Thorsten Heußer
Dr. sc. hum.

**Emission-Based Simultaneous Reconstruction of Attenuation and Activity in Hybrid Positron Emission Tomography/Magnetic Resonance Imaging**

Fach/Einrichtung: DKFZ (Deutsches Krebsforschungszentrum)
Doktorvater: Prof. Dr. rer. biol. hum. Marc Kachelrieß

During the last five years, hybrid PET/MR imaging has evolved as a new imaging modality with applications seen mainly in oncology and neurology. Compared to combined PET/CT imaging, which has been the workhorse in oncologic imaging for the last decade, PET/MR offers potential benefits due to improved soft tissue contrast and reduced radiation dose. However, the search for PET/MR key applications is still ongoing. One prerequisite for accurate PET quantification is precise compensation for the attenuation of the 511 keV annihilation photons both in the patient and in hardware components placed between patient and detector. This process, known as attenuation correction (AC), poses a major challenge in hybrid PET/MR imaging, since direct information on the attenuation of patient and hardware is not available based on the MR data. This is in contrast to PET/CT imaging, where precise attenuation information relevant for PET can easily be derived from the CT data. In current clinical PET/MR imaging, MR-based AC (MRAC) neglects bone attenuation which is treated as soft tissue instead. In addition, MRAC entirely neglects attenuation of flexible hardware components, such as MR signal receiving surface coils or MR-safe headphones. MRAC has been shown to significantly underestimate the PET activity distribution when compared to CT-based AC (CTAC). The activity underestimation is especially pronounced for anatomical regions in close proximity of dense bone tissue or in the vicinity of hardware components. The limited accuracy of PET quantification impairs the diagnostic value of hybrid PET/MR imaging, especially for tasks like tumor staging, tracer kinetic modeling, and therapy response monitoring. In this thesis, two algorithms are proposed with the aim of improving PET quantification for hybrid PET/MR imaging.

The first algorithm is an extension of the maximum-likelihood reconstruction of attenuation and activity (MLAA) algorithm for PET/MR. Since it incorporates MR-based prior information, it is referred to as MR-MLAA. It exploits the fact that the PET emission data contain information about both the attenuation and the activity distribution. Simultaneous reconstruction of attenuation and activity from the PET emission data is, however, challenging, since inherent cross-talk between attenuation and activity severely impairs the reconstruction results. To overcome this issue, MR-MLAA incorporates MR-based prior information on the attenuation distribution into the reconstruction. The prior information is derived from conventional diagnostic T1-weighted MR images and allows to express voxel-specific expectations on the attenuation distribution. In contrast to standard MRAC, MR-MLAA explicitly accounts for bone attenuation. In this thesis, MR-MLAA is applied to both simulated and clinical PET/MR data of the head region. In all cases, attenuation distributions obtained with MR-MLAA include attenuation on bone attenuation while preserving small air cavities like the nasal sinuses or the inner ears. However, inaccurate MR-derived prior information and tissue misclassifications may reduce the accuracy of MR-MLAA attenuation estimation. Nevertheless, PET quantification is significantly improved with MR-MLAA as compared to standard MRAC, both for the simulated and for the clinical PET/MR data. For the patient data investigated in this thesis, MR-MLAA reduced the average brain activity underestimation compared to the CTAC gold standard from 10.4% in case of MRAC to 2.1%. The improved PET quantification in the brain region may be of potential benefit in, e.g., brain tumor staging, monitoring of therapy response, and for neurologic applications.

The second algorithm proposed in this thesis is also based on the MLAA algorithm. However, in contrast to MR-MLAA, it does not aim at improving patient attenuation estimation but to find accurate attenuation estimates of hardware components utilized during data acquisition. Since it only obtains estimates of the attenuation distribution outside the MR-derived patient support, the proposed algorithm is referred to as external MLAA (xMLAA). Like MR-MLAA, xMLAA simultaneously reconstructs attenuation and activity distributions from the PET emission data. However, the attenuation is only reconstructed within a so-called hardware mask, which specifies the region outside the patient support where the hardware components are assumed to be located. Prior expectations on the attenuation distribution are incorporated into xMLAA to improve reconstruction results. In this thesis, xMLAA is applied for attenuation estimation of surface coils and MR-safe headphones, which are routinely used in clinical workflow but not considered during AC. In dedicated phantom experiments, it is demonstrated that xMLAA-based hardware attenuation estimation is very similar to the CT-based gold standard. Compared to neglecting hardware attenuation, xMLAA is shown to reduce local activity underestimation in close vicinity to the hardware components from up to 25% to below 3% in case of surface coils or MR-safe headphones.

In summary, both MR-MLAA and xMLAA improve PET quantification compared to conventional MRAC and thus, potentially, improve the diagnostic value of hybrid PET/MR imaging. Both algorithms make use of conventional MR imaging techniques only. Additional information from advanced MR sequences like UTE, from anatomical atlases, or from transmission measurements is not required. Therefore, MR-MLAA and xMLAA are both readily applicable to hybrid PET/MR imaging without modifying the clinical workflow. In addition, both MR-MLAA and xMLAA do not require time-of-flight (TOF) PET data, but are dedicated to conventional non-TOF PET data. However, improved accuracy is expected if TOF information is incorporated, at least for MR-MLAA. Further improvements are expected if more advanced techniques to derive MR-based prior expectations are employed and if precise prior knowledge of shape and location of hardware components are incorporated into the reconstruction.