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A 100-Year Review: From ascorbic acid to zinc—Mineral and vitamin nutrition of dairy cows[1]

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ABSTRACT

Mineral and vitamin nutrition of dairy cows was studied before the first volume of the *Journal of Dairy Science* was published and is still actively researched today. The initial studies on mineral nutrition of dairy cows were simple balance experiments (although the methods available at the time for measuring minerals were anything but simple). Output of Ca and P in feces, urine, and milk was subtracted from intake of Ca and P, and if values were negative it was often assumed that cows were lacking in the particular mineral. As analytical methods improved, more minerals were found to be required by dairy cows, and blood and tissue concentrations became primary response variables. Those measures often were poorly related to cow health, leading to the use of disease prevalence and immune function as a measure of mineral adequacy. As data were generated, mineral requirements became more accurate and included more sources of variation. In addition to milk yield and body weight inputs, bioavailability coefficients of minerals from different sources are used to formulate diets that can meet the needs of the cow without excessive excretion of minerals in manure, which negatively affects the environment. Milk, or more accurately the lack of milk in human diets, was central to the discovery of vitamins, but research into vitamin nutrition of cows developed slowly. For many decades bioassays were the only available method for measuring vitamin concentrations, which greatly limited research. The history of vitamin nutrition mirrors that of mineral nutrition. Among the first experiments conducted on vitamin nutrition of cows were those examining the factors affecting vitamin concentrations of milk. This was followed by determining the amount of vitamins needed to prevent deficiency diseases, which evolved into research to determine the amount of vitamins required to promote overall good health. The majority of research was conducted on vitamins A, D, and E because these vitamins have a dietary requirement, and clinical and marginal deficiencies became common as diets for cows changed from pasture and full exposure to the sun to stored forage and limited sun exposure. As researchers learned new functions of fat-soluble vitamins, requirements generally increased over time. Diets generally contain substantial amounts of B vitamins, and rumen bacteria can synthesize large quantities of many B vitamins; hence, research on water-soluble vitamins lagged behind. We now know that supplementation of specific water-soluble vitamins can enhance cow health and increase milk production in certain situations. Additional research is needed to define specific requirements for many water-soluble vitamins. Both mineral and vitamin research is hampered by the lack of sensitive biomarkers of status, but advanced molecular techniques may provide measures that respond to altered supply of minerals and vitamins and that are related to health or productive responses of the cow. The overall importance of proper mineral and vitamin nutrition is known, but as we discover new and more diverse functions, better supplementation strategies should lead to even better cow health and higher production.
Key words: vitamin, mineral, requirements, health

INTRODUCTION

By the mid to late 19th century we knew that animals needed to consume certain minerals to live and be productive, but we did not know which minerals and how much was needed. Investigation into the mineral nutrition of dairy cattle soon followed (Appendix Table A1). However, the science and application of mineral and vitamin nutrition of dairy cattle did not advance as quickly as other areas of nutrition. Advances were limited by (1) analytical difficulties in measuring minerals and vitamins, (2) the lack of sensitive response measures for several vitamins and minerals, (3) the fact that the often-subtle responses to changes in supply of minerals and vitamins require large number of animals to be used in experiments, (4) diet dependency of responses (e.g., mineral antagonists, concentrations and

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availability of vitamins and minerals in basal ingredients), and (5) the long experimental duration required to observe responses. Many of these difficulties were pointed out in the first paper published in the *Journal of Dairy Science* that addressed mineral nutrition of dairy cows:

> "[Investigation is] difficult because the environment of the animal is composed of such a complication of influences that it is impossible to determine the proportionate contribution of each of them, especially of the obscure and intricate facts of mineral metabolism; and also because, on account of the supreme importance of mineral metabolism, the animal is so wonderfully protected by mineral reserves and other safety provisions that unfavorable effects of treatment are slow to appear and are difficult to demonstrate in a clear-cut manner." (Forbes, 1919)

Although mineral nutrition was difficult to study when the journal was founded, the importance of developing mineral-adequate diets was discussed during the fifth year of the journal by Meigs (1923). Only Ca and P were discussed in that paper because, as Meigs stated, "There is little reason to think that deficiencies of any other mineral elements play a very large or general practical role under ordinary conditions." The state of the art at that time is reflected in how the Ca requirement was expressed in that paper: "1 pound of alfalfa hay for every 3 or 4 pounds of milk."

The vitamin theory was developing around the same time we recognized that animals needed certain minerals. In 1871, noting that death rates of children increased dramatically when milk became unavailable to citizens of Paris, Jean Baptiste Dumas (as quoted by Semba, 2012) hypothesized that milk contained "indefinite substances employed in the sustenance of life, in which the smallest and most insignificant traces of matter may prove to be not only efficacious but even indispensable." Vitamins A, B, and C were discovered in 1912, but the first studies on vitamins that appeared in the journal were not published until the seventh volume; these papers dealt with the nutritional value of milk and vitamin requirements of calves. As with minerals, requirements were expressed on a feedstuff basis (e.g., "2 ounces of cod liver oil" or "the juice of 2 oranges"). Progress in vitamin nutrition of dairy cattle has arguably been slower than that in mineral nutrition (Appendix Table A1). Vitamins can be extremely difficult to analyze. Concentrations are often in nanograms per kilogram, many are extensively metabolized or synthesized within the rumen, and clinical responses are often generic and subtle. Vitamins requirements were based on avoidance of classical deficiency diseases (e.g., rickets for vitamin D); if deficiency diseases were not observed, diets were assumed to be adequate in the vitamin.

ADVANCES IN MINERAL NUTRITION

Dairy cattle likely require at least 22 minerals (Table 1), and other minerals may be added to that list as our analytical abilities become more sensitive. Calcium and P nutrition have been studied longer than any other mineral, probably because they are major constituents of milk and because concentrations in biological samples were great enough to be measured using the analytical procedures available at the time. The initial studies on Ca and P nutrition were balance experiments (intake − fecal − urine − milk), and surprisingly Ca balance was negative in almost all experiments (Forbes et al., 1922). Phosphorus balances were also negative in several but not all experiments. The Ca concentrations of the diets were not presented, but most diets contained more than 50% alfalfa and some diets contained supplemental Ca; negative Ca balances would not be expected. Nonetheless, this led to the development of quantitative requirements for Ca and P (NRC, 1945).

1917–1945

During this period mineral research was limited mostly to Ca and P, and primary response variables were balance (intake − output of the mineral), blood concentrations, and milk production. However, one study (Huffman et al., 1933) evaluated the P requirement for reproduction using 14 heifers. Titration-type studies were being used to quantify requirements, and proper experimental protocols for evaluating mineral requirements were being developed. Also during this time the importance of interactions among minerals and other nutrients was being recognized. The dietary Ca:P ratio was often discussed and assumed to be important (although more recent experiments have shown that the ratio is not a major factor affecting absorption of either mineral). Vitamin D had been discovered, and studies with both calves and cows showed that Ca and P balances were greatly improved when vitamin D was provided (Wallis, 1938). Vitamin D status likely explains the data from Forbes et al. (1922) and illustrates the complexities of mineral nutrition and that establishing mineral requirements depends on the diet as well as the cow. The quantitative studies conducted during this period culminated in the first NRC nutrient requirement publication (NRC, 1945), in which 27 pages were dedicated to dairy cattle (NRC, 2001 was 381 pages). Requirements for maintenance, growth, and