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Review Article

Radiographic and radiological assessment of laminitis

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Summary

Radiographic studies are an essential component in evaluation of horses with laminitis. The standard radiographs that should be obtained to aid assessment of horses with laminitis are the lateromedial, horizontal dorsopalmar and dorsal 45° proximal palmarodistal oblique views. This article will summarise the assessment of these 3 projections in the laminitic horse as well as discuss the prognostic significance of common radiological abnormalities in horses with laminitis.

Introduction

A thorough physical examination of the feet, using a disciplined, methodical approach is integral in the assessment of horses with suspected laminitis and it has been suggested that clinical evaluation of the horse is a better prognostic indicator than any radiological abnormalities (Hunt 1993; Pollitt 1996; Parks and O'Grady 2003). However, even the most experienced clinician cannot determine the location of the osseous structures within the hoof capsule in the absence of radiography. Therefore, radiographs are indicated in every suspected laminitic case because they provide valuable information about the presence, severity, relative chronicity and progressive nature of the disease (Herthel and Hood 1999).

Horses with laminitis normally require repeated radiography during the treatment period, the frequency of which is dependent on each individual case. Factors worthy of consideration when determining the frequency of radiography include the speed of hoof wall growth, the clinical progression of the horse, risks of exacerbating the disease during transportation if portable radiography is not available and the necessity to use radiographic control for trimming and shoeing (Herthel and Hood 1999). It has been recommended that clinically unstable horses be radiographed weekly but the interval between radiographs can increase with increasing clinical stability. Clinically stable horses may benefit from being re-radiographed at 3–4 month intervals; however, any deterioration in a horse with laminitis warrants repeat radiography (Herthel and Hood 1999).

In order to attain maximum information from radiographs, preparation of the foot is essential. Particular attention should be paid to the cleanliness of the angles of the bars and the central and lateral sulci of the frog (Redden 2003d). The horse should ideally be standing squarely on 2 blocks of equal height for both lateral and horizontal dorsopalmar radiographs to encourage even weightbearing on both limbs. The metacarpus/metatarsus should be perpendicular to the ground surface and parallel to each other because the normal anatomical relationships between the hoof capsule and distal phalanx and between the phalanges can be altered if the horse is not standing in this way. Radiographs of the contralateral limb should also be obtained even in unilaterally affected horses and, in some cases, it may be essential to evaluate all 4 limbs radiologically.

In horses with laminitis, radiographs are primarily obtained to determine the position of the distal phalanx within the hoof and the nature of the soft tissue changes. The nomenclature used to describe these structures is well defined, but seldom adhered to. By anatomic definition, the hoof is all of the integument of the horse's foot; e.g. it includes epidermis, dermis and subcutaneous tissue. The keratinised portion of the hoof (formed by the *stratum corneum* of the limbus, corona, wall, sole, frog and heel bulbs) is termed the hoof capsule. The horny wall (comprised by *stratum internum*, *stratum medium* and *stratum externum*) is termed the hoof wall. The bulk of the hoof is formed by the stratum medium and is approximately 50–65% of the width of the dorsal aspect of the hoof, while the lamellar region is approximately 15% and the remainder is the sublamellar dermis and subcutaneous tissue.

Although radiographs are poor at imaging soft tissue, information can be gleaned from plain film radiographs obtained with soft tissues in mind (almost underexposed) (Redden 2003b) or using digital radiography. Acquisition of identically positioned views with differing exposure factors, or of digital radiographs can maximise the diagnostic information attained per view. Lateromedial radiographs can be utilised to identify the widths of the dorsal hoof capsule and the underlying nonkeratinised portion of the dorsal hoof separately. Additionally, indicating the clinically relevant anatomy with radio-opaque markers may assist in interpretation of radiographs, although this is no longer mandatory when using digital radiography providing appropriate exposures are used and a thorough radiological evaluation is performed. If need be, the dorsal hoof wall can be delineated with a radiodense marker such as barium paste (Parks and O'Grady 2003; Redden 2003b) or a metal strip. However, accurate placement of a metal strip on the surface of a distorted wall is difficult and may lead to misinterpretation of the radiograph; under these circumstances it is preferable to use barium paste. Positioning of this marker must be on the dorsal sagittal midline and the proximal extent must be consistent to allow comparisons between serial radiographs. The proximal extent of the marker should be located at the most proximal extent of the hoof wall identified through digital palpation; rasping the periople at the coronary band to make this landmark more readily and consistently identifiable has been advocated (Cripps and Eustace 1999a). This anatomic landmark can be marked with indelible ink to prevent interoperator variations during serial radiographic studies (Cripps and Eustace 1999a). The ground should be marked with a shoe or preferably with a radiodense marker within the block (Parks and O'Grady 2003; Redden 2003b). Some authors advocate marking the apex of the frog with a radiodense marker such as a thumb tack; however, others find this misleading as the frog is often overgrown which confuses identification of its apex (Parks and O'Grady 2003; Redden 2003d). For horizontal dorsopalmar radiographs, marking of the coronary band with a bead of barium paste at the midquarter prior to obtaining images enhances assessment of the relationship between the palmar processes and ipsilateral coronary band. Likewise, placing a line of barium paste on the abaxial wall may improve estimation of the thickness of the abaxial walls. As mentioned above, the use of digital radiographs has diminished the need to do this.

Radiographic views are standardised (Floyd 2007b) and include a lateromedial, horizontal dorsopalmar and dorsal 45° proximal-palmarodistal oblique (D45° Pr-PaDiO) projection. Lateromedial radiographs obtained for assessment of laminitis should be centred parallel to the ground and the heel bulbs, midway between the dorsal and palmar/plantar surface of the foot, approximately 15 mm proximal to the solar surface of the foot (Parks and O'Grady 2003). Lateromedial radiographs have long been considered essential in evaluation of acute and chronic laminitis; however, they only allow assessment in one plane (O'Grady and Parks 2008). The use of the horizontal dorsopalmar view centred approximately 15 mm above the ground surface has therefore gained popularity and is considered to be critical by several authors (Belknap 2006; O'Grady and Parks 2008). The D45° Pr-PaDiO projection is rarely considered part of a routine laminitic evaluation; however, this view highlights the solar margin of the distal phalanx which aids lesion identification in this area (Herthel and Hood 1999). Occasionally, further oblique horizontal and oblique dorsoproximal-palmarodistal views can also be useful for assessment of the margins of the distal phalanx (Parks and O'Grady 2003). In addition to plain studies, the use of contrast digital venography for evaluation of digital vascular perfusion is favoured by some clinicians; however, discussion of venography is beyond the scope of this paper.

The following section, diagrams and table aims to summarise the documented normal parameters relevant to horses with laminitis as an aid to their radiological evaluation. Use of a radiodense marker of a known dimension on the dorsal surface of the hoof wall allows the effect of magnification on specific measurements to be accounted for. Additionally, where applicable measurement of ratios negates the effect of magnification. Furthermore, the marked effect of individual (breed and size) variation in measurements within the feet and the effect of trimming should be taken into consideration during the radiological evaluation.

Radiological interpretation of the forefeet in the nonlaminitic horse

Lateromedial projections

The dorsal surface of the hoof wall and dorsal surface of the distal phalanx should be parallel or almost parallel (Linford *et al*. 1993; Dyson *et al*. 2011); some studies report that the angle between the ground surface and dorsal surface of the distal phalanx is more acute than the angle between the ground surface and dorsal hoof wall (dorsal hoof wall angle) (Cripps and Eustace 1999a; Kummer *et al*. 2006). The hoof-pastern axis is traditionally thought to be straight in most sound horses (Balch *et al*. 1993). Although it has been described that the dorsal surface of the hoof wall and heels should be parallel (Butler *et al*. 2008), more recently it has been noted that the heel angle of sound horses is slightly more acute (43.5 ± 6.3°) than the dorsal hoof wall angle (Dyson *et al*. 2011). In the front feet of normal horses, the mean dorsal hoof wall angle has been reported as 52.2 ± 3.7° (Dyson *et al*. 2011) consistent with previous findings (means range between 48.2 and 53.6°) (Verschooten *et al*. 1989; Linford *et al*. 1993; Cripps and Eustace 1999a; Eliashar *et al*. 2004).

The dorsal hoof wall should be straight and smooth radiologically in most horses; however, mild concavities (32%) and convexities (18%) have been noted in the dorsal surface of the hoof wall in sound horses (Dyson *et al*. 2011). Attention to the clinical appearance is necessary to verify that an iatrogenically smooth appearance to the hoof capsule has not been created through excessive trimming. The dorsal hoof width is the shortest distance from the dorsal surface of the distal phalanx to the dorsal surface of the hoof wall. In most normal adult feet, the hoof width should be similar along the entire proximal to distal length of the distal phalanx (Redden 2003b), such that the dorsal hoof wall is parallel to the dorsal parietal surface of the distal phalanx. However, the distal value may be slightly less than the proximal value due to the more acute angle of the distal phalanx to the ground surface compared with the dorsal hoof wall angle as noted previously (Cripps and Eustace 1999a; Kummer *et al*. 2006). Occasionally, the dorsal surface of the distal phalanx may appear 'bowed' dorsally in horses with a particularly deep crena in the toe region of the distal phalanx or, alternatively, changes in the dorsal contour of the hoof wall may alter the dorsal hoof width (Dyson *et al*. 2011). There are also variations in the width depending on the breed and size of the horse (Cripps and Eustace 1999a; Redden 2003b). In most Thoroughbreds, Quarter Horses and other light breeds, the width is 14–18 mm (Linford *et al*. 1993; Redden 1997; Cripps and Eustace 1999a) and has been reported as <19 mm (Baxter 1994; Fraley 2007). In Warmbloods, it is reported as 18–20 mm (Sloet Van Oldruitenborgh-Oosterbaan 1999) and in Standardbreds, heavy older brood mares and stallions, it may be even wider at 20–22 mm (Redden 1997, 2003b). Excessive rasping of the dorsal hoof wall can, however, alter these distances so care should be taken in interpretation under these circumstances (Redden 2003b). Redden has stated width of the hoof capsule should be approximately the same as the underlying lamellae and soft tissues (lamellae, nonlamellar dermis and subcutaneous tissues) as identified on digital films or plain films, taken with 'soft tissue exposure' (Redden 2003b), but our observation is that the capsule thickness is usually slightly greater than 50% of the thickness of the hoof. Additionally, there should be no radio-opacities or -lucencies within the hoof.

To overcome the wide individual variation in the dorsal hoof width measurement, some authors describe the dorsal hoof width as a percentage of the palmar length of the distal phalanx measured from the tip of the distal phalanx to its articulation with the navicular bone (Linford *et al*. 1993; Peloso *et al*. 1996). The dorsal hoof width in normal horses should be <30% of the palmar length of the distal phalanx.

The coronary extensor (CE) distance (also referred to as founder distance) is the vertical distance between the most proximal extent of the outer hoof wall immediately below the coronary band and the proximal aspect of the extensor process of the distal phalanx. It relies on accurate positioning of a radiodense marker at the proximal limit of the hoof wall. There is considerable individual (breed and horse size) dependence and therefore the reported values are variable (Cripps and Eustace 1999a). Normal Thoroughbreds have been reported as having a mean CE distance of 3.5 mm with a range of 0–10 mm (Eustace 1990). A mixed breed population of horses has been reported with a mean of 4.1 mm with a range of -1.8–9.7 mm (Cripps and Eustace 1999a; Baxter 2008). Another author has noted that, in most normal horses, it is 0–15 mm (Redden 2003a).

Sole depth is generally measured at the distal margin or apex of the distal phalanx. As 2 distances can potentially be measured (the tip of the distal phalanx to the solar surface of the foot or the tip of the distal phalanx to the ground), it is important to be consistent with measurements. Redden indicates that the true sole depth should be >15 mm thick, consisting of 10 mm for the papillae of the solar corium and 5 mm for the cornified sole (Redden 2003b); however, Linford reported a mean of 11.1 ± 1.6 mm in Thoroughbred racehorses aged 4–9 years (Linford *et al*. 1993). In addition to the sole depth at the toe, some authors also measure the sole depth at the palmar aspect of the palmar process of the distal phalanx which should be approximately 23 mm (Floyd 2007b).

The angle of the solar margin of the distal phalanx to the ground is the angle created between the ground or the distal surface of the hoof capsule and the solar margin of the distal phalanx. Measuring this angle using the distal surface of the hoof capsule in shod horses rather than the ground surface ensures accurate measurement of the relationship between the distal phalanx and the hoof capsule, thus excluding the effects of shoe type, for example, shoes with heel elevation (Redden 2003b). In most normal healthy feet, the angle of the solar margin of the distal phalanx is positive as the palmar processes of the distal phalanx are higher than the apex; however, the range of normal values is dependent on the breed of the horse, the way in which the foot has been trimmed and the way it is shod (Redden 2003b). In a mixed population of sound horses, the mean angle of the solar margin of the distal phalanx relative to the ground was 6.1° with a standard deviation of 2.84° (Smith *et al*. 2004). Others have reported that the angle of the solar margin of the distal phalanx relative to the ground of most horses is between 3 and 5° (Redden 2003c) and should be less than 10° with the solar surface of the distal phalanx sloping distally toward the toe. The junction between the solar surface of the distal phalanx and the dorsal surface of the distal phalanx should be sharp and triangular in shape; deviation from this is usually indicative of modelling of the distal phalanx. The angle of the solar border of the distal phalanx to the ground needs differentiating from the angle of the concave solar surface of the distal phalanx to the ground; this has been reported as 17.4 ± 2.76° in sound horses (Smith *et al*. 2004).

Horizontal dorsopalmar projections

The distal phalanx should appear approximately symmetrical within the hoof capsule in the normal foot. The importance of even weightbearing with straight axial alignment of the limbs when the radiograph is obtained cannot be overemphasised to prevent artefactual differences misleading the radiologist. The authors' preferred method of assessing for medial-lateral symmetry is to first evaluate the distal interphalangeal joint width as this should not vary with mild tilting of the distal phalanx within the hoof capsule in healthy horses and should be approximately even. Drawing lines across the articular surfaces of the distal phalanx or across the solar foramina indicates the relationship between the distal phalanx and the ground (Parks 2007; O'Grady and Parks 2008). The distance between the outer hoof wall and the abaxial edge of the distal phalanx should be measured and be approximately the same at similar heights on both sides of the foot; however, the shape of the abaxial surface of the distal phalanx and the slight variation between the medial and lateral palmar processes must be taken into account. Additionally, flaring of the medial or lateral wall is commonly present in the lower wall of many shod horses and if the flaring is uneven may lead to an inaccurate comparison between the 2 sides. The distance between the solar surface of the distal phalanx and the ground surface should be similar on both sides of the foot; again, slight asymmetry is not uncommon and of no significance if the distal interphalangeal joint space is symmetrical. Markers placed on the proximal medial and lateral walls allow the length of the wall and the relationship between the coronary band and palmar process to be evaluated. The parietal surfaces of the abaxial surface of the distal phalanx should be well demarcated and approximately the same length (Herthel and Hood 1999). They should also diverge slightly distally and not have an upright appearance.

Dorso 45° proximal-palmarodistal oblique projections

The solar margins of the distal phalanx should appear regular, well demarcated and show medial to lateral symmetry in the absence of fragmentation. The vascular channels should not appear enlarged or flared at the solar margin. In a group of sound Thoroughbred racehorses, the mean diameter of the largest vascular channel was reported as 3.4 mm with an s.d. of 0.6 mm (Linford *et al*. 1993) which is similar to previous reports of a mean maximum diameter of 4.5 mm (Rendano and Grant 1978).

Table 1 and **Figures 1a** and **b** demonstrate the reported normal radiological distances and proportions in the front feet of sound horses. Care must be taken in interpretation of these values as there is marked individual (breed and size) variability and many may be altered by farriery; therefore, there is significant overlap between normal and abnormal.

TABLE 1: Table to show reported normal radiological distances and proportions in the front feet of sound horses. Care must be taken in interpretation of these values as there is marked individual (breed and size) variability and many values may be altered by farriery; the measurements in this table do not represent the absolute minimum and maximum of normal values but rather they are representative of the centre of the range

Dorsal hoof wall angle	48–54°
Vertical distance between coronary band and extensor process (CE distance)	-2–15 mm
Dorsal hoof width	14–22 mm
% width hoof capsule of hoof width	50–65%
Dorsal hoof width relative to palmar length P3	<30%
Sole depth at toe	>11–15 mm
Angle between solar margin of distal phalanx and ground	3–8°
Maximum vascular channel diameter	3.5–4.5 mm
Heel angle	43.5 ± 6.3°

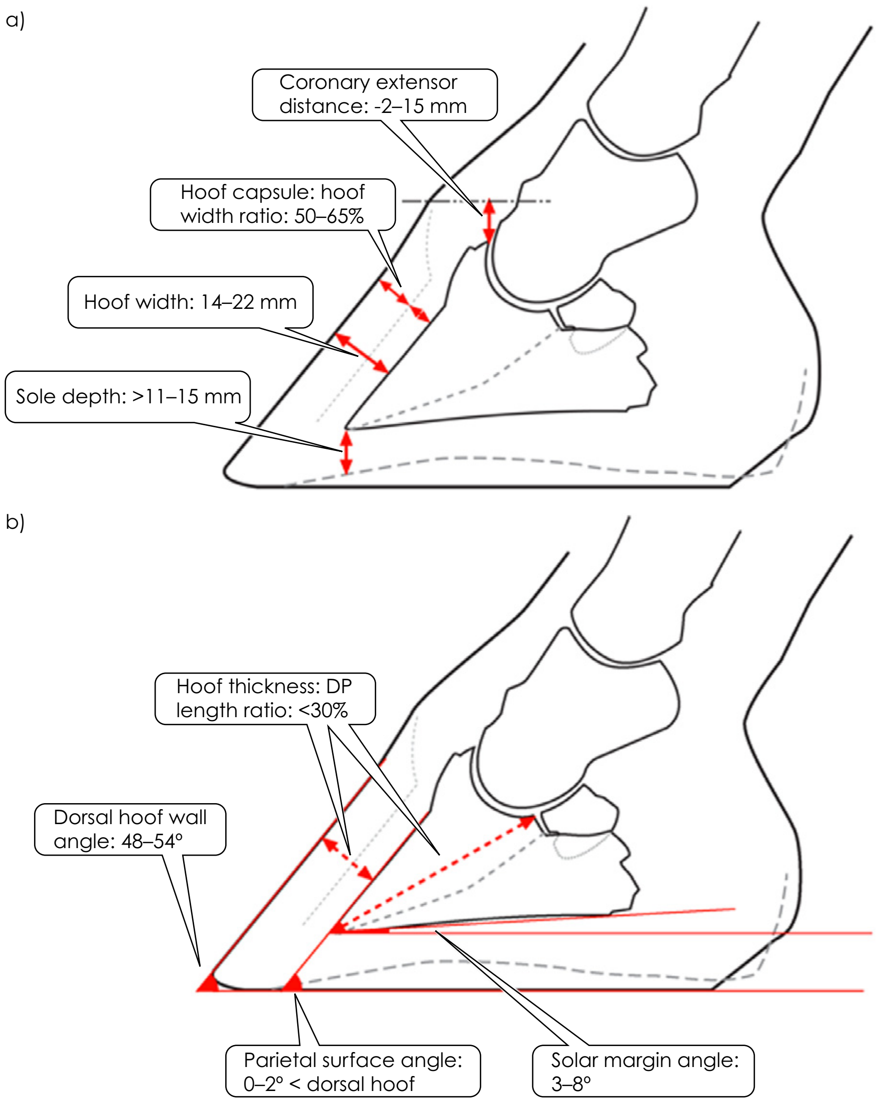

Fig 1: (a,b) Diagrams to show the normal radiological distances and proportions in the front feet of sound horses. Care must be taken in interpretation of these values as there is marked individual (breed and size) variability and many may be altered by farriery; the measurements in these diagrams do not represent the absolute minimum and maximum of normal values but rather they are representative of the centre of the range.

The measurements in these diagrams do not represent the absolute minimum and maximum of normal values but rather they are representative of the centre of the range.

Radiological interpretation of the forefeet in the laminitic horse

Although horses suffering from laminitis can be radiologically quiescent in the early stages of the disease (Baxter 2008), there is a wide array of potential radiological abnormalities that may occur. Broadly, radiological abnormalities result from movement of the distal phalanx in either the sagittal or frontal planes or a combination of the 2 and from the consequences of this movement.

This variable movement ensues as mechanical collapse of the lamellar attachment of the distal phalanx to the hoof wall can occur at any point around the bone (Peloso *et al*. 1996). The most common plane of distal phalanx movement is dorsal rotation, followed by symmetrical distal displacement or 'sinking'. It is likely that most horses have both dorsal rotation and distal displacement of the distal phalanx but that one predominates. Uniaxial distal displacement, most frequently seen medially, is the least common plane of distal phalanx movement (Baxter 2008); however, with the increasing utilisation of horizontal dorsopalmar radiographs, this form of distal phalanx movement may be recognised more commonly.

The radiological abnormalities associated with the development of laminitis include widening of the dorsal hoof, a decrease in sole depth at the tip of the distal phalanx, an increase in the angle of the solar and dorsal surfaces of the distal phalanx to the ground, a coronary band halo and radiolucent lines within the dorsal or solar hoof. These abnormalities will be discussed in more detail; however, it should be remembered that all radiological abnormalities must be assessed and interpreted in light of the clinical signs of the horse, the stage of the disease and any previous radiological findings. Angular measurements, dorsal hoof wall thickness and sole thickness can all be altered by trimming and this needs to be considered when evaluating radiographs (Eustace 2010). Ideally, radiographs would be acquired both before and after trimming; however, when finances preclude 2 sets of radiographs being obtained, pretrimming radiographs are more important than post trimming radiographs because the nature of the trim is dependent on assessment of the pretrimming radiographs.

Evaluation of the lateromedial radiograph

Dorsal rotation of the distal phalanx

Dorsal rotation is the most common and classic form of laminitis where the distal phalanx separates from the dorsal hoof wall and rotates about the distal interphalangeal joint, attributed to mechanical failure of the dorsal lamellae. As soon as it is noted radiologically, and the dorsal surface of the distal phalanx and hoof wall are no longer parallel and in line with the other phalanges, the horse has by definition entered the chronic phase of laminitis. The terms capsular rotation and phalangeal rotation are also used to further define the type of dorsal rotation (Parks and O'Grady 2003).

Capsular rotation is described as divergence of the dorsal parietal surface of the distal phalanx from the surface of the hoof such that the distance between the dorsal hoof and the dorsal parietal surface of the distal phalanx is greater distally than it is proximally. It is assessed by the magnitude of the angle formed by these 2 surfaces (**Figs 2–4**, **6**, **7**, **9** and **10**). In horses with recent dorsal rotation, capsular rotation is inevitably accompanied by phalangeal rotation. Capsular rotation without phalangeal rotation is only seen in horses in which the alignment of the phalanges has been corrected, but the capsular rotation persists (**Fig 3**).

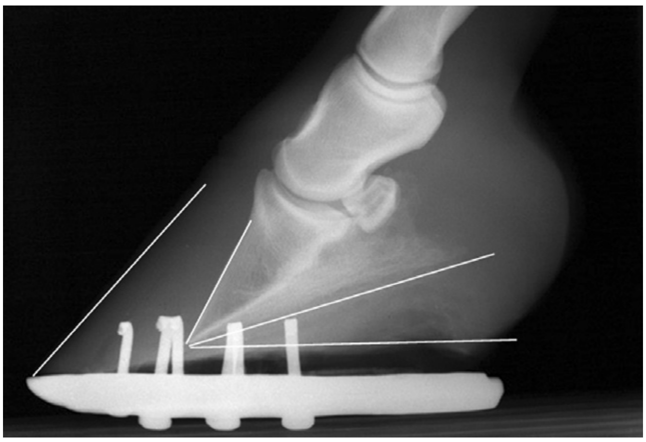

Fig 2: Lateromedial radiograph of the right forefoot of a horse. The dorsal surface of the hoof, dorsal surface of the distal phalanx and solar surface of the distal phalanx are emphasised by the white lines. Additionally, there is a horizontal white line parallel with the ground surface. There is evidence of dorsal capsular rotation of the distal phalanx (divergence of the dorsal parietal surface of the distal phalanx from the surface of the hoof) and there is also phalangeal rotation (deviation of the dorsal aspect of the distal phalanx from a line drawn down the dorsal aspects of the proximal and middle phalanges). In this radiograph, there is also evidence of an increased angle between the solar surface of the distal phalanx and the ground surface and decreased sole depth.

Fig 3: Lateromedial radiograph of the left forefoot of a horse. There is evidence of dorsal capsular rotation (divergence of the dorsal parietal surface of the distal phalanx from the surface of the hoof), but little evidence of phalangeal rotation as this has been largely corrected previously. There is also evidence of modelling of the distal phalanx characterised by flattening of the solar surface and 'lipping' at the dorsal distal surface of the distal phalanx and evidence of a 'lamella wedge' with widening of the dorsal hoof wall.

Fig 4: Lateromedial radiograph of the right forefoot of a miniature horse. There is evidence of both dorsal capsular rotation (divergence of the dorsal parietal surface of the distal phalanx from the surface of the hoof) and phalangeal rotation (deviation of the dorsal parietal surface of the distal phalanx from a line drawn down the dorsal aspects of the proximal and middle phalanges). Additionally, the phalangeal axis to the ground is increased suggestive of a secondary flexural deformity. There is also osteopenia of all osseous structures in the radiograph and modelling of the distal phalanx. The angle of solar margin of the distal phalanx to the ground is also markedly increased and there is deformation of both the dorsal and palmar surfaces of the hoof characterised by a 'lamellar wedge' dorsally and an excessively long heel palmarly.

Phalangeal rotation represents the deviation of the dorsal aspect of the distal phalanx from a line drawn down the dorsal aspects of the proximal and middle phalanges (**Figs 2**, **4**, **7** and **10**). It is assessed by the angle between these 2 lines. Assessment of phalangeal rotation is dependent on the position of the limb; assessment should only be made when the metacarpal bones are perpendicular to the ground and the horse is bearing weight evenly on both front feet.

The difference between capsular and phalangeal rotation becomes important when planning farriery as phalangeal rotation requires attention to the length of the heels.

Radiographic technique is important for assessment of dorsal rotational angles in horses with laminitis as it has been demonstrated that lateromedial radiographs centred on the coronary band that are taken obliquely at ≥5° in a dorsal direction and ≥10° in a palmar direction produce significantly different angles of distal phalanx rotation in cadaver limbs (Koblik *et al*. 1988). The magnitude of the underestimation was independent of the severity of the rotation thereby emphasising the importance of attention to radiographic alignment especially in horses with minimal rotation (Koblik *et al*. 1988). No studies have been performed to assess the effect of the height of focus on the assessment of distal phalangeal rotation to the authors' knowledge; however, consistency between radiographic series is recommended.

Coronary extensor (CE) distance (founder distance)

An increase in the CE distance is most commonly identified when the lamellae collapse evenly all around the hoof due to excessive shear forces. This causes the distal phalanx to drop within the hoof capsule (distal displacement of the distal phalanx, 'sinking'). The solar margin of the distal phalanx therefore becomes closer to the ground also increasing the distance between the parietal surface of the distal phalanx and the dorsal surface of the hoof capsule to >14–19 mm (**Fig 5**). This type of symmetrical distal displacement is the most common form of laminitis in horses that acquire supporting limb laminitis (Peloso *et al*. 1996). However, some degree of sinking is commonly identified in most horses with rotational displacement (Herthel and Hood 1999); if the distal phalanx rotates and the hoof capsule and distal interphalangeal joint maintain their normal position, then some increase in CE distance is inevitable.

Errors in radiographic obliquity do not significantly alter the recorded CE distance (Cripps and Eustace 1999a) in the same way that they alter assessment of dorsal rotation of the distal phalanx. There is a 1.5 mm change in the CE distance for every 100 mm change in beam height (Cripps and Eustace 1999a). Additionally, trimming the hoof capsule does not lead to inaccuracies in evaluation of CE distance (Eustace 2010).

Fig 5: Lateromedial radiograph of the left forefoot of a horse. There is evidence of distal displacement of the distal phalanx (sinking). The coronary band is delineated by radiodense barium paste. The white arrow therefore indicates the level of the coronary band and the double ended black arrow represents the increased coronary extensor distance. The distance between the dorsal hoof and the dorsal parietal surface of the distal phalanx is also increased and the distance between the solar surface of the distal phalanx and the ground surface is decreased. Additionally, there is a radiolucency within the dorsal hoof wall and a defect in the proximal dorsal hoof wall and the toe is excessively long.

Dorsal hoof width

Increases in the dorsal hoof width suggest laminar swelling, oedema and haemorrhage and often precede displacement of the distal phalanx (rotation or symmetrical distal displacement). Although breed dependent, a width >17 mm is suggestive of laminitis in Thoroughbreds (Linford *et al*. 1993). Increases in this width that are of the same magnitude along the entire proximal to distal length of the distal phalanx are suggestive of distal displacement of the distal phalanx (**Fig 5**) whereas a larger increase in the width distally in comparison to proximally is suggestive of dorsal rotation which may be alone or in combination with other patterns of distal phalanx displacement (**Figs 2–4** and **6–9**). Care must be taken when relying on the dorsal hoof width after farriers have trimmed the dorsal hoof wall excessively because this can mask changes in the dorsal hoof width (Redden 2003b). The components of hoof width should also be evaluated; if the dermal and subcutaneous tissue is of greater width than the hoof capsule, then laminitis is more likely and if the hoof capsule is wider, white line disease is more likely (Redden 2003b); however, it should be noted that in horses that have recovered from severe laminitis and have grown a new wall, the new wall is usually significantly wider than the original and this must be taken into consideration. Dorsal hoof widths of ≥30% of the palmar cortical length of the distal phalanx are suggestive of distal displacement of the distal phalanx (Peloso *et al*. 1996).

Sole depth

A sole depth at the toe of <15 mm is abnormal in most horses although Thoroughbreds may have thinner soles (average 11 mm [Linford *et al*. 1993]). Thinning of the sole is suggestive of structural damage as digital venograms performed in horses with soles <15 mm show solar papillae that are bent, compressed or even absent predisposing to further pain and lameness (Redden 2003b). Hence, in horses with laminitis a sole depth of <15 mm is likely to be clinically significant and is suggestive of displacement of the tip of the distal phalanx distally which causes crush injuries to the distal soft tissues (**Figs 2** and **5–7**).

Fig 6: Lateromedial radiograph of the right forefoot of a horse. There is an increase in the distance between the dorsal surface of the hoof and the dorsal surface of the distal phalanx (white double ended arrows) suggestive of symmetrical distal displacement of the distal phalanx. This increased distance is larger distally than proximally suggestive of concurrent dorsal capsular rotation. Additionally, there is a decrease in the sole depth at the toe and the toe is excessively long. Note the radiodense marker within the hoof block that delineates the ground surface.

Angle of the solar margin of the distal phalanx relative to the ground

A high angle of the solar margin of the distal phalanx relative to the ground beyond the normal values of 3–8° is appreciated in horses with dorsal rotation (**Figs 2**, **4** and **7**);

Fig 7: Lateromedial radiograph of the left forefoot of a horse. There is marked thinning of the sole at the toe (white arrows). Additionally, there is evidence of dorsal capsular and phalangeal rotation, an increase in the dorsal hoof thickness and radiolucencies within the dorsal hoof. The angle of the solar surface of the distal phalanx and the ground surface is increased. The dorsal surface of the dorsal hoof is also irregular.

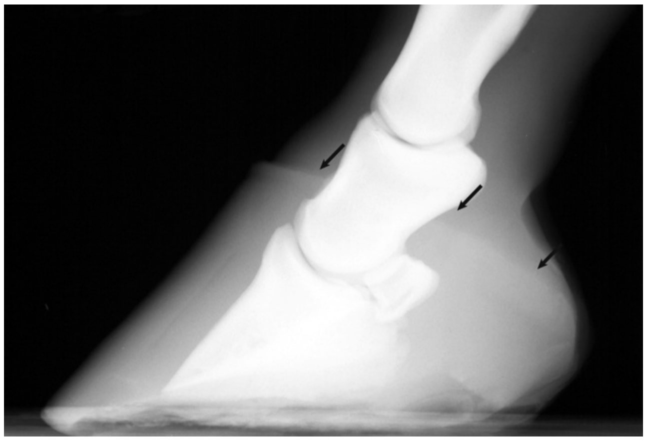

Fig 8: Lateromedial radiograph of the right forefoot of a horse. There is evidence of a coronary band halo (black arrows). Additionally, there is evidence of a thinned sole and there are radioluciencies within the hoof wall.

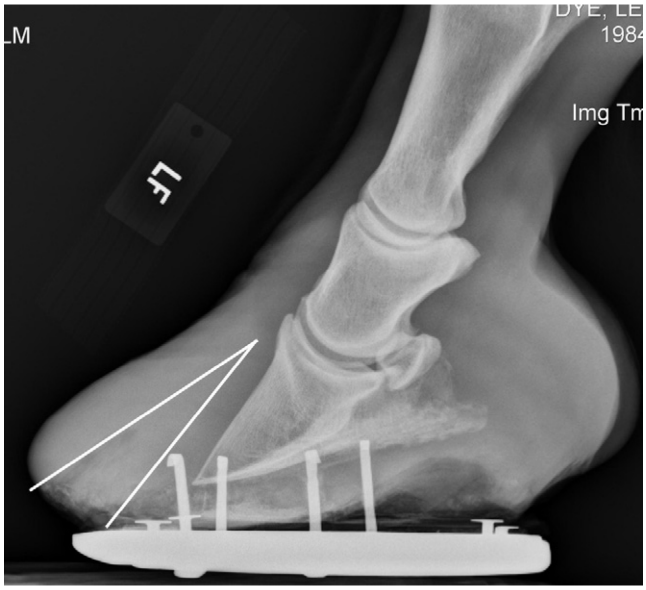

Fig 9: Lateromedial radiograph of the left forefoot of a horse. There is evidence of a 'lamellar wedge' (delineated by the diverging white lines) attributed to progressive increasing stretch and hypertrophy of the lamellae further distally. There is also dorsal capsular rotation and thickening of the dorsal hoof.

however, it may also be seen in horses with flexural deformities of the distal interphalangeal joint, e.g. in horses with club feet and as a result of trimming or shoeing (Redden 2003b).

Coronary band halo

The position of the proximal border of the coronary band is frequently difficult to identify on routine plain radiographs; however, it is easier to detect with manipulations in windowing on digital images. The coronary band can become more obvious if it has associated pathology. In horses with distal displacement of the distal phalanx, the skin of the pastern is drawn distally such that a shelf develops at the proximal border of the coronary band (coronet) that forms an abrupt change in contour of the junction of coronary band and skin. As the distal phalanx displaces even further distally and the skin is drawn below the proximal extent of the coronet, the coronet appears as a radiolucent band frequently termed the coronary band halo (Fraley 2007), which may be identified on either lateromedial or dorsopalmar radiographs (**Fig 8**). Clinical cavitation or depression of the coronary band has been reported as the most reliable clinical indicator of distal displacement of the distal phalanx in a group of 12 horses in which it was only radiologically appreciable in 4 horses (Baxter 1986).

Gas lines

Focal areas of radiolucency of varying sizes, configurations and shapes consistent with 'gas lines' may appear within the dorsal hoof at varying times in horses with laminitis (**Figs 5**, **7** and **8**).

Gas lines in the dorsal hoof in horses with severe acute onset laminitis early in the disease (20–40 h after lameness) generally communicate to the exterior at the coronary band (Herthel and Hood 1999).

Gas lines in the dorsal hoof that appear 2–18 days after an initial laminitic episode (Wagner and Hood 1997) usually do not communicate with the exterior of the foot and are initially 2.2 cm (range 2.0–2.8 cm) from the coronary band (Wagner and Hood 1997). They appear as a slowly developing, thin radiolucent line parallel to the dorsal hoof wall (Wagner and Hood 1997). Histology and mechanical testing of these areas identifies them as mummified lamellar tissue not associated with instability of the distal phalanx within the hoof capsule (Wagner and Hood 1997). The primary epidermal lamellar tissues remain attached to the underlying hypoplastic tissues; however, there is damage to the secondary lamellae and air is located between the remaining primary epidermal and dermal lamellae as well as at the tips of the dermal lamellae where they approach the *zona alba*. Significant numbers of bacteria are not identified nor are tracks leading to the coronary band. It was noted with increasing time in horses with laminitis of 34–150 days duration that the distance between the coronary band and proximal extent of the gas gradually increased with sequential radiographs, presumably moving distally as the hoof wall grew down (Wagner and Hood 1997). With time, it was also noted that the gas lines extended down to the solar surface of the foot (Wagner and Hood 1997). Interestingly, there was one horse that demonstrated signs of an additional acute episode during this period and the distance between the coronary band and proximal extent of the gas line decreased at this stage (Wagner and Hood 1997).

Some radiolucenices within the hoof wall are large irregular air spaces found in horses with more chronic disease after significant distal phalanx movement has occurred (Morgan *et al*. 1999) and these may signify physical separation of the hoof from the distal phalanx attachments or drainage from sepsis within the foot. These gas lucencies are found in the submural or subsolar areas. Although they may commence in the absence of external communication, it is invariably established as the hoof grows. Histologically, the majority appear to represent mechanical failure secondary to excessive forces on hyperproliferative lamellae (Morgan *et al*. 1999). The rapid onset in appearance and irregular shape of these spaces appears to be associated with rapid tissue contraction as it pulls away from the interior surface of the wall (Morgan *et al*. 1999).

The relationship between gas spaces and infection remains unclear. The gas spaces undoubtedly become contaminated when they communicate with the external hoof wall; however, they are normally lined by healthy cornified tissue. Alternatively, some can represent potential sources of sepsis or alternatively can provide a path of least resistance to allow drainage of infected areas within the foot (Morgan *et al*. 1999).

Hoof shape alterations in chronic laminitis

Horses with chronic laminitis may demonstrate changes in the contour of the dorsal hoof wall during the rehabilitation period (Herthel and Hood 1999). Alterations identifiable on lateromedial views include alterations of the contour of the dorsal hoof wall from proximal to distal; the proximal aspect is often parallel to the distal phalanx in contrast to the distal hoof wall, which is divergent from the dorsal surface of the distal phalanx. This concavity of the dorsal hoof wall is suggestive of an underlying 'lamellar wedge' due to progressively increasing stretch and hypertrophy of the lamellae further distally (**Figs 3**, **4** and **9**). Epidermal hyperproliferation occurs within the first 7–10 days after displacement of the distal phalanx and there remains a marked and progressive expansion in the first 28 days after displacement (Kuwano *et al*. 2002; Collins *et al*. 2010). With time and removal by the farrier, this divergent area may become reduced so the dorsal surface of the hoof again becomes parallel with the dorsal surface of the distal phalanx; however, it is not yet possible to determine in which horses the dorsal hoof wall will realign with the distal phalanx. Regardless, the dorsal hoof wall remains thickened suggestive of residual distal displacement of the distal phalanx (Herthel and Hood 1999).

Horses with chronic laminitis may also demonstrate contracture of the digital flexor tendons. The reason for the development of a secondary contracture is unknown, but it could follow the development of a wall growth differential between the heels and the toe, either because the heels have reduced weightbearing that results in increased heel growth or because the toe has reduced growth caused by the disease. Alternatively, it has been postulated that repeatedly placing the nails in the shoe too far palmar on the quarters reduces expansion of the foot with the subsequent development of a flexural deformity (Herthel and Hood 1999). This is radiologically apparent as a broken forward angle centred on the distal interphalangeal joint and the presence of upright feet with inappropriately long heels. Contracture in itself can be a cause of lameness so this issue should be addressed if recognised during the rehabilitation of a horse suffering from chronic laminitis.

Osseous alterations in chronic laminitis

Rotational and distal displacement cause increased loading and inflammation of the solar surface of the distal phalanx which models in reaction to the increased loading. The solar surface of the bone can lose its normal concavity (**Figs 3**, **4** and **10**) and the bone's solar and parietal surfaces may shorten (Herthel and Hood 1999). Additionally, a change in the angle of the solar palmar surface becomes evident most easily appreciated on the lateromedial views (Herthel and Hood 1999).

Osteoproliferation (lipping) at the distal dorsal parietal surface of the distal phalanx (**Figs 3**, **4** and **10**) can also occur in

Fig 10: Lateromedial radiograph of the left forefoot of a horse. There is marked modelling of the distal phalanx which has resulted in a flattened solar border and shortening of the apex of the bone. Additionally, there is new bone formation at the dorsal distal surface of the distal phalanx. There is also evidence of capsular and phalangeal rotation.

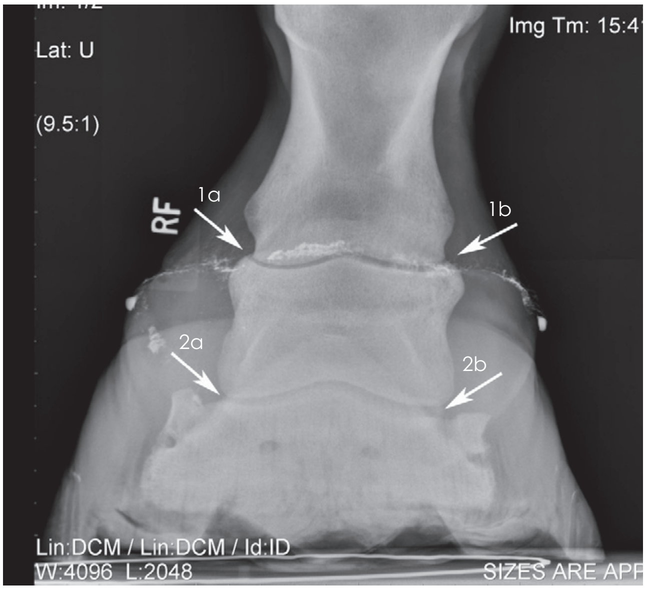

Fig 11: Horizontal dorsopalmar radiograph of the right forefoot of a horse. Lateral is to the left of the image and the coronary band is delineated by barium paste. There is widening of the medial aspect of the distal interphalangeal joint (arrow 2b) compared with the lateral aspect (arrow 2a). This is in contrast to the more symmetric lateral (arrow 1a) and medial (arrow 1b) joint space of the proximal interphalangeal joint. This is suggestive of uniaxial medial distal displacement of the distal phalanx. Additionally, the distance between the solar surface of the distal phalanx and the ground surface on the medial aspect is shorter than on the lateral aspect and the distal phalanx appears 'tilted' within the hoof supportive of uniaxial distal displacement.

response to altered forces in this area (Herthel and Hood 1999). These exostoses can be secondary to new bone proliferation, in the presence or absence of concurrent adjacent osteolysis. Severe radiological changes including complete loss of normal contour (**Fig 10**), sequestrum formation and localised regions of necrosis of the distal aspect of the distal phalanx may appear in chronic severe cases.

Osteitis of the dorsal parietal surface of the distal phalanx may also occur secondary to altered forces exerted by the collagen attachments on the surface of the bone; however, this abnormality is only appreciated on high quality radiographs (Herthel and Hood 1999). These exostoses are not necessarily associated with active disease (Herthel and Hood 1999).

Disuse has been implicated as a cause of bone reabsorption. These changes include a rarefaction of the bone (**Fig 4**); however, these changes are best seen on a D45° Pr-DiPaO view.

Evaluation of the horizontal dorsopalmar radiograph

Asymmetry of the distal interphalangeal joint space

In a horse with laminitis, unevenness of the distal interphalangeal joint space in which the wider side of the joint space is on the same side of limb in which the distal phalanx appears to be tilted distally is also suggestive of uniaxial distal displacement (**Figs 11–13**). However, because an uneven joint space can also be caused by poor positioning or foot imbalance, this finding must be interpreted cautiously. Horses are most likely to demonstrate medial rather than lateral distal displacement (Herthel and Hood 1999), the predisposition for which may be associated with the nonuniform forces applied through the horse's axial skeleton (Hood 1998); the observation that this form of distal displacement occurs on the medial side of the foot in conjunction with the foot offset laterally to the axis of the metacarpus is consistent with this explanation, but further studies are needed to validate this hypothesis.

Asymmetry of the distal phalanx within the hoof capsule

Lines drawn across the articular surface of the distal phalanx or through the solar foramina that are not parallel with the ground surface in the weight bearing horse suggest that the distal phalanx is not level within the hoof capsule, but tilted distally towards one side (Parks 2007; O'Grady and Parks 2008) (**Fig 12**). This is usually accompanied by a shorter distance between the solar surface of the distal phalanx and the ground surface on the side on which the distal phalanx appears to be displaced distally. These are usually the most obvious radiological signs that the distal phalanx has displaced uniaxially. However, care must be exercised in interpreting these findings because the distal phalanx may be tilted within the hoof capsule in horses that do not have laminitis and the distal border of the distal phalanx is subject to modelling by other disease processes. Therefore, they must be interpreted in conjunction with other radiological findings and most importantly the clinical signs.

Medial and lateral hoof width

The width of the hoof between the abaxial borders of the distal phalanx and surface of the adjacent hoof capsule on both the corresponding medial and lateral sides of the foot must be evaluated and compared. When the width of the hoof on one side is increased in relation to the other in a horse with laminitis, it is suggestive that the distal phalanx has displaced distally

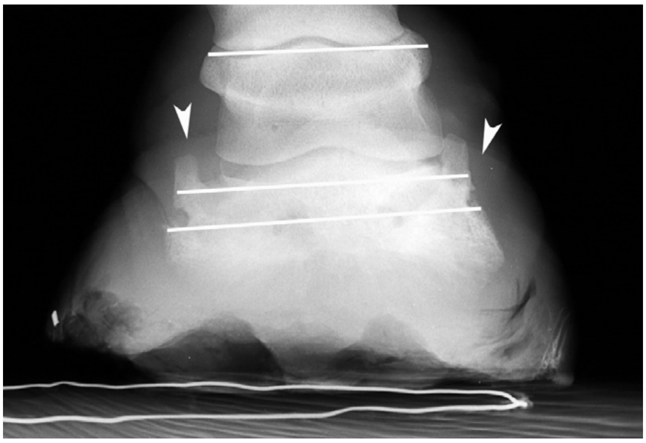

***Fig 12:** Horizontal dorsopalmar radiograph of the left forefoot of a horse. Medial is to the left of the image. The lines across the articular surface of the distal phalanx and the solar foramina are not parallel with either the line through the proximal interphalangeal joint or the weightbearing surface of the foot. The medial parietal surface of the distal phalanx appears more upright and shorter than the lateral parietal surface of the distal phalanx. Additionally, the medial aspect of the distal interphalangeal joint is wider than the lateral aspect of the joint. The hoof wall is markedly increased in thickness on the medial aspect of the hoof in comparison to the lateral aspect of the hoof. The radiographic abnormalities are suggestive of uniaxial medial distal displacement of the distal phalanx. Additionally, there is a subtle radiolucent line (white arrowheads) overlying the coronary band (coronary band halo) suggestive of biaxial distal displacement of the distal phalanx.*

on that side of the foot (**Figs 11–13**). Again, there are other pathological processes that can cause an increase in the width of one wall compared to the other, but when present with a distal phalanx that is tilted distally and a distal interphalangeal joint that is wider on the same side as the distal tilt, together they are very suggestive of uniaxial distal displacement.

Coronary band halo
Similarly to lateromedial radiographs, a subtle radiolucent line overlying the coronary band (coronary band halo) may be present in horses with acute sinking (Fraley 2007) on dorsopalmar radiographs (**Fig 12**).

Osseous changes
Occasionally, the medial or lateral parietal surfaces of the distal phalanx may lose their normal contour and divergence from proximal to distal and appear more upright (**Figs 11–13**); this may be associated with osteolysis secondary to disuse but these radiological changes are easier to identify on D45° Pr-PaDiO views.

Evaluation of the dorsal 45° proximal palmarodistal oblique radiograph

Osseous abnormalities
Although potentially appreciable on lateromedial and horizontal dorsopalmar views, bone reabsorption secondary to disuse is most readily seen on a D45° Pr-DiPaO view. Symmetrical alterations in the normal solar contour and widening of the vascular channels at the peripheral distal

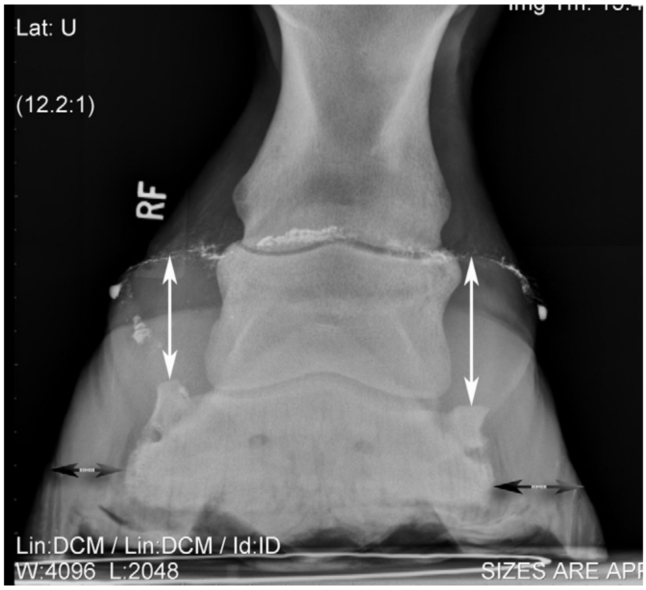

***Fig 13:** Horizontal dorsopalmar radiograph of the right forefoot of a horse. Lateral is to the left of the image and the coronary band is marked with barium paste. The distal phalanx is tilted so that the medial side is closer to the ground than the lateral side. There is a longer distance between the coronary band and the palmar process of the distal phalanx on the medial side compared with the lateral side of the hoof (white double ended arrows). Additionally, there is a longer distance between the distal abaxial aspect of the distal phalanx and the hoof wall on the medial aspect of the foot compared with the lateral aspect of the foot (black and white double ended arrows). There is also widening of the medial aspect of the distal interphalangeal joint and the sole is thinner on the medial side of the distal phalanx than the lateral side. These signs together are almost pathognomic for uniaxial medial distal displacement of the distal phalanx.*

edge of the bone frequently accompany bone reabsorption (Herthel and Hood 1999) but are not specific for laminitis.

Fractures of the solar margin through the parietal surfaces of the distal phalanx may also occur secondary to increased motion of the distal phalanx within the hoof in combination with reduced bone density secondary to disuse (Herthel and Hood 1999). These changes can sometimes be difficult to differentiate from sepsis of the distal phalanx and are best appreciated on the D45° Pr-DiPaO view and sometimes may be better characterised on other oblique views.

Radiological signs of laminitis as prognostic indicators

There are several studies that have examined radiological changes in horses with laminitis and tried to correlate these with the prognosis. Unfortunately, combining studies to improve interpretation is complicated because the studies examined different radiological parameters. The prognostic significance of the degree of capsular distal phalangeal rotation has been investigated and in one study was inversely correlated with return to athletic performance (Stick *et al*. 1982). In a study of 91 horses, those with rotation less than 5.5° returned to their former athletic function whereas those with more than 11.5° of rotation were unable to return to their former athletic function (Stick *et al*. 1982); however, there are reports of success in returning horses to athletic function after

≥11.5° of dorsal rotation in a smaller population treated with heart bar shoes (Eustace and Caldwell 1989). Other studies have also reported that horses that return to athleticism have significantly less dorsal rotation than horses that remain intermittently or persistently lame (Hunt 1993). However, in this same study there was no significant difference between the degree of phalangeal rotation in horses that were subjected to euthanasia or those returned to athletic soundness (Hunt 1993). The authors hypothesised that this could be attributed to the short survival time of horses with severe acute laminitis that is insufficient to allow for rotation or distal displacement of the distal phalanx to occur (Hunt 1993; Baxter 2008). Cripps and Eustace (1999b) found that radiological evidence of dorsal rotation was prognostically significant; however, other radiological parameters were more significant (Cripps and Eustace 1999b). More recent studies have not found the dorsal rotation angle a useful prognostic indicator for survival (Eastman *et al*. 1998).

The prognosis for horses and ponies of differing heights are not significantly different (Cripps and Eustace 1999b) although ponies have been reported to demonstrate significantly more distal phalanx rotation in comparison to horses (Stick *et al*. 1982).

Using stepwise regression, one study determined that the CE distance was the most significant prognostic parameter for horses that had a palpable depression just above the coronary band that extended a variable extent, but not all of the way, around the coronary band (Cripps and Eustace 1999b). It has been noted that horses with chronic laminitis, with a CE distance of <7.9 mm, were treatable in contrast to those with a CE distance of >15.2 mm very few of which survived or were rideable (Cripps and Eustace 1999b). It is commonly considered that distal displacement of the distal phalanx is associated with a poor prognosis (Baxter 1986); however, more recently, this has been questioned by some authors (Hood 1999). It is also of note that treatment of distal displacement of the distal phalanx varies from treatment of dorsally rotated horses. Horses with distal displacement generally require longer periods of medical management and surgical intervention is seldom indicated (Parks and O'Grady 2003).

Cripps and Eustace (1999b) found that the severity of lameness, presence of perforation of the sole and number of feet affected were significant prognostic indicators; however, they were less significant prognostic parameters than the CE distance (Cripps and Eustace 1999b). The severity of lameness was also previously noted to be associated with outcome (Hunt 1993), but there are some horses with severe lameness with no pathological alteration to the normal digital anatomy and therefore a better prognosis.

A sole depth of <15 mm and a high angle of the solar margin of the distal phalanx to the ground in horses with laminitis have been reported as useful indicators of the difficulty of treatment and rehabilitation of horses with laminitis (Parks and O'Grady 2009). Horses with chronic laminitis and sole depths of <10 mm and an angle of the solar margin of the distal phalanx of >15° have been recommended by some authors as candidates for deep digital flexor tenotomy and immediate digit realignment (Floyd 2007a). Others have reported that progressive dorsal rotation of the distal phalanx unresponsive to conservative treatment, unremitting pain in horses with dorsal capsular rotation and secondary flexural deformities of the distal interphalangeal joint as noted by phalangeal rotation are indications for deep digital flexor tendon tenotomy (Parks and O'Grady 2003). These indications again highlight the importance of close clinical monitoring and repeated radiographic series to thoroughly evaluate the disease.

A coronary band halo is suggestive of a circumferential loss of structural integrity of the lamellae and has therefore been associated with a poorer prognosis than dorsal rotation (Hunt *et al*. 1991; Pollitt 1996).

Radiolucent gas lines within the dorsal hoof wall seen early on in horses with acute severe disease are associated with a poor clinical prognosis (Herthel and Hood 1999). In contrast, those that appear as a slowly developing thin radiolucent line after an initial laminitic episode are not useful prognostically (Wagner and Hood 1997). The large irregular gas radioluciencies are also not useful prognostically, but are generally found in horses with more chronic disease after significant distal phalanx movement has occurred (Morgan *et al*. 1999).

Osteoproliferation (lipping) at the distal dorsal parietal surface of the distal phalanx appears to have no prognostic significance.

Asymmetric distal displacement of the distal phalanx is less well recognised than dorsal rotation or distal displacement so there is limited information regarding prognostic indicators; however, it is recognised that in itself, this pattern of displacement has an inferior prognosis than the other distal phalanx displacements reported. Only 65% of 11 horses with asymmetric displacement were treated successfully with wooden shoe application (O'Grady *et al*. 2007).

Conclusions

Interpretation of the horse with suspected laminitis is more complex than solely identifying the presence or absence of dorsal rotation. A thorough assessment of radiographs is essential as many abnormalities can be evident concurrently (Parks 2007).

There is controversy regarding the prognostic value of some of these radiological changes (Stick *et al*. 1982; Hunt 1993; Herthel and Hood 1999; Cripps and Eustace 1999b). Large scale studies investigating correlations between radiological parameters and prognosis are warranted. The most important factor in the long-term prognosis of the horse with laminitis is the extent of laminar pathology which influences the degree of instability between the distal phalanx and hoof wall; however, this is very difficult to determine (Redden 1997; Hunt 1998, 2008). Advanced diagnostic imaging modalities in conjunction with clinical signs may assist evaluation in the future, but currently assessment of a horse with laminitis relies on close attention to detail of serial plain radiographs, clinical evaluation and sometimes venographic studies.

Authors' declaration of interests

No conflicts of interest have been declared.

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