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Role of supplemental vitamin E in lamb survival and production: A review

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Abstract

Neonatal lamb mortality costs U.S. sheep producers approximately \$114 million annually. Mortality rates have been reported in excess of 20% with little improvement over the past 40 yr. The objective of this paper is to review literature pertinent to the potential role of supplemental vitamin E to increase neonatal lamb survival and production. Effects of vitamin E in humoral and, to a lesser extent, cell-mediated immunity have been well documented. However, the influence of supplemental vitamin E on immunity and other factors that may increase lamb survival and production are not clearly understood. Although supplementing the newborn lamb with vitamin E increases serum vitamin E concentration and may influence serum immunoglobulin levels, this administration of vitamin E may not be as effective in decreasing neonatal lamb mortality as supplementing the ewe during late gestation. In addition to the role of vitamin E in immune function, the potential role of vitamin E in neonatal energy status and stress are discussed. Strategic supplementation of the late gestating ewe with vitamin E may be a biologically and economically efficient method of reducing neonatal lamb mortality when environmental stresses are high. Whether this response is solely due to enhanced immune function or a combination of improved immunocompetence, fetal energy status, and a neonate more capable of dealing with stress is yet to be determined. Further research on how supplemental vitamin E may influence cell-mediated immunity, ameliorate stress, and improve fetal energy status is needed to clarify the role of vitamin E in neonatal lamb survival and production.

Key Words: Immunity, Lambs, Neonatal Mortality, Survival, Vitamin E

Introduction

Vitamin E is the generic term used for all tocol and tocotrienol derivatives that exhibit the activity of α -tocopherol. Ewes grazing lush green spring pasture typically have high concentrations of serum vitamin E. In contrast, ewes fed dry, stored feed or grazing dormant range typically have lower serum vitamin E concentrations. In addition, plasma vitamin E levels drop by approximately 50% 7 d prepartum and do not return to normal until 20 to 30 d postpartum. Thus, it is reasonable to speculate that gestating sheep grazing dormant range or fed harvested feeds preceding late winter or early spring lambing may need supplemental vitamin E that could ultimately affect lamb production.

Adipose tissue is the main body storage site for vitamin E (Puls, 1994). However, vitamin E is not stored in the body in appreciable concentrations, (Rammell, 1983) and prevention of white muscle disease has typically been the measure of determining adequacy. However, Nockels (1986) suggested that vitamin E at 6 to 20 times the NRC recommended concentrations would improve the immune response of animals. Thus, the focus of this paper will be a discussion of the role of supplemental vitamin E in enhancing neonatal lamb survival, through immunocompetence, and possible fetal energy status and alleviation of fetal stress. In addition, we will focus on the role of vitamin E in conditions of adequate selenium (Se), which is readily transmissible through the pla-

centa and concentrated in the liver for possible Se mobilization in postnatal life (Van Saun et al., 1989).

Discussion

Neonatal Lamb Mortality

Neonatal lamb mortality is a major factor reducing profitability in sheep operations. Rook (1997) concluded that 15 to 20% preweaning lamb losses are common in Michigan sheep operations. Neonatal lamb mortality rates of 10 to 35% are considered normal and acceptable in large sheep operations in the western United States (Rowland et al., 1992). In southern Australia, 29% of lambs die before weaning (Kleemann and Walker, 1993). Safford and Hoversland (1960) examined data recorded from a 3-yr study in Montana and found that preweaning death loss totaled 23.5%. Rowland et al. (1992) concluded that 66% of lamb deaths were preventable with improved management.

The majority of lamb mortality occurs in the first few weeks of life. Safford and Hoversland (1960), Alexander (1983), and Rook (1997) reported that approximately 50% of lamb mortality occurs within the first 3 d of life, independent of the production system. In a review of mortality records from typical Western range sheep operation, Rowland et al. (1992) reported that more than 50% of all lamb deaths occurred within 24 h after birth.

Causes of neonatal lamb mortality are similar regardless of geographic region. Rook (1997) found that hypothermia/starvation, still-birth/dystocia, and pneumonia were the three top causes of death in Michigan sheep operations. In Montana, Safford and Hoversland (1960), after examination of approximately 1,000 lamb necropsies, noted that pneumonia was the leading cause of death in neonatal lambs. Neonatal lamb mortality rates and causes reported by Safford and Hoversland (1960) are similar to those reported by recent research (Rowland et al., 1992; Nash et al., 1996; Rook, 1997). Results from these studies, spanning more than 30 yr, suggest that little improvement has been made in preventing neonatal lamb mortality.

The Role of Vitamin E

The underlying factor in the function of vitamin E is as a natural antioxidant. Vitamin E can prevent peroxidative degradation of fats in animal cells and the consequent formation of free radicals (Huber, 1988). By scavenging reactive oxygen species, molecules that are produced through normal metabolism, vitamin E spares oxidation of cell membranes (Horton et al., 1996). Reactive oxygen species create a potential threat to the integrity and function of all biomolecules, particularly proteins and lipids, due to their strong oxidizing ability. Vitamin E, through itself being oxidized by reactive oxygen species, can relieve the system of reactive oxygen species and thereby spare surrounding cells from being damaged (Coelho, 1991; Chew, 1996). Reffett et al. (1988) stated that glutathione peroxidase, which is part of the antioxidant defense system, may play an important role in disease resistance by increasing the efficiency of the antioxidant defense system. Macrophages and neutrophils produce oxygen radicals such as hydrogen peroxide and superoxide anions during phagocytosis of foreign particles. If these radicals are not promptly removed from the system, they may damage the membranes of phagocytic cells. Greater glutathione peroxidase activity may be associated with ridding the body of tissue-damaging oxygen radicals.

Immunity. Many attempts have been made to identify the immunological components that might be sensitive to change in vitamin E status, but results have been inconsistent and at times conflicting (Finch and Turner, 1996). Vitamin E is potentially involved in disease resistance through protection of membranes of immune system cells through antioxidant function (Coelho, 1991). Sheffy and Schultz (1979) suggested that vitamin E may have its primary effect on the immune system by antagonizing the peroxidation of arachidonic acid and limiting prostaglandin production; prostanoids are involved in immune function. Reactive oxygen molecules are produced through normal metabolism and through the phagocytic action of neutrophils and macrophages (Nockels, 1996). By having adequate antioxidants such as vitamin E, reactive oxygen molecules can be reduced in number and lessen the potential of cells and cell membranes being damaged. Scott (1980) suggested that vitamin E in cellular and subcellular membranes is the "first line of defense" against phospholipid peroxidation, which produces harmful perox-

ides. Any suppression of immune function caused by a vitamin E deficiency could result in a decline in production before any gross effects become apparent (Finch and Turner, 1996).

Immune responses are generally defined as either humoral or cell-mediated responses. The humoral branch of the immune system involves B lymphocytes interacting with foreign materials or antigens (Kuby, 1997). The humoral immune response also involves the proliferation and differentiation of B cells into antibody-secreting plasma cells. Antibodies are the effector molecules of the humoral branch, binding to antigens and either neutralizing or preparing the antigen for elimination by phagocytic cells. Immunoglobulins (Ig) function as antibodies, of which there are five classes: IgG, IgM, IgD, IgE, and IgA. Immunoglobulin G makes up approximately 80% of the total serum Ig. Humoral or antibody mediated immunity is effective against antigens dissolved in body fluids and extracellular pathogens such as bacteria (Tortora and Grabowski, 1996).

The cell-mediated branch involves T lymphocytes, which are generated in response to an antigen. The effector cells of the cell-mediated branch are activated T helper cells (T_H) and cytotoxic T lymphocytes (CTL). Activated T_H cells can activate phagocytic cells to kill or phagocytize microorganisms (Kuby, 1997). This is especially important in protecting an individual against intracellular bacteria and protozoa. Cytotoxic T lymphocytes are involved in killing altered self-cells, and that is important in killing virus-infected cells and tumor cells (Kuby, 1997). The cell-mediated branch of the immune system relies on antigen-specific and nonspecific cells. Antigen-specific cells include T_H cells and CTL cells and antigen nonspecific cells include macrophages, neutrophils, eosinophils, and natural killer cells (Tortora and Grabowski, 1996). Cell-mediated immunity is particularly effective against intracellular fungi, parasites, viruses, some cancer cells, and foreign tissue transplants (Tortora and Grabowski, 1996).

The most important determinant of neonatal lamb immunocompetence is the consumption of colostrum because newborns are essentially devoid of immunoglobulins (Perino and Rupp, 1994). Of the total antibodies available in colostrum, approximately 90% of the immunoglobulins are in the form of IgG (Maidment and Thomas, 1995). Colostral immunoglobulin levels are good indicators of passive immunity (Sawyer et al., 1977; Perino and Rupp, 1994; Maidment and Thomas, 1995), and serum or plasma immunoglobulin levels are good indicators of an animal's ability to mount an immune defense (Sawyer et al., 1977; Besser and Gay, 1994).

Although immunoglobulins are not present in neonatal lambs before nursing, immunity of neonates begins before parturition. Perino and Rupp (1994) reviewed immunization of the beef cow and its effect on the neonatal calf, and, according to their report, fetal immunocompetence begins during gestation, with lymphocytes being in the thymus as early as d 42 of gestation. At 75 to 80 d of gestation, these fetal lymphocytes have some suboptimal response capabilities to mitogens and by d 120 have the same response as a normal adult bovine.

Vitamin E has shown to increase lymphocyte proliferation in the presence of antigens such as on concanavalin-A, phytohemagglutinin, keyhole limpet hemocyanin, and poke-weed mitogen (Finch and Turner, 1989; Pollock et al., 1994). McDowell et al. (1996) stated that considerable attention is being paid to the role of vitamin E (and Se) in protecting leukocytes and macrophages during phagocytosis. However, no literature is available on the role of supplemental vitamin E (only) to sheep in the presence of adequate Se on lymphocyte or neutrophil function of neonatal lambs.

Vitamin E Requirements and Deficiency

Dietary vitamin E requirements for sheep are not clearly defined. The NRC (1985) recommends 10 to 70 mg of vitamin E/kg diet, which seems to be based on levels to prevent white muscle disease. Vitamin E plays a key role in maximizing immunocompetence by increasing cell-mediated and humoral immunity. All of which are most likely at dietary levels greater than those required for maximum growth rate (Puls, 1994).

An inadequate supply of vitamin E, especially in neonates, is a frequent cause of immunodeficiency, and supplementing the dam prior to parturition can increase lamb serum vitamin E concentrations (Daniels et al., 1999). Inadequate dietary vitamin E affects humoral immunity (Dreizen, 1979), which is responsible for the production of antibodies, including all five classes of immunoglobulins. Undernutrition also affects cell-mediated immunity, which is responsible for protection against viral, protozoal, and fungal infections. The fact that vitamin E does not cross the placenta in appreciable amounts make neonates highly susceptible to vitamin E deficiency (McDowell et al., 1996). However, increasing serum vitamin E in newborn lambs may not always affect survival and measures of humoral immunity (Montana State University, unpublished data). Kelleher (1991) concluded, after reviewing vitamin E studies both in humans and animals, that vitamin E requirements would be greater if the requirement was based on lymphocyte proliferation or, more generally, immune function than on indicators of muscle degeneration. Nockels (1986) suggested that vitamin E at 6 to 20 times the NRC recommended concentrations would improve the immune response of animals. Kott et al. (1998) reported increased lamb survivability when ewes were supplemented with approximately 10 times the NRC-recommended concentration of vitamin E. Although Daniels et al. (1999) supplemented ewes with over 10 times the NRC-recommended level, serum vitamin E concentrations were only marginal compared to values reported by Puls (1994).

Vitamin E is intimately associated with Se; both play the role of an antioxidant, and both have the ability to offset some deficiencies of the other. Selenium, as a component of enzyme glutathione peroxidase, has a primary role in destroying reactive oxygen species that inevitably form in three major ways (Scott, 1980). First by protecting the integrity of the pancreas, allowing normal vitamin E (fat) digestion to take place, second by reducing the amount of peroxides attacking the cell membranes by way of glutathione peroxi-

dase, and third by aiding in the retention of vitamin E in the blood.

Kelley and Bendich (1996) reviewed several studies concerning vitamin E and immunological function and suggested that by reducing fat content in the diet of humans the proliferation of peripheral blood lymphocytes will increase. In addition, lowering fat content in the diet in other studies showed increased secretion of interleukin-1, increased natural killer cell activity, and increased lymphocyte proliferation (Barone et al., 1989; Kelley et al., 1989). Kelley and Bendich (1996) stated that individuals consuming high-fat diets and having a low antioxidant-nutrient status (such as vitamin E) might be susceptible to a suppressed immune response. This statement is in agreement with Sheffy and Schultz (1979), who found that dogs deficient in vitamin E had significantly suppressed immune functions when fed a diet high in PUFA. Inhibition of lymphocyte proliferation caused by fish oil supplementation (high in PUFA) could be overcome with increased intake of vitamin E (Kelley and Bendich, 1996)

Serum Vitamin E. Although Puls (1994) stated that serum levels of vitamin E are reflective of recent dietary intake and may have limited value in assessing animal status, serum vitamin E concentrations are the best indicators of vitamin E status currently available. Njeru et al. (1994) found that lamb serum concentrations of α -tocopherol increased linearly with increasing levels of supplemental vitamin E. Platelet α -tocopherol concentrations also increased linearly with treatment levels and were found to be more sensitive to vitamin E supplementation than serum. Similar to Njeru et al. (1994), a 2-yr study at Montana State University (unpublished data) found that lambs receiving two oral doses (782 IU of vitamin E) had greater serum vitamin E than singly dosed (391 IU vitamin E) lambs. The singly dosed lambs had greater serum vitamin E than control lambs (no supplemental vitamin E).

Forms and Availability of Vitamin E. Route of administration and form of vitamin E can affect uptake and level of serum and plasma vitamin E concentrations. Hidiroglou and Karpinski (1987) examined the route of administration of supplemental vitamin E and its effect on uptake of vitamin E by sheep. Oral administration of vitamin E, via gelatin capsules, showed decreased bioavailability when compared to either intramuscular or intravenous administration. Oral administration of vitamin E showed a greater lag time appearing in the serum. Fry et al. (1996) found that oral supplementation and aqueous solutions given intramuscularly or subcutaneously of vitamin E were generally superior to oil-based vitamin E injections, with some sheep developing subclinical vitamin E deficiency symptoms when injected with oil-based vitamin E. This agrees with work by Hidiroglou and McDowell (1987) in which aqueous dispersion were found to have greater bioavailability than oil-based vitamin E injections.

Hidiroglou et al. (1992) examined the bioavailability of several forms of vitamin E and combinations of these forms. Supplementation of lambs with D- α -tocopheryl acetate plus D- α -tocopheryl polyethylene glycol succinate resulted in greater serum vitamin E concentrations than any other form

or combination of forms of vitamin E. Peak concentrations of serum vitamin E were observed between 15 and 21 d after supplementation began. Thus, the bioavailability of vitamin E seems to be dependent on the form administered, with D- α -tocopheryl acetate having the highest bioavailability.

Lamb Survival, Production, and Immune Response

As indicated in Tables 1 and 2, mixed results have been reported on the effectiveness of vitamin E in preventing neonatal lamb mortality, improving measures of lamb productivity, or affecting indices of immunocompetence. Providing supplemental vitamin E to the ewe during late gestation may have a beneficial effect on lamb production, but the environmental conditions (both climatic and in utero) under which supplemental vitamin E may express an increase in production are not clear. Injection of pregnant ewes with vitamin E 2 wk prepartum and again at lambing resulted in vigor score and average daily gains that were greater for lambs born to ewes injected with vitamin E than lambs born to untreated ewes (Williamson et al., 1996). However, there was no influence of vitamin E injection to the ewe on lamb mortality. Gentry et al. (1992) reported that, although lamb mortality was not affected by vitamin E injection to the ewe, lamb serum IgG, BW gain, and ultimately lamb weaning weight were greater in lambs reared by ewes treated with vitamin E than lambs from untreated ewes.

Thomas et al. (1995) used 470 ewes to determine the influence of feeding vitamin E for approximately 21 d during late pregnancy on lamb mortality. Lamb mortality was approximately 50% lower for lambs born to ewes supplemented with vitamin E that lambed early in the lambing season than lambs born to unsupplemented ewes (8.6 and 15.5% mortality, respectively). Thomas et al. (1995) suggested that lambs born early in the lambing season were subject to greater levels of environmental stress than late-born lambs and that vitamin E supplementation will only influence survival under adverse conditions that stress the newborn lamb.

Kott et al. (1998) used 1,302 mature ewes in a 3-yr study to evaluate the effects of supplemental vitamin E on lamb survival. Half of the ewes were supplemented with vitamin E for approximately 21 d prepartum. Lamb mortality was decreased by vitamin E supplementation over the 3 yr. As in the work by Thomas et al. (1995), lambs born to vitamin E-supplemented ewes had reduced mortality rates when born in the early part of the lambing season. Consequently, those supplemented ewes lambing in the early part of the lambing season weaned 2.6 kg more lamb than unsupplemented ewes. This was a function of lamb survival rather than of lamb BW gain. Lamb mortality was not affected by vitamin E supplementation when lambs were born during the late part of the lambing season. With a cost of \$.055/kg for adding vitamin E to an existing pelleted supplement (based on current industry price [1999]) and each ewe fed .23 kg of the supplement containing vitamin E, the cost of supplementing each ewe (including those lambing late) was \$.26. Over the 3-yr study period, all ewes supplemented with vitamin E weaned .9 kg more lamb than unsupplemented ewes. The return on invest-

ment for supplemental vitamin E ranged from 381 to an 846%, based on the lowest and highest lamb prices over the past 10 yr of \$.99 and \$2.20/kg live BW, respectively.

Stephens et al. (1979), Tengerdy et al. (1983), Afzal et al. (1984), and Ritacco et al. (1986) reported positive impacts of supplemental vitamin E on indices of immunocompetence in older lambs. Stephens et al. (1979) also noted an increase in BW gain and DMI by older lambs supplemented with vitamin E and challenged with chlamydia. However, Ritacco et al. (1986) and Fry et al. (1996) found no impact of supplemental vitamin E on older lamb BW gain. Gentry et al. (1992) noted an increase in lamb serum IgG in lambs injected with vitamin E at birth. These authors, along with Williamson et al. (1996), reported no advantage of supplemental vitamin E given to lambs at birth on survival and lamb BW gain. In a 2-yr study at Montana State University (unpublished data) using over 900 newborn lambs, which were orally supplemented with either a single (391 IU) or double dose (782 IU) of vitamin E, lamb survival, BW gain, and serum IgG concentration were not influenced by supplemental vitamin E.

Potential explanations for the variations in these studies are the level of vitamin E present in the base diet, ewe age, colostrum vitamin E concentration, a lack of exposure to environmental or pathogenic stress sufficient to elicit an immune or production response, and the different breeds of sheep used. Gentry et al. (1992) used Suffolk sheep, and the Wyoming and Montana studies used Whiteface Western range breeds. Bradley et al. (1972) reported higher mortality in Suffolk than in Targhee sheep. It may be reasonable to speculate that the role of supplemental vitamin E in influencing immunocompetence would be more pronounced in a less vigorous breed that is more susceptible to environmental and pathogenic stress.

Although supplemental vitamin E given to the lamb at birth will increase lamb serum vitamin E levels, this practice in most cases is not effective in reducing lamb mortality or increasing lamb performance. Supplemental vitamin E may have more benefit as an agent of physiological change in dams rather than as a nutrient provided to neonates.

Brown Adipose Tissue and Vitamin E

Vitamin E is an integral component of lipid membranes. Newborn lambs depend on brown adipose tissue (BAT) as the primary source of nonshivering heat production (Thompson and Jenkinson, 1969; Klein et al., 1983). Activation of BAT causes large increases in oxygen consumption and consequently causes increases in oxygen radical generation (Barja de Quiroga, 1992). The activity of BAT in the lamb would suggest a need for ample amounts of antioxidants to reduce the amount of free radical buildup. Barja de Quiroga (1992) states that with the relatively low activities of antioxidants in BAT and increased free radical generation, BAT activation could lead to a physiological oxidative stress on the body. Newborns are susceptible to vitamin E deficiency and, due to the negligible amount of vitamin E crossing to the fetus in utero, it is important that colostrum supplies the lamb

with sufficient amounts of vitamin E (Scott, 1980; McDowell et al., 1996). We were able to find no reports in the literature on whether supplemental vitamin E to ewes or lambs affects the use of BAT or thermogenesis in general in lambs.

Thomas et al. (1995) reported that lambs born to ewes supplemented with vitamin E during late gestation had fewer deaths caused by starvation, pneumonia (and other infectious diseases), and cold stress (Table 3). These types of death are probably more closely related to fetal and neonatal energy status than to immunocompetence. Moriguchi et al. (1990) stated that because vitamin E acts as an antioxidant in cellular membranes, it is capable of being a free radical scavenger by blocking the peroxidation of PUFA. An increase in reactive oxygen species arises when oxidative metabolic reactions are increased during gestation (Nockels, 1996). If energy does not need to be expended to repair or replace cells damaged during gestation, possibly more energy may then be available for fetal development. Possibly, late gestation supplementation of vitamin E can influence fetal energy status by increasing the amount of BAT in the fetus. However, this mechanism has not been studied.

Stress and Vitamin E

Stress often precedes sickness in animals and may decrease antioxidant levels needed later for a sufficient immune response (Nockels, 1996). The protective effects of vitamin E may be involved with its role in reducing glucocorticoids, produced in response to stress and known to be immunosuppressive (Golub and Gershwin, 1985). If these animals come into contact with pathogens, they may have a reduced immune response capacity. In sheep, vitamin E injections to the ewe have been shown to improve lamb vigor at birth (Williamson et al., 1996). Although lambs would likely experience high levels of stress immediately after birth, the effects of supplemental vitamin E to the ewe on lamb stress indicators have not been investigated.

Vitamin E supplementation has shown to positively affect mortality rates and levels of production in nonruminant species. In a study comparing high-stress levels and low-stress levels in pigs and the effect of vitamin E on the pigs (BASF, 1997), researchers reported that pigs fed vitamin E performed as well in a high-stress environment as did pigs that received no vitamin E in a low-stress environment. Pig mortality was also reduced when their dams were fed $381 \text{ IU} \cdot \text{sow}^{-1} \cdot \text{d}^{-1}$ of supplemental vitamin E compared with when the dam was fed $109 \text{ IU} \cdot \text{sow}^{-1} \cdot \text{d}^{-1}$ supplemental vitamin E. Low environmental stress in other studies may account for the lack of response to supplemental vitamin E (Gentry et al., 1992).

Implications

Supplementing newborn lambs with vitamin E raises serum vitamin E concentrations and may influence measures of immunity in older lambs. However, this method does not seem as effective in reducing neonatal mortality as providing

supplemental vitamin E to ewes during late gestation. In production and research, the advantages of supplemental vitamin E may not be apparent in conditions of low environmental and/or pathogenic stress. Recommended levels of dietary vitamin E would most likely be greater if based on physiological status, measures of immunity, and environmental stress. Research is needed that reflects the role of high levels of vitamin E on cell-mediated immunity, stress, and fetal energy status under conditions that allow application to actual production environments.

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Notes

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Table 1. Effects of supplemental vitamin E to sheep on animal performance

Supplementation	Route	Sheep	Response variable	Effect	Reference
300 IU/kg diet	Oral	Weaned lambs	BW gain and DMI	Increase	Stephens et al. (1979)
476 mg/kg diet	Oral	6-mo, all genders	Weight gain and DMI	None	Ritacco et al. (1986)
Two doses of 1,500 IU/ewe each	i.m.	Mature ewes	Lamb birth wt and BW gain	Increase	Gentry et al. (1992)
One dose of 900 IU/lamb	i.m.	Newborn lamb	Lamb BW gain	None	
300 IU \cdot ewe $^{-1}\cdot$ d $^{-1}$	Oral	Gestating ewes	Lamb BW	None	Bohn et al. (1995)
300 IU \cdot ewe $^{-1}\cdot$ d $^{-1}$	Oral	Gestating ewes	Lamb survival	Increase	Thomas et al. (1995)
120 mg/kg diet	Oral	4- to 6-mo wethers	BW gain and wool production	None	Fry et al. (1996)
1,000 mg	i.m.	4- to 6-mo wethers	BW gain and wool production	None	
2,000 mg	s.c.	4- to 6-mo wethers	BW gain and wool production	None	
One dose of 600 IU/lamb	s.c.	Newborn lambs	Lamb ADG, vigor, weaning wt, and survival	None	Williamson et al. (1996)
Two doses of 1,200 IU/ewe each	s.c.	Mature ewes	Lamb ADG and vigor	Increase	
			Lamb weaning wt and survival	None	
300 IU \cdot ewe $^{-1}\cdot$ d $^{-1}$	Oral	Gestating ewes	Lamb weaning wt	None	Kott et al. (1998)
			Lamb survival	Increase	
400 IU \cdot ewe $^{-1}\cdot$ d $^{-1}$	Oral	Gestating ewes	Lamb survival, vigor, and 30-d BW	None	Daniels et al. (1999)
Single dose of 391 IU/lamb	Oral	Newborn lambs	Lamb survival and 30-d BW	None	Montana State University (unpublished data)

Table 2. Effects of supplemental Vitamin E to sheep on antibody responses

Supplementation	Route	Sheep	Antigen/pathogen	Response	Effect	Reference
300 IU/kg diet	Oral	Weaned lambs	Chlamydia species	Recovery	Increase	Stephens et al. (1979)
300 mg/kg diet .85 mL (adjuvant)	Oral s.c.	3 to 6 mo, all genders 3 to 6 mo, all genders	<i>Clostridium perfringens</i> toxoids <i>Clostridium perfringens</i> toxoids	Antibody Antibody	Increase Increase	Tengerdy et al. (1983)
.85 mL (adjuvant)	s.c.	6-mo ram	<i>Brucella ovis</i>	Antibody	Increase	Afzal et al. (1984)
3,000 mg/d	Oral	6 mo, all genders	<i>Brucella ovis</i>	Antibody	Increase	Ritacco et al. (1986)
476 mg/kg diet	Oral	6 mo, all genders	Keyhole limpet hemocyanin	Antibody	Increase	
Two doses of 1,500 IU/ewe each	i.m.	Mature ewes	None	Ewe and lamb IgG	Increase	Gentry et al. (1992)
One dose of 900 IU/lamb	i.m.	Newborn lamb	None	IgG	Increase	
300 IU·ewe ⁻¹ ·d ⁻¹	Oral	Gestating ewes	None	Lamb IgG	None	Bohn et al. (1995)
400 IU·ewe ⁻¹ ·d ⁻¹	Oral	Gestating ewes	Parainfluenza type 3	Ewe and lamb Antibody	None None	Daniels et al. (1999)
				Ewe and lamb IgG Colostrum IgG	None None	
Single dose of 391 IU/lamb	Oral	Newborn lamb	None	IgG	None	Montana State University (unpublished data)

Table 3. Supplemental vitamin E to ewes and causes of lamb mortality^a

Cause of death	Supplemental vitamin E	No supplemental vitamin E
Starvation	5.5	14.6
Pneumonia and infectious disease	7.3	12.7
Cold stress	0	5.5

^a From Thomas et al., 1995.