Whole-Body [18F]-FDG-PET/MRI for Oncology: A Consensus Recommendation*

Konsensempfehlungen zur Anwendung der Ganzkörper [18F]-FDG-PET/MRT in der onkologischen Bildgebung

Authors
Lale Umutlu1, Thomas Beyer2, Johannes Stefan Grueneisen1, Christoph Rischpler3, Harald H. Quick4, Patrick Veit-Haibach5, Matthias Eiber6, Sandra Purz7, Gerald Antoch8, Sergios Gatidis9, Konstantin Nikolaou9, Jürgen F. Schaefer9, Ivo Rausch2, Ken Herrmann3

Vorstand der Interdisziplinären AG für Hybride Bildgebung in alphabetischer Reihenfolge:
K. Herrmann3, B. J. Krause10, S. O. Schoenberg11, L. Umutlu1

Vorstand der Deutschen Röntgengesellschaft (DRG) und der Deutschen Gesellschaft für Nuklearmedizin (DGN) in alphabetischer Reihenfolge:

Affiliations
1 Department of Diagnostic and Interventional Radiology and Neuroradiology, University-Hospital Essen, Germany
2 QIMP Group, Centre for Medical Imaging and Biomedical Engineering, Medical University of Vienna, Austria
3 Department of Nuclear Medicine, University-Hospital Essen, Germany
4 High-Field- and Hybrid-MR-Imaging, University-Hospital Essen, Germany
5 Joint Department of Medical Imaging, University of Toronto, Canada
6 Department of Nuclear Medicine, Klinikum rechts der Isar, Technical University of Munich, Germany
7 Department of Nuclear Medicine, University of Leipzig, Germany
8 Department of Diagnostic and Interventional Radiology, University Düsseldorf, Medical Faculty, Düsseldorf, Germany
9 Department of Diagnostic and Interventional Radiology, University-Hospital Tübingen, Germany
10 Department of Nuclear Medicine, University Medical Center Rostock, Germany
11 Department of Clinical Radiology and Nuclear Medicine, University Medical Center Mannheim, Germany
12 Deutsche Röntgengesellschaft, Berlin, Germany
13 Division of Nuclear Medicine, Department of Biomedical Imaging and Image-guided Therapy, Medical University Vienna, Austria
14 Department of Nuclear Medicine, University Hospital Marburg, Germany
15 Department of Radiology, Klinikum Ingolstadt, Germany

Für die DRG
Prof. Dr. Stefan Schönberg, Präsident
Prof. Dr. Dierk Vorwerk, stellvertretender Präsident
Prof. Dr. Gerald Antoch, President-elect
Dr. Frank Anton, Schatzmeister
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Prof. Dr. Markus Luster, Marburg, stellvertretender Präsident
Prof. Dr. Marcus Hacker, AKH Wien, Schriftführer

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Correspondence
Prof. Dr. Lale Umutlu
Institut für Diagnostische und Interventionelle Radiologie und Neuroradiologie, Universitätsklinik Essen, Hufelandstr. 55, 45147 Essen, Germany
Tel.: ++49/201/7 23 15 01
Fax: ++49/201/7 23 15 48
lale.umutlu@uk-essen.de

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Introduction

The aim of this consensus recommendation is to provide guidance to healthcare experts and physicians regarding clinical indications, execution and interpretation of [18F]-Fluorodeoxyglucose (FDG) Positron emission tomography/magnetic resonance imaging examinations ([18F]-FDG PET/MRI) for whole-body staging in oncology [1].

PET is a noninvasive imaging technique that provides quantitative information on 3-dimensional distributions of radioactively labelled biomolecules (tracer) in tissues. [18F]-FDG is a tracer composed of radiolabeled glucose, which is the most common tracer for oncology imaging indications [2]. For the majority of tumors, malignant cells display activated glycolytic pathways resulting in increased glucose utilization via upregulation of glucose transporter expression and hexokinase activity [3, 4]. Thus, more of the glucose analog, [18F]-FDG, is taken up in metabolically active cancerous cells than in surrounding healthy tissues. Therefore, [18F]-FDG-PET has been demonstrated to be a sensitive method and well-established imaging modality for detection, re-/staging as well as for the evaluation of therapy response of solid tumors [5, 6].

Magnetic resonance imaging (MRI) is a noninvasive technique that provides anatomical 3D visualization of tissues with high spatial resolution based on relative differences in resonance frequencies of spins following external excitation [7]. In addition, MRI employs multiple imaging sequences and associated soft-tissue contrasts that yield noninvasive insight into functional and cellular aspects of tissues and organs [8]. The magnetic field-based excitation and resonance measurement method sets MRI apart from computed tomography (CT), which is a pure transmission method based on the attenuation of ionizing radiation. In contrast to CT-based transmission imaging, MRI does not employ ionizing radiation. Thus, the exposure of patients undergoing PET/MRI to ionizing radiation originates from the PET portion only and therefore is significantly lower compared to PET/CT [9].

While attenuation correction is a well-established aspect of PET/CT imaging, it was a methodologically challenging task to overcome in integrated PET/MRI (please also refer to the section "Attenuation correction"). Thus, the introduction of MR-compatible PET detector systems provided the basis for the hardware integration of PET and MRI components into a single, integrated system [10, 11]. Prior work of developers of small-animal imaging systems [12] has helped to replace the photomultipliers in PET detectors with semiconductor-based diodes that are capable of am-
In the clinical routine, PET/MRI examinations do not include a transmission measurement, and, therefore, alternative means have to be provided to derive attenuation correction factors (ACF) for the PET data in order to quantify the molecular signals [24].

Artifacts comprise all types of PET and MR image distortions that include visually perceived deviations from typical representations of anatomy and function that may or may not cause a quantitative bias (e.g., lesion size, tracer concentration, etc.). These distortions are likely not to arise from a disease process but from methodological pitfalls or system malfunctions [25].
Beyond safety concerns, implants may cause artifacts, large-volume signal voids and geometric distortions in MR imaging. This may hamper image interpretation.

MRI safety

The following points relevant to MRI safety in PET/MRI are to be considered:

- Patients have to discard all removable metal objects (e.g., rings, piercings, medication pumps, etc.) before entering the PET/MRI examination room. In case of implanted ferromagnetic devices (e.g., pacemakers, ICD, LVAD, event recorders, stents, metal plates from orthopedic interventions, etc.) or metal splinters/shrapnel, PET/MRI examinations should only be performed after consultation with a radiologist/MR physicist and in accordance with MR safety guidelines [28] (please also refer to the section “MRI safety”).

- Tracer ([18F]-FDG) application
  - Blood glucose levels should be determined prior to [18F]-FDG injection. In case of hyperglycemia, [18F]-FDG uptake into the tumor may be decreased. Hence, in case the glucose level is above 150 – 200 mg/dl, the examination should either be rescheduled or appropriate insulin medication (including monitoring of blood glucose levels to ensure appropriate levels) should be considered [6].
  - Patients should rest comfortably in a reclining chair or on a bed. Patients should not speak or engage in physical activity during the uptake time of the tracer following tracer injection.
  - Please refer to the guidelines in Nuclear Medical Imaging (AWMF Guidelines Register 031/030) regarding general precautions for the application of [18F]-FDG [29].
  - Prior to the imaging examination, patients should be asked to void.

Attenuation correction

In contrast to CT-based attenuation correction (AC) in PET/CT [31], the attenuation properties of tissue cannot be derived directly from complementary MR images. Therefore, different concepts of MR-based attenuation correction have been introduced [24]. The most commonly applied method is based on a two-point Dixon technique, which facilitates a 4-compartment-model attenuation map (μ-map) to identify air, lung tissue, fat, and soft tissue [32 – 34]. Based on this segmentation of MR images into distinct tissue classes, the individual compartments are assigned a predefined linear attenuation coefficient (LAC) for the corresponding tissue [33, 35, 36].

A number of challenges including the systematic underestimation of PET quantification related to standard MR-based attenuation correction have been reported, the most prominent being the lack of consideration of bone tissue and the occurrence of truncation artifacts [36, 37] (for further information please refer to the section “Artifacts”). Different compensation approaches for brain and whole-body imaging have been proposed to account for the misclassification of bone tissue as soft tissue [38, 39]. Promising results for whole-body imaging were shown when utilizing a CT-based 3-dimensional bone-model of major bones as an adjunct to MR-based AC data [34, 40 – 42].

Artifacts

Following the introduction of integrated PET/MRI systems, a number of artifacts have been reported that are related to PET-only, MRI-only or integrated PET/MRI acquisitions. A selection of the most common artifacts and potential solutions is discussed in the following paragraph [25].

The most evident artifacts have been shown to be related to MR-based attenuation correction, causing a systematic underestimation of PET quantification when compared to PET/CT [43, 44]. Apart from the misclassification of bone tissue (please refer to the section “Attenuation correction”), truncation artifacts are a major concern in integrated PET/MRI. Due to the limited transaxial and lateral field of view (FOV) in MR imaging to a spherical diameter of about 50 cm, structures beyond these dimensions show geometric distortions and signal voids, resulting in truncation artifacts alongside the patient arms and incorrect PET quantification [25, 45]. In addition to the PET-based MLAA algorithm (maximum likelihood estimation of attenuation and activity) deriving the patient arms outer body contours from PET data [46, 47], a novel purely MR-based truncation correction method was introduced by Blumhagen et al. [48, 49]. This method, also referred to as HUGE (80 homogenization using gradient enhancement), enlarges the lateral FOV in MR imaging beyond the conventional 50 cm diameter, effectively eliminating truncation artifacts along the patient arms in MR-based attenuation correction [48, 50].

Involuntary patient and organ motion causing a misalignment of emission and attenuation data is a known challenge in PET/CT imaging that may be further enhanced in PET/MR imaging due to prolonged examination times. Unlike in PET/CT and owing to simultaneous PET and MR data acquisition, PET/MRI has potential for MR-based motion correction of PET data. Different methods for motion correction have been proposed to account e.g. for...
respiratory motion artifacts including real-time MR imaging and 4D MR data of breathing motion or free-breathing MR imaging to retrospectively perform motion correction [51 – 53].

The following points relevant to MR-based attenuation correction and artifacts in PET/MRI are to be considered:

- In PET/MRI, AC is based on MR imaging. Thus, artifacts in MR-AC have a direct effect on PET quantification. Consequently, MR-based AC needs to be accurate and free of artifacts to provide precise PET quantification. MR-AC images shall be routinely checked for artifacts, consistency and plausibility during PET/MR image reading. Typical artifacts are mis-segmentation of air/soft tissue/fat/bone and metal artifacts due to dental prostheses and due to metallic implants such as stents and surgical clips, etc. Artifacts may be displayed as signal voids, exceeding the true dimensions of metal inclusions. Thus, artifacts are mostly easily detectable in MR-AC, indicating regions of potentially inaccurate PET quantification [45, 54].

- While new features for the improvement of MR-AC are constantly developed and implemented into the commercial software of available PET/MRI systems, including high-resolution Dixon AC, ultrashort echo time (UTE), zero TE (ZTE) sequences and/or bone models for bone detection in PET/MRI attenuation correction [17, 34, 40, 41], users need to remain attentive to MR-AC related limitations and artifacts in SUV quantification.

- Truncation artifacts along patient arms in MR-AC may affect PET quantification. The standard method on all available PET/MRI systems for truncation correction is the PET-based MLAA algorithm [46]. A more recent method for improved MR-based truncation correction in MR-AC is HUGE [41, 48, 50].

- Only radiofrequency (RF) coils that are labelled for combined PET/MRI use should be used. Using standard RF coils that are labelled for MR-only use will not be considered in PET/MRI AC and may, thus, lead to inaccurate PET quantification and artifacts in PET [32, 55].

**Quality control**

Quality control of PET tracers is governed by the “Draft Guidelines for Radiopharmacy” [56]. Quality control and application recommendations for MR contrast agents are addressed in the guidelines of the European Society of Urogenital Radiology [26]. Quality control procedures for the PET and MRI subsystems should be set up in accordance with the published guidelines [57, 58] but shall at least follow the vendor’s recommendations. In addition, proper cross-calibration of the PET system with the respective dose calibrator has to be ensured. In routine operation, daily quality control scans (using a dedicated phantom) shall be conducted prior to patient scans to ensure correct PET acquisition and quantification.

**Imaging workflows**

Imaging workflows may vary with the clinical indication. Similar to PET/CT imaging in oncology, PET/MRI can be performed in whole-body mode, meaning that patients are scanned over multiple, consecutive bed positions to cover larger co-axial imaging ranges. Given the extensive variability of MR imaging protocols and the choice of MR sequences, whole-body PET/MRI examinations have been shown to take longer than PET/CT examinations of the same co-axial imaging range. Therefore, the need for optimized and standardized PET/MR imaging workflows has become widely recognized. Over the past years, a number of proposals have been published [59, 60]. This document sets out to describe suitable imaging conditions and protocols for whole-body [18F]-FDG-PET/MRI of oncology patients. Of note, specific protocols and MR sequences are subject to change depending on the user, vendor and indication for the examination.

For reasons of simplification and conformity to PET/CT imaging, all workflows mentioned below apply to whole-body coverage from skull-base to mid-thighs. This coverage is usually achieved within four to five bed positions (BP) depending on the patient height. Accordingly, a combination of dedicated (attenuation-corrected) radiofrequency (RF) head and neck coils and a varying number of phased-array body surface RF coils are utilized as needed [32]. Imaging is commonly performed in a supine position starting from mid-thigh to skull-base to ensure minimal impairment of lesions in the vicinity of the bladder due to increased [18F]-FDG activity in the bladder.

In a first step MRI localizers are acquired to define the axial range for the examination. Pre-scanning of the shimming and adjustment of the magnetic field are followed by the attenuation correction (AC) sequence for every BP (for detailed information regarding MR-based AC please refer to section “Attenuation correction”).

**Workflow 1: Ultra-fast PET/MRI**

This workflow is based on a 2-min/BP acquisition that facilitates ultra-fast “PET/CT-like” whole-body staging within a total time of just under 20 min [61]. The reasoning for this specific algorithm is to facilitate ultra-fast whole-body staging, e.g., in patients with low compliance (e.g. elderly, pediatric) or as a whole-body coverage adjunct to local dedicated imaging (e.g., local dedicated tumor staging in head and neck cancer or soft tissue sarcoma + whole-body ultra-fast).

Indications for this ultra-fast workflow include whole-body staging, e.g., for lymphoma or staging and exclusion of relapse of tumors.

Potential sequences to be obtained within the 2-min PET include:

1. Fast T2-weighted spin echo sequence (e.g. HASTE) and 2) non-enhanced fast fat-saturated T1-weighted gradient echo sequence (e.g. VIBE). Contrast media injection and acquisition of post-contrast fast T1-weighted fat-saturated imaging may be performed subsequent to the non-enhanced sequences. In case of primary tumors (e.g. malignant melanoma, neuroendocrine tumors) known to cause hyperarterIALIZED metastases of the parenchymatous organs, additional dynamic contrast-enhanced imaging of the upper abdomen (e.g. VIBE) can be added. The combination of the sequences above enables the combined assessment of T2, non-enhanced and contrast-enhanced features of potential lesions (Fig. 1).

**Workflow 2: Fast PET/MRI**

This workflow is based on a 4-min/bed acquisition that comprises diffusion-weighted imaging (DWI) in addition to the above-mentioned sequences listed in the ultra-fast algorithm (Fig. 2) [62, 63]. The additional diffusion-weighted sequence offers comple-
mentary tissue information to PET and may be applied as a “search” sequence as it is considered useful particularly in the detection of small lesions, e.g., liver metastases that may be too small to be picked up by PET. Together with potential post-contrast T1w gradient echo sequences, this “fast PET/MRI” algorithm should require less than 30 min depending on the total amount of BP and duration of shimming, etc. (Fig. 3).

**Workflow 3: Dedicated local and whole-body PET/MRI**

This workflow comprises dedicated local PET/MRI of the tumor region (e.g., head and neck, cervical cancer, soft tissue sarcoma of the limbs) and fast sequences for whole-body coverage. The aim of this workflow is to facilitate a dedicated workup of the primary cancer and whole-body staging in one examination. The MR protocol for the dedicated local PET/MRI scan should be selected in accordance with the primary tumor and guideline recommendations (e.g., cervical cancer [64]). Whole-body imaging can be performed utilizing the above-named ultra-fast or fast algorithm depending on patient compliance, potential benefit derived from DWI and desired length of the examination (Fig. 4, 5).

**Reading and reporting**

The following recommendations on reading and reporting are intended to serve as assistance to novice PET/MRI readers and help standardization. High quality reading and reporting of PET/MRI examinations is based on expert knowledge of PET and MRI imaging...
Hence, PET/MRI reading should be performed jointly by a radiologist and a nuclear medicine physician or by adequately trained dual-certified physicians (nuclear medicine and radiology). It is important to evaluate the “raw” MRI and PET data as well as fused imaging. In contrast to rather distinct differences in the required expertise and duration of reading MRI versus CT, PET/
Conclusion

Since its introduction in 2010, whole-body PET/MRI has become well-established in scientific and clinical imaging. Still, a number of basic, methodological and professional challenges have limited its wider general acceptance in the oncologic community as well as its utilization as a diagnostic alternative to PET/CT. The greatest obstacle is caused by extensive and heterogeneous protocols that have rendered PET/MRI a research tool that is incompatible with clinical use and is economically challenging. Thus, we introduced recommendations on workflow options that offer efficient and fast imaging protocols open for adaptation to meet the purpose of the examination. The three categories of imaging protocols above allow the standardization and harmonization of PET/MRI, which is a prerequisite for multi-center trials and the assessment of large patient cohorts. This may support the future adoption of PET/MRI in clinical routine imaging and institute reimbursement.

Conflict of Interest

Dr. Herrmann reports personal fees from Bayer, other from Sofie Biosciences, personal fees from SIEMENS, other from ABX, personal fees from Adacap, personal fees from Curium, personal fees from Endocyte, grants and personal fees from BTG, personal fees from IPSEN, personal fees and non-financial support from Siemens Healthineers, non-financial support from GE Healthcare, outside the submitted work.

The other authors declare that they have no conflict of interest.

References
