The Effect of Housing and Methionine Intake on Hoof Horn Hemorrhages in Primiparous Lactating Holstein Cows

R. A. Laven¹ and C. T. Livesey²

¹ADAS Bridgets Dairy Research Center, Martyr Worthy, Hants, UK

²Veterinary Laboratories Agency, Weybridge, Surrey, UK

ABSTRACT

This study investigated the effects of housing and nutrition on the development of hoof horn disease (as identified by the appearance of hoof horn hemorrhages) in primiparous lactating Holstein cows. The first objective was to investigate whether replacing butyl rubber mats in cubicles (free stalls) with thicker mattresses filled with chopped rubber would significantly reduce hoof horn hemorrhages, and if this reduction would so affect the level of hoof horn hemorrhages as to make it similar to that observed in primiparous cows in straw yards. The second objective was to investigate the effect of methionine supplementation for the first 13 wk of lactation on the development of such hemorrhages. This study confirmed that both sole and white line hemorrhages increase during early lactation in housed cows, although the pattern of development of white line hemorrhages is not identical to that of sole hemorrhages. Housing primiparous cows in straw yards after calving significantly reduced the development of hoof horn hemorrhages, but replacing cubicle mats with thicker mattresses had no significant effect. Providing 115% of calculated methionine requirements had no significant impact on the development of hoof horn hemorrhages.

(**Key words:** housing, methionine, hoof horn hemorrhages)

INTRODUCTION

In 1997, a Farm Animal Welfare Council report stated that there was an unacceptably high incidence of lameness in UK dairy cattle. Clarkson et al. (1996), from a survey of 37 UK dairy farms, reported a mean annual incidence of 54.6 new cases per 100 cows (range, 10.7 to 170.1) and a mean annual prevalence of 20.6% (range, 2.0 to 53.9%). Clarkson et al. (1996) also reported that over 60% of lameness was associated with hoof horn disease (i.e., sole ulcer, white line disease,

or sole bruising). In the UK, the increase in digital dermatitis since that report has probably reduced this percentage (Watson, 1999), but hoof horn disease is still the major cause of lameness in dairy cows in the UK and most other developed countries.

Hoof horn disease is a complex multifactorial disease in which nutritional and environmental factors play important roles (Vermunt, 2000). Previous research at ADAS Bridgets (Livesey et al., 1998) showed that primiparous cows in early lactation housed in straw yards had fewer and less severe, white line and sole hemorrhages than did primiparous cows housed in cubicles with butyl rubber mats and wood shavings bedding. In the same study, cows kept in cubicles and fed a higher forage diet had a lower incidence of sole hemorrhages than did those in the same housing fed a high starch diet.

Methionine is a limiting essential nutrient during early lactation, and commercial dairy cows frequently respond to methionine supplementation by increasing milk yield (Rulquin et al., 1993). Sulfur amino acids are probably also rate-limiting substrates in the production of hard keratins (Fraser et al., 1972; Clark and Rakes, 1982); therefore, a sub-optimal supply of methionine in early lactation might cause changes in the rate of keratin synthesis and the quality of hard keratin synthesized. Such results might affect hoof horn growth rate or quality and consequently affect susceptibility to the development of sole and white line hemorrhages.

This study was designed to investigate the effects of housing and nutrition on the development of hoof horn disease (as identified by the appearance of hoof horn hemorrhages) in postpartum, primiparous Holstein cows. The first objective was to investigate whether replacing butyl rubber cubicle mats with mattresses filled with chopped rubber would decrease the incidence and severity of sole and white line hemorrhages in early lactation. The second objective was to investigate the effect of methionine supplementation in early lactation on the development of these hemorrhages.

MATERIALS AND METHODS

Treatments

Sixty pregnant Holstein heifers due to calve between November and February were selected from the ADAS

Received October 1, 2003.

Accepted November 4, 2003.

Corresponding author: R. A. Laven, e-mail: r.laven@ed.sac.ac.uk.

Table 1. Diet formulations for the lactation rations (ingredients and chemical constituents as % of DM).

	Control diet	Methionine-supplemented diet
Maize silage	23.7	23.7
Grass silage	23.7	23.7
Soya 48 (extracted.)	10.3	10.3
Rapeseed meal (extracted.)	8.1	8.1
Smartamine	0	0.01
Wheat (coarse ground)	22.6	22.6
Sugar beet shreds (molassed)	9.4	9.4
Megalac	1.5	1.5
Minerals ¹	0.8	0.8
CP	19.4	19.4
NDF	29.4	29.4
Ash	5.9	5.9
Oil	4.3	4.3
NCGD ²	46.1	46.1
Starch	23.7	23.7

¹Mineral and vitamin supplement containing 21% Ca, 6% P, 3% Mg, 0.025% Cu, 0.0006% Co, 0.0015 Se, 2000 IU vitamin A/kg, and 3 IU of vitamin E/kg.

²NCGD = neutral cellulase gamanase digestibility.

Bridgets herd and blocked according to their origin (purchased or homebred), age, growth rate from birth, and calving date. Within blocks, heifers were randomly allocated to 6 groups in a 3 × 2 factorial arrangement of treatments.

The 3 primary treatments imposed were 3 different housing systems, all within the same single-span building, from 4 wk before predicted calving date until 26 wk after calving. Twenty cows were allocated to each of these housing treatments.

The secondary treatment was the level of dietary methionine. Ten of the 20 cows on each housing treatment received the control diet; the remaining 10 cows received an additional 15 g/d of protected methionine (Smartamine; Rhone-Poulenc, Antony, France) from calving until 13 wk later. Details of the diets are shown in Table 1. The concentration of methionine present in the methionine-supplemented diet was estimated (applying the French PDI system) to be 115% of requirements (Rulquin et al., 1993), but no analyses were carried out to confirm the total amount of methionine present in both diets. As cows were individually fed within each housing treatment, those cows receiving methionine were housed in the same pens as cows on the control diet.

Treatment 1—A straw yard with a concrete feed passage. Space allocation per cow was 6.2 m² per cow. The yard was bedded daily with approximately 250 kg of straw. The bed was cleaned out monthly.

Treatment 2—A cubicle (free stall) yard fitted with butyl rubber mats (Cow Comfort Ltd., Lancashire, UK). There was an allowance of one cubicle per

cow. Cubicle beds were 2.3 m long × 1.2 m clear between divisions, with a 75-mm fall from front to rear and 0.2-m rear step. The cubicle divisions were cantilevered, free-standing galvanized tubing. The cubicles were bedded daily with sawdust, and lime was applied weekly as a desiccant and disinfectant. The feed passage was of identical design to the equivalent passage in the straw yard.

Treatment 3—A cubicle yard fitted with mattresses (Batchelor Farm Supplies, Dorset, UK). The mattresses consisted of chopped rubber from recycled tires encased by a water-resistant hessian bag. There was an allowance of one cubicle per cow; the cubicle and feed passage design and management and space allocation were the same as for Treatment 2.

Concrete passages were cleaned by automatic slurry scrapers. These operated 4 times daily in the feed passages for both the cubicles and straw yards. An additional scraper in the passage between the cubicle rows operated 6 times daily.

All heifers calved in straw yards. They were moved into these straw yards from dry cow accommodation in a single cubicle yard approximately 2 d before calving and were allocated to the appropriate housing systems at 4 to 5 d after calving.

For the first 13 wk of lactation, all cattle were individually fed a TMR once daily through either Calan Broadbent individual feeders (straw yard) or Griffith Elder individual feeders (cubicle yards). For the remaining 13 wk of the study, all of the cows were group fed the same TMR, which was similar to the control diet.

Measurements and Records

The ADAS Bridgets dairy unit was an accredited facility for good laboratory practice. All studies were carried out under a formally documented quality system, including the use of standard operating procedures, appropriate training of personnel to use equipment and carry out examinations, calibration of equipment such as weighing machines, and auditable recording of all results.

Dry matter intakes were recorded for individual animals for the first 13 wk of lactation. This was achieved by supplying a weighed amount of TMR daily in individual feeder hoppers, collecting the residual TMR the following day, weighing it, and subtracting the residual amount from the amount supplied. These measurements were averaged to produce a mean daily individual cow intake for each week of the study.

Individual milk yields were recorded at each milking and averaged to produce a mean daily yield for each cow for each week. Milk fat and protein concentrations

were measured at 4-wk intervals using the MilkoScan system (Foss, Hillerd, Denmark).

The locomotion score of each animal was determined weekly from 4 wk prepartum until the end of the study at 26 wk postpartum using the 0- to 5-point scale in 0.5-point increments devised by Manson and Leaver (1988). The cows were walked and turned on a level concrete surface to assess locomotion score. A single experienced operator carried out all of the assessments.

Live weight and body condition scores were determined monthly throughout the study. All-flex weigh beams were used to weigh the cattle. These were calibrated and serviced prior to the beginning of the study. Condition scoring was carried out using a 0- to 5-point scale in 0.5-point increments (Anon, 1986). Two trained operators carried out all measurements.

Foot lesion assessments for both hind feet were made approximately 4 wk before predicted calving date and during wk 1, 6, 12, and 26 after calving. Lesions were recorded in the manner recommended by Greenough and Vermunt (1994). The type and sites of the lesions were indicated on a hoof map (Figure 1).

For each of the zones delineated on Figure 1, the severity and extent of the lesion was recorded (using the scoring system shown in Table 2). The severity of the lesion was multiplied by the extent to produce a score for that zone. The scores for Zones 1, 2, and 3 (for both hind feet) were then summed to create an overall white line hemorrhage score, and the scores for Zones 4 and 5 (again for both hind feet) were summed to create an overall sole hemorrhage score.

All procedures were undertaken in accordance with the UK Animal Scientific Procedures act (1986).

Statistical Analyses

All continuous data were modeled using a repeat measures ANOVA with cow as the random factor and level of methionine supplementation, type of housing, and time in relation to calving as the fixed factors. The residuals were examined for normality using the Kolmogorov-Smirnov test. Residuals for lesion score data were not normally distributed; thus, the data were transformed. Square root transformation of this dataset produced the best fit; thus, the square-root transformed lesion data were analyzed using the same repeated measures ANOVA. The Kruskal-Wallis ANOVA was used to analyze locomotion score data. Further analysis of significant effects was undertaken using Tukey's test where the ANOVA results indicated a significant effect. All analyses were undertaken using Statistica (StatSoft Ltd., Bedford, UK) except for the Tukey's test, which was undertaken using Minitab 13 (Minitab Inc.)

Figure 1. Hoof map used for lesion recording (Greenough and Vermunt, 1994).

RESULTS

DMI

Dry matter intake significantly increased during the 13-wk period of measurement ($P < 0.05$). However, there was no significant effect of housing and diet or any significant interaction between housing, diet, and time on DMI ($P > 0.1$).

Table 2. Scoring system for hoof hemorrhage severity and extent.

Score	Hemorrhage severity	Hemorrhage extent
1	Slight discoloration	<10% of site surface area
2	Moderate hemorrhage	10 to 50% of site surface area
3	Severe hemorrhage	>50% of site surface area

Figure 2. Effect of methionine supplementation on mean daily milk yield during the first 26 wk of lactation. The weekly figures for mean daily milk yield were calculated for each cow from individual milk yields recorded at each milking. M = Period of methionine supplementation (0 to 13 wk postpartum).

Milk Yield and Composition

There was a significant effect of time on milk yield ($P < 0.05$). Milk yield increased in early lactation, peaking at approximately wk 12 of lactation. Methionine supplementation apparently consistently increased milk yield. Over the 26-wk period of the study, the mean additional milk yield of cows supplemented with methionine over cows fed the control diet was 250 kg, although methionine supplementation ceased at wk 13 of the study. This effect of methionine supplementation on milk yield is summarized in Figure 2. However, this increase in milk yield was not statistically significant ($P > 0.1$). There was also no significant effect of housing on milk yield ($P > 0.1$). Furthermore, there were no significant interactions between housing, diet, and time on milk yield ($P > 0.1$).

There was also a significant effect of time on milk composition and yield of fat and protein ($P < 0.05$). There was no significant effect of diet or housing on milk composition or fat and protein yield ($P > 0.1$), nor was there any significant interaction between diet, housing, or time ($P > 0.1$). The results for each of the methionine-fed and control cows are summarized in Figure 3.

Locomotion Score

There was no significant effect or interaction of time, diet, or housing on mean locomotion score ($P > 0.05$). However, the effect of time was almost significant at the 5% level ($P = 0.058$), with the mean locomotion scores tending to be higher after calving than in late pregnancy. On all occasions after calving, the mean locomotion score for all cows at each weekly examination was higher than the average score for all examinations before calving. The data are summarized in Figure 4, with the cows divided by housing treatment only.

Twelve cows were recorded as lame (locomotion score > 2.5) during the study period. Only one heifer was recorded as lame before calving. Three cows were scored as lame on more than 10 occasions (this included the heifer that had been recorded as lame before calving), and one cow was recorded as lame on 6 occasions. The remainder were lame on 3 or fewer occasions. The median number of lame cows per examination was 3, and the peak was 5, which was recorded at 9, 14, and 16 wk postpartum.

Live Weight and Body Condition Score

Mean live weight and body condition score were reduced immediately postpartum in all treatment groups.

Figure 3. Effect of methionine supplementation on milk composition and fat and protein yield during the first 6 mo of lactation. Milk composition was measured monthly for all cows, and fat and protein yield were calculated for each cow from individual milk yields recorded at each milking. M = Period of methionine supplementation (0 to 13 wk postpartum).

The nadir for live weight was reached between 4 and 8 wk postpartum, whereas the nadir for body condition score was not reached until 20 wk postpartum. There were no significant effects or interactions of diet or housing on live weight and body condition score ($P > 0.1$); however, methionine-fed cows had consistently lower live weights and body condition scores throughout the period between calving and 26 wk postpartum.

Hoof Horn Hemorrhages

White line hemorrhages. The changes in white line hemorrhage score during the study period are summarized for each treatment group in Table 3.

White line hemorrhage scores increased during early lactation ($P < 0.001$) and subsequently decreased between wk 12 and 26 ($P < 0.001$). This is shown graphically in Figure 5.

In addition to the significant effect of time, there was also significant effect of housing type on white line hemorrhage score ($P < 0.0001$). However, there was no significant interaction between time and housing on mean white line hemorrhage score ($P > 0.1$).

Primiparous cows kept on straw had significantly lower ($P < 0.001$) mean white line hemorrhage scores over the study period (1.6 ± 0.17) than did cows kept on mattresses (2.7 ± 0.2) or mats (3.0 ± 0.19). However,

no significant differences were found between cows on mats or mattresses ($P > 0.1$). There was a similar effect on peak white line hemorrhage score. The mean peak white line hemorrhage score for cows on mats (5.2 ± 0.24) was significantly higher ($P < 0.001$) than the mean peak score for cows on straw yards (3.2 ± 0.3), but was not significantly different ($P > 0.1$) from the hemorrhage score of cows on mattresses (5.0 ± 0.24). There was no significant effect of methionine supplementation on white line hemorrhages ($P > 0.1$), nor were there any significant interactions between diet, housing, and time ($P > 0.1$).

Sole hemorrhages. The changes in sole hemorrhage score during the study period are summarized for each treatment group in Table 4.

Sole hemorrhage scores were significantly affected by time ($P < 0.001$) and housing ($P < 0.01$), but not by methionine supplementation ($P > 0.1$). There was also a significant interaction between time and housing ($P < 0.01$). This interaction is illustrated in Figure 6.

Sole hemorrhages significantly increased during the first 6 wk of lactation in all groups ($P < 0.05$). There was a further significant increase in mean sole hemorrhage score between wk 6 and wk 12 for cows on mats or mattresses ($P < 0.05$) but not for cows on straw ($P > 0.05$). For all three groups, there was no significant

Figure 4. Effect of housing on mean locomotion score from 3 wk before calving to 24 wk after calving. Locomotion score was measured weekly using a 0- to 5-point scale in 0.5-point increments (Manson and Leaver, 1998). M = Period of methionine supplementation (0 to 13 wk postpartum).

change in mean sole hemorrhage lesion score between wk 12 and wk 26 ($P > 0.05$).

The effect of housing on sole hemorrhages at specific times was significant only at wk 12 ($P < 0.05$), although the effect was almost significant at the 5% level at wk 26 ($P = 0.06$). Comparison of the mean hemorrhage score at wk 12 of cows on mats with those of cows on straw showed that cows on mats had significantly higher ($P < 0.05$) sole hemorrhage scores than those on straw (3.4 ± 0.3 vs. 2.3 ± 0.34). There was no significant difference between the mean sole lesion scores of cows on mattresses (3.7 ± 0.3) and those of cows on mats ($P > 0.05$). The effect on mean peak sole lesion score was similar to that observed for white line hemorrhages; the mean peak score for cows on mats (3.8 ± 0.21) was

higher ($P < 0.01$) than that of cows in straw yards (2.9 ± 0.27), but not different from those on mattresses (4.2 ± 0.24).

DISCUSSION

Although all housing systems were within the same structure and with similar environments except for bedding system used, those areas were technically not replicated, and the data should be interpreted with some caution. However, this study is consistent with the findings of Livesey et al. (1998), who reported that sole and white line hemorrhage scores increase in early lactation in housed cows and that housing primiparous lactating cows in straw yards postpartum can signifi-

Table 3. The effect of housing, diet, and time on mean white line hemorrhage score (untransformed means).

Treatment	no.	wk -3	wk 1	wk 6	wk 12	wk 26
Straw/control	9	0.7	4.8	9.4	6.7	3
Straw/methionine	9	1.5	1.7	8.7	9.2	2
Mats/control	10	1.9	4	13	15	14.3
Mats/methionine	9	3.5	5.8	18	22	6.5
Mattresses/control	10	3.3	8.5	24	29	8.8
Mattresses/methionine	10	2	8.1	16	17	9.3

Figure 5. Effect of time relative to calving on mean white line hemorrhage lesion scores (SEM). Data are derived from all cows regardless of treatment group, and data are transformed via square root. ^{a,b,c}Columns with different superscripts are different ($P < 0.05$).

cantly decrease the incidence and severity of hoof hemorrhages when compared with housing in cubicles. The most likely explanation for this difference is the reduced foot trauma experienced by cows housed in straw yards compared with cows housed in cubicles with concrete passageways.

The findings of this study are also in agreement with the evidence from Livesey et al. (1998) that the pathogenesis of white line and sole hemorrhages, although similar, are probably not identical. In this study, differences in white line hemorrhages recorded between cows on straw and those on mats were visible at wk 6, 12, and 26 for white line hemorrhages but only at wk 12 for sole hemorrhages. More research is required to increase our understanding of the difference in pathogenesis between white line and sole hemorrhages, as these differences may have a major impact on clinical disease and prevention regimes.

The trend in locomotion score is also in agreement with other studies that have shown a significant in-

crease in locomotion score postpartum (Chaplin et al., 2000). No significant effect of housing or diet on locomotion score was recorded. However, group mean locomotion score is an insensitive measure of lameness unless there is a moderately high prevalence of high locomotion scores within the particular group. In this study, there was very little lameness recorded, only 12 of the 60 cows had locomotion scores greater than 2.5, of which only 4 were lame on more than 3 occasions.

Thus, these results cannot be used as firm evidence that none of the treatments predisposed cows to lameness. Types of foot lameness, such as excessive wear and penetrations, require harsh underfoot conditions such as sharp objects, rough concrete, or excessive walking on roads and tracks. The treatments imposed in this study might have predisposed cows to lameness (as suggested by the differences in hemorrhage score), but lameness might not have occurred in the absence of necessary risk factors. The husbandry conditions in this study were very benign. The concrete in the yards

Table 4. The effect of housing, diet, and time on mean sole hemorrhage score (untransformed means).

	no.	wk -3	wk 1	wk 6	wk 12	wk 26
Straw/control	9	0.3	1.4	4.6	5.8	7.1
Straw/methionine	9	2	1	2.3	7.7	6.3
Mats/control	10	0.1	0.7	4.6	11	11
Mats/methionine	9	0.7	0.8	5.5	17	8.5
Mattresses/control	10	2.5	5	9	19	9.3
Mattresses/methionine	10	0.9	3.3	2.6	7.7	8.7

Figure 6. Effect of time relative to calving on mean sole hemorrhage scores (SEM). Data are derived from all cows regardless of treatment group, and data are transformed via square root.

was in good condition, there was no exposure to flints or similar sharp objects, the cows had only a short walk to the milking parlor, there were adequate numbers of cubicles provided for all cows to lie down simultaneously, and there was no evidence of bullying or other behavioral abnormalities.

This study found no apparent benefit, in terms of reduction in hoof horn hemorrhages, of replacing butyl rubber mats with chopped rubber mattresses, although cows on mattresses spent more time lying down than cows on mats (J. Metcalf, unpublished observations) and suffered significantly less hock damage (Livesey et al., 2002). For sole hemorrhages, it is possible that the large temporal changes in hemorrhage scores obscured any effect of cubicle bedding, as there was an interaction between time and housing; however, for white line hemorrhage, there was no such interaction. It is also possible that the presence of additional risk factors, particularly harsh underfoot conditions, induced larger differences in hemorrhage scores to be expressed between treatments.

In this study, the changes in appetite, milk yield, live weight, and body condition score followed the expected pattern for a well-managed, TMR-fed group of primiparous Holstein cattle. The higher mean milk yield (250 kg) achieved by methionine-supplemented cows (Figure 2) than control cows over the 26-wk study was biologically and economically significant. However, this did

not attain statistical significance, probably because of the innate variation in milk production between individual animals, especially in first lactation. This study lacked the statistical power to detect such differences in milk yield. Nevertheless the results do suggest that the amount of methionine in the control diet was probably sub-optimal and that the methionine-supplemented group was not receiving excess methionine.

Methionine supplementation had no significant effect on hoof hemorrhage scores in this study. Furthermore, the differences in hemorrhage scores between methionine-supplemented and control animals were, unlike the response in milk yield, not consistent (either in favor of, or detrimental to, the cows fed methionine). The differences were also much smaller in magnitude than the significant differences observed in sole and white line hemorrhages in other studies at ADAS Bridgets and elsewhere in response to treatments that varied the proportions of forage to concentrates and types of fermentable carbohydrate (Livesey et al., 1998; Blowey et al., 2000). This result suggests that, in contrast to the effect on milk production, the control diet was not sub-optimal in regard to prevention of hoof horn hemorrhages. The results obtained do not preclude the possibility that methionine could have had a beneficial effect on hoof horn hemorrhages if the control diet in this study had contained a lower concentration of methionine. As methionine supplementation could also

have an adverse effect if supplementation was excessive, a dose response study, using a larger group of animals, where the total amounts of methionine in the experimental diets were known, would be needed to investigate the benefits and limitations of methionine supplementation further.

CONCLUSION

This study provides evidence that straw yards can ameliorate the increase in hoof horn hemorrhages seen in first lactation cows housed in cubicles postpartum. Neither methionine supplementation postpartum nor the replacement of butyl rubber cubicle mats with chopped rubber mattresses had a significant effect on hoof horn hemorrhages under the conditions imposed by this study.

ACKNOWLEDGMENTS

This study was jointly funded by the Ministry of Agriculture, Fisheries, and Food and by the Milk Development Council. The authors thank Claire Collins and Sarah Brocklehurst for their assistance with the statistics, John Metcalf for original study directorship, and Cath Marsh for technical support.

REFERENCES

- Anonymous. 1986. Condition scoring of dairy cows. MAFF leaflet p. 216.
- Blowey, R.W., R. Phipps, A. K. Jones, and A. J. Barringer. 2000. A comparison of the effects of high fibre and high starch on hoof lesions in multiparous cows. Pages 337–339 in Proc. 11th Int. Symp. Disorders of the Ruminant Digit, Parma, Italy.
- Chaplin, S. J., G. Tierney, C. Stockwell, D. N. Logue, and M. Kelly. 2000. An evaluation of mattresses and mats in two dairy units. *Appl. Anim. Behav. Sci.* 66:263–272.
- Clark, A. K., and A.H. Rakes 1982 Effect of methionine hydroxy-analogue supplementation on dairy cow hoof growth and composition. *J. Dairy Sci.* 65:1493–1502.
- Clarkson, M. J., D. Y. Downham, W. B. Faull, J. W. Hughes, F. J. Manson, J. B. Merritt, R. D. Murray, W. B. Russell, J. E. Sutherst, and W. R. Ward. 1996. Incidence and prevalence of lameness in dairy cattle. *Vet. Rec.* 138:563–567.
- Farm Animal Welfare Council. 1997. Pages 26–30 in Report on the Welfare of Dairy Cattle. FAWC, Surbiton, Surrey.
- Fraser, R. D. B., T. P. Macrae, and G. E. Rogers. 1972. Keratins, their composition, structure and biosynthesis. Publication No. 845, American Lecture Series Ed. Kugelmass I.N.
- Greenough, P. R., and J. J. Vermunt. 1994. In search of an epidemiologic approach to investigating bovine lameness problems cows. Pages 186–196 in Proc. 9th Int. Symp. Disorders of the Ruminant Digit, Banff, Canada.
- Livesey, C. T., T. Harrington, A. M. Johnston, S. A. May, and J. A. Metcalf. 1998. The effect of diet and housing on the development of sole hemorrhages, white line hemorrhages and heel erosions in Holstein heifers. *Anim. Sci.* 67:9–16.
- Livesey, C. T., C. Marsh, J. A. Metcalf, and R. A. Laven. 2002. Hock injuries in cattle kept in straw yards or cubicles with rubber mats or mattresses *Vet. Rec.* 150:677–679.
- Manson, F. J., and J. D. Leaver. 1988. The influence of concentrate amount on locomotion and clinical lameness in dairy cattle. *Anim. Prod.* 47:185–190.
- Rulquin, H., P. M. Pisulewski, R. Vêrité, and J. Guinard. 1993. Milk production and composition as a function of postprandial lysine and methionine supply: A nutrient-response approach. *Livest. Prod. Sci.* 37:69–90.
- Vermunt, J. J. 2000 Risk factors of laminitis—An overview. Pages 34–45 in Proc. 11th Int. Symp. on Disorders of the Ruminant Digit, Parma, Italy.
- Watson, C. 1999 Lameness in cattle—Lesions and diseases of the skin—Part 1. *UK Vet.* 4:51–60.