

ACR–SPR–SSR PRACTICE PARAMETER FOR THE PERFORMANCE OF MAGNETIC RESONANCE IMAGING (MRI) OF BONE AND SOFT-TISSUE TUMORS

The American College of Radiology, with more than 40,000 members, is the principal organization of radiologists, radiation oncologists, and clinical medical physicists in the United States. The College is a nonprofit professional society whose primary purposes are to advance the science of radiology, improve radiologic services to the patient, study the socioeconomic aspects of the practice of radiology, and encourage continuing education for radiologists, radiation oncologists, medical physicists, and persons practicing in allied professional fields.

The American College of Radiology will periodically define new practice parameters and technical standards for radiologic practice to help advance the science of radiology and to improve the quality of service to patients throughout the United States. Existing practice parameters and technical standards will be reviewed for revision or renewal, as appropriate, on their fifth anniversary or sooner, if indicated.

Each practice parameter and technical standard, representing a policy statement by the College, has undergone a thorough consensus process in which it has been subjected to extensive review and approval. The practice parameters and technical standards recognize that the safe and effective use of diagnostic and therapeutic radiology requires specific training, skills, and techniques, as described in each document. Reproduction or modification of the published practice parameter and technical standard by those entities not providing these services is not authorized.

PREAMBLE

This document is an educational tool designed to assist practitioners in providing appropriate radiologic care for patients. Practice Parameters and Technical Standards are not inflexible rules or requirements of practice and are not intended, nor should they be used, to establish a legal standard of care¹. For these reasons and those set forth below, the American College of Radiology and our collaborating medical specialty societies caution against the use of these documents in litigation in which the clinical decisions of a practitioner are called into question. The ultimate judgment regarding the propriety of any specific procedure or course of action must be made by the practitioner considering all the circumstances presented. Thus, an approach that differs from the guidance in this document, standing alone, does not necessarily imply that the approach was below the standard of care. To the contrary, a conscientious practitioner may responsibly adopt a course of action different from that set forth in this document when, in the reasonable judgment of the practitioner, such course of action is indicated by variables such as the condition of the patient, limitations of available resources, or advances in knowledge or technology after publication of this document. However, a practitioner who employs an approach substantially different from the guidance in this document may consider documenting in the patient record information sufficient to explain the approach taken.

The practice of medicine involves the science, and the art of dealing with the prevention, diagnosis, alleviation, and treatment of disease. The variety and complexity of human conditions make it impossible to always reach the most appropriate diagnosis or to predict with certainty a particular response to treatment. Therefore, it should be recognized that adherence to the guidance in this document will not assure an accurate diagnosis or a successful outcome. All that should be expected is that the practitioner will follow a reasonable course of action based on current knowledge, available resources, and the needs of the patient to deliver effective and safe medical care. The purpose of this document is to assist practitioners in achieving this objective.

¹ *Iowa Medical Society and Iowa Society of Anesthesiologists v. Iowa Board of Nursing*, 831 N.W.2d 826 (Iowa 2013) Iowa Supreme Court refuses to find that the "ACR Technical Standard for Management of the Use of Radiation in Fluoroscopic Procedures (Revised 2008)" sets a national standard for who may perform fluoroscopic procedures in light of the standard's stated purpose that ACR standards are educational tools and not intended to establish a legal standard of care. See also, *Stanley v. McCarver*, 63 P.3d 1076 (Ariz. App. 2003) where in a concurring opinion the Court stated that "published standards or guidelines of specialty medical organizations are useful in determining the duty owed or the standard of care applicable in a given situation" even though ACR standards themselves do not establish the standard of care.

I. INTRODUCTION

This parameter was developed and written collaboratively by the American College of Radiology (ACR), the Society for Pediatric Radiology (SPR), and the Society of Skeletal Radiology (SSR).

Magnetic resonance imaging (MRI) is a proven and well-established imaging modality in the detection, evaluation, staging, and follow-up of tumors of the musculoskeletal system. Properly performed and interpreted, MRI not only contributes to initial diagnosis and identification of local recurrence but is also useful to guide

biopsy, inform treatment planning, and assess response to therapy. MRI of a tumor or suspected mass should be performed for a valid medical reason and after careful consideration of alternative imaging modalities. An analysis of the strengths of MRI and other modalities should be weighed against their suitability for particular patients and particular clinical conditions. Radiographs should be the initial imaging study obtained for clinical suspicion of bone tumors. In addition, radiographs are usually the first imaging test performed for most suspected soft-tissue masses and are particularly valuable for identifying the presence and character of calcification, fat, or other radiopaque material. For superficial palpable soft-tissue masses, ultrasound may be useful to characterize lesion location, detect internal vascularity, and differentiate solid from cystic lesions [1-3]. Technetium-99m–labeled diphosphonates with bone scintigraphy and single-photon emission computed tomography (SPECT), with or without CT coregistration, is often used when occult bone disease is suspected and to screen the entire skeleton for polyostotic disease conditions such as metastasis. Other nuclear medicine examinations have a role for specific clinical scenarios (eg, Indium-111 oxine, a labeled white blood cell scan for suspected osteomyelitis). CT shows detailed bone anatomy and aids in identifying osteoid and chondroid matrix. CT can also be useful to demonstrate the presence of fat within both bone and soft-tissue lesions. Conventional, MR, or CT angiography remains useful for evaluating tumor vascularity, identifying the relationship of the lesion to adjacent major blood vessels, planning resection and reconstruction, and providing a road map for presurgical embolization [4]. Positron emission tomography (PET) with or without CT or MR coregistration can be used to screen the skeleton for occult disease [5], help stage and grade tumors [6-11], assess response to therapy [12-15], and detect tumor recurrence [9, 16], but it may not reliably discriminate between benign and malignant tumors [5, 7, 17].

Although MRI is one of the most sensitive, noninvasive diagnostic tests for detecting anatomic abnormalities of the musculoskeletal system, findings may be misleading if not closely correlated with radiographs, and/or other previous imaging, clinical history, physical examination, and physiologic tests [18, 19]. Adherence to the following guidelines will enhance the probability of detecting such abnormalities.

II. INDICATIONS

Indications for MRI of soft-tissue and bone tumors include, but are not limited to, the following:

1. Initial detection, characterization, or exclusion of tumors [20-35]
2. Follow-up evaluation of tumors (consider follow up and/or reevaluation of tumors)
3. Local staging of tumors [36-40]
4. Evaluation of tumors before biopsy, surgery, chemotherapy, radiotherapy, embolization, and/or percutaneous ablation [25, 38, 41-45]
5. Evaluation of the response of tumors to treatment, including neoadjuvant or adjuvant chemotherapy, radiotherapy, embolization, and/or percutaneous ablation [46-56]
6. Detection and evaluation of complications related to tumors or their treatment, including hemorrhage, infection, and neurologic and vascular conditions [25, 47, 55-65]
7. Posttreatment and surveillance
8. Characterization of tumor recurrences [54, 66]

III. QUALIFICATIONS AND RESPONSIBILITIES OF PERSONNEL

See the [ACR Practice Parameter for Performing and Interpreting Magnetic Resonance Imaging \(MRI\)](#) [67].

IV. SPECIFICATIONS OF THE EXAMINATION

The written or electronic request for MRI of bone and soft-tissue tumors should provide sufficient information to demonstrate the medical necessity of the examination and allow for the proper performance and interpretation of the examination.

Documentation that satisfies medical necessity includes 1) signs and symptoms and/or 2) relevant history (including known diagnoses). The provision of additional information regarding the specific reason for the examination or a provisional diagnosis would be helpful and may at times be needed to allow for the proper performance and interpretation of the examination.

The request for the examination must be originated by a physician or other appropriately licensed health care

provider. The accompanying clinical information should be provided by a physician or other appropriately licensed health care provider familiar with the patient's clinical problem or question and consistent with the state's scope of practice requirements. (ACR Resolution 35 adopted in 2006 – revised in 2016, Resolution 12-b) The supervising physician must have adequate understanding of the indications, risks, and benefits of the examination, as well as alternative imaging procedures. The physician must be familiar with potential hazards associated with MRI, including potential adverse reactions to contrast media. The physician should be familiar with relevant previous ancillary studies. The physician performing MRI interpretation must have a clear understanding and knowledge of the relevant anatomy and pathophysiology.

The supervising physician must also understand the pulse sequences to be used and their effect on the appearance of the images, including the potential generation of image artifacts. Standard imaging protocols may be established and varied on a case-by-case basis when necessary. These protocols should be reviewed and updated periodically.

IV. SPECIFICATIONS OF THE EXAMINATION

A. Patient Selection

The physician responsible for the examination should supervise patient selection and preparation and should be available for consultation by direct communication. Patients must be screened and interviewed before the examination to exclude individuals who may have contraindications to MRI, in which the risks may outweigh the benefits.

Certain indications require administration of intravenous (IV) contrast media. IV contrast enhancement should be performed using appropriate injection protocols and in accordance with the institution's policy on IV contrast utilization (See the [ACR–SPR Practice Parameter for the Use of Intravascular Contrast Media](#) [68] and the [ACR Manual on Contrast Media](#) [69]).

Pediatric patients or patients suffering from anxiety or claustrophobia may require sedation or additional assistance. Administration of sedation or general anesthesia may be needed to achieve a successful examination. If minimal or moderate sedation is necessary, refer to the [ACR–SIR Practice Parameter for Minimal and/or Moderate Sedation/Analgesia](#) for further details. Young children may require sedation or general anesthesia to prevent patient motion during the MR examination. Strategies should be employed to mitigate the use of sedation whenever possible and should include motion-insensitive imaging acquisitions and the use of a child life specialist support [70].

IV. SPECIFICATIONS OF THE EXAMINATION

B. Facility Requirements

Appropriate emergency equipment and medications must be immediately available to treat adverse reactions associated with administered medications. The equipment and medications should be monitored for inventory and drug expiration dates on a regular basis. The equipment, medications, and other emergency support must also be appropriate for the range of ages and sizes in the patient population.

IV. SPECIFICATIONS OF THE EXAMINATION

C. Examination Technique

Diagnostic-quality MRI of suspected bone and soft-tissue masses can be performed using a variety of magnetic designs (closed-bore whole body, open whole body) and a variety of field strengths [23, 26, 32, 35]. Regardless of system design, efforts should be made to maximize signal-to-noise ratios (SNR). Field of view (FOV) should be tailored to the size of the patient and the size of the suspected mass [23, 64, 71, 72]. For example, a 48-cm FOV would be appropriate for an extremely large tumor of the pelvis or thigh, whereas a 12-cm FOV may be appropriate for a small mass in the foot. It is important to obtain as many transverse, sagittal, or coronal images through the lesion as is reasonable. Slice thicknesses will also vary depending on the size of the lesion [23]. For example, a 1-cm mass might require 3-mm-thick slices, whereas a tumor greater than 30 cm in size may be appropriately imaged with 1-cm slice thickness [23]. An interslice gap may be used but should not impair complete visualization of the mass. The imaging matrix should balance the intravoxel SNR with desired in-plane spatial resolution.

The size and location of the lesion will often dictate the most appropriate coil to use for imaging. Small lesions or lesions located in the extremities will often be best imaged using a local surface coil, a cylindrical coil, or a dedicated joint coil. For extremely large lesions or lesions involving the torso, the body or torso coil may be a more appropriate choice [23, 36, 41]. The entire soft-tissue or bone tumor and associated marrow signal abnormality in association with the possible tumor should be captured within the imaged volume. For some tumors, two separate but overlapping volumes might be necessary. The entire bone, including the adjacent joints, should be imaged to evaluate for skip lesions and regional metastases. The use of a multiple-channel receiver coil unit may allow the use of parallel imaging and compressed sensing imaging techniques to reduce overall scan time or improve SNR and may be useful in reducing motion-related artifacts [73-75]. Commercially available deep learning accelerated MRI reconstruction techniques can also further aid in reducing scan times.

For patients with more than one suspected bone or soft-tissue mass, it may be necessary to perform separate MR examinations. For example, a patient with a mass involving both the pelvis and leg may require two separate studies.

When imaging bone and soft-tissue tumors at field strengths less than 1.5T, imaging parameters, such as the receiver bandwidth and number of acquisitions, will require modification to ensure adequate spatial and contrast resolution for confident diagnosis. This is often at the expense of longer examination times [64, 76]. It may also be more difficult to achieve uniform fat suppression on low-field systems using spectrally selective radiofrequency (RF) presaturation pulses, potentially necessitating the use of Dixon or short tau inversion recovery (STIR) techniques [77]. Other systems may be more prone to imaging artifacts (eg, chemical shift artifact on high-field magnets), again necessitating modification of imaging parameters, such as receiver bandwidth, to ensure that these artifacts do not detract from the diagnostic quality of the resultant images. Some MRI systems may not be appropriate for specific indications. For example, high-resolution evaluation of a small mass may not be feasible with a low-field, open magnet, regardless of the chosen imaging parameters [78].

MRI of bone and soft-tissue tumors usually includes images in at least two orthogonal planes (transverse, sagittal, and coronal) [21, 23, 30, 32, 64]. The orientation of the images should be performed with respect to the tumor, or to patient anatomy. Coverage of the tumor must include all of the anterior, posterior, medial, lateral, superior, and inferior margins of the mass, unless clinically impractical [23, 32, 45]. Imaging of lesions that cannot be felt by examination or seen on radiograph should include a landmark such as a joint for localization if surgery is required.

MRI of suspected bone and soft-tissue tumors can be performed with a variety of pulse sequences. The choice of sequences can be tailored to optimize the examination for specific clinical questions and according to local preferences. An imaging protocol would usually be composed of at least one T1-weighted pulse sequence and one fluid-sensitive T2-weighted sequence with or without fat suppression.

Short echo time (TE) images with a relatively short repetition time (TR) (T1-weighted) are commonly used to evaluate tumors [23, 32, 72, 76]. Properly optimized, most institutions use fast spin-echo sequences for T1-weighted imaging. If image blurring with fast spin-echo imaging occurs with a short effective TE, conventional spin-echo imaging can be used [23, 32, 72, 76]. To demonstrate pathologic tissues, T2-weighted (fluid-sensitive) imaging using conventional spin-echo or fast spin-echo sequences are most commonly used [77, 79-82]. T1-weighted spoiled gradient-echo chemical shift imaging (ie, water-fat in-phase/opposed-phase imaging) can be used to demonstrate the presence of lipid components in tissues and may help discriminate benign from malignant disease processes, such as in evaluation of fractures and bone marrow infiltration [83, 84]. False-negative results have been described [85]. Gradient-recalled sequences may also be valuable, in particular in evaluating for internal areas of hemorrhage, gas, ossification, or calcification. Diffusion-weighted imaging (DWI) may also be useful to quantitatively and qualitatively assess bone and soft-tissue masses [86-88]. DWI uses the variability of Brownian motion of water to characterize lesions as having restricted or unrestricted motion of water, which correlates with lesion cellularity [89].

T1-weighted sequences are routinely done without fat suppression to depict anatomic relationships; however, the addition of fat suppression may be helpful to detect hemorrhage or fat within a mass and enhancement when IV contrast is given [90]. Fluid-sensitive images, obtained with long TR using conventional or fast spin-echo sequences, can be used to characterize bone and soft-tissue tumors, providing complementary information to the

T1-weighted images. Therefore, a combination of both T1-weighted and T2-weighted images is typically performed in each imaging plane [32, 77, 79, 81, 82]. Lesion conspicuity may be increased with the addition of fat suppression to fluid-sensitive images and therefore fat suppression is commonly employed with T2- as well as postcontrast T1 weighted imaging. However, fat-suppressed imaging decreases the variation in tumor signal intensities that may be useful in tissue characterization. Alternatively, STIR or Dixon sequences can be used [77, 79, 81]. A combination of techniques may prove advantageous. For example, the transverse images may be obtained with or without fat suppression and the long axis planes (sagittal and/or coronal images) performed with fat suppression or STIR sequences. The exact TR, TE, and flip angle chosen will depend on the field strength of the magnet and the relative contrast weighting desired [32, 64, 76].

Various techniques may be used to minimize the MR artifacts that can reduce imaging quality. Wraparound artifact, including that originating from signal received from other parts of the body, can be reduced by using phase oversampling, by switching the phase and frequency readout directions, by presaturation pulses, or by using RF shielding. Truncation (Gibbs) artifacts may obscure or mimic intralesional detail and can be reduced by changing the phase-encoding direction. Involuntary patient motion is best controlled by ensuring patient comfort combined with gentle immobilization or sedation when necessary and often requires sedation or general anesthesia for young children [64, 91]. Desensitizing "practice runs" orchestrated by a child life specialist may also be effective for children [70], as well as the use of MR video goggles. Use of MR systems and coils that provide a high SNR, such as high-field (3T) MR systems and multichannel coils, with or without parallel imaging and/or compressed sensing, can reduce overall scan duration and individual sequence scan times and may help reduce motion artifacts and patient discomfort [73, 75]. Motion artifact can also be reduced by sampling k-space in a rotating fashion, using radially directed imaging planes[92]. Flowing blood can produce ghosting artifacts, which can be reduced with presaturation pulses or the use of gradient moment nulling [64, 91].

In many cases, it may be advantageous to administer a gadolinium-based IV contrast agent [93-99]. IV contrast may be helpful to differentiate cysts from solid masses and may provide additional details of the imaging features of bone and soft-tissue masses [79, 96, 99]. Subtracting the precontrast images from the postcontrast images may be beneficial to show subtle areas of enhancement and to distinguish enhancement from adjacent fat or hemorrhage [100]. Fast, multiphase dynamic contrast-enhanced imaging can provide analysis of tumor perfusion kinetics, including parametric perfusion data, that may help to improve tumor detection, to distinguish malignant from benign tumors [101-103], to stage tumors and response to therapy [48, 104-106], to determine an optimal site for biopsy improve tumor detection, or to evaluate potential extension of tumor cells along related fascial planes [107]. The decision to use IV contrast should be based on medical appropriateness.

Follow-up MRI of musculoskeletal tumors is generally performed using sequences similar to those used for initial diagnosis, including T1-weighted and T2-weighted images [54, 66]. Because local recurrence may often appear similar to the original tumor, MRI following treatment or surgery should ideally be interpreted with comparison to previous MRI examinations, including the preoperative or pretreatment MRI, if available. Follow-up MR examinations of patients with previously treated soft-tissue tumors often benefit from the addition of IV contrast agents [56, 66]. Protocols for follow-up and interpretation of MRI findings vary depending on the type of tumor, the therapeutic methods used, and the aggressiveness of the tumor (see the [ACR Appropriateness Criteria[®], Malignant or Aggressive Musculoskeletal Tumor-Staging And Surveillance](#) [108]).

MR spectroscopy may be useful in gauging therapy response and tumor staging [109-114]. It may also be used to detect certain metabolites in tumors to help in lesion characterization [109, 115-120], but caution should be used in interpretation because some metabolites that were thought to be specific may not be (eg, choline for malignant tumors) [121]. Newer imaging sequences employing isotropic or near-isotropic 3-D sequences produce images with shorter scan duration but have not been thoroughly evaluated for imaging of musculoskeletal tumors at this time. Among other uses, whole-body MR screening examinations can be useful both for staging of disseminated or hematologic tumors, such as multiple myeloma, and to limit radiation dose to pediatric and pregnant patients [122-127].

For interpretation, images are most commonly viewed electronically on a workstation. MR examinations in patients with suspected tumors should be read cautiously and preferably in conjunction with available radiographs. There are many pitfalls and artifacts that can suggest that a nonneoplastic mass is an aggressive tumor or that a malignant tumor appears to be a benign lesion based on the MR appearance alone [79, 128, 129].

Furthermore, imaging artifacts can also contribute to incorrect staging of tumors [79, 128, 129].

V. DOCUMENTATION

Reporting should be in accordance with the [ACR Practice Parameter for Communication of Diagnostic Imaging Findings](#) [130].

The report should address the presence or absence of a mass, the size of the lesion and description of anatomic extent, composition (hemorrhage, necrosis, etc), signal intensity, and enhancement characteristics when IV contrast is administered. A diagnosis or differential diagnosis should be provided. A description of the anatomic location of a tumor, including its intracompartmental and extracompartmental extent, as well as its relationships to adjacent major muscles, vessels, and nerves, will contribute to the tumor's staging. The presence or absence of fascial extension of tumor should be described, which will contribute to the surgical resection planning. The presence or absence of any regional lymphadenopathy or skip lesions should be noted. Prudently, published scoring systems may be employed for standardized reporting, differentiation of benign from malignant bone lesions, and improved multidisciplinary communications [131-135].

See the [ACR Practice Parameter for Performing and Interpreting Magnetic Resonance Imaging \(MRI\)](#) [67], the [ACR Manual on MR Safety](#) [136], and the [ACR Manual on Contrast Media](#) [69].

Peer-reviewed literature pertaining to MR safety should be reviewed on a regular basis [138, 139].

VI. EQUIPMENT SPECIFICATIONS

Equipment monitoring should be in accordance with the [ACR-AAPM Technical Standard for Diagnostic Medical Physics Performance Monitoring of Magnetic Resonance Imaging \(MR\) Imaging Equipment](#) [140].

Specific policies and procedures related to MRI safety should be in place with documentation that is updated annually and compiled under the supervision and direction of the supervising MRI physician and/or MR safety officer. Guidelines should be provided that deal with potential hazards associated with MRI examination to the patient as well as to others in the immediate area [138, 139, 141]. Screening forms must also be provided to detect those patients who may be at risk for adverse events associated with the MRI examination [138, 139, 141, 142].

The MRI equipment specifications and performance must meet all state and federal requirements. The requirements include, but are not limited to, specifications of maximum static magnetic strength, maximum rate of change of the magnetic field strength (dB/dt), maximum RF power deposition (specific absorption rate), and maximum acoustic noise levels.

VII. QUALITY CONTROL AND IMPROVEMENT, SAFETY, INFECTION CONTROL, AND PATIENT EDUCATION

Policies and procedures related to quality, patient education, infection control, and safety should be developed and implemented in accordance with the ACR Policy on Quality Control and Improvement, Safety, Infection Control, and Patient Education appearing under the heading *ACR Position Statement on Quality Control and Improvement, Safety, Infection Control and Patient Education* on the ACR website (<https://www.acr.org/Advocacy-and-Economics/ACR-Position-Statements/Quality-Control-and-Improvement>).

ACKNOWLEDGEMENTS

This practice parameter was revised according to the process described under the heading *The Process for Developing ACR Practice Parameters and Technical Standards* on the ACR website (<https://www.acr.org/Clinical-Resources/Practice-Parameters-and-Technical-Standards>) by the Committee on Body Imaging (Musculoskeletal) of the Commission on Body Imaging and by the Committee on Practice Parameters – Pediatric Imaging of the Commission on Pediatric Radiology, in collaboration with the SPR and the SSR.

Writing Committee – members represent their societies in the initial and final revision of this practice parameter

ACR

Garner, Hillary W MD, Chair

Alizai, Hamza MD

Shah, Jordyn DO

SPR

Fadell, Michael F MD

Jones, Richard H MD

SSR

Lin, Dana J MD

Rhodes, Nicholas G MD

Committee on Musculoskeletal Imaging – Body Imaging

(ACR Committee responsible for sponsoring the draft through the process)

Subhas, Naveen MD, MPH, Chair

Bredella, Miriam A MD

Colak, Ceylan MD

Gelczer, Robert Kent MD

Gyftopoulos, Soterios MD, MSc

Mintz, Douglas N MD

Shah, Jordyn DO

Alaia, Erin MD

Chang, Connie Y MD

Garner, Hillary W MD

Gonzalez, Felix MD

Johnson, Stefan MD

Samet, Jonathan D MD

Committee on Practice Parameters and Technical Standards

(ACR Committee responsible for sponsoring the draft through the process)

Caplin, Drew M MD, Chair

Committee on Practice Parameters – Pediatric Imaging

(ACR Committee responsible for sponsoring the draft through the process)

Amodio, John B MD, Chair

Betz, Bradford W MD

Blumfield, Einat MD

Goldman-Yassen, Adam MD

Lala, Shailee V MD

Laufer, Adina MD

Li, Arleen MD

Noda, Sakura MD

Trout, Andrew T MD

Alizai, Hamza MD

Bhimaniya, Sudhir X MBBS, MD

Collard, Michael MD

Lai, Hollie A MD

Lasiacka, Zofia M MD, PhD

Levin, Terry L MD

Maloney, John A MD

Shah, Summit MD

Vatsky, Seth DO

Bulas, Dorothy I MD, Chair, Commission on Pediatric Radiology

Larson, David B MBA, MD, Chair, Commission on Quality and Safety

Rosenkrantz, Andrew MD, Chair, Commission on Body Imaging

Comments Reconciliation Committee

Rodgers, Daniel MD - CSC, Chair

Amodio, John B MD

Caplin, Drew M MD

Garner, Hillary W MD

Larson, David B MBA, MD

Rhodes, Nicholas G MD

Shah, Jordyn DO

Alizai, Hamza MD

Bulas, Dorothy I MD

Fadell, Michael F MD

Jones, Richard H MD

Lin, Dana J MD

Rosenkrantz, Andrew MD

Subhas, Naveen MD, MPH

REFERENCES

1. Pathria MN, Zlatkin M, Sartoris DJ, Scheible W, Resnick D. Ultrasonography of the popliteal fossa and lower extremities. Radiol Clin North Am. 1988 Jan;26(1):77-85.

2. Taylor GA, Perlman EJ, Scherer LR, Gearhart JP, Leventhal BG, Wiley J. Vascularity of tumors in children: evaluation with color Doppler imaging. *AJR Am J Roentgenol.* 1991 Dec;157(6):1267-71.
3. Carra BJ, Bui-Mansfield LT, O'Brien SD, Chen DC. Sonography of musculoskeletal soft-tissue masses: techniques, pearls, and pitfalls. [Review]. *AJR Am J Roentgenol.* 202(6):1281-90, 2014 Jun.
4. Lois JF, Fischer HJ, Deutsch LS, Stambuk EC, Gomes AS. Angiography in soft tissue sarcomas. *Cardiovasc Intervent Radiol.* 1984;7(6):309-16.
5. Chang CY, Gill CM, Joseph Simeone F, et al. Comparison of the diagnostic accuracy of 99 m-Tc-MDP bone scintigraphy and 18 F-FDG PET/CT for the detection of skeletal metastases. *Acta Radiol.* 57(1):58-65, 2016 Jan.
6. Eary JF, O'Sullivan F, Powitan Y, et al. Sarcoma tumor FDG uptake measured by PET and patient outcome: a retrospective analysis. *Eur J Nucl Med Mol Imaging.* 2002 Sep;29(9):1149-54.
7. Ioannidis JP, Lau J. 18F-FDG PET for the diagnosis and grading of soft-tissue sarcoma: a meta-analysis. *J Nucl Med.* 2003 May;44(5):717-24.
8. Lisle JW, Eary JF, O'Sullivan J, Conrad EU. Risk assessment based on FDG-PET imaging in patients with synovial sarcoma. *Clin Orthop Relat Res.* 2009 Jun;467(6):1605-11.
9. Lucas JD, O'Doherty MJ, Wong JC, et al. Evaluation of fluorodeoxyglucose positron emission tomography in the management of soft-tissue sarcomas. *J Bone Joint Surg Br.* 1998 May;80(3):441-7.
10. Tateishi U, Yamaguchi U, Seki K, Terauchi T, Arai Y, Kim EE. Bone and soft-tissue sarcoma: preoperative staging with fluorine 18 fluorodeoxyglucose PET/CT and conventional imaging. *Radiology.* 245(3):839-47, 2007 Dec.
11. Volker T, Denecke T, Steffen I, et al. Positron emission tomography for staging of pediatric sarcoma patients: results of a prospective multicenter trial. *J Clin Oncol.* 25(34):5435-41, 2007 Dec 01.
12. Kasper B, Dietrich S, Dimitrakopoulou-Strauss A, et al. Early prediction of therapy outcome in patients with high-risk soft tissue sarcoma using positron emission tomography. *Onkologie.* 2008 Mar;31(3):107-12.
13. Schuetze SM, Rubin BP, Vernon C, et al. Use of positron emission tomography in localized extremity soft tissue sarcoma treated with neoadjuvant chemotherapy. *Cancer.* 103(2):339-48, 2005 Jan 15.
14. Vernon CB, Eary JF, Rubin BP, Conrad EU, Schuetze S. FDG PET imaging guided re-evaluation of histopathologic response in a patient with high-grade sarcoma. *Skeletal Radiol.* 2003 Mar;32(3):139-42.
15. Ye Z, Zhu J, Tian M, et al. Response of osteogenic sarcoma to neoadjuvant therapy: evaluated by 18F-FDG-PET. *Ann Nucl Med.* 22(6):475-80, 2008 Jul.
16. Johnson GR, Zhuang H, Khan J, Chiang SB, Alavi A. Roles of positron emission tomography with fluorine-18-deoxyglucose in the detection of local recurrent and distant metastatic sarcoma. *Clin Nucl Med.* 2003 Oct;28(10):815-20.
17. Strobel K, Bode B, Lardinois D, Exner U. PET-positive fibrous dysplasia--a potentially misleading incidental finding in a patient with intimal sarcoma of the pulmonary artery. *Skeletal Radiol.* 2007 Jun;36 Suppl 1():S24-8.
18. Oliveira AM, Nascimento AG. Grading in soft tissue tumors: principles and problems. *Skeletal Radiol.* 2001 Oct;30(10):543-59.
19. Stacy GS, Mahal RS, Peabody TD. Staging of bone tumors: a review with illustrative examples. *AJR Am J Roentgenol.* 2006 Apr;186(4):967-76.
20. Ma LD. Magnetic resonance imaging of musculoskeletal tumors: skeletal and soft tissue masses. *Curr Probl Diagn Radiol.* 1999;28(2):29-62.
21. Sundaram M. Magnetic resonance imaging for solitary lesions of bone: when, why, how useful?. *J Orthop Sci.* 1999;4(5):384-96.
22. Aboulafia AJ, Kennon RE, Jelinek JS. Benign bone tumors of childhood. *J Am Acad Orthop Surg.* 1999;7(6):377-88.
23. Kransdorf MJ, Bancroft LW, Peterson JJ, Murphey MD, Foster WC, Temple HT. Imaging of fatty tumors: distinction of lipoma and well-differentiated liposarcoma. *Radiology.* 2002 Jul;224(1):99-104.
24. Hoffer FA. Primary skeletal neoplasms: osteosarcoma and ewing sarcoma. *Top Magn Reson Imaging.* 2002 Aug;13(4):231-9.
25. Nomikos GC, Murphey MD, Kransdorf MJ, Bancroft LW, Peterson JJ. Primary bone tumors of the lower extremities. *Radiol Clin North Am.* 2002 Sep;40(5):971-90.
26. Ritchie DA, Davies AM. MR imaging of tumors and tumor-like lesions of the shoulder girdle. *Magn Reson Imaging Clin N Am.* 2004 Feb;12(1):125-41, vii.
27. Sundaram M, McLeod RA. MR imaging of tumor and tumorlike lesions of bone and soft tissue. *AJR.* 1990; 155(4):817-824.
28. Dalinka MK, Zlatkin MB, Chao P, Kricun ME, Kressel HY. The use of magnetic resonance imaging in the evaluation of bone and soft-tissue tumors. *Radiol Clin North Am.* 1990 Mar;28(2):461-70.
29. Tehranzadeh J, Mnaymneh W, Ghavam C, Morillo G, Murphy BJ. Comparison of CT and MR imaging in

- musculoskeletal neoplasms. *J Comput Assist Tomogr.* 1989;13(3):466-72.
- 30.** Kransdorf MJ, Jelinek JS, Moser RP, et al. Soft-tissue masses: diagnosis using MR imaging. *AJR Am J Roentgenol.* 1989 Sep;153(3):541-7.
- 31.** Sundaram M, McGuire MH. Computed tomography or magnetic resonance for evaluating the solitary tumor or tumor-like lesion of bone?. *Skeletal Radiol.* 1988;17(6):393-401.
- 32.** Hagggar AM, Froelich JW. MR imaging strategies in primary and metastatic malignancy. *Radiol Clin North Am.* 1988 May;26(3):689-96.
- 33.** Sundaram M, McGuire MH, Herbold DR. Magnetic resonance imaging of soft tissue masses: an evaluation of fifty-three histologically proven tumors. *Magn Reson Imaging.* 1988;6(3):237-248.
- 34.** Pettersson H, Gillespy T, Hamlin DJ, et al. Primary musculoskeletal tumors: examination with MR imaging compared with conventional modalities. *Radiology.* 1987 Jul;164(1):237-41.
- 35.** Murphey MD, Gross TM, Rosenthal HG, Neff JR. Magnetic resonance imaging of soft tissue and cystic masses about the knee. *Top Magn Reson Imaging.* 1993;5(4):263-82.
- 36.** Saifuddin A. The accuracy of imaging in the local staging of appendicular osteosarcoma. *Skeletal Radiol.* 2002 Apr;31(4):191-201.
- 37.** Frank JA, Ling A, Patronas NJ, et al. Detection of malignant bone tumors: MR imaging vs scintigraphy. *AJR.* 1990; 155(5):1043-1048.
- 38.** Bloem JL, Taminiau AH, Eulderink F, Hermans J, Pauwels EK. Radiologic staging of primary bone sarcoma: MR imaging, scintigraphy, angiography, and CT correlated with pathologic examination. *Radiology.* 1988; 169(3):805-810.
- 39.** Demas BE, Heelan RT, Lane J, Marcove R, Hajdu S, Brennan MF. Soft-tissue sarcomas of the extremities: comparison of MR and CT in determining the extent of disease. *AJR Am J Roentgenol.* 1988 Mar;150(3):615-20.
- 40.** Panicek DM, Gatsonis C, Rosenthal DI, et al. CT and MR imaging in the local staging of primary malignant musculoskeletal neoplasms: Report of the Radiology Diagnostic Oncology Group. *Radiology.* 1997;202(1):237-246.
- 41.** Mouloupoulos LA, Dimopoulos MA, Vourtsi A, Gouliamos A, Vlahos L. Bone lesions with soft-tissue mass: magnetic resonance imaging diagnosis of lymphomatous involvement of the bone marrow versus multiple myeloma and bone metastases. *Leuk Lymphoma.* 1999 Jun;34(1-2):179-84.
- 42.** Elias DA, White LM, Simpson DJ, et al. Osseous invasion by soft-tissue sarcoma: assessment with MR imaging. *Radiology.* 2003 Oct;229(1):145-52.
- 43.** Feydy A, Anract P, Tomeno B, Chevrot A, Drape JL. Assessment of vascular invasion by musculoskeletal tumors of the limbs: use of contrast-enhanced MR angiography. *Radiology.* 238(2):611-21, 2006 Feb.
- 44.** Enneking WF, Spanier SS, Goodman MA. A system for the surgical staging of musculoskeletal sarcoma. *Clin Orthop Relat Res.* 1980;(153):106-20.
- 45.** Swan JS, Grist TM, Sproat IA, Heiner JP, Wiersma SR, Heisey DM. Musculoskeletal neoplasms: preoperative evaluation with MR angiography. *Radiology.* 1995; 194(2):519-524.
- 46.** Bearcroft PW, Davies AM. Follow-up of musculoskeletal tumours. 2. Metastatic disease. *Eur Radiol.* 1999;9(2):192-200.
- 47.** Verstraete KL, Lang P. Post-therapeutic magnetic resonance imaging of bone tumors. *Top Magn Reson Imaging.* 1999 Aug;10(4):237-46.
- 48.** Dyke JP, Panicek DM, Healey JH, et al. Osteogenic and Ewing sarcomas: estimation of necrotic fraction during induction chemotherapy with dynamic contrast-enhanced MR imaging. *Radiology.* 2003 Jul;228(1):271-8.
- 49.** Baur A, Stähler A, Wendtner CM, et al. MR-imaging changes of musculoskeletal soft-tissue sarcomas associated with neoadjuvant chemotherapy and hyperthermia. *Int J Hyperthermia.* 2003;19(4):391-401.
- 50.** Biondetti PR, Ehman RL. Soft-tissue sarcomas: use of textural patterns in skeletal muscle as a diagnostic feature in postoperative MR imaging. *Radiology.* 1992 Jun;183(3):845-8.
- 51.** Choi H, Varma DG, Fornage BD, Kim EE, Johnston DA. Soft-tissue sarcoma: MR imaging vs sonography for detection of local recurrence after surgery. *AJR Am J Roentgenol.* 1991 Aug;157(2):353-8.
- 52.** Fletcher BD. Response of osteosarcoma and Ewing sarcoma to chemotherapy: imaging evaluation. *AJR Am J Roentgenol.* 1991 Oct;157(4):825-33.
- 53.** Reuther G, Mutschler W. Detection of local recurrent disease in musculoskeletal tumors: magnetic resonance imaging versus computed tomography. *Skeletal Radiol.* 1990;19(2):85-90.
- 54.** Vanel D, Shapeero LG, De Baere T, et al. MR imaging in the follow-up of malignant and aggressive soft-tissue tumors: results of 511 examinations. *Radiology.* 1994; 190(1):263-268.
- 55.** Varma DG, Jackson EF, Pollock RE, Benjamin RS. Soft-tissue sarcoma of the extremities. MR appearance of post-treatment changes and local recurrences. *Magn Reson Imaging Clin N Am.* 1995 Nov;3(4):695-712.
- 56.** van der Woude HJ, Bloem JL, Hogendoorn PC. Preoperative evaluation and monitoring chemotherapy in

- patients with high-grade osteogenic and Ewing's sarcoma: review of current imaging modalities. *Skeletal Radiol.* 1998 Feb;27(2):57-71.
57. Roebuck DJ. Skeletal complications in pediatric oncology patients. *Radiographics.* 1999;19(4):873-85.
58. Bush CH. The magnetic resonance imaging of musculoskeletal hemorrhage. *Skeletal Radiol.* 2000 Jan;29(1):1-9.
59. Struk DW, Munk PL, Lee MJ, Ho SG, Worsley DF. Imaging of soft tissue infections. *Radiol Clin North Am.* 2001 Mar;39(2):277-303.
60. Kothari NA, Pelchovitz DJ, Meyer JS. Imaging of musculoskeletal infections. *Radiol Clin North Am.* 2001 Jul;39(4):653-71.
61. Panicek DM, Casper ES, Brennan MF, Hajdu SI, Heelan RT. Hemorrhage simulating tumor growth in malignant fibrous histiocytoma at MR imaging. *Radiology.* 1991 Nov;181(2):398-400.
62. Fritz RC, Helms CA, Steinbach LS, Genant HK. Suprascapular nerve entrapment: evaluation with MR imaging. *Radiology.* 1992 Feb;182(2):437-44.
63. Unger EC, Glazer HS, Lee JK, Ling D. MRI of extracranial hematomas: preliminary observations. *AJR Am J Roentgenol.* 1986 Feb;146(2):403-7.
64. Rubin DA, Kneeland JB. MR imaging of the musculoskeletal system: technical considerations for enhancing image quality and diagnostic yield. *AJR Am J Roentgenol.* 1994 Nov;163(5):1155-63.
65. Lenchik L, Dovgan DJ, Kier R. CT of the iliopsoas compartment: value in differentiating tumor, abscess, and hematoma. *AJR.* 1994;162(1):83-86.
66. Vanel D, Lacombe MJ, Couanet D, Kalifa C, Spielmann M, Genin J. Musculoskeletal tumors: follow-up with MR imaging after treatment with surgery and radiation therapy. *Radiology.* 1987 Jul;164(1):243-5.
67. American College of Radiology. ACR Practice Parameter for Performing and Interpreting Magnetic Resonance Imaging (MRI). Available at: <https://gravitas.acr.org/PPTS/GetDocumentView?docId=146+&releaseId=2>
68. American College of Radiology. ACR-SPR Practice Parameter for the use of Intravascular Contrast Media. Available at <https://gravitas.acr.org/PPTS/GetDocumentView?docId=142+&releaseId=2>
69. American College of Radiology. ACR Committee on Drugs and Contrast Media. Manual on Contrast Media. Available at: <https://www.acr.org/Clinical-Resources/Clinical-Tools-and-Reference/Contrast-Manual>.
70. Edwards AD, Arthurs OJ. Paediatric MRI under sedation: is it necessary? What is the evidence for the alternatives?. *Pediatr Radiol.* 2011 Nov;41(11):1353-64.
71. Pettersson H, Slone RM, Spanier S, Gillespy T, Fitzsimmons JR, Scott KN. Musculoskeletal tumors: T1 and T2 relaxation times. *Radiology.* 1988 Jun;167(3):783-5.
72. Kneeland JB, Shimakawa A, Wehrli FW. Effect of intersection spacing on MR image contrast and study time. *Radiology.* 1986 Mar;158(3):819-22.
73. Romaneehsen B, Oberholzer K, Müller LP, Kreitner KF. Rapid musculoskeletal magnetic resonance imaging using integrated parallel acquisition techniques (IPAT)--initial experiences. *Rofo.* 2003 Sep;175(9):1193-7.
74. Lustig M, Donoho D, Pauly JM. Sparse MRI: The application of compressed sensing for rapid MR imaging. *Magn Reson Med.* 2007 Dec;58(6):1182-95.
75. Jaramillo D, Laor T. Pediatric musculoskeletal MRI: basic principles to optimize success. *Pediatr Radiol.* 2008 Apr;38(4):379-91.
76. Erickson SJ. High-resolution imaging of the musculoskeletal system. *Radiology.* 1997 Dec;205(3):593-618.
77. Mirowitz SA. Fast scanning and fat-suppression MR imaging of musculoskeletal disorders. *AJR Am J Roentgenol.* 1993;161(6):1147-1157.
78. Ziedses des Plantes BG, Koster K. Comparison of low-field versus high-field MR imaging. *Eur J Radiol.* 1995 Jul;20(2):156-8.
79. Kransdorf MJ, Murphey, MD. *Imaging of Soft Tissue Tumors.* 2nd ed. Philadelphia, Pa.: Lippincott Williams & Wilkins; 2006.
80. Delfaut EM, Beltran J, Johnson G, Rousseau J, Marchandise X, Cotten A. Fat suppression in MR imaging: techniques and pitfalls. *Radiographics.* 1999;19(2):373-82.
81. Rybicki FJ, Chung T, Reid J, Jaramillo D, Mulkern RV, Ma J. Fast three-point dixon MR imaging using low-resolution images for phase correction: a comparison with chemical shift selective fat suppression for pediatric musculoskeletal imaging. *AJR Am J Roentgenol.* 2001 Nov;177(5):1019-23.
82. Shuman WP, Baron RL, Peters MJ, Tazioli PK. Comparison of STIR and spin-echo MR imaging at 1.5 T in 90 lesions of the chest, liver, and pelvis. *AJR Am J Roentgenol.* 1989 Apr;152(4):853-9.
83. Zajick DC, Jr., Morrison WB, Schweitzer ME, Parellada JA, Carrino JA. Benign and malignant processes: normal values and differentiation with chemical shift MR imaging in vertebral marrow. *Radiology.* 2005;237(2):590-596.
84. Rosen BR, Fleming DM, Kushner DC, et al. Hematologic bone marrow disorders: quantitative chemical shift MR imaging. *Radiology.* 1988 Dec;169(3):799-804.

- 85.** Oki N, Ikebe Y, Koike H, Ideguchi R, Niino D, Uetani M. FDG-PET vs. chemical shift MR imaging in differentiating intertrabecular metastasis from hematopoietic bone marrow hyperplasia. *Jpn J Radiol.* 2021 Nov;39(11):1077-1085.
- 86.** van Rijswijk CS, Kunz P, Hogendoorn PC, Taminiau AH, Doornbos J, Bloem JL. Diffusion-weighted MRI in the characterization of soft-tissue tumors. *J Magn Reson Imaging.* 2002 Mar;15(3):302-7.
- 87.** Oka K, Yakushiji T, Sato H, et al. Usefulness of diffusion-weighted imaging for differentiating between desmoid tumors and malignant soft tissue tumors. *J Magn Reson Imaging.* 33(1):189-93, 2011 Jan.
- 88.** Neubauer H, Evangelista L, Hassold N, et al. Diffusion-weighted MRI for detection and differentiation of musculoskeletal tumorous and tumor-like lesions in pediatric patients. *World J Pediatr.* 8(4):342-9, 2012 Nov.
- 89.** Ahlawat S, Khandheria P, Subhawong TK, Fayad LM. Differentiation of benign and malignant skeletal lesions with quantitative diffusion weighted MRI at 3T. *Eur J Radiol.* 2015 Jun;84(6):S0720-048X(15)00111-4.
- 90.** Gielen JL, De Schepper AM, Parizel PM, Wang XL, Vanhoenacker F. Additional value of magnetic resonance with spin echo T1-weighted imaging with fat suppression in characterization of soft tissue tumors. *J Comput Assist Tomogr.* 2003;27(3):434-41.
- 91.** Haacke EM, Lenz GW. Improving MR image quality in the presence of motion by using rephasing gradients. *AJR Am J Roentgenol.* 1987 Jun;148(6):1251-8.
- 92.** Lavdas E, Mavroidis P, Kostopoulos S, et al. Reduction of motion, truncation and flow artifacts using BLADE sequences in cervical spine MR imaging. *Magn Reson Imaging.* 2015 Feb;33(2):S0730-725X(14)00339-7.
- 93.** Verstraete KL, Lang P. Bone and soft tissue tumors: the role of contrast agents for MR imaging. *Eur J Radiol.* 2000 Jun;34(3):229-46.
- 94.** Shapeero LG, Vanel D, Verstraete KL, Bloem JL. Dynamic Contrast-Enhanced MR Imaging for Soft Tissue Sarcomas. *Semin Musculoskelet Radiol.* 1999;3(2):101-114.
- 95.** Mirowitz SA, Totty WG, Lee JK. Characterization of musculoskeletal masses using dynamic Gd-DTPA enhanced spin-echo MRI. *J Comput Assist Tomogr.* 1992;16(1):120-5.
- 96.** Erlemann R, Reiser MF, Peters PE, et al. Musculoskeletal neoplasms: static and dynamic Gd-DTPA--enhanced MR imaging. *Radiology.* 1989;171(3):767-773.
- 97.** Pettersson H, Eliasson J, Egund N, et al. Gadolinium-DTPA enhancement of soft tissue tumors in magnetic resonance imaging--preliminary clinical experience in five patients. *Skeletal Radiol.* 1988;17(5):319-23.
- 98.** Benedikt RA, Jelinek JS, Kransdorf MJ, Moser RP, Berrey BH. MR imaging of soft-tissue masses: role of gadopentetate dimeglumine. *J Magn Reson Imaging.* 1994;4(3):485-90.
- 99.** Kransdorf MJ, Murphey MD. The use of gadolinium in the MR evaluation of soft tissue tumors. *Semin Ultrasound CT MR* 1997;18:251-68.
- 100.** Hanna SL, Langston JW, Gronemeyer SA, Fletcher BD. Subtraction technique for contrast-enhanced MR images of musculoskeletal tumors. *Magn Reson Imaging.* 1990;8(3):213-5.
- 101.** Tuncbilek N, Karakas HM, Okten OO. Dynamic contrast enhanced MRI in the differential diagnosis of soft tissue tumors. *Eur J Radiol.* 53(3):500-5, 2005 Mar.
- 102.** van der Woude HJ, Verstraete KL, Hogendoorn PC, Taminiau AH, Hermans J, Bloem JL. Musculoskeletal tumors: does fast dynamic contrast-enhanced subtraction MR imaging contribute to the characterization? *Radiology.* 1998; 208(3):821-828.
- 103.** van Rijswijk CS, Geirnaerd MJ, Hogendoorn PC, et al. Soft-tissue tumors: value of static and dynamic gadopentetate dimeglumine-enhanced MR imaging in prediction of malignancy. *Radiology.* 2004; 233(2):493-502.
- 104.** Shapeero LG, Vanel D, Verstraete KL, Bloem JL. Fast magnetic resonance imaging with contrast for soft tissue sarcoma viability. *Clin Orthop Relat Res.* 2002 Apr;(397):212-27.
- 105.** Fletcher BD, Hanna SL, Fairclough DL, Gronemeyer SA. Pediatric musculoskeletal tumors: use of dynamic, contrast-enhanced MR imaging to monitor response to chemotherapy. *Radiology.* 1992 Jul;184(1):243-8.
- 106.** Verstraete KL, Dierick A, De Deene Y, et al. First-pass images of musculoskeletal lesions: a new and useful diagnostic application of dynamic contrast-enhanced MRI. *Magn Reson Imaging.* 1994;12(5):687-702.
- 107.** Liu PT, Chivers FS, Roberts CC, Schultz CJ, Beauchamp CP. Imaging of osteoid osteoma with dynamic gadolinium-enhanced MR imaging. *Radiology.* 2003 Jun;227(3):691-700.
- 108.** Stanborough R, Demertzis JL, Wessell DE, et al. ACR Appropriateness Criteria® Malignant or Aggressive Primary Musculoskeletal Tumor-Staging and Surveillance: 2022 Update. *J Am Coll Radiol* 2022;19:S374-S89.
- 109.** Millis K, Weybright P, Campbell N, et al. Classification of human liposarcoma and lipoma using ex vivo proton NMR spectroscopy. *Magn Reson Med.* 1999 Feb;41(2):257-67.
- 110.** Kettelhack C, Wickede Mv, Vogl T, Schneider U, Hohenberger P. 31Phosphorus-magnetic resonance spectroscopy to assess histologic tumor response noninvasively after isolated limb perfusion for soft tissue tumors. *Cancer.* 2002 Mar 01;94(5):1557-64.

- 111.** Zakian KL, Shukla-Dave A, Meyers P, et al. Identification of prognostic markers in bone sarcomas using proton-decoupled phosphorus magnetic resonance spectroscopy. *Cancer Res.* 2003 Dec 15;63(24):9042-7.
- 112.** Ballinger JR, Kang H, Sweeney CA, Scott JD, Croker BP, Scott KN. P-31 changes as a measure of therapy response in resistant and sensitive osteosarcomas implanted into nude mice. *Magn Reson Imaging.* 1995;13(6):877-83.
- 113.** Möller HE, Vermathen P, Rummeny E, et al. In vivo ³¹P NMR spectroscopy of human musculoskeletal tumors as a measure of response to chemotherapy. *NMR Biomed.* 1996 Dec;9(8):347-58.
- 114.** Singer S, Millis K, Souza K, Fletcher C. Correlation of lipid content and composition with liposarcoma histology and grade. *Ann Surg Oncol.* 1997;4(7):557-63.
- 115.** Oya N, Aoki J, Shinozaki T, Watanabe H, Takagishi K, Endo K. Preliminary study of proton magnetic resonance spectroscopy in bone and soft tissue tumors: an unassigned signal at 2.0-2.1 ppm may be a possible indicator of malignant neuroectodermal tumor. *Radiat Med.* 2000;18(3):193-8.
- 116.** Wang CK, Li CW, Hsieh TJ, Chien SH, Liu GC, Tsai KB. Characterization of bone and soft-tissue tumors with in vivo ¹H MR spectroscopy: initial results. *Radiology.* 232(2):599-605, 2004 Aug.
- 117.** Fayad LM, Bluemke DA, McCarthy EF, Weber KL, Barker PB, Jacobs MA. Musculoskeletal tumors: use of proton MR spectroscopic imaging for characterization. *J Magn Reson Imaging.* 2006 Jan;23(1):23-8.
- 118.** Fayad LM, Barker PB, Jacobs MA, et al. Characterization of musculoskeletal lesions on 3-T proton MR spectroscopy. *AJR Am J Roentgenol.* 2007 Jun;188(6):1513-20.
- 119.** Fayad LM, Barker PB, Bluemke DA. Molecular characterization of musculoskeletal tumors by proton MR spectroscopy. *Semin Musculoskelet Radiol.* 2007 Sep;11(3):240-5.
- 120.** Schick F, Duda SH, Lutz O, Claussen CD. Lipids in bone tumors assessed by magnetic resonance: chemical shift imaging and proton spectroscopy in vivo. *Anticancer Res.* 1996;16(3B):1569-74.
- 121.** Sah PL, Sharma R, Kandpal H, et al. In vivo proton spectroscopy of giant cell tumor of the bone. *AJR Am J Roentgenol.* 2008 Feb;190(2):W133-9.
- 122.** Goo HW, Yang DH, Ra YS, et al. Whole-body MRI of Langerhans cell histiocytosis: comparison with radiography and bone scintigraphy. *Pediatr Radiol.* 2006 Oct;36(10):1019-31.
- 123.** Baur-Melnyk A, Buhmann S, Becker C, et al. Whole-body MRI versus whole-body MDCT for staging of multiple myeloma. *AJR Am J Roentgenol.* 2008 Apr;190(4):1097-104.
- 124.** Dinter DJ, Neff WK, Klaus J, et al. Comparison of whole-body MR imaging and conventional X-ray examination in patients with multiple myeloma and implications for therapy. *Ann Hematol.* 88(5):457-64, 2009 May.
- 125.** Krohmer S, Sorge I, Krause A, et al. Whole-body MRI for primary evaluation of malignant disease in children. *Eur J Radiol.* 2010 Apr;74(1):256-61.
- 126.** Shortt CP, Gleeson TG, Breen KA, et al. Whole-Body MRI versus PET in assessment of multiple myeloma disease activity. *AJR Am J Roentgenol.* 2009 Apr;192(4):980-6.
- 127.** Messiou C, Hillengass J, Delorme S, et al. Guidelines for Acquisition, Interpretation, and Reporting of Whole-Body MRI in Myeloma: Myeloma Response Assessment and Diagnosis System (MY-RADS). *Radiology.* 2019 Apr;291(1):5-13.
- 128.** Peh WC, Chan JH. Artifacts in musculoskeletal magnetic resonance imaging: identification and correction. *Skeletal Radiol.* 2001 Apr;30(4):179-91.
- 129.** Ma LD, Frassica FJ, Scott WW, Fishman EK, Zerbouni EA. Differentiation of benign and malignant musculoskeletal tumors: potential pitfalls with MR imaging. *Radiographics.* 1995 Mar;15(2):349-66.
- 130.** American College of Radiology. ACR Practice Parameter for Communication of Diagnostic Imaging Findings. Available at <https://gravitas.acr.org/PPTS/GetDocumentView?docId=74+&releaseId=2>
- 131.** Chhabra A, Gupta A, Thakur U, et al. Osseous Tumor Reporting and Data System-Multireader Validation Study. *J Comput Assist Tomogr.* 45(4):571-585, 2021 Jul-Aug 01.
- 132.** Guirguis M, Gupta A, Thakur U, et al. Osseous-Tissue Tumor Reporting and Data System With Diffusion-Weighted Imaging of Bone Tumors-An Interreader Analysis and Whether It Adds Incremental Value on Tumor Grading Over Conventional Magnetic Resonance Imaging. *J Comput Assist Tomogr.* ;47(2):255-263.
- 133.** Caracciolo JT, Ali S, Chang CY, et al. Bone Tumor Risk Stratification and Management System: A Consensus Guideline from the ACR Bone Reporting and Data System Committee. *J Am Coll Radiol.* 2023 Oct;20(10):S1546-1440(23)00595-1.
- 134.** Ghasemi A, Ahlawat S. Bone Reporting and Data System (Bone-RADS) and Other Proposed Practice Guidelines for Reporting Bone Tumors. *Rofo.* 2024 Nov;196(11):1134-1142.
- 135.** Park C, Azhideh A, Pooyan A, et al. Diagnostic performance and inter-reader reliability of bone reporting and data system (Bone-RADS) on computed tomography. *Skeletal Radiol.* 2025 Feb;54(2):209-217.
- 136.** American College of Radiology. ACR Committee on MR Safety. 2026 ACR Manual on MR Safety. Available at:

<https://edge.sitecorecloud.io/americancoldf5f-acrorgf92a-productioncb02-Revision-2025/Resolution-5>
<https://www.aacr.org/clinical/radiology-safety/manual-on-mr-safety.pdf>

137. Kanal E, Barkovich AJ, Bell C, et al. ACR guidance document for safe MR practices: 2007. AJR. 2007; 188(6):1447-1474.

138. Shellock FG. Reference Manual for Magnetic Resonance Safety, Implants, and Devices. Playa Del Rey, CA Biomedical Research Publishing Group; 2013.

139. Shellock FG, Crues JV. MR procedures: biologic effects, safety, and patient care. Radiology. 2004 Sep;232(3):635-52.

140. American College of Radiology. ACR–AAPM Technical Standard for Diagnostic Medical Physics Performance Monitoring of Magnetic Resonance (MR) Imaging Equipment. Available at <https://gravitas.acr.org/PPTS/GetDocumentView?docId=57+&releaseId=2>

141. Shellock FG. Magnetic Resonance Procedures: Health Effects and Safety. Boca Raton, Fla.: CRC Press; 2001.

142. Sawyer-Glover AM, Shellock FG. Pre-MRI procedure screening: recommendations and safety considerations for biomedical implants and devices. J Magn Reson Imaging. 2000 Jul;12(1):92-106.

*Parameters and standards are published annually with an effective date of October 1 in the year in which amended, revised, or approved by the ACR Council. For parameters and standards published before 1999, the effective date was January 1 following the year in which the parameter or standard was amended, revised, or approved by the ACR Council.

Development Chronology for this Practice Parameter

2005 (Resolution 8)

Amended 2006 (Resolution 35)

Revised 2010 (Resolution 18)

Amended 2014 (Resolution 39)

Revised 2015 (Resolution 5)

Revised 2020 (Resolution 30)

Amended 2023 (Resolution 2c)

Revised 2025 (Resolution 5)