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*Review*

# Magnetic resonance protocols in equine lameness examination, used sequences, and interpretation

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## Abstract

Magnetic resonance is a great diagnostic tool in equine lameness examination. Its value is most significantly visible in evaluating distal extremities. Problems with podotrochlear apparatus, laminitis or distal interphalangeal joint osteoarthritis are the most common disorders diagnosed in equine patients. Without using magnetic resonance it was impossible to clearly assess which structures are involved in each of these diseases. One of the most important things in MRI is the choice of sequence. Most commonly used are T1 GE, T2 FSE, STIR and T2\* GE, in sagittal, transverse and dorsal planes. To make a reliable diagnosis it is important to compare findings in all these sequences.

**Key words:** magnetic resonance sequences, equine lameness, protocols

## Introduction

Pain associated with podotrochlear apparatus is responsible for about one-third of chronic forelimb lameness in equine patients (Colles 1982). Without using magnetic resonance it was impossible to make detailed diagnosis antemortem, because damage to several structures within the hoof capsule may occur concurrently and none of imaging modalities, except magnetic resonance, gives a possibility to provide information about both soft tissues and osseous injuries (Mehl et al. 1998, Kleiter et al. 1999, Widmer et al. 2000, Tucker and Sande 2001, Whitton et al. 2003, Werpy 2004, Tucker and Sampson 2007). In chronic laminitis laminar disruption, areas of laminar gas, laminar fluid and bone medullary fluid, as well as increased size and number of vascular channels, alter-

ations in the corium coronae, and distal interphalangeal joint distention, can be observed with MRI but not with radiography (Murray et al. 2003). Radiography is also limited when evaluating the joint cartilage, which is not visible on radiographs (Choi and Gold 2011). It only allows to visualize the secondary irreversible changes like narrowing of the joint space distance (Boegard et al, 1998) or osteophyte formation (Gold and Mosher 2009, Olive 2010). This is especially useful in diagnosing of septic arthritis, when arthrocentesis cannot be performed and is visible with joint distention with concurrent bone and extracapsular tissue hiperintensity (Easley 2011). In horses with navicular foot pain, radiography is also limited, while many of these patients have no radiological changes (Dyson and Marks 2003, Murray and Mair 2005). Ultrasonography is limited within the hoof capsule.

(Busoni and Denoix 2001). Collateral ligaments desmopathy of the distal interphalangeal joint (DIP joint) has a prevalence of 15-30% in horses undergoing MRI examination (Dyson et al. 2005, Martinelli and Rantanen 2005), but when using only ultrasonography lesions in the distal portion of these ligaments are difficult to detect (Martinelli and Rantanen 2005). Magnetic resonance imaging is also the only imaging technique which provides complete information about trabecular bone lesions in phalanges (Olive 2009) and the navicular bone (Dyson et al. 2005). Magnetic resonance imaging has become a cutting edge in equine orthopedy. It can provide detailed information, but the examiner should be aware of anatomic variations as well as artifacts that may lead to misdiagnosis (Murray and Dyson 2007).

### Sequences

When the patient is exposed to a short RF pulse, protons in the tissue absorb the energy and change their alignment within the main magnetic field, which results in decay of longitudinal magnetization and transverse magnetization increase. When the RF pulse is switched off protons relax and emit signal which is collected to create an image on a computer (Weishaupt et al. 2006, Chaby et al. 2011).

Different pulse techniques which produce images depend on the spin-lattice relaxation time (T1, where the energy is given back to the environment) and spin-spin relaxation time (T2, where the energy is transferred between two nuclei) (Gore 1986). As a result of variable tissue properties, different tissue types appear in shade of gray, what is determined by used sequence (Werpy 2004), by tissue chemical composition and/or physiologic characteristics (Gore 1986), as well as the mobility and density of hydrogen nuclei within the tissue (Murray and Dyson 2007).

One of the most important things in clinical MRI is the choice of RF pulse sequences, what is based on developed study protocols, in order to receive the best diagnostic information in the possibly shortest time (Gore et al. 1986, Tucker and Sampson 2007). Choosing special TR (the time between two excitation RF pulses) and TE (the time between the pulse and data collection), the examiner can determine the tissue appearance by influencing the choice of the sequence (Bolas 2011). Thus, using short TR and short TE will result in T1-weighted image, dependent on longitudinal relaxation time, choosing long TR and long TE will result in T2-weighted image, which depend on transversal relaxation time (Weishaupt et al. 2006, Chaby et al. 2011). When the examiner chooses long TR and short TE, tissue appearance is no more in-

fluenced by the relaxation properties but by the density of protons within the tissue. This image is called PD-weighted (proton density).

Standard protocol consist of T1-weighted, T2-weighted, PD and fat suppressed images, which include Spin Echo (SE), Turbo Spin Echo (TSE), Gradient Echo (GE), and Inversion Recovery (IR) (Tucker and Sampson 2007). The difference between them is the way and the time in which RF signals are pulsed into the tissue and then collected to produce an image (Tucker and Sampson 2007). SE sequence is obtained by using a combination of 90° pulse followed by 180° pulse. However, this combination is quite time consuming. To decrease the examination time and lower the time under general anesthesia, examiner can use faster sequences, what can be achieved in two ways. Firstly, by decreasing the time between two 90° pulses, and thus receiving fast spin echo (FSE) sequence (or turbo spin echo – TSE), which also provides images of higher resolution and fluid contrast when compared to traditional SE (Westbrook et al. 2005, McRobbie 2007). Secondly, by reversing the direction of magnetic field gradient and by sending a puls which is less than 90°. The latter combination is called gradient echo sequence (GE). GE and SE sequences have higher signal to noise ratio, that is why images are of higher resolution, when compared to inversion recovery sequences (Werpy 2007). GE sequences are superior to typical SE, because they use short repetition times, and they are less time consuming, but they are also more susceptible to magnetic field heterogeneities (Tucker and Sampson 2007). GE images are also said to provide less soft tissue contrast and differentiation of fluid from tissue in comparison to PD and fat suppressed images (STIR- short tau inversion recovery) (Maher et al. 2011). T1w sequences are useful for describing anatomical details (Werpy 2004, Mair 2005, Tucker and Sampson 2007). In T1-weighted images, the postmortem synovial fluid and the articular cartilage have high signal intensity, while tendons and ligaments are of low signal intensity (Erickson et al. 1991, Crass et al. 1992, Erickson et al. 1993, Kleiter 1999). However, when assessing the articular cartilage in living patients it has intermediate signal intensity with adjacent low signal intensity of synovial fluid (Stoller 1993, Haaga et al. 1994). According to Werpy et al. (2010) T1w GE sequence on low-field system was the most accurate for articular cartilage lesion detection. T1w images also provide good visualization of bone structures, because of the contrast between hypointense bone margin and the hyperintense soft tissues (Werpy et al. 2006, Olive et al. 2010). Although, it should be mentioned that the fibrotic tissue within the joint capsule or soft tissue attachment concurrent to osteophytosis may result



Fig. 1. 3D Sharc sequence in the sagittal plane of the right front foot in the twelve years old hannover gelding with the history of six months lameness improving after palmar digital nerve block. There is distention of the navicular bursa (arrow), and thickening of the collateral sesamoidean ligament (arrow head).

in altered signal which is usually decreased (Olive et al. 2010). Pathology as oedema or increased capillaries causes the affected tissue appears darker than healthy tissue on T1w images (Murray and Mair 2005).

T2w sequences are useful when looking for fluid, which is hiperintensive thus easily identified (Werpy 2004, Murray and Dyson 2011) (Fig. 1). Acute injuries provide increased signal intensity what is the result of the greater water content in cases such as oedema, cellular infiltration, or hemorrhage, and in this pathology stage T2w image is preferred (Mair and Kinns 2005). In Schramme et al. (2010) research the signal from surgically induced superficial digital flexor tendon lesions decreased firstly in T2 TSE sequence suggesting the usefulness of that image in detecting acute injuries and recognition of the fibrous scar tissue in later stages.

Another useful sequence is proton density sequence (PD), which depends on the amount of protons within the tissue. PD images provide good anatomical details, and when compared to T1w images, the contrast is higher (Werpy 2004). They show any change in the density of protons, causing the production of different signal intensities among injured tissues. According to Murray et al. (2007), PD images are accurate to show the position of the distal phalanx, but pathologies among tendons and ligaments are less clear. Werpy et al. (2010) suggest PD-FS (fat suppression) is the sequence of choice in high-field systems to detect articular cartilage lesions.

The pulse sequence that is needed when performing MR examination is a fat suppressed sequence, which is the way to remove signal from fat and thus improves identification of fluid within the bone and soft tissues. It is used especially on PD and T2w

sequences, but can also improve T1w contrast between the articular cartilage and synovial fluid (Murray and Mair 2005, Werpy 2007). Fat suppression may be achieved by using short tau inversion recovery sequence (STIR), as well as fat saturation technique (Peterfy 1997, Bushberg 2002, Murray and Mair 2005, McKnight 2012). The first method gives higher contrast and the latter one is more selective (Murray and Mair 2005). However, fat saturation technique is not reliable in low-field system, because of little difference in the frequency of protons in water and fat (Werpy 2007). In STIR sequence, 180° pulse is applied before the main 90° pulse, which results in flipping the longitudinal magnetization into the negative axis. When the 90° pulse is applied, there is no signal from fat because at this time fat has no longitudinal magnetization, while water magnetization is negative resulting in signal emission (Adrian 2012). In fat suppressed images hypointense bone margin is better distinguished from hyperintense adjacent soft tissues because of higher contrast between them (Olive 2010). But when compared to FSE and GRE sequences, inversion recovery images are more time consuming and have lower resolution (Werpy 2012).

### Artifacts

Artifacts may be derived from imperfections in MR system, differences between pulse programming and pulse produced or from movements of the patient, which are called patient-related artifacts (Murray and Dyson 2007). Patient movements are mostly the problem in standing MRI, but in anesthetized horses, physiological motion due to breathing or blood flow may also cause imperfections in images, and it is important not to misinterpret them as pathological changes (Murray and Dyson 2007). Metallic artifacts are better seen on GE than on SE sequences (Murray and Dyson 2007). They are caused by different metallic objects like hoof nails, screws, pins or intramedullary nails. It is said that some artifacts may be seen even after removal of implants, especially when screws and pins are used additionally to intramedullary nails (Bagheri et al. 2010). Titanium, platinum, or gadolinium are paramagnetic materials, which contain unpaired electrons, that align parallel or antiparallel to main magnetic field, and thereby produce higher net magnetization (Boxerman et al. 1996). When more dipoles align parallel, the field signal is accentuated (Kaur et al. 2007). These susceptibility artifacts may be reduced by using spin echo (SE) pulse sequence (Kaur et al. 2007), however they are less marked in low-field systems than in high-field systems (Bellon et al. 1986, Farahani et al. 1990, Sta-

bler et al. 2007). Magic angle phenomenon is the cause of increased signal on short echo time images, when the tendon or ligament is positioned in 55° to the main magnetic field (Li and Mirowitz 2003). Lower TE values result in greater magic angle effect (Erickson et al. 1991, Erickson et al. 1993, Hayes, Parcellada et al. 1996, Zurlo et al. 2000), so this phenomenon can be avoided by increasing TE values (Peh and Chan 1998). When the tendon is positioned in 55° to the main magnetic field, the T2 relaxation time increases approximately 100 times, to 22 ms (Fullerton et al. 1985, Li and Mirowitz 2003). To distinguish magic angle effect from pathologic change, examiner should compare T1w images to T2w images where phenomenon is less apparent (Erickson et al. 1993). Interestingly, magic angle may be used for detection of tendon lesions. Naturally occurring lesions which have low signal on all standard images, are impossible to detect, due to the lack of contrast between them and the healthy tendon, however, they become visible when the normal tendon appears brighter with magic angle image (Spiret et al. 2012).

Truncation artifacts produce hyperintensive lines around the interfaces of high and low signal, and they are said to be more common in low-field systems (Arena et al. 1995). They may be a cause of pronounced signal intensity for as much as 22% of actual intensity (Frank et al. 1997). The examiner should keep in mind that increased signal within the tissue is not always the result of pathology, but may be connected with imaging failures.

### Protocols

Tucker and Sampson (2007) suggest that for foot and pastern imaging sequences as sagittal, transverse and dorsal PD and T2 STIR are the basic. Additionally to standard protocol in evaluation of DIP joint multiple oblique planes can be obtained, especially when it is indicated by results from routine straight planes (Olive 2010). According to Sherlock et al. (2007) good protocol for scanning both the distal and middle phalanges consists of 2D T1 GE, 3D T1 GE, T2 FSE and STIR. Olive et al. (2009) additionally to this protocol, also used sequences as 2D T2\* GE and 3D T2\* GE, all in three planes- sagittal, frontal and dorsal. T2\* relaxation (T2 star) is achieved with gradient echo sequence as a consequence of transverse magnetization decay and the influence of spin-spin relaxation and magnetic field inhomogeneity (Chavhan et al. 2009). T2\* GE image is helpful in detecting hemorrhage, vascular malformations, and is useful for articular cartilage evaluation which is more hyperintense, compared to hypointense bones (Chavhan et al.



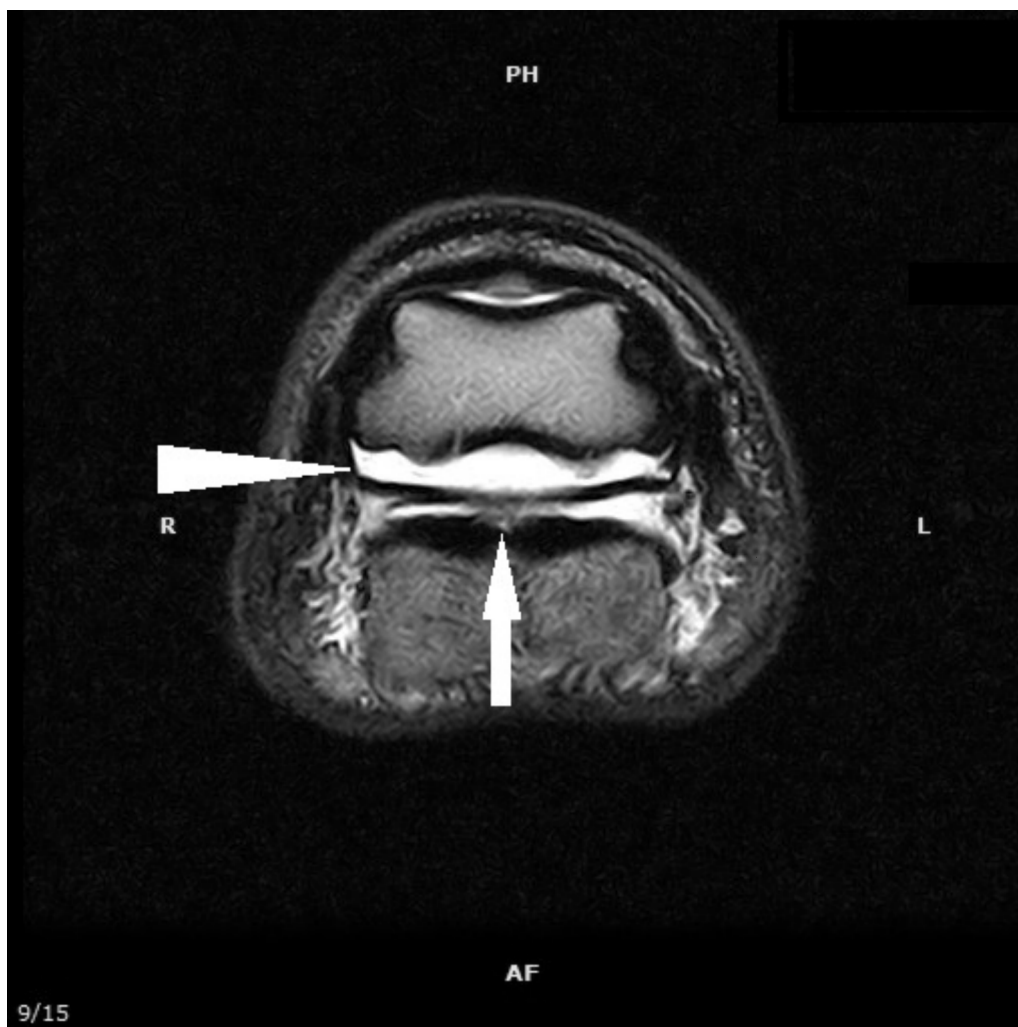


Fig. 2. Transverse T2 FSE image of the left front foot in eight years old wielkopolski horse gelding with history of four months lameness improving after palmar digital nerve block. There are adhesions between the collateral sesamoidean ligament, navicular bursa and deep digital flexor tendon (arrow). The distal interphalangeal joint recess is distended (arrow head).

2009). This sequence gives good view for assessing distal phalanx vascularity, and bone surface irregularities, especially on fat saturated T2\* GE (Murray et al. 2007). T2\* GE is also the most useful sequence in detecting solar penetrated wounds, because of short scanning time, and due to improvement of hemorrhage visualization (Del Junco et al. 2012). T2\* GE should be used especially when looking for hyperacute blood, because it detects effects of methemoglobin and deoxyhemoglobin (Edelman 1986, Kidwell et al. 2004). The value of T2\* GE is limited in protocol for deep digital flexor tendon, while its signal is similar to T1 GE and does not significantly change during the process of healing (Vanel et al. 2012). In standing low-field MRI basic protocol may consist of T1 GE, T2 FSE and STIR in sagittal, transverse and frontal planes (Mair and Kinns 2005). When looking for magic angle effect in collateral ligaments of distal interphalangeal joint Spriet et al. (2007) have chosen

sequences as SE T1, PD TSE, T2 TSE, T1 3D GE dorsal and transverse views. For diagnosing navicular bursa adhesions Holowinski et al. (2012) have recommended to use images in sagittal and perpendicular to the deep digital flexor tendon transverse planes favorably in PD, STIR and T2w sequences (Fig. 2).

### Pathology

The MR properties of a tissue are altered by damage. The stage of damage and healing may be determined by differences in signal intensity patterns, the shape and size of different structures (Murray and Dyson 2011). To assess the nature of pathological change, it is important to compare images in all sequences, and ideally in all three planes-transverse, sagittal and dorsal (Kleiter 1999, Dyson and Murray 2007). Increased signal in the injured ligaments on

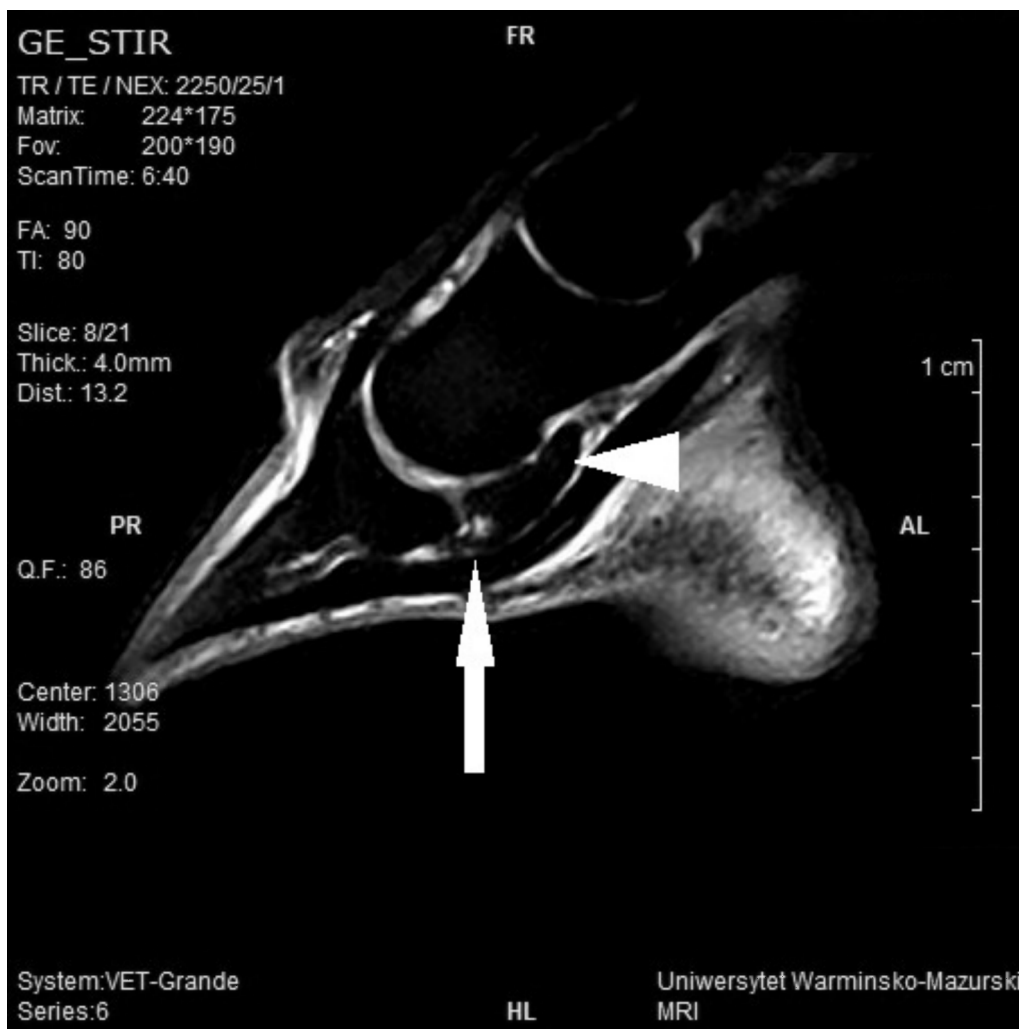


Fig. 3. Sagittal STIR GE image of the foot in the same horse as in Fig. 1. There is a hyperintense focal area of increased signal intensity within the distal border of the navicular bone suggesting navicular cyst (arrow). There is also thickening of the collateral sesamoidean ligament (arrow head).

PD, T2w and STIR images were consistent with inflammation/degenerative changes, while decreased signal on PD and T2w is consistent with fibrosis/scarring (Selberg and Werpny 2011). Maher et al. (2011) have suggested that tendon lesions with increased signal on PD images without signal increase on STIR and T2w images can be associated with degeneration. What is more, this pattern is visible during early stages of injury, and can retain even months or years after tendon fiber disruption (Maher et al. 2011). Vanel et al. (2012) have assumed that STIR FSE sequence is the most reliable in deep digital flexor tendinopathy outcome and decreased signal was associated with lameness improvement. Tendons or ligaments that are oriented in  $55^\circ$  to  $B_0$  will be hyperintense on short TE images, what is due to the magic angle effect (Spriet et al. 2007). Also some physiological signal

variations between paired ligaments, like collateral ligaments of the distal interphalangeal joint may exist (Gutierrez-Nibeyro et al. 2011). When hyperintense signal of tendon and ligament is present on PD and T1w images, it is important to compare it to T2w sequence, which is less prone to this artifact (Hayes and Parellada 1996). If the high signal is still visible on T2 sequence, that may mean the real lesion is present (Madden 2006). Holowinski et al. (2010) found a correlation between decreasing signal intensity within the injured tendon or ligament on STIR image and the resolution of lameness, consistent with tissue fibrocartilaginous metaplasia, or fibroplasia. They concluded that high signal intensity lesions on STIR images represent early stage of injury, and can be caused by edema, hemorrhage or necrosis, while bright signal from damaged area on T1w image indicates fibrosis,

as a chronic stage of healing process (Holowinski et al. 2010).

When looking for bone pathology it is important to use T1w images, where decreased signal intensity may be related to bone sclerosis, fibrosis, oedema and necrosis (Werpy et al. 2006). But when comparing with other sequences it is possible to assess the possible kind of pathology. When trabecular bone has low signal on T1w image with low signal on T2 FSE image it is probably due to bone sclerosis, whereas decreased signal on T1w image with high signal intensity on T2 FSE image and T2\* GE suggests bone marrow lesion (Olive et al. 2009). According to Werpy (2012) fluid and bone sclerosis can be distinguished when comparing T1w with STIR image. When signal within the bone is decreased in both T1w and STIR image it is related to bone sclerosis, while increased signal in fat suppressed images may be associated with bone oedema (Werpy 2012) or contusion, bruising and cellular infiltration (Gonzalez et al. 2010). In McKnight and Posh research (2012) 3D T1 GE sequence provided well recognition of articular cartilage lesions, as well as fibrocartilage layer degeneration on the flexor margin of the navicular bone, which both appeared hypointensive in the mentioned sequence.

Hematoma, bone hemorrhage in most cases appears as increased signal on both T1- and T2w images (Selberg and Werpy 2011, Werpy 2012).

The hyperintensity in the navicular bone observed with STIR sequences could be indicative of hemorrhage, synovial fluid, bone necrosis, fibrosis or inflammation (Widmer et al. 2000, Busoni et al. 2005, Schramme et al. 2005, Murray et al. 2006) (Fig 3). Sclerosis of the ossified unguis cartilage was observed as an area of low signal intensity on T1w and PD images (Selberg and Werpy 2011).

Articular cartilage damage is characterized by high signal intensity on T2\* GE and T2w FSE and low signal intensity on T1 GE (Smith et al. 2012).

According to Urraca del Junco et al. (2012) hemorrhage caused by solar penetrated wounds has low intensity on T1w and T2\* GE, and high signal intensity on STIR images.

## Conclusions

In summary, magnetic resonance is a valuable tool for investigation of equine orthopedic disorders. It provides detailed information about the type and degree of pathology. However, the ground knowledge of anatomy, and proper interpretation of signal alterations in different sequences are compulsory.

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