MAGNETIC RESONANCE IMAGING-GUIDED PERCUTANEOUS MUSCULOSKELETAL BIOPSIES AND THERAPEUTIC BONE DRILLINGS

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Abstract

Magnetic resonance imaging (MRI) is a well-established imaging modality for disorders of the musculoskeletal system. The distinguishing advantages of MRI are absence of ionizing radiation, excellent tissue contrast and the ability to use any arbitrary imaging plane. MRI can also be used as a guidance method for various percutaneous procedures.

The purpose of this study was to evaluate the feasibility of MRI guidance for musculoskeletal biopsies and therapeutic bone drillings. A 0.23 tesla open configuration MRI scanner with an interventional optical guidance system was used.

172 percutaneous biopsies performed using MRI guidance were reviewed to define the safety and accuracy of the guidance method. The value of fine needle aspiration biopsy (FNAB) as a supplementary diagnostic procedure for core biopsy was also evaluated. The overall diagnostic accuracy of MRI-guided biopsy was 0.95, sensitivity 0.91, and specificity 0.98. The diagnostic accuracy of histological biopsy alone was 0.93, sensitivity 0.89, and specificity 0.98, and accuracy for FNAB alone was 0.85, sensitivity 0.80, and specificity 0.90. MRI guidance was deemed feasible and accurate and fine needle biopsy a useful supplement.

The feasibility and safety of MRI-guided retrograde drilling of osteochondritis dissecans of the knee were evaluated by analysing ten procedures. All the lesions were successfully located and reached without complications. All patients experienced pain alleviation and follow-up MRI showed ossification in all.

The feasibility and safety of MRI-guided retrograde drilling of osteochondritis dissecans of the talus were assessed by evaluating four procedures. Technical success was achieved in all cases and no complications were reported. All patients experienced some clinical benefit, although the changes in the pathological imaging findings were subtle.

The feasibility and safety of MRI-guided core decompression for avascular necrosis of the femoral head were assessed by analysing twelve such procedures. The patients quantified their symptoms before and after the procedure. All procedures were successful without complications. All patients with low-stage disease benefited from the procedure. MRI guidance seems accurate, safe and technically feasible for the therapeutic bone drillings studied.

Keywords: biopsy, bone drilling, imaging guidance, magnetic resonance imaging, musculoskeletal, percutaneous
Magneettikuvaus (MK) on vakiintunut tuki- ja liikuntaelimistön sairauksien kuvantamismenetelmänä. Sen erityispiirteitä ovat ionisoivan säteilyn puuttuminen, erinomainen kudoskontrasti sekä mahdollisuus saada kuvia mielivaltaisesta leiketasosta. Magneettikuvausta voidaan myös käyttää ohjausmenetelmänä useiden perkutaanisten toimenpiteiden yhteydessä.

Tämän tutkimuksen tavoitteena oli selvittää MK-ohjauksen käyttökelpoisuus tuki- ja liikuntaelimistön neulanäytteenottojen ja hoidollisten luuporausten ohjausmenetelmänä. Tutkimuksessa käytettiin 0.23 teslan avomagneettia, jossa oli lisäksi optinen ohjausjärjestelmä.

MK-ohjauksen turvallisuuden ja tarkkuuden selvittämiseksi tutkittiin 172 perkutaanista MK-ohjattua neulanäytteenottoa. Myös paksuneulanäytteen yhteydessä otetun ohutneulanäytteen antama lisäarvo arvioitiin. MK-ohjatun neulanäytteenoton kokonaistarkkuus oli 0.95, herkkyys 0.91 ja speisifisyyys 0.98. Pelkän histologisen näytteenoton vastaavat tunnusluvut olivat 0.93, 0.89 ja 0.90 ja pelkän ohutneulanäytteen tunnusluvut olivat 0.85, 0.80 ja 0.90. Magneettikuvaus todettiin käyttökelpaiseksi ja tarkaksi ohjausmenetelmäksi ja ohutneulanäytte hyödylliseksi lisätoimenpiteeksi.


MK-ohjauksen turvallisuutta ja soveltuvuutta telalauun osteokondriitin poraushoidon arviotiin neljän toimenpiteen perusteella. Toimenpiteet onnistuivat teknisesti kaikissa tapauksissa, eikä komplikaatioita esiintynyt. Kaikki potilaat hyötyivät jonkin verran, mutta poikkeava kuvalöysös muuttui vain vähän.


Magneettikuvaus vaikuttaa tarkalta, turvalliselta ja teknisesti soveltuvalta ohjausmenetelmältä tutkittujen terapeuttisten luuporausten yhteydessä.

Asiasanat: biopsia, kuvantamisohjaus, luuporaus, magneettikuvaus, perkutaaninen, tuki- ja liikuntaelimistö
Perheelleni
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The enthusiastic and skilled professionals of the whole Department of Radiology deserve to be mentioned with gratitude and respect. Their positive attitude towards constantly seeking new knowledge and passing it on to the next generation of radiologists, radiographers and physicists keeps inspiring me and sets this working environment above many others. I would also like to thank Ms Leila Salo for her help and Ms Hanna Pesonen, PhD, at the Faculty of Medicine for guiding me through the dense jungle of practical issues related to the doctoral degree.

My deepest gratitude must be expressed towards my parents Pirkko and Mikko. Your love, wisdom and values have led me here. I will strive to give my own offspring, my dear Sonja and Ville, an equal opportunity to grow and flourish. I have been given a lot; I will try to give in return. I have no lesser
appreciation of the love and support of my beloved wife Heli, whose ability to provide a second opinion and another point of view has opened my eyes many times, not only during this very journey.

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Oulu, October 2015

Pekka Kerimaa
**Abbreviations**

<table>
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<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tbody>
<tr>
<td>ACD</td>
<td>advanced core decompression</td>
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<tr>
<td>ALARA</td>
<td>as low as reasonably achievable</td>
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<td>ANFH</td>
<td>avascular necrosis of the femoral head</td>
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<td>ARCO</td>
<td>Association Research Circulation Osseous</td>
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<tr>
<td>B-FFE</td>
<td>balanced fast field echo</td>
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<tr>
<td>CD</td>
<td>core decompression</td>
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<td>CEUS</td>
<td>contrast-enhanced ultrasound</td>
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<td>CT</td>
<td>computed tomography</td>
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<td>FNAB</td>
<td>fine needle aspiration biopsy</td>
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<td>FSE</td>
<td>fast spin echo</td>
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<tr>
<td>JOCD</td>
<td>juvenile osteochondritis dissecans</td>
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<td>MR</td>
<td>magnetic resonance</td>
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<td>MRI</td>
<td>magnetic resonance imaging</td>
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<td>NPV</td>
<td>negative predictive value</td>
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<td>OCD</td>
<td>osteochondritis dissecans</td>
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<td>PD</td>
<td>proton density</td>
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<tr>
<td>PPV</td>
<td>positive predictive value</td>
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<tr>
<td>SNR</td>
<td>signal-to-noise ratio</td>
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<td>SSFP</td>
<td>steady-state free precession</td>
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<td>STIR</td>
<td>short tau inversion recovery</td>
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<td>T</td>
<td>tesla</td>
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<td>T1</td>
<td>T1-weighted</td>
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<tr>
<td>T2</td>
<td>T2-weighted</td>
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<tr>
<td>THA</td>
<td>total hip arthroplasty</td>
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<td>VAS</td>
<td>visual analogue scale</td>
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Original publications

This thesis is based on the following original publications, which are referred to in the text by their Roman numerals:


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1 Introduction

Using imaging for guidance has made it possible to reach almost any conceivable target in the human body with a suitable instrument through the skin, without making a wound any bigger than the diameter of the instrument being used. Even better, when the other structures pierced on the way can be identified beforehand, the risks are well controlled. Of course, the percutaneous approach can justify its existence only if it can reliably provide important diagnostic information or deliver a healing effect without being too difficult, risky, time-consuming or expensive. At their best, percutaneous procedures serve well the principle of harming the patient as little as possible. It is no surprise that percutaneous imaging-guided biopsies and therapeutic procedures have become an integral part of everyday practice of modern medicine.

Since its dawn in the early 1980s, magnetic resonance imaging (MRI) has established its position in the diagnostics of musculoskeletal disorders. Therefore, using MRI for guidance makes perfect sense when a focal abnormality of the musculoskeletal system needs to be sampled for diagnostic purposes or approached percutaneously with a therapeutic device. Although there are reasons that have kept MRI from becoming quite the everyday workhorse for percutaneous interventions, MRI guidance has been studied and found useful for a number of musculoskeletal interventional applications, and thanks to its unique advantageous characteristics, it can be hypothesized that MRI is well suited for a great many more. Four such applications are described and studied in the original publications of this thesis. Three of them were performed for the first time on live patients in an actual clinical setting.
2 Review of the literature

2.1 Percutaneous needle biopsy

Despite huge advances in both imaging and clinical medicine, the pathologist still has the last word in diagnostics after analysing a tissue sample or a cytological specimen. This is especially true when trying to determine whether a local pathological finding represents a malignant aetiology or not. Consequently, a need for targeted biopsies remains. The majority of such biopsies are harvested percutaneously, necessitating a guidance method of some kind to visualize and hit the target accurately and safely.

There are obvious and undisputed advantages to an imaging-guided percutaneous biopsy compared to open surgical tissue sampling or blind percutaneous techniques. Morbidity and mortality are significantly reduced, not to mention increased patient comfort and compliance. Even very small and/or deep-set focal lesions can be targeted successfully. (Weiss et al. 2008).

The first reported percutaneous biopsy was performed in 1883 by Paul Erlich, later a Nobel prize winner (Reuben 2003). The technique became more of a mainstream clinical practice in the early 1900s, and imaging-guidance followed (Rasmussen et al. 1972, Stein & Evans 1966). Today, imaging-guided percutaneous biopsy is often the first invasive step in the diagnostic workup of a musculoskeletal lesion. It has been proven feasible and accurate, and possible complications are rare and mostly minor. (Jelinek et al. 2002, Mitsuyoshi et al. 2006, Shin et al. 2007a, Welker et al. 2000) The vast and very heterogeneous pool of biopsy targets in the musculoskeletal system and the diversity of scientific reports make it difficult to reliably compare quantitative parameters, however.

The choice of biopsy equipment in each case depends on the imaging modality used, the anatomic location, vascularity and expected composition of the target lesion and the clinical setting. Fine needle aspiration biopsy (FNAB) is performed using a needle generally less than 1mm wide, and the aspirated material is in most cases fluid or separate cells. When successful, the yield is sufficient for microbiological and cytological analysis. Histological biopsy, or core needle biopsy, is harvested with a larger cutting needle, and the catch is a piece of target tissue fit for histological analysis. Core biopsy has been shown to be more informative than FNAB (Vimpeli et al. 2008), but best results can be achieved when both techniques are used in conjunction (Tikkakoski et al. 1993),
even with skeletal lesions (Schweitzer et al. 1996, Tikkakoski et al. 1992). Approaching a skeletal lesion or sampling a lesion consisting of dense bone may require the use of a trephine. Such a device produces a cylindrical sample, also well suited for histological analysis.

Ultrasound, fluoroscopy and computed tomography (CT) are the most widely used imaging modalities for biopsy guidance. All three have their own advantages and limitations, but all are able to provide excellent accuracy and success rates when utilized accordingly. (Ghelman 1998, Joines et al. 2007, Soudack et al. 2006, Tikkakoski et al. 1992). Nevertheless, MRI guidance can be advantageous and preferable over other modalities in certain situations. Obviously, if the target lesion – or a critical surrounding structure – can only be sufficiently visualized by using magnetic resonance imaging (MRI), that should be the modality to guide the biopsy as well. Furthermore, MRI has the capability to depict the most viable part of a tumour, for example, and thus increase the biopsy yield by targeting the most active part of the lesion (Carrino et al. 2007, Kaplan et al. 1998). The unlimited multiplanar capabilities of MR imaging can prove to be invaluable when the target lesion resides in such a place that the safe biopsy path is long and very oblique (Adam et al. 1999). Finally, the inherent lack of ionizing radiation is such a major advantage that MR guidance should be considered as an alternative to CT guidance in juvenile patients. Contraindications for a percutaneous biopsy itself are more or less relative and include uncorrected coagulopathy, lack of a safe biopsy path and lack of sufficient patient cooperation.

2.2 Retrograde drilling of osteochondritis dissecans of the knee and the talus

Osteochondritis dissecans (OCD) is an idiopathic disorder of the subchondral bone, with or without involvement of the articular cartilage. The term was first used by König in 1888 (König 1888) to describe loose bodies in the knee joint. A similar lesion in the ankle joint was first reported by Kappis (Kappis 1922). Although the condition is most likely multifactorial, the most recognized risk factor is high level of sports activity, with repeated microtrauma as the probable pathomechanism, causing a sort of a local stress fracture. (Edge & Porter 2011, Hefti et al. 1999, Hughston et al. 1984, Kocher et al. 2006, Strouse 2010).

The most commonly affected joint is the knee (75% of all cases), followed by the ankle and the elbow (Edge & Porter 2011, Edmonds & Polousky 2013). The most commonly affected site in the knee is the medial condyle (85%), usually
its lateral aspect (Hefti et al. 1999). In the ankle, the medial central articular surface of the talar dome is most commonly affected (Elias et al. 2007, Hembree et al. 2012). The prevalence of OCD of the knee is reported to be 15 to 30 per 100,000 persons (Hughston et al. 1984) and its incidence 2.3 to 18.1 per 100,000 (Kessler et al. 2014a). According to the literature, OCD of the talus is less common, with a reported prevalence of only 0.002 per 100,000 (Bauer et al. 1987, Flick & Gould 1985) and incidence of 0.7 to 8.9 per 100,000 (Kessler et al. 2014b). Consequently, literature on OCD is clearly concentrated on the knee.

Fig. 1. OCD of the knee. Proton density (PD) image in coronal plane, showing an OCD lesion (arrow) of the medial condyle of the femur of a 21-year-old female.

When symptomatic, the most common presenting symptom of osteochondritis dissecans is pain, which is usually associated with activity or simply weight bearing. Joint effusion may also present, periodically or otherwise. As the condition progresses, the lesion becomes unstable and eventually transforms into a mobile loose body inside the joint. This brings about the more characteristic symptoms of joint catching and locking, not to mention more abundant pain and swelling (Schenck & Goodnight 1996, Zanon et al. 2014).
Two distinct forms of OCD are recognized, the juvenile form and the adult form, differentiated by the status of the growth plate. In the juvenile form of OCD (JOCD), generally involving ages 5 to 15, the bone maturation is still under way and the growth plate is open whereas in the adult form it is closed, i.e., ossified. Although the adult form of OCD may present at any age, it usually involves young adults and is rather rare in joints above 50 years of age. The mean age at presentation of JOCD seems to be decreasing, which is speculated to be due to growing participation of young children in competitive sports involving jumping or other axial stress. The very same explanation has been offered for the growing prevalence among girls, although 70 to 85% of patients are reported to be males. (Cahill 1995, Edge & Porter 2011) What blurs the line between the juvenile and the adult form of OCD is that a lesion may originate during adolescence but remain asymptomatic until adulthood (McCullough & Venugopal 1979).

Whether situated in the knee or in the ankle, it is clear that the characteristics of an OCD lesion are best appreciated noninvasively on MR imaging (Fig. 1) (Chen et al. 2013, De Smet et al. 1990, Hembree et al. 2012, Kijowski et al. 2008), although pitfalls do exist (De Smet et al. 1990, Heywood et al. 2011).

Berndt and Harty (Berndt & Harty 1959) described a classification system for OCD, and it remains the most widely used, despite a number of newer approaches (Cahill 1995).

Although the line between an OCD lesion circumferentially and rigidly connected to the underlying bone and a completely loose fragment is blurred, several criteria have been proposed for determining the stability of an OCD lesion. These are slightly different for juvenile and adult forms of the condition. For adult OCD, a bright signal rim separating the lesion from its donor bone in T2-weighted imaging is clearly considered a reliable sign of instability, as is the presence of cysts around the fragment. For juvenile OCD, a similar T2 bright rim is a sign of instability only if it represents the same signal intensity as joint fluid or is accompanied by a second lower intensity rim or abruptions in the subchondral bone plate. Furthermore, cysts indicate instability only if they are multiple or larger than 5mm in size. (Kijowski et al. 2008) More intricate MR imaging methods and criteria have also been proposed (Chen et al. 2013).

Despite ongoing debate regarding most aspects of both juvenile and adult forms of OCD, the distinction is important as the juvenile form of OCD has a much better prognosis. Adult OCD rarely heals without operative intervention, whereas 50% of JOCD cases are estimated to heal with conservative treatment (Cahill 1995, Edge & Porter 2011). Less encouraging results from conservative
treatment have also been published (Perumal et al. 2007). Large lesions in relation to the condyle size, joint swelling and mechanical symptoms are associated with less favourable response to conservative treatment, which consists of activity modification and immobilization (Wall et al. 2008).

Surgical management of OCD encompasses a number of techniques ranging from arthroscopic transchondral or transepiphyseal drilling to open surgery in both OCD of the knee and the talus (Cahill 1995, Murawski & Kennedy 2013, van Bergen et al. 2008). While no single technique has proved superior and further studies are warranted, surgical treatment leads to healing at least in most cases of juvenile OCD of the knee (Abouassaly et al. 2014, Gunton et al. 2013).

Retrograde and antegrade drilling have provided comparable short-term outcome and radiographic healing of a stable lesion in juvenile OCD of the knee (Gunton et al. 2013). The rationale of subchondral drilling is to stimulate local revascularization and to promote ossification of the lesion. The terms antegrade and retrograde are not self-evident when it comes to joints, so let it be emphasized that in the context of this study (I – IV), the term retrograde means approaching the target “from below”, i.e., without traversing the joint capsule or, more importantly, the articular cartilage (Fig. 2). Using an extra-articular approach has the obvious advantage of preserving the integrity of the articular cartilage. A uniform joint surface is a necessity at least for the success of any surgical repair (Cahill 1995). Fluoroscopy is by far the most widely used guidance method when performing retrograde drilling of an OCD lesion (Lebolt & Wall 2007). The challenge of fluoroscopy-guided drilling is reaching the lesion adequately but without damaging the overlying cartilage. Also, OCD lesions of the talus can be difficult to reach due to the rather complex anatomy of the region (Navid & Myerson 2002). MRI as a guidance method can be postulated to be superior in both aspects, as an OCD lesion can be readily identified and then approached from the most suitable direction while avoiding major neurovascular structures and tendons. Furthermore, MRI has the ability to depict the most disease-affected region of an OCD lesion. MRI guidance has been investigated on cadaveric joints (Seebauer et al. 2010, Seebauer et al. 2009), but its clinical use has not been described in the literature before.
2.3 Core decompression of avascular necrosis of the femoral head

Avascular necrosis of the femoral head (ANFH) of the femoral head bears a number of similarities with osteochondritis dissecans, and so does treating the condition with extra-articular drilling. ANFH, or osteonecrosis, as the name suggests, is an ischaemic process of the bone. The pathomechanism involves disruption of adequate blood supply to the subchondral bone of the femoral head. The aetiology is thought to be multifactorial. The most recognized risk factors include prior hip trauma, corticosteroid use, smoking, alcoholism, coagulopathies and haemoglobinopathies, but also prior hip surgery, hyperlipidaemia, juvenile hip disorders, organ transplantation, gout, chronic liver disease, HIV infection, genetic predisposition, pregnancy and even deep sea diving have been mentioned. The actual prevalence of the condition is unknown, but some 10,000 to 20,000 cases are reported in the United States per year, and 5 to 18% of all total hip arthroplasties (THA) are performed for avascular necrosis of the femoral head. Approximately three out of five patients are males and the disease typically
presents in patients between the ages of twenty and forty years. (Babis et al. 2011, Kaushik et al. 2012, Marker et al. 2008a, Mont et al. 2006a, Mont et al. 2010).

The treatment method and the prognosis depend largely on the stage of the disease. Several classification systems have been developed to evaluate ANFH (Ficat 1985, Gardeniers 1993, Steinberg et al. 1995). They share many common elements and while all are usable, none of them seems to rise above the rest (Mont et al. 2006b). The ARCO (Association Research Circulation Osseous) classification system was used for this study. ARCO classification consists of stages 0 to 4. ARCO stage zero represents asymptomatic bone necrosis without any imaging abnormalities, detectable only – more or less theoretically – by biopsy. Stage one disease can be detected with MRI or scintigraphy, but plain film x-ray and CT-scan findings remain normal. At stage two, bone abnormalities are evident on all imaging modalities. Findings include sclerosis, osteolysis and focal porosis. Stage three involves mechanical failure of the femoral head and a subchondral fracture can be seen, typically as a so-called ‘crescent sign’. The dome of the femoral head may lose its spherical shape, but stage three is still without joint space narrowing and secondary acetabular involvement. Stage four represents a deformed femoral head with a collapsed articular surface and secondary osteoarthritis. Stages one, two and three are each divided into substages A, B and C depending on the area involved (Fig. 3). (Gardeniers 1993).

Fig. 3. Avascular necrosis of the femoral head. ARCO subclassification, substages A, B and C according to Gardeniers (1993).

MR imaging has been found to be highly sensitive and specific for diagnosing and classifying ANFH. Imaging findings are fundamental elements of the most common classification systems and MRI is definitely the cornerstone of diagnostics of ANFH. (Karantanas & Drakonaki 2011, Malizos et al. 2007, Mont et al. 2006b).
By far the most common clinical manifestation of ANFH is pain, usually felt deep in the groin and amplified with weight bearing. If the condition is allowed to take its typical natural course, the avascular bone eventually fails under stress, which leads to collapse of the articular surface of the femoral head and consequently to severe disability. Total hip arthroplasty is the definite treatment at advanced stages of the disease. As the patients are generally young adults, it makes sense to try to halt the progression of the disease and thus postpone, if not entirely avoid, the need for THA. Non-operative treatments include limiting weight bearing, activity modification, physical therapy and abstinence from smoking and alcohol, but these methods have shown limited success in preventing disease progression even at early-stage disease. (Babis et al. 2011, Malizos et al. 2007, Mont et al. 2010, Zalavras & Lieberman 2014).

Core decompression (CD) is a procedure where a cylindrical tunnel or several tunnels are drilled into the necrotic subchondral bone. This can be performed percutaneously. The extra-articular pathway of the trephine penetrates the lateral cortex of the femur somewhere near the great trochanter and goes through the neck of the femur into the diseased bone in the head of the femur (Fig. 4). The rationale of this technique is to relieve intraosseous pressure, remove necrotic bone and thus facilitate neovascularization and healing. CD is currently the most common mini-invasive procedure performed for ANFH and it has proven to be efficient and potentially cost-effective at early stages of the disease, but not at more advanced stages when the articular surface is irreversibly damaged (Castro, Jr. & Barrack 2000, Marker et al. 2008b, Rajagopal et al. 2012, Soohoo et al. 2006). Over the years, the procedure has been augmented with stem cells, growth factors and bone grafts with favourable results (Petrigliano & Lieberman 2007, Steinberg et al. 2001). CD with several small drill channels has been found to be more effective than CD with just a single channel (Floerkemeier et al. 2011). On the other hand, the use of an expandable reamer together with injectable bone graft substitute has been investigated, allowing for efficient removal of necrotic bone without compromising bone stability. The procedure has been named advanced core decompression (ACD) (Landgraeb et al. 2013, Lazik et al. 2015).
Core decompression is usually performed using x-ray fluoroscopy guidance. The use of MRI guidance has not been reported before, although the benefits seem clear. MRI has been firmly established as the best modality to detect and diagnose ANFH (Malizos et al. 2007, Zibis et al. 2007) and it can accurately depict and target the most disease-affected region of the subchondral bone. Once again, the ability to use arbitrary imaging planes with instrument tracking and navigation and the capability to visualize the articular cartilage seem advantageous, as does the inherent lack of ionizing radiation, especially when treating young adults.

2.4 Imaging-guidance methods for percutaneous procedures of the musculoskeletal system

2.4.1 X-Ray Fluoroscopy

Fluoroscopy has been and still remains the most widely used method of guidance for therapeutic percutaneous musculoskeletal procedures. It provides excellent spatial and temporal resolution. While bony structures and metallic instruments
are visualized with excellent contrast, they are usually perceived in one viewing
plane at a time, making it impossible to determine the exact position of the
instruments without rotating the imaging plane. Of course, dual-plane x-ray
fluoroscopy equipment does exist, as do more advanced techniques (Acosta et al.
2005, Berndt & Harty 1959, Lekovic et al. 2007). The native soft tissue contrast
of x-ray fluoroscopy is poor, which makes, for example, direct visualization of the
articular cartilage impossible without the use of a contrast agent.

Another major drawback of x-ray fluoroscopy is the radiation exposure,
which is an important consideration especially when treating juveniles (Connolly
et al. 2006). The dose reduction introduced by advances in imaging technology,
radiation protection and awareness (Pearl et al. 2015, Weinberg et al. 2015) may
be counteracted by more demanding and thus more time-consuming procedures.

The arrival of cone beam CT technology to fluoroscopy devices has brought
fluoroscopy and CT imaging together, making it possible to have accurate real-
time 3D guidance with excellent spatial and temporal resolution. The radiation
doses of cone beam CT have proven to be lower than with CT fluoroscopy but
higher than with conventional x-ray fluoroscopy. (Braak et al. 2013, Powell et al.
2010, Tselikas et al. 2014) Also, many fluoroscopy devices are equipped with
feasible guidance aids that provide optimal imaging planes after the procedure has
been planned.

2.4.2 Ultrasound

Ultrasound probably remains the most widely used method of guidance for
percutaneous biopsies, and the same principles apply whether or not the target
actually is musculoskeletal. Ultrasound generally provides sufficient soft tissue
contrast, but practically lacks bone and gas penetration altogether. This excludes
ultrasound guidance for all biopsy targets surrounded by either one and may make
visualizing a safe biopsy path difficult if gas or calcification exists in the region of
interest.

Soft tissue demarcation can be further augmented by using intravenous
microbubble contrast agents (contrast-enhanced ultrasound, CEUS). For example,
contrast enhancement can be applied to visualize the most viable part of a tumour
or to detect vascular structures in order to avoid damaging them. CEUS is
considered rather safe and non-nephrotoxic. (Wilson et al. 2009). Doppler
ultrasound is capable of depicting flow and thus can also be used to detect patent
blood vessels (Taylor & Holland 1990).
Ultrasound provides real-time visualization, but only in the thin plane of the hand-held transducer, unless a specific 4D transducer is used. (Kim & Choi 2007, Voloshin 2015) Ultrasound also suffers from many technical pitfalls, such as varying visualization of instruments depending on numerous technical and operator-related variables. The spatial resolution of ultrasound imaging largely depends on the demand for penetration and vice versa (Rose & Goldberg 1980). In practice, ultrasound guidance is hardly usable even in optimal conditions if the target is more than 15 to 20 cm deep, which can be a problem with obese patients.

Some of these challenges can be overcome with technical aids, such as image fusion to visualize a target otherwise undetectable by ultrasound (Mauri et al. 2014), virtual needle navigation to better illustrate the needle position and direction, or a simple needle guide to help aim, stabilize and align the needle parallel to the transducer. 3D visualization and guidance methods are being developed, even to be used in such complex regions as the spine (Brudfors et al. 2015).

Ultrasound units have always been more or less movable, but as modern devices have become smaller, lighter and more ergonomically versatile, the modality has become fully mobile. This enables effortless bedside procedures, and combining ultrasound-guidance with other modalities is easy wherever needed. In addition, the significant fact that ultrasound does not involve any ionizing radiation has paved its way to become the everyday workhorse in both diagnostic use and as a guidance method. Ultrasound guidance has been shown to be fast and cost-effective (Memel et al. 1996, Ojalehto et al. 2002). High-quality ultrasound units are widely available and using them for ultrasound-guided procedures does not necessarily require any additional appliances.

2.4.3 Computed tomography

Computed tomography (CT) is an established guidance method and has been widely used in a number of percutaneous musculoskeletal interventions (Dupuy et al. 1998, Huch et al. 2007, Rimondi et al. 2011, Thanos et al. 2004). The image formation is based on ionizing radiation, which poses a significant disadvantage. CT is a major source of radiation to the population and the interventional radiologist. This necessitates certain measures to be taken, but rigid shields and such may easily obstruct the access to the patient. (Kloeckner et al. 2013, Mahnken et al. 2012, Sarti et al. 2012).
On the other hand, CT has great spatial resolution and although its native soft tissue contrast is not great, excellent demarcation of bony structures and metallic instruments makes it a valuable tool for guiding percutaneous musculoskeletal biopsies and interventions (Dupuy et al. 1998, Huch et al. 2007, Rimondi et al. 2011, Thanos et al. 2004). Deep-set targets are usually not a problem, but procedures can be more time-consuming, and image quality may degrade and the radiation dose may increase if the patient is severely obese, as reported by Li et al. (Li et al. 2010) on liver lesion biopsy patients.

Conventional CT imaging suites may have suboptimal ergonomics for interventional procedures. The physical properties of the gantry provide limited access to the patient and also limit the length of the instrument that can be inserted in parallel to the imaging plane. Also, tilting the gantry is usually limited to near-axial planes and real-time imaging is not possible. Continuous or intermittent CT fluoroscopy makes the guidance modality practically real-time, but requires awareness of the potentially higher radiation doses involved (Carlson et al. 2001, Paulson et al. 2001).

### 2.4.4 Magnetic resonance imaging

Magnetic resonance imaging (MRI) is widely adopted as an imaging method and has proven especially valuable in diagnosing diseases of the musculoskeletal system. MRI-guided interventions were introduced in the late 1980s (Duckwiler et al. 1989, Mueller et al. 1986). During the last two decades, the role of MRI as a guidance method for a number of interventional applications has been established. (Adam et al. 1999, Carrino et al. 2007, Kariniemi et al. 2005, Ojala et al. 2000, Sequeiros & Carrino 2005, Smith & Carrino 2008).

#### Technical considerations

MR images are derived from radiofrequency resonance signals emitted by protons that are first aligned by the strong static magnetic field of the scanner and then misaligned by a transient radiofrequency pulse. The need for a sufficiently strong, stable and homogeneous magnetic field dictates some of the physical dimensions and properties of an MRI scanner. In general, the more closed the design, the easier it is to achieve such a field and good image quality. In contrast, the more open the design, the easier it is to fit in a patient and have ergonomic interventional access. The most commonly used scanner configuration for modern
MR imaging is a cylindrical tube, generally with a bore diameter of 70 cm or less, and a superconductive magnet producing a static magnetic field of 1.5 tesla or more. This provides a suitable environment for achieving good image quality and the tube can physically accommodate any patient that does not suffer from severe obesity or claustrophobia. However, this configuration offers limited interventional access to the very region being imaged. In practice, the patient has to be moved outwards in order to reach and advance a needle, for example, and then in again to acquire the next image, which is time-consuming. Obviously, the shorter and wider the bore of the scanner, the more room is left for the interventionalist and his equipment. As this also improves patient comfort in diagnostic imaging, the evolution of MRI scanners has favoured these qualities, and such devices have been successfully used for interventional procedures as well (Stattaus et al. 2008).

A typical biplanar open configuration MRI scanner, such as the one used in this research, consists of a C-arm or a column supporting two separate magnetic poles. The patient is positioned in the gap between the poles and the physical access is virtually unobstructed from the side. This configuration makes it possible for the target area to remain motionless in the imaging isocentre while doing interventional procedures, which is an advantage especially when considering ergonomics and speed. The field strength of such a scanner is usually something between 0.064 T and 0.3 T, but devices operating at 1.0 T have also been introduced into clinical practice (Fischbach et al. 2011, Streitparth et al. 2013). In general, higher strength of the static magnetic field brings about better signal-to-noise ratio (SNR) and faster imaging. In diagnostic use, higher field strength is considered to provide more information (Magee et al. 2003). On the other hand, higher field strength is associated with more pronounced artefacts from a number of sources. For example, scanners utilizing lower field strength suffer less from field inhomogeneity that may be caused by, for example, the hands of the performing physician. MR-compatible instruments cause less susceptibility artefacts at lower field strength and are thus more accurately visualized at 0.2 T than at 1.5 T (Frahm et al. 1996). All in all, the spatial and temporal resolution of low-field scanners has been demonstrated to be sufficient for guiding interventions (Kariniemi et al. 2005, Ojala et al. 2000).

The inherently excellent soft tissue contrast of MR imaging can be considered one of the most important advantages of the modality. This contrast can be further augmented with gadolinium contrast agents (Caravan et al. 1999), and different tissue characteristics can be elicited during a single imaging session.
using different pulse sequences. MRI can readily identify the most viable part of a
tumour (Geirnaerdt et al. 1998) or the most disease-affected region of a bone
abnormality (Kaplan et al. 1998). Furthermore, patent blood vessels can be
visualized even without using any contrast agent (Masia et al. 2010). Similarly,
articular cartilage is well demarcated (Burstein et al. 2000), and thus preserved,
even during an intervention to the bone just underneath it. Finally, MRI also has
high sensitivity for temperature changes, which sets it apart from other imaging
modalities and makes it exceptionally useful for monitoring thermal tumour
ablation therapies (Rieke & Pauly 2008).

The ability to acquire images in any arbitrary plane is another major
advantage. The direction of the biopsy path is not limited by the guiding modality
in any way, and approaching a target lesion with a needle or a trephine is
obviously less difficult when one can visualize the progress from an imaging
plane perfectly parallel to the instrument.

The lack of any ionizing radiation is a clear benefit for all patients and
personnel and almost a necessity for children and pregnant women. Not having to
undertake any protective measures against radiation can also be considered a
slight ergonomic advantage. However, other safety issues emerge from the strong
magnetic field. While exposure to a static magnetic field or the radiofrequency
radiation used in medical MR imaging is not considered harmful to humans
(Shellock 2000, Yamaguchi-Sekino et al. 2011), certain medical devices and other
foreign objects are affected. For example, implantable cardiac monitors,
pacemakers and defibrillators, breast implants with magnetic ports, certain
monitoring devices and neurostimulators with conductive leads, ferromagnetic
foreign bodies, otologic implants and recently implanted coronary stents have to
be taken into consideration and can even be a contraindication to MR imaging.

All instruments and equipment present in the MRI suite must be compatible
with the magnetic field, whether it is the actual tool held by the interventionalist,
the patient monitoring system, the equipment for general anaesthesia, or simply
the headphones for the patient. Loose ferromagnetic objects pose a serious risk if
they are brought into the magnetic field, as they are strongly attracted by the field
and can hurtle into the scanner forcefully enough to injure or kill a person.
(Durbridge 2011, Simmons & Hakansson 2010).
**Instrument visualization and tracking**

Even MRI-compatible metallic instruments create susceptibility artefacts, presenting as a local signal void area. This kind of direct visualization, or passive tracking, of the instrument is advantageous unless the artefact is large enough to block out the surroundings of the instrument as well. Susceptibility artefacts are more pronounced at higher static field strengths and when the needle is perpendicular to the field or the frequency encoding direction. Gradient echo sequences create larger artefacts than spin echo sequences and the composition of the instrument also matters. MRI-compatible instruments are well demarcated in the images without generating too abundant artefacts (Frahm *et al.* 1996) – or being attracted by the magnet. If necessary, a nonmagnetic instrument, for example a catheter made of plastic, can be made visible on MR images by equipping it with a conducting wire and applying an electric current that will cause local field inhomogeneity and a corresponding signal void area (Glowinski 1998).

This kind of direct visualization with freehand guidance is quite feasible, widely used and even possible in real time under certain circumstances (Maurer *et al.* 2014). However, other indirect and more automated means of visualization and guidance have been developed to fulfil the need to perceive the position and the orientation of the instrument in real time. A noteworthy advantage of such external active instrument tracking is the possibility to interactively keep the imaging plane aligned parallel – or perpendicular – to the needle.

Several instrument-tracking techniques have been developed. The method used in this study is optical tracking with an external referencing system (Blanco Sequeiros *et al.* 2002, Ojala *et al.* 2000). An infrared camera monitors a group of spherical reflectors attached to an instrument holder. One reflector is permanently attached to the upper magnetic pole of the scanner to provide a fixed reference point. When the physical dimensions of the current instrument are known and the instrument is rigidly mounted in the holder, the system can determine the orientation and the position of the instrument and produce a real-time graphical overlay of the instrument and its trajectory on the MR images. Furthermore, the image set can be set to automatically centre on the tip of the instrument and the imaging plane can be set to follow the orientation of the instrument. Any bending of the instrument will cause inaccuracy, as it cannot be detected by this kind of tracking setup. Of course, the instruments, whether bent or not, are at the same time easily distinguished in the MR images also due to their susceptibility...
artefacts. An unobstructed line between the reflectors and the camera is necessary, although the camera can be repositioned as needed.

Another way to detect the position and the orientation of the instrument is by detecting several fiducial markers mounted on the instrument, tuned into the resonance frequency of the scanner and linked to the measuring unit of the scanner. If a marker is mounted in the tip of the instrument as well, possible bending of the instrument will not go unnoticed. An even more complex augmented reality setup with preprocedural needle path planning and image overlays has been investigated on cadaveric bone biopsies and other targets as well (Fritz et al. 2013).

With interventional MR imaging, the need for fast imaging, i.e., low latency, is obvious, as numerous image acquisitions are performed in rapid succession. In many cases, the balanced steady-state free precession (SSFP) sequence has been found to provide sufficient contrast between pathologic and normal tissue, good instrument visualization and direct visualization of blood vessels with subsecond acquisition times per slice (Duerk et al. 1998). The image contrast is generally based on T2 to T1 ratio, i.e., it is T2/T1-weighted, although the weighting can be adjusted by making changes in the sequence (Huang et al. 2002). The choice of a specific sequence eventually depends on the scanner, the tracking and navigation system, the target anatomy and the procedure being performed.
3 Purpose of the study

The purpose of this study was to assess the clinical value of MRI guidance in the named musculoskeletal procedures in terms of accuracy, safety and practical feasibility. The particular aims were to

1. assess the accuracy and safety of MRI guidance for musculoskeletal biopsies
2. study the clinical feasibility and effectiveness of MRI guidance for retrograde drilling of the knee
3. study the clinical feasibility and safety of MRI guidance for retrograde drilling of the talus
4. assess the feasibility, safety and clinical value of MRI-guided core decompression in avascular necrosis of the femoral head
4 Materials and methods

4.1 Study population

4.1.1 Musculoskeletal biopsies (I)

A total of 163 patients with a musculoskeletal focal lesion of unconfirmed nature underwent 172 percutaneous MRI-guided tissue biopsies that were retrospectively analysed. In addition, 114 fine needle aspiration biopsies were performed either as a complementary procedure (112 cases) or as a stand-alone procedure (two cases). A lesion in the bone was targeted in 156 of the 172 biopsies. The mean age of the patients at the time of each biopsy was 49 years (range 1 to 87), with 89 biopsies on men and 83 on women.

The maximum lesion diameter was 0.3 cm to 15.0 cm (mean 2.7 cm). Lesions were graded by preoperative or perioperative MR imaging as oedematous (n = 83, 48.3%), destructive (n = 33, 19.2%), sclerotic (n = 35, 20.3%) or cystic (n= 20, 11.6%). In one case (0.6%) myopathy of levator scapulae muscle was suspected and the target tissue was graded normal. A malignancy was suspected in 70 cases (40.7%). The anatomic locations of the target lesions are given in Table 1, with lesions in the soft tissue grouped as one due to their heterogeneous anatomic distribution.

Table 1. Musculoskeletal biopsies: anatomic locations of the target lesions.

<table>
<thead>
<tr>
<th>Anatomic Site</th>
<th>Frequency</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Femur</td>
<td>55</td>
<td>32.0</td>
</tr>
<tr>
<td>Spinal vertebrae</td>
<td>37</td>
<td>21.5</td>
</tr>
<tr>
<td>Pelvic bones</td>
<td>30</td>
<td>17.4</td>
</tr>
<tr>
<td>Upper extremity bones</td>
<td>15</td>
<td>8.7</td>
</tr>
<tr>
<td>Tibia</td>
<td>10</td>
<td>5.8</td>
</tr>
<tr>
<td>Bony thorax</td>
<td>5</td>
<td>2.9</td>
</tr>
<tr>
<td>Foot bones</td>
<td>4</td>
<td>2.3</td>
</tr>
<tr>
<td>Soft tissue</td>
<td>16</td>
<td>9.3</td>
</tr>
<tr>
<td>Total</td>
<td>172</td>
<td>100</td>
</tr>
</tbody>
</table>
4.1.2 Retrograde drilling of osteochondritis dissecans of the knee (II)

Ten patients with a total of ten OCD lesions of the distal femur treated with MRI-guided retrograde drilling were retrospectively evaluated for study II. Five lesions were of juvenile type (immature bone, open growth plates) and five lesions were of adult type OCD. The mean age of the patients was 15 years (range 7 to 21 years). All the patients had severe limitation of mobility due to OCD-related pain and were initially observed for at least six months without any operative treatment. The condition was preoperatively diagnosed with a 1.5 tesla MRI scanner (General Electric Signa Twinspeed, Milwaukee, WI, USA). This was also done to exclude any possible unstable lesions that could be dislodged into the joint space by an attempted drilling. An OCD lesion was considered stable when the articular cartilage was unbroken and no continuous fluid signal in between the lesion and the underlying bone was present. The size of the OCD lesions ranged from 9 x 9 mm to 27 x 19 mm. Three lesions were located in the lateral femoral condyle and seven in the medial condyle. Detailed information on the patients and the target lesions is provided in Table 2.

**Table 2. OCD of the knee, patient and lesion details.**

<table>
<thead>
<tr>
<th>Patient No.</th>
<th>Age and gender</th>
<th>Lesion site in distal femur</th>
<th>Lesion size mm</th>
<th>No. of drillholes</th>
<th>Procedure duration min</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20, male</td>
<td>Right lateral</td>
<td>15x13x6</td>
<td>2</td>
<td>65</td>
</tr>
<tr>
<td>2</td>
<td>18, female</td>
<td>Right medial</td>
<td>20x17x9</td>
<td>1</td>
<td>22</td>
</tr>
<tr>
<td>3</td>
<td>21, male</td>
<td>Right medial</td>
<td>20x18x9</td>
<td>2</td>
<td>25</td>
</tr>
<tr>
<td>4</td>
<td>7, male</td>
<td>Right lateral</td>
<td>19x16x10</td>
<td>1</td>
<td>23</td>
</tr>
<tr>
<td>5</td>
<td>17, male</td>
<td>Right medial</td>
<td>26x20x9</td>
<td>2</td>
<td>26</td>
</tr>
<tr>
<td>6</td>
<td>14, male</td>
<td>Right medial</td>
<td>28x28x9</td>
<td>3</td>
<td>43</td>
</tr>
<tr>
<td>7</td>
<td>11, female</td>
<td>Right medial</td>
<td>18x16x5</td>
<td>2</td>
<td>46</td>
</tr>
<tr>
<td>8</td>
<td>12, male</td>
<td>Left lateral</td>
<td>9x9x7</td>
<td>2</td>
<td>43</td>
</tr>
<tr>
<td>9</td>
<td>20, male</td>
<td>Left medial</td>
<td>27x19x9</td>
<td>2 + 1&lt;sup&gt;1&lt;/sup&gt;</td>
<td>38&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>10</td>
<td>8, female</td>
<td>Right medial</td>
<td>13x10x7</td>
<td>2</td>
<td>56</td>
</tr>
</tbody>
</table>

<sup>1</sup> Two separate drillings were performed on the same lesion  
<sup>2</sup> Duration of the first procedure

4.1.3 Retrograde drilling of osteochondritis dissecans of the talus (III)

In study III, four patients with symptomatic osteochondritis dissecans of the talus were treated with MRI-guided retrograde drilling after 2 to 11 months of
unsuccessful conservative treatment. The procedures were evaluated retrospectively. Three patients were female and the average age was 20.5 years (range 11 to 31 years). All osteochondral lesions were located in the middle or posterior third of the medial border of the talar dome. The mean size of the lesion was 14 x 9 x 6 mm. Three lesions were of adult type OCD and one lesion was of juvenile type OCD, with immature bone and open growth lines. More detailed information on the patients and the lesions is provided in Table 3.

**Table 3. OCD of the talus: patient and lesion details.**

<table>
<thead>
<tr>
<th>Patient No.</th>
<th>Age and gender</th>
<th>Lesion size, mm</th>
<th>Conservative treatment, months</th>
<th>Follow-up, months and modality</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11, female</td>
<td>11 x 8 x 5</td>
<td>11</td>
<td>3+7, MRI+X-ray</td>
</tr>
<tr>
<td>2</td>
<td>23, female</td>
<td>14 x 7 x 5</td>
<td>4</td>
<td>3, MRI</td>
</tr>
<tr>
<td>3</td>
<td>31, male</td>
<td>18 x 10 x 7</td>
<td>2</td>
<td>9, MRI</td>
</tr>
<tr>
<td>4</td>
<td>17, female</td>
<td>14 x 10 x 6</td>
<td>6</td>
<td>9, X-ray</td>
</tr>
</tbody>
</table>

Preprocedural 1.5 T MR imaging was done to confirm the diagnosis of OCD of the talus and to determine the stability of the osteochondral lesion. The lesion was determined to be stable and thus suitable for retrograde drilling when the cartilage was unbroken and no continuous fluid signal separating the lesion from the underlying bone was seen. The imaging sequences used were chosen by the current radiologist.

**4.1.4 Core decompression of osteonecrosis of the femoral head (IV)**

The cohort for this study consisted of eight patients with symptomatic ANFH. A total of twelve MRI-guided core decompressions were performed and retrospectively evaluated. Seven patients were males and the mean age of the patients at the time of the procedure was 46 years (range 19 to 53 years). Patient and target details are provided in Table 4. Six patients had known risk factors for ANFH. The patients for this procedure were selected by the referring surgeon from a clinical standpoint.

The ARCO classification system was used to grade the severity of the disease in each hip both before and after each procedure. Three hips were preoperatively classified as ARCO stage one (two 1A and one 1B), five hips as stage two (one 2B and four 2C) and four hips as stage three (two 3B and two 3C).
Table 4. Patient and ANFH lesion details.

<table>
<thead>
<tr>
<th>Patient No.</th>
<th>Drilling No.</th>
<th>Age and gender</th>
<th>laterality</th>
<th>preoperative ARCO stage</th>
<th>Eventual arthroplasty</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>I</td>
<td>50, male</td>
<td>L</td>
<td>2C</td>
<td>no</td>
</tr>
<tr>
<td>1</td>
<td>II</td>
<td>50, male</td>
<td>R</td>
<td>1A</td>
<td>no</td>
</tr>
<tr>
<td>1</td>
<td>III</td>
<td>52, male</td>
<td>L</td>
<td>2C</td>
<td>no</td>
</tr>
<tr>
<td>1</td>
<td>IV</td>
<td>53, male</td>
<td>L</td>
<td>2C</td>
<td>no</td>
</tr>
<tr>
<td>2</td>
<td>V</td>
<td>51, male</td>
<td>L</td>
<td>3B</td>
<td>yes</td>
</tr>
<tr>
<td>2</td>
<td>VI</td>
<td>51, male</td>
<td>R</td>
<td>3B</td>
<td>no</td>
</tr>
<tr>
<td>3</td>
<td>VII</td>
<td>19, male</td>
<td>R</td>
<td>1A</td>
<td>no</td>
</tr>
<tr>
<td>4</td>
<td>VIII</td>
<td>51, female</td>
<td>L</td>
<td>2B</td>
<td>yes</td>
</tr>
<tr>
<td>5</td>
<td>IX</td>
<td>38, male</td>
<td>R</td>
<td>3C</td>
<td>yes</td>
</tr>
<tr>
<td>6</td>
<td>X</td>
<td>49, male</td>
<td>L</td>
<td>2C</td>
<td>no</td>
</tr>
<tr>
<td>7</td>
<td>XI</td>
<td>37, male</td>
<td>L</td>
<td>3C</td>
<td>yes</td>
</tr>
<tr>
<td>8</td>
<td>XII</td>
<td>47, male</td>
<td>R</td>
<td>1B</td>
<td>no</td>
</tr>
</tbody>
</table>

4.2 Interventional magnetic resonance suite and the guidance system

All procedures were performed using a horizontally open 0.23 T MRI scanner (Panorama 0.23T, Philips Medical Systems, Vantaa, Finland) equipped with interventional optical tracking equipment and software. The open C-configuration with one supporting pillar provides generous access to the patient from three directions from a gap of 46 cm between the magnetic poles. The patient can remain immobile in the scanner for the whole duration of the procedure. A ring-shaped surface coil was used. The room was also equipped with an MRI-compatible patient monitoring system and a respirator.

Real-time instrument tracking was performed using an infrared navigation system. One reflector is fixed onto the magnet, providing an immobile reference point. A group of spherical reflectors is attached to a needle holder. A camera unit sends infrared light, detects the reflections and thus sees the location and the orientation of the instruments in 3D space. Each needle holder is identified by a unique configuration of reflectors and the needle length is calibrated with the software before each procedure. The imaging plane and centre can be fixed, or they can be set to follow the orientation of the instruments. A target point in the image can be chosen. The target point, the instrument and its trajectory are shown in real time as a graphic overlay in the image set during the procedure. The
optical tracking system provides spatial accuracy of 2 mm in the centre and 8 mm at the edge of the imaging area.

4.3 **The procedures**

4.3.1 **Technical execution**

Each procedure was prepared and performed in a normal sterile surgical fashion and MRI-compatible equipment and instruments were used. For core decompression of the femoral head, either general anaesthesia (n=3) or spinal anaesthesia (n=6) was used. The form of anaesthesia was not reported in three cases of CD. For retrograde drilling of OCD of the knee, one patient was under general anaesthesia and the remaining nine had spinal anaesthesia. All patients referred for drilling of OCD of the talus were under general anaesthesia (n=4). Local anaesthetic (lidocaine 10 mg/ml or 20 mg/ml) was also infiltrated into the soft tissue of the entry site in all therapeutic procedures. For the biopsies (I), 87 procedures were performed under general anaesthesia, 56 under spinal anaesthesia, 21 under local anaesthesia and 3 under epidural anaesthesia. In five biopsy cases, the method of anaesthesia was not specified.

For the therapeutic drillings (II, III and IV), the patients received an intravenous prophylactic dose of cefuroxime (a weight-dependent dose for patients weighing under 50 kg, 1 gram for patients weighing 50 to 60 kg and 1.5 grams for patients over 60 kg). Similar prophylaxis was administered before 31 biopsies, but this information was missing in 24 biopsy cases.

The lesions seen in preoperative high-field MR images were clearly outlined and targeted using the 0.23 T scanner as well. The most affected pathologic region of OCD lesion or the femoral head was selected as the target for the drilling. The aim was to drill into the target from an extra-articular direction and deep enough but without damaging the overlying cartilage. Traversing the growth plate of a juvenile patient was avoided, along with tendons, major vessels and nerves. The most typical direction of approach for drilling of OCD of the knee was from the oblique craniomedial or craniolateral direction, as seen Fig. 2. For core decompression of ANFH, the target area was approached through the great trochanter and via the neck of the femur (Fig. 4). OCD of the talus was typically drilled from an oblique anterolateral direction (Fig. 5).
Fig. 5. Retrograde drilling of OCD of the talus, with the drill (white arrow) reaching the intended target. A perioperative oblique sagittal B-FFE image.

For the MRI-guided biopsies, the most viable-appearing part of the lesion was selected as the target. A biopsy path with the least amount of cortical or otherwise sclerotic bone was selected for skeletal targets and any extraosseous part of the lesion was preferred when available.

The path to the chosen target was planned by marking the estimated entry point with a finger or the tracker-mounted instrument and acquiring a set of MR images to visualize the target and the route. The skin was incised with a scalpel and the cortical bone penetrated with a coaxial cannula in a single location. Then, a cylindrical drill (II, III, IV and bony targets in I) was advanced through the cannula into the lesion, as guided by the tracker generated graphic overlay alongside with anatomic landmarks and the susceptibility artefacts created by the instruments. MRI acquisitions parallel to the drill were repeated as necessary.

In case of OCD of the knee (II) and ANFH (IV), one to three 3-mm channels were drilled from the same entry point to cover the target lesion. A single channel was drilled in OCD of the talus. For the MRI-guided biopsies of a bony lesion, a hollow cylindrical drill either 2, 3 or 6 mm in diameter was advanced into the lesion through a coaxial cannula to collect a sample. This was repeated if the
sample seemed insufficient on visual inspection. For histological biopsy targets in the soft tissue, a 16-gauge biopsy gun with a side-cutting needle was used. The cytological sample was aspirated with an 18 or 20 gauge needle. The tissue biopsy samples were fixed in 10% formalin and the fine needle aspiration material was fixed in 50% ethanol. The samples were processed further at the pathology department. All therapeutic procedures (II, III and IV) and most biopsies (I) were performed by two radiologists experienced in interventional and musculoskeletal MRI.

### 4.3.2 Perioperative imaging

For the bone drillings (II, III and IV), a balanced fast-field echo sequence (B-FFE, TR 8.3 ms, TE 4.2 ms, slice thickness/spacing 5.0/5.0 mm, FOV 380 x 380 mm and matrix 256 x 256 pixels) was used to visualize the target and the biopsy set during the procedure.

For the MRI-guided biopsies T1-weighted fast spin echo sequences were used in addition to B-FFE during the procedure (Table 5). Furthermore, T1- and T2-weighted sequences were used for preprocedural assessing of the target lesion whenever previous MR imaging was lacking. If pre- or periprocedural imaging suggested that the use of contrast agent might be beneficial, intravenous contrast medium (0.1 ml/kg gadobutrol, Gadovist®, Bayer Pharma, Leverkusen, Germany) was administered, as was done in eight cases.

The 0.23 T scanner with the instrument tracking and navigation system described in chapter 4.2 was used for all therapeutic drillings and biopsies.

Table 5. 0.23 T MR imaging sequences used for musculoskeletal biopsies

<table>
<thead>
<tr>
<th>Sequence</th>
<th>TR (ms)</th>
<th>TE (ms)</th>
<th>Slice thickness (mm)</th>
<th>Slice interval (mm)</th>
<th>FOV (mm)</th>
<th>Matrix (pixels)</th>
<th>No. of Slices</th>
<th>Acquisition time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1 FSE</td>
<td>95</td>
<td>7</td>
<td>7.0</td>
<td>7.0</td>
<td>380x380</td>
<td>300x300</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>T1 FSE</td>
<td>130</td>
<td>11</td>
<td>10.0</td>
<td>10.0</td>
<td>380x380</td>
<td>256x256</td>
<td>5</td>
<td>18</td>
</tr>
<tr>
<td>T1 FSE w/ contrast</td>
<td>400</td>
<td>16</td>
<td>7.0</td>
<td>8.0</td>
<td>380x380</td>
<td>324x324</td>
<td>5</td>
<td>23</td>
</tr>
<tr>
<td>T2 FSE</td>
<td>3500</td>
<td>150</td>
<td>7.0</td>
<td>8.0</td>
<td>380x380</td>
<td>192x192</td>
<td>9</td>
<td>35</td>
</tr>
<tr>
<td>B-FFE</td>
<td>8.4</td>
<td>4.2</td>
<td>5.0</td>
<td>5.0</td>
<td>380x380</td>
<td>256x256</td>
<td>8</td>
<td>24</td>
</tr>
<tr>
<td>B-FFE</td>
<td>9.2</td>
<td>4.5</td>
<td>10.0</td>
<td>10.0</td>
<td>380x380</td>
<td>256x256</td>
<td>1</td>
<td>1.5</td>
</tr>
</tbody>
</table>
4.4 Evaluation of the procedures and follow-up

4.4.1 Needle biopsy (I)

The samples were analysed by experienced pathologists and deemed as either sufficient or insufficient for diagnostic use. The FNAB findings were divided into five diagnostic categories: 0 = insufficient, 1 = normal, 2 = benign atypia, 3 = possibly malignant, 4 = highly suspicious of malignancy and 5 = malignant.

The results of the pathological analysis were compared with the final diagnosis based on at least one year of clinical and/or imaging follow-up to determine the diagnostic performance of the biopsy. The biopsy results were classified as true positive, true negative, false positive or false negative. If no technical failure was reported, the result of no specific histopathological findings was interpreted as a successful procedure and a true finding. Typically, this was associated with osteoid osteomas, haemangiomas and other such benign lesions, where the biopsy often yields normal tissue. In the few cases of cytological class three where the interpretation of the biopsy outcome between true and false was ambivalent, the decision was made against the biopsy method.

Technical success, or lack thereof, and any possible complications were noted. Diagnostic sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV) and accuracy were calculated for the whole material and separately for histological biopsy and FNAB. The same measures were calculated separately for lesions in the bone and in the soft tissue.

4.4.2 Retrograde drilling of osteochondritis dissecans of the knee (II)

The patients were encouraged to use crutches until most of the postoperative pain had alleviated, and then to return gradually to normal activity. Clinical follow-up and postoperative imaging were performed within six months to evaluate the clinical response and any possible changes in the imaging findings. Total follow-up time of these patients ranged from 4 months to 6.6 years (mean 36.6 months). Hughston scoring scale was used to evaluate the patients’ ability to return to their normal activities (Hughston et al. 1984). OCD-related pain was assessed using the visual analogue scale both before and after the procedure.
4.4.3 Retrograde drilling of osteochondritis dissecans of the talus (III)

Postoperatively, the patients were advised to refrain from strenuous exercise for three to six weeks. Both clinical and imaging follow-up were performed. Mean clinical follow-up time was 2.3 years. Visual analogue scale (VAS, 0-10) was used to evaluate the pain related to the condition, with 0 representing no pain at all and 10 being the worst pain imaginable.

Follow-up imaging of three patients was performed with a 1.5 T high-field MRI. Only plain film imaging was used for one patient. Imaging was performed three to nine months after the procedure. In all cases with MRI follow-up at least one T1-weighted (matrix 512×512, resolution 0.33×0.33 mm, spacing 4.5 mm), one STIR (matrix 512×512, resolution 0.35×0.35 mm, spacing 4.5 mm) and two proton density (matrix 512×512, resolution 0.33×0.33 mm, spacing 4.5 mm and matrix 512×512, resolution 0.35×0.35 mm, spacing 3.0 mm) sequences were used. The follow-up imaging findings were evaluated especially regarding ossification of the lesion and, when possible, bone oedema.

4.4.4 Core decompression of ANFH (IV)

MR images acquired before and after each drilling were reviewed and the stage of the disease was determined at each point using the ARCO scale. Any changes in the imaging findings and clinical symptoms were documented. Each patient was sent a questionnaire to assess their subjective pain on a visual analogue scale from 0 to 10 before and after each procedure, as well as currently. Their ability to function was assessed in a similar fashion on a scale from 0 to 10, with 0 representing no ability to function at all and 10 representing complete freedom from any limitations related to the condition. The duration of possible benefit from each procedure was reported by the patient as well.

The average period between the preoperative MRI and the core decompression procedure was 44 days (range 8–164 days) and the average time between the procedure and the first follow-up MRI was 112 days (range 55–179 days). Preoperative and follow-up imaging was usually performed on a 1.5 T scanner (General Electric Signa Twinspeed) with the following sequences common to all patients: T1 coronal, T2 axial and STIR coronal (each with matrix 512 × 512, resolution 0.7 × 0.7, 0.74 × 0.74 or 0.78 × 0.78 mm, slice spacing 4.5, 5.0 or 6.0 mm). In one case, follow-up imaging was performed 6 months after the
core decompression with the same 0.23 T open-bore scanner as used for the procedure. Sequences similar to those used in other follow up MRI’s were used: T1 coronal (matrix $360 \times 360$, resolution $1.1 \times 1.1$ mm, slice spacing 6 mm), T2 axial (matrix $364 \times 364$, resolution $1.1 \times 1.1$ mm, slice spacing 6 mm) and STIR coronal (matrix $288 \times 288$, resolution $1.4 \times 1.4$ mm, slice spacing 7.2 mm). The preoperative images of one patient were lost. Only plain film x-ray images were available for imaging follow-up in one case (patient No. 4 in Table 4).
5 Results

5.1 Needle biopsy (I)

The biopsy target was successfully reached, as judged from periprocedural imaging, in all but one of the 172 cases. The length of the trephine biopsy set was insufficient in that one case and FNAB failed to provide a diagnostic sample. All other histological biopsies hit the target and yielded an adequate amount of material and were thus technically successful (yield 99.4%). The FNAB sample was insufficient in a total of fifteen cases (yield 86.8%), twelve of which were skeletal lesions. This left 99 FNAB samples sufficient for diagnostic purposes.

Two complications were reported. A pathologic fracture occurred seven days after trephine biopsy of the femur, which necessitated surgical bone augmentation. In another case a local 5 cm haematoma developed after trephine biopsy of a pelvic bone metastasis from breast cancer. The haematoma resolved on its own. Undoubtedly other smaller haematomas developed as well, but went unnoticed.

The mean procedural time from instrument entry to retraction was 45 minutes. The mean duration between the patient entering the room and leaving was 87 minutes, including the time for anaesthesia and other preparations. A therapeutic procedure, such as laser ablation of the lesion, was conducted at the same time on a few occasions, which obviously prolonged the procedure.

Of the 171 technically successful biopsies 74 were retrospectively interpreted as true positive findings and 87 as true negative after at least one year of follow-up. There were two false positive results in which both histological biopsy and FNAB wrongly suggested a malignancy.

Seven samples were interpreted as false negative. One target turned out to be an enchondroma, one a bone cyst and a malignancy was missed in five cases. A FNAB detected two malignancies that the concurrent histological biopsy missed: a chondrosarcoma (cytological class 3) and a metastasis from adrenal cancer (cytological class 5). There were ten false negative FNABs and the histological biopsy was true positive in five of those.

Measures of diagnostic performance were also calculated for histological biopsy and FNAB on target lesions in the bone and in the soft tissue separately. The low number of lesions in the soft tissue makes these measures less substantial, but it seems that a sufficient sample is more difficult to harvest from a
target in the bone, as would be expected. The diagnostic performance is summarized in Table 6.

The cytological finding concurred with the histological finding in 89 out of 99 cases (89.9%). For the ten contradicting biopsies, there were the aforementioned two malignancies detected by FNAB alone and three class 3 findings that proved to be benign: an enchondroma, postradiation fibrosis and Paget’s disease of the bone. The rest of the contradicting cases were tumours missed by FNAB but detected by histological biopsy: an enchondroma and four missed malignancies.
Table 6. Diagnostic performance of MRI-guided musculoskeletal biopsies

<table>
<thead>
<tr>
<th>Biopsy type and target</th>
<th>Total</th>
<th>Non-diagnostic</th>
<th>True positive</th>
<th>True negative</th>
<th>False positive</th>
<th>False negative</th>
<th>Sensitivity</th>
<th>Specificity</th>
<th>PPV</th>
<th>NPV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Histological</td>
<td>170</td>
<td>1</td>
<td>71</td>
<td>87</td>
<td>2</td>
<td>9</td>
<td>0.89</td>
<td>0.98</td>
<td>0.97</td>
<td>0.91</td>
</tr>
<tr>
<td>HB Bone(^1)</td>
<td>154</td>
<td>1</td>
<td>63</td>
<td>80</td>
<td>1</td>
<td>9</td>
<td>0.88</td>
<td>0.99</td>
<td>0.98</td>
<td>0.90</td>
</tr>
<tr>
<td>HB Soft(^2)</td>
<td>16</td>
<td>0</td>
<td>8</td>
<td>7</td>
<td>1</td>
<td>0</td>
<td>1.00</td>
<td>0.88</td>
<td>0.89</td>
<td>1.00</td>
</tr>
<tr>
<td>FNAB</td>
<td>114</td>
<td>15</td>
<td>40</td>
<td>44</td>
<td>5</td>
<td>10</td>
<td>0.80</td>
<td>0.90</td>
<td>0.89</td>
<td>0.82</td>
</tr>
<tr>
<td>FNAB(^3) Bone</td>
<td>101</td>
<td>12</td>
<td>34</td>
<td>41</td>
<td>4</td>
<td>10</td>
<td>0.77</td>
<td>0.91</td>
<td>0.90</td>
<td>0.80</td>
</tr>
<tr>
<td>FNAB(^3) Soft</td>
<td>13</td>
<td>3</td>
<td>6</td>
<td>3</td>
<td>1</td>
<td>0</td>
<td>1.00</td>
<td>0.75</td>
<td>0.86</td>
<td>1.00</td>
</tr>
<tr>
<td>All Bone</td>
<td>156</td>
<td>1</td>
<td>66</td>
<td>81</td>
<td>1</td>
<td>7</td>
<td>0.90</td>
<td>0.99</td>
<td>0.99</td>
<td>0.92</td>
</tr>
<tr>
<td>All Soft</td>
<td>16</td>
<td>0</td>
<td>8</td>
<td>7</td>
<td>1</td>
<td>0</td>
<td>1.00</td>
<td>0.88</td>
<td>0.89</td>
<td>1.00</td>
</tr>
<tr>
<td>All</td>
<td>172</td>
<td>1</td>
<td>74</td>
<td>88</td>
<td>2</td>
<td>7</td>
<td>0.91</td>
<td>0.98</td>
<td>0.97</td>
<td>0.93</td>
</tr>
</tbody>
</table>

\(^1\) Histological biopsy of a target lesion in the bone, \(^2\) Histological biopsy of a target in the soft tissue, \(^3\) Fine needle aspiration biopsy
5.2 Retrograde drilling of osteochondritis dissecans of the knee (II)

All ten procedures were successful in reaching the intended target and no complications were recorded. The image quality during the procedure enabled identification of the bone-cartilage interface and any damage to the cartilage was avoided, as confirmed by the follow-up MR imaging as well. The mean procedural time from skin incision to withdrawal of the drill was 39 minutes (range 22 to 65 minutes).

All lesions showed some ossification on follow-up MR imaging and all patients got some pain relief. Eight patients experienced complete or otherwise significant relief from their symptoms. Mean VAS score declined from 6 to 2 in clinical follow-up. Limiting symptoms persisted in two cases and arthroscopy and transchondral fixation of the OCD lesion were eventually performed.

5.3 Retrograde drilling of osteochondritis dissecans of the talus (III)

Periprocedural MR imaging and the three follow-up MRIs confirmed that the intended direction and depth of the drilling was achieved in all cases. The overlying cartilage was not damaged and no complications occurred. The mean procedural time was 48 minutes.

The visible effect of the procedure on the pathological MRI findings was slight. Some ossification was seen in one follow-up MRI and decreased bone oedema in three follow-up MRIs. However, clear ossification of the OCD lesion was seen in the one case with only plain film follow-up imaging; this patient had the best clinical response as well.

All patients experienced some clinical improvement. Mean pain related to OCD declined from 7.5 to 1.75 as measured on the visual analogue scale. Three patients were left with no or minor symptoms and were able to return to normal physical activity. One patient was referred for arthroscopic debridement due to recurrence of symptoms after initially experiencing some relief from pain.

5.4 Core decompression of osteonecrosis of the femoral head (IV)

All twelve procedures were technically successful and without any reported complications. Judging from the perioperative and postoperative MR images, drill
channels were as planned, going from the lateral aspect of the femur via its neck into the affected subchondral cancellous bone. The average duration of the procedure was 54 minutes (range 26 to 86) from skin incision to instrument retraction.

In ten cases, initial benefit from the procedure was reported. The average amount of pain on the visual analogue scale was 6.5 before the core decompression and 2.2 after the procedure. Respectively, the average ability to function on a scale from 0 to 10 was reported as 4.7 and 7.3. The alleviation of pain and improved ability to function was sustained for the duration of the follow-up period in five of these cases. The average duration of relief was 10.6 months in the seven cases with recurring symptoms. Four hips eventually went through total hip arthroplasty (ARCO stages 2C, 3B and two 3Cs).

The ARCO stage was set lower postoperatively in three cases. All pathologic findings were seen to disappear, in one case preoperatively staged 1A and in another case staged 1B (Fig. 6), resulting in stage 0. One hip was staged 2C before and 2A after the procedure. The remaining nine cases had the same ARCO stage before and after the procedure.

![Fig. 6. Core decompression of ANFH. Axial proton density images showing complete resolution of bone oedema. Preoperative image (left) one month prior to CD and postoperative image (right) four months after the procedure (patient 8 in Table 4). Drill channels are visible postoperatively (arrow).](image-url)
6 Discussion

6.1 Magnetic resonance imaging as a guidance method

The purpose of this study was to evaluate the accuracy, safety and clinical feasibility of MRI guidance for percutaneous musculoskeletal biopsies and certain therapeutic procedures.

It is justified to ask what additional value and advantages MRI guidance brings in comparison with other modalities, and do they outweigh the possible disadvantages. At a glance, MRI seems like an ideal method of guidance if one is to percutaneously approach a specific point of the musculoskeletal system. MR imaging may well be the best way to depict pathologic conditions of the musculoskeletal system, meaning the target and the important surrounding structures will be visualized in great detail. The instruments will be nicely visible as well, either directly or illustrated by a navigation system of some kind – or both. The patient may lie comfortably, without being exposed to any ionizing radiation, meaning one can take one’s time and carry out as many acquisitions as desired, and the patient will not be harmed. On the other hand, an MRI scanner is relatively expensive and rather demanding to operate. An MRI suite is a very particular environment, where dedicated equipment and instruments are needed. Furthermore, the ergonomics of a tubular scanner are far from ideal for interventional use and image acquisition is prone to certain artefacts. MRI-guided biopsy has been found more expensive than CT-guided biopsy (Alanen et al. 2004). However, an MRI-guided therapeutic procedure has been found to be a financially competitive alternative to surgery at least for an osteoid osteoma (Ronkainen et al. 2006).

MRI is generally deemed the most suitable modality to diagnose a wide variety of diseases of the musculoskeletal system. Particularly oedematous lesions and lesions replacing bone marrow fat are best visualized with MRI (Adam et al. 1999, Carrino et al. 2007, Carroll et al. 2013, Hoane et al. 1991, Kaplan et al. 1998, Shin et al. 2007a).

The fact that MR imaging does not involve any ionizing radiation is highly advantageous especially when performing procedures on children, adolescents or pregnant females. The same advantage is significant for the performing physician and other staff as well and helps adhere to the ALARA (as low as reasonably achievable) principle for radiation use in medical imaging.
Modern MR imaging techniques, such as steady state imaging and parallel acquisition, have sped up the sequences used for guidance to the point where imaging speed is not a decisive problem. The acquisition time for a single B-FFE slice is 1.5 seconds while the other commonly used low-field MRI sequences consisting of three to eight slices take 12 to 35 seconds (Table 5).

While an MRI scanner with the common tubular configuration is not at all the most ergonomic environment for interventions, a scanner with open configuration comes close. The unobstructed access to the patient and the target area without having to move the operating table or the patient is most beneficial regarding both speed and ease of operation. As mentioned before, an array of imaging sequences in any imaging plane is available without having to reposition the patient, which is just as beneficial. The low field strength of most open configuration scanners is associated with less pronounced imaging artefacts.

The optical tracking feature was used in all procedures of this study. It provides real-time visualization of the instruments, the intended trajectory and the possibility to align the imaging plane with the instrument. Although it is not a necessity, it proved to be beneficial and may well speed up the procedure. Of course, such an indirect guidance method cannot take into account needle bending or patient motion, and actual instrument position must be confirmed by direct visualization of the target and the instrument. Patient immobilization is thus essential not only during an image acquisition, but for the whole duration of the procedure. In many cases, best patient comfort and co-operation is achieved with general anaesthesia.

CT has established itself as a reliable guidance method in skeletal biopsies (Ghelman 1998, Leffler & Chew 1999, Settle et al. 1990, Tikkakoski et al. 1992). It does not suffer from superposition of other structures like fluoroscopy does, but both of these bear the burden of ionizing radiation. CT has excellent spatial contrast and bone to soft tissue contrast. Thus, it may be preferred in certain skeletal regions, such as the cervical spine. Furthermore, MRI-compatible instruments made of titanium alloys are more prone to bending and less suitable for penetration of cortical bone when compared with their steely counterparts.

Ultrasound is readily available, inexpensive, mobile, lacks ionizing radiation and provides real-time visualization with excellent soft tissue contrast, making it the most preferable guidance method for percutaneous biopsies and procedures of targets in the soft tissue, especially superficial ones (Joines et al. 2007, Soudack et al. 2006). Contrast enhancement may bring added value to ultrasound as a guidance method (Loizides et al. 2011). However, total acoustic shadowing from
bone and gas and eventual lack of tissue penetration limit its use for skeletal indications and more deep-set targets and, in current clinical practice, ultrasound-guidance is hardly considered an option for most skeletal biopsies and is not really useful for any of the therapeutic procedures studied here.

The use of MRI guidance is well documented in the literature and a great number of different musculoskeletal percutaneous procedures involving both soft tissue and skeletal structures have been successfully performed under MRI guidance (Blanco Sequeiros et al. 2003, Blanco Sequeiros et al. 2008, Duckwiler et al. 1989, Ojala et al. 2000, Smith & Carrino 2008). Nevertheless, in clinical practice, cases not exclusively reserved for MRI guidance for a specific reason tend to get taken care of under other methods of guidance, as they are more readily available and mastered by most radiologists. In short, if MRI guidance is not necessary, it is not used. This has to do with numerous factors. First, the availability of an interventional MR suite, where one exists, may be limited due to excessive demand for diagnostic imaging. This way, MRI guidance may not become an everyday tool for all radiologists practising interventions, and perhaps only a few will eventually master the modality as a guidance method. Secondly, if an imaging-guided procedure can be performed easily, safely and quickly under a method of guidance that is already established for this use and readily available, should MRI guidance even be considered? There is an increased demand for diagnostic MRI. At the same time, ultrasound, CT and fluoroscopy equipment evolve.

Whether or not MRI will be routinely utilized as a guidance method in everyday practice eventually comes down to indications and practical feasibility. MRI guidance seems a clear choice whenever the target simply cannot be reliably visualized with any other modality. MRI may be the best choice if the patient is a juvenile with a target unreachable under ultrasound guidance, such as most lesions of the bone. Visualizing the most appropriate target point inside a tumour or diseased bone may be of additional value. According to the results of these studies, MRI guidance is safe and accurate. It seems feasible for clinical use, with unique characteristics to favour its use in certain cases.

6.2 Needle biopsy (I)

In the diagnosis of musculoskeletal lesions of uncertain character, the next step after clinical and imaging workup is undoubtedly percutaneous imaging-guided biopsy. It has been shown to be a cost-effective and highly accurate technique.

All target lesions in our series, detected preoperatively with CT, 1.5 T MRI or scintigraphy, were also observed with the 0.23 T scanner. While not on par with CT or 1.5 T MRI in terms of spatial resolution, the image quality was sufficient to identify the target and to provide a safe biopsy route.

The results of this biopsy series are comparable to those obtained with CT guidance (Leffler & Chew 1999, Tikkakoski et al. 1992). The good positive and negative predictive values, especially with histological biopsy, seem noteworthy. The patient cohorts have been smaller in all previous MRI bone biopsy studies (Blanco Sequeiros et al. 2002, Buecker et al. 1998, Carrino et al. 2007) and suboptimal sample quality has impaired diagnostic performance (Neuerburg et al. 1998). The use of a cylindrical trephine instead of a biopsy gun may have led to better preservation of the fine structure of bony samples in this series.

FNAB in conjunction with a histological biopsy has been shown to bring added value without increasing the risk of complications (Tikkakoski et al. 1993), even with skeletal lesions (Tikkakoski et al. 1992). The cytological diagnosis agreed with histology in the majority of cases in this series, and FNAB revealed two malignancies that had been missed by histological biopsy, a chondrosarcoma and a metastasis from adrenal cancer. Especially when the target has been reached with a coaxial needle, FNAB is fast and easy to perform and brings about little or no additional trauma or cost. In some cases, a repeat procedure can be avoided. In this series, histological biopsy alone was performed in 58 cases. All but three of these targets were skeletal, and supposedly FNAB was not used due to the dense nature of the target lesion.

42 biopsies were technically successful, but the histological and/or cytological analysis led to nonspecific histopathological findings or to difficulties in interpreting the result. This seemed to be associated with benign skeletal lesions where the representative tissue is either without any specific histopathological findings or an adequate sample for diagnostic use is difficult to obtain. Most of such cases eventually turned out to be osteoid osteomas, osteoblastomas, haemangiomas, cystic bone lesions, osteochondritis dissecans and infectious or inflammatory non-neoplastic lesions.

The study population comprised a heterogeneous group of biopsy indications and suspected target lesion types and locations, which is typical for an actual clinical setting. The number of malignant primary bone tumours was low, as these are rare. For this study, the targets were classified as skeletal and soft tissue
lesions according to their anatomic location, although the actual consistency of a
target lesion may be more important in relation to the biopsy procedure.
Classifying the targets further into bony lesions and soft lesions might lead to
different results.

Although general anaesthesia is an actual necessity only for children, it
provides good patient comfort, an immobile target and an accurately reproducible
apnoea when needed, for example in the thorax region. Spinal anaesthesia is an
option when the target is in the lumbar region or more caudally.

According to these results, MRI-guided percutaneous biopsy of
musculoskeletal lesions is accurate and safe. MRI guidance may be preferred in
certain patient groups and with certain target lesions. Fine needle aspiration
biopsy is an advantageous low-cost supplement to histological biopsy at least
with soft tissue targets.

6.3 Retrograde drilling of osteochondritis dissecans of the knee
and the talus (II and III)

Osteochondritis dissecans is a not an uncommon disorder. The prevalence is
reported to be 15 to 30 per 100,000, and especially children and adolescents are
affected. Although the condition is most likely multifactorial, the most recognized
risk factor is high level of sports activity, with repeated microtrauma as the
probable pathomechanism, causing a sort of a local stress fracture. (Hefti et al.
commonly affected are the knee, ankle and elbow (Edmonds & Polousky 2013).
The most commonly affected site in the knee is the lateral aspect of the medial
condyle (Hefti et al. 1999) and medial central articular surface of the talar dome
in the ankle (Elias et al. 2007, Hembree et al. 2012). These localizations were
also prevalent in this study (II and III).

MRI is definitely the preferred imaging method in the diagnosis, staging and
follow-up of OCD (Chen et al. 2013, De Smet et al. 1990, Hembree et al. 2012,
Kijowski et al. 2008). Clear depiction of the lesion itself and the ability to identify
the most disease-affected region, the overlying cartilage and the unfused growth
plate of an adolescent are important points favouring the use of MRI guidance in
these applications. The stability of an OCD fragment in relation to the underlying
donor bone is a decisive factor regarding treatment. Obviously, applying a
mechanical force from below poses a threat of dislodging an unstable OCD
fragment into the joint cavity. Absence of a continuous fluid signal between the
fragment and the underlying bone with an intact overlying articular cartilage was used as an indicator for a stable lesion in these series (II and III). We did not encounter any problems related to lesion stability in any procedure and we feel confident that all the fragments drilled into were still mechanically connected to the underlying bone, at least firmly enough to resist being dislodged.

With 48 minutes from skin incision to needle retraction in retrograde drilling of OCD of the talus (III), no speed advantage is evident when compared with fluoroscopic technique (Hoffmann et al. 2012). The duration can be expected to shorten with more experience, but the real advantages of MRI guidance are its overall flexibility, the lack of ionizing radiation and the ability to visualize the overlying cartilage in relation to the instruments. Furthermore, the ability to use multiplanar imaging in arbitrary angles and real-time guidance definitely helps when navigating complex anatomies while having to avoid traversing certain structures.

The low number of patients treated, ten OCDs in the knee (II) and four OCDs in the ankle (III), and the lack of a control group can be seen as major limitations, especially when it comes to evaluating the clinical benefit from the procedures. Again, the patient population was quite heterogeneous. Both imaging and clinical follow-up was somewhat inconsistent in some cases. Retrograde drilling of the talus has been proposed to be effective especially in larger (>15 mm) and more cystic lesions (van Bergen et al. 2008), which were not present in this population. Also, some clinical improvement may be due to spontaneous healing, as there is overlap with documented spontaneous resolution of pain from OCD of the talus (3 – 13 months) (Lam & Siow 2012) and the duration of conservative treatment in this cohort (2 – 11 months).

A larger series with more consistent patient selection and structured, long-running follow-up would provide information on the clinical value of MRI-guided retrograde drilling of OCD of the talus and the knee.

6.4 Core decompression of avascular necrosis of the femoral head (IV)

Avascular necrosis of the femoral head can be devastating, as the natural course of the disease may lead to collapse of the femoral head, secondary osteoarthritis and severe disability (Mont et al. 2010). Diagnosing the condition at its early stages and postponing, if not evading, the need for hip replacement with less invasive methods should be the primary goal with these patients. One and perhaps
the foremost of such methods is percutaneous core decompression, where ossification and healing of the subchondral bone is promoted by removing necrotic bone and relieving intraosseous pressure through channels drilled from an extra-articular approach.

Avascular necrosis of the femoral head is best diagnosed and classified with MR imaging (Malizos et al. 2007, Mont et al. 2006b). Reliable classification of ANFH is decisive, as mini-invasive procedures are effective only on pre-collapse femurs, i.e., at early stage ANFH (Castro, Jr. & Barrack 2000, Marker et al. 2008a). Once again, MRI can be postulated to be a suitable method of guidance, as it can not only depict the disease, but also show an appropriate pathway to the most disease-affected region of the femoral head using flexible imaging possibilities and navigation methods. Lack of ionizing radiation also sets it apart from the more commonly used guidance method, x-ray fluoroscopy.

In our series, technical success rate was 100% and no complications were reported. The average duration of the procedure was 54 minutes (range 26 to 86 minutes). This is tolerable and can be expected to shorten as experience is gathered. Consequently, MRI as a guidance method does seem well suited for core decompression of ANFH.

The study population was small, which prevents any other conclusions to be drawn. Still, the clinical outcome of these few patients was in agreement with the literature (Aigner et al. 2002, Simank et al. 1999). Most of the hips at early stages of ANFH seemed to gain encouraging benefit from the procedure. In some cases, the disease eventually progressed and lead to worsening of the symptoms and, consequently, surgical hip replacement. As expected, this was seen particularly with the cases of more advanced stages of ANFH. Although eventually treated with THA, it could be proposed that surgical treatment was perhaps postponed by the procedure in three cases (drillings V, IX and XI in Table 4). The core decompression procedure did not interfere with THA in any way.

Core decompression was observed to have a beneficial effect on pathological MRI findings in several low stage cases, which is in agreement with previous literature (Aigner et al. 2002). The ARCO classification system has been found to have poor interobserver reliability and regarded as insufficient to assess the status of ANFH alone (Schmitt-Sody et al. 2008). However, it is useful in a number of ways. Most importantly, the ARCO classification system is able to distinguish the early stages of the disease that are still applicable for mini-invasive treatment from the more advanced cases, and serves as a reliable tool for comparison and follow-up. A recent study has suggested that bone oedema in ANFH indicates a
subchondral fracture (Meier et al. 2014). This is in contradiction with some of the classification principles used for this study. Bone oedema without any additional imaging abnormalities has been classified as a stage 1 finding in this series. It remains unknown whether or not the bone oedema seen preoperatively in the hip of, for example, patient number 8 in Table 4 (see also Fig. 6), represents a microscopic subchondral fracture.

The study cohort was small and without a control group. Consequently, no direct comparison with other guidance methods or treatments can be made. The retrospective approach of the study, inconsistent imaging and clinical follow-up present a notable weakness as well. The patient questionnaire used to assess any possible benefit from the procedure was sent retrospectively, and the patients had to go back even several years in time when they were asked to evaluate their pain and their ability to function before and after each procedure.

The most important merit of these series is describing a novel yet feasible method of guidance for therapeutic bone drillings. In the end, MRI guidance for retrograde drilling of OCD in both ankle and knee and for core decompression of ANFH is accurate and safe.
7 Summary and conclusions

1. MR imaging and optical instrument tracking together provide an accurate, safe and clinically feasible guidance method for biopsies of the musculoskeletal system. Fine needle aspiration biopsy is a valuable supplement to core biopsy especially on soft tissue targets.

2. MRI guidance can successfully and safely be used for retrograde drilling of stable osteochondritis dissecans of the knee.

3. MRI guidance can successfully and safely be used for retrograde drilling of stable osteochondritis dissecans of the talus.

4. MRI guidance is safe and feasible for core decompression of avascular necrosis of the femoral head.


Original publications

This thesis is based on the following original publications, which are referred to in the text by their Roman numerals:


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Pekka Kerimaa

MAGNETIC RESONANCE IMAGING-GUIDED PERCUTANEOUS MUSCULOSKELETAL BIOPSIES AND THERAPEUTIC BONE DRILLINGS