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Improved nutritional quality of animal products through manipulations of trace element and calcium status

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ABSTRACT

Research on the requirements and metabolism of trace elements in grazing livestock is revealing new ways in which the nutritional status of people might be improved. Our understanding of how to manage the mineral status of cattle and sheep can create additional impact through enhancing the quality and value of milk and meat. For example, by optimising the familiar selenium and iodine supplementation strategies used to prevent deficiencies and maintain animal mineral requirements, we can tailor the element content of the resulting animal products. Simple Se and I supplementation produces commensurate increases in milk and meat, but the concentrations of calcium and iron are not so easily manipulated, so other smarter strategies are called for. For these four nutritionally essential elements, maximum concentration and bioavailability to humans is affected by age of animal, stage of lactation, plus element chemical form and distribution among the milk and meat fractions.

Keywords: calcium; iodine; iron; selenium; milk; meat; dietary intake.

OPPORTUNITY AND SIGNIFICANCE

Milk and meat contain a range of nutritionally essential elements, and these foods are ideal vehicles for improving the mineral nutrition of human consumers. Boosting human daily dietary intake of elements such as calcium (Ca), iron (Fe), iodine (I) and selenium (Se) is of considerable health interest, so increasing their concentrations in milk and meat would generate valuable marketing opportunities. Such products would have the advantage of natural, endogenous mineral content, incorporated at the time of milk or meat synthesis. These enhanced-mineral foods could also serve as unique raw materials for milk powder and infant formula producers, reducing reliance on other forms of health food supplements such as pills and additives.

Elsewhere during the contract session the importance of elements to NZ livestock health and productivity is discussed, but in this paper the emphasis is on relevance to wellbeing of humans. The research experience, knowledge and techniques established around animal health issues can be refocused for animal product quality, ultimately to create better food with greater appeal.

Some macro-, minor- and trace element nutrients are traditional strong suits of milk and meat, such Ca and Fe. Others are less familiar or have significance mostly to niche markets and special populations, such as Se and I. Demand for dietary Ca and Fe is high worldwide, as daily intakes are commonly inadequate to meet dietary reference intakes (DRI), and the links between deficiencies and diseases such as osteoporosis and anaemia are well documented. Selenium and I are of special concern in New Zealand where soils are often low in these elements. Concomitant low concentration in the crops and animal products that comprise typical New Zealander diets has reduced the average Se and I intake of children and adults (Robinson, 1988). Though severe deficiency is rare, a marginal Se status can reduce antioxidant capacity and alter thyroxine metabolism. Selenium also has putative roles in ageing, fertility, carcinogenesis and immunocompetence, but mechanisms are as yet undefined. Chronic I deficiency leads to goitre and cretinism.

When consumed as part of a whole meal, the contribution made by a serving of milk or meat to meeting

TABLE 1. Typical concentration ranges of elements in plasma, milk and meat from unsupplemented grazing New Zealand cattle and sheep.

		Plasma	Milk			Meat		
Element		Conc.[1]	Conc.	Abs. coeff[2] (%)	Contrib to DRI[3] (%)	Conc.	Abs. coeff (%)	Contrib. to DRI (%)
Ca	mM	2.2-2.8	25-40	30[4]	30	0.7-1.5		1
Fe	µM	25-45	2-15[5]	10-30[6]	1	180-800	25	30
I	nM	150-500	200-2000[7]		15	100-1000[8]		5
Se	nM	100	30-80	>70	2	300-1200[9]		10

[1] Concentration per L of plasma or whole milk, or per kg of raw meat.

[2] Dietary absorption coefficient.

[3] Contribution based on percent of the adult Dietary Reference Intakes provided by a serving of 250ml milk or 100g lean meat.

[4] Calcium fraction absorption taken from Weaver & Plawecki (1994), and most other foods are similar.

[5] Iron content varies with stage of lactation, and skim milk concentration is about 75% that of whole milk.

[6] Iron bioavailability to adults is at the lower end of this range. Note that absorption by infants of iron from human milk is 45-100%, and absorption of iron salts from supplemented infant formulas is 2-7%.

[7] Iodine content of NZ milk is typically lower than concentrations reported overseas.

[8] Iodine content of human and sheep muscle (Belling 1988).

[9] Selenium concentration in NZ sheep meat tends toward lower end of this range.

the DRI of essential elements varies from minor to substantial (see Table 1). The true nutritional value of that contribution equals the element concentration times its “bioavailability”, a term that takes account of percent absorption of a nutrient, its distribution, and utilisation. Bioavailability is a function of chemical form, quantity in the diet, dietary interactions, and the nutritional or health status of the consumer. In many cases the bioavailability of a nutrient in its “natural” state is optimal, as provider and receiver (i.e. the gut and metabolism of the consumer) have evolved in concert. For instance the absorption of Fe from meat and milk (particularly human milk) is high relative to other foods, and this gives these products an inherent health and marketing advantage. Calcium absorption efficiency is fairly high and similar for most foods, except those rich in oxalate and phytate. Iodine from milk and Se in milk and meat are almost completely absorbed.

When milk or dairy products are the main constituents of a limited diet, as with bottle-fed babies, enhanced-element foods could significantly improve diet and well-being by helping to meet daily intake requirements. For instance, infant DRIs are 7-13 mmol Ca, 0.10-0.18 mmol Fe, 130-190 nmol Se, and 300-400 nmol I (about 425 mg, 8 mg, 13 µg, and 45 µg, respectively). If infants consume cows milk at 0.75 L/day, the milk element concentrations necessary to fully meet DRI would be 9-17 mmol Ca/L, 0.13-0.24 mmol Fe/L, 170-250 nmol Se/L, and 400-500 nmol I/L.

TECHNIQUES AND STRATEGIES

Sheep and cattle in New Zealand are routinely supplemented with trace elements by mineral lick, drench, pour-on, injection or intraruminal device in order to maintain animal productivity. In some cases such supplementation can produce commensurate increases in meat and milk concentrations. But not all elements are this easily manipulated, because macro-, minor-, and trace element metabolisms are governed by diverse biochemical mechanisms.

For elements such as Se and I, these small anions are readily absorbed across digestive tract membranes, so blood, then milk and eventually meat concentrations reflect dietary intake. In contrast, Ca and Fe require specific membrane transporters, their absorption is strictly limited by intestinal regulatory processes, and absorption efficiency depends on nutritional need (Mertz, 1985). This homeostasis means that blood concentrations are essentially invariant and independent of intake. Blood responsiveness to diet can be ordered as Se = I > Cu = Zn > Ca = Fe. Muscle and mammary tissue are able to accumulate or exclude elements from blood plasma, and maintain greater or lesser concentrations. For instance, the milk:plasma ratio of elements varies over two orders of magnitude, summarised as Ca >> I = Se > Fe.

When simple or familiar animal supplements are unable to increase milk and meat element content, other smarter strategies are called for. These can include higher technology injectables or implants allowing sustained release rates, selective breeding for maximum concentration, or adding elements to foods during processing, as described below.

Calcium in milk

If increasing the concentration of some milk and meat elements via diet is difficult, then fortifying during processing can be a successful alternative. Such is the case with Tararua Calci-Trim™ (and imitators). Calcium content is enriched 70% over standard milk using only “natural” forms of Ca sourced from concentrated whey permeate. Calci-Trim™ could succumb to its own popularity however, if high consumer demand eventually outstrips the supply of suitable whey, so research into alternative point-of-origin methods (i.e. at the cow) is still required.

Fortification of milk with other elements is not always so desirable. For instance, addition of unchelated Fe and Cu produces oxidation and off-flavours (Hegenauer *et al.*, 1979), and tariff barriers or government regulations that define the allowable composition of *fresh* milk may limit or prohibit any additions of mineral salts. In either case, it’s unlikely that the resulting milk has the bioavailability advantage of natural, endogenous mineral content, incorporated at the time of milk synthesis.

Selection and breeding could be exploited to produce high milk Ca, because significant variation in milk Ca content exists between cows. In a large survey of Dexcel herds, milk Ca concentrations varied between 25mM and 40mM, with average Ca content generally greater in Jersey than in Friesian. About one-third of milk Ca was found in the whey, and whey Ca ranged from 6 to 15mM. Breed and milk protein content explained over 70% of the Ca variation. Groups of Jersey and Friesian cows selected on the basis of milk Ca as low (about 29mM) or high (about 36mM) maintained those characteristics across seasons (Davis *et al.*, 2000).

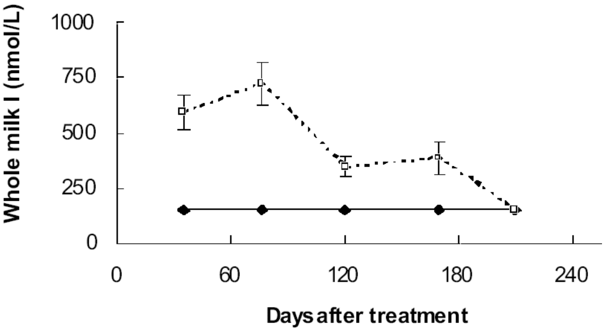
Developing the genome for maximum Ca secretion into milk will require the support of optimised nutritional management, possibly requiring dietary cation:anion balancing to maintain Ca homeostasis. Further basic work at both whole body and cellular levels is essential to define how to partition more Ca into milk (but not at expense of bone desorption) and appropriate nutritional support.

Iodine in milk

Iodine content in milk and dairy products reflects not only cow dietary I intake but also I contamination from milk handling and storage, as the iodophore sanitisers used to clean dairy equipment contribute substantially to milk I content and can mask the endogenous I concentration (Sutcliff, 1990). With the substitution of non-iodate sanitisers on most New Zealand dairy farms however, commercial milk I is declining to much lower “unadulterated” concentrations. The I status of New Zealanders might no longer be considered adequate and may once again be approaching levels of intake associated with clinical I deficiency (Thomson *et al.*, 1997).

The emphasis of most I supplementation strategies has been maintenance of stock health in areas of I-poor soils or goitrogenic plants (Waghorn & Northover, 1992), but Grace *et al.* (1996) have shown the efficacy of

FIGURE 1. Effect of long acting injectable I on milk I concentrations in grazing dairy cows. Treated cows received a single intramuscular injection of 2 g I in poppyseed oil. (n=40, mean ± SEM). Limit of detection in milk is 155 nmol I/L. Control (–◆–); Intramuscular I injection (—□—).

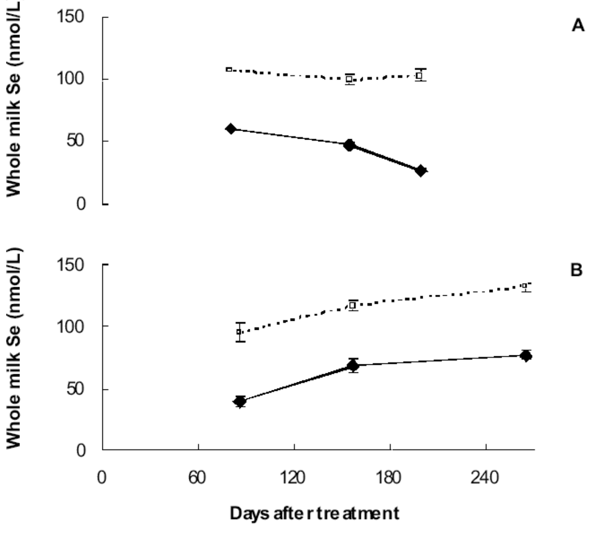


injectable I supplements to enhance milk I for human nutrition. When a single dose of 2 g I as iodised poppyseed oil was given via intramuscular injection to dairy cows grazing pastures of low but adequate I content (0.17-0.26 mg I/kg dry matter), milk I concentration was doubled, from < 150 nmol/L to 380 nmol/L, for 170 days (Figure 1). Two such injections, administered six months apart, would be sufficient to maintain milk I at or above 300 nmol/L year-round.

Selenium in milk and meat

The best characterised, and probably only, biologically active form of Se is selenocysteine. The redox functions of enzymes such as glutathione peroxidase (GSH-Px), formate dehydrogenase and iodothyronine deiodinase rely on selenocysteine incorporated into their active sites. Most of the Se content of milk and meat however, is incorporated *non-specifically* at low abundance into nearly all proteins as the amino acid analogue selenomethionine. In milk, that Se is found primarily in the casein fraction, approximately in proportion to the number of methionine residues in each protein. Depending on the type of foodstuff consumed, 50-80% of dietary Se is absorbed (Levander, 1983). Using an *in vitro* monogastric system, Cabrera *et al*. (1996) confirmed absorption of Se from a variety of dairy products to be > 70%.

FIGURE 2. Effect of (A) intraruminal Se boluses and (B) long acting injectable Se on whole milk Se concentrations in grazing dairy cows. Treated cows received either two 30 g boluses (10% Se:90% Fe by weight) at the start of the trial plus a further single bolus on day 147 of the trial (n=20, mean ± SEM), or a single subcutaneous injection of 0.5 g Se as $BaSeO_4$. (n=20, mean ± SEM). Control (–◆–); Se treated (—□—).



The milk Se concentrations of dairy cows can be increased by Se supplementation through dietary (pasture topdressing with selenised fertilisers), oral (bolus or drench) or parenteral (injection) routes. In long term efficacy trials, Grace *et al*. (1997) gave multiple intraruminal Se boluses containing 3 g elemental Se or a single injection of 0.50 g Se as $BaSeO_4$ to cows grazing Se-deficient pastures (<0.03 mg Se/kg dry matter). Both treatments significantly raised animal Se status over controls, with milk Se concentrations increased three-fold (< 27 nM vs. 100 nM) and two-fold (77 nM vs. 130 nM) respectively (Figure2). This increase in Se concentration is sufficient to make a substantial contribution to daily Se intake of bottle-fed infants.

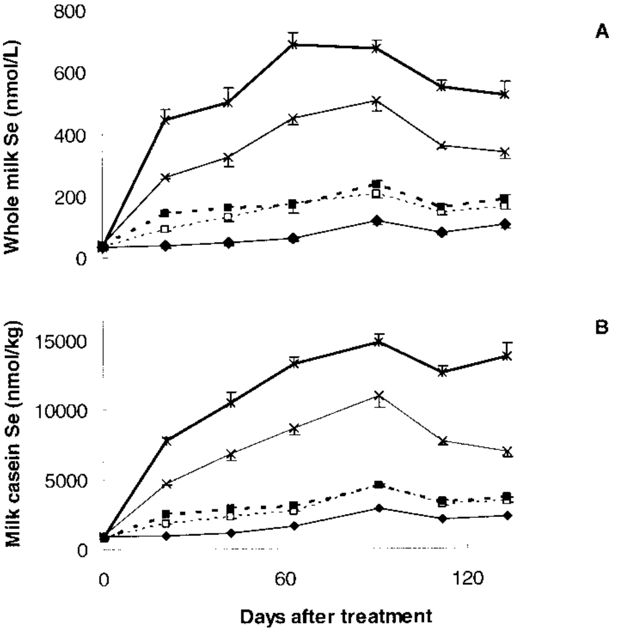
To study the fate of supplemental Se, its partitioning among metabolic pools, and its distribution in milk casein and whey fractions, Knowles *et al*. (1999) compared two chemical forms of Se administered orally at two dose levels. Inorganic sodium selenate or organic Se-enriched yeast (Sel-Plex 50™, Alltech Inc.) was given thrice-weekly for four months as drenches to previously unsupplemented cows grazing low Se pastures (0.035 mg Se/kg dry matter) during mid lactation. Animals received up to 4 mg Se per day. Selenium in the yeast was primarily selenomethionine and selenocysteine (Foster & Sumar, 1995).

Yeast Se was more effective than the corresponding selenate dose at increasing Se concentration in blood, whole milk and milk casein (Figure 3). After three months of treatment, the Se concentration of whole milk was enriched about ten-fold over controls, to nearly 700 nM, with uptake into milk of Se from yeast two to four times more efficient than uptake from selenate. The Se content of casein mostly mirrored that of whole milk, with about 75% of total milk Se associated with the ultracentrifugation casein fraction. Milk Se derived from yeast may also be more bioavailable than Se derived from inorganic forms of supplements. Jenkins and Hidiroglou (1971) observed that suckling lambs absorbed a greater proportion of the Se in milk from selenomethionine-treated ewes than did lambs suckling selenite-treated ewes.

These results demonstrate the ability of Se supplements to enhance the Se content of milk. Further research will define and manage the changes in milk Se observed over the course of lactation (see Figure 3), which might otherwise lead to inconsistently enhanced Se products. Work is also needed to describe and predict the distribution of Se between casein and whey, so that Se-rich fractions are not lost during dairy processing.

Increasing human dietary intake of Se by modifying meat is an idea already in the public domain. Molnár *et al*. (1997) have espoused the idea in sheep, while Hintze *et al*. (2001) showed that beef from cattle raised in seleniferous areas of the USA has a Se concentration high enough to provide 100% of human daily requirement per

FIGURE 3. Effects of Se supplementation on (A) whole milk Se and (B) milk casein Se concentrations in grazing dairy cows. Inorganic sodium selenate ($Na_2SeO_4 \cdot 10H_2O$) or organic Se-enriched yeast was given thrice-weekly as oral drenches for four months during mid lactation. Animals received the equivalent of 0, 2 or 4 mg Se per day (n=7, mean ± SEM). Control (–◆–); 2mg inorganic Se (—☐—); 4mg inorganic Se (—■—); 2mg yeast Se (–X–); 4mg yeast Se (–*–).



serving. And in the pig industry, some Korean producers are beginning to capitalise on the advantages of dietary yeast Se to increase the Se content of pork, with such foods attracting price differentials of 5-15%. In New Zealand we have used proprietary methods to increase the endogenous Se concentration of lamb muscle, and preliminary results show meat Se content enhanced tenfold over control animals, exceeding 2500 nmol/kg. A 100g serving would thus provide 25% of adult DRI. As with enhanced milk products, novel Se-enriched meats will require new value chains to feedback price signals to the farm gate and so encourage technology uptake by growers and processors.

Iron in meat and milk

The importance of chemical form in determining bioavailability of mineral nutrients is exemplified by the distinction between haem and non-haem (inorganic or salts) forms of Fe. Separate biochemical mechanisms in gut provide absorption from diet of > 25% and about 5-16%, respectively. About three-quarters of the Fe in meat is present as haem, with only minor differences in Fe concentration between forage-fed beef and lamb, or among muscle cuts. There appears to be little scope for substantially changing those concentrations; Fe supplied at three times the normal intake for sheep grazing ryegrass/white clover pasture does not affect meat Fe (Grace and Lee, 1990).

In milk, there is no haem but Fe is bound to lactoferrin (an Fe-binding transport protein), transferrin, casein micelles and fat globule membranes, with resulting high bioavailability. High-Fe milk is something of a holy grail in nutrition research, as dairy products provide an ideal vehicle for delivering essential Fe to the populations most in need. Endogenous high Fe would satisfy legal criteria for fresh milk, and has natural marketing value. We have used proprietary methods to increase the Fe content of milk from lactating dairy goats. Early results show Fe concentration increased as much as 20 times over basal levels. Future research will evaluate the persistence of enhanced Fe throughout lactation, characterise milk fractions where that Fe is located, and utilise *in vitro* methods to estimate its bioavailability.

CONCLUSIONS

Not all macro- minor or trace elements in milk can be altered with equal ease. Enrichment of Ca via processing addition is successful, and Se and I by animal supplementation is achievable, but increasing the milk concentrations of Fe or Ca at the point-of-origin remains challenging. Raising milk and meat elemental content does not automatically equate to improved nutritional value for consumers, as the chemical form and distribution of the elements within a food are important determinants of its ultimate bioavailability. Further investigations will examine how best to make desirable increases in trace element composition of milk and meat products, but in the end, consumer demand, industry interest, and public policy will determine whether enriched milk and meat is a means suited to improving the mineral nutrition of consumers locally and abroad.

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