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Quantitative MR imaging in fracture dating—Initial results

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ABSTRACT

For exact age determinations of bone fractures in a forensic context (e.g. in cases of child abuse) improved knowledge of the time course of the healing process and use of non-invasive modern imaging technology is of high importance. To date, fracture dating is based on radiographic methods by determining the callus status and thereby relying on an expert's experience. As a novel approach, this study aims to investigate the applicability of magnetic resonance imaging (MRI) for bone fracture dating by systematically investigating time-resolved changes in quantitative MR characteristics after a fracture event. Prior to investigating fracture healing in children, adults were examined for this study in order to test the methodology for this application. Altogether, 31 MR examinations in 17 subjects (♀: 11 ♂: 6; median age 34 ± 15 y, scanned 1–5 times over a period of up to 200 days after the fracture event) were performed on a clinical 3 T MR scanner (TimTrio, Siemens AG, Germany). All subjects were treated conservatively for a fracture in either a long bone or in the collar bone. Both, qualitative and quantitative MR measurements were performed in all subjects. MR sequences for a quantitative measurement of relaxation times T1 and T2 in the fracture gap and musculature were applied. Maps of quantitative MR parameters T1, T2, and magnetisation transfer ratio (MTR) were calculated and evaluated by investigating changes over time in the fractured area by defined ROIs. Additionally, muscle areas were examined as reference regions to validate this approach. Quantitative evaluation of 23 MR data sets (12 test subjects, ♀: 7 ♂: 5) showed an initial peak in T1 values in the fractured area (T1 = 1895 ± 607 ms), which decreased over time to a value of 1094 ± 182 ms (200 days after the fracture event). T2 values also peaked for early-stage fractures (T2 = 115 ± 80 ms) and decreased to 73 ± 33 ms within 21 days after the fracture event. After that time point, no significant changes could be detected for T2. MTR remained constant at 35.5 ± 8.0% over time. The study shows that the quantitative assessment of T1 and T2 behaviour over time in the fractured region enable the generation of a novel model allowing for an objective age determination of a fracture.

1. Introduction

In clinical forensic medicine different kinds of injuries have to be assessed whether and how they have been inflicted by a third party. In cases of inflicted fractures, the determination of the time of occurrence plays an important role as it can lead to an inclusion or exclusion of possible offenders as well as to the differentiation of multiple events. Therefore, the determination of a fracture's age may concern cases regarding maltreatment of vulnerable persons, torture and abuses of adults and may be of importance in cases of insurance litigations. Additionally, the determination of the fracture's age in alleged cases of child abuse is of crucial importance. According to Kogutt et al., fractures occur in up to 55% of cases of child abuse [1], and 80% of the investigated fractures of abused children occur in infants younger than 1.5 years [2]. Additionally, these children often present multiple fractures in different healing stages [3–5]. As children of this age cannot give information on the fracture event themselves, the determination of a fracture's age is currently mainly based on the assessment of radiographs, according to a timetable of fracture healing phases [6,7].

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1.1. Radiography in fracture healing

The bone healing process, which is consistently discussed in literature, starts with haemorrhage inflammation, followed by primary soft callus formation, callus mineralisation, and finally bone remodelling. However, the time intervals of these phases are dependent on the age of an individual, as well as other physiological and external factors such as mobility or dietary habits [5,8–10].

To date, radiographic imaging is routinely used for the examination of fractures in clinical medicine [11]. These radiographs provide a basis for the clinical diagnosis, therapeutic monitoring, and forensic assessment of fractures by displaying the fractured region, callus formation, and bone remodelling. However, the assessment of fractures in orthopaedic trauma literature lacks consensus about the definition of fracture healing regarding the specific time course. According to Prosser et al. [7], estimations of the duration of the fracture healing process are rather based on experience than on actual evidence, and until now lack a scientific validation in clinical practice. A large amount of literature exists concerning the mechanical stimuli needed for a proper fracture healing ([12,13] and references therein). However, only a few researchers describe fracture healing processes over the course of time, dating of inflicted fractures related to child abuse using radiographs and additional validation by histology [14–21]. Still, radiographic imaging lacks information on surrounding soft tissue and reliability of the evaluation of fracture healing [4,22–25].

1.2. MRI in fracture healing

Magnetic resonance imaging (MRI) allows the investigation of bone and surrounding soft tissue structures without any exposure to radiation by using magnetic fields and radiofrequency (RF) pulses which excite the protons in the tissues. As the excited protons relax back into equilibrium, a RF signal is emitted which is picked up by a receiver coil or antenna. The tissue contrast visible in MRI is defined by the sequence and characteristics of the RF pulses and the tissue characteristics [26].

Therefore, MRI techniques provide more information on the surrounding tissue, including the visibility of bone marrow, muscles, periosteum and fat as well as occult fractures [27,28]. Nevertheless, due to the fact that cortical bone contains almost no free protons and has a very short T2 relaxation time, MR imaging has only sporadically been implemented in fracture dating and the diagnosis of child abuse [11]. Burger et al. [27] analysed signal intensity qualitatively in radius fractures over time and observed a decline of the signal in fracture areas in T1-weighted images, whereas signal intensity increased in T2-weighted images over time. In medical practice, quantitative MRI (measurements of the relaxation times T1 and T2, or the magnetisation transfer ratio MTR) is already implemented in several diagnostic fields and can aid to evaluate specific diseases associated with tissue changes, e.g. neuromuscular diseases. Multiple studies examined lower limb muscles regarding their quantifiable changes in T1, T2, and MTR over time. In addition, follow up studies have been reported focusing on effects of exercise, body-weight or gender [29–31]. It was confirmed that MRI can represent a valuable method to detect metabolic, inflammatory, and dystrophic changes in soft tissue (reviewed in [32]) [33,34]. Additionally, Lai et al. described changes in MRI signal intensities after analysing damages to the soft tissue and related degradation of haemoglobin to methaemoglobin [35]. Since the fracture healing phases are defined by tissue changes, a transition from one healing phase to another will most certainly involve a concomitant change of quantitative MR values.

1.3. Aims

Quantitative MRI is expected to provide additional and more detailed information compared to the currently used method applied for fracture dating, i.e. radiography. In addition to being free of ionizing radiation, the assessment of quantitative features of tissue using MRI would enhance an objective evaluation of the age of fractures. This methodology may give the basis for a systematic approach of fracture dating, which can then be especially important in alleged cases of child abuse. Therefore, this study aims to apply quantitative MRI during fracture healing in adults as a first step to develop a model enabling the estimation of a fracture's age by investigating time resolved changes in MR parameters. This includes as well the validation of the quantitative approach by using MR relaxometry of muscles as reference values and comparison with values known from literature.

2. Materials and methods

The performed experiments were approved by the responsible ethical commission of the local university.

2.1. Subjects and MRI examination schedule

A total of 17 test subjects (Table 1) with at least one conservatively treated fracture of a long bone or collar bone participated in this study (6 males and 11 females, median age 34 ± 15 y; body mass index: 23 ± 2.80). All subjects were older than 18 years, could provide exact information on the time the fracture occurred, and signed an informed written consent prior to being included in the study. Each participant was scanned at least once, the maximum number of examinations being five within a time period of 190 days after the fracture event, resulting in a total of 31 MRI scans.

2.2. MRI protocol

All measurements were performed on a clinical 3 T MR whole-body scanner (TimTrio, Siemens AG, Erlangen, Germany). All morphological scans as well as the sequences for quantitative analyses were based on product sequences of the manufacturer, readily implementable on standard MRI systems with unmodified software.

Overall, a total of nine MR sequences were applied after recording scout images for proper slice positioning, for the determination of both, qualitative (sequences 1–4 in Table 2) and quantitative (sequences 5–9 in Table 2) parameters.

2.3. Data processing and analysis

In total, 31 MR scans were anonymised and morphologically evaluated by a board certified radiologist with 4 years of experience in clinical radiology including MRI and 3 years of experience in forensic imaging, without knowledge of the time point when datasets were recorded in the course of fracture healing. The morphological analysis included the determination of the fracture type as well as the description of the bone alignment in the fracture area in order to enable accurate evaluation of the fractured region. Five out of these 31 scans were used to optimize the MR protocol (Table 1, yellow). After the exclusion of three data sets due to non-evaluable image properties (Table 1, red), 23 data sets were evaluated quantitatively.

Firstly, quantitative maps for visualization of the spatial distribution of relaxation times T1 and T2 and the MTR were calculated using Matlab (R2014a, The Mathworks, Natick, MA, USA). Prior to the construction of quantitative maps, all data were noise reduced according to the method proposed by Gudbjartsson