ender 1971 equation) from the analyses conducted by Iwaniuk and Erdman (2015) and those of Hu and Murphy (2004).

		66% of maximum	80% of maximum	Hu and Murphy (2004)
Item	Maximum response, kg/d	---- DCAD, mEq/kg of dietary DM required -----		
DMI	1.92	290	425	275
Milk	1.11	150	225	215
FCM	4.82	450	675	No maximum

Formulating for DCAD

Diet formulation for DCAD begins with feed ingredient selection. **Table 6** shows a comparison of selected feed ingredients and their relative mineral and DCAD concentrations. The first thing that is apparent is that most feeds have a relatively low Na content and vary substantially in K, and to a lesser extent, Cl and S. Therefore, feeds that are high in DCAD in which the cations (K and Na) are greater than the anions (Cl and S) are usually feeds that are high in K. Feeds like soybean meal, alfalfa haylage, barley, and grass silages are high K and also high DCAD. Corn silage, because it is a mixture of the corn plant (stalk and leaves) and grain, is intermediate in DCAD content. Protein supplements such as DDGS and canola meal are intermediate in K content and are low DCAD feeds because of their high S content. Thus, in selection of feed ingredients for high DCAD, you will normally look for feeds that are high in K content. Feeds like soybean meal and forages, especially alfalfa and small grain silages, will increase DCAD.

Generally, high NDF feeds (forages) are also high DCAD feeds because of their K content. One side benefit of increasing fiber (NDF) in the diet to increase milk fat is that this also indirectly increases DCAD. Dairy producers frequently attribute the increase in milk fat when NDF is increased to the added NDF, but part of the response is likely due to increased DCAD caused by substitution of low fiber and low DCAD feeds like corn for high fiber and high DCAD feeds like grass or small grain silages.

Table 6. Comparison of cation (K and Na), anion (Cl and S), and DCAD concentrations (mEq/kg of dietary DM) along with % crude protein (CP) and % NDF of feed ingredients.

Feed ingredient	K	Na	Cl	S	DCAD	CP, %	NDF, %
Shelled corn	107	9	-23	-63	31	9.4	9.5
DDGS	281	130	-28	-275	109	29.7	38.8
SBM	775	13	-155	-244	389	53.8	9.8
Canola meal	361	30	-11	-456	-76	37.8	29.8
Corn silage	307	4	-82	-88	142	8.8	45
Alfalfa haylage	775	13	-155	-188	445	22.8	36.3
Grass silage	795	22	-181	-131	505	18	49.9
Barley silage	621	57	-203	-106	369	12	56.3

Supplements That Can Be Used to Increase DCAD

There are a variety of Na and K carbonate and bicarbonate salts that can be used to raise DCAD once the inherent DCAD in feed ingredients has been accounted for. **Table 7** shows some commonly supplemented K and Na mineral salts used in dairy cattle diets. Please note that common salt (**NaCl**) and potassium chloride (**KCl**) are DCAD neutral since the cation (Na or K) is balanced by a corresponding anion (Cl). While salt and KCl are highly available sources of Na, K, and Cl, supplementing with these minerals will have no effect on DCAD. In order to raise DCAD, nutritionists must select from mineral supplements such as potassium carbonate, sodium bicarbonate, or sodium sesquicarbonate. Surprisingly, there is very little difference among these in their relative DCAD content (Table 7). Adding 0.75%, 0.83%, or 0.75% of commercially available potassium carbonate, sodium bicarbonate or sodium sesquicarbonate, respectively to dietary DM will increase DCAD by 100 mEq/kg dietary DM. At that point the choice of supplement is based on cost unless the minimum requirements for Na and K have not been met.

Conclusions

Dietary Anion Cation Difference is not only important for dry cows but also for lactating cows. Optimal DCAD for dry cow diets is typically zero or negative while feeding low DCAD diets to lactating cows will depress feed intake, milk production, and milk fat concentration. The minimal DCAD for lactating cows is most likely about 300 mEq/kg of feed DM (30 mEq/100 g of feed DM). However, the optimal DCAD will be dependent on the value of milk fat, which is the primary economic response to DCAD, and the cost of increasing DCAD above the diet's inherent DCAD concentration with mineral supplements.

Table 7. Composition of Na and K mineral supplements.

Mineral supplement	K, %	Na, %	Cl, %	DCAD, Eq/lb	DCAD, Eq/kg	DCAD
Salt (NaCl)	0.0	39.3	60.7	0	0	Neutral
Potassium chloride (KCl)	52.4	0.0	47.6	0	0	Neutral
Potassium carbonate (K_2CO_3)	52.4	0.0	0.0	609	1340	Positive
Sodium bicarbonate ($NaHCO_3$)	0.0	27.7	0.0	547	1203	Positive
Sodium sesquicarbonate ($Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$)	0.0	30.5	0.0	602	1325	Positive

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SESSION NOTES