REVIEWS ARTICLE

Advances in magnetic resonance imaging of musculoskeletal tumours

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Summary Functional magnetic resonance imaging (MRI) improves tissue characterisation and staging of bone and soft-tissue tumours compared to the information usually supplied by structural imaging. Perfusion MRI, diffusion MRI, and in-phase/opposed-phase MRI can be performed in everyday practice. Nuclear magnetic resonance (NMR) spectroscopic imaging is a challenging technique that is available only in specialised centres. Tumour characterisation can benefit from perfusion MRI with dynamic gadolinium injection and enhancement time-intensity curve analysis or from diffusion MRI. Highly cellular malignant tumours restrict diffusion and consequently decrease the apparent diffusion coefficient (ADC). With some tumours, tissue heterogeneity or the presence of a myxoid component can hinder this evaluation. Chronic hematoma can be distinguished from haemorrhagic sarcoma. Perfusion and diffusion MRI contribute to the evaluation of tumour spread, in particular by differentiating oedema from tumour tissue. Another advantage of perfusion MRI and ADC mapping is the early identification of good responders to chemotherapy. The use of NMR spectroscopy remains limited. Evaluation of the choline peak can help to differentiate benign and malignant tumours. All available functional MRI techniques have limitations and leave some overlap between benign and malignant tumours. Functional MRI can be used only as an adjunctive imaging modality to complement morphological imaging. © 2012 Elsevier Masson SAS. All rights reserved.

Introduction

Magnetic resonance imaging (MRI) is now indispensable for the preoperative workup and therapeutic follow-up of patients with musculoskeletal tumours [1,2]. Standard MRI uses structural criteria to assess tumour spread to the bone or soft tissues but makes only a limited contribution to the differentiation of benign and malignant tumours and to the characterisation of the tumour tissue [2,3]. Among other imaging tools, the most specific for determining that the lesion is neoplastic is radiography, which determines whether MRI is in order [1]. In many patients, standard MRI cannot determine the exact extent of tumour necrosis or the presence of viable tumour cells, two criteria used to evaluate the treatment response and predict the outcome [2,4]. Patients in this situation can benefit from the latest...
advances in MRI such as perfusion imaging, proton nuclear magnetic resonance (NMR) spectroscopy, diffusion imaging, and in-phase/opposed-phase imaging [2].

**Perfusion imaging by dynamic contrast-agent injection**

Dynamic perfusion MRI is a functional imaging technique in which early enhancement of the tumour is monitored after an intravenous gadolinium bolus injection [5]. This technique provides information on vascularisation and perfusion, capillary permeability, and interstitial compartment volume [1,5]. It is often used to evaluate musculoskeletal tumours [6–8]. The main contributions of dynamic perfusion MRI are identification of viable tumour sites to guide the biopsy, monitoring of preoperative chemotherapy, and differentiation of residual tumour from scarring. The injection is monitored for about 5 minutes within a region of interest (ROI) appropriate for the size of the tumour.

To evaluate perfusion, three ROIs of identical size are positioned at a site of marked early tumour enhancement, in an artery, and in healthy muscle, respectively [2]. The time-intensity curves indicate the time from bolus arrival to tumour enhancement, maximal enhancement, and the enhancement slope [5]. The curves can be classified into five types (Fig. 1):

- type 1, no enhancement (e.g., lipoma or haematoma);
- type 2, faint and gradual enhancement (e.g., benign tumours or schwannoma);
- type 3, rapid early enhancement followed by a plateau (limited specificity for tumour characterisation: benign vascular tumours, desmoid tumours, abscesses, some malignant tumours);
- type 4, rapid early enhancement followed by a washout phase (highly vascular tumours with a small interstitial compartment including several malignant tumours [malignant histiocytotibroma, synovial cell sarcoma, and leiomyosarcoma] and several benign tumours [e.g., giant cell tumour and osteoid osteoma nidus]);
- type 5, rapid early enhancement followed by slow gradual enhancement (e.g., tumours after radiotherapy or chemotherapy and tumours with large interstitial compartments such as myxoid tumours). A colour map of enhancement parameters can be produced.

![Figure 1](image-url) The various types of MRI enhancement time-intensity curves after gadolinium injection.
Characterisation of the tumour tissue

In dynamic imaging, the first pass of the contrast agent serves to evaluate tissue vascularisation and tumour perfusion [1,6]. Enhancement occurs earlier and is more marked in tissues characterised by an abundant vasculature and high capillary permeability than in poorly vascularised tissues [9]. However, both quantitative and qualitative overlap occurs between the time-intensity curves of highly vascular benign tumours and those of poorly vascularised malignant tumours [1,6].

Staging of clinical tumour spread

A detailed clinical and radiological assessment of local and general tumour spread is crucial to management decisions such as the choice of the biopsy site and determination of the tumour resection margins [5]. The initial slopes of tumours and non-tumour tissues vary widely [10,11]. Dynamic imaging can provide a more accurate determination of the tumour contours, as enhancement occurs earlier in the tumour tissue than in the surrounding oedema.

Viable tumour sites

Identification of well-vascularised areas of viable tumour tissue is crucial to select the biopsy site. This step ensures that the biopsy is not performed at sites of poorly vascularised tumour tissue with oedema and necrosis [1,5].

Chemotherapy monitoring

An accurate evaluation of the tumour response during the initial treatment phase is of the utmost importance to assess treatment effectiveness, plan the rest of the treatment strategy, and predict the outcome [8]. The quantitative criterion used to assess the effectiveness of preoperative chemotherapy, most accurately in patients with chemo-sensitive tumours of bone (e.g., osteosarcoma and Ewing’s sarcoma) and soft tissues (e.g., synovial cell sarcoma) is the percentage of tumour necrosis, which separates responders from non-responders [1]. During follow-up in poor responders, the time-intensity curve and slope value increase, remain unchanged, or show only small decreases [1]. Changes in the time-intensity curve with an at least 60% decrease in the slope value indicate more than 90% of tumour necrosis, which defines a good treatment response.

Dynamic perfusion MRI makes a major contribution to patient follow-up during chemotherapy. Its diagnostic accuracy for differentiating good and poor responders has ranged from 85.7% to 100% [1,6]. Optimal follow-up requires three dynamic perfusion MRI studies, before the biopsy, during chemotherapy, and immediately before surgery, respectively [1].

Detection of residual or recurrent tumours

Dynamic perfusion MRI is useful for detecting viable tumour tissue and differentiating it from reactive tissue changes caused by the treatment. With standard MRI, residual or recurrent tumour may be difficult to distinguish from bone marrow reconversion, inflammation, or reactive fibrosis [1]. During dynamic perfusion MRI, first-pass enhancement occurs earlier and faster in residual or recurrent tumour tissue than in reactive tissue or pseudo-tumours, where enhancement occurs later and more slowly, at the same rate as in healthy muscle [1,5].

Proton nuclear magnetic resonance spectroscopy

Proton NMR spectroscopy can be used to characterise the molecules present in malignant musculoskeletal tumours [3,12]. Proton NMR spectroscopy is more widely used for brain imaging [13]. The lesions are characterised based on their metabolic constituents, such as choline, a phospholipid found in the cell membrane [11]. An increased proportion of choline indicates accelerated cell-membrane turnover, which is an indirect marker for malignancy [3,12]. The in vivo choline/creatinine ratio differentiates malignant extra-cranial head-and-neck tumours from healthy muscle. Proton NMR spectroscopy has been used in bone and soft-tissue tumours, breast cancer, prostate cancer, and cervical cancer. The results differentiate malignant from benign musculoskeletal tumours [3,12].

Proton NMR spectroscopy results can be translated into pixel intensity maps based on the relative signal from the metabolite (water, choline, creatine, and lipids), using multi-voxel and single-voxel techniques. Multi-voxel proton NMR spectroscopy has been proved feasible for characterising musculoskeletal tumours [12]. The ROIs must be painstakingly positioned at sites of early marked enhancement that do not contain bony structures, necrotic or haemorrhagic foci, calcifications, fat, or muscle. For tumours exhibiting weak and slow enhancement or no enhancement after 5 minutes, the voxel is positioned at sites of delayed enhancement.

The choline peak serves to differentiate benign and malignant tumours. A choline peak is in favour of a malignant lesion but can be found in metabolically active benign lesions and in abscesses [3,13]. A lipid peak is usually visible in abscess walls, solid components of malignant masses, and treated tumours, where it reflects cell-membrane turnover. Care should be taken to avoid peak contamination by neighbouring structures, as well as excessive noise.

Diffusion magnetic resonance imaging

Diffusion MRI provides quantitative and qualitative assessments of tissue cellularity and cell-membrane integrity. It is widely used for tumour detection, characterisation, and monitoring during treatment. Diffusion MRI supplies functional information that complements the structural evaluation [2].

Diffusion MRI measures the random movements of water molecules in the body (Brownian motion). Water molecule motion is assessed in vivo in the extracellular, intracellular, and transcellular compartments, as well as in the intravascular compartment (microcirculation-perfusion) [11]. Blood flow in the intravascular compartment leads to water molecule diffusion over longer distances, compared to the extracellular and intracellular compartments. The contri-
distribution of intravascular water-molecule diffusion to the diffusion image varies across tissues; it can be significant in highly vascularised tumours. Restriction of water-molecule diffusion within biological tissues correlates negatively with tissue cellularity and membrane integrity [14]. Restriction is greater in highly cellular tissues that have intact cell membranes and a small extracellular compartment.

Tumours differ regarding their cellular characteristics, and the differences can serve to differentiate tumour types. Cellularity is greater in malignant tumours, in which restriction of water-molecule diffusion tends to be greater, compared to benign tumours [2,15].

Qualitative diffusion magnetic resonance imaging

Diffusion MRI is performed using a conventional T2-weighted sequence with diffusion gradients to filter the signal from highly mobile water molecules and to improve the detection of diffusion and mobility. Available diffusion sequences include spin echo diffusion-weighted imaging (DWI), echo-planar imaging (EPI), and steady-state free precession (SSFP) imaging [11]. EPI has a short acquisition time and is consequently the most widely used sequence, with a single-shot or multi-shot technique. To improve interpretation accuracy, at least two different b values are generally used (0 and 600 or 1000 s/mm²). The b value reflects the diffusion force and diffusion weighting of the image, just as the echo time (TE) reflects T2 weighting of T2 images [2,11]. Cystic tumours exhibit greater signal attenuation on high b-value images, reflecting the smaller degree of water-molecule motion restriction, whereas solid masses and cellular tumours continue to generate a high-intensity signal.

Quantitative diffusion imaging

Diffusion MRI with multiple b values provides a quantitative analysis via the apparent diffusion coefficient (ADC). ADC is an exponential function of the tumour signal on the images acquired with different b values. The ADC is computed for each pixel of the image, and a map of the ADC values is created. Tissues can be differentiated by using ROIs on the ADC map. Highly cellular sites with restricted diffusion have lower ADC values compared to sites characterised by lower cell densities. Sites with low ADC values generate higher signal intensity on diffusion images. However, the ADC depends not only on water-molecule diffusion in the extracellular tumour compartment, but also on the degree of tumour perfusion [15]. The perfusion fraction (microcirculation) in malignant soft-tissue tumours tends to be greater and to make a larger contribution to ADC elevation than in benign soft-tissue tumours. Thus, perfusion can produce a larger ADC increase in malignant tumours, leading to overlap between ADC values of malignant and benign tumours [2]. Diffusion images corrected for perfusion (perfusion-insensitive ADC value, PIADC) limit the impact of this effect [15]. Conventional ADC values are measured with b values of 0 and 600 s/mm². Water molecules that move freely and diffuse over long distances (e.g., in the intravascular compartment) show signal attenuation at low b values (50–100 s/mm²). In contrast, water molecules that move slowly or diffuse over short distances exhibit more gradual signal attenuation with increasing b values (1000 s/mm²). Tumour cellularity correlates linearly with the minimum ADC value (Pearson coefficient, −0.88), and high-grade lesions tend to produce lower values [16]. However, benign non-myxoid tumours have a higher mean ADC value compared to malignant lesions (1.31 ± 0.46 × 10⁻³ mm²/s versus 0.94 ± 0.25 × 10⁻³ mm²/s, P < 0.001) (Fig. 2) [17]. In combination with standard structural MRI parameters, the ADC value improves tumour characterisation [18].

Diffusion MRI can also be used to monitor tumours during chemotherapy. Tumour necroses results in loss of cell-membrane integrity and in expansion of the extracellular compartment, leading to greater water-molecule diffusion with an increase in the ADC value [2].

Figure 2  High-grade synovial cell sarcoma of the left knee (arrows). (a) Coronal section, T2 FS (TR 6230/TE 160 ms): moderate signal intensity that rules out a predominant myxoid component (b) apparent diffusion coefficient (ADC) map (b = 0–600 s/mm²): low mean ADC of 0.81 × 10⁻³ mm²/s suggesting a malignancy.
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In-phase and opposed-phase imaging

Chemical shift imaging relies on the lipid/water ratio in a given tissue voxel. This imaging modality can differentiate malignant from benign tumours and is widely used to evaluate tumours of the liver and adrenal glands [19,20]. It can also be applied to bone tumours. Signal changes between in-phase images (TE = 4.6 ms) and opposed-phase images (TE = 2.4 ms) differ between tumours and non-neoplastic lesions of the spine [21]. Chemical shift imaging is indicated to differentiate a crush fracture due to a tumour from an acute mechanical crush fracture. Another possible use is the monitoring of tumours during treatment [20].

The bone marrow has high fat and water contents, but the differences in the amounts of fat and water produce the bone signal during MRI [21]. The simultaneous presence of fat and water in the normal marrow results in signal suppression on opposed-phase images. Infiltration of the bone marrow by the tumour completely replaces the fat component, leading to loss of signal suppression on opposed-phase images [19,20]. Water and fat protons have different precession frequencies, reflecting the differences in their environments. ROIs can be positioned in doubtful areas and the ratio of the bone-marrow signal intensities on the two images computed. A cut-off value of 0.8 has been suggested, with higher values indicating a tumour and lower values a non-neoplastic lesion [20,21].

Clinical applications

We will use a few examples to illustrate the contribution of advanced MRI techniques to the evaluation of musculoskeletal tumours.

Osteoid osteoma

In most patients, radiographs, computed tomography, and bone scintigraphy are sufficient to establish the diagnosis by visualising a nidus with a variable degree of calcification, a surrounding rim of sclerosis, and cortical thickening [22]. At some sites, however, the diagnosis may be challenging. MRI evidence of oedema surrounding the tumour is suggestive but may mask the nidus in some cases. The vascular groove sign around the nidus lacks sensitivity but is highly specific for differentiating an osteoid osteoma from another lesion by CT. Although MRI is classically considered less informative for detecting the nidus, dynamic perfusion MRI may be helpful [22,23]. Enhancement maps can distinguish an osteoid osteoma from an infection (Brodie abscess), synovitis, and other tumour types. Most osteoid osteomas exhibit arterial enhancement followed by rapid partial washout, reflecting the marked vascularisation of the nidus (Fig. 3). Dynamic 3D sequences with thin sections and no gap can be used to monitor the injection and to produce an enhancement map.

Chemical shift imaging may also be useful in this indication. The ratio of opposed-phase and in-phase nidus signals is greater than 1 (from 1.04 to 1.26), whereas the surrounding tissue has a low ratio of 0.36 on average.

Abscesses, hematomas, and necrotic tumours

A definite diagnosis of abscess modifies the management strategy, as drainage is in order. Abscesses may have a rich blood supply with perfusion slopes similar to those seen in malignant tumours [6]. On the other hand, malignant tumours exhibiting extensive necrosis may have low slope values similar to those seen in benign tumours [6]. In addition, benign lesions that contain inflammatory cells, such as abscesses, can produce choline peaks despite the absence of malignant transformation.

Diffusion MRI of brain abscesses typically shows a marked reduction of the ADC value in the necrotic core [2]. Abscesses contain inflammatory cells, a protein matrix, cellular debris, and bacteria within highly viscous pus, limiting water-molecule mobility. Therefore, the abscess cavity is characterised by high signal during diffusion MRI, with a low
ADC value. Diffusion tends to be greater in the necrotic part of necrotised tumours than in abscesses. The ADC map shows a greater degree of diffusion restriction in the solid part of aggressive malignancies [2].

Differentiating a haematoma from a haemorrhagic malignant tumour may be challenging [2]. Diffusion MRI can differentiate a growing chronic haematoma from a malignant tumour. The mean ADC value is significantly higher in haematomas than in soft-tissue malignancies (1.55 ± 0.121 × 10⁻³ mm²/s versus 0.92 ± 0.139 × 10⁻³ mm²/s, P < 0.01). Acute and subacute haematomas produce characteristic MRI features, and the ADC map shows restricted diffusion in the centre of the lesion. Contrast enhancement is rare in benign haematomas. Haemoglobin breakdown products complicate the NMR spectroscopy analysis of haematomas. Nevertheless, haemorrhagic malignancies tend to produce a choline peak in the solid part of the tumour, reflecting active cell division.

Myxoid tumours

Myxoid tissue is found in myxoma, myxoid liposarcoma, and myxoid malignant fibrous histiocytoma [1]. ADC values are higher in malignant and non-malignant myxoid soft-tissue tumours than in non-myxoid tumours (2.08 ± 0.51 × 10⁻³ mm²/s versus 1.13 ± 0.40 × 10⁻³ mm²/s, P < 0.001) [2,15]. The high ADC values are related to the high mucin and low collagen contents of these water-rich lesions [2]. The presence of a myxoid component results in considerable overlap between the ADC values of benign and malignant myxoid tumours.

Myxoid liposarcoma is a malignant fatty tumour that accounts for one-third of all liposarcomas. The low-intensity signal on T1 images and high-intensity signal on T2 images may suggest a cyst. Myxoid liposarcoma may be indistinguishable from most benign and malignant soft-tissue tumours [1,2]. Perfusion techniques are useful for distinguishing cysts from myxoid tumours: cysts show no enhancement, whereas the myxoid component of sarcomas exhibit marked and rapid enhancement [1].

Intramuscular myxoma is a benign tumour characterised by an abundant myxoid stroma and the virtual absence of blood vessels. Nevertheless, enhancement occurs during perfusion imaging, albeit in a gradual fashion. Tumour filling occurs gradually over the first few minutes after the bolus injection, because of both the large interstitial component and the low perfusion rate [1]. Rapid filling of a myxoid tumour should suggest a malignancy such as a myxoid liposarcoma or synovial cell sarcoma. A comparison of the structural data from conventional MRI and of the perfusion and diffusion MRI data improves diagnostic accuracy in myxoid tumours [2].

Lesions of the cartilage

Distinguishing an enchondroma from a low-grade chondrosarcoma is crucial to select the treatment strategy. Radiographs, CT, and even standard MRI cannot easily distinguish these two lesions, and neither is bone scintigraphy reliable [1]. The use of dynamic perfusion MRI has been suggested as a means of distinguishing low-grade chondrosarcoma and active enchondroma from inactive enchondroma. Inactive enchondroma is characterised by limited enhancement and perfusion, contrasting with the early rapid enhancement of both active enchondroma and chondrosarcoma [1]. Perfusion MRI cannot distinguish these last two lesions.

Malignant tumours of cartilage can exhibit higher ADC values than benign tumours [2]. In both benign and malignant tumours, high ADC values are due to the chondroid matrix. Further studies are needed to determine the contribution of diffusion MRI to the evaluation of cartilage lesions.

Osteosarcoma and Ewing’s sarcoma

Osteosarcoma and Ewing’s sarcoma account for over 90% of all primary bone tumours in children. Chemotherapy is usually given before surgery is performed. An accurate evaluation of the tumour response to the initial chemotherapy phase is valuable for adjusting the treatment regimen and predicting the outcome [8]. Histological examination of the operative specimen is the reference standard for evaluating the treatment response. In good responders, more than 90% of the tumour tissue is necrotic. Survival is considerably longer in good responders than in poor responders. Standard contrast-enhanced MRI cannot provide an evaluation of the extent of the necrosis [1]. Both viable tissue and necrotic tissue generate high signal on T2 images. Chemotherapy can cause bleeding, necrosis, oedema, and hypervascular fibrosis with no distinctive features by MRI [2,6,8]. In addition, effective chemotherapy usually fails to shrink osteosarcomas, since there is little effect on the mineralised tumour matrix. Studies of enhancement curves show that a greater than 60% decrease in slope value at the sites of maximal slope before chemotherapy is the best marker for a good treatment response [8]. This technique is sufficiently specific only when used at least 4 to 6 weeks after chemotherapy initiation. Poorly vascularised tumour tissue, such as chemotherapy-resistant chondroblastic foci of osteosarcomas, may mimic tumour necrosis. On the other hand, foci of granulation tissue replacing necrotic tumour tissue may mimic viable tumour tissue. The dynamic study is best performed 3 months after chemotherapy initiation, when the granulation tissue has decreased but the residual tumour tissue is still abundantly vascularised and perfused.

By diffusion MRI, the ADC values of viable tumour tissue and necrotic tumour tissue differ considerably. Therefore, diffusion MRI can be used to assess the treatment response. This technique can detect earlier modifications, as changes at the cell level precede gross tumour shrinkage. Diffusion MRI visualises highly cellular foci in the regions that have been altered by the treatment [24]. In osteosarcomas, treatment-induced ADC changes correlate directly with the extent of tumour necrosis (Fig. 4). The minimal ADC values of the solid components of osteosarcomas differ significantly between good and poor responders [25]. Diffusion MRI is emerging as a promising tool for monitoring the treatment of osteosarcoma [2,25].

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Miscellaneous malignant bone tumours — vertebral crush fractures

Diffusion MRI of a body site or the whole body used in combination with conventional MRI has considerable diagnostic value for detecting bone metastases. Compared to positron-emission tomography (PET) and bone scintigraphy, diffusion MRI detects a larger number of metastases, as well as metastases of smaller size [26]. Bone metastasis detection is crucial for cancer staging and for selecting the treatment strategy.

Acute vertebral crush fracture is a common clinical problem in elderly individuals and is often due to osteoporosis or metastatic bone disease. In difficult cases, to avoid having to perform a percutaneous bone biopsy, monitoring by MRI (gradual fat signal recovery in the event of a mechanical crush fracture) or positron-emission tomography/computed tomography may be helpful. Crush fractures due to tumours are characterised by increased fluorodeoxyglucose (FDG) uptake. MRI evaluation of the peak and first-pass enhancement slope in the vertebral bodies shows that a type 4 curve with rapid enhancement followed by a washout phase has high positive predictive value (PPV) for a bone metastasis. A type 5 curve with rapid enhancement then a second phase of weaker enhancement has high PPV for a benign crush fracture. In-phase and opposed-phase imaging can also be useful for differentiating benign and metastatic crush fractures. For the signal-intensity decrease on the opposed-phase image compared to the in-phase image, 35% is the cut-off for differentiating the two lesions. This cut-off can also serve as an early marker for the response to spinal radiotherapy.

Proton NMR spectroscopy is also useful, since a choline peak suggests a malignant crush fracture [12]. Qualitative and quantitative diffusion imaging improves diagnostic specificity [11].

A high-intensity signal by diffusion MRI suggests a malignant crush fracture [27]. Image quality is best with low b values. With a b value of about 300 s/mm², fractional anisotropy (FA) is significantly diminished in the event of a neoplastic crush fracture. Lower b values have no discriminating potential [28] and higher b values have the disadvantage of decreasing the signal-to-noise ratio.

Monitoring the treatment response

Diffusion MRI can also be used to estimate residual tumour activity after treatment and to detect recurrences at an early stage when curative treatment is still possible. Differentiating treatment-related tissue changes from residual or recurrent tumour tissue is a common problem, given the lack of specificity of the signal abnormalities by standard MRI (low signal on T1 images and high signal on T2 images). Diffusion shows larger increases in foci of treatment-related tumour necrosis than in viable tumour recurrences [28]. Solid tumours are characterised by high cellularity and intact cell membranes, contrasting with the lower cellularity and membrane damage seen in treatment-altered tissues [29]. Necrosis of osteosarcomas results in elevated ADC values [30]. Both the minimum and the mean ADC values of osteosarcomas are significantly increased after chemotherapy, compared to baseline. The minimum ADC value is even significantly higher in good responders (more than 90% of necrosis by histological examination) than in poor responders (1.01 ± 0.22 versus 0.5 ± 0.29, P < 0.05) (Fig. 5) [30].

Dynamic perfusion MRI is the method of choice for estimating the response to preoperative chemotherapy. Good and poor responders can be separated based on the first-pass subtraction images or enhancement time-intensity curves. Recurrent bone tumours (with the exception of the cartilage components) exhibit earlier and faster enhancement compared to the reference tissue (healthy muscle) [1].

Figure 4 Osteosarcoma of the right femur. MRI after chemotherapy and before surgery. (a) sagittal section, STIR sequence: heterogeneous signals from ill-defined necrotic foci (b) apparent diffusion coefficient (ADC) map (b = 0–600 s/mm²): marked elevation of the minimum ADC value (2.13 × 10⁻³ mm²/s) in the necrotic foci compared to the minimum ADC value in the residual tumour (0.94 × 10⁻³ mm²/s).
In soft-tissue sarcomas, the foci of early and rapidly progressive enhancement are composed of residual or recurrent tumour, whereas absence of early enhancement indicates a good response. Radiotherapy may lead to neovascularisation with increased perfusion. A reaction containing granulation tissue may be difficult to distinguish from tumour tissue during the first 3 to 6 months after radiotherapy. Monitoring is indispensable in this situation: over time, perfusion decreases within reactive masses but increases in tumour tissue, which is richly vascularised.

Conclusion

Advanced MRI techniques complement standard MRI but remain insufficiently used. They delineate tissue heterogeneity with greater specificity and therefore help to guide the biopsy. Advanced MRI techniques also provide an early evaluation of good responders and ensure the detection of residual or recurrent tumour.

In cases that remain doubtful despite standard MRI, a choice must be made in clinical practice among the many available advanced techniques:

- atypical osteoid osteoma: dynamic perfusion MRI with gadolinium injection and enhancement time-intensity curves;
- tumour haematoma (?): diffusion MRI;
- vertebral crush fracture due to a tumour or to osteoporosis (?): diffusion MRI with determination of the ADC, with in-phase and opposed-phase imaging;
- treatment response in soft-tissue sarcomas:
  - a recurrent mass generating high signal on T2 images does not require complementary functional MRI techniques,
  - in the event of marked oedema on T2 images with no well-defined mass, dynamic perfusion MRI with gadolinium injection and enhancement time-intensity curves and/or diffusion MRI;
- early osteosarcoma response to chemotherapy: dynamic perfusion MRI with gadolinium injection and enhancement time-intensity curves; diffusion imaging is being evaluated in this situation.

Disclosure of interest

The author declares that he has no conflicts of interest concerning this article.

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