Environmental influences on claw function and integrity

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INTRODUCTION

Lameness in dairy cattle causes crippling economic losses to the industry with up to 52% (average 20-25%) of dairy cows becoming lame each year (Clarkson et al., 1996; Green et al., 2002; Warnick et al., 2001). Lameness is caused by many diseases being the clinical manifestation of an animal’s attempt to relieve pain. Pain causes stress and, therefore, the attendant suffering is a highly important animal welfare issue (Whay et al., 1998; Whay et al., 2003).

During the past 10 years there has been a large number of research reports resulting in an improved understanding of the mechanisms involved in the pathogenesis of foot disorders in dairy cattle. Research has focused in particular on a condition called ‘subclinical laminitis’ (SCL) or ‘claw horn disruption’ (CHD) (Hoblet & Weiss, 2001). SCL weakens the integrity of claw tissues predisposing them to secondary lesions such as white line disease and sole ulcers. It is now accepted that SCL has a multi-factorial etiology and a complex physiopathology resulting from a multitude of ‘risk factors’ inherent to dairy farming (Bosman et al., 1991; Ebeid, 1993; Greenough, 1985; Greenough & Vermunt, 1991; Lischer & Ossent, 1994; Mülling & Lischer, 2002). Nocek (1997) postulates that nutritional management and improved cow comfort are major risk factors to be considered in the attempt to reduce lameness in dairy cattle. Inappropriate genetic selection accelerated breeding protocols, poor periparturient management and even farmer knowledge and skills have been implicated as risk factors.

The bovine foot, or more precisely the claw, serves as an interface between the animal and its environment. The claw is exposed, internally to the influences of the metabolism of the animal while the same time being exposed to the impact of mechanical, chemical and biological agents from the environment. Traditionally, the physiopathology and pathogenesis of SCL has been considered from the perspective of being completely related to nutrition and metabolism (Nocek, 1997). In this ‘classical’ approach, a cascade of events starts with a metabolic problem i.e. ruminal acidosis and then the story develops down to the changes and lesions of the foot. Today much greater importance is attached to inadequate housing, foot care and parturition than to nutrition and feeding (Tarlton et al., 2000; Webster, 2001, 2003).

This paper focuses on the influence of environmental and nutritional factors on horn production and on structural key elements of the hoof and describes our understanding of events that take place inside the claw in response to nutritional (metabolic) and environmental challenges and that ultimately lead to claw diseases.

The performance of the foot is genetically determined and limited. In high-performance dairy cows under conditions of intensive-management the foot is continuously challenged by environmental and metabolic factors. The interaction between the below listed structures and the environment results in a cascade of physiopathological events leading to adaptation changes, alterations or damage in the
tissues. Any weakening of the structural integrity of the claw has immediate functional consequences followed by all of its biological, economical and welfare consequences.

The functional important tissue components of the claw responding to nutritional and environmental challenges are:

1. the horn producing living epidermis
2. the dermo-epidermal junction
3. the dermis (including the suspensory apparatus of the digit)
4. the dermal vascular system
5. the sub cutis (digital cushion)

**HORN PRODUCING LIVING EPIDERMIS**

The claw epidermis consists of living epidermal cells in the basal and spiny layers and of dead epidermal cells in the horny layer. Production of claw horn is the result of a dynamic process of proliferation, cellular differentiation (i.e. keratinisation) and programmed cell death called cornification (Mülling & Budras, 1998; Tomlinson et al., 2004). This process is controlled by a variety of bioactive molecules including growth factors and neuropeptides provided by the dermal cells and/or the vascular system.

The keratinising epidermal cells are specialised for a high rate of keratin protein synthesis. At the end of the differentiation during cornification, the keratins are cross-linked by formation of disulphide-bonds which consist of a stable protein-complex which provides mechanical and chemical stability to the horn. The second product of keratinising epidermal cells is the intercellular cementing substance consisting of glycoprotein and complex lipids such as phospholipids glycolipids and acylglycosylceramides. Its major function is to establish cell to cell adhesion providing mechanical stability to the horn. The lipids of the cementing substance establish a permeability barrier in the intercellular space. This barrier prevents the passage of aqueous solutions through the horn and thus protects horn cells from excessive loss of water as well as from extreme hydration (Mülling & Budras, 1998).

The highly active horn producing epidermal cells depend on a sufficient and balanced supply of nutrients and oxygen. Required nutrients for normal keratinisation are (Tomlinson et al., 2004): amino acids, especially sulphur containing amino acids such as cysteine, fatty acids, such as linoleic and arachidonic acid, minerals, in particular calcium, furthermore trace elements like zinc, and vitamins, in particular Biotin. The supply with all these substances has entirely to be performed by diffusion from the blood vessels in the underlying dermis, because the epidermis itself is a completely avascular tissue. Mechanical overload and tissue compression interfere with the perfusion of fluids and with supplies to horn producing tissue. Bioactive molecules derived from metabolic activity or systemic disease will impact on vascular walls and perfusion. These factors have the potential to change the diameter of the dermal vessels or to damage the endothelial wall. Of particular relevance is metabolic stress related to parturition, lactation or dietary problems resulting in metabolic disorders like ketosis or acidosis. Some factors such as histamine, lactate, endotoxin can directly damage the endothelial lining of the vessels and increase transvascular movement. Vasoactive factors such as serotonin or bradykinine will cause constriction of vascular walls with the result of reduced perfusion or reduced drainage form the capillary bed. The latter will result in increased transvascular movement and increased pressure inside the claw capsule (Christmann et al., 2002). Both reduced perfusion and
alterations in the vessel themselves will impair horn production and finally provoke horn of inferior quality. A significant weakening of the horn capsule is a central result of subclinical laminitis. The consequence is an increased susceptibility of the claw to damage and lesions secondary to laminitis.

Pressure is transferred via the cornified and living epidermis to the basal cell layer stimulating proliferation of cells thereby accelerating the production of horn. If the load on a foot is unevenly distributed between the two claws the imbalanced increase in the rate of horn production. The claw with the greatest load will produce more horn and increase in size usually at the heel (overburdening). This causes more pressure more horn and a vicious circle is initiated. Functional claw trimming with the objective of distributing load evenly between both claws, and thereby breaking the vicious circle, is the appropriate measure to interrupt this circle.

There is growing evidence from morphological and in vitro studies that disruption of the differentiation of keratinocytes in the differentiating hoof epidermis is the major reactive event during pathogenesis of laminitis. This disruption occurs following dermal alterations resulting in disruption of appropriate supplies to the epidermis (Hendry et al., 1999, 2001). Most of the findings observed in the claw capsule in subacute or chronic laminitis are related to or a result of the reactive changes in the epidermis impacting of horn production and horn quality.

**DERMO-EPIDERMAL JUNCTION**

The dermo-epidermal interface is a highly developed and specialized region at the border between dermis (connective tissue) and epidermis (epithelium) (Mülling & Budras, 2002). The living epidermal cells located on the interface proliferate and show high metabolic activity. All nutrients, substances and factors required for the epidermal activities have to pass from the dermis into the epidermis and vice versa. During proliferation and synthesis the mitotic cells have to withstand a high mechanical load while transferring all the mechanical forces between the underlying bone and the outer horn capsule and the environment. With its functions the dermo-epidermal junction is a structure of crucial importance for the integrity and normal function of the claw. It establishes the attachment of the living epidermis to the underlying dermis. Signals between dermal and epidermal cells also run through this interface.

Epidermal-dermal interactions play an important role in regulating the proliferation and differentiation of keratinocytes, i.e. the amount and quality of the horn produced. Theses interactions also play an important role in repairing surgical and traumatic injuries of the claw capsule. Early in the pathogenesis of laminitis alterations in the dermo-epidermal region have been reported such as initial molecular and structural changes followed by functional disturbances. In addition, on the dermal side, activation of MMPs (Tarlton et al., 2000) leading to degradation of collagen as well as activation of growth and necrosis factors, molecular and structural alterations in the basement membrane (Hendry et al., 2003) and alterations of capillary walls.

**DERMIS INCLUDING THE SUSPENDING SYSTEM OF THE PEDAL BONE**

The suspensory apparatus of the pedal bone consists of collagen fibres that run upwards from their insertion in the bone to the basement membrane of the dermal
lamellae were they are anchored and thus connected to the lamellar epidermal of the claw capsule. The lamellar region of the wall segment is far smaller and the carrying capacity of the suspensory apparatus of the digit is far less in cattle than it is in the horse (Westerfeld et al., 2000, 2004). In cattle the heel plays a greater role by providing cushioning support.

The system of fibres suspending the pedal bone is responsible for transferring the load (weight of the animal) from the pedal bone to the claw capsule (Westerfeld et al., 2000, 2004). All of the structures between the surface of the bone and the inner aspect of the cornified claw capsule contribute to suspensory functionality. The dermal and epidermal components of the suspensory apparatus are arranged in interdigitating dermal and epidermal laminae. Collagen fibres of the connective tissue are the crucial structural and functional components of the suspensory apparatus of the digit. The quality of these fibres is of critical importance if the pedal bone is be held in a stable position inside the claw capsule (Lischer et al., 2002; Maierl et al., 2002; Tarlton and Webster, 2002; Westerfeld & Mülling, 2000). For whatever reason a loosening or increase in length of this connective tissue occurs it will lead to displacement (sinking, rotation, tilting) of the pedal bone within the horn capsule and subsequent increase in pressure onto the soft tissue between bone and horn.

An elongation, loosening or an increasing elasticity in the collagen system suspending the pedal bone inside the claw capsule are central to hypotheses explaining the pathogenesis of subclinical laminitis (Mülling & Lischer, 2002; Mülling et al., 2004). During the peri-parturition period and throughout the onset of lactation the properties of the connective tissue of the suspensory apparatus (more precisely the extracellular matrix in the connective tissue, the collagen fibres) undergo changes leading to decreased stability of the dermis (Holah et al., 2002; Mülling et al., 2004). As a result, there is increased mobility of the pedal bone inside the claw capsule (Lischer et al., 2002; Mülling & Lischer, 2002). The he critical questions however are: What are the hazards/risk factors causing degradation of the collagen? And what are the local mechanisms in the claw mediating alterations of tissue? Experiments designed to explore the importance of housing, feeding and parturition/lactation indicate that the structural integrity of connective tissue was most severely compromised by housing in cubicles. Parturition and lactation amplified this effect whereas feeding had no significant influence (Webster, 2001, 2003; Webster et al., 2005). Within this context it must be re-emphasized that the dermis is exposed to high local mechanical pressure (Hinterhofer et al., 2006; van der Tol, 2002), particularly when cows stand for excessively long period throughout the day. Cubicle housing in comparison to straw yards leads to elevated level of pro MMP2 and active MMP 2 in the connective tissue of the claw (Tarlton et al., 2000; Webster et al., 2005).

A group of proteolytic enzymes resident in connective tissue, the Matrix Metalloproteinases (MMPs) play a central role in the degradation of collagen. Basing on studies on the effects of MMP-2 and MMP-9 on dermo-epidermal explants (Hendry et al., 2003) and a proteolytic enzyme, “hoofase”, (Tarlton & Webster, 2000) two major hypothesis have been developed. One hypothesis favours the central role of MMPs and their activation by proteases (Tarlton & Webster, 2000) or other known activators of MMPs such as cytokines and inflammatory factors (Mülling et al., 2004). The other hypothesis is based on the direct effects of hormones on the connective tissue leading to instability or a loosening of the collagen fibre system.

Pathological activity of MMPs leads to increased collagen degradation and loosening and elongation of collagen fibres. The subsequent increased mobility of the pedal bone within the capsule causes displacement (sinking and/or rotation or tilting or a combination of these movements) of the pedal bone to a degree depending on the localization and
severity of the collagen degradation. If housing and exposure to concrete are the major hazards to claw tissue integrity then mechanical irritation and or overload are the cause of MMP activation and collagen degradation.

**DERMAL VASCULAR SYSTEM**

The dermal vascular system of the claw is unique in its three-dimensional arrangement, complexity and density, which is the reason for its high susceptibility to structural damage and disturbances to the perfusion of blood (Hirschberg et al., 1998, 2001). The dermal microvascularisation and the perfusion patterns are highly adaptable to metabolic and functional requirements. Mechanical forces during weight-bearing deform the papillae and open or close pathways within the vascular system of the papillae. Thus, the perfusion pattern of the microvascular bed is regulated by demand and by mechanical forces. Structural adaptation of the angioarchitecture is facilitated by active remodelling processes of the capillaries by sprouting and intussusception (Hirschberg & Plendl, 2005).

Pressure in the vessels and tissues increases during laminitis which could be explained by compromised function of AVA’s but a much more likely explanation would be coagulopathy. The pressure increases in the capillaries together with transvascular movement of fluid in tissues may be caused by an increased post-capillary resistance. This resistance is believed to be the result of a reduction in the diameter of the venules in the periphery draining blood from the capillary bed (Christmann et al. 2002).

**SUBCUTIS WITH THE SUPPORTING DIGITAL CUSHIONS**

The digital cushion extends forward beneath the pedal bone and is made up of three cylindrical parallel oriented bodies each with a capsule of connective tissue filled with soft fat (Räber et al., 2004). During normal gait the heel bulbs make the first contact with the ground and the weight will be distributed equally between the outer and inner claw. While the resilient bulbs reduce the initial shock on the posterior part of the claws the weight of the animal is smoothly transferred to the wall and adjacent sole by slight splaying of the claws. The dermis of the sole and heel and the underlying fat cushions in the subcutis function as ‘shock absorbers’ bearing a considerable proportion of the impact of the first phase of each step the animal makes when walking. It has been assumed that the weight distribution between the medial and lateral claws is equal. However, the medial claw is frequently smaller than its lateral counterpart. Prolonged exposure to concrete surfaces causes the solear surface of the lateral claw to flatten and increase in width. This process changes the dynamics inside the claw. Instead of weight-bearing being confined to the wall part of the load is transferred to the central part of the sole of the sole. This creates abnormal pressure on the dermis of the sole. This process accounts for the ‘traumatic’ component in the etiology of SCL.

There is a marked change in the composition of the digital cushions as the animal gets older. In heifers the fat cushions are not completely developed and functional. They develop to full shock absorbing capacity during the first 2 lactations. The fat content is significantly higher in cows (38%) than in heifers (27%) (Räber, 2000; Räber et al., 2004). The cushions in the heifers are composed predominantly of loose connective tissue with abundant amorphous ground substance. In cows however, there was a marked
increase of adipose tissue with progressing age (Räber et al., 2004). A comparison of the digital cushions between sound claws and claws with sole ulcers revealed that the phalanx of ulcerated claws had sunken and the solear dermis and subcutis were thinner than in the controls. The cushions contained significantly less adipose tissue than the controls but had been replaced by collagenous connective tissue (Lischer et al., 2002). The fatty acid composition and the size of the fat cushions change under the influence of metabolic disorders, in particular in cows with lipid mobilisation syndrome (LMS, ketosis). The fat in the digital cushion has a high content of monounsaturated fatty acids (MUFA). MUFA are mainly produced endogenously and the greater the quantity of these fatty acids in the fat tissue, the softer it is; the structural fat in the digital cushion possesses its own ‘fat softener’ (Räber et al., 2002). Heifers have significantly less fat in the cushions and slightly more saturated fatty acids (SFA) than the cows. This indicates that the change from SFA to MUFA and the proliferation of fat occurs at first parturition and during the following lactation. It is possible that these changes in the heifer's digital cushions make them less resistant to pressure load. Epidemiological studies have shown that there is a higher tendency for sole lesions to occur at the beginning of the first lactation (Boosman et al., 1991; Enevoldsen et al., 1991; Greenough & Vermunt 1991; Smilie et al., 1999).

CONCLUSIONS

The concept of a multi-factorial etiology of claw diseases is as valid as it ever was. The disorder cannot be managed simply from a nutritional perspective. Multi-factorial means that practically every aspect of dairy cow management has to be scrutinized for its potential impact on the claw. Preventive measures must be geared to managing the stress level that precipitates the complex physiopathology intrinsic to the foot.

As with other production diseases management decisions are critical to reduce most lameness risk factors. Thus, the possibility to prevent lameness increases if farmers or managers understand and are aware of the problem and its consequences. Cow comfort is not just a sentimental myth but must be interpreted as part of the interaction between the foot of a dairy cow and its internal and external challenges; the most critical period in this aspect is the time around calving. There are anatomical differences in the digital cushion between heifers and cows. It is therefore important to give the heifers enough time to adapt to the new housing conditions of dairy cows.

Looking at the biomechanical components of laminitis it is clear that professional functional hoof trimming helps to reduce the impact of laminitic alterations on the structure and function of the claw. Routine claw trimming helps to balance the load born by the claw. Sole ulcers develop as a consequence of a partial failure of the suspensory apparatus. Whenever possible the ulcerated claw should be unloaded with a claw block on the sound claw.

Laminitis with secondary claw lesions is frequently a herd problem. Systemic events in the peripartal period compromise the suspending and supporting elements of the foot and predispose the animal to laminitis-like lesions. Laminitis is syndrome multi-factorial in origin and prepares the path for development of a variety of associated lesion, like haemorrhages, double sole and sole ulcers. These lesions impact on the productivity, well being and longevity of the animals. Although we do not completely understand the link between metabolic disease and claw lesions, adequate nutrition and optimal feeding management of dairy cows are of outstanding importance.
Nutrition AND cow comfort are key factors in effective prevention of laminitis and associated problems in cattle.
In addition to the measures applied to the animals and their environment it is imperative to develop the herd managers/farmers awareness of the problem, to improve education, dissemination of knowledge and to promote sustainable management strategies for reduction of foot problems.

REFERENCES


