



A Review of the Peer Reviewed Literature on the
Treatment and Prevention of Foot Lameness in Cattle
Published Between 2000 and 2011

Sarah Potterton¹, Nick Bell², Becky Why³, David Main³ & Jon Huxley¹

¹School of Veterinary Medicine and Science, University of Nottingham

²Royal Veterinary College, London

³School of Veterinary Sciences, University of Bristol

Index

Introduction	3
Materials & Methods	6
Gap Analysis	9
Treatment of Digital Dermatitis	15
Treatment of Sole Ulcers	37
Treatment of White Line Disease	39
Treatment of Non-Specific Lameness	40
Prevention of Digital Dermatitis	41
Prevention of Sole Ulceration & Sole Haemorrhage	49
Prevention of White Line Disease	60
Prevention of Non-Specific Claw Disease / Lesions	80
Prevention of Non-Specific Lameness	83

Introduction

This review, generously funded by DairyCo, was conducted during the spring of 2011. The review was restricted in terms of both the time and financial resources available and consequently the reader is referred to the information in this introduction and the Material & Methods before reading the review in order to appreciate its scope. Following the Material & Methods we have provided a 'Gap Analysis', designed to highlight what the authors believe are the predominant gaps in current knowledge in the peer reviewed literature. Finally the review itself is divided into nine sections, four on treatment (Digital Dermatitis, Sole Ulcers, White Line Disease and Non-Specific Lameness) and five on prevention (Digital Dermatitis, Sole Ulceration & Sole Haemorrhage, White Line Disease, Non-Specific Claw Disease / Lesions and Non-Specific Lameness). 'Treatment of Non-Specific Lameness' covers material on treating lameness in which the authors have not identified a specific lesion in the paper. 'Prevention of Non-Specific Claw Disease / Lesions' covers material on preventing lameness in which the authors have not identified a specific lesion in the paper i.e. usually lesions were grouped into a measure such as 'foot disorders' or 'claw lesions'. 'Prevention of Non-Specific Lameness' refers to studies in which the authors have used a measure of lameness, usually lameness or mobility score as their outcome rather than identification of foot lesions.

The number of papers in this review is extensive and consequently a list of references has not been provided. Instead if the reader requires information on individual papers, the review should be read in conjunction with the Endnote database provided (**'2000-2011 Cattle Lameness Reference Database'**). The paper number quoted in the review refers to the Record Number in the Endnote database. Additionally two further electronic resources support the review; they are a MS Access database (**'Cattle Lameness Review Papers'**) containing information on paper classification, critical appraisal and notes taken during the review process and an MS Excel spreadsheet (**'Assessment of Lameness Control Material'**) containing the results of the review of non-peer reviewed literature on lameness control (see Materials & Methods for details).

The review was restricted in terms of both the time and financial resources available. The review we conducted was constrained by these factors and was consequently limited in a number of aspects:

- The review is limited to novel (i.e. reviews were excluded) peer reviewed papers published in the English language between January 2000 and February 2011 covering the treatment and prevention of foot lameness in cattle.

- Three databases (Ovid, PubMed and Web of Science) were used to search the literature; it remains possible that some papers which meet the specified criteria were not identified because they are not contained in any of the search engines employed.
- Whilst the search terms we used are extensive and have been used previously (Hirst et al 2002) they may not identify all pertinent papers even if they are contained in the databases we searched
- Limited auditing and cross checking of the methodological steps was possible, therefore it remains possible that the review contains a small quantity of undetected error e.g.
 - Not all papers may have been correctly classified and therefore included
 - Salient results from papers which were reviewed may have been missed or incorrectly excluded
- The review has not necessarily identified all papers containing relevant information if the paper or the results were not linked directly to lameness by the authors of these papers (these papers may not have been identified by the search terms we employed). For example, decreased lying time is considered a risk for lameness. It is possible that papers have been published which consider this factor for another reason e.g. welfare, without linking the work directly to lameness.
- Whilst we have reviewed the quality of each paper, we have made relatively limited comment on this in the final report, principally because of the constraints of the study. The results of our quality review of each paper are available in the Access database ('**Cattle Lameness Review Papers**') which should be read in conjunction with the report.
- Whilst all the collation, classification and review of papers was conducted by a single researcher (SP), different sections of the final report were written by one of three author (SP, NB & JH). Whilst a similar skeleton has been retained between sections, variations remain which reflect the different approaches and writing styles of the authors.
- Finally it is important to note that we have reviewed the literature systematically i.e. we defined a methodology before we began, designed to maximise coverage and reduce bias, however, it should be noted that our approach does not constitute a full 'Systematic Review' as defined by The Cochrane Collaboration or similar organisation.

Finally during interpretation of this review, we would like to remind the reader of a number of salient points to aid interpretation:

- In our report and in the papers we have reviewed, the term 'odds' or 'odds ratio' is often quoted as an outcome from the study. The reader is reminded that odds ratio is not the same as a 'relative risk ratio'. Odds ratio is a term used to describe the output from a statistical model; it cannot be converted to or interpreted as relative risk i.e. an odds ratio of 2 does not mean that the outcome is twice as likely in that group. If an odds ratio is significant the factor is a risk, however the magnitude of the risk remains unknown.
- All other things being equal, experimental studies provide stronger evidence than observational studies
- The results of cross sectional studies should be interpreted with caution, because causality cannot be attributed in this type of study. For example, a cross sectional study may link the height of the cubicle step to the incidence of sole ulceration. Height of the cubicle step may in fact be a marker for an unidentified risk factor which was not measured in the study e.g. a certain type of cubicle divider or step height may be strongly correlated with another factor (e.g. cubicle length) and only one of these factors was significant in the final statistical model. Similarly cross sectional studies give no indication of the direction of risk. For example the severity of hock lesions are positively correlated with elevation of locomotion score. The two could be correlated because lame cows alter their lying / standing behaviour increasing the risk that they develop hock lesions or because hock lesions are painful making the animal lame.
- Of course even when risk factors are tested experimentally, results may not show differences (even if they exist) or come to incorrect conclusions due to deficits in study design (particularly duration of follow up for long term lesions like sole ulceration). The nature and duration of this review has not allowed us to comment extensively in this area
- Finally, the level of detail from each paper, included in the final report is necessarily brief. The reader is advised to refer and review the full paper if high significance or specific recommendations are to be made based on the information reported.

Materials & Methods

At the start of January 2011, a steering group meeting was held between the authors (Sarah Potterton, Nick Bell, Becky Whay and Jon Huxley) a representative of DairyCo (Elizabeth Berry) and a private practitioner with a specific interest in the field (Owen Atkinson). The steering group developed and refined the methodology described based on agreement between the members.

Non-Peer Reviewed Literature on Lameness Control

A concise review of the non-peer reviewed literature on the treatment and prevention of lameness in dairy cows was conducted. All the non-peer reviewed material (e.g. text books, lameness control plans and lameness control materials) in possession of the steering group were collated (NB non-peer reviewed journal papers were excluded). Additionally, colleagues of the group from around the world were contacted electronically to ask if they held or were aware of other materials on the subject. Finally the British Library was searched for text books on lameness or disease in cattle.

Once collated the material was reviewed and categorized by source type (e.g. text book, control programme), date of publication, target audience (e.g. farmers, vets etc), whether the material was referenced, volume of material, treatment recommended for digital dermatitis, sole ulceration and white line disease and prevention strategy recommended for digital dermatitis, sole ulceration and white line disease. In total 23 text books, 6 control plans and 17 other sources of information were included in the review, the results of which are available in a MS Excel spreadsheet (**'Assessment of Lameness Control Material'**).

Peer Reviewed Literature

Three databases were generated by the use of the defined search terms in three separate databases: Ovid, PubMed, and Web of Science. The search terms specified were those previously published by Hirst *et al.* (2002), with two additional terms added: (mobility and scor*) and (digital cushion*). The complete set of search terms used is listed below:

a) (bovine* or cattle* or cow or cows or heifer* or (dairy and calf) or (dairy and calv*) or (beef and calf) or (beef and calv*) or buiatric* or (dairy and herd*) or (dairy and farm*) or (beef and herd*) or (beef and farm*)) and

b) (lame or lameness or (locomotion and scor*) or (solar and ulcer*) or (solar and haemorrhage*) or (solar and hemorrhage*) or (claw and lesion*) or (sole and ulcer*) or (sole and haemorrhage*) or (sole and hemorrhage*) or (sole and lesion*) or (solear and ulcer*) or (solear and haemorrhage*) or (solear and hemorrhage*) or (solear and lesion*) or (hoof and lesion*) or (solar and lesion*) or (foot and lesion*) or (foul and foot) or (footrot) or (white and line and lesion*) or (white and line and disease*) or (white and zone and lesion*) or (white and zone and disease*) or (white and line and abscess*) or (white and zone and abscess*) or (hoof and health) or (heel and abscess) or (heel and erosion) or (slurry and heel) or (Mortellaro*) or laminitis or coriitis or sandcrack or (interdigital* and dermatitis) or (digit* and dermatitis) or (pododermatitis and circumscripta) or (pododermatitis and septica) or (pododermatitis and aseptica) or (phlegmona and interdigitalis) or (hyperplasia and interdigital*) or (fissura and unguulae and longitudinalis) or (erosio and unguulae) or (ungulae and deformans) or (toe and ulcer*) or (heel and ulcer*) or (claw and health) or (claw and trimming) or (hoof and trimming) or (foot and trimming) or (claw and paring) or (hoof and paring) or (foot and paring) or gait or (mobility and scor*) or (digital cushion*)).

Searches were run on the 7th February 2011, and were restricted to the years 2000 to 2011 inclusive, and English language papers only. The three searches returned 628, 704 and 1473 records respectively. The three sets of records were exported separately into the reference management software package EndNote® (version X4.0.2, Thomson Reuters, U.S.) to create three databases. Each of the databases was sorted to remove duplicate records, non-peer reviewed articles, and non original material (i.e. review papers). Articles that related to species other than cattle, or were specific to lameness that was not a result of foot lesions were also removed. The resulting databases contained 365, 390, and 592 records. The three refined databases were combined to produce a single dataset with 1364 records, which was filtered to remove all duplicate records, leaving a total of 591 records. The 591 records were categorised on the basis of title and abstract by S.P., according to whether they were concerned with treatment or prevention of: digital dermatitis, sole ulcer, white line disease, non specific claw disease or lesions, or non specific lameness i.e. one of ten categories (NB papers could belong to more than one category if they covered material from more than one category). These papers (a total of 363) were selected for review. Seventy seven of these articles were discarded during the review process as on more detailed inspection they were found to have been categorised incorrectly and were judged not to be relevant to the treatment and prevention of lameness. In total 286 papers were reviewed; the number of papers in each category are outlined in Table 1. The methods and results sections of the papers were appraised according to the standard appraisal questions set

out by Crombie (1996), which are: (1) are the aims clearly stated; (2) was the sample size justified; (3) are the measurements likely to be valid and reliable; (4) are the statistical methods described; (5) did untoward events occur during the study; (6) were the basic data adequately described; and (7) was the statistical significance assessed. The responses to the appraisal questions, details of treatments applied during the studies, and the key findings of the studies were entered into a relational database (Microsoft Access 2007; Microsoft Corporation, Redmond, WA; 'Cattle Lameness Review Papers').

Table 1: Number of papers reviewed in each category.

	Treatment	Prevention
Digital Dermatitis	27	62
Sole Ulceration	3	87
White Line Disease	0	75
Non-Specific Claw Disease / Lesions	0	32
Non-Specific Lameness	1	151

Gap Analysis

There were 591 papers found in the systematic search of the lameness literature between 2000 and February 2011 of which 363 reported on the treatment or prevention of lameness. Despite this large number, many topic areas were weakly represented or absent in the literature. However, this could conceivably be because some topic areas were well researched prior to the review period.

It is important to emphasise there is value in repeating research, particularly that which is most important and relevant to the UK dairy farmer. This is particularly significant if findings are not readily generalisable to other farms or populations by virtue of different exposure to risk factors such as genotype, climate or husbandry. If research *is* repeated, then study design should follow the guidance of Crombie (1996) as stated earlier. Furthermore, future work should use standardised outcome measures whenever possible to allow future meta analysis.

Many of the papers reported lameness or locomotion score as an outcome. Future research should, whenever possible, be focussed on testing interventions and evaluate foot lesion outcomes. Only through the use of lesion outcomes can research inform on the relevance and impact of the intervention at farm level. Therefore, this gap analysis will concentrate on lesion specific research questions.

The following lists the topics which appear to be lacking or weakly covered in the scientific literature.

TREATMENT OF LAMENESS

There was a total of 30 papers, of which 27 were related to digital dermatitis and 3 were related to sole ulceration. There were no papers on the treatment of white line disease.

Digital Dermatitis

- Topical treatment of digital dermatitis with antibiotics involved just oxytetracycline and lincomycin (the former is the only licensed antibiotic in the UK). However, given the variation in reported cure rates, further work is needed to investigate the optimal treatment regime.
- There has been some indication that systemic antibiotics are beneficial in the treatment of digital dermatitis, although this has been restricted to studies involving cefquinome, oxytetracycline and erythromycin. While not a gap, there is clear potential to repeat this work for other antimicrobial agents and to investigate herd control approaches in line with recommendations on the rationale use of antimicrobials in food producing animals.

- Other topical antibacterial agents were reported in the scientific literature, but as unlicensed products, they are unable to make treatment claims and have an uncertain status as an on-farm treatment. Therefore, they probably do not constitute a gap in the research although they do appear in the grey literature.
- No trials went beyond a comparison of antibacterial agents topically administered. While the use of foot trimming, debridement, lesion cleaning/drying, use of bandages and use of analgesia are referred to in trials and case report, there has been no evaluation of their importance.
- Similarly, with respect to foot bathing, no trials have gone beyond a comparison of agents and the concentration used in foot baths.

Sole Ulcers

- There were just three papers on sole ulcer treatment; report describing a series of cases given systemic antibiotics and a foot trim (90); the second consisted of a case-series from a Kenyan veterinary hospital; and the third evaluated the effect of biotin supplementation on lesion recovery (87). Therefore, the relative importance of aspects of current clinical practice in the UK (therapeutic foot trim using the Dutch five step method, orthopaedic block, bandage, topical antibacterial agents, cutting away granulation tissue, intravenous anaesthesia/antibiotics (IVRA), NSAIDs, cautery, systemic antibiotics, aftercare/management during the recovery period) have not been investigated in a well design clinical trial.

White Line Disease

- There were no publications on the treatment of white line disease in the peer reviewed literature. This represents a major gap in the scientific literature.

PREVENTION OF LAMENESS

Digital Dermatitis

- Evidence that standing times in slurry contaminated yards contributes to digital dermatitis is still limited to a small number of observational studies. Therefore, the significance of this risk factor remains uncertain.
- There is a substantial body of evidence showing the importance of housing system and under-foot conditions for the prevention of digital dermatitis (reported under claw trauma). Given that most systems for dairying are chosen for ease of management and cost-effectiveness of management, there may be limited scope for implementing changes to straw yards or slatted systems.

However, findings from these papers could be used to test recommendations for design of buildings, walkways and tracks for minimising risk of infection.

- The importance of diet and feeding in the prevention of digital dermatitis is unclear from the literature with several conflicting results. When rumen health is potentially compromised it remains unclear as to the role of environmental contamination with slurry as the mediator for a nutritional effect. Cow-level interventions inducing acidosis and loose faeces may not be ethically justifiable but herd level interventions aimed at reducing the risk of loose faeces could be considered, albeit with production and rationing costs taken into account.
- Despite its importance, there were only five papers reporting on environmental hygiene in relation to digital dermatitis. None of these were intervention studies. This has to represent one of the key areas requiring further research for the control of digital dermatitis.
- There were seven papers examining the use foot bathing for the prevention of digital dermatitis infections. Despite conflicting results reported by observational studies, there appears to be good evidence from intervention studies to support foot bathing. There appears limited evidence on how effective foot baths are at prevention of digital dermatitis in the long term and, as described earlier, no evidence informing farmers on how to optimise the use of footbathing systems.
- Foot trimming would appear to be a potential risk factor for the spread of digital dermatitis, although the evidence is conflicting. Further work could be conducted to assess the likelihood of this being a route of spread and interventions aimed at mitigating the infectious spread at trimming.
- Vaccination trials conducted in the US appear to be disappointing although this may be a major area of pharmaceutical interest in the future.
- It is unknown how many farms are free of digital dermatitis infection in the UK. Given the small amount of evidence in the literature, it would seem reasonable to examine methods of maintaining digital dermatitis-free status for these herds, and possible eradication in others.
- Research into the heritability of digital dermatitis reveals some potential for genetic selection. This may represent one of the most exiting long-term interventions to be researched.

Sole Ulceration & Sole Haemorrhage

- Considering the importance now placed on standing time on concrete as a risk for sole ulceration and haemorrhage in lameness control plans, there remains relatively little direct evidence indicating that this is the case (245, 96). Whilst

additional supportive evidence is provided by the papers which demonstrate that these lesions are more common on harder lying surfaces (e.g. 44, 93, 157, 129) these results could be confounded by other factors. Similarly reducing standing time in the collecting yard is often stated as an important control measure in the UK, no studies have investigated this association. Further high quality experimental work is needed in this area to ensure that farmers are given the correct advice in what is an expensive area to make management and husbandry changes.

- Classically sole ulcers were thought to be associated with high concentrate diets and rumen acidosis. The literature since 2000 provides virtually no evidence that this is the case.
- The literature since 2000 reveals a weight of evidence that high yield is a significant risk factor for ulceration and haemorrhage. This may in part explain the historic link between high concentrate diets and sole lesions noted above i.e. high yielding animals are fed high levels of concentrates to support the high yield, however it is the high yield which is the risk factor rather than the high concentrate diet. More work is urgently needed in this area to better understand why high yielding animals develop more sole lesions.
- A number of high quality experimental studies have demonstrated that management at calving and in the immediate period before and after can either increase or decrease the risk of developing sole lesions many months into lactation (107, 108, 96). Laxity in the suspensory apparatus of the foot around calving have been postulated as one possible cause (127). Further work is desperately needed to further our understanding of how sole ulcers develop so that animals can be management appropriately to reduce the risk of disease.
- Few studies have followed animals for more than a few months and even more rarely for more than a lactation. Whilst of course, experiments with long time courses are more expensive to complete, sole ulceration is a disease with a protracted time course. Therefore, there is a danger that studies with short time courses either do not identify risks which are present or worse incorrectly apportion significance to factors which are markers for other risks.
- The literature since 2000 reveals a weight of evidence that sole ulceration and haemorrhage are more common in older animals. Whilst the reason for this is unclear, two papers (57, 126) suggest that a previous history of lameness is a risk factor. Preventing and or effectively treating sole lesions in early lactations may prevent recurrence in the future years.

White Line Disease

Whilst there is a substantial list of references relating to white line disease, the greatest focus of research has been on nutrition with other risks being relatively under-researched. There are several studies that have indicated that long term interventions are required to detect differences in lameness due to white line disease, with a minimum of 6 months required for biotin.

- Three papers examined standing time in relation to white line lesions. The evidence from these three papers suggests there may be a correlation between white line lesion prevalence and standing times, but further work is required to establish if this is directly causal and the stages of the disease process. For example, it is unclear whether prolonged standing time is important directly as a source of trauma and bruising, or whether there is an increased risk of a dynamic force or whether it is lack of opportunity to recover that is important for the development of this lesion or a combination of one or more of these factors.
- In the review only five risk factor surveys has reported physical factors in the environment of the foot as important for white line disease (44, 104, 67, 128, 129). There have been three studies (81, 84, 179) that have examined reduction in traumatic forces using rubber matting interventions. Physical injury of the sole and white line from rough, stony tracks is a commonly reported cause of non-specific lameness in pasture-based systems in New Zealand (Chesterton *et al* 1989) and it is therefore surprising that there have been so few reports on this topic.
- Further research is required to understand the disease process leading to white line disease in cattle but the body of evidence would suggest increasing the access to pasture is likely to increase the prevalence and incidence of white line disease, but factors relating to management and resource provision in housed and pasture-based systems are likely to greatly influence the outcome.
- The role of claw trimming remains uncertain, with four observations studies reporting a relationship but only one short term intervention which found no effect.
- Nutritional interventions have been well investigated with 20 reports (vs one observational report)
- There is some evidence to support breeding interventions, but considerable development is required before an intervention could be tested on farms
- Some research confirms the association between wet conditions underfoot and white line lesions but further work is required to test this under controlled conditions

PREVENTION OF NON-SPECIFIC LAMENESS

As mentioned previously, research without lesion specific outcome measures are difficult to interpret as they may be confounded by many risk factors. Consequently, they may be more challenging to apply to farms which will often have well defined, lesion specific problems. None-the-less, there may be interventions which are applicable to non-specific lameness, such as screening, foot trimming methods and good housing design. Furthermore, there is some evidence to suggest the three commonest foot lesions causing lameness in dairy cattle (sole ulcer, white line disease and digital dermatitis) are insensitive outcome measures due the lag between exposure to inciting factor and becoming diagnosable lesions, and the effort required to reliably diagnose these disorders. Therefore, minor lesions (e.g. sole haemorrhage or heel erosion) or cow behaviour (e.g. lying times, back arch or locomotion/mobility score) may make superior outcome measures. Finally, outcomes relevant to the motivation of farmers should be a major consideration in future research

The key gaps include science and application relating to:

- The relationship over time of different lesions causing lameness and inciting risk factors
- Screening for lameness using different methods of detection
- Dutch five step foot trimming

Treatment of Digital Dermatitis

Digital dermatitis is an infectious skin disorder of the foot associated with a number, and possibly a mixed combination, of bacterial organisms (Logue and Offer 2005). The overwhelming evidence implicates phylogroups of Treponeme spirochaete bacteria (29, 403, 426, 430,431,432,437, 438, 439, 442, 445, 446, 447, 448, 454, 455, 458) although other bacteria have been isolated which was reviewed by Demirhan *et al*(2000) and Murray *et al*(2004) in a conference paper. Since these reports one further organism, *Guggenheimella bovis* has been found in association with the Treponemes (449).

The following review of the published literature since 2000 will consider individual animal treatment with topical antibiotics, topical antibacterial agents and parenteral (i.e. injectable) treatments, as well as the herd treatments using foot baths. Some consideration of best clinical practice will also be evaluated, looking at the evidence for policies on whether to debride, the benefits of pain management and optimal aftercare. There were 27 papers on topics relating to the treatment of digital dermatitis, of which 17 were experimental by design, five were case reports, two were pharmacokinetic studies, two were in vitro antibiotic sensitivity studies and one was a prospective cohort study. Eleven papers describe the use of topical antibiotic treatments, five describe non-antibiotic topical treatments, three reported on injectable antibiotics, nine on foot bathing and one on vaccines. Many studies involved combinations or comparisons of treatments delivered in different ways.

Table 2 A summary of the subjects relating to digital dermatitis treatment covered by papers identified in the review (paper identification number given in brackets)

Treatment	Number of experimental reports	Other studies
Topical antibiotic		2 in vitro (6, 29)
Oxytetracycline	4 (15, 3; positive controls in 8, 7)	3 case series (4, 85, 18)
Chlortetracycline	1 (25)	1 case series (17)
Lincomycin	3 (3, 11, 16)	
Topical non-antibiotics		
Protexin	1 (8)	
Copper peroxide and cationic agent	2 (16, 22)	
2% glutaraldehyde	1 (15)	

8% copper sulphate	1 (25)	
8% zinc sulphate	1 (25)	
8% formalin	1 (25)	
3% peracetic acid	1 (25)	
Best clinical practice for topical treatments		
Cleaned lesion	7 (18, 15, 3, 16, 8, 22, 25, 7)	2 (17,18)
Dried lesion	1 (8)	
Debrided lesion	2 (23, 460)	
Intravenous regional anaesthesia	1 (23)	
Repeated application after brief drying period	1 (8)	
Bandage	3 (15, 3, 16)	3 (17, 18, 85)
Dry standing after treatment	1 (8)	
No bandage, repeated treatments	5 (11, 8, 22, 25, 7)	1 (17)
Repeated bandage	1 (15)	
Injectable antibiotics		
Cefquinome	1 (10)	
Erythromycin	1 (10)	
Oxytracycline	1 (23)	
Intravenous vs I.V. regional oxytetracycline		1 (20 – pharmacokinetic)
Foot bathing		
Erythromycin	1 (12)	2 (13 – case study, 27 – pharmacokinetic study)
Formalin	1 (12); 2 as positive controls (30, 38)	
Copper sulphate	3 (12, 15, 24); 1 positive control (38)	
Zinc sulphate		
Peracetic acid	1 (12)	
Hypochlorite	2 (23, 24)	
Commercial multicomponent	1 (30)	

Sodium carbonate	1 (30)	
Glutaraldehyde and ammonium	1 (26)	
Quarternary ammonium	1 (26)	
Hydrogen peroxide, acetic acid, peracetic acid	1 (26)	
Vaccine	1 (5)	

TOPICAL ANTIBIOTIC TREATMENT

Given that digital dermatitis is likely to be a bacterial infection, in most cases superficial affecting the epidermis and dermis, the rationale for using topical antibiotics to treat digital dermatitis is strong. In a study of in vitro susceptibility of 19 digital dermatitis spirochaetes to eight common antimicrobials was investigated by Evans *et al*(2009) (6). Nineteen isolates from three phylogroups were tested. Group 3 treponeme isolates (closely related to *Treponema denticola*/*T. putidum*) were more susceptible to gentamicin than groups 1 or 2, with group 2 isolates more susceptible to lincomycin than the other 2 groups. All isolates were most susceptible to penicillin and erythromycin, and were not particularly susceptible to enrofloxacin. One isolate was spectinomycin resistant.

A more quantitative investigation was conducted in Japan by (29) in which minimum inhibitory concentrations were measured for 15 antimicrobial agents on 23 *Treponema phagadenis*-like isolates. For each of the 23 spirochaete strains isolated from cattle with DD lesions susceptibility tended to be similar across the individual antimicrobial agents. The 15 antimicrobial agents differed in their minimum inhibitory concentrations against the isolates. Penicillin G, ampicillin and erythromycin demonstrated the lowest minimum inhibitory concentrations, with oxytetracycline, lincomycin, enrofloxacin, chloramphenicol, ceftiofur, and gentamicin showing intermediate values. Kanamycin, streptomycin, rifampicin, sulfamethoxazole, trimethoprim, and colistin showed highest MICs. No resistance was reported, but the results appear consistent with those of Evans *et al*(2009) (6). On the basis of these studies, penicillin or erythromycin would appear to be most appropriate antibiotics for treating digital dermatitis if the assumptions about spirochaetes being the causal agents hold true.

A number of studies have examined the use of topical oxytetracycline and the closely related chlortetracycline. In the UK, products containing these antibiotics

(Terramycin spray; Pfizer and Cyclo spray; Eurovet) are the only ones licensed for topical treatment.

Proposed best practice has been based on completing a course of topical applications of antibiotic for at least three days. In a case report involving nine cows treated for digital dermatitis in this way reported 'all cases responded well' to treatment (4). However, there were very limited details regarding method and outcome assessment.

(85) reported on DD in four Brazilian dairy herds which used topical applications of oxytetracycline powder in combination with a formaldehyde spray, bandaged for 3 to 5 days. This was reported to be highly effective in treating the lesions. The use of oxytetracycline foot baths (6g/litre) for 10 minutes daily over 3 days was also reported to be beneficial as a control measure, as was improvement of general housing hygiene. In a Japanese report on a case series (18) followed 89 lactating cows with a hindfoot DD lesion (erosive or granular appearance along the plantar aspect of the coronary band, characterised by a red-grey, strawberry-like surface with or without filiform papillae and with painful reaction after palpation). All animals were maintained under the same management and housing conditions throughout the study, but there were no controls. The affected feet were rinsed clean before single topical application of 5ml oxytetracycline solution (100mg/ml) on a cotton pad, again, held in place with a bandage. Bandages were not actively removed (left to fall off) before re-examination at day 29 after treatment. Lesion size was significantly reduced by day 29, but the proportion of treated lesions completely healed was only 13.8% in primiparous heifers and 38.7% in multiparous cows. The authors concluded a single application of oxytetracycline was insufficient in the treatment of digital dermatitis.

Another case series report (17) followed cows with a DD lesion (at any stage) treated with topical salicylic acid and chlortetracycline. One hundred and fifty one cows were examined at approximately 5 week intervals (mean 39 days) with date of onset or recovery of lesions determined at midpoint between the two consecutive recordings, with the duration of lesions the difference in days between date of onset and recovery. Prior to antibiotic, lesions were treated with topical application of salicylic acid and bandaged for four days. Following removal of bandage, lesions received a daily topical treatment of chlortetracycline for 5 days. All lesions recovered eventually, with the last lesion taking almost 120 days to recover. Median duration of lesions was 42 days although the precision of this finding was limited by the 5 week examination interval; consequently, lesion duration is likely to be less than this figure.

Manske *et al*(2002) (15) used a blind, quasi-random trial (choice of two treatments alternated following a coin toss to determined first treatment) with a within cow control was conducted to evaluate topical oxytetracycline (100mg/ml) and topical 2% glutaraldehyde in the treatment of digital dermatitis. All cows were in a single herd

and all cows included irrespective of DD lesion presence, severity and stage or presence or severity of other foot lesions. The trial was stratified (blocked according to DIM, parity and breed). Feet were trimmed (as needed - therapeutic or aggressive), the heel cleaned prior to application of 5ml of treatment and a light bandage (not controls). Treatment was repeated at day 5. At 32 days after treatment 87% of lesions were cured compared with 34% in the control group (trim alone) and 41% receiving glutaraldehyde. This finding was statistically significant.

One other RCT has demonstrated the effectiveness of topical oxytetracycline bandaged in place for four days in the treatment of digital dermatitis (3) and this trial is described in the next section. Evidence supporting the use of repeated applications of tetracyclines for the treatment of uncomplicated digital dermatitis appears to be strong, although none of the treatment protocols had 100% cure rates.

Lincomycin and other comparative studies

Lincomycin is a lincosamide antibiotic, licensed in the UK for the treatment of mastitis in cattle and proliferative enteropathy in pigs. Berry *et al*(2010) (3) used a RCT to compare oxytetracycline and lincomycin treatments (10g oxytetracycline or 10g lincomycin) with a control group of three cows. All cows had single or multiple skin lesions consistent with digital dermatitis according to pathological and histological features described elsewhere. Feet were washed, and a single application of topical paste was applied using gauze and a bandage left in place for four days. Control cows were just bandaged after biopsy. There was no significant difference in lesion response to oxytetracycline or lincomycin, so results were pooled. Antimicrobial treatment increased the probability of the lesion being healed at day 14 (73%) and day 30 (68%) than control cows (33%). The study was weakened by the small number of control cows (n=3 in a total of n=25), and a lack of details concerning exposure of all cows to the same environment between days 1 and 14 or 30. The study did highlight the limited effectiveness of a single treatment, with 32% of antibiotic treated cows not healing by day 30 and half of those that appeared healed on visual inspection having spirochaetes on histological examination. One of the three control cows healed with bandaging alone.

Laven and Hunt (11) compared Lincomycin with valnemulin, a pleuromutilin antibiotic (a peptidyl transferase) which is licensed for the treatment of swine dysentery in pigs in the UK. In this study they used lincomycin solution (0.6mg/ml) or valnemulin (100mg/ml) given as treatments each 48hrs apart with 25ml of solution applied to each lesion at each application. There was random allocation of cows with lesions to the two treatments (no control), with exclusion of animals with other foot lesions at time of exam. Using this approach they found a significant reduction in lesion score over time for both treatment groups. Lesion scores significantly different from day 0 on day 14 (not 1, 2, 3, 4, 6, 8 or 10). There was no significant difference between groups at day 14. However, cure rates

were only 6/15 (lincomycin) and 5/18 (valnemulin) and there was no monitoring beyond day 14. There was no mention of the environment of individual study cows and so it can only be assumed that this remained unchanged and similar for all cows.

In a randomized controlled trial, Moore *et al*(2001) (16) used either a high concentration of lincomycin in a paste (10g with 3ml water) or 20ml soluble copper with peroxide and a cationic agent compared with a control. All cows treated were from a single herd with an active red DD lesion, a pain response and were less than 200 days in milk. Feet were cleaned before application of treatment. Paste was applied on gauze and held in place by bandage for 5 days. Lesions were reassessed 29 days after treatment and retreated if signs of an active lesion or pain, except control cows which were randomly allocated to one of the two treatments. Cows at day 60 or beyond with evidence of lesions were treated with lincomycin. Cows treated with lincomycin or the non-antibiotic cream showed significant reductions in all clinical lesion scores at day 29 (except lesion maturity score). Treatment with lincomycin was significantly more likely to result in reduced lesion size, and to not need re-treatment at day 29 than the non-antibiotic. There were no significant differences between the two treatments at day 29 for reduction in pain score or days to recurrence of a lesion (up to 130 days).

Summary

All of the reports on topical antibiotic treatments have involved tetracyclines or lincomycin. Reports on the use of erythromycin have been restricted to foot bathing trials and are described later.

TOPICAL NON-ANTIBIOTIC, ANTIBACTERIAL AGENTS

The effectiveness of several non-antibiotic agents with antibacterial properties has been investigated. These include 8% copper sulphate solution (25); 8% zinc sulphate solution (25); 8% formalin solution (25); 3% peracetic acid solution(25); glutaraldehyde (15); copper with peroxide and a cationic agent (16, 22); gel containing copper/zinc/organic acids/essential oils (8). Many other products are available commercially without published clinical trial data.

Kofler *et al*(2004) (8) tested a treatment containing organic acid, copper salts, zinc salts and essential oils compared (Protexin Hoof-Care) with oxytetracycline as a positive control. Cows with acute stages of DD on the skin of the heels or the dorsal coronet associated with moderate or high pain were recruited and randomly assigned to one of the two treatments. Each cow underwent functional claw trimming, followed by washing and drying of lesions. A topical dose of treatment was applied twice in 30

seconds. In the 28 days following treatment some individuals received extra treatments on day 4 and 10, with the criteria for multiple treatments not given. Twenty five of 52 required a treatment on day 4 and 8 required treatment on day 10. Following treatment, cows were kept on a dry standing for 30 minutes following application. There was no significant difference between topical oxytetracycline and Protexin Hoof-Care in treatment of DD lesions. By day 4 both groups demonstrated significant improvements in pain, lameness and weight-bearing scores. By day 10 over 50% of cows showed at least partial resolution of lesions. By day 28 92% of lesions were completely healed. The study was weakened by a lack of reported details with respect to multiple treatments and power calculations. The rates of healing and retreatment in the protexin and oxytetracycline groups were not clear.

As described earlier, Moore *et al*(2001) (16) tested a cream containing soluble copper with peroxide and a cationic agent in a randomized controlled trial. Cows were treated with: (1) 20ml topical nonantimicrobial cream (soluble copper with peroxide and a cationic agent); (2) lincomycin paste (10g with 3 ml water); (3) no treatment. Like the cows receiving antibiotic, cows receiving non-antimicrobial cream showed significant reductions in all clinical lesion scores at day 29 (except lesion maturity score). Treatment with lincomycin was significantly more likely to result in reduced lesion size, and to not need re-treatment at day 29 than the non-antimicrobial. There were no significant differences between the two treatments at day 29 for reduction in pain score or days to recurrence of a lesion (up to 130 days).

In another study involving containing soluble copper, a peroxide compound, and a cationic agent ('Victory') Shearer and Hernandez (2000) (22) compared various formulations of Victory with oxytetracycline as a positive control. Seventy eight cows with DD lesions on a single rear foot associated with signs of severe pain were randomly allocated to one of four treatment groups: (1) oxytetracycline solution (25mg/ml); (2) 'Victory'; (3) modified formulation of Victory (reduced soluble copper and peroxide compound, but increased concentrations of the cationic agent compared to the original); and (4) modified formulation of Victory (with reduced levels of the peroxide compound compared to the original). Cows were treated once per day for 5 consecutive days, not treated for 2 days, then treated once per day for an additional three days. Solutions were applied topically by spraying, with lesions first washed. The proportion of cows with signs of pain on day 14 was significantly greater in group 1 than in groups 2 and 3, and on day 28 was significantly greater in both groups 1 and 2 compared to groups 3 and 4. However, there were no significant differences in presence of lesions between treatment groups (assessed at days 7, 14 and 28 after treatment). The study was weakened by a loss of 17% of the cows by day 28. While cows were randomly allocated to groups, there were considerable (but non-significant) differences in median 'days in milk' with group A

and D differing by 124 days. The percentages of cows with lesions at day 28 were 80%, 74%, 67%, 44% for the four treatment groups respectively.

In a quasi-randomised controlled trial describe earlier, (15) treated digital dermatitis with either 5ml glutaraldehyde formula (1:50 dilution) or 5ml oxytetracycline solution (100mg/ml). There was no significant difference between treatment with glutaraldehyde or foot trimming alone for cure of DD.

Stevancevic *et al*(2009) (25) compared several commonly used disinfectants with chlortetracycline positive control and a negative control. Cows were allocated to one of four treatment groups with a topical antiseptic solution, or a negative or positive control group. Treatment groups were: (1) 8% copper sulphate solution; (2) 8% zinc sulphate solution; (3) 8% formalin solution; and (4) 3% peracetic acid solution. Prior to treatment debris was removed from the lesions using a cotton swab and sterile saline solution. After application of the antiseptic solution the affected area was covered with a Vaseline ointment. Treatments were repeated once a day for the first 7 days, and then once every 2 days up to day 30. The negative control consisted of cleansing the lesion with saline and covering with Vaseline, and the positive control treatment with chlortetracycline spray once per day for 1 week. At day 15 after start of treatment there was a significant difference in lesion score between treatment groups. Cows in the positive control group had significantly lower mean lesion scores compared to cows in all four treatment groups, while cows in the negative control group had significantly higher mean lesion scores compared to positive controls and all four treatment groups. Cows treated with zinc sulphate had significantly lower mean lesion scores than cows in the other three treatment groups. By day 30 there were significant improvements in mean lesion score across all four treatment groups. Mean lesion score for cows in the negative control group was significantly higher than for cows in the four treatment groups and the positive control group. Mean lesion score for cows in the positive control group was significantly lower than for animals treated with copper sulphate, formalin and peracetic acid. Mean lesion score for cows treated with zinc sulphate was significantly lower than for cows in the other 3 treatment groups. Cows treated with copper sulphate had a significantly lower mean lesion score compared to cows treated with peracetic acid. The results of this study would indicate the commonly used disinfectants may aid healing but are less efficacious than chlortetracycline antibiotic. Cure rates for the various treatments were not given.

The reports on non-antibiotic antibacterial agents would appear varied with some working as well as antibiotics (8), some reported as better (22) and others as worse but better than the negative control (16, 25) and finally one no different to the negative control (15). It should be emphasized that in the UK only licensed treatments can make

claims with respect to lesion treatment making clinical research trials into non-antibiotic treatments of questionable value to commercial organizations.

Best clinical practice for topical treatments

No studies have been reported that investigate features of best clinical practice. A number of practices, however, are incorporated into various studies. These include: conducting a functional and corrective foot trim; washing clean lesions; drying lesions; applying two layers of treatment; using a clean standing area for 30 minutes. Table 3 summarizes the practices reported and the clinical outcome.

Some researchers have speculated that immunosuppression in early lactation contributes to disease onset and progression; poor immunity is one explanation for higher morbidity rates in heifers. Interestingly, (18) found lesion duration following treatment was higher in early lactation animals but there was no difference in primiparous heifers compared with multiparous cows. However, (16) found cows that were 3rd lactation or more were more likely to respond well to treatment.

Hernandez and Shearer (2000) (7) investigated the effectiveness of treatments on DD lesions at various anatomical sites. Seventy cows with DD lesions on the inter-digital cleft, heels or dewclaw were recruited from a single herd. Feet were washed and topical oxytetracycline spray applied (25mg/ml) daily for 5 consecutive days, left for 2 days, followed by 3 further treatments (on alternate days). On days 14 and 30 pain scores were found to be significantly higher for cows with lesions on the inter-digital cleft, compared with those with lesions on the dewclaw. On day 30 lesion size scores were significantly higher for cows with lesions on the heel or cleft than on the dewclaw. On day 30 the proportion of cows with a lesion was significantly higher among cows with lesions on the cleft compared with cows with lesions on the dewclaw. The study was weakened by 21 cows of a total of 70 not completing the study (although the proportions did not differ significantly between the location of lesion groups) and it was not then clear how the analysis has dealt with this. Efficacy of treatment (differences between day 0 and 14 and 30) was not examined. This experiment highlights the difficulty of treating inter-digital cleft lesions with topical sprays.

Table 3 Features of topical treatment protocols (antibiotic and non-antibiotics)

Study	Antibacterial agent(s) in trial	Washed clean	Number of applications	Other feature of treatment protocol	Outcome
85	Oxytetracycline powder with formalin		Bandaged 3-5 days		'Highly effective'
18	Oxytetracycline solution (100mg/ml)	Rinsed	Bandaged for up to 29 days		Cure in 13.8% primiparous heifers and 38.7% in multiparous cows
17	Salicylic acid and Chlortetracycline	Washed	salicylic acid and bandaged for four days; Chlortetracycline applied daily for 5 days		Median duration of lesion 42 days
15	Oxytetracycline (100mg/ml)	Heels cleaned	Light bandage and repeated after 5 days	Foot trim	At 32 days after treatment 87% of lesions were cured compared with 34% in the control group (trim alone)
3	10g oxytetracycline or 10g lincomycin	Washed feet	Bandaged for four days		73% healed at day 14 and 68% of lesions healed at day 30
11	lincomycin solution (0.6mg/ml) or valnemulin (100mg/ml)		Two doses of 25ml of solution applied to lesion at a 48 hour interval		cure rates 6/15 (lincomycin) and 5/18 (valnemulin). No monitoring beyond day 14

16	lincomycin (10g with 3ml water) or 20ml soluble copper with peroxide and a cationic agent	Cleaned	Bandaged for 5 days		Lincomycin 64.5% healed, Non-antibiotic cream 45.5.% healed, control 21.9% healed by day 29
8	Protexin Hoof-Care or oxytetracycline	Cleaned and dried (cited Dopfer, 1994; Metzner et al., 1995; Kofler, 1997)	Topical application twice in 30 seconds and then repeated as needed on day 4 and 10 according to pain	30 minutes standing on dry standing after treatment	Some of the results pooled - 92% healed by 28 days
22	Oxytetracycline; Victory or modified formulations of Victory	Cleaned	Once per day for 5 consecutive days, not treated for 2 days, then treated once per day for an additional three days		Percentage of cows with lesions at day 28 were 80%, 74%, 67%, 44%
25	(1) 8% copper sulphate solution; (2) 8% zinc sulphate solution; (3) 8% formalin solution; and (4) 3% peracetic acid solution	Cleaned with cotton swab and sterile saline solution	Treatments were repeated once a day for the first 7 days, and then once every 2 days up to day 30	Covered with vaseline	Cure rates not reported but according to lesion score all treatment were better than the negative control; positive control was best, followed by zinc then copper.
7	Oxytetracycline spray applied (25mg/ml)	Washed	Daily for 5 consecutive days, left for 2 days, followed by 3 further treatments (on alternate days).		Dew claw lesions was most responsive; inter-digital cleft lesion least responsive

Only two reports (23, 460) describe surgical debridement as part of the treatment protocol. (23) used debridement on all cows undergoing a randomized controlled trial and this study is described later. In the surgical case series by (460), early ulcerative cases of DD are treated by deep scraping of the lesion and topical application of 20% oxytetracycline solution or benzathine penicillin powder and a bandage for one week, a reduction of lameness was seen within the first 6-12 hours, with complete therapeutic resolution within 5-7 days in all 30 animals. Treatment of chronic cases was again by excision of the lesion and topical application of oxytetracycline solution or benzathine powder with a fresh bandage applied every week, and this resulted in complete resolution after an average of three weeks. Recurrence of lesions (early and chronic) had occurred in approximately 10% of the 50 animals at 10-15 weeks after initial resolution. Treatment also involved removing the wet dirty muddy underfoot conditions of the cows (paper not clear as to how this was achieved). The report lacked details on who was responsible for scoring of lesions, which may have affected the reliability of measures. No statistical tests performed on the data. None-the-less, debridement may be an important aspect of treatment required for lesion resolution.

In some instance surgery may be indicated. Rodrigues *et al*(2010) (21) reported on cases of DD affecting the accessory digit. Fifteen holsteins (male and female) with DD of the accessory digits were treated by amputation of the digits. After suturing of the wounds oxytetracycline powder was applied topically and bandaged. Animals were given a single injection of oxytetracycline IM (20mg/kg). In the year following treatment no recurrence of the lesions was observed.

One of the key features associated with successful treatment appears to be the use of antibiotic and the prolonged exposure to treatment, either through repeated applications of treatment until resolution or through well managed bandages. None-the-less, the findings of Berry *et al*(2010) (3) illustrate that even when there is apparent resolution of lesions, histological appearances are contradictory. In some instances, recrudescence may be a problem that is not being reported.

None of the studies described the use of systemic anti-inflammatory drugs, and only one used intravenous regional anaesthesia during debridement (23) and one described the use of salicylic acid topically. This may be a topic warranting further investigation.

INJECTABLE ANTIBIOTIC TREATMENTS

There were only three papers that reported the outcome of treatment involving injectable antibiotics, although there have been several publications prior to the review

period. Currently, only cefquinome is licensed for the treatment of digital dermatitis in cattle by the parenteral route.

In a short communication by Laven (2006) (10) the efficacy of cefquinome and erythromycin were compared. Pregnant heifers or cows within 2 weeks of drying off were recruited from a single farm. The animals recruited had digital dermatitis but had not received treatment in the 14 days prior to the study and had no other infectious foot disease. They were randomly allocated to one of four treatments: (1) foot bath with 35g erythromycin/100 litres on 2 occasions 24 hrs apart (feet prewashed); (2) 1 mg/kg cefquinome IM for 3 days; (3) 1 mg/kg cefquinome for 5 days; (4) 10mg/kg erythromycin IM single dose. With all four treatments there was a reduction in lesion score over the 42 days (from day 4 onwards), although significance of this was not tested. Significant differences between treatments were observed at days 21 and 42. At day 21 cows treated with cefquinome 5 day had significantly lower lesion scores than those treated with cefquinome 3 day or erythromycin IM. Cows foot bathed in erythromycin also had lower lesion scores than cow treated with erythromycin IM or cefquinome 3 day. At day 42 cows treated with cefquinome 5 day had significantly lower lesion scores than cows on all of the other three treatments. This paper gives a strong indication that injectable antibiotics may be more efficacious than topical antibiotic foot baths in the treatment of digital dermatitis when given as a five day course.

In a Brazilian study, Silva *et al*(2005) (23) examined various combinations of treatment, including debridement, parenteral antibiotics and foot bathing. All hooves could be cleaned and trimmed, and lesions debrided. Intravenous regional anaesthesia was induced using 2% lidocaine hydrochloride so all necrotic tissue could be removed, as well as any granulomas or compromised tissues. Groups of animals with initial and advanced DD lesions were then randomly allocated to one of four treatment groups: (1) foot bathed with 1% sodium hypochlorite twice/day for 30 days with 4 doses of IV oxytetracycline (10mg/kg) at intervals of 48 hours; (2) foot bathed with 1% sodium hypochlorite twice/day for 30 days; (3) 4 doses of IV oxytetracycline (10mg/kg) at intervals of 48 hours; and (4) treated with 'Miosthal' (dicloro divynil pirrolidona, ortoiododimetil, para-nitofenilfosforotioato in a tar-based ointment) immediately after debridement. Cows that were foot bathed passed through a bath containing water first. There was a significant difference between treatment groups at day 45 in the proportion of animals judged to have recovered. In order of the greatest proportion of animals recovered, the groups were: 1, 2, 3, 4. Results were not presented separately for initial and advanced lesions so it is not possible to tell if one treatment option was sufficient for milder lesions. Furthermore, there was very little information on lesion classification (extent or severity of lesions). At day 45 lesions were judged to be recovered or not

recovered. None-the-less, this study highlighted the potential importance of parenteral antibiotics, full courses of antibiotics and foot hygiene following treatment.

In a pharmacokinetic study of two treatment routes, Rodrigues *et al*(2010) (20) compared systemic administration of oxytetracycline via the jugular with regional intravenous antibiotics (IVRA) injected into the medial or lateral digital veins with a tourniquet applied for 45 minutes. Twelve Holstein cows with papillomatous DD were randomly assigned to one of 2 groups: (1) single injection of tetracycline hydrochloride (10mg/kg) via jugular; and (2) 1000mg tetracycline hydrochloride via IVRA. With the exception of one animal, there were no changes in lameness score or lesion severity in the 7 days after treatment. Concentrations of tetracycline in milk, plasma and synovial fluid were monitored over the first 5 days after treatment. Between 22 minutes and 48 hours plasma concentrations were significantly higher in group 1, and between 22 minutes and 24 hours synovial fluid concentrations were significantly lower in group 1 compared to group 2. With the exception of one time point, milk concentrations were significantly higher in group 1 between 22 minutes and 120 hours compared to group 2. Apart from lameness score, no lesion score data or cure rate was reported. None-the-less, this study illustrated the high local concentrations achievable with IVRA without increasing residues in the milk.

FOOT BATHING CHEMICAL AGENTS AND REGIME

There were six papers reporting on the results of foot bathing interventions (27, 12, 13, 26, 24, 15, 30). Currently there are no licensed products for the treatment of DD using foot baths in the UK.

Laven and Proven (2000) (13) reported the use of erythromycin in foot baths. One hundred and eleven cows with DD on six farms were enrolled. Cows with DD were identified by stockpersons and a diagnosis confirmed by a vet at examination prior to enrolment. Cows were then randomly assigned to a treatment and a control (the control group had a four day delay before the treatment foot bath initiated). Cows were run through a foot bath containing erythromycin (350mg/100litre) at two consecutive milkings. No pre-washing of feet was performed. Comparison of control (untreated) and treated cows at day 4 revealed significant differences in pain score and clinical appearance of lesion. A further evaluation took place on day 11 (seven days after the start of treatment for the control group) when the treatment with erythromycin resulted in a significant improvement in clinical appearance of lesion, pain scores and lameness for both groups indicating the benefit was sustained.

Antibiotics used in foot baths are unlicensed treatments, and as such, require a seven day milk withdrawal and 28 day meat withdrawal period. Plausible concerns relate

to the risk of absorption of antibiotic through the lesion, antibiotic transference from the feet onto the teats and udder and then the milk; and possible oral ingestion after licking feet. Harthog *et al*(2001) (27) published one of the first pharmacokinetic reports on the use of antibiotics in foot baths for the treatment of DD. Four cows with digital dermatitis had their feet washed before being made to stand for two minutes with all 4 feet immersed in a foot bath filled to 130mm solution containing erythromycin (690mg/litre of water). This was conducted once per day for three days, with the foot bath being topped up to 130mm with 920mg/litre erythromycin. The researchers failed to detect erythromycin in milk samples taken over five days (including the three days on which animals were treated), and only one of 40 plasma samples was found to contain erythromycin across the three treatment days.

When Laven and Hunt (2002) (12) compared erythromycin treatment with other non-antibiotic antibacterial agents these were found to perform favourably. Cows with DD but no other foot lesions at time of examination were enrolled from one farm with cows managed in 4 houses. The feet were washed before cows walked through foot bath one of four treatments randomly allocated to each housing group: (1) erythrocin (210g/100 litres) daily for 2 days; (2) formalin (6 litres/100 litres) daily for 7 days; (3) copper sulphate (2kg/100 litres) daily for 7 days; (4) peracetic acid (1kg/100 litres) daily for 7 days. Cows were made to stand for at least 20 seconds in a bath that was filled to 130mm. The researchers found that there was a significant reduction in lesion score over time for all four treatment groups, with mean lesion scores on days 7 and 21 being lower than on day 0 for all groups. Rate of decrease in lesion score was not significantly different for the 4 treatments, nor was proportion of cows with unhealed lesions at any time point. While not significantly different, lesions scores for 1% peracetic acid were least improved. However, on day 21, almost 50% of cows going through erythromycin and peracetic acid still had lesions while approximately 25% of cows in the copper group had lesions and 35% of cows in the formalin group had lesions. None of these differences were significant suggesting the study may have lacked statistical power. The study was weakened by the unbalanced groups and some missing scores.

On the basis of the previous study and others, some foot bathing studies have used formalin or copper sulphate as a positive control. Teixeira *et al*(2010) (38) compared a commercial disinfectant with 5% formalin and then 10% copper sulphate in one such trial. Cows 406 cows were randomly allocated to a group foot bathed with formalin (5%) or 'Dragonhyde' (a commercially available disinfectant agent) (5%). In a second trial, a new group of 356 cows were randomly allocated to foot baths with copper sulphate (10%) or dragonhyde (5%). In both trials, feet were washed prior to bathing and cows were run through the foot bath twice weekly for 4 weeks. In the first trial there were no differences in the odds of new and cured DD between the two treatment

groups. The prevalence of DD was higher in the formalin treated group than in the Dragonhyde group. In the second trial there were no differences in the odds of new and cured DD between the two treatment groups.

Anecdotally, circulation wash water ('parlour washings'), usually containing hypochlorite have proved popular for foot bathing dairy cattle. In a study described earlier, Silva *et al*(2005) (23) used 1% sodium hypochlorite foot baths twice per day for 30 days following surgical treatment of digital dermatitis in parallel or combination with other treatments and found a positive effective. Groups of animals with initial and advanced DD lesions were randomly allocated to one of 4 treatment groups: (1) foot bathed with 1% sodium hypochlorite twice/day for 30 days with 4 doses of IV oxytetracycline (10mg/kg) at intervals of 48 hours; (2) foot bathed with 1% sodium hypochlorite twice/day for 30 days; (3) 4 doses of IV oxytetracycline (10mg/kg) at intervals of 48 hours; and (4) treated with 'Miosthal' (dicloro divynil pirrolidona, ortoiododimetil, para-nitofenilfosforotioato in a tar-based ointment) immediately after debridement. Cows that were foot bathed passed through a bath containing water first. In order of the greatest proportion of animals recovered, the groups were: 1, 2, 3, and 4. The limitations of this study were described earlier, but the results indicate the potential benefit of passing cows through disinfectant as part of aftercare of cows undergoing treatment.

Following on from this, Speijers *et al*(2010) (24) conducted a series of three randomized controlled trials over 5, 8 and 10 weeks. In experiment 1, cows were allocated to one of 3 treatment groups for 5 weeks: (1) foot bath with 5% copper sulphate; (2) foot bath with 2% sodium hypochlorite; or (3) no foot bath (control). Foot bathed animals passed through water before the treatment bath, and were foot bathed at four consecutive milkings per week. At the end of the study there was a significantly greater proportions of animals with no lesions, and with healing and chronic lesions, and significantly smaller proportions of animals with ulcerative and early stage lesions in group 1 compared to groups 2 and 3. In group 2 there was a significantly smaller proportion of animals with early stage lesions compared to group 3. This finding challenges the previous study which suggested that DD lesions recovery was improved when cows were foot bathed with 1% hypochlorite solution (albeit in addition to a systemic antibiotic treatment) (Silva *et al*2005) (23). It should be noted that in this study cows were foot bathed less intensively. However, more importantly in the Silva *et al*(2005) (23) paper, there was a systemic treatment.

In experiment 2, Speijers *et al*(2010) (24) compared foot bathing at 2% and 5% copper sulphate concentration, and weekly vs. every other week regimes, this time over 8 weeks. Consequently, animals were allocated to one of 4 foot bath treatment groups for 8 weeks: (1) 5% copper sulphate at 4 consecutive milkings per week; (2) 2% copper

sulphate at 4 consecutive milkings per week; (3) 5% copper sulphate at 4 consecutive milkings every 2 weeks; and (4) 2% copper sulphate at 4 consecutive milkings every 2 weeks. At the end of the study a significantly greater proportion of the cows foot bathed weekly with 5% copper sulphate had no lesions compared to the group treated weekly with 2% solution. Of the cows treated fortnightly, there was a significantly greater proportion of cows with no lesions, and significantly smaller proportions of cows with early stage, healing and chronic lesions amongst the group treated with 5% solution compared to 2% solution. By the end of the trial there was no difference between the weekly and fortnightly intervals although the authors commented on the more pronounced sawtooth pattern seen on a plot of active lesions over time in the fortnightly group. On the basis of these results they recommended the use of weekly 5% copper sulphate on 4 consecutive days in situations of high DD prevalence would be more effective than 2%.

In experiment 3, Speijers *et al*(2010) (24) compared regimes aimed at reducing copper sulphate usage but maintaining passes through a foot bathing. They allocated cows to one of three treatments for 10 weeks: (1) cows were foot bathed at 4 consecutive milkings per week, alternating between 5% copper sulphate and 10% salt water on alternate weeks; (2) cows were foot bathed at 4 consecutive milkings per week, alternating between 5% copper sulphate and tap water on alternate weeks; and (3) cows were foot bathed at 4 consecutive milkings every 2 weeks with 5% copper sulphate. At the end of the study a significantly greater proportion of the cows in the salt water treatment group had no lesions compared to animals in group 3. Significantly greater proportions of the animals in groups 1 and 3 had ulcerative lesions compared to group 2. From this study it was possible to conclude the use of tap water on alternate weeks as a substitute for 5% copper sulphate has some merit for controlling digital dermatitis and reducing copper sulphate usage. However, a significantly greater proportion of the animals in group 1 had healing lesions compared to both groups 2 and 3 indicating this concept may need further investigation. On the basis of these findings the authors concluded that there is no advantage to using salt water on the intervening week when a fortnightly 5% copper sulphate regime is being used.

Another strategy for reducing copper sulphate usage is the use of acidified solutions to improve ionisation of copper at low concentrations. Manske *et al*(2002) (15) followed 44 cows with 64 lesions from a single herd over 6 months in a controlled trial (no randomization). Over the course of a summer, these cows were foot bathed with acidified ionised copper (0.6%) (right feet) or water (left feet) in 5 periods of foot bathing totaling 47 days (3 to 16 days in duration at intervals of 4 to 14 days). Cows passed through foot bath twice daily and the solution was replaced when visually contaminated and within 3 days (300 cow passages). Dimension, depth and volume of

the foot bath was not reported. The proportion of cows cured was significantly greater for treated hindfeet (20/24) than untreated hindfeet (12/23). There was no significant difference in proportion of cures for forefeet between treatment and control groups (7/8 and 8/9 respectively). There was no significant difference between groups in number of new cases (although they did occur in 20 of 112 feet). It was stated that assessments of lesions was blind following treatment. The study was weakened with 25% of herd culled by 6 months. Prior to study, a foot treatment intervention had been conducted (reported in same paper) which may have confounded the results. Duration of individual periods of foot bathing in study 2 and length of time between varied due to practicalities making this study difficult to replicate and interpret.

Other studies have used 4% formalin as a positive control reference group. Holzhauser *et al*(2008) (30) allocated cows from a single herd to one of 5 treatment groups for 24 weeks: (1) reference group foot bathed twice per day, one day per week using 4% formalin and stood on clean concrete for 30 minutes after treatment; (2) foot bathed twice per day, one day per 2 weeks using 4% formalin and stood on clean concrete for 30 minutes after treatment; (3) stood for 20 minutes in a 2% multi-compound solution on days 7, 28 and 90, with feet washed beforehand; (4) foot bathed twice per day, one day per week using 2% multi compound solution; or (5) foot bathed twice per day one day per week using 3% sodium carbonate solution. Cows foot bathed in sodium carbonate had significantly lower odds of remaining free of DD compared to animals in the reference group and had significantly greater odds of experiencing a 'normal' infection (from no lesion, to an increasingly large and painful lesion, to a healing lesion, and finally to a healed lesion) compared to animals in the reference group. Animals in groups 2 and 4 both had significantly greater odds of a lesion with a persistent infectious stage compared to animals in the reference group.

Other antibacterial agents have been tested in a randomized controlled trial without apparent effectiveness compared to a within-cow control (26). Thomsen *et al*(2008) (26) evaluated glutaraldehyde and ammonium compounds; quarternary ammonium compounds; and hydrogen peroxide, acetic acid and peracetic acid. A split bath was used with one side empty to create a within cow control. There were no significant differences at the end of the study between the control and treated hind claws in the percentage of cures and new infections for any of the 3 products.

Best clinical practice for herd foot bathing treatments

A number of published studies have evaluated antibiotic and antibacterial chemicals in a number of regimes, but none have investigated how foot baths are managed. However, Table 4 summarises the foot bathing management practices adopted in the studies reviewed in the previous section.

Table 4 A summary of foot bathing approaches used in the evaluation of foot bathing agents

Study	Foot bathing agent	Foot cleaning	Frequency of bathing	Depth and length of bath	Other features	Outcome
13	Erythromycin (350mg/100litre)	No	Two consecutive milkings	130mm deep, 3m long	Topped up with approximately 47mg/litre	Difference between treatment and control at 4 days
27	Erythromycin 690mg/litre	'Washed'	Daily for three days	130mm deep, 3m long	Stood in solution for 30 seconds; topped up with 690mg/litre erythromycin	No antibiotic residues
12	(1) erythrocin (210g/100 litres); (2) formalin (6 litres/100 litres); (3) copper sulphate (2kg/100 litres); (4) peracetic acid (1kg/100 litres)	Hosed	(1) erythrocin daily for 2 days; (2) formalin daily for 7 days; (3) copper sulphate daily for 7 days; (4) peracetic acid daily for 7 days.	130mm deep, 3m long	Stood in solution for at least 20 seconds	On day 21, almost 50% of cows going through erythromycin and peracetic acid still had lesions while approximately 25% of cows in the copper group had lesions and 35% of cows in the formalin group had lesions.
23	1% sodium hypochlorite	Pre-wash water bath	Twice daily for 30 days	Not specified	Replaced every 120 cows or 3 days (whichever first)	Treatment groups involving hypochlorite gave superior results to no foot bath
24	5% copper sulphate;	Pre-rinse	Four consecutive	16.5cm deep,	Solutions changed after	Various cure rates according

	2% copper sulphate; 2% hypochlorite	bath	days, tested either every week or fortnightly	207cm long	200 cow passages	to regime and duration
15	Acidified ionised copper (0.6%)	Not specified	Twice daily, in bouts 3 to 16 days in duration at intervals of 4 to 14 days	No details given apart from maximum of 300 cow passes		20/24 cured compared with 12/23 in the control limbs
30	4% formalin; 2% multi compound solution; and 3% sodium carbonate solution	Yes- for multi- compound treatment only	Various regimes including foot bathed twice per day, one day per week or fortnightly tested	300cm long and 12 cm deep; for standing, 400cmx 300cm	Stood on clean concrete for 30 minutes after treatment; or stood in treatment for 20 minutes	Various
26	(1) Virocid (main active compounds: glutaraldehyde and ammonium compounds); (2) Hoofcare DA (quarternary ammonium compunds); and (3)	No	Twice per day for 2 days per week	230cm long, 20cm deep	Split foot bath; replenished after 100 cows passages	Treatments no better than controls

	Kickstart 2 (hydrogen peroxide, acetic acid and peracetic acid).					
38	5% formalin; 10% copper sulphate; or 'Dragonhyde' commercial disinfectant	Pre-wash	Twice weekly for four weeks	Axes of dimensions unclear: 1m x1.5m x0.10m (150 litres)	(Abandoned split foot bath due to injury of cows and cross- contamination)	No difference in outcome – formalin 17% cured, Dragonhyde 31%; study 2 - copper sulphate 24%, Dragonhyde 18% cured.

Common features that appear to influence the effectiveness of treatments include: hosing feet clean (12, 27) or using a pre-rinse bath (23, 24, 30, 38); concentration of agent, with increased concentration improving outcome (24); and frequency of bathing (24). It is unclear from the above studies, what are the optimal foot bath dimensions and the optimal depth to fill the foot bath.

A number of factors that have been reported to influence topical treatments could feasibly influence the effectiveness of foot bathing. For instance (30) found animals in parities 1 and 2 had significantly lower odds of remaining free of DD compared to animals in parities 3 and above in one foot bathing trial.

VACCINES

In the UK there are no licensed vaccines for digital dermatitis. There was one paper describing a trial for a potential vaccine (5). Animals from 2 dairy herds with and without DD lesions were enrolled. Animals were inoculated with either a vaccine against DD or a placebo. Vaccinated animals had significantly higher serological titres (of antibodies against *Treponema spp*) at three time points after treatment compared to the placebo group. Despite this, there were no consistent significant prophylactic or therapeutic effects of the vaccine on DD. On one of the 2 herds the proportion of first lactation animals with DD lesions was lower amongst the vaccinated group compared to the placebo group at month 3 for animals without lesions and in month 6 for animals with lesions (diagnosed at the start of the study by one of 2 hoof trimmers or the author with high agreement between individuals). The exact criteria for diagnosing DD lesions were not given in paper.

Conclusions

Digital dermatitis treatment and control (with foot bathing) is probably one of the most thoroughly investigated topics relating to lameness in dairy cattle. None-the-less, there are still many questions about best practice. There have been several studies that have achieved high cure rates and good levels of improvement but many others have reported disappointing results.

Treatment of Sole Ulcers

There were just three peer reviewed papers published on treatment of sole ulcers in cattle identified by the review process revealing the limited evidence-base for the treatment of this lesion. Of these papers there was a report describing a series of cases given systemic antibiotics and a foot trim (90); the second consisted of a case-series from a Kenyan veterinary hospital; and the third evaluated the effect of biotin supplementation on lesion recovery (87).

Durmus *et al*(2005) (90) described a case series of 68 sole ulcers in Indian dairy cattle (male and female of 4 different breeds and a range of ages). Cattle with sole ulcers were treated with parenteral broad spectrum antibiotics for 7 days before draining of the affected part of the hoof and trimming of deformed hooves. A wet antiseptic dressing was also applied. This study was unclear in its aims, following only one treatment used (no control either positive or negative included) over an undetermined period of time. Observations made between treatment and the 4-5 month evaluation, if made, were not reported. No statistical tests performed on the data and there is insufficient methodology to ascertain the validity or repeatability of this study. Therefore the results need interpreting with caution and do not extend beyond stating that most of the sole ulcers had recovered at 4-5 months after treatment.

In another case series based on medical records of cases admitted to a large animal hospital in Nairobi over a 25 year period reported by Nguhiu-Mwangi *et al*(2008) (88). The records showed that overall after treatment, 90% of all foot lesions were healed while the remaining 10% failed to heal. For individual claw disorders the proportion of affected animals healed was: sole abscess (93%) and sole necrosis (86%). No definitions given for cases of individual claw disorders, and not known how many vets these cases were recording. Treatment involved washing and trimming the affected foot. The type of topical and systemic treatment depended on the nature of the foot condition. 'Exposed infection of the claw was treated topically by dipping in or washing the claws with either 10% copper sulphate solution applied every day (for 1 week) or every second day (for 2 weeks); or 5% formalin applied every second day (for about 10 days). The records indicated that routine systemic treatment for all foot infections consisted of trimethoprim-potentiated sulphonamides (either sulphadiazine or sulphadoxine) at a dosage of 150-200 mg/kg body weight once per day administered as a single injection or repeated for 3 days depending on the severity of the infection. The alternative treatment used was 10% oxytetracycline at a dosage of 7 mg/kg body weight once a day for 3-5 days depending on severity. Both drugs were administered either intravenously or intramuscularly.' For sole abscess pus was drained by trimming. 'In cases of severely

eroded and necrotized horn of the sole, curetting or debriding of the necrotic tissue and the eroded parts was done before topical application of 10% copper sulphate or 5% formalin solutions.

In a double-blind controlled trial with placebo (randomization not stated) Lischer *et al*(2002) (87) tested the efficacy of biotin supplementation on the rate of healing of 24 cows with mild, uncomplicated sole ulcers. Animals in treatment group were supplemented with 40mg biotin daily for 50 days. Additionally the feet of all cows (assumed) were trimmed following intravenous regional anaesthesia, before disinfection of exposed corium with chlorhexidine, had an orthopaedic block fitted and bandaging for minimum of 30 days (bandage changed at days 5, 10, 15 and 20). Locomotion score, horn quality and keratogenic period (time until the corium of the lesion was fully covered by a solid layer of horn that could not easily be separated from the corium) were assessed although the number of observers was not stated. There was no statistical significance between the treatment and control groups at the end of the study in terms of locomotion score or keratogenic period. However, there was an improvement in horn quality in the treatment group between the start and end of the study was statistically significant.

Treatment of White Line Disease

There were no papers that reported on the treatment of white line disease in the review period.

Treatment of Non-Specific Lameness

There was a single paper identified on non-specific lameness treatment (183). This study evaluated walking parameters of eight cows 2 days before and 2 days after foot trimming. There were significant increases in walking rate, step length, and stepping rate after trimming. There were significant changes in a number of limb angle measurements, back posture, and the range of vertical fluctuation in the back between observations before and after trimming. Some cows had minor sole lesions which were also treated at trimming (although cows were not visibly lame at this time), hence changes in walking parameters may have not necessarily be solely attributed to claw trimming. None-the-less, the study provides some support for the practice of foot trimming to improve cow locomotion.

Prevention of Digital Dermatitis

STANDING TIME ON CONCRETE

Cubicle design

In cubicle houses in the Netherlands Newton Rigg cubicles were associated with lower odds of DD than 'R' type cubicles (37). Cubicles measuring less than 220cm or more than 230cm in length were associated with reduced odds of DD compared with cubicles measuring between 220 and 230cm (37). Cubicles measuring more than 115cm in width were associated with reduced odds of DD compared with cubicles measuring between 110 and 115cm (37).

CLAW TRAUMA

Housing Type

There was evidence that cows out at pasture had a reduced prevalence or severity of DD lesions compared to animals housed in both cubicles (36, 66, 85) and straw yards (36). However, a number of studies have found no significant differences in the prevalence of DD according to whether cattle are housed or at pasture (49), and housed all year round or not (99). A survey of Dutch dairy herds, which were predominantly cubicle housed, demonstrated that in herds where cows had more than eight hours access to pasture/day there was in fact a higher risk of DD than in herds where the cows had no access to pasture (34). For animals out at pasture greater odds of DD were associated with tracks of less than 150m in length (compared to tracks measuring between 15 and 500m), and restricted grazing systems (compared to full grazing systems) (37).

A survey of cattle presented at auctions in Austria found no difference between animals from tie stall and cubicle housing systems in the prevalence of DD (49). However, a number of other studies have observed a greater prevalence of DD in cubicle housed herds than in herds with tie stall housing (59, 67, 128). Within cubicle housing no significant associations were detected between DD and bed type (concrete or mats vs. mattresses, sand or deep litter) (99). Amongst animals housed in straw yards or cubicles there was no association between the occurrence of DD and the amount of bedding used per cow/day ($\leq 0.4\text{kg/cow/day}$ or $> 0.4\text{kg/cow/day}$) (99). In tie stall herds where cows had year round provision for outside exercise there was a higher prevalence of DD than in herds where there was no provision for outside exercise (83).

Cubicle systems have also been compared to straw yard housing and out wintering pads. A survey of Danish Holsteins found no differences in the occurrence of DD between straw yard and cubicle housing (99). Overall, cows in cubicles had lower DD scores than cows on a covered out-wintering pad or an unsheltered out-wintering pad (self-feed) (42). At calving there was a higher proportion of cows with DD on the unsheltered out-wintering pad (self-feed) than on the covered out-wintering pad (42).

In a survey of Danish Holsteins there were no differences between housing systems with solid concrete or concrete slat floors on the occurrence of DD (99). However, in a sample of Dutch dairy herds cows on slatted floors had significantly less DD than cows on solid or grooved concrete floors (80). Cows on slatted floors have been found to have reduced odds of DD compared to cows in zero grazed herds, and greater odds than cows in straw yards (72). Cows housed with solid grooved concrete floors had greater odds of DD than cows on non-grooved floors (44). Comparisons of concrete flooring and rubber matting have produced conflicting results. Amongst cubicle housed crossbred cows of German Holstein and German Fleckvieh origin there was some evidence of a greater incidence of DD amongst cows housed with rubber matted passageways as opposed to concrete passageways (71). However, amongst cubicle housed Holsteins and Holstein-Friesians there were no significant effects of either concrete flooring or rubber matting on DD lesion scores (84, 179). Within tie stalls with rubber flooring Swedish Red and White cows had lower odds of DD on slatted floors than on solid floors (46).

Amongst Danish Holsteins housed in straw yards or cubicles there was no association between the occurrence of DD and the condition of the flooring (acceptable or worn down) (99). However, amongst Holstein-Friesians across a range of housing systems poor flooring condition was associated with a reduced incidence of DD compared to ideal flooring, although level concrete flooring was associated with a greater incidence of DD than a 'perfect non-slippery, clean, and level surface' (36).

DIETS AND FEEDING

Case studies have suggested that high levels of, and sudden increases in, dietary protein are associated with outbreaks of DD in cattle (32). In herds where 'by products' (e.g. from the food industry, and potentially protein-rich) were fed to cows there were increased odds of DD compared to herds where by products were not fed (37).

Where the length of time after calving to maximum dietary concentrate amount was less than two weeks there were increased odds of DD compared to where maximum levels were reached at between two to three weeks post calving (37). Holstein-Friesians

studied for the effect of genetic group and feeding system had greater odds of DD when fed a high concentrate diet than when fed a low concentrate diet (48).

Housed lactating Holstein-Friesian cows that had previously been fed a high energy ration had a greater risk of an active DD lesion than animals previously fed a low energy ration, or that had been grazed (40). Cubicle-housed Holstein-Friesian cows allocated to a low nutrition group (lower concentrate or herbage allowances depending on season) had higher DD scores than animals in a high nutrition group (62). There were no significant differences amongst tie-stall housed Swedish Red and White cows fed either a fermented grass silage based diet or a dry unfermented straw based diet until first calving in the prevalence of dermatitis (digital or interdigital) (155). There were no significant differences between cubicle housed Holstein-Friesian cows fed either a low starch, high fibre diet, with a zinc methionate and biotin premix, or a diet higher in starch, lower in fibre and with a placebo premix in the incidence or severity of DD (176).

There were no significant effects of supplementing cows with biotin at a rate of 20mg/day for eighteen months on the incidence of DD (56). When animals' diets had been supplemented with complex trace minerals in the previous year there was evidence of a reduced proportion of animals with PDD in the following year (61). There were no significant differences between cows supplemented with minerals in sulphate form and those supplemented with a proportion of minerals in sulphate form and a proportion as complex trace minerals on the occurrence of digital dermatitis (164).

ENVIRONMENTAL HYGIENE

Animals with an 'acceptable' level of dirtiness had lower odds of erosive and verrucose dermatitis than unacceptably dirty cows (59). Similarly, slurry or wet conditions underfoot represented a significant hazard for DD (73), and improvements in general housing hygiene were reported to be beneficial as a control measure against DD (85). However, in cubicle herds there was a higher prevalence of DD where scraping was more frequent than seven times/day (compared to herds where passageways were scraped less than three times/day) (83). In a survey of Danish Holsteins in loose housing systems there were no significant associations detected between DD and animal hygiene scores or the frequency of scraping of passageways (99).

DETECTION, PREVENTION AND TREATMENT

The inadequate detection and treatment of lameness within a herd represented a significant hazard for DD, yet, there was no significant difference between herds that did and did not participate in a lameness control program on the prevalence of DD (73).

Foot bathing

A large survey of cubicle housed Holstein-Frisians in Danish dairy herds demonstrated that the odds of an animal having DD were greater in herds where animals were foot bathed regularly (147). However, amongst cubicle housed Holstein cows in Greek dairy herds there were significantly greater odds of dermatitis being present in herds where cows were never foot bathed when compared to herds where foot bathing was carried out at least once/month (76). A number of different specific foot bathing regimes have been compared in clinical trials. A single case report also suggested that the use of an oxytetracycline foot bath (6g/litre) for ten minutes per day over three days was beneficial as a control measure against DD (85). A survey of cows in tie stalls herds demonstrated a higher prevalence of DD in herds where cows' feet were routinely sprayed in comparison to herds where they were not (83).

For animals foot bathed twice/day on two days/week for eight weeks, with either (1) Virocid (main active compounds: glutaraldehyde and ammonium compounds); (2) Hoofcare DA (quaternary ammonium compounds); or (3) Kickstart 2 (hydrogen peroxide, acetic acid and peracetic acid) there were no significant differences at the end of the study between control and treated hind claws in the percentage of cures effected by any of the three products (26).

Cows foot bathed twice/day once per week using a 2% multi compound solution had lower odds of remaining free of DD, but greater odds of experiencing a 'normal' infection (from no lesion, to an increasingly large and painful lesion, to a healing lesion, and finally to a healed lesion), compared to animals foot bathed twice/day once per week using 4% formalin and stood on clean concrete for 30 minutes after treatment (30). Both animals foot bathed twice/day once every two weeks using 4% formalin and stood on clean concrete for 30 minutes after treatment, and those foot bathed twice/day once per week using 2% multi compound solution, had greater odds of a lesion with a persistent infectious stage compared to animals foot bathed twice/day once per week using 4% formalin and stood on clean concrete for 30 minutes after treatment (30). Overall, animals had reduced odds of having a 'normal' infection during the treatment period compared to the pre intervention period (30).

There were no differences in the odds of either new DD infections or cures between cows foot bathed twice weekly for four weeks with 'Dragonhyde' (a commercially available disinfectant agent) (5%) or with either formalin (5%) or copper sulphate (10%) (38). In the comparison of Dragonhyde and copper sulphate there were

no differences in the prevalence of DD according to treatment group. In the comparison of Dragonhyde and formalin there was a higher prevalence of lesions amongst the animals foot bathed with formalin (38).

Preventative trimming

For Danish Holsteins housed in straw yards or cubicle housing there were no significant associations detected between DD and the number of times per year they had their feet trimmed (99 – survey). Other studies have indicated lower risks of DD associated with both more frequent (37 – survey, 55 - survey) and less frequent trimming (34 – survey). For cubicle housed Holsteins the prevalence of DD was lower in herds where trimming was carried out in the summer or autumn compared to herds where trimming was conducted in spring (83 – survey).

Cubicle housed cows in a single herd had their feet trimmed by one of two methods, either the standard Dutch method, or an alternative method where the soles were hollowed out (125 – cohort). Three months after trimming the presence of digital dermatitis was lower for cows housed on slatted concrete floors that had been trimmed according to the alternative method, but for cows housed on rubber slats the converse was true.

Vaccination

There were found to be no consistent significant prophylactic or therapeutic effects of a vaccine against DD, when compared to a placebo (5). However, at individual time points there was evidence of a lower proportion of DD lesions amongst the vaccinated animals. Vaccinated animals also had higher serological titres (of antibodies against *Treponema* spp) at a number of time points after treatment compared to the placebo group.

BIOSECURITY

Increases in PDD related problems have been observed following herd expansions (33). There was a trend for herds that introduced cattle from sources with unknown backgrounds and health statuses to experience the largest number of different diseases during expansion (which included PDD) (33).

OTHER RISK FACTORS

Parity

Generally, the odds of DD are observed to decrease with increasing parity number (37), with the prevalence or odds of DD found to be higher in multiparous animals than in

primiparous animals (38, 48). Animals in parities three and above had greater odds of remaining free of DD compared to animals in parities one and two (30); and a lower risk of DD than first parity cows (34, 59). In Brazilian dairy herds DD was mainly observed amongst young lactating animals (85).

Stage of lactation

After calving significant increases in DD lesion scores were seen, irrespective of whether the animals had lesions prior to, or at calving, or not (35). Although DD was seen in dry cows (85), these animals had lower odds of DD than cows within the first month of lactation (37). Month of lactation was negatively correlated with the prevalence of dermatitis amongst Norwegian Red cows in both tie stall and cubicle housing (55). Similarly, cows that had been calved at least six months had reduced odds of DD compared to cows in the first month after calving (44), and cows calved for more than four months had a reduced risk of an active DD lesion, or any DD, compared to cows between two and four months into lactation respectively (40, 147). However, Ettema *et al.* (2009) also found that the odds of an animal having DD were lower within the first two months of lactation than in month five and above of lactation (147).

Breed and genetics

Holstein -Friesian cows (pure and crossbred) had a higher risk of DD than Meuse Rhine Ijssel cows (34), and Swedish Holsteins had lower odds of dermatitis than Swedish Red and White cows (59). In an Irish dairy system, cows with a high economic breeding index (EBI) generally had lower odds of DD than cows with a lower EBI (48 – cohort). The heritability of DD was estimated at between 0.09 and 0.10 in animals with predominantly Holstein-Friesian genetics (69, 70).

BCS

In studies of the efficacy of different foot bathing agents against DD, the odds of a new DD lesion increased with both increasing and decreasing BCS, but the prevalence decreased with decreasing BCS (38).

Limb

There were significantly greater proportions of hind claws affected by digital dermatitis in comparison to front claws (65).

Milk production

Both positive phenotypic and genetic correlations have been observed between milk yield and the occurrence of DD (41, 45, 47, 68). There were also positive genetic correlations

between DD and SCC (47), and positive associations between the presence of DD and BMSCC (39). However, the presence of DD has also been negatively correlated with milk yield (36, 39), and negatively correlated with both the lifespan and the fat yield of the animal (36). In a large sample of Holstein cows the incidence of DD was associated with a decrease in test day milk yield, although affected cows produced more milk at the following test day than healthy animals (41). A number of studies have found no significant association between milk yield and DD (52, 75). There was also no association between the frequency of milking and animals' DD scores (62). Following treatment, animals with DD produced more milk than they did prior to treatment (43).

Fertility

An evaluation of records from first lactation Holstein-Friesian animals demonstrated an association between DD and greater conception rates and reduced calving intervals (36).

Other health disorders

There are positive associations between the presence of DD or dermatitis and other claw disorders including: interdigital dermatitis (34, 53, 81), interdigital phlegmon (34), interdigital hyperplasia (34, 60, 99), heel horn erosion (34, 40, 60, 67, 99), sole lesions (51) including sole haemorrhage (53, 60, 67, 99) and sole ulceration (60), double sole (60), and white line lesions (53, 60, 99). Moderate to large positive genetic correlations were reported between DD and interdigital dermatitis (0.56 to 0.75) (69), interdigital hyperplasia/heel horn erosion (0.46 to 0.65) (69, 70), sole ulceration (0.56) and wall disorders (0.34) (47). The presence of DD prior to calving (35) or during lactation (40, 125) also increased the likelihood of an animal having DD again later on in lactation.

The prevalence of DD in heifers was not significantly associated with any aspect of the herd health planning process (207).

Management of animal groups

Where calves were introduced into the milking cow accommodation at twelve months of age there were lower odds of DD than where the calves were not introduced at an early age (37). Where dry cows were introduced into the milking herd up to two weeks prior to calving there were increased odds of DD compared to herds where they were introduced after calving (37).

Herd effect

There is a significant effect of herd on the incidence of DD (47, 67). A number of studies have associated larger herd sizes with greater odds of DD, in spite of differences in the classification of herds into small and large herd sizes (34, 76, 147). However, in a survey

of Danish Holsteins in loose housing systems no significant association was found between the occurrence of DD and the size of the herd (99).

Season

A survey of cattle presented at auctions in Austria observed no difference in the prevalence of DD according to season (49). However, an examination of a sample of veterinary records in the UK found that there were fewer reports of DD for all months between June and October than in February (58). Also within the UK a lower prevalence of DD was observed in both spring and autumn than in winter (73).

Other variables associated with DD

DD scores change with time (84), with year of study observed to have an effect on the prevalence of DD (73). Another significant hazard for DD was suboptimal claw condition (73).

Prevention of Sole Ulcers & Sole Haemorrhage

STANDING TIME ON CONCRETE

Cubicle lying surface

A number of studies have compared bedding in cubicles and tie stalls, all have demonstrated reduced risk as the 'comfort' of the bedding surface increases. In a 27 farm, observational study, cows that were housed on sparse bedding for at least 4 months of the study had increased risk of sole ulceration compared to cows that were not housed on sparse bedding for this time (44). In cubicle herds where the bedding consisted of mats (with bedding) or sawdust or straw the odds of sole ulcer were significantly greater than in herds where mattresses (with bedding) was used (93). Norring et al (157) compared sand and straw bedded cubicles. The change in overall hoof health score was significantly greater for cows kept on sand over the duration of the study (the number of sole haemorrhage lesions was numerically but not significantly lower). Livesey et al (119) compared cubicles bedded with wood shavings or chopped straw. Bedding had no impact on sole haemorrhage 6 or 12 weeks after calving. In tie stall herds, animals kept on mats (compared to hard flooring) had a lower odds of developing sole ulcers (99) and had a lower odds of sole haemorrhage if the stall was bedded with a mat compared to hard floors (129). Finally, the use of lime in cubicles was associated with increased odds of SU (44).

Cubicle design

In a large observational study in Norway, the prevalence of haemorrhages of the sole and sole ulcers was significantly higher in cubicle-based herds than in tie stall herds (67, 128). Additionally, there were significantly fewer haemorrhages of the sole in stalls less than 2 years old than in older stalls (67). Using the same data set, the authors also demonstrated that there were significantly fewer haemorrhages of the sole when cubicle length increased above 200cm (104).

Cubicle Behaviour

Cubicle behaviour, particularly standing times are often quoted as a risk for sole lesions. However the number of published studies is relatively small. In one high quality observations study, the number of sole lesions did increase significantly with an increase in total standing time (245); there were no significant differences in the number of animals affected by sole lesions according to time spent feeding, standing still, or standing half in a cubicle. In the same study, the authors demonstrated that behaviour was affected by social rank, low ranking cows had significantly lower lying times, and

spent longer standing in the passageway and standing half in a cubicle, compared to animals of middle or high rank (245). Ouweltjes et al (121) compared unrestricted and restricted cubicle access (access prevented for 6 hours during the night) in heifer from calving. Restricted access to cubicles had little impact on sole haemorrhage, however animals in this group altered their daily schedule and stood for similar periods of time to animals with unrestricted access. Finally, compared to animals that did not develop lesions, cows that developed sole haemorrhages and sole ulcers in mid lactation had significantly greater standing times in the 2 weeks before calving and in the 24 hours after calving. In the 24 hours after calving they also had significantly less standing bouts, a lower frequency of standing bouts, and significantly longer duration of bouts. Perching time during the 2 weeks before calving was significantly higher for animals that developed lesions (96).

Loberg et al (155) compared the effect of four different levels of exercise on the claws of tie stalled cows. No significant effects were identified although the authors comments that the power of the study may not have been adequate for this purpose.

Housing Type (e.g. pasture vs cubicles vs straw yards)

Grass-based summer-grazed animals had significantly greater sole and total lesion scores than indoor-housed animals on both low and high concentrate diets (51). Conversely, pasture-based cows had significantly lower scores for sole haemorrhages than housed cows; lying bouts and total lying time were longer for pasture-based cows than housed cows (66). Somers et al (72) compared cows kept in different housing types in an observational study in Holland. Animals housed in straw yards had a significantly lower prevalence of sole haemorrhage compared to slatted and solid concrete floors at the end of winter housing. This was also true at the end of summer grazing, despite all animals spending the season at grass. At the end of a grazing season, animals managed at grass had a lower prevalence of sole ulceration compared to zero grazed animals (72).

Webster et al (107, 108), compared sole haemorrhage lesions in heifers housed in cubicles from 4 weeks prior to parturition through into lactation compared to animals housed in a straw yard until 8 weeks post calving. Animals housed in cubicles had significantly higher sole haemorrhage scores at all time points post calving. Using data from the same study, Knott et al (127) demonstrated that laxity in the support structures of the foot were significantly worse in those animals kept in cubicles.

O'Driscoll et al (124) compared cows in indoor cubicle systems to those on out-wintering pads (either covered or uncovered). Animals on uncovered pads had significantly higher sole lesion scores at 12 week post partum. The same authors went on to compare cubicles, unsheltered out-wintering pad, covered out-wintering pad and

unsheltered out-wintering pad with self-feed silage (42). In this study, treatment had no effect on sole lesion score.

Housing Walking Surface

A number of studies have compared the newer rubber flooring surfaces to concrete, results have been equivocal. Three papers have demonstrated no difference in the floor surfaces tested. There were no significant effects of floor (concrete or rubber mat) on sole haemorrhage scores or the proportion of cows affected by severe lesions (84) and results from a study in which rubber and concrete walkways were compared along with three cubicle types (mattress, concrete and sand) were equivocal (perhaps because animals were only followed for 15 weeks (81)). Vanegas et al (179) studies the impact of rubber and concrete flooring on hoof health, over the course of the study no differences were observed for sole haemorrhage or sole ulceration.

Two studies have demonstrated a beneficial effect of rubber flooring. Ouweltjes et al (121) compared concrete and rubber floors in heifers from calving. At week 9 and 14 weeks, animals housed on rubber had lower average sole haemorrhage scores and Ouweltjes et al (125) compared slatted concrete floors to slatted rubber floors. At both months 1 and 3 the prevalence of sole haemorrhages was significantly greater on the concrete floor than on the rubber floor.

Finally one study demonstrated that rubber flooring was worse than concrete in some respects. In the group with rubber matted passageways there was a greater incidence of sole ulcer at 150 and 305 DIM; a greater incidence of sole haemorrhages (distal to insertion of the DFT) at 150 DIM than in the group with concrete passageways. However, in the group with concrete passageways there was a greater incidence of sole haemorrhages (not distal to insertion of DFT) than in the rubber mat group (71).

CLAW TRAUMA

Size and management of groups

Capion et al (99), did not identify any significant associations between sole haemorrhage and sole ulceration and herd size.

Tracks and Roadways

The absence of cow tracks (i.e. direct access to the field from the yard) and the use of concrete tracks or roadways (compared to rough dirt or stone tracks) was associated with increased odds of sole ulceration in one observational study (44).

Claw wear

O'Driscoll et al identified that there was a low negative correlation between hoof hardness and sole lesion score (42).

DIETS AND FEEDING

Diet Formulation

Eleven clinical trials have investigated the impact of a number of aspects of diet, including its water, energy, forage and concentrate content, its physical structure, the nature of grazing and the content of fermented feeds. Webster (108) investigated the impact of wet and dry diets fed to in calf heifers housed in either cubicles or straw yards. Sole haemorrhage was scored every four weeks from 4 weeks before to 24 weeks after calving. Animals fed the wet diet in cubicles had the worst scores although the effect of diet alone was not significant i.e. housing had the most impact on outcome. Using a complex experimental design, Knott et al (127) fed maiden and in-calf heifers either a forage diet or a mixed diet designed to support production. Diet had no impact on either sole haemorrhage lesions or the integrity of the support structures of the foot (tested mechanically post mortem). Livesey et al (119) replaced starch carbohydrate with sugar beet pulp in the diet of dairy heifers in early lactation. The diet change had no impact on sole haemorrhage scores 6 or 12 weeks post calving. Olmos et al (48) compared high forage / low concentrate feeding system to a high concentrate system. Animals on the high concentrate system had a significantly higher odds of sole haemorrhage 35 days into lactation although the difference was absent at 230 days calved. O'Driscoll et al (620) fed cows on either a high or low concentrate diet; diet had no impact on the development of sole lesions. Offer et al (103) fed dairy heifers on either a low dry matter fermented diet based on silage or a high dry matter unfermented diet based on straw. Sole lesions were significantly worst both pre and post calving in the low dry matter group. Offer et al (175) fed dairy heifers on either a hay or a silage based diet from early pregnancy until calving. Animals fed on the silage based diet had significantly worse lesion scores (including haemorrhage and ulceration) post calving. Donovan et al (146) trialled four pre and post partum diets containing either high or low net energy (low-high, low-low, high-low and high-high). The worst hoof scores were seen in the low-high group. Cows were followed for 4 lactations and grazed during the summer according to one of 2 treatments, either grass/clover on which no artificial nitrogen fertiliser was used or conventionally managed pasture with addition of nitrogen fertiliser (concentrates and straights fed differed between groups to balance silage quality and manage production). There were no significant differences in claw lesion scores between treatments (177). De Campeneere et al (118) fed beef bulls four diets with different physical structural values. Whilst animals in different groups had significantly different claw lesion scores,

the authors did not link any of these to diet. Lastly a low starch high fibre diet supplemented with zinc and biotin had no impact on sole lesions compared to an unsupplemented high starch low fibre diet when fed to heifers (176). In a further survey, the presence of sole bruising was associated with regular concentrate feeding (2-4 times/day) (109)

Minerals

Three clinical trials studied the impact of amino acid supplements. Metal-specific amino acid complexes led to a reduction in sole haemorrhages and sole ulcers on 5 farms although the authors acknowledge that the results may be confounded by temporal differences (61). Nocek et al (133) investigated the effect of trace mineral fortification level and source (4 treatment groups) on sole haemorrhage and sole ulceration in dairy cows over a two year period. Treatment group led to significant differences in sole haemorrhage scores at one time point (start of second dry period) and had no impact on sole ulceration. Siciliano-Jones et al (164) investigated the impact of two mineral sources (sulphate form or partly amino acid complexes). The animals in the partly AA complexed mineral group had a significantly lower incidence of sole ulceration 36 weeks after calving. In a further survey, regular mineral supplementation (once/day) was protective against sole bruising (109).

A number of studies have investigated the impact of Biotin supplementation with varying effects. Supplementation led to significant reduction in sole haemorrhage compared to control animals in one herd (122), however Biotin had no impact on the incidence of sole ulceration on 5 farms (56) and no impact on hoof haemorrhage scores in either feedlot steers (153) or 14 cattle supplemented for 5 months (134)

Feeding Behaviour

Compared to animals that did not develop lesions, cows that developed sole haemorrhages and sole ulcers in mid lactation had significantly higher DMI in the 24 hours after calving and in the first week after calving; had significantly greater feeding rates in the 2 weeks before calving; ate more frequently in the 2 weeks before calving and in the 24 hrs after calving; and ate bigger meals in the week after calving (96).

BREEDING

A number of papers have investigated the heritability of foot disease. Sole ulcers had a heritability of 0.086 and were positively correlated with other foot disorders i.e. foot health problems were clustered (47). Van Der Linde et al (69), demonstrated that sole haemorrhage and sole ulcers had a heritability values of 0.06 and 0.12. Sole

haemorrhage was significantly associated with sole ulceration and white line disease. Sole ulceration was significantly associated with white line disease, feet and legs (a descriptive trait) and sole haemorrhage. Van Der Waaij et al (70) concluded that sole haemorrhage and sole ulcers had heritability values of 0.08 and 0.01 and again demonstrated predominantly positive associations between different foot lesions. Wassmuth et al (97) estimated the heritability of sole ulceration in Danish Red and Danish Friesian cattle was 0.01 and 0.001 respectively. In Danish Reds there were significant positive correlations between the incidence of sole ulcer and energy corrected milk yield in first parity cows.

In a longitudinal study investigating risk factors for disease, Capion et al (112) demonstrated that sole haemorrhage was significantly associated with cow-hockedness, toe-wall concavity and asymmetry of claws.

ENVIRONMENTAL HYGIENE

Cleanliness

In one study animals with an 'acceptable' level of dirtiness had lower odds of sole haemorrhages and sole ulcer than 'unacceptably' dirty cows (59) and in a second paper there was a significant positive correlation between sole ulceration / haemorrhage and cleanliness of the foot (dirtier feet were associated with disease) (46). However in two other papers hygiene score had no impact on claw disorders (76) or sole haemorrhage and sole ulceration (109).

Slurry

In one clinical trial, prolonged standing in slurry was a significant hazard for sole ulceration (73). However in two observational studies, there was a significantly greater prevalence of sole ulcers in herds where passageways were scraped 3 or more times/day, compared to herds where scraping was less than 3 times/day (83) and another found no significant associations between sole haemorrhage and sole ulcer and frequency of scraping (109).

DETECTION, PREVENTION AND TREATMENT

Foot Trimming

Foot Trimming Frequency

A number of studies have investigated the impact of foot trimming frequency on sole haemorrhage and sole ulceration. Studies have demonstrated that both increased (59,

83, 126) and decreased (55, 95) frequency of trimming are risks for sole haemorrhage and ulceration or that foot trimming has no impact on risk (99).

Smith et al (126) compared annual trimming at drying off to trimming every four months. Cows that had their feet trimmed every 4 months were significantly less likely to develop a sole ulcer. In other studies animals that were trimmed in the autumn and spring had lower odds of sole haemorrhages and sole ulcers, than cows trimmed in the spring only (59) and the prevalence of sole ulcers was significantly greater in tie stall herds where less than 50% of cows were trimmed compared to herds where 100% were trimmed (83). Conversely, in tie stalls, herds never trimmed had lower odds of sole ulcers compared to herds trimmed occasionally and in free-stalls, herd never trimmed had lower odds of haemorrhage of the sole compared to herds routinely trimmed (55). In another study, animals trimmed more than once during lactation had increased odds of having a sole ulcer diagnosed in both loose housing and tie stalls (95). However as the authors point out, the more frequently an animal is trimmed and examined the more likely it is a lesion will be identified.

Foot Trimming Timing

In comparison to herds which trimmed in late summer, herds that trimmed in late winter had significantly lower odds of sole ulcer (93).

Foot Trimming Method

Ouweltjes et al (125), compared an alternative trimming method (trimming for more concavity of the sole) to the standard Dutch method on slated concrete and rubber floors. Treatment had no effect on claw disorders, including sole ulcers.

Foot Bathing

Randhawa et al (86) compared trimming and foot bathing (4% formalin solution on the first, second and third day of every fortnight over 5 months) to trimming only. There was a significant reduction in the average number of sole haemorrhages/ulcers in the foot bathing group

Lesion Interaction

A number of studies have identified an interactions between different lesion types (51, 67, 93, 95, 99, 129). In tie stalls there were significant positive correlations sole haemorrhages and dermatitis, heel horn erosions, and white line haemorrhages; in cubicles there were significant positive correlations between sole haemorrhages and heel horn erosions, and white line haemorrhages (67). The odds of sole ulcer was significantly greater in animals that had sole haemorrhages, chronic laminitis, WLD, or interdigital

hyperplasia (93). In tie stalls, the odds of an animal having a sole ulcer during lactation were significantly greater for animals that were also diagnosed with haemorrhages, corkscrew claws or heel horn erosion; in loose-housed herds the odds of a sole ulcer were significantly increased in animals that were also diagnosed with haemorrhages (95). In tie stall herds, there were increased odds of haemorrhages for cows also diagnosed with heel horn erosion or corkscrew claws and in loose housed herds there were also significantly greater odds for animals also diagnosed with corkscrew claws during the lactation (129). In a further study there were significant positive correlations between many of the individual claw disorders including sole haemorrhage, sole ulcer, DD, WLD, and white line lesion (99). Finally, animals with DD had significantly greater sole lesion scores than animals without DD (51)

Prevention Programmes

Bell et al tested a herd level lameness control programme for dairy heifers. Whilst broadly the plan was ineffective, principally because of compliance failure, the significant hazard for sole ulcer was suboptimal claw conditions in early lactation (SOCC) and prolonged standing in slurry (if SOCC was excluded from the model).

OTHER RISK FACTORS

Breed

The Holstein breed appears predisposed to sole lesions compared to other breeds. Norwegian Reds had lower sole lesion scores than Holstein-Friesians (42); Swedish Holsteins had a higher odds of haemorrhages and sole ulcer than Swedish Red and Whites (59); Holsteins had a significantly greater risk of a sole ulcer (95) and odds of sole haemorrhage (129) compared to Ayrshires.

Age / Parity

The literature suggests a very clear and positive relationship between age / parity and the incidence of ulceration. The incidence of sole ulceration was positively correlated with increasing parity (43); cows in parity 4 or above had a greater odds of sole ulcers than first parity cows (44); the incidence of sole ulceration was significantly greater in animals in parity 3 and above compared to animals of parities 1 and 2 (47); the odds of having a sole disorder increased with increasing lactation number (52); animals in parities 4 and above had greater odds of sole ulcers and lameness than animals in parity 1(59); amongst beef cows there were significantly more 'laminitis' related lesions (incl. haemorrhages of the sole and sole ulcers) in older animals (aged 5 years and above) than in younger animals (2-4 years of age) (53); the odds of sole ulcer increased

significantly with increasing parity (93) and compared to young animals, animals in parity 4 and above had a significantly greater risk of a sole ulcer during lactation (95).

Interestingly, the relationship does not appear as straightforward when considering sole haemorrhage. Animals in parities 2-4 had lower odds of haemorrhages than primiparous animals, and animals in parities 5 and above had greater odds (59); there was a greater prevalence of sole haemorrhages in animals in parity 1 compared to animals in parities 3 and above (104); first parity animals had a greater odds of sole haemorrhage compared to older animals (129).

Lastly, two papers considered sole lesion scores combining both haemorrhage and ulceration; sole lesion scores were higher in lactation 4 than in earlier lactation (177) and mean and maximum sole lesions scores were described as significantly different between first and second lactation animals although the direction of the difference is not apparent from the presented data (176).

Yield

The interaction between yield and lesion incidence appears complex. Broadly speaking there is a weight of literature which suggests that high yield is a risk factor for the development of sole haemorrhage and ulceration. Higher milk yields in early lactation were associated with higher incidences of sole ulceration (47); the odds of having a sole disorder were positively correlated with milk yield (52); animals with sole haemorrhage were generally higher yielding than those without, over a whole lactation (68); 305d milk yield was significantly associated with the odds of a sole ulcer (95); in Danish Reds there were significant positive correlations between the incidence of sole ulcers and energy corrected milk yield in first parity cows (97); animals with sole haemorrhages had significantly greater milk production than other animals (122); animals diagnosed with a sole ulcer were higher yielding than those which remained free of the lesion (41) and 5 months before diagnosis, cows with a sole ulcer produced approximately 1.5Kg more milk per day than unaffected cows (43). However, once diagnosed animals with a sole ulcer give less milk than their unaffected counterparts; overall these animals produced 547Kg less milk per lactation, with the losses occurring in the months following treatment (43) and cows with sole ulcer on seven farms in Chile produced significantly less milk from 3 months before until 1 month after treatment compared with non lame animals (45).

Stage of Lactation

The literature suggests that the prevalence of both sole haemorrhage and sole ulcerations varies throughout lactation. Various studies have demonstrated that mean sole haemorrhage score was positively correlated with DIM (53); animals in peak or mid

lactation had greater odds of haemorrhages than animals in late lactation (59) and more sole haemorrhages were seen in animals that had been calved for 4-6 months than in other animals (104). Similarly, animals in early, peak or mid lactation had greater odds of a sole ulcer than animals in late lactation (59); the odds of sole ulceration were significantly reduced in early lactation (less than 60 DIM) and during the dry period compared to the period greater than 60 DIM (93); the mean day of diagnosis was 88 days calved (41) and in a US study, the hazard ratio for a sole ulcer was lowest at the end of lactation compared to the start (113). In studies in which haemorrhage and ulceration were assessed in combination, sole lesion scores reached a peak 16 – 20 weeks after calving (177) and the odds of a sole disorder were significantly lower in animals above 200 DIM, compared to animals below this point (52). Broadly speaking the literature suggests that both haemorrhage and ulceration are most common during peak and mid lactation and least common at the start and end of lactation although defining the exact period is difficult because of the various definitions of time period used in the different studies.

Herd

Unsurprisingly, studies have demonstrate that herd of origin has a significant effect on the incidence of both sole ulceration (47, 52) and haemorrhages of the sole (55), implying that the levels of disease vary between farms, almost certainly because of the different risks present on different units.

Month / Season

The season of examination has a significant effect on the odds of sole disorders (52). In one study, there were statistically fewer reports of sole ulceration in July and September than in February (58) and in another the hazard ratio for a sole ulcer was higher in the summer compared to other seasons (113). These studies are from different countries and from cows managed under different system, it is therefore difficult to attribute risk to a specific period but what can be said is that the risk of a sole lesions varies throughout the year.

Lameness History

Animals which were lame in their first lactation had a significantly greater hazard of claw disorders (including sole ulceration) in their second lactation compared to cows that were not previously lame (57). Animals that had no previous history of lameness were significantly less likely to develop a sole ulcer (126).

Milking frequency

In an experimental study comparing once and twice a day milking in cows fed on either a high or low herbage allowance, demonstrated that cows milked once/day had significantly lower sole lesion scores than cows milked twice/day (62)

Open vs Closed

In a cross sectional study, herds in which heifers were bought in had a significantly greater odds of sole ulceration than in herds where they were not (93).

Thin Soles

The hazard ratio for the presence of sole ulcers was significantly higher in those animals which had thin soles concurrently and those that had thin soles 31-60 days previously (113).

Other Disease

Moderate and severe sole haemorrhages were positively associated with milk fever, as were the presence of sole ulcers (when adjusted for peak milk yield and parity) (105).

Social Rank

There was a significant difference in the proportion of animals that were classed as low, middle or high ranking that developed sole haemorrhage and sole ulcers. Lesions were more common in both low and high ranking cows compared to mid ranking cows (96).

Management post calving

O'Connell et al investigated the effects of three strategies for introducing heifers to the milking herd: heifers added on their own 24 hours after calving, heifer added on their own 7 days after calving and heifers added as one of a pair 7 days after calving. Three months after calving, heifers added on their own, seven days after calving had significantly lower sole and heel lesion scores compared to the other groups (158).

Prevention of White Line Disease

Abbreviations:

CHD claw horn disruption

DD digital dermatitis

NRC National Research Council

WLD white line disease

WLL white line lesion

WLS white line separation

RCT randomised controlled trial

Introduction

White line disease covers a spectrum of lesions affecting the anatomical junction between the wall and sole horn of the claw. It includes white line haemorrhage, fissures or horn separation, abscessation and chronic infection of the laminar corium acquired through white line defects. While some studies have been conducted to understand the cause of lesions and the progression of disease (Leach *et al*/1997) (aetiology and pathogenesis) it remains one of the least well understood lesions affecting the bovine foot. Therefore, to understand the risk factors leading to disease we are still reliant on findings from a relatively small number of observational and intervention studies.

In the review of peer reviewed lameness literature published since 2000 there were no papers on treatment of white line lesions. However, there were 59 papers that reported on white line disease in cattle as an outcome in relations to putative risk factors. There were no systematic reviews specific to this lesion; there were 39 papers of experimental design, 22 papers that were cross-sectional observational studies and five that were longitudinal observational studies (Table 5).

Table 5 Numbers of papers reporting outcomes for white line disease in relation to putative/postulated causal mechanisms, classified according to whether they are observational (cross-sectional or longitudinal) or experimental in design.

<i>Risk factor topic</i>	<i>Number of observational cross-sectional studies</i>	<i>Number of longitudinal observational studies</i>	<i>Number of experimental reports</i>
Standing time on concrete	1 (73)		2 (62, 158)
Claw trauma	5 (44, 67, 104,		4 (81, 84, 155, 179)

	128, 129)		
Housing			
Straw yards	1 (72)		2 (102, 107)
Out-wintering pads			2 (42, 132)
Cubicle bedding	3 (83, 129)		2 (102, 157)
Access to grazing	2 (44, 83)		2 (51, 66)
Foot trimming	4 (52, 55, 67, 83)		1 (125)
Diets and feeding			
Biotin			4 (56, 130, 134, 153, 176)
Trace elements	1 (109)		4 (102, 133, 164, 176)
Forage: concentrate ratio			4 (48, 51, 119, 546)
Grass herbage quantity			2 (62, 177)
Dry matter			4 (103, 101, 108, 175)
Maiden heifer diets			3 (101, 103, 115)
Heifer breeding	5 (41, 47, 52, 69, 129)	4 (43, 45, 112, 210)	4 (42, 48, 51, 153)
Environmental hygiene			
Wet conditions	1 (58)		3 (46, 76, 103)
Other			
Season	4 (52, 58, 59, 73)	1 (113)	
Behaviour			
Parity/Age	9 (44, 47, 52, 54, 59, 68, 110, 129, 147)	1 (43)	4 (48, 56, 107, 177)
Stage of lactation	4 (44, 55, 104, 147)		3 (48, 102, 107)
Milk yield	3 (41, 47, 52)	2 (43,45)	
Herd size	1 (67)		
Other lesions	2 (57, 60)	2 (53, 113)	

STANDING TIME ON CONCRETE

There were three papers (one sample survey, two randomised controlled trials) that directly examined standing times in relation to white line disease incidence or prevalence. Investigations on the related subject of lying comfort are reviewed in a later section (housing, related management systems and lying comfort).

A cross-sectional risk factor survey involving 60 UK dairy farms modelled risks of deep white line lesions (presence or absence) in heifer cohorts using risk assessment data grouped according to critical control points (73). Prolonged standing, estimated from management practices and resource provision during lactation (including lying comfort), was the most significant factor explaining the variation in heifers examined between 60 and 120 days into lactation. However, in this study white line lesion prevalence was low and it was not possible to determine whether these lesions were pre-existing defects acquired before calving.

O'Driscoll *et al*(62) conducted a RCT over 12 months that compared claw lesions in cows milked once a day and cows milked twice a day. Cows milked once a day spent more time lying down and had significantly lower sole lesion scores and WLD scores than cows milked twice a day. However, as well as influencing standing times, reduced milking frequency also reduced the exposure of cattle to a range of other potential risk factors, including walking on cow tracks, flight behaviour, bully cow interactions, turns in and around the parlour and dietary disturbances associated with time away from feed.

In a study of transition management and social integration of heifers, O'Connell *et al*(2008) (158) tested one of three integration strategies: adding heifers after calving to an established group of animals individually within 24 hrs of calving; adding individually one week after calving after being housed singly on straw; or adding as one of pair one week after calving after being housed as a pair on straw. There were few significant differences between treatments in the behaviour of the heifers after being added to the established group although heifers added as part of a pair spent significantly more time standing during the first month than heifers added singly. Scores for sole/heel area lesions at three months were significantly greater for animals added as pairs and animals added singly one day after calving than for animals added singly after one week. At three months after calving heifers added as one of a pair had significantly greater total lesion scores and white line lesion scores than heifers added singly.

The evidence from these three papers suggests there may be a correlation between white line lesion prevalence and standing times, but further work is required to establish if this is directly causal and the stages of the disease process. For example, it is unclear whether prolonged standing time is important directly as a source of trauma and bruising, or whether there is an increased risk of a dynamic force or whether it is lack of

opportunity to recover that is important for the development of this lesion or a combination of one or more of these factors.

CLAW TRAUMA

Physical injury of the sole and white line from rough, stony tracks is a commonly reported cause of non-specific lameness in pasture-based systems in New Zealand (Chesterton *et al*/1989). In the review only five risk factor surveys has reported physical factors in the environment of the foot as important for white line disease (44, 104, 67, 128, 129). There have been three studies (81, 84, 179) that have examined reduction in traumatic forces using rubber matting interventions.

In a retrospective survey of 27 farmers in England and Wales, Barker *et al*(2009) (44) found the odds of WLD recorded as a cause of lameness increased with solid grooved concrete floors in comparison to non-grooved surfaces. Other features such as age of concrete were not ascertained, and again, without understanding the disease process we have to interpret this correlation with some caution.

In a Norwegian cross-sectional survey involving foot trimmer records from 57 dairy farms (104) a greater prevalence of white line *haemorrhages* were found in cows housed with solid concrete passageways compared to slatted floors. However, more white line *fissures* were found in the cows housed on slats. This finding highlights the importance of differentiating white line lesions and not assuming they all share the same inciting risk factors. This study would support the hypothesis that focal physical trauma due to uneven underfoot surfaces contributes to gross white line separation, whereas sole haemorrhage is associated with more generalised trauma on flat concrete.

The impact of cow movements and activity may be best evaluated by comparing cows managed on cubicle units with tie-stalls. Sogstad *et al*/2005 (67) reported the results of a cross-sectional survey of 55 tie-stall herds and 57 cubicle-housed dairy herds in Norway. There was a significantly higher prevalence of cows with white line haemorrhage (7.3% versus 13.6%) and fissures (5.5% versus 9.7%) in the hind feet of cubicle-based herds than in tie stall herds. A similar finding was reported by a US study (128) and Finnish study (129). Interestingly, in the Norwegian study there were significantly fewer haemorrhages of the white line and sole in cubicle facilities less than 2 years old than in older stalls.

Loberg *et al*(2004) (155) assessed the impact of various exercising regimes using cows in ties stalls using an outdoor exercise paddock consisting of grass on clay soil. The cows were assigned to one of 4 treatments for 6 months of winter housing: (1) exercise 1 hr/day 7 days/week; (2) exercise 1 hr/day 2 days/week; (3) exercise 1 hr/day 1

day/week; (4) no exercise. There were no significant effects of treatment on presence of claw lesions, although there was a tendency for the cows exercised every day to have better claw conformation, but more 'laminitis-related' lesions and digital dermatitis. This study indicated the protection afforded by tie stalls reported by the Norwegian study (67) may be related to physical injury rather than difference in blood circulation associated with exercise (or lack of) as suggested by some authorities.

Rubber yard matting

Numerous intervention studies have compared the effect of rubber floor surfaces with concrete with inconclusive results with respect to white line disease perhaps suggesting white line disease requires more than just physical trauma from concrete to develop.

In a RCT described by Vanegas *et al*(2006) (179) cows were randomly allocated to one of 2 cubicle pens (concrete passageways or passageways with rubber flooring) at between 10-30 DIM and monitored until 130 DIM. There were no significant effects of treatment on the odds of white line abscesses improving or becoming worse over the course of the study. However, it should be noted that findings from other interventions such as the studies into biotin (56) indicated that lameness due to white line disease may not manifest until months after exposure to risk. For example, Hedges *et al*(56) failed to detect benefit in the first 5 months of biotin supplementation. Therefore, monitoring until 140-160 days in milk may not be sufficient duration to detect a difference in lesion outcome. Sample size and power calculations were not performed.

Boyle *et al*(2007) (84) similarly found no significant effects of floor (concrete vs. rubber mat) on haemorrhage scores or the proportion of cows affected by severe claw lesions, although it was observed that cows stood on cubicle beds with rubber when it was not provided in the alleys indicating cows adapted to their environment to mitigate risk. None-the-less, reduced exposure to dynamic concussive forces as cows walked on concrete would be reduced in the rubber mat (intervention) group. Again, the study was conducted over just 4 months.

In a study examining yard and cubicle provision cows were allocated to treatments in a 3x2 factorial design for 105 days (Vokey *et al*2001)(81). Flooring in the passageways was either concrete or rubber, with cubicle beds of rubber mattress bedded with sawdust, concrete bedded with sawdust, or deep sand. During the study there were significant increases in claw lesion scores (representing WLD and sole haemorrhage/ulcer) for all animals housed with concrete passageways, and for animals with rubber passageways and mattress beds. Again, the short duration of this trial meant some of the protective benefit of rubber may have been missed.

Given the widely held belief that white line disease is caused by traumatic underfoot environment there is remarkably little in the recent published literature to

support this. For many of the studies involving rubber matting interventions, the duration of the trial was probably insufficient to detect improvements in lameness due to white line disease. Furthermore, foot hygiene and the level of moisture requires better monitoring to better understand the interaction of risk factors.

There were no studies specifically investigating the relationship between white line disease and cow bullying behaviour or social hierarchy, stocking rates, cow tracks or cow flow. However, (113) found increased age at first calving significantly decreased the hazard of WLD which could have been mediated by bullying.

Current advice is probably based on a single New Zealand case-control survey that did not have lesion specific findings, involved pasture based systems and New Zealand Friesians or Jerseys. Consequently these finding may or may not be generalisable to the UK.

Housing, related management systems and lying comfort

Several studies have evaluated the effect of various management *systems* on the prevalence of white line lesions. The strength of these studies is that they compare systems of relevance to farmers. However, the major limitation is that they combine potential risk factors, such as standing times, lying comfort, claw trauma and exposure to wet conditions, to degrees that are difficult to quantify, analyse separately or report separately. The relative importance of each risk factor therefore remains unquantified.

Straw yards

Somers *et al*2003 (72) in a cross-sectional survey of Dutch farms compared foot trimming records in herds in a variety of housing conditions after the summer grazing period and after the winter housing period. Housing with slats was the comparative reference group. After the grazing period the straw yard herds the cows had reduced odds white line abscesses, but greater odds of white line separation than in herds with slatted floors. In straw yard herds after the housing period the cows still had greater odds of white line separation than cows housed with slatted floors but not difference in white line abscesses.

Webster 2002 (107) compared white line haemorrhages in heifers housed in cubicles from four weeks prior to parturition until 24 weeks post-partum, with heifers in a straw yard from 4 weeks prior to parturition until 8 weeks post calving before being moved to a cubicle yard. Despite major differences for sole haemorrhage (and sole ulcers) there were no significant difference in mean white line lesion scores, although overall there was a significant effect of time over the course of the study. Although white line lesion score peaked eight weeks after calving, again, a longer duration of study may have been necessary to detect differences in white line lesions causing lameness.

In contrast, Laven and Livesay (2004) (102) did find a significant difference when heifers were managed on straw yards compared with cubicles. Heifers were monitored from 4 weeks prior to calving to 26 weeks after calving. Like most other studies, there was a significant effect of time after parturition on white line haemorrhage scores. Animals housed in straw yards had significantly lower mean white line haemorrhage scores compared to cows housed in cubicles with mats or mattresses. The peak white line haemorrhage score at 12 weeks was significantly higher on mats than in straw yards.

Both interventions described by Webster (2002) and Laven and Livesey (2004) monitored heifers in order to exclude pre-existing disease as recommended by Logue *et al*(1994). However, monitoring heifer cohorts has clear limitations due to the low prevalence of white line lesions causing lameness as reported in other studies (52, 73). Furthermore, the significance of lesions detected by lesion scoring in primiparous heifers to subsequent development of a lesion causing lameness has not been investigated. The increased prevalence of white line disease in straw yard groups reported by (72) requires further investigation to establish if there is a causal mechanism.

Out-wintering pads

In an evaluation of out-wintering pads O'Driscoll *et al*(42) assessed white line disease lesions in four different environments for dry cows: cubicles; unsheltered out-wintering pad; covered out-wintering pad; unsheltered out-wintering pad with self-feed silage. There were no differences between treatments in WLD scores or the proportion of animals affected at evaluations which continued until 14 weeks post-partum; and there were also no differences over time.

In another study of Charolais x Friesian steers (132) three space allowances in sheltered or exposed out wintering pads were compared with one group housed indoors on a slatted floor at a lower space allowance than the outside treatments for 150 days. Animals housed indoors were significantly more likely to have WLD of the front left lateral claw compared to animals housed on the out wintering pads.

As expected, there were no published reports that evaluated white line disease incidence or prevalence in cows that were milking and managed on out-wintering pads.

Cubicle bedding

In a 12 month cross-sectional survey conducted in Ontario, involving 134 tie-stall herds there was a significantly greater prevalence of white line abscesses in herds where wood was used as bedding compared to straw (83). However, this was not detected in 134 cubicle housed herds followed in the same survey. Similarly, Kujala *et al*(2010) (129) found there were reduced odds of WLD for animals bedded on mats compared to hard

floors but this finding was not reported for loose house herds. In these studies, the effect of cubicle bed may have been hidden by a much greater effect of activity, or these may be type I statistical errors the chance of which are very likely to occur when many risks factors are being compared with many foot lesions in surveys. This is particularly important when it is considered that many risk factor surveys that include cubicle bed parameters and foot lesion outcomes that do not detect differences but these non-significant findings goes unnoticed.

In an intervention reported by Norring *et al*(2008) (157) cows were allocated to either deep straw bedded cubicles or sand bedded cubicles for 21 weeks. The change in overall hoof health score was significantly greater for cows kept on sand compared to those housed on straw over the length of the study (scores improved on sand but deteriorated slightly on straw). There were no other significant effects detected or tested for with regard to individual lesion types (sole haemorrhage, white line disease or other). Again, the relatively short duration of this study may not have been sufficient to detect differences in lameness due to white line lesions.

Access to grazing

White line lesions and sole penetrations are regarded the predominant cause of lameness in New Zealand (Personal Communication, Neil Chesterton). However, scientific reports on the relationship between white line lesions and access to grazing appear to be conflicting. Studies in UK (44), US (83) and Northern Ireland (51) have all reported increased levels of white line disease when cows have outdoor access. Barker *et al*(2009) (44) found in a cross-sectional survey of 27 dairy farms that cows turned out during the day had increased odds of WLD compared to cows that were housed 24 hours per day. Similarly Cramer *et al*(2009) (83) found the prevalence of white line separation was significantly greater where cows had year round access to an outside exercise area than where there was no provision for outside exercise. In the Northern Irish study (51), animals on the grass-based grazing system had the highest white line lesion scores. Only one study reported better white line health on pasture-based systems with cows having significantly lower scores for sole and white line haemorrhages, WLD, and digital dermatitis than housed cows in a RCT (66). Further research is required to understand the causal mechanism but the body of evidence would suggest increasing the access to pasture is likely to increase the prevalence and incidence of white line disease, but factors relating to management and resource provision in housed and pasture-based systems are likely to greatly influence the outcome.

DETECTION, PREVENTION AND TREATMENT

Preventative trimming and foot bathing

In one of the most comprehensive investigations of foot trimming and the effect on white line disease (125) assigned cows to one of four treatments 3-4 months after calving which remained on study for three months. These included: (1) housed with concrete slatted floors and trimmed according to the standard Dutch trimming method; (2) housed with concrete slatted floors and trimmed according to an alternative method; (3) housed on slatted rubber floors and trimmed according to the standard Dutch trimming method; (4) housed with rubber slatted floors and trimmed according to an alternative method. There were no effects of treatment on sole ulcer and white line defects although the period of evaluation was only 3 months.

Three studies have looked at the effect of trimmer on the prevalence of white line disease (52, 55, 67). Both (52) and (55) indicated the herd and claw trimmer had significant effects on the odds of an animal having a white line disorder while (67) found the trimmer effect was detected in front feet only and just white line fissures. (55) also reported that trimming routine had an effect on white line haemorrhages. (83) found herds where heifers were trimmed prior to calving there were significantly lower odds of white line abscesses compared to herds where they weren't trimmed. However, as observational reports these four studies need interpreting with caution as herd differences, seasonal differences and differences in trimmer lesion recognition or recording are difficult to account for. For instance, (99) found limited agreement between individual claw trimmers and the trainer in identifying some claw disorders.

DIETS AND FEEDING

Biotin

There were five papers on biotin identified in the review: four papers identified that reported on the effect of biotin supplementation on white line disease in dairy cattle and one on beef cattle. Two of these papers were published from a single randomised control trial, one paper had limited power (176), one conducted on heifers (176) and another paper described a trial that was not randomised, was not blind and had no statistical analysis (134) (Table 6).

Table 6 A critical appraisal of papers found during the review that describe the effect of biotin on lameness and white line lesions in cattle

Author, date and region	Patient group	Study type	Outcomes	Key results	Study Weaknesses
Hedges <i>et al</i> (56), Gloucestershire, UK	900 (453 Treatment and 447 control) Holstein Friesian milking cows and milking heifers on five farms with 1120 cow years	Within farm RCT (18 month longitudinal prospective intervention)	Lesions causing lameness	Risk of lameness due to white line separation halved with supplementation of 20mg/animal/ day (Cox proportional hazard survival analysis hazard ratio=0.57). The reduction was observed on two of the farms.	Results from one of the five farms excluded due to unreliability of the data. There was lack of blinding to treatment as cows were grouped and there was no placebo.
Potzsch <i>et al</i> 2003 (130,131)			Lameness caused by white line disease	Supplementation reduced WLD lameness by 45% in multiparous cows down to 8.5cases per 100 cow years. Supplementation of multiparous cows for at least 6 months was required to produce a significant benefit.	
Randhawa <i>et al</i> 2008 (134)	28 crossbred dairy cows (14 treatments, 14 controls) in Punjab,	5 month field trial – not specified if randomised and blind	Locomotion score and claw lesions	No significant difference between treatment and control groups	Not randomised, not blinded, statistical tests not described, low

	India. Breed and parity not specified.				statistical power, power not calculated.
Laurence <i>et al</i> /2008 (153), Australia	108 F1 Wagyu/Black Angus steers in one Australian feedlot	Split-plot, randomised by sire with four replicates of 3 treatments for 300 days: (1) basal diet with no additional biotin; (2) basal diet with 10mg biotin/steer/day; (3) basal diet with 20 mg biotin/steer/day.	Claw growth rate, horn integrity, claw lesions	There was no significant effect of biotin supplementation on the number of hoof lesions (haemorrhages), or the width or dry matter content of the white on medial or lateral claws. Grandsire did have a significant effect on width of the white line on both lateral and medial claws	Basic data could have been more fully described
Offer <i>et al</i> /(2004) (176)	2x20 First and second lactation Holstein Friesians	Randomised controlled trial involving one of two treatments pre-calving: (1) low starch, high fibre, with zinc methionate and biotin premix; or (2) higher starch, lower fibre than treatment 1 and placebo premix	Locomotion score; the incidence or prevalence of lameness; the incidence or severity of DD; or development of claw horn lesions in the sole or white line	No significant difference in intervention group	Small numbers of animals. First and second lactation Holstein Friesians meant low prevalence of lameness due to WLD

Hedges *et al*(56) conducted a within-farm, non-blinded, randomised controlled trial involving the supplementation of biotin at 20mg per head per day for up to 18 months on five farms (Table 6). The researchers found a significant difference in the incidence rate of lameness between cows supplemented and not supplemented with biotin within 2 of the 5 farms (lower in the supplemented group). Within 1 farm, and overall, the incidence of white line separation was significantly lower in the supplemented group and when the results from all cows were pooled there was a significant reduction in lameness due to white line separation. There were no significant differences between treatment groups in the incidence of sole ulcer or digital dermatitis (DD). In some further analysis of the same dataset (130), it was found that while there were benefits for shorter periods of supplementation, it was multiparous animals that had been supplemented for at least 6 months that had a significantly lower risk of lameness due to white line separation compared to unsupplemented animals. This long duration of supplementation may explain the lack of effect reported by other researchers. The researchers excluded a farm effect by testing for *farm x biotin* interaction which indicated the lack of a significant difference on some farms was down to small numbers of cows affected on each farm.

In a RCT involving 1st and 2nd lactation animals (176) cows were randomly allocated to one of 2 treatments pre-calving: (1) low starch, high fibre, with zinc methionate and biotin premix; or (2) higher starch, lower fibre than treatment 1 and placebo premix. Cows remained on study for 20 weeks post calving and a further evaluation took place at 42 weeks to assess for long term benefits. There was no significant effect of treatment on locomotion score; the incidence or prevalence of lameness; the incidence or severity of DD; or development of claw horn lesions in the sole or white line during the study. However, the use of first and second lactation animals may have masked potential benefits.

Studies which have not found a positive effect of biotin supplementation have included one conducted on Australian feedlot beef steers (153). None-the-less, the evidence for the benefit of biotin supplementation looks strong.

Trace minerals

Studies investigating the impact of trace mineral supplementation on white line lesions have included one survey and four RCTs. The single survey conducted in Kenya using 300 cows on 32 farms (109) found that regular mineral supplementation was associated with a reduced prevalence (protective factors) as well as a risk factor when there was no supplementation. The relevance of this work to the UK situation remains questionable but this paper illustrates the potential for added protection when supplementation is above daily recommended levels.

Most of the interventions involving trace element supplementation have included an evaluation of over-supplementation, as well as a consideration of presentation (inorganic vs. complexed, sulphate or non-sulphate based). In particular, studies have investigated the role of zinc supplementation (133, 164, and 176), methionine (102, 133, 176) or sulphates (164). In the latter study the use of Zn, Mn, Cu and Co did not appear to affect the incidence of white line separation or abscess in one 35 week trial, although sole ulcer incidence was higher in the sulphate group. 61 found overall, and in individual herds, there was evidence of reduced proportions of animals with white line separation, sole haemorrhage, sole ulcer and DD in the year following supplementation with complexed trace minerals when compared to the previous year. This illustrates the importance of long term monitoring in the evaluation of nutritional studies.

Nocek *et al*(2006) (133) randomly assigned 573 cows to one of four treatments for the duration of nearly two complete lactations. Treatment groups were balanced by parity and milk yield (305 day mature equivalent). These included (1) 75% complexed Zn, Mn, Cu and Co supplied at 75% of NRC guidelines by complexed trace minerals (zinc methionine, copper lysine, manganese methionine, cobalt glucoheptonate); (2) 100% inorganic Zn, Mn, Cu and Co supplied at 100% of NRC (by zinc, manganese, copper and cobalt sulphate); (3) 100% complexed Zn, Mn, Cu and Co supplied at 100% of NRC by complexed trace minerals; (4) complexed/inorganic Zn and Cu supplied at 100% of NRC using a combination of complexed trace minerals and sulphates. Overall there were significant effects of treatment on the incidence of white line separation with the highest incidence in treatment 1, and the lowest in treatment 2 (treatments 3 and 4 were not significantly different from either). With respect to severity, significantly lower scores were seen on treatments 3 and 4 compared to treatment 2. There were also significant effects of time on the incidence of sole haemorrhage, white line separation, and sole ulcer and the severity of sole haemorrhage. At individual time-points there were also significant effects of treatment on the incidence and severity of sole haemorrhage and sole ulcer (for full details refer to Tables 7 and 10 of the paper). Biological differences between treatments appeared small, and possibly not measurable using lameness or locomotion score as outcome measures.

Laven and Livesey (2004) (102) studied 60 Holstein heifers that were supplemented with 115% of calculated methionine requirement for 13 weeks and found no significant effects on white line haemorrhage scores when monitored from 4 weeks prior to calving to 26 weeks after calving. In a similar study conducted by (176) cows were allocated to one of 2 treatments pre-calving and remained on the study until 20 weeks post calving. The treatments were: low starch, high fibre, with zinc methionate and biotin premix; or higher starch, lower fibre than treatment 1 and placebo premix. Like Laven and Livesey

(2004) there was no significant effect of treatment on: locomotion score; the incidence or prevalence of lameness; the incidence or severity of DD; or development of claw horn lesions in the sole or white line during the study. However, there were significant effects of parity on mean and maximum sole and white line lesion scores.

Factors relating to rumen health

There have been numerous studies examining concentrate, starch content and dry matter content of diets in randomised controlled trials. A single risk factor survey was conducted (109) which did not yield new insights, was described earlier and was of limited scientific value.

Concentrate feeding and Forage to concentrate ratio

Abel *et al*(2001) (546) clearly demonstrated that substituting forage for concentrate could raise levels of biotin naturally synthesised by the rumen, so it could be expected that a similar intervention applied under controlled field trial conditions would result in less white line disease. Differing forage to concentrate ratios could therefore confound biotin supplementation studies.

In a Northern Irish RCT (51) the effect of high and low concentrate rations were examined under housed versus grazed conditions over two lactations (first two lactations). Cows on the low concentrate system (indoor housed) had lower white line lesion scores than either the animals on the high concentrate system or grazed when the animals with digital dermatitis (DD) were excluded. In animals with DD, those on the high concentrate system had the lowest white line lesion scores, and those on the grass-based grazing system had the highest white line lesion scores. The study was weakened by the loss of 20 animals from a group of 104 (15 Holstein-Friesian and 5 Norwegian), and by the use of young animals with a lower prevalence of white line disease.

In a shorter RCT (119) evaluating 2 diets (high fibre and high starch) and 2 housing treatments (cubicles with rubber mats bedded with either wood shavings or chopped straw) from 6 weeks pre-calving until 12 weeks post-calving, there were no significant differences between groups in locomotion score or claw lesion score. However this study was weakened by the short duration of investigation.

In an investigation into genetic merit (48) that compared high genetic merit American Holsteins and high genetic merit New Zealand Friesians with low genetic merit equivalents, it was found feed system had no effect on WLD at either time point. Difference in lameness and white line disease was attributed to differences in genetic merit not concentrate provision, which may also have confounded other research studies examining white line disease.

Amount of grass herbage provision

In a six month RCT (62) conducted in Ireland there were no significant effects of pasture nutrition level (high or low pasture herbage allowances) on sole lesion scores, WLD scores, overall locomotion score, overall spine curvature, walking speed, tracking, head carriage, or total lying time. In a similar study Offer *et al*(2000) (177) followed cows for 4 lactations. Cows were grazed during the summer according to one of 2 treatments: (1) grazed on grass/clover on which no artificial nitrogen fertiliser was used; and (2) grazed on conventionally managed pasture with addition of nitrogen fertiliser (concentrates and straights fed differed between groups to balance silage quality and manage production). There were no significant differences in claw lesion scores between treatments. Total lesion scores were significantly higher in lactation 4 than in earlier lactations.

Dry matter content of heifer rearing and lactation diets

In an intervention aimed at evaluating the importance of dry matter content of replacement heifer rations, Offer *et al*(2001) (175) randomly allocated heifers to one of 2 treatments in early pregnancy for 98 days: (1) hay plus barley based concentrate or (2) grass silage. They were then monitored for 30 weeks post calving. At 20 weeks after calving claw lesion scores were significantly higher for heifers fed on silage compared to those for animals fed on hay. For both groups lesion scores increased significantly 10 weeks after calving. Total lesion score was significantly positively correlated with claw angles and claw lengths, with a significant negative association with bulb hardness. There was a significant positive correlation between heel erosion score and total lesion score. The exact causal mechanism could not be ascertained, and differences in underfoot conditions as a consequence of wetter faeces in the low dry matter diet group, were considered important potential mediators of the result.

In a simplification of the previous study, Offer *et al*(2003) (103) fed heifers from weaning until first calving on: (1) low DM fermented diet based on grass silage (2) high DM unfermented diet based on a straw and concentrate mix. One month before calving heifers were switched onto a grass-silage based diet. Claw lesions were assessed 6 months after calving. White line lesions were significantly worse in heifers on the wet silage diet, before and after calving. Again, the relative importance of conditions underfoot associated with wet faeces on treatment one could not be evaluated but was thought to be important. In a similar study by Leach *et al*(2005) (115) repeated the treatments but formulated to equalise growth rates. Overall there were significantly more animals on the wet fermented with clinical lameness due to claw horn lesions than on the dry unfermented diet.

In a study that built on the findings of the previous study, Carson *et al*(2004) (101) reported a RCT using heifers were reared on one of 4 treatments: (1) reared to

calve at 540kg, offered grass silage-based diets in the winter and grass-based diets during the summer; (2) reared to calve at 620kg, fed as for treatment 1 but with the addition of concentrates; (3) reared to calve at 620kg, offered a straw/concentrate diet during the winter and a grass-based diet during the summer; (4) reared to calve at 620kg, fed as for treatment 3 during the winter, but housed in summer and offered a straw/concentrate diet. They found a significantly greater proportion of animals reared on treatment 4 had a white line lesions in the front claws compared with animals in the other treatments. There was a significantly greater proportion of cows on treatment 4 with a sole lesion compared to cows in treatment 3.

Finally, Webster (2001) (108) evaluated first lactation heifers on two lactation rations (1) heifers housed in straw yard and fed a 'dry' forage diet; (2) heifers housed in straw yard and fed a 'wet' diet (forage soaked in water); (3) heifers housed in cubicles and fed a 'dry' forage diet; (4) heifers housed in cubicles and fed a 'wet' diet. There were no significant effects of feed on white line lesion scores.

The outcome of these studies has been a recommendation that heifer rearing diets should be formulated using forages of a dry matter content of at least 25%. However, the likelihood is that wet faeces are an important factor mediating this effect and so environmental hygiene and management of slurry may be important factors that could potentially confound studies.

HEIFER BREEDING

The relationship between lameness due to white line lesions and milk yield loss has been well reported (41, 43, 52, 210). A positive genetic correlations between white line disease and milk yield has been reported (41, 47). Positive phenotypic correlations between milk yield and the 3 claw disorders was reported too, although the correlations was generally smaller than the genetic correlations (41). (52) found the presence of a white line disorder was positively correlated with milk yield. (68) found a significant negative interaction effect of DIM and white line haemorrhages on milk yield. However, a number of studies have indicated that cows that develop lameness due to white line lesions are more productive prior to the episode (41, 43, 45, 47). Higher milk yields in early lactation have been associated with higher incidences of SU and WLD (47), until 1 month prior to the lameness episode (43). For sole ulcers this has been found to be 2 months prior to lameness (43). Cows with WLD have been shown to produce more milk than non-lame cows at 4 months after treatment (45).

A number of studies have attempted to examine the effect of breed on white line lesion incidence or prevalence with Norwegian reds having lower scores than Holstein Friesians (42, 51). (129) found in tie stall herds there was a significant interaction effect

between parity and breed on the odds of an animal having WLD (both increasing parity and being of Holstein breed as opposed to Ayrshire increased the odds) while on loose housing there were significantly greater odds of WLD in Holsteins compared to Ayrshires.

(48) found the odds of WLD at day 230 were generally higher in the high EBI genetic group than in the low EBI group dependent on threshold used. (153) reported the results of a RCT using Wagyu/Black Angus feedlot steers allocated to one of 3 nutritional treatments for 300 days. Grandsire did have a significant effect on width of the white line on both lateral and medial claws, while there was no effect of nutritional treatment. (69) investigated the heritability of individual claw disorders including WLD and found they were all heritable. There were significant genetic correlations among different disorders including: sole haemorrhage and WLD; and sole ulcer and WLD and between other lesions. There were also significant genetic correlations between conformation traits and individual claw disorders but not WLD. However, 112 found an increase in severity of white line lesion was associated with increased claw asymmetry.

ENVIRONMENTAL HYGIENE

Reports in New Zealand (Neil Chesterton, personal communication) and UK (58) show the marked seasonal variation in lameness due to white line lesions which is largely attributed to rainfall and wet conditions. There may be three potential causal mechanisms: erosion of track surfaces exposing sharp stones, or concealing damaging stones in mud or pooled water; horn may be softened; or sudden changes between wet and dry conditions may predispose the claw horn to damage. The association may be coincidental and related to some other factor such as nutrition, heat stress, time since calving or increased standing times as milking group sizes change. Further work is needed to investigate this.

The importance of underfoot hygiene could not be excluded from one dietary intervention conducted at SAC that reported improved claw health (103). This factor was used to explain the deterioration in claw health on one intervention study involving a comparison of housing on rubber vs. concrete yards (76). This hypothesis was supported by findings from Sweden which assessed claw health of cows over 2 years on slatted rubber floors (46) and found a significant positive correlation between sole ulcer/haemorrhage or white line haemorrhage and cleanliness of the foot (dirtier feet associated with disorder of the white line/sole). Cows on slatted rubber floors were cleaner than those on solid concrete and had significantly lower odds of a hind foot sole ulcer, sole haemorrhage or white line haemorrhage (odds ratio 0.34).

OTHER RISK FACTORS

Season

Five studies have reported a seasonal variation in the incidence of lameness due to white line disease (52, 58, 59, 73, 113). Using Swedish foot trimmer records, (59) found animals that were trimmed in the autumn (and spring) had lower odds of haemorrhages (white line or sole), sole ulcers, separations and lameness than cows not trimmed in the autumn (only spring). Animals trimmed in March, April or May had greater odds of separations than cows trimmed in February. Similarly, in a US study (113) the hazard of WLD was significantly greater in spring, summer and autumn compared to winter. (73) found season and year had a significant effect on the prevalence of WLD in heifers, with higher prevalence in the winter and in the year with higher rainfall. In a study of lameness treatments conducted by UK veterinary surgeons (58) there were statistically more reports of WLD in August and October than in February. This finding was different from historic reports from the same surveillance network. No conclusions were drawn about why there may have been a shift in seasonal pattern but given climatic changes and nutritional risk factors are likely to have remained relatively constant, the change must be related to other managemental changes such as increased production, altered calving pattern and increased herd sizes in relation to environmental maintenance investments.

Parity

A number of publications found an increased risk or odds of white line disease with increasing parity (43, 44, 47, 52, 54, 56, 59, 113, 129 and 177). This finding has clear implications for herds looking to increase longevity while maintaining good standards of foot health. However, (110) suggested that in Kibbutz dairy herds there are a greater proportion of first parity animals with white line haemorrhages in both front and hind claws than amongst animals of parity 2 and above, while white line separation was greater in multiparous cows. The latter finding emphasises the importance of differentiating between white line haemorrhage and white line separation/fissures as heifers may have higher levels of sole haemorrhage. 110 also reported that there was a difference in the distribution of white line separation in front and hind claws between primiparous and multiparous animals with primiparous cows having more relatively more lesions in forefeet. Some workers have proposed this difference is explained by greater heifer avoidance behaviour (Neil Chesterton, personal communication) but this has not been investigated.

Stage of lactation

Several studies have detected an effect of stage of lactation on white line disease (44, 55, 102, 104, 107). For white line haemorrhages in heifers, Webster (2002) (107) found lesions peaked at 2 months after calving. Laven and Livesey (2004) (102) detected a similar peak at 3 months after calving. Similarly, (44) found cows in the third month from calving had increased odds of WLD compared to cows in the first month after calving and (104) observed more white line haemorrhages in animals that had been calved for 3-5 months than in other animals. 177 showed the peaks in white line lesion score increased at each parity upto parity 3, and the peak came later in lactation after each successive calving peaking at 25-30 weeks for fourth parity animals.

As indicated earlier, the various white lesions appear to have different inciting risk factors and different chronology of development. So rather than using a composite score, (48) analysed the time effect separately and found the prevalence of white line haemorrhages was lower at 230 days post calving than at day 35 while the prevalence of cows with WLD was greater at day 230 than day 35. However, findings of (147) disagreed; namely the odds of CHD (white line lesion and disease, sole ulcer, and double sole) were significantly lower for animals 0-60 DIM than for animals more than 120 DIM.

Herd size

In a Swedish study of cubicle and tie-stall housed cows, (67) found larger herds had significantly fewer cows with white line fissures in the front feet. However, herd size *per se* provides little information about intensity and duration of risk factors and this is the only paper to have reported on this.

Presence of other lesions or disorders

(57) modelled data from a large epidemiological study and concluded cows that had been previously lame (in the first lactation) had a significantly greater hazard in the second lactation for lameness (all types) and CHD (sole ulcer and WLD) than cows that were not previously lame. Other studies had examined correlations (53, 60, 113).

(53) reported mean sole haemorrhage score was positively correlated with mean white line lesion (WLL) score. Mean WLL score was positively correlated with both mean heel horn erosion and mean DD score.

Similarly, (60) reported correlations at the hoof level (positive correlations between white line haemorrhage and erosive dermatitis, heel horn erosion, double sole, sole ulcer, abnormal claw shape and sole haemorrhage; white line fissures and erosive dermatitis, interdigital hyperplasia sole ulcer, abnormal claw shape, heel horn erosion, sole and white line haemorrhages and double sole). Correlations between the different lesion types were also seen at the level of the cow and herd (see Table 4 in paper for further details). In a US study (113) the presence of WLD was significantly associated

with thin soles and with other miscellaneous claw lesions (mostly DD) on the same day, as well as other claw lesions in the periods prior to examination (1 to 30 days and 61 to 180 days prior).

The presence of other lesions may be causal or may be a correlation due to common risk factors. The absence of longitudinal studies means there is still much uncertainty relating to the significance of these findings, other than to say it is another potentially confounding factor for studies looking into white line lesions specifically..

Conclusions

There were few reported risk factors for white line that were not easily categorised into clinically plausible risk factor groups. It should be emphasized that this categorisation is based on an assumption that the disease process (aetiology) is primarily based on a compromise of claw horn quality and/or physical trauma to the claw in the environment. Only one reported risk factor could not be easily categorised. In a study of Finnish tie-stalls and cubicle ('loose') housing, (129) reported the odds of WLD were also significantly greater in 'warm loose housing with slatted floors' compared to 'cold loose housing'. However, there was no definition of warm or cold given so this finding remains of questionable significance.

Whilst there is a substantial list of references relating to white disease, the greatest focus of research has been on nutrition with other risks being relatively under-researched. There are several studies that have indicated that long term interventions are required to detect differences in lameness due to white line disease, with a minimum of 6 months required for biotin. There is a substantial body of evidence indicating lameness due to white line disease is more significant in multiparous animals, but that factors affecting horn quality can influence the onset of lesions from as young as weaning age (115). The mechanism by which nutritional interventions influence the onset of clinical white line lesions is poorly understood, but faecal consistency leading to wet conditions under foot may be as important as the quality of horn being produced, if not more so. Dry and non-traumatic conditions underfoot would seem to be the factor that consistently reduces risk of lameness due to white line disease. A consistent rise in lesion score through lactation is likely to reflect exposure to physical and nutritional risk during lactation and the time taken for lesions to appear at the bearing surface, but physiological changes experienced at around calving cannot be excluded.

The long term nature of white line disease development and the many potentially confounding factors that need to be controlled for makes this disease particularly challenging to investigate. This may be why it is one of the least well understood and reported diseases affecting cattle.

Prevention of Non-Specific Claw Disease / Lesions

There were eighteen observational studies that examined associations between non specific claw lesions and other parameters.

DIETS AND FEEDING

Calves that had been supplemented with 0.25mg/kg BW sodium selenite per day for 45-60 days showed signs of swelling of the coronet, enlargement and cracking of hooves, and intradigital lesions (162). The extent and severity of the lesions was reported to increase with time (animals supplemented for a total of 98 days) (162). Amongst animals supplemented with 20 mg biotin/day for thirteen months there were reductions in: the number of left (fore and rear) hooves with moderate to severe damage to the digits; in the number of outer digits affected by hoof disorders; and in the number of antibiotic treatments administered to animals for hoof disorders (172).

OTHER RISK FACTORS

Age and parity

The proportion of bulls at two AI stations that were affected by claw diseases was greater at ten months of age compared to five months of age (89). Fleischer *et al.* (2001) also noted a positive correlation between the lactational incidence risk of claw disease and lactation number amongst Holstein-Friesian cows (148). However, Busato *et al.* (2000) found no significant effects of age on claw lesions amongst 1886 cows of mixed breeds (171).

Stage of lactation

Amongst predominantly tie stall housed cows, of mixed breed, there were no significant effects of month of lactation on claw lesions (171). Within a group of twenty heifers there were no significant differences between those that were freshly calved and those that were in the early stages of pregnancy in terms of the area covered by foot lesions, however, the lactating animals did have greater total lesion scores (which included a measure of severity) than the non-lactating animals (221).

Body Condition Score and Body Weight

Fewer claw lesions were associated with both increasing BCS and body weight of animals (171).

Breed and genetics

Amongst predominantly tie stall housed cows, of mixed breed (predominantly Simmental, Simmental x Red Holstein crossbreeds, and Brown Swiss) there were no significant effects of breed on claw lesions (171). However, Norwegian cows were observed to have lower total lesion scores than Holstein-Friesian animals (51). The heritability of claw diseases was reported to be between 0.01 and 0.03 amongst German Holstein cattle (152), and amongst Iranian Holsteins the heritability of foot and leg diseases was estimated to be between 0.15 and 0.22 (264).

Growth of animals

There were positive genetic correlations between foot disorders and: the weight of the animals at weaning; their growth rate at weaning; and their maximum growth rate (212).

Milk production

Amongst 29 pairs of animals (4 Brown Swiss, 11 Holstein Friesian and 14 Simmental x Red Holstein pairs) there were no significant differences in diagnosed problems of the claw or feet according to milk yield (either high yielding or in line with the herd average for lactational milk yield) (169). Also, amongst 1886 animals of mixed breed there were no effects of milk yield on claw lesions (171). Amongst Holstein-Friesians there were positive correlations between claw disease and both 200d and 305d milk yields (148). Within a large sample of Holstein cows there were positive genetic correlations between claw and leg diseases and the following traits: persistency of milk yield, persistency of fat yield, and persistency of milk energy yield (174).

Fertility

There was a positive genetic correlation between claw diseases and fertility diseases amongst German Holstein cattle (152). However, oestrus expression amongst Holstein-Friesians was not correlated with claw lesion score (250).

Behaviour of animals

Amongst tie stall housed cows there were no differences detected in water or dry matter intake by animals in association with hoof treatments (408).

Other health disorders including previous lameness

Data from ten German Holstein herds revealed that the lactational incidence risk of claw disorders was not associated with the occurrence of any of seven other recorded disorders, which included: parturient paresis, retained placenta, displaced abomasum,

metritis, clinical ketosis, clinical mastitis, and ovarian cysts (149). Amongst Iranian Holsteins the genetic correlations between foot and leg disease and both cystic ovarian disease and displaced abomasum were low in the first three lactations (264).

Housing system

Amongst Holstein-Friesian and Norwegian cattle those animals at grass had greater total lesion scores than indoor-housed animals on both low and high concentrate diets (51). Amongst twelve Friesian crossbred animals in a Thai dairy system there were no hoof injuries diagnosed in the animals at pasture, while there was some evidence of hoof disorders in animals that were housed (161).

There were no significant differences between bulls housed on either slatted concrete floors or slatted concrete floors with rubber mats groups in the proportion of claws affected by lesions (DD, sole ulceration, wall disorder, and/or interdigital hyperplasia), although animals on concrete tended to have a lower proportion of affected claws compared to those on rubber (160). There were also no significant differences between cows housed with grooved or slatted concrete floors in terms of claw health (165).

When lying areas with wooden planks were compared to other lying surfaces, animals on rubber mats were found to have lower odds of claw lesions, and animals on concrete were found to have greater odds of lesions (171). There were however, no significant effects of: type of housing (cubicles vs. tie stalls); bedding material (sawdust or chopped straw vs. straw); or presence or absence of outdoor corrals on the occurrence of claw lesions (171).

Herd effects

There were no significant effects of herd or farm size or the geographical location of the farm on claw lesions (171). Where the main activity of the farm was crop or livestock associated (but not specifically dairy) there were lower odds of claw lesions than on farms where dairying was the main activity (171).

Time

Claw lesion scores change over time (51).

Prevention of Non-Specific Lameness

STANDING TIME ON CONCRETE

Cubicle design

A number of aspects of cubicle design are associated with lameness in dairy herds. Increased risks of lameness have been associated with: smaller cubicle lying areas per cow (307); both wider (235) and narrower cubicles (104); a lying area of less than 178cm in length (235); kerb heights of 15cm or less (205); cubicle gradients of between 0 and 1.5% (254); head lunge impediments (234); brisket board heights above 15.2cm (237); and cubicles where the area behind the brisket board was filled with concrete (237). Factors explaining lameness also include the position of the neck rail (290) and the length of the neck rail diagonal (305) (direction of effects not given in papers). Significant negative correlations have been observed between both the proportion of lame cows in the herd and gait scores and neck rail height (243). Shorter neck rail diagonals were also associated with an increased risk of lameness (234). In cubicle based herds there was a significant interaction between length of the lunging space and hip width on the level of lameness (the lowest lameness scores were generally associated with greater lunging space) (254). Only one study identified no effects of the characteristics of the cubicles including cubicle type and dimensions on clinical lameness (331).

Cubicle lying surface

A factor associated with an increased risk of lameness was an abrasive cubicle lying surface (206). Animals on rubber mats had reduced odds of lameness compared to cows housed in cubicles with concrete bases (59). Cows on deep cubicle bases in turn, had reduced risks of lameness compared to those animals on mats and mattresses (234, 235). Specifically, both deep sand (227, 228, 238, 407) and deep sawdust (407) were associated with a reduced prevalence of lame or severely lame animals. In comparing mats and mattresses, no significant differences have been detected in respect of locomotion score or the prevalence of lameness (102, 222). In cubicle-housed Austrian dairy herds one of the most important factors explaining lameness was the use of, and type and depth of bedding (direction of effects not given in papers) (290, 305). However, in a survey of 70 French dairy herds using cubicle housing there were no significant effects of bedding type, or, cubicle surface on the occurrence of clinical lameness (331). There were also no differences detected in locomotion score between cows on rubber mattresses with sawdust, concrete with sawdust, or deep sand (81),

although the cubicle surface, in combination with the type of flooring in the passageway, had an effect on the growth and wear rates of the claws (81).

Time in collecting yard/at milking

The prevalence of lameness was significantly higher for animals spending longer away from the housing during milking (237).

CLAW TRAUMA

Housing system

In zero-grazed herds cows had significantly greater lameness scores (254), and increased odds of being a 'loser cow' (295, 325) than in herds where the animals were turned out to grass during the summer, however, there were also differences in diet between grazed and housed animals that may also have had an effect on lameness. Studies comparing housed cows and animals at grass have found greater odds of clinical lameness, increased risks of poor locomotion, and a greater risk of abnormalities of tracking, spine curvature, head bobbing, general symmetry and ab/adduction amongst housed cows (66, 294). Lameness or gait score, tracking up, and claw conformation were all found to improve over the grazing period (231, 260). Additionally, within grazed herds in the UK the prevalence of lameness was negatively correlated with the length of the grazing season (307), and increased with increasing length of time from grazing (206). When animals were housed in cubicles during the day, there was no significant effect on gait score of housing them at pasture overnight (220). For animals that were housed in tie stall barns there was no significant effect on mean lameness score of allowing them to graze during the summer (231).

In UK herds the prevalence and incidence of lame cows is observed to be higher amongst cows in cubicles than in straw yards (254, 307, 357, 575). However, a survey of cubicle based herds in England and Wales revealed that higher mean herd locomotion scores were significantly associated with housing dry cows on straw yards (compared to cubicles) (205). This study, and others, found no significant differences in locomotion score between cows housed in straw yards and cows in cubicles (102, 173, 205).

The comparison of lameness and conformation traits in tie stall and cubicle housing reveals conflicting evidence. The odds of being lame were significantly greater in tie-stall barns (with no provision for exercise) than in cubicle yards (52), and cows generally scored better for: depth of heel, rear leg rear view, foot angle, bone quality, rear leg side view, and feet and legs in cubicle housing (240). However, in a sample of herds in the US the mean prevalence of lameness was significantly higher amongst cubicle based herds than in herds with tie stalls (but only during the winter, and not

during the summer) (227). In a sample of 196 Swedish herds moving from tie stalls to cubicle housing there were increased risks of lameness in the twelve to eighteen months after the transition (265). In the opinion of US producers that had moved their herd from tie stall or cubicle housing, to a compost dairy barn, the prevalence of lameness was reduced in the new system (203).

Housing design (including condition and maintenance of walking surfaces)

Passageway widths of less than 3m were associated with increased herd locomotion scores (205). The use of automatic scrapers was also associated with an increased risk of lameness (205, 206). Floor type appeared to be linked to the occurrence of lameness (290 - direction of effect not stated in paper), with slatted floors representing a greater risk of lameness than solid or partially slatted floors (235, 305). Floor type was also observed to have an effect on individual aspects of gait (323). Cows on concrete slats generally walked slower, had shorter stride and step length, and tracked less well than cows on other surfaces (323). Cows on sand generally performed best with respect to these parameters, with cows on continuous rubber, rubber slats or solid concrete falling between the two groups (323). Cows on clean, non slippery, level floors had better locomotion than cows on dirty, slippery, uneven surfaces (294). An increased risk of lameness was also associated with damaged concrete in yards or passageways (206). Step length, number of daily steps per cow, and the occurrence of mounting activity and licking behaviour were all greater on rubber flooring than on concrete flooring (302). Given a choice between rubber and concrete flooring, cows showed a preference for a rubber walkway (302). Two studies identified no difference in locomotion score between cows housed with rubber or concrete flooring in the passageways, or in the feed area. (81, 293). There were no significant differences between floor types (solid, slatted or grooved concrete and straw yards) in the observed prevalence of lameness in Dutch dairy herds (79). A high incidence of lameness in a herd of buffalo was attributed to abrasive newly laid concrete, in combination with increased movement of the animals as they adjusted to a new social group (163).

Across cubicle-based UK dairy herds the prevalence of lameness was negatively correlated with the standing area per cow in the parlour (307). A further variable related to lameness was the provision of an outside run (290 - direction of effect not stated in paper). Amongst Simmental cows on Austrian dairy farms there were greater odds of being lame if the animals had access to an outdoor loafing area (235). However, in a further larger study of Simmentals in cubicle housing it was demonstrated that access to an outside area was generally associated with a reduction in the proportion of lame cows in the herd (305). Amongst cows in tie stalls the odds of lameness were lower where

animals had regular exercise throughout the year compared to in herds with provision for regular exercise throughout the summer, but minimal exercise during winter (304).

Size and management of groups

The stocking density of cubicle sheds was associated with lameness amongst dairy herds (direction of effect not given in paper (290)). The proportion of lame cows in a herd was found to be negatively correlated with the space allowance per cow. In cubicle-housed herds higher locomotion scores have been associated with mixing pregnant heifers with milking cows (as opposed to dry cows) before calving (205). After calving, there was no effect of housing animals with herd mates in the same lactation period, as opposed to animals at different stages of lactation, on lameness score or the number of treatments for infectious hoof disorders (296). However, a high incidence of lameness in a herd of buffalo was associated with animals adjusting to a new social group, with a severely lame animal known to be particularly aggressive, and observed to pace incessantly (163).

Cow flow and herding

Risk factors associated with increased lameness included sharp turns near the parlour exit or entrance, and cows pushing each other (206).

Claw condition

There was a significant positive correlation between claw conformation and lameness (231). Cows with greater length of claws in a herd were associated with an increased risk or prevalence of lameness (233, 307). Factors that cause trauma to the claws represented an increased hazard of unsoundness, and suboptimal claw condition was associated with an increased risk of unsoundness and severe lameness (73).

DIETS AND FEEDING

Cows housed all year round and fed a high concentrate low forage diet had higher locomotion scores than cows that were out at grass during the summer and fed a low concentrate high forage diet, however, the effects of housing and diet could not be separated in the study (295). For animals in a grass-based feeding system there was no effect of level of concentrates fed on the number of cases of clinical lameness, however, cows on the high concentrate diet had a lower hazard of increased head bobbing compared to the low concentrate group (48). In another study of animals in a grass-based feeding system there were no effects of concentrate levels in the diet on locomotion score, spine curvature, walking speed, tracking, or head carriage, but at

certain time points scores for spine curvature and ab/adduction were higher for cows fed larger quantities of concentrates (62).

Holstein cows were fed diets varying in energy and fibre content from three weeks pre partum to three weeks postpartum (164). While there were no effects of diet alone on locomotion score, at a number of time points during the first 40 days of lactation locomotion scores were higher on the high energy (low fibre) diet. Greater locomotion scores have also been associated with feeding corn silage to lactating animals (205) and feeding high protein diets (312). In a study involving Israeli Holstein cows there was no effect on the proportion of animals with a metabolic disorder (lameness or ketosis) within the first 90 DIM according to whether a proportion of the dietary corn silage and vetch hay was replaced by soy hulls (287). In a survey of high producing Holsteins Espejo and Endres (2007) found no association between the prevalence of lameness and the crude protein or neutral detergent fibre content of the TMR (237). An increased prevalence of lameness has also been associated with increased levels of aflatoxin in the milk (301).

The effect of feeding animals a diet either low or high in phosphorus from the start of their first lactation has been examined, with the results indicating that there was no difference in the proportion of cows treated for lameness, but that animals fed a high phosphorus diet had lower locomotion scores during their third lactation than cows fed the low phosphorus diet (241). Lower incidences of lameness have been associated with biotin supplementation (20mg/day for thirteen months) (172), and lower incidences of non infectious lameness with the feeding of monensin to animals (347). Lower locomotion scores and smaller proportions of lame and severely lame animals are associated with the provision of supplemental vitamins and minerals to lactating cows (195), but animals fed a vitamin B blend (3g/cow/day) showed significant increases in locomotion score compared to animals that were not supplemented (308). Dosing animals with oligofructose was associated with increases in locomotion score (232), and evidence of both lameness and claw pain, i.e. development of laminitis (324).

Cows grazed in an area associated with high levels of molybdenum, and supplemented with copper sulphate had significantly lower levels of lameness than animals not supplemented with copper sulphate (280). The incidence of lameness was also higher amongst animals that had not had previous exposure to the grazing area compared to those that had previously been exposed. There was a significant interaction effect between previous exposure and supplementation on lameness, with the odds of lameness lower for naïve cattle in the supplemented group than in the control group.

A number of studies have found no effect on lameness parameters of various dietary manipulations, including: additional dietary methionine fed to heifers (102); ractopamine hydrochloride fed to cull cows (194); yeast culture fed to multiparous

Holsteins (213); different levels and forms of zinc supplementation in Holstein-Friesians (230); varying amounts of Gossypol fed to primiparous and multiparous Holsteins (309); feeding rumen-protected conjugated linoleic acid to Piemontese bulls (312); and feeding organic trace mineral complexes (Availa4®) to early lactation Holsteins (326).

DETECTION, PREVENTION AND TREATMENT

Treatment and monitoring

Inadequate detection or treatment of lameness represented an increased hazard for both unsoundness and severe lameness in dairy cows (73). In herds where the farmer did not treat lame cows within 48hrs of diagnosis, there was an increased risk of lameness (206). Amongst herds participating in a lameness control plan there were negative correlations between both the adherence of the farmer and the vet to the plan and the change in the prevalence of unsound cows, and the adherence of the farmer to the plan and the change in the prevalence of severely lame cows (73). Treatment of lame cows was more likely to be successful in bringing about improvements in locomotion score or recovery, the lower the cumulative locomotion score of the animal during the preceding weeks (257).

Preventative trimming and foot bathing

The individual claw trimmer had an effect on the odds of the animals in a herd being lame (52). Higher herd locomotion scores and a higher proportion of animals that were lame or severely lame were both associated with the presence of a foot trimming stall on the farm (195). In herds where cows were trimmed twice per year there were lower odds of lameness than where cows were trimmed only once (59), or on an irregular basis/only when needed (76). Lower herd locomotion scores and a decreased prevalence of lameness were also associated with the practice of routine foot trimming, when compared to herds where there was no routine (205), or where cows were trimmed only when deemed necessary (237). Trimming of cows has been associated with increases in gait score and decreases in walking speed, while trimming of lame cows was associated with an improvement in symmetry of weight bearing on the rear legs, but also an increase in weight shifting (349). Over trimming of cows' feet by inexperienced foot trimmers has also been linked to a high incidence of lameness amongst dairy cows (163). While a number of studies have detected an effect of lameness control plans, including foot trimming and its frequency, on lameness, gait and locomotion score, some have detected no differences. No differences were detected following a single trim (229),

or according to: foot trimming routine (55; 233; 259), implementation of a lameness control plan (73), or number of months since last foot trimming session (233).

Studies related to non-specific lameness and foot bathing have been limited over the past ten years, and have shown no positive effects of the practice. The presence of a foot bath on a farm was associated with a higher farm locomotion score and a higher proportion of animals that were lame or severely lame, when compared to farms without a foot bath (195). Amongst cubicle-based herds of high producing Holsteins the use of foot bathing was not associated with the prevalence of lameness (237). A comparison of animals that were foot bathed regularly over a five month period (in 4% formalin) with a group of animals not foot bathed at all during this time, also revealed no significant changes in locomotion score in either group (86).

ENVIRONMENTAL HYGIENE

One study found no difference between 'clean' and 'dirty' herds in the presence of lameness (76), however, a number of other studies have identified an association between the cleanliness of the cows or their environment and lameness. In herds where there was wet slurry underfoot (73) and where manure was removed less frequently (283) there were increased risks of unsoundness and severe lameness, and a greater prevalence of lameness respectively. Dirty cows were more likely to be lame than other animals (233). A greater prevalence of cows with a back arch in a herd has been associated with a greater prevalence of cows with moderately dirty hind limbs, and with dirty udders (343). However, there was a negative correlation between the prevalence of cows with rotated hind claws and the prevalence of cows with dirty udders (343).

Biosecurity

Open herds (307) and breaches of herd biosecurity (73) have both been observed to pose hazards for an increased prevalence of lameness and severe lameness respectively. On farms where cattle grazed pasture that was also grazed by sheep there was an increased risk of lameness (206).

OTHER RISK FACTORS

Breeding and genetics

The heritability of locomotion score was estimated at 0.11 for Holstein Friesians in UK herds (294), and 0.06 for Holsteins in Canadian herds (328). Estimates of the heritability of lameness also vary, with an estimated value of 0.12 amongst Danish Holstein

Friesians (266), and 0.04 to 0.07 in a large sample of US herds (345, 346). The value obtained for the heritability of lameness is dependent on the model used, with estimates of 0.019 and 0.079 amongst UK Holstein Friesians achieved from linear and threshold models respectively (268). The mean predicted transmitting ability for the probability of lameness across 581 US herds for the ten best and ten worst sires was 0.077 and 0.131 respectively (345).

The proportion of Holstein genes in an animal has a significant effect on a number of linear and composite traits including locomotion score, rear leg side view, foot angle, legs and feet, and bone quality (direction of effects not stated in paper) (294). Holstein Friesians have been associated with lower locomotion scores (51), but an increased herd prevalence of lameness in comparison to other breeds (206). Gait differences have been detected between Swedish Red and White cattle and Swedish Holsteins; with the former found to have larger step angles, longer strides, and improved tracking (323). However, no significant differences in locomotion score were detected between Holstein-Friesians and Norwegian cattle (337), and no significant differences in lameness between Holsteins and Czech Pied cattle (233). In a herd where animals were maintained under a single housing system throughout the study there was a lower incidence of lameness amongst Jersey cows than amongst Holstein-Friesians (202). However, where animals were moved between two sets of cubicle housing no significant differences were detected in the occurrence of lameness between Jersey cows and Holsteins (339). In an Irish dairy system, cows with a high economic breeding index (EBI) had a significantly lower hazard of being lame, and lower odds of clinical lameness during the first 200 days in milk (DIM) than animals with a lower EBI (48).

Positive genetic correlations have been observed between foot disorders and: the weight of the animal at weaning; its growth rate at weaning; and the maximum growth rate of the animal (212). However, there were no significant genetic correlations between lameness in the animal and measures of its weight and growth rate (212). The odds of a cow becoming lame during lactation have also been associated with the birth weight of her calf and the ratio between the weight of the calf and the size of the cow (277); the greater the weight of the calf in relation to the size of the cow the greater the odds of lameness were (277).

Conformation

There were significant negative genetic correlations within Holstein cows between the animal's locomotion score or a case of lameness (leg or foot) and: pin width, bone quality, foot angle, udder depth, udder texture, both front and rear udder attachment (328), and the chest width of the animals (348). There was a significant positive genetic correlation between locomotion score and rear leg set (328). Amongst Holstein-Friesian

cattle there were moderate genetic correlations between locomotion score and foot angle and mammary composite (294). There was a high phenotypic and genetic correlation between locomotion score and legs and feet (294). There were negative correlations between the predicted transmitting ability for the probability of lameness and the following parameters: stature, strength, body depth, dairy form, rump angle, rear legs rear view, foot angle, rear udder height, and udder cleft (346). There were positive correlations between the PTA for the probability of lameness and the following parameters: thurl width, rear legs side view, fore udder attachment, rear udder width, udder depth, front teat placement, and teat length (346).

Age and Lactation number

Generally, locomotion score, or the odds of an animal being lame, increases with lactation number (48, 52, 62, 104, 199, 220, 233, 234, 235, 238, 254, 262, 288, 293, 307, 336, 351); few studies have identified no effect of lactation number on locomotion score (79, 81, 339). The odds of an animal being classed as a 'loser cow' (which includes an assessment of lameness) was lower for heifers than older animals (325). Individual aspects of gait were also affected by parity; animals in parity two were found to walk faster than animals in parity three (293), and cows in parity three and above had larger strides than heifers (323).

Age at first calving

Across UK dairy herds a significantly greater prevalence of lameness was observed in animals that were less than 26 months old at first calving compared to those that were older at calving (307). Ettema and Santos (2004) however, found no effect of age at first calving on incidence of lameness (239).

Stage of lactation

Stage of lactation has been observed to have a significant effect on locomotion score, as well as other traits, including: rear leg side view, foot angle, legs and feet, and bone quality (direction of effects not stated in paper) (294). Amongst Holsteins and Holstein-Friesians in Scotland and Denmark positive correlations have been demonstrated between DIM and locomotion score (53, 295). However, in studies of UK, Swedish and Iranian herds, across a range of housing systems, the odds of lameness peaked in the first six months of lactation (59, 262, 288). A number of studies have found no association between the prevalence of lameness and DIM, or month of lactation (79, 233, 238).

BCS and BW

In general, cows with lower BCS tend to be at a greater risk of lameness than animals with more condition on them (234, 235, 238, 263, 334), and herds with a greater proportion of fat cows had a greater prevalence of lameness (305). Loss of BCS around calving was associated with an increased risk of lameness compared to maintenance of a constant BCS, or an increase in BCS, with the greatest losses of condition associated with the greatest risk (263). In contrast to the aforementioned studies, data collected from a single herd of Holstein-Friesians over two years revealed that higher BCS was significantly associated with higher locomotion scores, as was lower bodyweight (295). While these and other studies (290) have demonstrated an association between lameness and BCS, a study of Holstein herds in Canada revealed only a low phenotypic correlation between the two parameters, and no significant genetic correlation between them (328).

Milk production

A number of studies in the last ten years have found associations between animals with higher milk yields, and an increased risk or prevalence of lameness (52, 198, 251, 288, 307). Data collected from two cubicle-housed herds of Holsteins demonstrated that animals that became lame during lactation had greater milk yields prior to diagnosis, but reduced yields after the event (340). Other studies have also shown reductions in milk yield both prior to and after an occurrence of lameness (198, 199, 251, 258, 267, 295, 336), with the decrease in milk production found to be greatest for cows in their second lactation and above, and with a tendency to increase with an increase in the severity of lameness (336). Amongst Karan Fries cross bred cows in an Indian dairy herd 305d milk yields and monthly milk yields were greater for non-lame animals (317). Even when animals were diagnosed to be lame, either before calving or during the second month of lactation, monthly milk yields were still greater for healthy animals in months one to five of lactation than for lame animals (317). One study detected an association between the risk of lameness and total milk yield, but the direction of effect was not clear from the paper (311). Studies have also detected no significant differences in locomotion score between low and high yielding cows (173), and no significant phenotypic (267) or genetic correlation between locomotion score and milk production (328).

Lameness is associated not only with yield, but also with other parameters of milk production. A two year study of cubicle-housed Holstein-Friesians revealed significant differences between lame and healthy animals in terms of: milk yield; yield of value corrected milk, fat, protein and dry matter; and the percentage of fat, protein and dry matter in the milk (286). The proportion of fat and dry matter in the milk were both consistently higher in lame than non-lame animals (286), but differences in the other parameters varied with lactation number. For Simmental cows the greatest odds of being

lame were associated with a milk protein content less than 3.2% or greater than 3.8% (235). Juarez *et al.* (2003) demonstrated that milk protein yields decreased significantly with increases in locomotion score, with the percentage of milk protein being greatest for animals of intermediate locomotion scores (267). Amongst cows in New Zealand grass-based systems there was an association between lameness and total protein yield, although the direction of effect was not clear from the paper (311). Amongst multiparous Holstein cows there were no effects of locomotion score on milk composition (267). The persistency of cows also varies according to lameness; cows that were not lame before 60 DIM demonstrated greater persistency than cows that were lame during this period (295). However, Appuhamy *et al.* (2009) found no significant relationship between lameness and persistency of either milk yield or fat yield (196). Similarly, Appuhamy *et al.* (2007) found no associations between lameness and persistency, or, peak yield, or DIM at peak yield (197). The predicted transmitting ability for the probability of lameness have also been associated with milk production parameters. Negative correlations have been shown between the PTA for the probability of lameness and both percentage fat and protein in the milk, with positive correlations between the PTA for probability of lameness and both milk production and SCC (346).

Cows milked once/day demonstrated less vertical movement of the head during walking, and greater walking speed than cows milked twice/day. There was also some evidence of greater ab/adduction amongst cows milked once/day, and these animals generally had lower locomotion scores than cows milked twice/day (62). There were no significant effects of milking frequency on spine curvature or tracking (62). Another study revealed no significant effects of milking frequency on the number of cows sent to the hospital for lameness during a given period of time (330).

A comparison of the gait of cows before and after milking revealed that after milking cows had significantly greater stride length and height, and speed, shorter duration of both stride and stance, and a reduced proportion of time in triple support (three hooves in contact with the ground) (92). Tracking-up also improved significantly after milking (92). The process of habituating heifers to the milking routine, prior to calving, was not shown to have an effect on locomotion score (337). There were also no significant associations between lameness and the kicking or stepping behaviour of the animal during milking (306).

Fertility

Lame cows exhibited longer intervals to the first luteal phase after calving than non-lame cows (247, 300), with longer intervals to the first ovulatory oestrus also (300). Animals found to be lame were in fact less likely to ovulate than animals that were not lame

(289), or were less likely to be observed in oestrus (333). Overall, they had significantly greater odds of delayed cyclicity post partum than non-lame cows (247, 299).

Lame cows have been demonstrated to have shorter oestrus periods (319), and to spend less time expressing oestrus behaviour than non-lame animals (334). Oestrus periods in lame cows were of reduced intensity compared to those in non-lame cows (332, 333). Lame cows were found to have lower maximum progesterone concentrations than non-lame animals (332, 333), and lower basal progesterone concentrations (333). They demonstrated a reduced frequency of total mounting activity (332), which included: standing to be mounted on a less frequent basis, reduced duration of standing time; reduced mounting of other animals; and a decrease in mounting at the head (319, 333). They also exhibited a reduced frequency of sniffing behaviour (332).

Lame cows show longer days to first service (257, 270, 300, 327), and have longer calving to conception intervals than non-lame animals (257, 270, 351). They had a greater number of services per conception than non-lame animals (288, 327), however, cows treated for lameness were also seen to have fewer inseminations per service period than their non-lame counterparts. Both first service conception rates (270; 285), and overall conception rates (200, 213, 257, 270, 285, 351) are lower for lame cows than non-lame animals, with cows that become lame having a greater number of days open (288, 327). There was a negative association between locomotion score and embryo survival rate to day 25 after AI (208). Negative correlations have also been demonstrated between the predicted transmitting ability for the probability of lameness and daughter pregnancy rates (346).

Lame cows had significantly greater odds of being diagnosed with ovarian cysts during lactation than non lame animals (285), and were more likely to be culled before a reproductive event than non lame animals (285).

A small number of studies have found no significant differences between lame and non-lame animals according to a number of fertility parameters, including: cyclicity and duration of the luteal phase (299); expression of oestrus behaviour and occurrence of ovulation (250, 289); conception rate (223); and maintenance of pregnancies (278).

Season

Numerous studies have reported an effect of season on lameness. The prevalence of lameness was higher during winter than in other seasons (355), in particular summer (227, 575), and greater in spring than autumn (288, 307). The odds of lameness were also reported to be greater between August and November than between December and April (265), and to increase through the year from June to May (262). Only one study detected no seasonal difference, with no significant differences in the prevalence of

lameness between winter and summer (76). However, another of the studies found no seasonal difference amongst cows housed in cubicles bedded with sand (227). The season in which the animal calved also had an effect; heifers that calved in the autumn were more likely to be lame than animals that calved during other seasons (239).

Herd effects

The herd itself has a significant effect on the odds of the animals being lame (52). Associated with this, herd size had an effect, although both larger (76), and smaller herds (235, 261) have been associated with an increased risk of lameness. The proportion of herds that reported one or more cases of lameness in adult cows increased with an increase in herd size (261). Where farmers expected their herd size to increase (as opposed to herd size remaining unchanged), there were greater odds of cows being 'loser cows' (325). The region in which the herd is located can also affect the odds of lameness (235), although a regional difference is not always observed (282). The proportion of animals culled due to lameness was equal across herds in both industrial and non-industrial areas (214). The age of the herd had an effect on lameness (direction of effect not given in paper) (290).

Both the prevalence of lameness and the odds of an animal being a 'loser cow' were greater in conventional herds than in organic herds. (307, 325). Scheme membership also had an effect on the odds of the animals being lame, with cows belonging to herds that were a member of the RSPCA Freedom Food scheme having greater odds of being lame than cows on farms that weren't a member of the scheme (279).

Time

Locomotion and gait scores vary with time (220, 262, 295). In studies where data has been collected over multiple years, the year had an effect on the prevalence of unsound and severely lame cows (73), and on the clinical case rate of lameness (357).

Welfare management and stockperson behaviour

In cubicle-housed Austrian dairy herds lameness was related to the behaviour of the milkers and 'welfare management' on the farm (290 – direction of effects not stated in paper). The prevalence of lameness was positively correlated with concerns by farmers about accreditation issues, and the farmers' pride in their herd (275 – survey). In herds with a lameness problem farmers were less likely to be reviewing their health records, with the extent of record review found to be negatively correlated with the prevalence of lameness (207). A greater proportion of lame cows has been associated with fewer positive tactile interactions between the stockperson and the cows during milking. The

proportion of lame cows was also related to the number of neutral interactions between the stockperson and the cow during milking, and management decisions that affected the well-being of the cows (direction of effects not clear from paper) (305).

Productivity/efficiency

Farms with an increased probability of lameness had reduced technical efficiency (level of inputs relative to level of outputs i.e. milk) (273). There was also a significant interaction effect of lameness and amount of labour (man hours) on technical efficiency (273). There was no significant association between lameness risk and return over feed index (284). There were negative correlations between the predicted transmitting ability for the probability of lameness and the productive life of the animal (346).

Barriers and motivators to lameness control

The efforts that farmers put into controlling health issues were positively correlated with the estimated cost to the business of the individual disease (274). The reasons that farmers most frequently cited for putting less effort into controlling lameness than other disorders were: another disease being seen as a bigger problem; and lameness not being seen as a big problem (274). The barriers to lameness control considered most frequently by farmers to be very or extremely important were limits to time and labour (274). Farmers did not always implement lameness control suggestions, with the most common reasons for this being due to: cost, lack of time or labour, lack of necessary resources, and lack of interest or confidence in a lameness control measure (274). Vets were the most frequently cited source of information on lameness control (274).

The proportion of farmers that rated the following outcomes of lameness as very or extremely important are given in brackets: pain and suffering (94%); reduced profitability, poor cow condition, reduced milk production, and reduced fertility (each 78-80%); and poor public image (74%) (275). Extra time spent working with lame cows, treatment costs, and failure to gain accreditation were all ranked lower in importance (275). The most important factors motivating farmers to control lameness were pride in a healthy herd and feeling sorry for lame cows (275). Factors most frequently rated as not being important motivators were a desire to be better than other farmers, and risks to farm assurance as a consequence of lameness (275). Factors that farmers thought would motivate other farmers to take more action to control lameness were split evenly between economic drivers and other suggestions (275). The most frequently cited economic drivers were more information on the costs associated with lameness, and an increase in milk price. The most frequently cited of the other suggestions were discussion groups (275).

Behaviour and lameness

The evidence regarding the relationship between lying behaviour and lameness is conflicting. Moderately lame animals in cubicles bedded with mattresses or sand spent less time lying down than non lame and slightly lame animals (228). Amongst animals housed in sand cubicles increases in gait score were correlated with increases in lying time (349). In cubicle-based herds with mattresses lame cows had significantly longer lying times than non lame animals (407). Lame Holstein-Friesians at pasture spent more time lying down, lying down ruminating, and lying down and not ruminating when compared to non lame animals (334). In herds with deep bedded cubicles severely lame cows spent more time lying down, had greater duration of lying bouts, and had higher standard deviations of bout length than other animals (407). In herds with deep bedded cubicles severely lame cows spent more time lying down than in herds with cubicles and mattresses (407). The prevalence or odds of lameness were negatively correlated with both the cow comfort index (CCI) (235) and the cow comfort quotient (CCQ) (237). In contrast, it has also been observed that the proportion of cows lying down in a pen increases with an increase in locomotion score (267, (359). Lame cows spent a greater proportion of time lying outside of the cubicles than non lame animals (608). The risk of lameness was also positively correlated with abnormal rising movements, and an increased duration of this behaviour (234, 235, 304).

Animals that became lame later in lactation showed no significant differences in the time spent standing up compared to animals that did become lame (246), however, they did spend more time standing half in a cubicle than those cows that did not become lame (246). Once lame, animals spent a smaller proportion of their time walking (334, 608), and less time standing (with and without ruminating and in total), and up on their feet compared to non lame animals (334). Animals that were moderately lame had fewer cubicle standing bouts per day than non lame and slightly lame animals (228). Both slightly lame and moderately lame animals spent less time standing in a passageway compared to non lame animals (228), and more time standing in a cubicle (228, 358, 605). There was a significant effect of locomotion on location of the animal relative to the pen entrance (distance being greatest for animals of intermediate locomotion scores) (267).

In herds with automatic milking systems the distance between the position of the feed trough visited and the AMS decreased with an increase in locomotion score (199). There were negative effects of locomotion score on total eating time, number of meals, and total DMI (199). In animals that were later affected by an acute locomotion disorder or chronic lameness, there were prior negative effects on feed intake/day, feeding time/day, length of meals/day, number of meals/day and number of visits to the feeder/day (406). Feeding rate on the other hand increased prior to diagnosis, in both

groups of animals (406). During the 30 days prior to diagnosis of chronic lameness the changes in feeding time/day, length of meals/day, feeding rate and number of visits to the feeder/day were significantly different between those animals that did and didn't later suffer from chronic lameness (406). In the 30 days after diagnosis of chronic lameness there was an increase in the number of visits/day to the feeder by lame cows (406). In herds out at grass the lame cows had lower bite rates than non lame animals (334).

In herds with automatic milking systems there were negative effects of locomotion score on total number of milkings and number of voluntary milkings (199). In herds with a conventional milking parlour there was a significant positive effect of locomotion score on the time taken by the animal to return to the pen after milking (267). In herds out at pasture, animals with the greatest odds of lameness left the field for milking, and entered the parlour later than non lame animals (311, 334), and were further down the walking order on the way to the milking shed (311). Both cows that were always milked in the last quarter and cows that always walked in the last quarter (across five observations) had greater odds of becoming lame compared to animals were never milked or that never walked in the last quarter (311). Animals that became lame showed less variation in their walking order position compared to animals that did not become lame (311).

Higher ranking cows had a longer duration to a first case of lameness during lactation than lower ranking cows (245). Cows which became lame had a lower index of displacements than other animals (246). Lame cows were also less likely to initiate an aggressive interaction, more likely to initiate and be the recipient of a non agonistic interaction, and were significantly more likely to be licked by another cow, when compared to non lame animals (608). In a study of grass-based herds there was no effect of the dominance status of the animal on the likelihood of it becoming lame (311).

Behaviour

Given the links demonstrated between aspects of behaviour and parameters of lameness, other factors which affect behaviour may also have an impact on lameness.

Significant differences were observed in the behaviour of animals between straw yards and cubicle housing (173). Cows in early lactation in straw yards spent greater amounts of time: lying, ruminating, standing on the bed, and eating straw, and had greater synchronicity of lying behaviour than cows in cubicles, but spent less time standing in the passageways and feeding. Cows in mid to late lactation in straw yards, also spent greater amounts of time standing on the bed and eating straw, but less time standing in passageways than cows in cubicles. Holstein heifers housed continuously in cubicles demonstrated greater frequency of lying bouts than animals housed at pasture

overnight in the weeks immediately pre and post calving (220). Similarly, multiparous Holsteins in mid to late lactation at pasture had greater frequency of lying bouts, but spent less time lying down than cows housed in cubicles (260). In contrast, total lying time and length of lying bouts were greater for pasture-based Holstein-Friesian cows of varying parities (66).

Within cubicles, cows housed on mattresses showed increases in: lying time, ruminating while lying, and total ruminating time, as well as increases in length of lying bouts compared to cows housed on mats, but, decreases in time spent: idling and idling in cubicles, as well as a reduction in the number of lying bouts (222). Comparisons of cow behaviour on mattresses bedded with organic material (e.g. sawdust) or deep sand cubicles (with or without a mattress base) have demonstrated increases in time spent standing in the cubicle (228, 605) and increased length of standing bouts amongst cows housed on the former surface type (228), and increases in: time spent feeding (228), number of cubicle use sessions (228), proportion of lying bouts greater than 60 minutes (228), and duration of all lying bouts (605) on the latter.

Higher neck rails were associated with reduced cubicle standing times (with all four feet in the cubicle), and with fewer lying bouts (despite similar lying times) (209). High neck rails, as well as a flat cubicle base, and a lack of regular cleaning of the rear part of the cubicle were all associated with abnormal lying and rising behaviour (331). The presence of a brisket board in cubicles was associated with increases in the time animals spent in idling or lying down, and an increase in the frequency and duration of lying intentions (331). Cantilevered U.S. style cubicles were associated with reductions in idling time and increases in lying time compared to Euroconfort cubicles and freestanding U.S. cubicles (331). Compared to the Euroconfort cubicles, they were also associated with longer lying bouts. Cubicle types with larger lying areas (cantilever or loop type) were associated with a greater proportion of cows lying down in the post peak feeding period than in cubicles with smaller lying areas (Newton Rigg with back rail reaching curb) (359).

Smaller standing areas in passageways were associated with a smaller proportion of cows standing in the passageway (359). Cows forced to stand on concrete (during wet weather in grass based systems) demonstrated shorter gait length than cows stood on a sand/gravel lane or in a paddock (242). The number of lying bouts was reduced for animals confined to a wood chip pad during stand-off periods, when compared to animals held on concrete, lane or a paddock (242). Cows forced to stand on floor surfaces of different compressibility demonstrated no differences in stepping or feeding behaviour, or in latency to lie down (606). Cows deprived of the ability to lie down or feed demonstrated increases in time spent: standing (both while ruminating and not ruminating), stamping legs and shifting weight, and in the number of times that they

repositioned themselves, touched their noses to the ground, and butted compared to control animals (229). They also demonstrated reductions in the amount of time spent both drinking and walking. After periods of lying and feeding deprivation animals demonstrated greater length of meals and lying bouts (229). There were no effects of milking frequency on total lying time (62), but there was a positive correlation between the time taken for animals to return to the pen after milking and the proportion of cows seen to be lying down (267).

The amount of concentrates fed to adult cattle had no effect on total lying time, but cows fed higher levels lay down sooner after milking than animals fed less concentrates (62). Administration of an oligofructose overload (used experimentally to induce ruminal acidosis) was generally associated with increases in the length of time from initiation of pre-lying intention movements until kneeling and the total duration of the lying down sequence in cattle (291).

Heifers spent more time feeding than multiparous animals (605). Freshly calved heifers spent less time lying down and standing idling, more time standing in cubicles, and had shorter lying bouts than heifers in early pregnancy, as well as receiving less aggression and grooming per animal (221). Lying times and length of lying bouts increased for Holstein Friesian animals, both at pasture and when housed in cubicles with DIM (66). It was also observed that earlier on in lactation cows lay down sooner after morning milking than later on in lactation (62). Low social ranking cows spent less time lying down, including lying outside of the cubicles (245), and more time standing still and perching in cubicles (245, 246) than cows judged to be middle or high ranking.

A number of other factors besides the housing system, standing surface, cubicle design, diet and the cow herself have been associated with the behaviour of cattle. Within organic herds, smaller proportions of cubicle housed cows were observed lying down when compared to conventional cubicle housed herds, with the former demonstrating lower cubicle occupancy measures (359). Cows generally spent a greater proportion of time lying down in the hours immediately after morning milking than during other parts of the day (62). Animals under mild to moderate heat stress spent less time lying down, and more time both drinking and standing in the passageways than animals not under heat stress (358). Between the hours of 00.00 and 06.00 cows spent increasing amounts of time standing in the stall with increasing temperature (358). Following foot trimming cows spent longer lying down than they had before foot trimming, with the effect maintained for up to five weeks after trimming (349).

Other health disorders

Calves with a fair score for hooves and lower legs had an increased frequency of medical treatments compared with calves with a score of good or excellent (180). However amongst cows, the incidence of recorded medical treatments was negatively correlated with the prevalence of lameness (304). Amongst multiparous Holstein cattle there were positive correlations between the occurrence of all types of locomotive disorder (laminitis, leg problems, hock problems and inflamed thigh) and both the occurrence of laminitis and all other health disorders (mammary, locomotive, digestive, reproductive) (348). Animals diagnosed with moderate or severe lameness within the first 70 DIM had an increased risk of being culled or dying compared with other animals (351).

Calves with poor or very poor hoof and leg scores had an increased frequency of medical treatments for respiratory problems compared with calves with good or excellent scores (180). Cows that had previously been lame were more likely to become lame again when compared to cows that had not previously been lame (57, 126). The genetic correlations between lameness and displaced abomasum and ketosis were estimated at 0.07 ± 0.14 and 0.19 ± 0.21 respectively (346). The odds of the loser cow state was increased with an increase in the proportion of stillborn calves, and for animals that had twins at their last calving (325). There were significant genetic and phenotypic correlations between lameness and coat condition (266). A comparison of cows at different stages of lactation revealed a high prevalence of lameness in the most recently calved animals, in association with a high prevalence of scouring, a low mean rumen pH, low mean VFA concentration and high mean concentrations of D-lactate and L-lactate of rumen fluid (211). Lameness has been associated with cattle grazing in areas with high levels of molybdenum in the water and plants (281). The use of slow release copper boluses in these animals resulted in no significant differences in the proportion of lame cows (281).

There are positive correlations between the number or percentage of hock lesions per animal or herd and the proportion of lame cows (243, 254, 269, 290, 304). As well as phenotypic correlations, there are also genetic correlations between lameness and hock lesions (266). Lameness was also positively correlated with the presence of carpal injuries (290, 304). Significant genetic and phenotypic correlations have been observed between lameness and other skin lesions (266, 304). However, a survey of dairy farms with Holstein or Czech Pied cattle revealed no association between lameness and skin lesions (233).

There were positive correlations between the proportion of lame cows and both the somatic cell counts in a herd (243), and the incidence of subclinical mastitis (284). The incidence rate of clinical mastitis was also positively correlated with the proportion of cows with claw disease in the previous year (310). The genetic correlation between lameness and mastitis was estimated at 0.20 ± 0.20 (346). The odds of an animal being

a loser cow increased significantly with an increase in average somatic cell count, and with an increase in the mean bacterial count of bulk milk (325).

There were negative correlations between locomotive disorders and both minimum energy balance and total energy deficit (348). Total energy deficit was significantly lower in animals affected by locomotive disorders compared to unaffected animals (348). Mean energy balance between days ten and 50 of lactation, minimum energy balance, and total energy deficit were all significantly lower for animals affected by laminitis compared to unaffected animals, with number of days in negative energy balance significantly greater for the affected animals (348).

Animals given an injection of vitamin E prior to calving had a lower incidence rate of lameness in the first 30 days after calving than animals not injected (276). There were no significant effects of injecting animals with bst at regular intervals between 21 days prior to calving and 42 days after calving on the incidence of lameness in the first 60 days post partum (253). There were also no significant effects of bst administration on the number of cows sent to the hospital for lameness (330).

Blood parameters

Serum levels of phosphorus and zinc were lower in cows that were lame in the first 60 days postpartum than in control animals (270). Concentrations of sialic acid and malondialdehyde in lactating Holsteins increased with increasing locomotion score (313). Concentrations of retinol in Holstein cows were lowest amongst the severely lame animals (313). There were no significant effects of lameness score on serum levels of total protein, triglyceride, cholesterol, albumin, aspartate amino transferase, or alanine amino transferase (341).