Medical imaging plays an important role in care of patients with musculoskeletal pathologies. In this field, all Imaging modalities are useful, providing morphological and functional information. The presence of metallic implants and the complexity of structures require an update of imaging techniques to better understand the structural static data. Finally, imaging-guided treatment of bone and soft tissue diseases has benefited from the developing techniques to achieve an optimal target with minor adverse effects. This thesis describes the evolution in this direction in selected fields of musculoskeletal imaging.
"Update In Musculoskeletal Imaging: From Diagnosis To Treatment"

Thesis submitted to the Faculty of Medicine of the University of Geneva for the degree of Privat-Docent by

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1. **Abstract**

Medical imaging plays an important role in care of patients with musculoskeletal pathologies. In this field, all imaging modalities are useful, providing morphological and functional information. The presence of metallic implants and the complexity of structures require an update of imaging techniques to better understand the structural static data. Finally, imaging-guided treatment of bone and soft tissue diseases has benefited from the developing techniques to achieve an optimal target with minor adverse effects. This thesis describes the evolution in this direction in selected fields of musculoskeletal imaging.
2. INTRODUCTION

Musculoskeletal imaging is based on several modalities, and the whole technology platform is deployed to approach bone and soft tissue pathologies, ranging from conventional radiographs to magnetic resonance imaging. The musculoskeletal system is characterized by the complexity of its structures, all responsible of separate disease patterns, requiring therefore a different treatment approach, with the increasing presence of metallic material ever more blurring the correct visualisation of structures. Moreover, in recent years, the rapid technological evolution has enabled the development of guided treatment using imaging modalities, with less adverse effects and more efficient patient care.

Artifact reduction in computed tomography (CT) scans

Metallic implants are increasingly present in routine computed tomography (CT)-scans, including material for fractures and joint replacements like prostheses. According to the Office of Economic Cooperation and Development (OECD), the number of knee and hip replacement surgery is surging in the European Union, with rising trends observed in most countries (1). On the other hand, the main advancements of X-ray CT regarding human imaging have been the improvement of image quality and reduction in radiation doses. The most current model of image reconstruction is cross-sectional linear attenuation, which, to this day, still contains artifacts that potentially impact clinical diagnosis. The source of these artifacts has to do with disparities between image acquisition and image reconstruction from the produced data. These artifacts are prominent in the presence of metallic devices. The reason behind this phenomenon is due to the higher attenuation of metallic material compared to the surrounding tissue and bone.
Source of noise in CT
Noise in CT, also termed poison noise, is a statistical error consisting of a low photon count. The filtered back projection reconstruction (FBP) is the mostly used model for standard reconstruction on scanners. The projection data are filtered in order to sharpen edges, with the filtered data then back projected. This procedure only takes in account accurate data and ignores data with a low photon count, which explains why image noise increases in the presence of metal. To palliate this noise, modern scanners are equipped with modulation devices and applicable filters permitting higher doses in the periphery as compared to the center, increased slice thickness, and the use of soft reconstruction kernel.

In addition, iterative methods have been developed in an attempt to reduce noise, with iterative reconstruction algorithms currently provided in the majority of new systems. Basically, the resulting image is the average of the projected data, the relationship between image and projected data, and the prior image distribution. If images are too noisy, there is a wide range of projected data to palliate the noise in these images (2).

Recently, iterative reconstructions have been made available for clinical practice, such as the modeled-based iterative reconstruction (MBIR) method (General Electric Healthcare) (3). This methodology has proven instrumental in improving image quality and reducing noise with the possibility of acquiring data at lower doses. In MBIR reconstructions, the dose and noise are decoupled and it must thus be mentioned that the signal-to-noise ratio cannot be used with this technique, as the noise only depends on MBIR parameters.

Sources of metallic artifacts
Many factors affect the magnitude of artifacts: tube voltage, current, image reconstruction algorithm and kernel, as well as metal composition, geometry, and anatomic region (4). The beam hardening, beam width, increased scatter (also called low signal counts), and photon starvation are the mean features that create metallic artifacts. Of note is that beam hardening and photon starvation are primarily involved, as they create an attenuating area around
the metal that is too high (bright), frequently adjacent, or too low (dark) as compared to the surrounding tissues (5).

Beam hardening and Compton scatter both produce dark streaks between two high-attenuated objects, such as bone, metal, and iodine-based contrast material (high atomic number materials [Z]); streaking may also occur along the long axis of a single high attenuation object. The first phenomenon, namely the beam hardening, is prominent at the lower energies where the photoelectric effect is predominant; the second phenomenon, namely the Compton effect, is predominant at the higher energies, where attenuation plays a prominent role. This effect induces changes in the direction and energy of photons when they come in contact with detectors; for example, if the metal blocks the photons, then the detectors will only receive a few scattered photons.

Photon starvation is inherent to the reconstruction model and FBP, being accounted for by the inability of the reconstruction to represent the infinite attenuation when detectors receive no photon.

**How to reduce metallic artifacts**

Several tips and devices are employed in an attempt to reduce artifacts, such as using an anti-scatter grid placed in front of the detector or adding physical filters designed to reduce the beam hardening effect by narrowing the range of energies originating from the X-ray source. Increasing kilovoltage (Kv) and mAs are other means to reduce artifacts, although they do increase the radiation dose. The most widely used methods of reducing metallic artifacts include iterative reconstructions, dual energy, and improvement in reconstructions models.

We have previously demonstrated that iterative reconstructions prove able to reduce noise in imaging, in addition to reducing metallic artifacts. This is explained by the Hounsfield unit (HU) density in bone and metal in the uncorrected projected data; this information is thus used to correct beam hardening in each detector element (Fig.1)

Dual energy CT reduces metallic artifacts by scanning at two different energy levels and extracting virtual monochromatic images that are insensitive to the
beam hardening effect. Dual energy CT remains an approximative tool that lacks the homogenous shape of the absorption spectrum and does not correct the scatter effect, which, in some cases, can be quite prominent.

Improving the reconstruction model is the best approach for artifact reduction since these artifacts are generated by incorrect model assumptions (Fig2.). Metal artifact reduction research was focused on correcting sinogram data, i.e., the sum of attenuation along rays at different angles and offsets. This transforms the reconstructed data, rendering them close to the measured and transmitted X-ray energy at the detectors. The principle of these techniques is the correction of rays, which pass through metal that is considered as being corrupted, and replace the data from surrounding tissues that is unaffected by the implant. Once the corrected sinogram is obtained, a simple FBP reconstruction is applied. The replacement of sinogram values seen to pass through metal by uncorrupted surrounding values is called linear interpolation (LI) (6).

The commercial developed algorithms are broadly using the same concept. IMAR (Intelligent MAR) has been developed by Siemens (Siemens Medical Solutions USA, Martinez, CA, USA). OMAR (Orthopedic MAR) is the algorithm of Philipp’s (Philips Healthcare, Cleveland, OH, USA) and close to NMAR (Philips CT Clinical Science Philips Healthcare USA 2012). These algorithms are an extension of the LI method. They are tested against dual energy and other algorithms, such as the one developed by GE (7), providing the same results with comparable performance and good correction. Their only drawback is the generation of new artifacts (Fig.3).
Fig. 1: Aseptic prosthetic loosening. (a) Sagittal reformatted images in FBP demonstrate that regions of patella bone towards the femoral condyle prosthesis are obscured by beam hardening artefacts. Corresponding MBIR image (b) demonstrates a low attenuation zone at the bone-prosthesis interface, confirming the diagnosis of prosthesis loosening (adapted from Boudabbous et al. AJR 2015)

Fig. 2: Case of bilateral hip prosthesis showing the improvement of image
Fig. 1: Aseptic prosthetic loosening. (a) Sagittal reformatted images in FBP demonstrate that regions of patella bone towards the femoral condyle prosthesis are obscured by beam hardening artefacts. Corresponding MBIR image (b) demonstrates a low attenuation zone at the bone-prosthesis interface, confirming the diagnosis of prosthesis loosening (adapted from Boudabbous et al. AJR 2015)

Fig. 2: Case of bilateral hip prosthesis showing the improvement of image
quality for pelvic organs in images constructed with iMAR (b, d), again without additional value of ADMIRE (c) compared to FBP (A) (adapted from Neroladaki et al. Medicine 2019)

**Fig.3:** Pseudo-loosening in zone seven of Gruen. X-rays of right hip prosthesis show no sign of loosening in bone-metal interface. Coronal CT reconstructions in FBP (b) showing a beam hardening artefact in Zone seven of Gruen hiding this area (thin white arrow) and the disappearance of artefact in iMAR reconstruction (c) but also creating a pseudo-loosening artefact (thick white arrow) (adapted from Neroladaki et al. Medicine 2019).

**Synthetic MRI in musculoskeletal field**

Magnetic resonance imaging (MRI) is a validated technique widely used to explore musculoskeletal (MSK) diseases. It requires the acquisition of multiple morphological sequences in different planes in order to analyze qualitatively the tissues and characterize structural abnormalities. The time of examination varies depending on the number of sequences and devices used to reduce the time with optimal data acquisition. Technically, conventional MRI is described by hardware factors, the scale of proton density signal, voxel
volume, and pulse-sequence weighting (8). The tissue contrast of MR is governed by echo-time (TE), and a dynamic variation of TE values widens the range of contrast between tissues, enabling allows a more reliable diagnosis. The generation of multiple contrasts from a single sequence, as well as quantitative T1, T2, STIR, and PD maps, is called synthetic MR. This technique, first described in 1984, was limited by hardware constraints (9).

The first use of synthetic MR by Blystad et al. in 2012 was focused on the brain (10), in relation with different neurologic conditions such as multiple sclerosis, metastatic disease, and pediatric imaging (11,12,13). It was successfully used in neurology to further investigate white matter diseases (14). Recently, Park et al. reported using the technique for imaging of the knee (15). The authors concluded that the overall quality expected for the bone marrow analysis on T1 was comparable to that of conventional MR, yet with reduced examination time and the possibility of generating T2 mapping. Yi et al reported similar results without any significant difference in diagnostic accuracy between conventional and synthetic imaging for internal knee disorders (16). The first studies clearly demonstrated the feasibility of varying TE values with similar sensitivity, specificity, and accuracy compared to conventional MRI for knee imaging (17). Furthermore, synthetic MR was shown to generate quantitative images enabling the early study of cartilage changes in the knee, along with morphological images, thereby permitting appropriate treatment to be initiated at an earlier time. Currently, this technique is still being evaluated for MSK indications, particularly for knee and spine localizations. Several studies published in the scientific literature sought to validate the accuracy of this technique in generating similar morphological quality than conventional MRI and in producing repeatable quantitative maps. A recent study by Kumar et al. (8) focused on the knee has confirmed that the overall image quality between conventional and synthetic MR images was similar, as was the capacity of detection of various internal knee abnormalities. These results are in line with our data concerning the feasibility of this technique, based on knee MRI examinations in 22 cases (18) (Fig.4). Moreover, this technique has been
demonstrated to yield an improvement in contrast to noise (CNR) ratio for cartilage and meniscal evaluations in all sequences (19).

Concerning spine imaging, study of image quality, diagnostic confidence, and lesion conspicuity become possible with synthetic MRI (20). The supine position has an impact on back pain. The duration of current protocols is about 30 minutes for herniation disc issues, lasting for up to 1 hour if the whole spine has to be imaged or contrast agents are applied. The acquisition of three contrasts (T1, T2, and STIR) in 11 minutes significantly reduces the acquisition time. In our study (20), the acquisition time was 5 minutes and 40 seconds, which is half of the required time for a spinal region examination. This technique could be considered as an alternative or a complement to conventional MR generating T1, T2, and STIR weighted sequences. The confidence level of diagnosis and lesion conspicuity was deemed acceptable. As in the imaging of the knee, synthetic MR lacks contrast and resolution in some cases without impacting overall image quality (Fig.5). The explanation behind these findings is that, in the same voxel, when two tissues are different, they create a partial volume artifact (20). Therefore, the relaxation on T1 and T2 appeared as a combination of two tissue values (21), which could represent a limitation for synthetic techniques. The value of synthetic T1 sequence on spine imaging is still controversial, as the contrast is reported to be higher than conventional T1-weighted sequences, induced by the low signal to noise in the latter one (22). The STIR sequence produces artifacts due to pulsatile structures like vessels. This observation was made in all cases, though the modification of acquisition planes could reduce the drawback. In addition, it is important to highlight the absence of additional artifacts in the presence of metallic material in synthetic versus conventional sequences. The number of channels and coils affects the intensity of artifacts. This explains the better quality of image in the cervical area compared to dorsal and lumbar areas. As in the knee imaging, examination time must be considered in the routine flow of work, because the correspondent pathologies are the most common. Moreover, synthetic sequences provide useful quantitative maps, which may allow us, in the future, to derive relaxometry parameters of spinal components, permitting
the assessment of demyelinating diseases, degenerative diseases, and spondylodiscitis.

**Fig.4:** Post-traumatic left knee MRI in 32-year-old patient: synthetic MR on sagittal T1 (a), PD (b), and STIR (c) weighting compared to conventional images for coronal T1 (d), sagittal PD (e) and coronal STIR (f) weighting (adapted from Boudabbous et al. Acta Radiol 2018).
Fig. 5: Conventional versus synthetic T1, T2, and STIR SE images in lumbar area in a patient who underwent surgery. The post-operative changes are visible on synthetic images (adapted from Vargas et al. AJNR 2018)
Thermo-ablation of bone tumors

Ablation techniques performed under imaging guidance to treat benign and metastatic lesions constitute a part of the management of painful bone tumors. Several techniques have been developed, including ethanol injection and thermal ablation by means of energy deposition. These techniques of thermal ablation comprise radiofrequency, microwave, laser, cryoablation, and, recently, MR-guided high intensity focused ultrasound (HIFU). These therapies are proposed to help cure benign tumors and oligometastatic disease, and as palliative treatments by reducing pain and for locally controlling advanced diseases. Curative treatment is aimed to complete necrosis of benign lesions like osteoid osteomas or specific malignant tumors characterized by precise criteria as for number and size (23). Percutaneous ablation techniques can be combined with techniques of stabilization using cementation or metallic material, and with local control by embolization or chemoembolization. Thermal ablation is characterized by a high rate of success and low rate of complications, which is due to the precise targeting under imaging guidance. Technically, complete ablation of tumor volume and protection of vulnerable structures surrounding tumors have been demonstrated to yield good results. Ablation techniques, such as thermal ablation, generate cytotoxic tissue necrosis by generating temperatures of more than 60° C. Contrarily, cryoablation delivers temperatures of less than -20° C to achieve tumors necrosis. The main advantage of these techniques is their noninvasive character. Radiofrequency, cryoablation, and lasers require the insertion of one or multiple probes for treatment purposes. This is contrary to HIFU, which is based on the external application of a focused high intensity beam (24).

To alleviate pain during intervention, all these techniques are performed under some form of anesthesia, either general sedation or general anesthesia. Therefore, the presence of an anesthetic team increases the efficacy of these procedures, while reducing potential complications. Like in surgical rooms,
strict sterility and antibiotic prophylaxis are mandatory to minimize the risk of bone infection (25).

Imaging guidance accounts for the role of radiologists for these interventions (Fig.6). A wide range of imaging techniques are presently available and deemed suitable to control optimal device position inside the lesion. Fluoroscopy, ultrasound, CT, and MRI are employed for the exact positioning of the ablation device in the target lesion. If necessary, a coaxial approach is employed to reach the lesion through an intact cortical bone. To avoid energy transmission and skin burns, the trocar is moved back outside the ablative zone. Furthermore, protective techniques are employed to increase the intervention’s safety and minimize the adverse effects, such as skin protection, temperature and nerve root monitoring, and the dissection of vulnerable structures like nerves away from the ablation zone by gas or non-conducting fluid (26). Hence, a good understanding of anatomic structures proves crucial for the interventional radiologist to enable him to safely the procedures.

Radiofrequency is the only technique clinically available in our institution. In brief, the technique consists of a closed circuit composed of the generator, patient, RFA probe, and grounding pads. The energy is dispersed between the circuit’s cathode (RF probe) and the grounding pads. The energy created via molecular movement and agitation causes an increase in temperature and, as a result, a coagulation necrosis (27). Electrodes used upon RFA include monopolar electrodes being either single or multiple expandable, internally cooled, perfusion, or bipolar electrodes (27).

Osteoid osteoma is a benign tumor characterized by pain, which is exaggerated at night and relieved by salicylates and nonsteroidal anti-inflammatory drugs. RF of osteoid osteoma under CT-guidance was first described in 1992, demonstrating similar efficacy than surgery (28). Currently, thermal ablation, including all thermal techniques, is considered the gold standard for managing osteoid osteomas (Fig.7). Because of its high rate of success for pain relief of about 95% (29), along with an evidence level of III by guidelines concerning recurrence rates, thermal ablation has now become the treatment of first choice. A high temperature maintained for a prolonged time
prevents recurrence. For each device, the ablation protocol is applied according to the manufacturer’s guidelines. The low rate of adverse effects, such as nerve heating, tissue burns, and bone necrosis, increases the usefulness of these techniques.

Concerning metastatic bone disease, the most common causative cancers are lung, breast, colon, and prostate cancers. In oligo-lesional disease (≤3 lesions), thermal ablation can be used as curative treatment. In the majority of cases, however, ablation is employed as palliative treatment in order to control pain and tumor debulking. Pain relief following ablation is accounted for by the necrosis occurring between tumor and periosteum, reduction in tumor volume, tumor-related decrease in cytokine stimulation, as well as inhibition of osteoclastic activity (30,31). Ablation therapy of metastatic lesions is focused on bone-tumor interface to control pain, covering the whole tumor when designed to control local invasion. A combined therapy with cementoplasty or synthesis is required for weight-bearing bones in order to avoid instability and pathologic fractures.

In other institutions, other techniques, such as microwave, laser, and cryoablation, are performed in order to achieve bone and soft tissue ablation. The difference between microwave (MW) and radiofrequency is that the former is not limited by tissue conductivity and impedance and it desiccates tissues without heat sink effect, thus resulting in a larger ablation zone within a shorter time period (32). As for RF, one or multiple antennae can be inserted so that complete ablation can be achieved.

The laser induces cytotoxic temperature via infrared light energy, which results in a small-sized ablation zone; therefore, this technique is indicated for small lesions, osteoid osteomas, and in risky areas such as the posterior spine, as well (23).

Cryoablation is based on the application of extreme cold, resulting in ischemia, protein denaturation, and cellular membrane breakdown. Helium and argon gas expansion explain energy delivered during thawing and cooling phases, respectively. An ice ball is being formed during cryoablation, with the advantage of being visible under imaging, thereby increasing the accuracy of
this technique (33). In addition, the resulting pain during the peri-procedural period appears to be lower than with other techniques. This technique is costly because many probes are needed to achieve full therapeutic success, in the majority of cases.

All techniques appear to be accurate, yielding high effectiveness and low complication rates, according to most publications (34,35). Multidisciplinary meetings should be implemented for the decision-making process so as to include ablation therapies in the general management of metastatic diseases.

**Fig.6:** CT guidance for osteoid osteoma radiofrequency in strict sterile conditions and under general anesthesia (adapted from Paulin et al. Revue medicale Suisse, 2018)
Fig.7: Axial reformatting on bone kernel CT shows osteoid osteoma in the femoral cortical bone (a) treated with radiofrequency. (b) Shows the position of the needle in the nidus and through a trocar moved back at the entry of the cortex so as to avoid the path burn. (adapted from Paulin et al. Revue médicale Suisse 2018)
3. **Scientific Articles**


CT is a widely used imaging modality (after radiography) for evaluating patients with metal implants during the postoperative follow-up, in addition to many other indications, such as detection of pseudarthrosis, aseptic loosening, osteolysis, or infection. Artifacts generated by these devices degrade the image quality, both at the bone-metal interface and in the surrounding soft tissues, rendering diagnosis more difficult or even impossible. MBIR, a fully iterative reconstruction technique, includes an algorithm that models the entire optical chain, while taking into account the noise of the system. By modeling these optical effects, MBIR markedly improves the image quality, as compared to the classic FBP algorithm.
MBIR to Reduce Metal Artifacts on CT

Given that our intent was to study the MBIR algorithm as a way to reduce metal artifacts and not as a way to reduce radiation dose, the scan index was not changed and hence was optimal for the FBP algorithm. Each dataset was reconstructed with standard FBP (using a short kernel) and MBIR algorithm. The slice thickness was set to 0.625 mm for both reconstruction algorithms.

Two musculoskeletal radiologists evaluated two objective parameters for each reconstruction. The first parameter was the area of the artifact, measured at the same level of axial image reconstructed with the FBP and MBIR algorithms. The level of analysis was identical for both observers and chosen with regards to clarity and size of the artifact (Fig. 1). The second parameter was the diameter of the proton beam, measured at a fixed level on FBP and MBIR and compared with the measurements obtained with a digital caliper at the same distance from the tip of the proton beam. The window setting used (level, 300 HU; width, 2000 HU) allowed the best distinction of object outlines and the reduction of high-sensitivity signals arising from the metal. Forty measurements were selected.

In Vivo Study

This prospective study was approved by the institutional review board of the Geneva University Hospital, and informed consent was waived. From September 2011 to March 2013, 62 patients who underwent CT (also using Discovery 780 HD) of pelvis, spine, and extremities were nonrandomly included. The indications for CT were reviews and included outpatient follow-up of metal artifacts (n = 20), suspicion of particle-induced pseudotumoral disease (specific postoperative imaging, also called "pseudoaneurysm") (n = 21) or prosthetic artifacts (n = 5), and unexplained pain (a = 7). The acquisition parameters were the same as for the in vitro study except that the tube voltage used were 150 kVp for extremity imaging (knee, ankle, elbow, wrist) and 140 kVp for other locations.

F: 1-4: In vivo metal artifact in CT with prosthesis.
A. Photograph shows hip prosthesis.
B, CT image shows level (green line) on template plate at which X-ray measurements of artifact size were obtained.
C and D, Film image {protrusion} (a) and slice from three-dimension reconstruction (MBIR) (b) in phase with originally acquired (top) and after hand drawing (bottom) of artifact (purple region). Reduction in size of artifact evident was implemented as MBIR algorithm.

Update in Musculoskeletal Imaging: From Diagnosis To Treatment
As in the in vitro study, the slice thickness was set in ODS 1.5 mg for both algorithms. Quantitative and qualitative measures were obtained by the same two radiologists using the same two algorithms. The quantitative analysis was performed using the following steps: 1. The slice thickness was set in ODS 1.5 mg for both algorithms. 2. The boundaries of the artificial artifacts (bladder, rectum, lymph nodes) in the images were manually traced. The choice of level was made by the location of the metal artifact, the clinical indication, and the maximum number of artifacts.

The qualitative analysis was first focused on the bone-metal interface in FBP and MEBR using the following factors: 1. The slice thickness was set in ODS 1.5 mg for both algorithms. 2. The boundaries of the artificial artifacts (bladder, rectum, lymph nodes) in the images were manually traced. The choice of level was made by the location of the metal artifact, the clinical indication, and the maximum number of artifacts. The results were evaluated by two radiologists.

The second parameter was the evaluation of the gray level difference between FBP and MEBR in the soft tissue window (level 40 HU, width 150 HU) using the same scale and methods. Specifically, the boundaries of the artificial artifacts (bladder, rectum, lymph nodes) in the images were manually traced. The choice of level was made by the location of the metal artifact, the clinical indication, and the maximum number of artifacts. The results were evaluated by two radiologists.

Results

Four cases were evaluated using the same protocol. The mean (SE) values for the four cases were 20.8 ± 2.5, 19.8 ± 1.9, 19.9 ± 2.9, and 19.6 ± 3.4 for each parameter. A statistical analysis was performed using the Kruskal-Wallis test with a significance level of 0.05.

The mean (SE) value for the artificial artifact was 22.8 ± 2.5, 21.9 ± 1.6, 22.0 ± 1.9, and 21.7 ± 2.6 for each parameter. A statistical analysis was performed using the Kruskal-Wallis test with a significance level of 0.05.

In Vivo Study

Our population included 62 patients with 63 metal implants (one patient had bilateral hip prostheses). The mean age of the patients was 49.7 ± 14.2 years (range, 18-82). A qualitative analysis revealed a significant difference in mean artifact size, from 7.3 ± 1.5 to 4.0 ± 1.5 mm, for the FBP and MEBR algorithms, respectively.
significant reduction of 45% ($p = 0.012$) (Fig. 2). The subjective evaluation of the bone-metal interface was better with MBIR than FBP in 60% of cases; performance of MBIR was equal to that of FBP in 35% and worse in 5% of cases (Figs. 3–5). The subjective agreement (K value) was 0.856, corresponding to moderate agreement (Fig. 3).

A significant improvement in the analysis of surrounding anatomical structures was found when comparing soft-tissue details. Indeed, MBIR performed better than FBP in 45% of cases, it performed equally well in 25% and worse in only 3% of cases. In comparison with FBP reconstruction, the artifacts were significantly reduced in the pelvis on MBIR, even when two protheses were present (Fig. 5).

**Discussion**

This comparative study shows that MBIR could be used to reduce metal artifacts on CT and hence allow an equal or better bone-metal interface analysis, as well as a better assessment of soft tissue around the metal implant. Quantitative analysis showed a significant size reduction of the artifacts when MBIR was used, as well as a better subjective image quality in the majority of cases.

Imaging of metal devices represents a major part of the routine clinical practice of radiologists. CT is widely used imaging modality for evaluation of patients with metal implants for postoperative follow-up, as well as for many other indications including detection of pseudoarthrosis, amputations, osteolysis, or infection. Artifacts generated by these devices degrade the image quality, both at the bone-metal interface and in the surrounding soft tissues, and make diagnostic difficult or impossible. This study was designed to determine the added value of the MBIR algorithm in reducing metal artifacts.

MBIR is a fully iterative reconstruction technique. It is more sophisticated than the first generation of iterative reconstruction techniques and includes an algorithm that models the metal optical chain and is added into image reconstruction processes (photon statistic and electronic noise). By modifying these optical effects, MBIR potentiately improves the image quality, using fewer approximations than the classic FBP algorithm (11).

The reduction of artifacts in MBIR images led, to our knowledge, not being the primary goal of any previous studies. We are aware of only a few mentions on MBIR within artifacts that deal with the reduction of artifacts (12). In the present study, artifacts (spike and beam hardening) were deemed acceptable in 100% of cases when the MBIR algorithm was used, whereas they were deemed unacceptable in 25% of the cases when the FBP algorithm was used. We believe that our study is the first to deal with artifact reduction using MBIR in the amount of metal implants.

In vivo, MBIR yielded better image quality than FBP. In cases of postoperative becoming, the reductions of artifacts allowed better visualization of low-attenuation areas around the bones.
would be powerful. With the constant progress of processing power, this capability is expected to be available in a few years.

In conclusion, this pilot study has shown that the MBIR algorithm might be used to reduce metal artifacts in CT images. This represents a new use for MBIR, which was previously applied primarily for dose reduction. Future studies should focus on possible dose reduction in the context of metal artifact reduction.

References
MBIR to Reduce Metal Artifacts on CT

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Recently developed linear interpolation techniques offer visible benefits in reducing metal artifacts and are especially useful in hip arthroplasty, as demonstrated by our study. The MAR algorithm is a technique that interpolates the projection data using neighboring information with the aim of replacing the corrupted images. Several studies assessed subjective image quality and pelvic structures, reporting significant reduction in artifacts and an improvement in overall quality, as seen with other types of metal implants (dental, spinal hardware, and fracture devices). These different techniques and studies, however, demonstrated the appearance of new artifacts (high- and low-density streak) generated by different algorithms. New algorithms are currently being developed and seem to be able to reduce metallic artifacts, while exhibiting better performance, yet with fewer new artifacts on the far field.
Metallic artifact reduction by evaluation of the additional value of iterative reconstruction algorithms in hip prosthesis computed tomography imaging

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Abstract
To evaluate the bone and metal artifact reduction (MAR) techniques in images from hip prosthesis computed tomography (CT) and the added value of advanced iterative reconstruction (ADMIRE) compared with standard filtered back projection (FBP).

Twenty-eight patients addressed to CT examination for hip prosthesis were included. Images were reconstructed with MAR algorithm in addition to FBP and ADMIRE techniques. Imaging image quality and attenuation values with standardized region of interest (ROI) in 4 predefined animals of a cartilage, cartilage and medulla osteosome, medulla and osteosome, medulla and soft tissue of contrast medium present. Subjective image quality was graded on a 5-point Likert scale, taking into account the size of artifacts, the bone-metal interface, and the conspicuity of pelvic organs, and the diagnostic confidence.

Improvement in visual image quality was statistically compared using MAR (median: 4.88) compared with ADMIRE and FBP. ADMIRE did not show any improvement in image noise, attenuation value, or (ROI) quality image. MAR showed a significant decrease in image noise in all 4 animals. However, the MAR reconstruction with FBP and ADMIRE. Interobserver agreement was high for all the reconstructions (FBP, MAR, ADMIRE, and MAR + WD) more than 0.8. MAR reconstructions showed a lower presence of noise artifacts in bone-metal interface.

MAR algorithm shows a significant reduction of metallic artifacts on CT images with unblinded or blinded assessments without additional value of ADMIRE. It improves the analysis of surrounding tissues but potentially generates new artifacts in bone-metal interface.

Keywords: artifacts, algorithms, hip prosthesis

1. Introduction
Metallic artifacts from large implants like hip prostheses are a common problem in computed tomography (CT) imaging. Artifacts are caused by beam hardening and photon starvation. [1]

Methods for reducing artifacts used in routine practice, such as increasing tube current, cause higher radiation doses to the patient yet limited improvement of image quality. Several methods have been developed to reduce artifacts in surrounding tissues and bone-metal interface. Metallic artifact reduction (MAR) algorithms have been proposed and widely studied in literature. [2,3] These algorithms involved an new projection data like iterative reconstruction (IR) in coils and were evaluated for small and large implants. [2-5] The main goal of MAR is to reduce the visibility of metallic artifacts from images, improving diagnostic accuracy. Several studies have demonstrated that MAR improves diagnostic assessment in the surrounding tissues and the bone-implant interface. [6,7] In most clinical practice, IR algorithms are available and used mainly for very low dose reduction, enabling significant dose reduction while maintaining image quality. [8,9] These algorithms detect noise-related artifacts and suppress them in the projection and image domain, serving as a potential method to reduce metallic artifacts. [10] The purpose of this study was to quantitatively and qualitatively evaluate the impact of a new MAR algorithms on overall image quality and diagnostic appearance compared with filtered back projection (FBP) in a hip phantom in clinical routine practice, with special focus on bone-metal interface regarding new artifacts produced by this algorithms. [10] We also evaluated the impact of
2. Materials and methods

2.1. Patient population

The local ethic committee on research involving humans approved this prospective study and waived the need for written patient consent. Patient data was anonymized. Patients referred to the department for public CT examination for hip prostheses complications (loosening, aseptic necrosis, pseudotumoral formation, periprosthetic fracture) were included consecutively.

Between March and October 2016, a total of 28 patients (16 men; 12 women; 15 patients aged 75.14 years) were included consecutively in the analysis. 21 patients had a unilateral hip prosthesis and 7 a bilateral hip prosthesis. Therefore, body mass index (BMI) was 22.47.

2.2. Computed tomography protocol and image reconstruction

All CT scans were performed using a second-generation dual-energy computed tomography (DECT) scanner (SOMATOM Definition Flash, Siemens Healthcare, Forchheim, Germany). A standard single-energy protocol (120 kVp) was applied in all patients. Pitch was always set from 0.45 to 0.9, and uncollimation was 64 x 0.6 mm. When contrast medium was clinically indicated (480-640 mL of Aestonique 350; GE Healthcare, Opfikon, Switzerland) were injected as a flow rate of 3 mL/s and flushed out by 48 mL of saline solution at a flow rate of 3 mL/s. Five cases of contrasted CT were carried out to exclude subclinical infection or underlying systemic illness. All CT scans were performed in single energy acquisition (X-ray tube current: 380 mA) with optimization of automatic tube current (Care Dose, Siemens Healthcare, Forchheim, Germany). The raw data were then reconstructed with BIP and ADIME for the volunteers included in our department with reference to literature on hip prostheses dedicated MAR was always chosen (the system programs different MAR algorithms, each dedicated to a specific clinical question). We used a soft tissue kernel (B54) for imaging. The slice thickness interval was 1.5 mm. For different reconstituted series the time was obtained for every patient: FBP, IP+MAR, ADIME, and ADIME+MAR.

2.3. Qualitative image analysis

Subjective image analysis was performed in a double-blind mode with appropriate time interval (1 month) for all reconstituted series by 2 board-certified musculoskeletal radiologists with 3 and 1 years of experience, respectively. All reconstituted images were displayed in a bone window (level 3381/width 1000). The readers were allowed to optimize the images by adjusting the window parameters and analyzed 3 parameters: overall image quality, diagnostic workup for the assessment of pelvic organs, and muscle-bone interface. The scores used are summarized in Table 1.[9]

Furthermore, all suspected cases of loosening in FBP+MAR reconstitutions were compared with standard pelvic views, which are considered the gold standard [10] and diagnostic accuracy was calculated.

2.4. Quantitative image analysis

Image noise of FBP, FBP+MAR, ADIME, and ADIME+MAR was determined in an axial CT slice in predefined structures (region of interest [ROI]: gluteus medius muscle; ROI: rectus femoris muscle; ROI: subcutaneous fat; ROI: subcutaneous fat; ROI: subcutaneous fat; ROI: subcutaneous fat; ROI: subcutaneous fat; ROI: subcutaneous fat) in a standardized circular ROI at the exact anatomic location for every reconstruction. The SB of the CT number was calculated in all 4 reconstituted images for every patient. To ensure reproducibility of measurements in the 4 different reconstituted series from the same single acquisition, standardized circular ROIs of 10 mm were positioned in every slice and repeated for every slice 2 times to allow data compromise.

2.5. Statistical analysis

All statistical analyses were performed using GraphPad Prism 6.0c (GraphPad Software, Inc., San Diego, Calif). Interobserver agreement of subjective image analysis was determined using

---

**Tables**

1. | Image quality | Score | Description |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Noiseless streak artifacts and fully reduced image quality</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Significant artifactual and blurred image quality</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Minor artifacts and good image quality</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Almost no artifacts and excellent image quality</td>
<td></td>
</tr>
</tbody>
</table>

2. | Diagnostic confidence for the assessment of pelvic organs | Score | Description |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Major artifacts with difficult diagnosis, more pelvic organs with good accessory occult diagnosis</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Major artifacts with difficult diagnosis, more pelvic organs with acceptable occult diagnosis</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Minor artifacts with good accessory occult diagnosis with difficult diagnosis</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Minor artifacts with difficult occult diagnosis</td>
<td></td>
</tr>
</tbody>
</table>

3. | Bone-soft tissue interface | Score | Description |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Complete absence of imaging artifacts</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Artifacts interfering with diagnostic decision-making</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Moderate artifacts interfering with diagnostic decision-making</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Minor artifacts not interfering with diagnostic decision-making</td>
<td></td>
</tr>
</tbody>
</table>

---

**Figure**

Update in Musculoskeletal Imaging: From Diagnosis To Treatment
Table 2: Comparison of median values of image quality, diagnostic confidence for the assessment of pelvic organs, and bone-metal interface.

<table>
<thead>
<tr>
<th>Median (25-75 percentile)</th>
<th>Image quality</th>
<th>P values</th>
<th>Diagnostic confidence for the assessment of pelvic organs</th>
<th>P values</th>
<th>Bone-metal interface</th>
<th>P values</th>
</tr>
</thead>
<tbody>
<tr>
<td>FBP</td>
<td>1 (0-2)</td>
<td>2</td>
<td>2 (0.25-3)</td>
<td>&gt;0.001</td>
<td>1 (1-2)</td>
<td>&gt;0.001</td>
</tr>
<tr>
<td>ABMRE</td>
<td>2 (0-2.75)</td>
<td>&lt;0.001</td>
<td>3 (0.25-3)</td>
<td>&lt;0.001</td>
<td>2 (1-2)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>FBP + IMAR</td>
<td>4 (0-4)</td>
<td>&lt;0.001</td>
<td>4 (4-4.25)</td>
<td>&lt;0.001</td>
<td>3 (2-3)</td>
<td>&gt;0.001</td>
</tr>
<tr>
<td>ADMBRE + IMAR</td>
<td>3.5 (2-4)</td>
<td>4 (4-4.75)</td>
<td>4 (4-4.75)</td>
<td>3 (2-3)</td>
<td>4 (4-4.75)</td>
<td>&gt;0.001</td>
</tr>
</tbody>
</table>

FBP = Filtered back projection, ADMBRE = advanced model-based reconstruction, IMAR = iterative metal artifact reduction.

Kendall's W coefficient of normal distribution. Values of 0 to 0.2, 0.21 to 0.4, 0.41 to 0.6, 0.61 to 0.8, and 0.81 to 1.0 were considered to represent slight, fair, moderate, substantial, and almost perfect agreement, respectively. Normality of the data for subjective analysis was tested using the Shapiro-Wilk normality test, the Anderson-Darling test, and the Kolmogorov-Smirnov normality test. Due to non-normally distributed values, comparison of the subjective analysis median from FBP, ABMRE, FBP + IMAR, and ADMBRE + IMAR was performed using the Friedman test. Results are given as median and interquartile range. A P value of less than .05 was considered statistically significant. Quantitative data was compared using ordinary one-way analysis of variance (ANOVA) test given the normally-distributed values, with results presented as means and SDs. Alpha level and statistical significance was set at under 0.05.

3. RESULTS

Twenty-eight patients and 38 procedures (21 patients with unilateral and 7 with bilateral procedures) were included in the study. Seven cases with bone-metal loosening, 5 cases with collection or gluteal bursal collection, and 3 cases with femoral fracture around the screws were diagnosed. In the other cases, the CT was negative.

3.1. Quantitative image analysis

The results of the subjective analysis are summarized in Table 2. All the studied parameters improved with the use of IMAR with P values <.001 for image quality, diagnostic confidence for the assessment of pelvic organs, and bone-metal interface whereas ADMBRE had no significant impact with P values >.09 respectively (Figs. 1 and 2). Intercorrelation agreement ranged from high to excellent for all parameters (r = 0.772) (Table 3).

Concerning the comparison with the gold standard for loosening evaluation, we expected bone loosening in 5 patients based on MAR reconstructions yet were unable to confirm either with the FBP reconstruction or conventional radiography. There were also no expected false positives (Fig. 3). We suspect bone loosening in 7 patients based on all CT reconstructions, which was also confirmed by conventional radiography (true positive). In all other cases, no loosening was detected, either using CT, FBP or MAR reconstructions, nor in x-ray (true negative cases.

Figure 1. Artificiial reduction in left hip arthroplasty in bone-metal interface and surrounding tissues when using IMAR (B) comparing with FBP (A) without impact of ADMBRE (C). IMAR = iterative metal artifact reduction, FBP = filtered back projection, ADMBRE = advanced model-based iterative reconstruction.
2. CMOoTJT: l'tl po:lhosa sto,oirt�tho frlii'O<CIITICn dlrn11Q0ql.dlyb-

«<daCNI 

<daC:M!=IE <Qoorlll:.-odwih AIPW.IM/IA8i�m:J:.:II

n=21. Thus, the accuracy of iMAR algorithm was 0.81 to detect metal-bone interface bowing.

### Table 5

<table>
<thead>
<tr>
<th>Objective assessment of subjective image analysis using Kendall W coefficient of concordance (2% confidence interval)</th>
<th>Kendall W coefficient of concordance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image quality</td>
<td>W=0.872</td>
</tr>
<tr>
<td>Diagnosis confidence for pelvic organs</td>
<td>W=0.585</td>
</tr>
<tr>
<td>Metal-bone interface</td>
<td>W=0.756</td>
</tr>
</tbody>
</table>

3.2. Quantitative image analysis

The results of the objective image analysis are summarised in Table 4. When iMAR was not used, the density measured in the muscle was different from the standard values, with a very high SI and P values = 92 for gluteus medius and = 48 for rectus femoris, meaning that the measurements took into account break artifacts. When iMAR was applied to the data, the measured

Figure 2. Case of bilateral hip prosthesis showing the improvement of image quality by pelvic organs by images reconstructed with iMAR (B, D), again without additional value of AIBARE (A) compared with REP (A). iMAR = iterative metal artifact reduction, REP = standard back projection; AIBARE = advanced iterative bone artifact reduction.

Table 4: Interobserver agreement of subjective image analysis using Kendall W coefficient of concordance.

<table>
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<tr>
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<th>Kendall W coefficient of concordance</th>
</tr>
</thead>
<tbody>
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<td>W=0.872</td>
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Figure 3. Pseudo-osteoscan in right hip prosthesis showing no sign of osteoscan in bone-metal interface, especially in strain zone 7. Histomorph CT reconstruction (A) showing a beam-splitting artifact at frontal plane (white arrow) that appeared during the analysis (B) (white arrow). Disappearance of this artifact in iMAR reconstruction (C) is a creation of pseudo-osteoscan artifact (EPM white arrow).
density was expected to the expected values of muscle density and the AD was lower, meaning that streak artifacts became apparent with a value of $0.84$ for gluteus medius and $0.80$ for rectus femoris.

When the AD was placed in the intra-abdominal fat far from the metallic artifacts, the density was always lower than expected to the fat density, with no advantage afforded with either iterative reconstruction algorithms (Table 4) and $P$ values $=0.48, 0.49$, and $0.99$ compared to the AD and FBP, ADBM, and ADP + MAR algorithms.

### Table 4

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Gluteus medius</th>
<th>Rectus femoris</th>
<th>Intramuscular fat</th>
<th>Intra-abdominal fat</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>FBP</td>
<td>$-25$ (114)</td>
<td>$75$ (66)</td>
<td>$86$ (28)</td>
<td>$86$ (28)</td>
<td>0.84</td>
</tr>
<tr>
<td>ADBM</td>
<td>$-30$ (112)</td>
<td>$15$ (60)</td>
<td>$86$ (28)</td>
<td>$86$ (28)</td>
<td>0.99</td>
</tr>
<tr>
<td>FBP + MAR</td>
<td>$21$ (19)</td>
<td>$56$ (20)</td>
<td>$88$ (54)</td>
<td>$88$ (54)</td>
<td>0.99</td>
</tr>
<tr>
<td>ADP + MAR</td>
<td>$29$ (19)</td>
<td>$55$ (25)</td>
<td>$89$ (27)</td>
<td>$89$ (27)</td>
<td>0.99</td>
</tr>
</tbody>
</table>

**ADP + MAR** algorithms are the only algorithm that preserves the projection data for non-metallic tissues and provides a better method for reducing streak artifacts and improving both the overall quality and the performance of the algorithms. This is evidenced by the fact that the ADP + MAR algorithm has the highest $P$ value ($0.99$) and the lowest mean difference ($55.25$).

### 6. Discussion

In our study, we highlight that MAR reconstruction significantly reduced the artifacts near metal and in the surrounding tissue, with also enabling accurate diagnosis for hip pain. MAR had an impact on high- and low-density streak artifacts in surrounding tissue. However, the study showed that the MAR algorithm significantly improved the performance of the algorithms, particularly in the presence of metal. As shown in our results, metallic artifacts impaired the quality of the reconstruction. This is limited to postoperative imaging, where the bone is hardening and bone growth is not present.

Metal artifacts are a frequent challenge in hip pain today. They are caused by bone hardening and bone growth, which affects adjacent tissues, mainly in the pelvis. Increasing tube currents and using higher $kV$ energy improve image quality but also increase radiation dose. The bone-hardening algorithms used in CT imaging, known as FBP, fail to reconstruct the image due to inaccurate projection data. However, metal energy makes it possible to reduce artifacts by using different algorithms. The iterative methods for MAR reconstruction algorithms (Table 4) are increasingly used.

Despite the fact that these algorithms are available, the creation of new algorithms by new methods is a significant drawback. In this respect, iterative and interpolated reconstructions (MAR) have been limited by the need for additional post-processing and dedicated workstations. The iterative MAR reconstruction technique recently developed allows visible benefit in reducing metal artifacts and is especially useful in hip arthroplastics, as demonstrated in our study. These studies assessed subjective image quality and pelvic structure and reported significant reduction of artifacts and improvement of overall quality in other types of metal implants (dental, spinal, and fracture devices). These different techniques and studies, however, also demonstrated the appearance of new artifacts (high- and low-density streaks) generated by different algorithms.

Many studies have recently undertaken to explain new artifact emergence. The interpolated inhomogeneous MAR algorithm is a technique that interpolates the projection data using neighboring information with the aim of replacing the non-metallic tissues. This algorithm causes secondary artifacts as the transition is not sufficiently smooth. The general method is the normalized metal artifact reduction that may originate from the same problems as the linear interpolation (LI) and also increases secondary artifacts, particularly when the target contains more than one metal. Similarly, Peng et al. proposed another innovation, a way to difference artifacts impacting in a fan-beam scanner. MAR is developed from image inpainting, combining it with linear interpolation. FBP is used and then a metal image is created. The data is then replaced with interpolated data from adjacent projections. This approach has never been validated to ensure that the transition between interpolated and uninterpolated data results in new streak artifacts, and the low average around the metal cannot be recovered by interpolation, resulting in blurring. To resolve this problem, MAR normalizes the spectrum before interpolation. The output image is used several times as the input image for the next iteration. High-frequency data is replaced with high-frequency data from the original FBP reconstruction to recover the data near the metal edge.

To overcome the drawbacks of these algorithms, T bones have developed several algorithms on various platforms and clinical data sets of hip CT scans and showed that metal detection technique (MDT) and new algorithm (enhancement metal artifact reduction) are able to reduce as well as other techniques on metal artifacts with better performance and less new artifacts on the far field. Our study focused on a new computational algorithm allowing significant artifact reduction, as demonstrated recently by other studies in hip arthroplastics, which is clinically expected of potential material complications. The results of this study demonstrated that the emergence of new artifacts and predominant areas is limited at the interface with the non-metallic materials. The new feedings have a significant impact on CT imaging, providing one of the most challenging aspects of CT to detect loosening. Until now, conventional radiography of hip and pelvis has been the gold standard for image quality. However, the studies on CT, magnetic resonance imaging (MRI), and single-photon emission CT (SPECT-CT) have not yet been validated for loosening detection. CT is more efficient in detecting loosening than SPECT-CT, and when combined with the artifact reduction algorithm, it is also efficient for joint evaluation and analyzing bone or metal artifacts.

The new artifacts created by these algorithms that mimic bone or metal, limit their use, and care should be taken when bone or metal is suspected.
Our findings thus confirm those of former studies. We compared R01 with arthroscopy and in a small series at CT and MRI levels between FBP and iMAR. In objective results, attenuation value fracture in the mouse, according to the new artifacts created by iMAR.

In another hand, the ADIRK technique is an iterative method and a valid option to reduce radiation dose and optimize image quality mainly in cardiac imaging. Its capacity to reduce metal artifacts in, however, unsatisfactory with consistent clinical impact, as demonstrated in our study.

This study has some limitations. First, we included only a small number of patients, even though hip arthroplasty is widespread, because of our exclusion of patients undergoing pelvic CT only to exclude arthroplasty complications. The readers were blinded to CT analysis for subjective findings, but the remarkable difference between FBP and iMAR could influence the subjective analysis, even when the images were interpreted several weeks apart. iMAR is a noninvasive technique available from 1 constructor. This study evaluated the impact of additional iterative reconstruction (ADIRK) but did not evaluate the advantage of iMAR when scanning at lower energies. Our work confirmed the superiority of iMAR even with FBP in terms of image quality and metal artifact reduction provided constructive findings to those of previous studies in terms of its ability to detect pathologic lesions near synovium with more confidence in a phantom model. It should not be forgotten that reconstructions are performed iteratively, and with the increasing availability of these techniques from multiple constructors this technique could be used in routine practice. Comparison with FBP is mandatory, and its is even recommended to compare it with other techniques (FATC, SMART, or FBPCT-CT) to avoid subjective diagnosis of bone lesions on iMAR images, which is still a concern with imagers improving techniques.

6 Conclusion

This work confirms the multi-modality-invasive iMAR’s capacity to improve image quality as well as to reduce metal artifacts due to hip prosthesis. The combination of iMAR with iterative reconstruction (designed for dense structures) has not proven to be of additional value for detecting metal artifacts. The emergence of new artifacts in the bone-metal interface is visible and may be a sign of successful reconstruction in addition to reconstructions with other imaging modalities.

Author contributions

Conceptualization: Angélique Norouladji, Xin Baguiatine, Xavier Montet, Sara Boudabbous.
Data curation: Angélique Norouladji, Steve Philippe Martin, Sara Boudabbous.
Formal analysis: Xin Baguiatine, Marion Hamard, Sara Boudabbous.
Investigation: Angélique Norouladji, Némaïa Benouahma, Sara Boudabbous.
Methodology: Steve Philippe Martin, Xavier Montet, Sara Boudabbous.
Resources: Angélique Norouladji, Némaïa Benouahma, Resources Steve Philippe Martin, Xin Baguiatine, Marion Hamard.
Supervision: Sara Boudabbous.
Validation: Steve Philippe Martin, Xavier Montet, Sara Boudabbous.
Visualization: Marion Hamard, Sara Boudabbous.
Writing – original draft: Sara Boudabbous.
Writing – review & editing: Xavier Montet, Sara Boudabbous.

References


One of the most significant benefits of synthetic MRI is the reduction in examination time, which is achieved by generating multiple image contrasts based on a single scan. In our study, we focused on the diagnostic quality of synthetic MRI with a scan time of 7 min. For comparison, conventional protocols take roughly 11.5 min. This is a clear advantage for clinical practice, and it should not be forgotten that other contrasts can still be generated using the same single acquisition. Another advantage of synthetic MRI that was not analysed in the first feasibility study is its tissue characterization capacities, enabling the quantification of T1, T2, and PD values. This likely provides additional information for the diagnosis and should thus be further investigated in the future. Tissue characterization offers the added advantage of enabling volume estimation and facilitating follow-up of diseases, such as bone marrow infection or malignant disease.
Feasibility of synthetic MRI in knee imaging in routine practice

Sana Boudabbous1, Angélique Nerotadaki1, Ilia Bagetacos1, Marion Hamard1, Bénédicte MA Delattre1 and Maria Isabel Vargas2.

Abstract

Background: Synthetic magnetic resonance imaging (MRI) is a method allowing reduction of examination time and access to quantitative imaging.

Purpose: This study sought to assess the image quality and diagnostic accuracy of synthetic magnetic resonance imaging (MRI) compared to standard MRI in patients with knee pain.

Material and Methods: In total, 22 patients underwent standard 1.5 T MRI with an added synthetic sequence. Quantum T1, T2, and proton density (PD) images were generated synthetically. T1, PD, and short tau inversion recovery (STIR) weighted images were acquired with echoes echo time (TE), repetition time (TR), and inversion time (TI). Two blinded musculoskeletal radiologists evaluated the overall sequence quality, visualization of anatomical structures, and presence of artefacts using a 5-point score.

Results: The synthetic sequence was acquired in 39% less time than the conventional MRI. Synthetic PD, T1, and STIR images were rated fair (2%), good (95%), and poor (5%), respectively, despite the presence of some minor artefacts. Cartilage and menisci were well visualized in all cases. Articular cartilage and menisci were easily identified on T1 and STIR sequences, respectively.

Conclusions: Our pilot study confirmed the feasibility of synthetic MRI in knee examinations, proving faster and achieving appropriate quality and good diagnostic confidence.

Keywords

Knee, magnetic resonance imaging, synthetic, quantitative imaging, articular, sub-chondral injuries, cartilage

Data received 6 December 2018; accepted 14 March 2019

Introduction

Magnetic resonance imaging (MRI) is a widely available modality for investigating knee trauma. It is a crucial tool in clinical applications for detecting bone, cartilage, and soft-tissue injuries, offering excellent anatomical details (1,2). MRI has been proven to shorten time to diagnosis and change knee trauma management (3). Numerous studies have demonstrated the high accuracy of MRI in the detection of meniscal and anterior cruciate ligament injury, reaching 95% in one study (1,4-7). Assessing cartilage lesions is still difficult, even when using cartilage-specific sequences (8,9) and MRI offers good specificity with poor sensitivity (10). The standard protocol is usually composed of an intermediate two-dimensional (2D) T1-weighted spin echo MRI (proton density [PD]-weighted sequence) in all three planes and a T1-weighted (T1W) sequence in one plane (mostly the coronal plane), both sensitive for ligament and meniscal injuries (11). The protocol takes 13 min (12). Sequences such as short tau inversion recovery (STIR), which are more specific for the
As concerns the application of synthetic MRI in some typical day and a significant number of patients must be scanned in a acquisition time. Most important imaging and especially on within matter disease (16,17), our knowledge. Nonetheless, it stems promising to put advantages of providing multiplanar reconstructions. The duration of sequences differs between protocols, reaching 10 min in some studies (13). Furthermore, all studies were carried out using high field (3-T).

However, advanced-imaging techniques, such as quantitative imaging, are not possible without a special sequence able to perform T2 mapping, which increases acquisition time. Furthermore, time is one of the most important factors when working with MRI, as a significant number of patients must be scanned in a typical day and each must be allocated a well-defined time slot.

Recently, a new sequence called synthetic MRI has become available, which enables both a significant reduction in examination time and access to quantitative imaging. This technique has already been used in some central as demonstrated, and in multiple sclerosis. There are only a few publications concerning this technique in the literature, most focused on brain imaging and especially on white matter diseases (16,17).

As concerns the applications of synthetic MRI in musculoskeletal imaging, there are no publications at all as our knowledge. Nevertheless, it seems promising to put standard imaging protocols in place, such as those established for bone imaging, with the advantage of not only reducing acquisition time but also generating mapping of the cartilage, for example.

This study might be assess the overall image quality and diagnostic accuracy of synthetic MRI compared to conventional MRI in patients with post-traumatic or degenerative knees.

**Material and Methods**

**Patients**

This study received approval from the institutional review ethics board and informed consent was waived.

We included 22 patients referred to our department between March and October 2016 for MRI due to knee pain. The mean age was 42 ± 19 years and the gender ratio was 0.29 (5 women, 17 men). Indications for MRI were suspected meniscal, ligament, or cartilage injury due to trauma or arthritis. Patients with one of the following criteria were excluded: massive traumatic injuring postoperative knee; advanced chondropathy; and tunnel or inflammatory diseases.

**MRI**

Before synthetic MRI, all patients underwent a conventional MRI examination according to our center's protocol, using an Insigna 1.5-T MRI Philips (Best, Netherlands) with a 16-channel-knee phased-array coil. The protocol included coronal fast spin-echo T1W, coronal STIR, and sagittal fast spin-echo PD-weighted scanning. We usually also include 3D isotropic fat-suppressed PD-weighted sequences. This sequence was not, however, included in the study, as the synthetic sequence is 2D without the possibility of multiplanar reconstructions. All sequence parameters are provided in Table 1.

**Sagittal SynAc** (multiple-dynamic multiple-echo [MRME] sequence, provided by Synthetic MRI AB, Linkoping, Sweden) was added to the protocol. We opted for the sagittal plane primarily to assess the cruciate ligaments for feasibility. Adding the coronal and axial planes would significantly lengthen the examination time and not conform to the daily MRI workflow. The SynAc sequence is based on a TSE sequence with a saturation pulse (180°), with four different inversion times (TI) and two echo times (TE), providing eight images with different contrasts. These images are used by the SyMRI v8 software (SyntheticMRI Inc.).

**Table 1. Summary of sequence parameters.**

<table>
<thead>
<tr>
<th>Sequence</th>
<th>FOV X</th>
<th>FOV Y</th>
<th>Res X</th>
<th>Res Y</th>
<th>Rec num</th>
<th>Rec res</th>
<th>Y (mm)</th>
<th>TE (ms)</th>
<th>TR (ms)</th>
<th>TI (ms)</th>
<th>Slices</th>
<th>Thickness (mm)</th>
<th>Gap (mm)</th>
<th>Acquisition time</th>
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</thead>
<tbody>
<tr>
<td>TI car</td>
<td>160</td>
<td>160</td>
<td>0.35</td>
<td>0.49</td>
<td>0.25</td>
<td>0.25</td>
<td>10</td>
<td>524</td>
<td>NA</td>
<td>NA</td>
<td>3</td>
<td>0.02 03 13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>STIR car</td>
<td>160</td>
<td>160</td>
<td>0.61</td>
<td>0.73</td>
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<td>0.37</td>
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<td>PD sig</td>
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<td>SynAc sig</td>
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Cor, coronal; sag, sagittal; PD, proton density; STIR, short tau inversion recovery; Rec, resolution; FOV, field of view; Rec, reconstruction; TR, echo time; TI, repetition time; TI, inversion time.
AB, Linköping, Sweden) to generate quantitative TI, T2, and PD images, then it synthetically creates TI, PD, and STIR images with unmeasured TE, repetition time (TR) and TI. The sequence parameters are summarized in Table 1. In this study, we chose TE/TR to match the conventional sequences and adequate TI to suppress the fat signal in the image (190ms).

**Image analysis**

Two blinded, experienced, musculoskeletal radiologists (with five and two years of experience) separately evaluated the conventional MRI and synthetic images, analyzed by a third person. The acquisition time was compared between the two techniques. Overall sequence quality and visualization of anatomical structures (bone, intra-articular cartilage, menisci, anterior and posterior cruciate ligaments, and extensor tendons) were evaluated using a 3-point score (1=poor, 2=fair, 3=good). The presence of artifacts was also assessed using a 3-point score (1=severe, 2=moderate, 3=none). Conventional MRI images (henceforth referred to with “c” prefix) were coronal cTI, cSTIR, and sagittal cPD-weighted images. Synthetic MRI (henceforth referred to with “s” prefix) were sagittal sTI, sSTIR, and sPD-weighted images. Sequence quality and visualization were compared between conventional and synthetic MRI. Ligamentous structures were also evaluated, since the Synthetic sequence was only acquired in the sagittal plane. T1 and T2 mapping were not evaluated in this preliminary study of technique feasibility.

**Statistical analysis**

Evaluation of score data was performed with median value. Comparison of scores between conventional and synthetic images was performed based on the results given by Reader 1 (the most experienced), using a signed-rank Wilcoxon paired test. Comparison between the two readers was also performed with a signed-rank Wilcoxon paired test. Kappa was not used to test inter-rater reliability, due to the high similarity of scores between the two readers (18).

**Results**

**MRI**

The Synthetic sequence was acquired in 35% less time than the conventional sequences (1 min 48 s for conventional vs. 7 min 7 s for Synthetic).

**Image quality**

Fig. 1 shows the distribution of scores given for each parameter evaluated by Reader 1.

The synthetic image quality was rated “good” for all contrasts. All structures were well visualized (median score = 3) with all three contrasts, except for the cruciate ligaments in sSTIR (2) “good,” 1 “fair,” 3 “good”). Reconstruction cartilage, menisci, and extensor tendons were well visualized in all cases in cTI, cPD, and cSTIR, with a median score of 3 (all “good,” except 1 “poor” on sPD; 1 “fair” on cTI, and 2 “fair” on cSTIR), as illustrated in Fig. 2.

We particularly observed good sensitivity for the assessment of bone edema, rated “good” (only 1 “poor” and 1 “fair”) in cSTIR when present, as illustrated in Fig. 3.

The median score for artifacts differed for overall motion in T1 (P = 0.003) and partial pulsation in STIR (P = 0.02) (Fig. 4) between conventional and synthetic sequences. However, we obtained good reliability with no significant difference between the two methods for the rest of the sequences.

Table 2 presents the results of the different evaluated parameters. Despite a median score of 3 (good) for ligament visualization on sPD and sSTIR contrast (all “good,” except 2 “poor,” 5 “fair,” and 6 “poor,” 2 “fair,” respectively), we obtained a significantly lower rating with the synthetic sequence compared to the conventional sequence, whereas the visualization on the sTI sequence was clearly rated “poor” (13 “poor,” 2 “fair,” 3 “good”). This may be explained by the low contrast and artifacts in interpolated notch obscuring the ligament outline (Fig. 5).

Some parameters were also rated differently by the two radiologists, particularly for T1 and STIR contrasts, even though the median scores were still “good” overall. The PD contrast, which is one of the most commonly used sequences in knee examination, was rated “good” for all evaluated parameters by both readers, with no artifacts. Only the ligament structures generated different ratings between readers. Cruciate-ligament visualization was rated “poor” by Reader 1 in 7%, 14%, and 30% of cases on sPD, sSTIR, and sTI contrasts, respectively, due to inadequate visualization of the anterior cruciate ligament, despite good visualization of the posterior cruciate ligament. This was attributed to the slice thickness (3 mm in synthetic MRI, 3 mm in conventional PD sagittal) and had no impact on diagnosis.

Finally, diagnostic accuracy was identical in conventional and synthetic MRI in all cases, i.e. all findings observed on the conventional sequences were also found on the synthetic sequences for visualized structures in the sagittal plane, namely for meniscal tear (Fig. 6).
In this preliminary study, we demonstrated the feasibility of using synthetic MRI in musculoskeletal imaging, taking the knee as an example. The knee joint is among the most frequently investigated structures in trauma centers, and in the majority of cases, conventional MRI is needed to exclude soft-tissue injuries, including meniscus and ligament tears and bone or cartilage bruising. The accuracy of MRI is assessed traumatic...
Fig. 2. Post-traumatic left knee MRI in a 32-year-old patient: synthetic MRI with sagittal T1 (a), PD (b), and STIR (c) weighting compared to conventional images for coronal T1 (d), sagittal PD (e), and coronal STIR (f) weighting.

Fig. 3. Comparison of conventional MRI on coronal T1 and STIR (a, b) vs. synthetic STIR on sagittal T1 and STIR (c, d) for a 45-year-old patient consulting for internal knee pain. For this particular example, the conventional STIR was acquired also in the sagittal orientation (usually in coronal). The edema is clearly visible on the tibial meniscus on synthetic imaging.

Lesions is close to 95% (4), and as high for meniscus and cruciate ligaments too in some studies. Synthetic MRI is proposed by our pilot study as a new technique enabling the acquisition of T1, PD, and STIR contrasts with a single acquisition. Synthetic MRI is an emerging tool in neuroradiology, used until now used in the analysis of white-matter diseases like multiple sclerosis (17,19). Studies performed in the brain have
demotrated that the contrast in synthetic MRI is higher, yet so is the level of noise, in T1 and T2, and that despite an inferior image quality, synthetic MRI achieved similar diagnostic accuracy as conventional sequences (20). Visual assessment of the image did not suggest any loss of signal-to-noise ratio (SNR) in our study, nor doubt due to the greater slice thickness used in synthetic MRI than in conventional images. Another study in children’s brains produced similar conclusions about the potential use of synthetic sequences for diagnosis, yet outlined some limitations regarding the FLAIR contrast, which proved lower quality than conventional sequence (21). All in all, both studies reported that the synthetic sequence’s shorter acquisition time was a great advantage compared to conventional sequences.

Fig. 4. Illustration of popliteal pulsations in STIR sequences in a 37-year-old man, in synthetic (a) and conventional (b) MRI. When STIR was acquired in the sagittal plane, pulsatile pulsations were more evident, with no significant difference with synthetic acquisition.

<table>
<thead>
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<th>Table 2. Median scores obtained for all evaluated parameters.</th>
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<td><strong>Medias</strong></td>
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<td>Tendons</td>
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<td>Overall median</td>
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<td>Popliteal pulsation</td>
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For image quality and visualization of the different structures, 3 = good, 2 = fair, 1 = poor. For overall median and popliteal pulsation, 3 = normal, 2 = moderate, 1 = severe. Boldface values indicate significant differences. When the difference is significant between T1 and T2, it is indicated as p < 0.01 or p < 0.001.

One of the most significant benefits of synthetic MRI is its reduction of examination time by generating multiple image contrasts based on a single scan. In our study, we focused on the diagnostic quality of synthetic MRI with a scan time of 7 min in comparison to conventional protocol taking 11.5 min. This is a clear advantage for clinical practice, and it should also not be forgotten that other contrasts can also still be generated with the same single acquisition. Another advantage of synthetic MRI that was not analyzed in this first feasibility study is its tissue characterization capacity with the quantification of T1, T2, and PD values. This can provide additional information for the diagnosis and should be investigated in more detail in the future. Tissue characterization offers the added advantage of enabling volume estimation,
The first limitation of our study was the small number of patients due to our exclusion of non-traumatic cases and time constraints. The second limitation was the acquisition in sagittal plane for synthetic MRI, rendering analysis of collateral ligaments difficult, and ideally an additional coronal plane would have been beneficial. We chose this orientation due to our focus on the cruciate ligaments in this preliminary study. For the future, the acquisition will be evaluated in the coronal orientation instead of sagittal. Another limitation for this preliminary study was the slice thickness of 5mm offered by this first-generation synthetic
sequence, compared to the 3 mm of conventional sequences. This thickness was obligatory due to the use of a 1.5-T field in this study, as well as the compromise between acquisition time and image quality for synthetic MRI. There is now the possibility of implementing this sequence in a 3-T field using thinner slices and better spatial resolution, which should be considered. The second limitation was the absence of quantitative evaluation. Synthetic MRI offers access to T1, T2, and PB quantification, which is certainly of high potential for the characterization of various pathologies, such as the distinction between benign and malignant diseases like bone marrow disease. T2 mapping is already of great interest for cartilage assessment and can thus be obtained without additional acquisition time. Moreover, the combination of quantitative T1 and T2 also reveals new information, completely independent of the MRI technique, and is expected to be more accurate and relevant than traditional MRI results according to a recent publication from the European Society of Radiology (9). Furthermore, the effect of constraint again has not been studied. Finally, we must clarify that synthetic MRI is intrinsically incapable of producing spectral fat saturation in its current design. Synthetic MRI is based on T1, T2, and PB measurements in each voxel, which allows the measurement of signal intensity using Bloch equations for a spin echo sequence. This can produce any signal intensity for a given TE, TR, or TI. In this workflow, therefore, the addition of a spectrally selective fat suppression was not included. The only way to perform suppression of lipid signal is to use inversion recovery, as we did using the STIR sequence. The advantage here is that the synthetic STIR is produced with the same spatial resolution as the other sequences, which is surely the reason why we decided to use this sequence has a lower SNR than conventional sequences (without fat saturation) due to the inversion of the spins.

For the future, the application of this technique at higher field strengths could benefit from higher SNR and enhance the acquisition of thinner slices. Also, one major improvement in the MRI technique was the development of 3D isotropic sequences, which improved cartilage visualization, thus rendering multiplanar reconstructions available. It is clear that the development of a 3D sequence for synthetic acquisition would be of great interest in the future and would probably benefit knee imaging.

Synthetic MRI also provided good diagnostic confidence, with overall good image quality. This promising technique can be used in musculoskeletal medicine when several contrasts are needed, such as T1, T2, PD, or fat saturation weighted. The image quality is still slightly lower; however, particularly in T1 or STIR contrasts, with low artifacts in the proximal femur.

In conclusion, our preliminary study showed that synthetic MRI is a method with potential use for evaluating the knee and provides as good quality as conventional sequences in a shorter time, despite the presence of some artifacts and its limitations in terms of interpreting high-signal structures. We believe that these limitations can be overcome with the use of another acquisition orientation and thinner slices, and that the additional benefit of having a true quantitative acquisition is an important step for MRI standardization for lesion characterization. Further study with large numbers of cases is needed to validate this technique.

Declaration of conflicting interests
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References
10. Smitt TB, Brown WT, Tomsa AP, et al. Accuracy of magnetic resonance imaging: magnetic resonance arthrography and computed tomography for the detection of

MR imaging time should be considered in spine imaging due to the high prevalence of spinal pathology and, consequently, the high number of requests for MR imaging of this region. Furthermore, patients frequently requiring spinal imaging often suffer from back pain, finding it difficult to remain supine for long periods. In the reported study, the acquisition time of synthetic MR imaging (5 minutes 40 seconds) was approximately half of that required for conventional sequences. In this pilot study, synthetic MR has been shown to be a feasible alternative or complement to conventional T1WI, T2WI, and STIR sequences in spine imaging. Image quality was considered not considered to be significantly different from that generated by conventional sequences, and both diagnostic confidence and lesion conspicuity were at acceptable levels.
Feasibility of a Synthetic MR Imaging Sequence for Spine Imaging

M.I. Vargas, O.M. Drake-Pérez, BMA Delattre, C. Bote, C.K. Lovlad, and O.S. Boudabous

ABSTRACT

BACKGROUND AND PURPOSE: Synthetic MR imaging is a method that can produce multiple contrasts from a single acquisition, as well as quantitative maps. Our aim was to determine the feasibility of a synthetic MR image for spine imaging.

MATERIALS AND METHODS: Fifty-eight patients with clinical indications of infectious, degenerative, and neoplastic disease underwent an MR imaging of the spine (T1, T2, and 19 )-lungmagnetized MR imaging study. The Synthetic sequence, with an acquisition time of 5 minutes, was added to the conventional protocol consisting of conventional sagittal T1, T2, and STIR TSE.

RESULTS: Synthetic T1-weighted, T2-weighted, and T1W images were of adequate quality, and the acquisition time was 55% lower than with conventional MR imaging. The image quality was rated as "good" for both synthetic and conventional images. Interobserver agreement concerning lesion conspicuity was good with a Cohen's κ of 0.77. Artifacts consisting of white plaque originating across contrast views, as well as flow artifacts, were more common in the synthetic sequence, particularly in synthetic STIR. There were no statistically significant differences between readers concerning the scores assigned for lesion conspicuity and lesion conspicuity.

CONCLUSIONS: Our study shows that synthetic MR imaging is feasible in spine imaging and pediatrics and provides good lesion and diagnostic information. Furthermore, the short acquisition times and the ability to obtain quantitative measurements, as well as to perform several contrasts with a single acquisition, promise a bright future for synthetic MR imaging in clinical routine.

Radiologists base their diagnoses on morphologic and, increasingly, more quantitative imaging. The current trend in imaging is to reach a diagnosis based on not only morphologic and qualitative evaluation but also methods that can provide quantitative information. Quantitative imaging can be achieved by different techniques: synthetic used in clinical practice and fingerprinting (used only for research purposes). Synthetic MR imaging is a method that can produce multiple contrasts from a single sequence, as well as quantitative T1, T2, STIR, and proton-density maps. This offers the possibility of shortening the study duration and the option of relying on more objective parameters to reach a diagnosis. Recently, this emerging technique has been applied to several brain diseases in adults and children, but to our knowledge, it has never been used in spine imaging. The purpose of this work was to apply synthetic MR imaging to the spine and pediatric and to compare the overall image quality and diagnostic confidence produced by synthetic MR imaging with conventional sequences.

MATERIALS AND METHODS

Patients

The local ethics committee approved this study (CECR16-1821). A synthetic MR image was added to the usual spine imaging protocol in 38 patients referred to our institution with suspicion of multiple sclerosis or degenerative diseases, and neoplastic diseases. There were children, pregnant women, and motion artifacts on the images.

Image Acquisition

Synthetic imaging was performed in addition to the conventional sequences (T1, TSE, T2, proton-density, and STIR) in daily clinical practice at our hospital. The patients were

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The study cohort was retrospectively selected from the patient database of a tertiary care center in the Netherlands.

Image quality for each method was scored by two independent readers (R1 and R2) on a 5-point scale: 1 = poor, 2 = fair, 3 = good, 4 = very good, 5 = excellent. The agreement between readers was assessed using Fleiss' Kappa.

The study found that synthetic MR images provided better diagnostic accuracy compared to conventional images. The results also showed that the use of artificial intelligence algorithms in MR imaging can improve diagnostic accuracy and efficiency in musculoskeletal imaging.

**Discussion**

The use of synthetic MR images in musculoskeletal imaging has been shown to improve diagnostic accuracy compared to conventional MR images. This study supports the use of artificial intelligence algorithms in MR imaging for improving diagnostic accuracy and efficiency in musculoskeletal imaging.
FIG 1. Conventional MRI T2 (A), spinecho T1 (B), and STIR (C) images show a postsurgical lumbar IDRM with postoperative changes in the spinal soft tissues. The synthetic images (D-E) depict these changes with similar detail. Note the dirty appearance of the ventral bodies observed in the synthetic reconstructions and how different from the norm, especially in the STIR sequence.

have since assessed the clinical feasibility of synthetic MRA imaging across different anatomic conditions such as multiple sclerosis and metastatic disease of the brain and in the pediatric population. This technique has also been recently used for musculoskeletal imaging. A recent study, focusing on imaging of the normal knee, assessed the feasibility and diagnostic accuracy of synthetic MRA imaging compared with conventional MRA imaging in...
FIG 6  Screenshot of conventional T2 (B) and spin-echo T1 (F) images and synthetic T2 (C), T1 (E), and STIR (G) images illustrating a stenosis of the cervical cord. Note the same level of detail in both types of sequences.

well as the utility of synthetic quantitative T2 maps of the different bone structures compared with conventional T2 mapping sequences. The conclusion was that synthetic MR imaging for bone pathology, conventional T1 mapping, and bone quality and offered the potential to reduce the overall examination time. An advantage was noted for bone marrow where the relative signal intensity and contrast of synthetic T1 images were lower than their conventional counterparts. Other studies focused on the feasibility of synthetic MR imaging for bone pathology. To our knowledge, this is the first study exploring the potential utility of synthetic MR imaging for spine and spinal cord imaging in clinical routine (Figs 4 and 5). In this pilot study, synthetic MR has been shown to be a feasible alternative to conventional T1WI, T2WI, and STIR sequences in spin-echo imaging. Image quality was considered not different from that produced by conventional sequences, and both diagnostic confidence and lesion conspicuity were at acceptable levels. These results are in agreement with previous reporting that synthetic and conventional imaging have similar diagnostic utility.5,6,9,10

Some differences were notwithstanding observed between the 2 methods. The synthetic images, as expected, lack contrast, a "dirty" appearance in the images, and have resolution (Fig 5), resulting in lower image-quality scores assigned by the readers in most cases. These differences were, however, not statistically significant and did not affect the overall perception of imaging quality or the diagnostic confidence. As previously reported, arbitrary signal changes found in the vertebral discs that are particularly different are thought to be partial volume artifacts because they cannot be described using a conventional function. Consequently, high T1 and T2 relaxation appears as a combination of the 2 tissue values6,9,15 and can represent a limitation in synthetic imaging. In contrast, some authors described synthetic T1-weighted images having higher but not significantly different mean overall image-quality scores than conventional images and has subjective testing. This finding was due to the relatively low signal-to-noise ratio on conventional T1-weighted images.

The different backgrounds of the 2 readers (neuromuscular and musculoskeletal radiology, respectively) can be the main factor affecting the lack of agreement observed in some cases. For example, some lesions identified by spondylomyelitis, were identified as abnormalities by reader 3, but missed by reader 1.

With respect to the artifacts produced by synthetic MR imaging, it is known that synthetic FLAIR images of the brain have more pronounced artifacts, requiring adding conventional FLAIR sequences to the imaging protocol. At the level of the spine, image artifacts were particularly noticeable in the synthetic STIR sequence, parallel (vascular) fur images (Fig 2) being the most frequent ones. Additionally, a dirty appearance to the images was observed in all synthetic sequences. Artifacts according to the presence of metal in the spine were identified on the synthetic images, but were not more pronounced than in the conventional images (Fig 6).

These artifacts occurred more often in the cervical and thoraco-lumbar spines, where the synthetic images showed more noise compared with scans of the cervical spine. The stenosis due to a higher number of channels and coils used in imaging area (spine and cervical coils versus spine used only in the lumbar region).
MR imaging time should be considered, especially in cases of imaging due to the high prevalence of spinal pathology and, consequently, the high number of requests for MR imaging of this region. Furthermore, patients requiring spinal imaging frequently have back pain and find it more difficult to remain supine for long periods. Currently used imaging protocols for the spine have an average duration of approximately 30 minutes when the clinical indication does not warrant the use of contrast agent or only part of the spine needs to be imaged, as in disc herniation. When contrast administration is indicated or the whole spine needs to be imaged, the acquisition time is approximately 1 hour.

The hybrid sequence was adapted for spine imaging and can produce at least 5 conventional sequences (T1, T2, STIR), which generally require an acquisition time of 60 minutes 30 seconds, offering the possibility of generating other contrasts required.
FIG 6. Sagittal conventional FS T2 (A), transverse T1 (B), and STIR (C) sequences and corresponding synthetic sequences (D–F) in a patient with an intervertebral disk herniation. Note that the degree of magnetic susceptibility artifacts is the same in both sequences.

In the present study, the acquisition time of standard MRI imaging (6 minutes 40 seconds) was approximately halved that required for conventional sequences. Sagittal synthetic spine MRI imaging could therefore potentially replace conventional sagittal T1, T2, and STIR sequences for imaging 1 spinal region (cervical, dorsal, or lumbar) and halve the acquisition time. However, if fat-saturated proton-density sequences were needed, they would be obtained separately by conventional methods.

In addition to allowing shorter acquisition times, synthetic sequences provide quantitative T1, T2, and proton-density maps (Fig 7). These can be used to derive laminographic parameters of spinal components, thus providing quantitative information of...
interest for research and potentially clinical purposes with a view to using these quantified parameters during the assessment of common spinal diseases (degenerative conditions, inflammatory conditions, ossification).

In this study, identical TR and TE parameters were used in all patients to produce the synthetic images.

The main limitations of this study were the relatively small sample size and the limited number of pathologies in the patients included. From our observations, a compromise is still needed to increase the SNR while maintaining an acceptable acquisition time in the thoracolumbar region. This could potentially be improved with the implementation of this sequence on 3T MR imaging. Conversely, in our study, the image quality and diagnostic confidence were very good in the cervical area, where the synthetic sequence correctly produces the best results.

We believe that our findings could facilitate the integration of quantitative MR imaging in clinical routine.

CONCLUSIONS

Synthetic MR imaging is feasible image processing. However, some work and development are still required to improve synthetic STIR to reduce flow artifacts and increase the signal-to-noise ratio, particularly in the lumbar region. We believe that in the future, a significant reduction in acquisition time will be possible with this technique without sacrificing diagnostic accuracy. Furthermore, the quantitative information generated...
Update in Musculoskeletal Imaging: From Diagnosis To Treatment

1. Wee J, B. Method and Validation of MRI-based quantification of trabecular bone inhomogeneity using the 


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7. Wee J, B. Method and Validation of MRI-based quantification of trabecular bone inhomogeneity using the 

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Ablation techniques performed under imaging guidance to treat benign and metastatic lesions constitute a part of the management of painful bone tumors. Osteoid osteoma is a commonly encountered benign tumor. Because of its painful features, osteoid osteomas are given specific consideration by the medical community. Currently, various treatment options are available, with percutaneous treatment increasingly applied. RF has been widely validated as an efficient method without serious adverse effects and only low recurrence rates. Ablation therapy of metastatic lesions focuses on bone-tumor interface to control pain, covering the whole tumor when employed to control local invasion. The HIFU is a promising minimally-invasive technique. The major advantage of HIFU, which is guided by MR imaging, is its ability to monitor thermal damage in real-time, in addition to the continuous temperature mapping of targeted tissues. Pain-combined therapy is a proposed new concept, which aims at reducing radiotherapy doses, along with the possibility to perform re-irradiation. Multidisciplinary meetings should be implemented for the decision-making process in order to include ablation therapies in the general management of metastatic diseases.
Le point sur le traitement percutané des ostéomes ostéoides

Des Annies Paulin*, Antoinette Monjard Vichon*, Per Robin Peter* et Dr Sarah Bourgeois*

Rés Méd Ultrasound 2005; 14: 1-5

Un ostéome ostéoid est une tumeur osseuse bénigne relativement fréquente initialement décrite par Liebermann en 1930, puis comme une entité propre grâce aux recherches de Acker en 1932. Intégré à la lignée des ostéomes ostéoides, il a été toutefois de nombreux obstacles dans la communauté scientifique en particulier concernant son diagnostic, ses caractéristiques pathologiques, ses bords et traitements. C'est sur cette dernière question que les éloignements ont été les plus marquants et c'est ainsi que les possibilités thérapeutiques basées dans la littérature apparemment variées. Toutefois, les résultats très favorables des traitements percutanés et en particulier de la radiofréquence, de même que le faible taux de récidives et de complications de ces traitements, ont amené de nombreux pays à les considérer comme le meilleur traitement en première intention. A travers cette revue de la littérature et de notre pratique clinique, nous souhaitons rappeler les connaissances actuelles thérapeutiques et persévérer dans l'avancement de notre technique.

INTRODUCTION

L'ostéome ostéoid est une tumeur osseuse bénigne relativement fréquente initialement décrite par Liebermann en 1930, puis comme une entité propre grâce aux recherches de Acker en 1932. Intégré à la lignée des ostéomes ostéoides, il a été toutefois de nombreux obstacles dans la communauté scientifique en particulier concernant son diagnostic, ses caractéristiques pathologiques, ses bords et traitements. C'est sur cette dernière question que les éloignements ont été les plus marquants et c'est ainsi que les possibilités thérapeutiques basées dans la littérature apparemment variées. Toutefois, les résultats très favorables des traitements percutanés et en particulier de la radiofréquence, de même que le faible taux de récidives et de complications de ces traitements, ont amené de nombreux pays à les considérer comme le meilleur traitement en première intention. A travers cette revue de la littérature et de notre pratique clinique, nous souhaitons rappeler les connaissances actuelles thérapeutiques et persévérer dans l'avancement de notre technique.
TRAITEMENT CONSERVATEUR

L'évolution naturelle de l'ostéosynthese se fait vers la guérison, mais est précédée pendant de 1 à 2 ans. Cette caractéristique est un aléatoire traitable à la médication et l'évolution de contact osseux de l'ostéosynthèse effectuée par AOIS avec un résultat ultérieur et même une réévaluation de la guérison en trois à cinq mois. De plus, il semble que les résultats à long terme ne sont pas équivalents avec un traitement conservateur ou chirurgical, mais que la contribution de l'ostéosynthèse de longue durée peut être réalisée dans le plan de la guérison.

En conclusion, l'utilisation de l'ostéosynthèse est générale aux résultats (probabilité de traitement optimale de 60 à 80%) avec un meilleur résultats possible. Les résultats de l'ostéosynthèse sont comparables à une technique chirurgicale en cas de guérison et ont pour avantage d'obtenir une technique chirurgicale sans risques et d'avoir une meilleure proportion de cicatrisation sans risques.

TRAITEMENT CHIRURGICAL

L'ostéosynthèse chirurgicale du milieu a été le premier traitement utilisé pour une dissection complété et rapide de symptômes (résultat satisfaisant dans 85 à 100% des cas). L'ostéosynthèse chirurgicale est une technique d'ostéosynthèse par absence de cicatrisation et par réduction des symptômes. Toutefois, la prévention du recul est probablement plus importante que la cicatrisation de l'os et de l'osseux.

En outre, l'ostéosynthèse de recul peut être utilisée, sans complications immédiates et toujours réalisées et qui peut être réalisée dans le même temps un geste chirurgical, voire de greffe osseuse et nécessairement dirigé vers la période de réparation osseuse. 

FIG 3 Visualisation de l'œdème parasystélique

La survenue d'œdème parasystélique, la formation de pseudotumeur parasystélique et le risque de fracture interne. Il est mené au développement de techniques moins agressives telles que l'ostéosynthèse et une ostéosynthèse guidée par CT-scanner mais également des techniques chirurgicales moins invasives comme l'ostéosynthèse non chirurgicale.

Ces techniques ont été agressives présentant le même risque de recul (34 à 100%).
CONCLUSION

L'ostéodystrophie, maladie séquellaire, est une maladie qui impose une attention particulière à la prise en charge des patients. Les complications de cette pathologie sont nombreuses et peuvent être graves. Il est donc essentiel de mettre en place des protocoles de traitement adaptés à chaque cas.

La chirurgie est un traitement de choix dans les cas où les autres options thérapeutiques ont échoué. Elle permet de pallier les symptômes et de rétablir une mobilité fonctionnelle.

La mise en place d'un traitement antalgique approprié est également essentielle pour améliorer la qualité de vie des patients. L'utilisation de médicaments anti-inflammatoires non stéroïdiens (MIS) est couramment utilisée.

En conclusion, l'ostéodystrophie nécessite une prise en charge pluridisciplinaire, associant médicaments, thérapies physiques et chirurgie, pour obtenir les meilleurs résultats possibles.

**STRATÉGIE DE RECHERCHE ET CRITÈRES DE SÉLECTION**

- Les données utilisées pour cette revue ont été extraites par un programme informatique et codées dans les bases de données. Les articles ont ensuite été sélectionnés en fonction de critères précis définis.
- L'objectif est d'identifier les facteurs de risque et de protocoles de traitement les plus efficaces.
- Les résultats sont présentés sous forme de tableaux et de graphiques.
4. Future Perspectives

1. Palliation of new artifacts on linear interpolation reconstructions

Concerning metallic artifacts, LI is a fast and reliable method of removing metallic artifacts, but it creates new artifacts related to the linearity-interpolated values, which do not match the real attenuation. These new artifacts have become a drawback of these techniques, and additional work has been carried out to reduce these artifacts. Normalized metal artifact reduction (NMAR) has been developed, but it shows a loss of detail near the metal (36) addressed with further reconstruction called FSMAR (frequency-Split MAR). This reintroduces data from the original reconstruction but at the same time also some of the original artifacts, thereby limiting the methods’ overall accuracy (37). An example of this is the metal deletion technique (MDT), which was developed to compensate for the new artifacts observed with LI (38), as well as for total variation (TV) (39) or, more recently, refinement MAR (RMAR) (5). Of course, these techniques are based on the application of additional filters designed to improve the iteration of sinogram correction, to reconstruct the non-metal portion of the image, MDT uses the high-quality images of non-metal data. Metal data are initially deleted, within accurate metal data replaced with forward projected values from the previous iteration for each iteration. A study evaluating small and large metals revealed image improvement in 73% and 75% of cases, respectively, of images (40). RMAR was compared in vivo and ex-vivo to a broad range of commercial algorithms from a quantitative and qualitative perspective, demonstrating a better performance and improved clinical images. These techniques were shown able to reduce the new artifacts, while providing more details close to the metal (38).
2. Quantitative imaging on Synthetic MR

Concerning the efficiency of synthetic MRI imaging in comparison with conventional MR imaging, the reduction in time acquisition depends on the number of required sequences and the use of quantitative conventional sequences, such as mapping T2. Moreover, combining this technique with an emerging sequence called compressed sensing appears to be quite useful in the MSK field. Reducing the examination time of different sequences including 3D proves to be an additional advancement, rendering it possible to perform reliable exams within shorter time periods, yet with similar quality (Work Delattre and al. submitted 2019).

Concerning the quantitative MRI evaluation using these new techniques, the results appear acceptable for clinical use, as based on phantom-derived model corrections on T1, T2, and PD sequences. Synthetic MR permits the detection of cartilage changes on T2 relaxation time, as demonstrated in a study involving an osteoarthritis cohort (41). Despite these encouraging data, these results are still deemed preliminary, and correlation with arthroscopic results is required for diagnostic accuracy of cartilage abnormalities (Fig.8).

Moreover, despite the progress of this technique and the improvement of CNR between knee structures (cartilage, meniscus), there are still artifacts that may interfere with the proper analysis of knee diseases. Correction of B1 inhomogeneity and using additional chemical shift imaging are required in order to reduce artifacts on STIR and correct the contrast on T1-weighted MR images, respectively. Another promising synthetic advancement is PD mapping, which has been shown able to investigate histological and biomechanical cartilage abnormalities (42). In addition, it has permitted the generation of double inversion recovery images that may possibly replace
images after contrast medium injection (43).

**Fig.8:** Example of T2 quantitative images in a patient with a lesion in the tibial cartilage (black arrow), left ROI placed on normal cartilage, right ROI placed in the lesion, the R1 (1/T1) and R2 (1/T2) values show more dispersion in this area as expected (personal data).

As in knee imaging, the quantitative study of the spine is increasingly reported in the literature as a complement to qualitative standard imaging in an attempt to improve the investigation of tissue contrast. The physical properties of tissues (PD, longitudinal T1, transverse T2 relaxation rates, and correction for B1-inhomogeneities) are used, as based on a single multi-echo, saturation recovery turbo spin echo (TSE) sequence. These absolute parameters allow for the generation of “synthetic” T1WI or T2WI contrasts (11). The advantages inherent to these techniques are the time reduction and the possibility of automatic tissue segmentation and volume measurement (44).
and T2 relaxation times and PD values are measured in normal structures of spine MR imaging (cerebro-spinal fluid (CSF), spinal cord, intervertebral disc, vertebral body). Synthetic MR relaxation sequences have shown results that were comparable to those found in the literature for CSF. Numerous studies have yielded very similar values (45,46,47) with bias for PD value calculation and for T1 explained by slice thickness. Depending on the strength of the field employed in these studies (3T and 7T), the mean of synthetic MR may vary for T1 relaxation and T2 with respect to the spinal cord (48,49). The cervical area differed from the dorsal and lumbar regions in T2 and PD, yet without any significant difference in T1. These results are accounted for by the density of spinal tracts and different segments of the spinal cord due to the normal variation in the gray/white matter ratio, as well as the variation in the total number of tracts decreasing from the cervical to the lumbar areas. These results allow us to employ spinal cord normal values as biomarkers of myelin and axonal integrity, and compare them to demyelinating diseases such as proposed in the brain (50). On synthetic MR, disc dehydration and, as a result, disc degeneration inversely correlates with the mean relaxation time of T1, T2, and PD. The explanation behind this is as follows: T2 relaxation is related to disc water and proteoglycan content, while degeneration diminishes T2 values. Herein, a difference between spine segments was found, with T2 relaxation time found the lowest in cervical areas (51). The smaller size of cervical discs may account for the lower values of T2 relaxation, given that nucleus fibrosis could be included in the region of interest (ROI). More importantly, the range of age is to be considered for the relaxation values of discs, since the variability depends on the range of included ages; the establishment of cutoffs appears relevant with respect to levels and age. Finally, according to the findings of existing literature (46), the relaxation time in vertebral bodies was not found to significantly differ in T2 among spinal levels, with a decrease from cervical to lumbar areas found in T1 values due to the normal distribution of water and fat in the bone marrow. This last finding is very interesting with respect to detecting vertebral bone marrow infiltration diseases, such as myeloma, considering the normal variations with age and physiological changes in the vertebra.
3. HIFU for bone metastases’ pain relief

Concerning bone metastases and pain relief, MR guided HIFU, validated in ex-vivo experiments at our institution (Fig9), appears to be a promising ablation technique.

Fig.9. Bone pseudo-tumor (a) heated by MRgFUS at 6°C above the baseline. Note the anatomical image and the temperature maps (b) and steady state control (c) (personal data).

As mentioned before, the bone is a common target for metastases from advanced cancers (52) (75% as reported by Coleman 2001) and the third target to which cancer metastasizes (53), particularly breast and prostate cancer. Pain due to bone metastases is very common and often severe in advanced cases, significantly limiting the quality of life of affected patients (54,55). Pain management remains a serious challenge, as the underlying mechanisms are still unclear. The treatment of pain is often palliative, with a broad spectrum of therapies proposed. Until now, radiotherapy has been the standard treatment for bone metastases, designed to alleviate pain and control metastatic disease progression (56,57). It has been shown ineffective in 20-30% of patients, with pain recurrence observed in 23-25% cases (58), only 50% of patients reporting pain relief after 4 weeks (59), relapse being common at 3 months post-treatment (60). The cumulative dose limits the possibilities of re-irradiation, characterized by limited effectiveness, yet more undesirable effects (61). Development of alternative treatment modalities appears crucial primarily designed to (58, 62) improve patient comfort.
HIFU is a minimally-invasive technique that induces sharp lesions in a focal point, while preserving adjacent structures (63). The thermal effect of the technique was earlier investigated by our group, as well as by other for other sites, in order to assess thermal distribution by using PRFS temperature estimation in soft tissues adjacent to the rib. Treatment must be applied quite carefully, as the true temperature inside the bone proves to be much higher than the one measured in the periosteal region, with conclusions in concordance with previous studies (64). HIFU does not require ionizing radiation and can be repeated several times. The major advantage of HIFU guided by MR imaging is the real-time monitoring of thermal damage and continuous temperature mapping of targeted tissues (24). The fluoroscopic sensor was applied to estimate the real temperature inside the bone (63).

Clinical application of MR-imaging-guided HIFU has been limited due to the high absorption rate of cortical bone, with only a minimal fraction of energy penetrating across the cortex (65). Its application has so far been limited to pain palliation form superficial lesions, because the energy at the surface rapidly increases. This damages the periosteum, which is highly innervated, its ablation has been revealed effective for pain management (58). Modulation of treatment (low frequency) permits heating beyond the cortex, as demonstrated by Chen et al (66).

HIFU has been proposed in an attempt to heat the periosteum, which is richly innervated, thereby creating irreversible damage (24). In order to confirm this claim, a pre-clinical study was conducted (55) involving osteoblastic-induced metastases in rabbits. Histological analysis confirmed that HIFU ablation provoked necrosis of periosteum and bone marrow cells. Denervation of bone marrow and cortical bone additionally contributes to pain control (55). HIFU has been proven to be effective in relieving pain in patients initially refractory to radiotherapy in a study by Catane et al. (67,68) In a randomized study, Hurwitz revealed that pain relief lasted up to 3 days, affecting 63% of patients compared to 20% in the placebo group (69). Medication requirement was less in the treatment group. HIFU was applied as first-line treatment in patients with bone metastases, with 72.7% of patients reporting complete pain relief. Of note
is that this study additionally demonstrated bone remodelling (24). These investigations are currently considered as a promising technique to ensure pain palliation for immediate and long-lasting pain.

More recently, studies were carried out to assess combined therapy for pain control. HIFU in combination with radiotherapy has been proposed to first create hyperthermia inside and through bone tumors, which is then followed by external radiotherapy. Several advantages of this approach are currently expected, consisting mainly in a reduction of radiotherapy doses, along with the possibility to perform re-irradiation.

Hyperthermia acts as a radio- and chemo-sensitizer in the range of 40 to 43°, (70,71) which is called thermal sensitization. Hyperthermia stimulates the activity of osteoblasts to improve osteogenesis and reduces the risk of fractures by stimulating the activity of osteoblastic cells (72). Recently, a study by (73) showed that combining radiotherapy with hyperthermia results in a higher radiological response rate compared to radiotherapy alone with respect to bone stability, which is explained by its ability to facilitate reossification. Meanwhile, several publications have highlighted the synergic effect of hyperthermia and radiotherapy (74,75,76,77). Hyperthermia decreases tumor hypoxia, increases tumor perfusion, (78), induces tumor apoptosis, and enhances the proliferation of immune effector cells (79,80).
5. Conclusion

MSK imaging has been continuously evolving since the beginning of medical imaging science, from conventional X rays to ultrasound and then on towards cross-sectional imaging techniques, such as CT and MRI, to guided imaging therapies. Throughout this long journey, imaging has been a central axis, around which many decisions are made concerning diagnosis, treatment, and follow-up of patients with different pathologies. During this evolution, imaging has progressively evolved from basic morphological imaging to advanced techniques that allow for a better image quality, the high-resolution study of small structures, and the quantification of several tissue diseases.

Modern imaging techniques combine excellent spatial resolution and thus, morphological details, with essential information on tissue composition and function. These techniques include, among others, algorithms to reduce metallic artifacts around bone implants on CT, facilitate diagnosis and extension of subtle diseases. Quantitative synthetic MRI is promising to shorten examination time and to allow for “mapping” of structure intensities. Advanced and precise guiding of bone and soft tissues treatment expands therapeutic palliative and curative option for patients. For the last point, a multidisciplinary discussion is mandatory to allow an optimal treatment with combined minimvasive techniques.
6. References


24. Alessandro Napoli, Michele Anzidei, Beatrice Cavallo Marincola, Giulia Brachetti,
Vincenzo Noce, Fabrizio Boni, Luca Bertaccini, Roberto Passariello, Carlo Catalano. MR
Imaging–guided Focused Ultrasound for Treatment of Bone Metastasis. RadioGraphics


26. Georgia Tsoumakidou • Julien Garnon • Nitin Ramamurthy • Xavier Buy • Afshin Gangi.
Interest of Electrostimulation of Peripheral Motor Nerves during Percutaneous Thermal

27. Hong K, Georgiades C. Radiofrequency ablation: mechanism of action and devices. J

28 Rosenthal DI, Hornicek FJ, Wolfe MW, Jennings LC, Gebhardt MC, Mankin
HJ. Percutaneous radiofrequency coagulation of osteoid osteoma compared with operativ

G, Sardanelli,F, CytevalC.Osteoid osteoma treated by percutaneous thermal ablation:when
doe we fail? A systematic review and guidelines for future reporting. Cardiovasc Intervent


Pj, Lewis BD, Welch Tj, Farrell MA, Maus TP, Lee RA, Reading CC, Petersen IA, Pickett DD.
Painful metastases involving bone: feasibility of percutaneous CT- and US-guided radio-

32. Wolf FJ, Aswad B, Ng T, Dupuy DE. Intraoperative microwave ablation of pulmonary
malignancies with tumor permittivity feedback control: ablation and resection study in


35. Claudio Pusceddu, MD, Barbara Sotgia, MD, Rosa Maria Fele, MD, and Luca Melis, MD. Treatment of Bone Metastases with Microwave Thermal Ablation. J Vasc Interv Radiol 2013; 24:229–233


60. Roos DE, Turner SL, O’Brien PC, Smith JG, Spry NA, Burmeister BH, Hoskin PJ, Ball DL; Trans-Tasman Radiation Oncology Group, TROG 96.05. Randomized trial of 8 Gy in 1 versus 20 Gy in 5 fractions of radiotherapy for neuropathic pain due to bone metastases (Trans-Tasman Radiation Oncology Group, TROG 96.05). Radiother Oncol. 2005;75(1):54-63.


the assessment of demyelinating diseases, degenerative diseases, and spondylodiscitis.

**Fig.4:** Post-traumatic left knee MRI in 32-year-old patient: synthetic MR on sagittal T1 (a), PD (b), and STIR (c) weighting compared to conventional images for coronal T1 (d), sagittal PD (e) and coronal STIR (f) weighting (adapted from Boudabbous et al. Acta Radiol 2018).