Serum total iodine concentrations in pasture-fed pregnant ewes and newborn lambs challenged by iodine supplementation and goitrogenic kale

S. O. Knowles*3 and N. D. Grace†

*Food Nutrition and Health Team, Food and Bio-based Products Group, AgResearch Limited, Grasslands Research Centre, Private Bag 11008, Palmerston North 4442, New Zealand; and †26 Williams Road, RD 4, Palmerston North 4474, New Zealand

ABSTRACT: Iodine deficiency can impair the reproductive performance of livestock and affect perinatal mortality of offspring, yet diagnosis of deficiency is complicated and guidelines for I supplementation are imprecise. We challenged pasture-grazing pregnant ewes with a long-acting I supplement and a goitrogenic forage, then monitored their I status during gestation and lactation and in their lambs from birth to weaning. Approximately 46 d into gestation, 376 ewes were assigned to 6 groups comprising 3 supplementation levels × 2 diet regimens. On d 0 the groups received an intramuscular injection of iodized oil providing 0, 300, or 400 mg of I. They grazed until d 23, then half of each supplementation group were fed brassica kale until d 85, then all groups returned to pasture for lambing (parturition approximately d 99) and remained there until weaning (d 192). Serum total I concentration (STIC) was measured repeatedly in 8 ‘monitor’ ewes per group and in their lambs and in milk sampled postpartum. Severity of goiter was determined as the thyroid-weight:birth-weight (TW:BW) ratio in 82 newborn dead lambs. Mean ± SE STIC for all ewes was initially 42 ± 2 (range 24 to 105) µg/L. Diet did not affect I concentrations in ewe serum or milk. Responses to iodized oil were proportional to dose level; STIC increased to approximately 150 and 240 µg/L for the 300- and 400-mg I groups and remained greater than 0-mg I groups for 161 d (P < 0.05). Milk contained 26, 271, and 425 µg I/L for the 0-, 300-, and 400-mg I groups, respectively. Mean STIC of lambs from supplemented ewes did not differ by diet; concentrations for the 300- and 400-mg I groups were 237 and 287 µg I/L at birth, and by weaning all groups were similar (62 ± 3 µg/L). Lamb STIC measured at birth correlated with exposure to I in utero (R² = 0.59), which was estimated from the area under the curve (AUC) of ewe STIC measured during the last 99 d of gestation. Thyroid enlargement in lambs affecting the TW:BW ratio was a sensitive indicator of maternal nutrition, being greater with kale feeding (1.27 vs. 0.51 g/kg) and lesser with I supplementation (0.35 vs. 1.44 g/kg). Results support the use of STIC as a biochemical criterion. It was sensitive to the effects of I supplementation with responses in ewes and lambs proportional to dose level and it reflected the relationship between ewe and lamb I metabolism. However STIC did not discriminate between groups of ewes fed pasture vs. goitrogenic forage during pregnancy.

Key words: ewe, goiter, iodized oil, lamb, milk iodine, serum total iodine

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INTRODUCTION

Iodine deficiency affects cellular energy, growth, and differentiation. Among ruminants the deficiency manifests primarily as diminished reproductive performance in dams and increased perinatal mortality of offspring (Sinclair and Andrews, 1958; Clark et al., 1998; Campbell et al., 2012). This can occur when grazing low-I pasture, and risk is increased when complementary crops such as brassica kale, swedes,
and rutabaga are fed during gestation. These forages have low I concentration and contain glucosinolates, which release thiocyanate goitrogens that inhibit utilization of I by the thyroid gland (Stoewsand, 1995).

Diagnosis of I deficiency is difficult because no environmental, biochemical, or physiological criteria have been found that correlate with states of marginal I status. For example, serum concentrations of I hormones T₄ and T₃ are unreliable in their ability to differentiate responsive flocks in I-supplementation trials (Clark et al., 1998). The classical sign of I deficiency, hyperplasia of the thyroid gland, is unambiguous but only retrospectively (Knowles and Grace, 2007). Serum concentrations of total I and inorganic I may be sufficiently sensitive and specific; however, more data are needed to establish reference ranges (Clark et al., 1985; Hill et al., 2013).

Supplementation mitigates I deficiency (Ferri et al., 2003), and administration to dams early in gestation ensures that that fetal I requirement is met. A practical application for free-range sheep is injection with iodized oil to create a slow-release depot. This benefits ewe reproductive performance (Sargison et al., 1998), but little is known about how the depot sustains ewe I status over time or its transfer to lambs in utero and through milk postpartum.

Our study addressed 3 overlapping aims: 1) to validate serum total I concentration (STIC) as a biochemical marker of I status in sheep; 2) to evaluate the efficacy and transfer of supplemental I in pregnant ewes and their lambs; and 3) to quantify the effect of supplemental I on the reproductive performance of ewes with low I status, in terms of ewe fecundity and severity of goiter in newborn lambs.

**MATERIALS AND METHODS**

Procedures involving the management, husbandry, treatment, and sampling of animals were reviewed and approved by the Palmerston North Crown Research Institute Animal Ethics Committee, number 03/04_01, and New Zealand Food Safety Authority (Agricultural Compounds and Veterinary Medicines group) Research Approval A9292.

**Experimental Design**

To evaluate the first and second aims, 6 treatment groups were organized according to a 3 × 2 dose–response format comprising 3 levels of I supplement (as control, medium, and high) and 2 forms of diet (as goitrogenic and control). For evaluation of the third aim, 4 treatment groups were organized in a 2 × 2 factorial with 2 levels of I supplement (control and high) and 2 forms of diet (goitrogenic and control).

**Animals, Supplements, and Timeline**

The field trial was performed from June through December (ending during the Southern Hemisphere summer) at the AgResearch Flock House farm, near Bulls on the west coast of the lower North Island. The site is a 1,000 ha commercial operation based on free-range grazing. To ensure a short and predictable lambing period, 500 Romney ewes were estrus-synchronized by controlled internal drug-releasing devices (CIDR) containing progesterone. The CIDR were removed after 10 d and the ewes were mated with Suffolk rams. Approximately 42 d into gestation, pregnant ewes were ultrasound scanned to assess their litter size. A total of 376 ewes (72% carrying twins) were randomly assigned to 6 experimental groups matched for similar average litter size.

On d 0 of the study, approximately 46 d into gestation, supplemental I was administered via intramuscular injection. Two groups of 89 ewes received 400 mg I, 2 groups of 10 ewes received 300 mg I, and 2 groups of 89 ewes were not supplemented. Reasonably large flocks of ewes (in our case 89 per group) are necessary to measure reproductive outcomes such as lambing percentage and to ensure sufficient newborn dead lambs for statistical analysis. Only small cohorts (in our case 10 animals per group) are necessary to evaluate tissue parameters such as STIC with adequate statistical power.

The injectable product was a proprietary formulation developed by AgResearch Ltd. to prevent I and Se deficiencies in flocks and was manufactured to our specifications by Stockguard Laboratories Ltd. (Hamilton, New Zealand) under GMP Compliance Certificate number NZ/083V/2004. Each mL contained 100 mg of I as iodized arachis oil and 15 mg of Se as barium selenate. From each group, 8 ewes were randomly selected and marked as “monitor” ewes for the purpose of repeatedly collecting blood and milk samples for chemical analyses.

From d 0 through d 22 of the study, all 6 groups of ewes grazed together on pasture. On d 23, 1 group from each I level was shifted to a field of goitrogenic kale, where they stayed until d 85 (approximately 131 d into gestation and 14 d before parturition), then each group of ewes was set-stocked to a separate paddock of pasture. This separation ensured accurate identification of newborn lambs with their dams within each I level-by-diet group. One lamb born to each of the monitor ewes was marked for the purpose of repeatedly collecting blood samples. After the lambing period was complete, on d 105, all 6 groups were brought together to graze pasture until the lambs were weaned on d 192 (approximately 93 d of age). The ewes were then returned to the commercial breeding flock. At no time during the study was animal weight gain or ewe condition score assessed.
**Diets**

Pasture was a mixed sward of herbage species with perennial ryegrass (Lolium perenne) and white clover (Trifolium repens) predominant (grass supplying 60 to 80%; Nobilly et al., 2013). Livestock were rotationally grazed across 30 ha of fenced paddocks at a stocking rate of approximately 15 ewes/ha. Animals were shifted at intervals of 6 to 10 d to maintain post-grazing mass of 1,000 to 1,500 kg DM/kg ha providing approximately 12 MJ ME/kg DM. No commercial compound feeds were provided.

Seven months before the start of the study, a single field of 4.7 ha was sown in kale (Brassica oleracea ssp. acephala). Yield of the kale crop was estimated to be 9,000 kg DM/ha providing approximately 10 MJ ME/kg DM, of which approximately 50% would be utilized by the sheep. Forage crops are routinely used in New Zealand to complement pasture-based systems.

**Sample Collection**

On 7 occasions at approximately monthly intervals from June through December, pasture herbage was harvested from paddocks along 100-m transects just before being grazed. Likewise, kale was collected during the period of kale feeding, with the plants being divided into leaf and stem portions. The bulk samples contained 3 to 5 kg of material. From each, a representative subsample of 400 to 500 g was removed. This unwashed material was dried at 80°C for 48 h and then ground to a fine, homogeneous powder, with no separation by sieving, in preparation for chemical analysis.

Samples of jugular vein blood were repeatedly collected from the same monitor ewes on d 0 (before I injection), 23, 63, 99, 127, 161, and 192 and from their marked lambs on d 99 (birth), 127 (docking), 161, and 192 (weaning). Blood was drawn into a 9-mL Vacutainer tube (Becton Dickinson, Plymouth, UK) containing K$_3$EDTA for whole blood and a 9-mL tube containing no anticoagulant additive for serum separation. Serum was harvested after centrifugation at 2,000 × g for 20 min at 4°C. Samples (5 to 20 mL) of early milk that may have included colostrum were collected from the monitor ewes within 2-d postpartum, and a further set of milk samples was collected at the time of weaning. Serum, blood, and milk were stored at 4°C and sent to the analytical laboratory within 36 h.

As a consequence of CIDR estrus synchronization before mating and selection of ewes mated during the first cycle, greater than 90% of births occurred during a 6-d period. Only during this period did shepherds count and collect dead lambs. These lambs were born dead or died soon thereafter. Dead lambs were delivered to the pathology lab each day. As expected, each of the large groups of 89 ewes produced enough lambs to provide at least 16 dead lambs suitable for necropsy. Dead lambs were not collected from either of the small groups of 10 ewes that received 300 mg of I. No live lambs were killed for the study.

**Laboratory Analysis and Necropsies**

Measurements of total I concentration in serum, milk, and plant material were performed by Hill Laboratories (Hamilton, New Zealand) using an organic alkali digestion followed by inductively coupled plasma mass spectroscopy (Fecher et al., 1998). Limits of detection were 20 µg I/L and 0.05 mg I/kg DM. Selenium concentration in blood was measured by Gribbles/Alpha Diagnostic Laboratory (Hamilton, New Zealand) using a semi-automated fluorimetric method. Necropsy of lambs was performed by Gribbles Veterinary Pathology (Palmerston North, New Zealand). Dead lambs were weighed, thyroid glands removed, and the thyroid-weight:birth-weight (TW:BW) ratio calculated in units of g/kg. No histological examinations were made.

**Statistical Analysis**

Ewe I status and the exposure of lambs to I in utero was evaluated from area under the time-course curve (AUC) of ewe serum I concentrations. The AUC is a type of weighted average summary statistic used in pharmacokinetics and suited to curvilinear responses over irregular-interval sampling. The AUC was computed for each monitor ewe as trapezoidal area above a baseline of 0 µg/L STIC and then means calculated by group. Only ewes that had complete data for all 7 blood sampling times were included. Values of AUC were determined for the period commencing 46 d into gestation through parturition (i.e., from study d 0 to 99) and for the entire study duration, which included the period of lactation (i.e., from d 0 to 192).

Ewe serum I AUC, the concentrations of I in ewe milk at each sampling time and in lamb serum at birth, and lamb birth weights and TW:BW ratios were analyzed by ANOVA using the GLM procedure of SAS (version 9.3 for Windows, SAS Inst. Inc., Cary NC). The effects of supplementation, diet, and supplementation × diet interaction were determined from Type III sum of squares. Least squares means were used for comparing means, with the Tukey-Kramer adjustment for multiple comparisons. For lamb birth weights and TW:BW ratios, hypotheses were tested using the ESTIMATE and CONTRAST options of GLM, which accommodate interactions in a factorial design. Results are expressed as group mean ± SE. For some response variables, imbalance in the number of experimental
units per treatment precluded calculation of a pooled SE. Therefore, in Tables 1 and 2 the root mean squared error (RMSE) term of ANOVA is presented. Dividing RMSE by the square root of \( n \) for each treatment group provides the approximate effective SE for that group.

Efficacy of I supplementation, in terms of the maximum duration that a significant difference was maintained between supplemented and unsupplemented animals, was analyzed by one-way ANOVA of the effect of supplementation using the GLM procedure, with Dunnett’s test of LSmeans greater than control.

Correlation between the serum I AUC of ewes and the serum I concentration in their lambs measured at birth was analyzed using the REG procedure of SAS.

### RESULTS

Iodine concentrations in pasture each month from June through December were 0.24, 0.13, 0.09, 0.08, 0.23, 0.11, and 0.19 (mean 0.15 ± 0.07 SD) mg I/kg DM. Concentrations in kale leaf and stem were always ≤ 0.05 mg I/kg DM.

Serum I concentrations and serum AUC of the monitor ewes were affected by supplementation but not by diet or the interaction (Fig. 1 and Table 1). The mean STIC for all groups of ewes was initially 42 ± 2 (range 24 to 105) µg I/L. Over the entire study, the mean for the unsupplemented groups was 45 ± 1 µg I/L, with no difference due to diet (\( P = 0.59 \)). As shown in Fig. 1, ewe STIC was increased by supple-

### Table 1. Mean concentrations or areas under the curve of I in serum and milk from ewes and I in serum of newborn live lambs

<table>
<thead>
<tr>
<th>Item</th>
<th>Treatments</th>
<th>RMSE</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ewes treated, ( n )</td>
<td>89</td>
<td>10</td>
<td>89</td>
</tr>
<tr>
<td>Ewe serum AUC, ( n )</td>
<td>6</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>During late gestation, d*µg I/L</td>
<td>3812b</td>
<td>12,100d</td>
<td>16,320d</td>
</tr>
<tr>
<td>Over entire study, d*µg I/L</td>
<td>8129b</td>
<td>21,170d</td>
<td>28,760d</td>
</tr>
<tr>
<td>Ewe milk, ( n )</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>At 0 to 2 d postpartum, µg I/L</td>
<td>27c</td>
<td>234b</td>
<td>383ab</td>
</tr>
<tr>
<td>At weaning, µg I/L</td>
<td>49c</td>
<td>81bcd</td>
<td>155a</td>
</tr>
<tr>
<td>Lamb serum, ( n )</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>At birth, µg I/L</td>
<td>78b</td>
<td>234a</td>
<td>300a</td>
</tr>
</tbody>
</table>

\( a–d \) Within a row, means without a common superscript differ (\( P < 0.05 \)).

1Grazing ewes were supplemented with a single intramuscular injection of 0, 300, or 400 mg of I as iodized oil administered at d 0 (46 d into gestation) and fed a diet of pasture or kale from d 23 through d 85, with lambs born at approximately d 99. The prototype injectable product was developed by AgResearch Ltd. and manufactured by Stockguard Laboratories Ltd. (Hamilton, New Zealand).

2RMSE = Root mean squared error. Division by the square root of \( n \) provides the pooled SE value for each treatment group.

3AUC = Area under the time-course curve calculated for each ewe for the period from supplementation to parturition (from d 0 to 99) and for the entire study duration (from d 0 to 192). Eight ewes per experimental group were monitored and any ewe that did not have a complete time-course of 7 serum measurements was not included in AUC calculations.

### Table 2. Lambing percentage of the flock and the birth weight and severity of goiter in necropsied newborn dead lambs

<table>
<thead>
<tr>
<th>Item</th>
<th>Pasture diet</th>
<th>Kale diet</th>
<th>RMSE2</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ewes treated, ( n )</td>
<td>89</td>
<td>89</td>
<td>89</td>
<td>89</td>
</tr>
<tr>
<td>Lambing percentage</td>
<td>126%</td>
<td>121%</td>
<td>135%</td>
<td>143%</td>
</tr>
<tr>
<td>Lambams necropsied, ( n )</td>
<td>24</td>
<td>16</td>
<td>24</td>
<td>18</td>
</tr>
<tr>
<td>Birth weight, kg</td>
<td>4.80a</td>
<td>4.55a</td>
<td>3.22b</td>
<td>4.36a</td>
</tr>
<tr>
<td>TW:BW3 ratio, g/kg</td>
<td>0.75b</td>
<td>0.27b</td>
<td>2.13a</td>
<td>0.42b</td>
</tr>
</tbody>
</table>

\( a–b \) Within a row, means without a common superscript differ (\( P < 0.01 \)).

1Grazing ewes were supplemented with a single intramuscular injection of 0 or 400 mg of I as iodized oil administered at d 0 (46 d into gestation) and fed a diet of pasture or kale from d 23 through d 85, with lambs born at approximately d 99. The prototype injectable product was developed by AgResearch Ltd. and manufactured by Stockguard Laboratories Ltd. (Hamilton, New Zealand). Note that animal reproductive outcomes were not measured in the groups of ewes treated with 300 mg of I.

2RMSE = Root mean squared error. Division by the square root of \( n \) provides the pooled SE value for each treatment group.

3TW:BW = Thyroid-weight:birth-weight.
Manipulating iodine status in ewes and lambs

Mentation to approximately 150 and 240 µg I/L for the 300- and 400-mg I groups and was maintained greater than unsupplemented controls for 161 d (P < 0.05). This response was biphasic, with peak concentrations interrupted by a 50% decrease at parturition. Responses to I supplementation were proportional to dose level. Mean serum AUC for the 300-mg I groups was 74% of the AUC for the 400-mg I groups over the 99 d of gestation between supplementation with I and parturition. It was 70% over the entire duration of the 192-d study, which included lactation.

A goitrogenic diet of kale consumed for 62 d during gestation had minimal effect on the concentrations of I in early milk (P > 0.09), which were 26 ± 2, 271 ± 24, and 425 ± 46 µg I/L for the 0-, 300-, and 400-mg I groups, respectively. At weaning, the respective milk concentrations were 44 ± 4, 91 ± 10, and 139 ± 13 µg I/L (Table 1).

Kale intake by the pregnant ewes had mixed effects on the I status of their offspring (Fig. 2). At birth, the STIC of lambs from unsupplemented ewes differed due to diet (78 vs. 132 µg I/L; P < 0.001 by t test), whereas the STIC of lambs from supplemented ewes was greater than unsupplemented control groups but did not differ by diet; mean concentrations were 237 ± 18 and 287 ± 18 µg I/L for the 300- and 400-mg I groups, respectively. The STIC of lambs from the 400-mg I groups was greater than controls for 62 d (P = 0.001). At the time of weaning, lamb STIC did not differ by diet or by dose level, at 62 ± 3 µg/L.

The relationship between the serum AUC of each monitor ewe measured over the final 99 d of gestation versus the STIC of its monitor lamb measured at birth is shown in Fig. 3. Exposure to I in utero was a good predictor of I status in newborn live lambs, and a dose–response to ewe supplementation was evident. Linear regression slope values differed slightly by diet (24%, P = 0.28). The overall relationship was y = 64 ± 22 + 0.0141 ± 0.0019x (R² = 0.59, P < 0.001, n = 42).

Animal reproductive performance outcomes of birth weight and TW:BW ratio were measured in newborn dead lambs from the groups of ewes that received 0 or 400 mg of I (Table 2). Dead lambs born to ewes fed kale weighed less than those born to ewes fed pasture (3.79 vs. 4.67 kg, P < 0.001) and had greater mean TW:BW ratios (1.27 vs. 0.51 g/kg, P = 0.007).

**Figure 1.** Mean ± SE serum total I concentrations (µg/L) in grazing ewes that were supplemented approximately 46 d into gestation by intramuscular injection with (A) 400 mg I (□, ■), (B) 300 mg I (∆, ▲), or 0 mg I (○, ●) and fed either pasture (□,∆,○) or kale (■,▲,●) for a period of 62 d during the latter half of gestation. STIC = serum total I concentration.

**Figure 2.** Mean ± SE serum total I concentrations (µg/L) in lambs born to grazing ewes that were supplemented by intramuscular injection with (A) 400 mg I (□, ■), (B) 300 mg I (∆, ▲), or 0 mg I (○, ●) and fed either pasture (□,∆,○) or kale (■,▲,●) for a period of 62 d during the latter half of gestation. STIC = serum total I concentration.

**Figure 3.** The relationship between the serum total I concentration (µg/L) in each lamb at birth and the serum area under the curve measurement of utero exposure to I (d*µg I/L) in its dam for the period from supplementation to parturition (from d 0 to d 99 of the study): y = 64 ± 22 + 0.0141 ± 0.0019x (R² = 0.59, P < 0.001, n = 42). The ewes had been supplemented by intramuscular injection with 400 mg I (□, ■), 300 mg I (∆, ▲), or 0 mg I (○, ●) and fed either pasture (□,∆,○) or kale (■,▲,●) for a period of 62 d during the latter half of gestation. STIC = serum total I concentration.
Supplementation with I had a tendency to increase birth weight (4.46 vs. 4.01 kg, \(P = 0.08\)), but TW:BW ratios were a more sensitive indicator of this effect (0.35 vs. 1.44 g/kg, \(P < 0.001\)).

Lambing percentages at the time of docking (approximately 28 d of age) ranged from 121 to 143% docked lambs per pregnant ewe (Table 2). Effects of supplementation or diet could not be statistically tested.

Selenium concentrations in pasture each month from June through December were 0.04, 0.05, 0.03, 0.02, 0.03, 0.02, and 0.03 (mean 0.03 ± 0.01 SD) mg Se/kg DM. During the period of kale feeding, concentrations in kale leaf were 0.04, 0.03, 0.01, and 0.03 and in stem were 0.02, 0.03, 0.01, and 0.03 mg Se/kg DM.

On d 0, the mean blood Se concentration of all monitor ewes was 296 ± 24 nmol/L, which was well in excess of the level classified as deficient for free-range grazing sheep (130 nmol/L; Grace and Knowles, 2002). Among the unsupplemented groups, blood Se concentrations gradually decreased over time; on d 23, 63, and 99 (parturition), the mean values were 239, 162, and 104 nmol Se/L, respectively. Among the groups injected on d 0 with 45 or 60 mg of Se, blood Se concentrations were increased within 23 d to greater than 1,000 nmol Se/L and remained so for the duration of the study. A goitrogenic diet of kale consumed for 62 d during gestation had no effect on blood Se concentrations. Detailed description of the efficacy of Se supplementation on the Se status of ewes and lambs is the subject of a separate report.

**DISCUSSION**

**Biochemical Criteria of I Status**

Although numerous blood markers of I metabolism have been identified, none has proven to be a reliable indicator of animal I status or I reserves. Thyroid-related hormones are commonly measured but are vexing to interpret (Clark et al., 1998). They often fail to discriminate between adequate and marginal I status in pasture-fed livestock during I-supplementation trials, probably due to the complex, adaptive systems maintaining homeostasis of these important regulators of cell growth and metabolic rate. Reported concentrations are quite variable and difficult to compare between studies because of differences in animal conditions and assay methodologies (Todini, 2007).

Serum total I concentration is an elemental determination that comprises the iodinated hormones plus various chemical forms of serum inorganic I (SIIC). It is infrequently reported (Abdollahi et al., 2013) but can clearly identify the effects of I supplementation (Grace et al., 2001). The criteria of STIC and SIIC might be interchangeable. Limited data from sheep indicate they are strongly correlated across the STIC range of 35 to 90 µg I/L (STIC = 1.32*SIIC + 16; \(R^2 = 0.92\); Hill et al., 2013).

In the current study, STIC was shown to be practical for monitoring changes in the I status of unsupplemented ewes, the time-course effects of I supplementation at differing dose levels, and the transfer of I from ewe to lamb during gestation. It had a limit of detection of <24 µg I/L and was responsive over a 16-fold range.

**Supplementation with I**

Susceptibility to I deficiency begins in utero, particularly during the final months of gestation, when radiiodine studies have shown that the rate of uptake of I into the fetal thyroid glands is four fold greater than that of maternal uptake (Wright and Sinclair, 1959). Iodine supplementation to benefit the neonate is best delivered via the dam. In this study, a long-acting form of injectable I was administered approximately 46 d into gestation at 300 or 400 mg of I per ewe (6 to 8 mg I/kg BW). The larger quantity is a typical dose for commercial formulations of iodized oil and there are no published data describing lesser doses. This route of administration is more practical for free-range grazing animals than dietary or per os supplementation (Bik, 2003; Rose et al., 2007). We found that STIC responses in ewes and lambs were proportional to the dose level of supplementation in terms of their magnitude and AUC; however, durations were similar. This implies that doses of iodized oil could be titrated to animal body weight and state of deficiency.

The elevated STIC of supplemented ewes (>150 µg I/L) was interrupted by a 50% reduction at parturition, with no correlation to changes occurring in dietary I intake. The dip coincided with parturition, and we speculate that it might have been caused by high demand for I from the near-term fetus or perhaps shifts in I pools to accommodate the onset of lactation. This event was not observed in the unsupplemented groups, where the overall mean STIC was much lower at 45 µg I/L. Nor did it occur during a previous study of sheep grazing ryegrass/clover pastures in which ewes were supplemented with iodized oil much earlier in their reproductive cycle (i.e., 4 wk before mating; Grace et al., 2001).

Regardless of diet, concentrations of I in milk from the unsupplemented groups of ewes in this study were similar to those observed in hay-fed ewes (Kursa et al., 2000) and were less than the 45 to 98 µg I/L observed in some Australian flocks in which goiter was diagnosed (Azuolas and Caple, 1984). Among the groups of supplemented ewes, milk I concentrations reflected their elevated I status.

Supplementation of ewes markedly increased the STIC of lambs. A lamb’s STIC at birth reflected its exposure to I in utero, which was estimated from the
AUC of ewe STIC during the final 99 d of gestation. A relationship between maternal I nutrition and offspring status would be expected, but has not previously been demonstrated and quantified in this way in sheep. This evidence supports the use of STIC as a biochemical criterion of I status.

Dietary Intake of I and Goitrogenic Feeds

Dietary intake of I is usually adequate for grazing livestock when concentrations are greater than 0.20 to 0.30 mg I/kg DM (Barry et al., 1983; Grace and Knowles, 2010). The dietary requirement is complicated by endogenous, environmental, and nutritional factors (Todini, 2007) and by the impact of goitrogenic compounds in some plants. These compounds inhibit thyroperoxidase and reduce I incorporation into iodothyronines, with the diminished production of thyroid hormones leading to hyperplasia of the gland and goiter (Suttle, 2010). For these reasons, I intake is a poor predictor of I status and the risk of deficiency. Pasture I concentrations in the current study were low for several months, ranging from 0.08 to 0.24 mg I/kg DM. This was similar to pastures measured during a previous farm trial (0.07 to 0.23 mg I/kg DM), yet on that property, there was no evidence of goiter among unsupplemented flocks (Grace et al., 2001). That might have been a consequence of differing sward composition and herbage compounds, for example lesser amounts of cyanogenic glucosides in white clover, which can have unpredictable effects on I status (Fenwick and Heaney, 1983; Crush and Caradus, 1995).

The brassica kale diet fed to groups of ewes during their final months of pregnancy had a very low I concentration (<0.05 mg/kg DM) and was presumed to contain glucosinolate precursors of thiocyanates (Barry et al., 1983). However, it did not cause a decrease in STIC of ewes or lambs compared to the pasture diet. Nor did thiocyanates appear to inhibit the sodium iodide symporter responsible for uptake of I by the mammary gland, because milk I concentrations were not decreased (Laurberg et al., 2002). Unexpectedly, those concentrations at parturition were numerically greater in the kale-fed groups, despite lower total dietary I intake and the presence of goitrogens. Thus milk I concentration may be unreliable as a biochemical criterion of I status of ewes.

Developmental assessments in newborn dead lambs could discriminate the effects of maternal diet. Thyroid glands were appreciably enlarged (i.e., TW:BW ratio ≥ 0.8 g/kg; Knowles and Grace, 2007) in newborn dead lambs from unsupplemented ewes fed kale compared to pasture (2.13 vs. 0.75 g/kg). For both diets, goiter was prevented by I supplementation. As described above, goiter is the gland’s reaction to low I intake, insufficient circulating I, and inhibitors of I metabolism. It is a cumulative sign of the animal’s chronic condition rather than a point-in-time measurement. Unfortunately it is not suited to prospective diagnosis of I deficiency and there are no clear relationships between the incidence or severity of goiter and any easily accessible biochemical criteria of I status. Nevertheless, goiter and the TW:BW ratio are useful information for commercial sheep farms, where conventional practice is to necropsy newborn dead lambs for clues about the current health and nutrition of the flock and then adjust farm management to benefit next year’s flock.

The presence of mild goiter in live animals does not always presage ill thrift or poor performance. In published reports where thyroid size was qualitatively assessed by palpation or ultrasound, mild goiter was associated with only a small reduction in the growth rate of very young lambs (Robertson et al., 2008) or had minor influence on the growth of weaned lambs (Sinclair and Andrews, 1959; Barry et al., 1983). Conversely, measurements of BW or BW gain would not be expected to be precise or specific as indices of marginal I status or as predictors of goiter.

Effect of Selenium

The injectable supplement used in this study contained I and Se in long-acting, depot-forming chemical forms. This formulation may be advantageous for grazing livestock anywhere that inadequate intake of these elements occurs in tandem. Detailed description of the efficacy of the Se component on the Se status of ewes and lambs is the subject of a separate report.

Selenium plays several roles in I metabolism, for example as a selenoenzyme that deiodinates T4 to T3 (Berry et al., 1991). Supplemental Se at 45 or 60 mg Se/ewe was unlikely to be a factor in effects attributed to I supplementation because the Se status of all ewes (including those not supplemented) was adequate from mating to mid gestation. This period included the most important at-risk time during early pregnancy, when Se deficiency has been shown to cause embryonic mortality 3- to 4-wk postconception (Hartley, 1963). There was no indication that the lambing percentage of these flocks was impaired, as all groups of ewes had percentages as good or better than the national average of 121% (Beef + Lamb New Zealand Economic Service, 2013).

CONCLUSIONS

Concentrations of total I measured in serum clearly discriminated between I-supplemented and unsupplemented groups of ewes. However, this biochemical
criterion did not reflect the effect of feeding goitrogenic forage during pregnancy. The STIC responses in ewes and lambs were proportional to dose level of the I supplement, implying that doses of I can be titrated to suit deficiency conditions. When the STIC of pregnant ewes was greater than approximately 150 µg/L, there was no goiter in newborn dead lambs. Feeding brassica kale presumed to contain goitrogens and with <0.05 mg I/kg DM to unsupplemented ewes was detrimental to the I metabolism of lambs; birth weights were decreased and TW:BW ratios were much greater than the 0.8 g/kg benchmark of overt I deficiency (Knowles and Grace, 2007). In such cases, I supplementation is recommended and ongoing assessment of the TW:BW ratio is a practical approach to monitoring and managing the risks of I deficiency in flocks.

LITERATURE CITED


