MLAA-Based Headphone Attenuation Estimation in Hybrid PET/MR Imaging

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Introduction

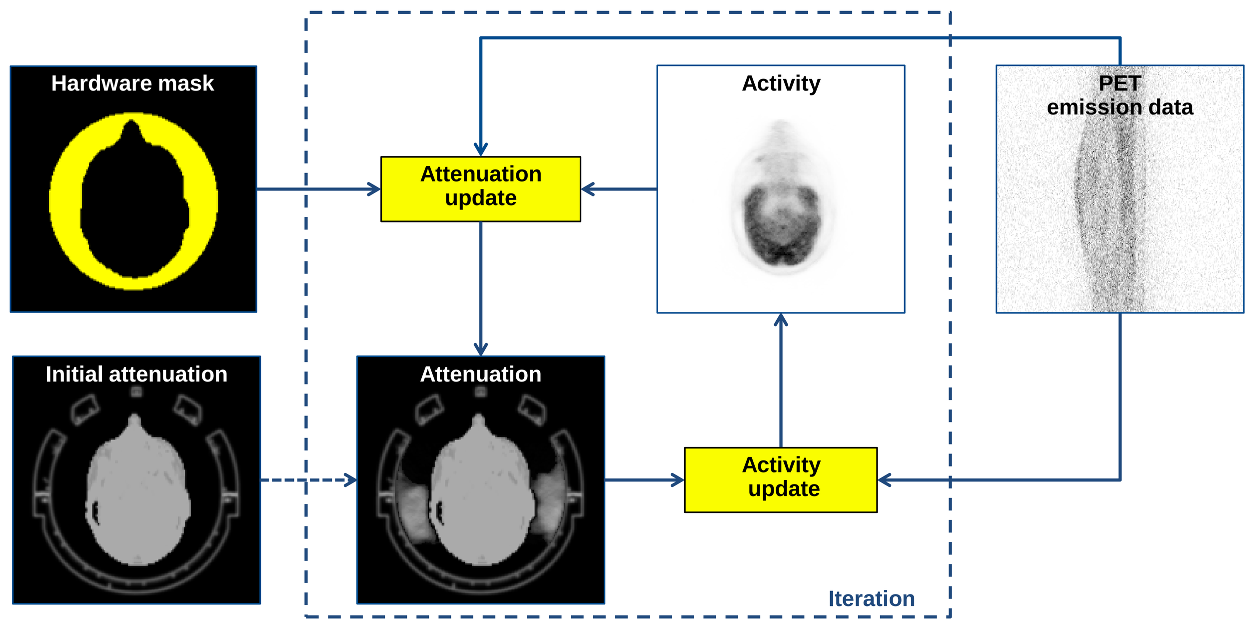
Accurate quantification in PET requires attenuation correction (AC) for both patient and hardware attenuation of the 511 keV annihilation photons. In hybrid PET/MR imaging, AC for stationary hardware components such as patient table and MR head coil is relatively straightforward using CT-derived attenuation templates. AC for flexible hardware components such as MR surface coils and MR-safe pneumatic headphones is more challenging. Registration-based approaches, aligning transmission-based attenuation templates with the current patient position, have been proposed but are not used in clinical routine. Neglecting headphone attenuation has been shown to result in local brain activity underestimation values of up to 15%. In this study, we propose a method to estimate headphone attenuation employing a modified maximum-likelihood reconstruction of attenuation and activity (MLAA) algorithm[1]. The proposed method is evaluated for both phantom and patient data acquired with a Siemens Biograph mMR (Siemens Healthineers, Erlangen, Germany).

Materials and Methods

Algorithm: The MLAA algorithm[1] is used to simultaneously estimate attenuation and activity distributions from the PET emission data. Compared to the original MLAA algorithm, our implementation applies the attenuation update only outside the patient body outline, i.e., the patient attenuation map is not modified. The region where the attenuation update is applied, i.e., where the headphones are assumed to be located, is defined by the so-called hardware mask, which is physically confined by the MR head coil. Prior terms in the cost function favor smooth attenuation maps and the occurrence of either air (μ = 0.0 mm^{-1}) or headphone material (μ = 0.01 mm^{-1}). More details on the MLAA update equations and the prior terms can be found in references 1 and 2.

Phantom Data: We used a 15 cm diameter PMMA cylinder filled with 5 L water and 48 MBq ^{68}Ga. A pair of MR-safe pneumatic headphones was securely fixed to the phantom using adhesive tape. The phantom with the headphones attached was placed inside the MR head coil and PET data were acquired (59×10^6 prompt events). With the headphones still in identical position, the phantom was scanned with a clinical CT system after the activity had been decayed the next day. To obtain a CT-based attenuation template, the CT image with and without headphones was converted to 511 keV applying bilinear scaling. For headphone attenuation estimation, we applied MLAA as described above, performing 50 iterations, i.e., 50 activity and attenuation updates. In a second attempt, we only applied a single MLAA iteration, segmented the headphones and applied pre-defined attenuation coefficients (μ = 0.005 mm^{-1} (MLAA Seg 1) or μ_{lo} = 0.003 mm^{-1} and μ_{hi} = 0.0009 mm^{-1} (MLAA Seg 2)).

MLAA for Hardware Attenuation Estimation



MLAA Cost Function

Cost function *C*:

$$C(\boldsymbol{\lambda},\boldsymbol{\mu}) = L(\boldsymbol{\lambda},\boldsymbol{\mu}) + \beta_\mathrm{S} L_\mathrm{S}(\boldsymbol{\mu}) + \beta_\mathrm{I} L_\mathrm{I}(\boldsymbol{\mu})$$

$\boldsymbol{\lambda}$ Activity
$\boldsymbol{\mu}$ Attenuation

Log-likelihood *L*:

$$L(\boldsymbol{\lambda},\boldsymbol{\mu}) = \sum_j \left(p_j \ln \hat{p}_j - \hat{p}_j\right)$$

with $$\hat{p}_j = \frac{a_j}{n_j}\sum_i M_{ij}\lambda_i + \frac{s_j}{n_j} + r_j$$

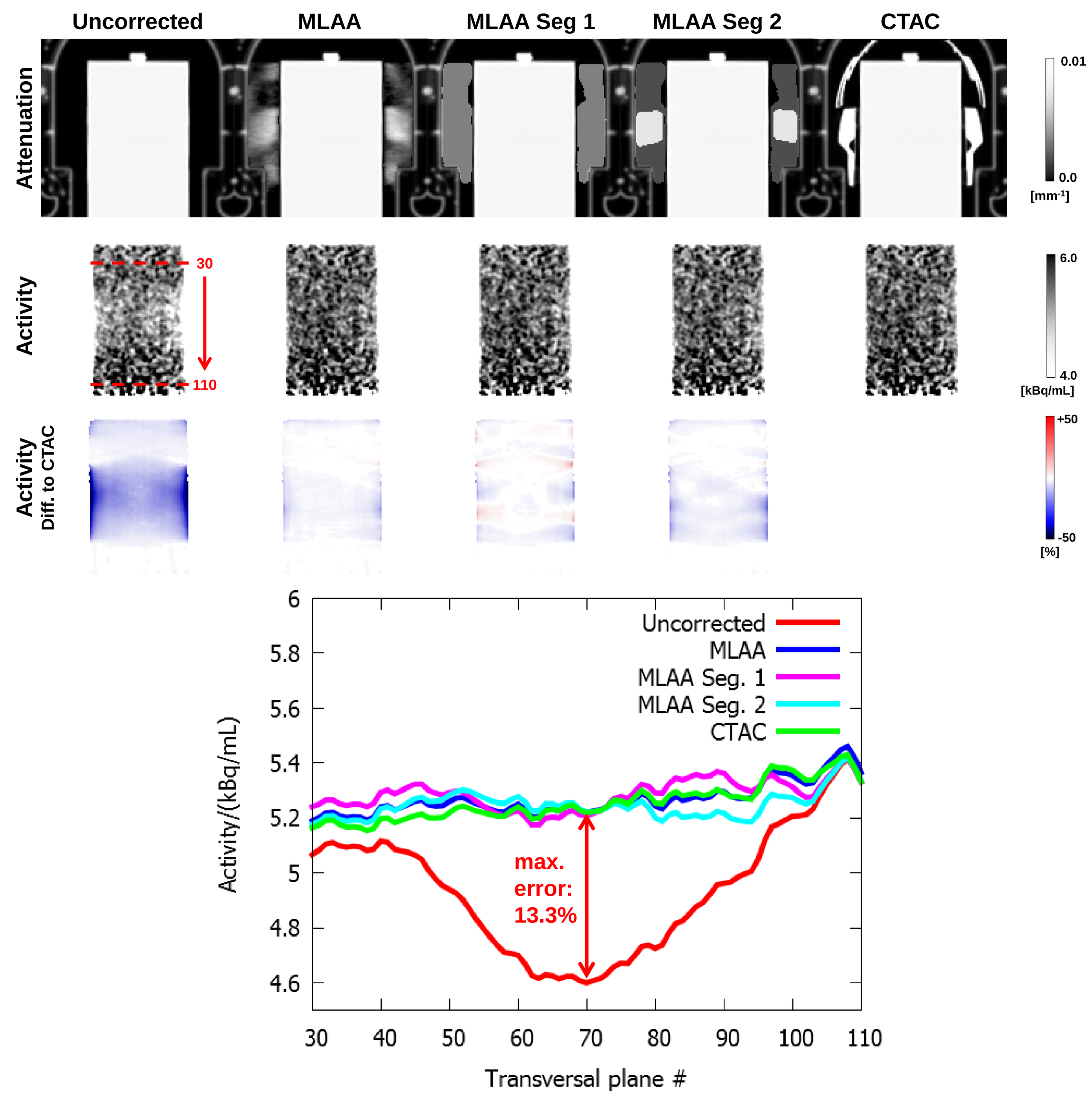
and $$a_j = e^{-\sum_i \mu_i l_{ij}}$$

Smoothing prior L_S with weight β_S

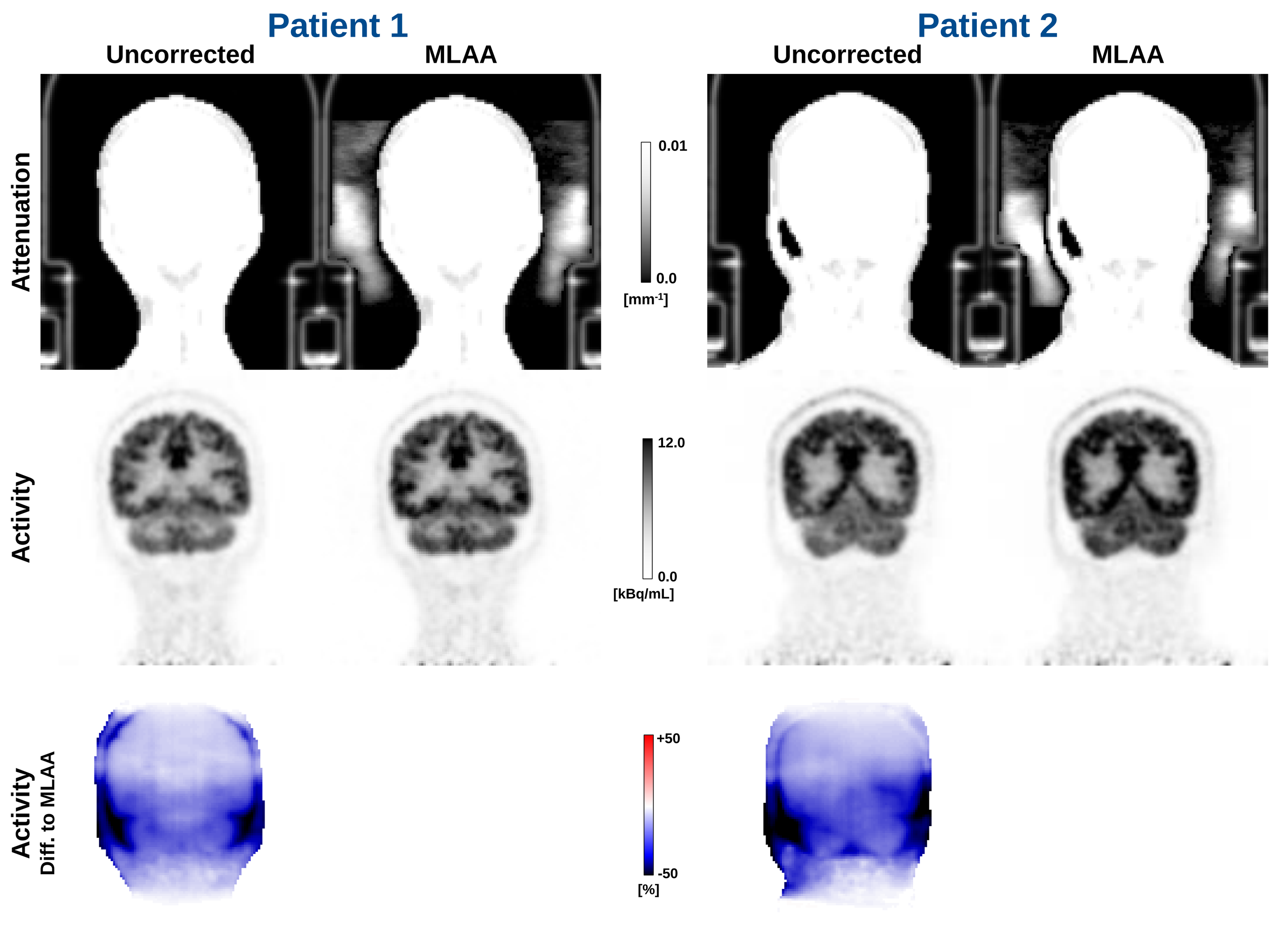
Intensity prior L_I with weight β_I

i Voxel index
j LOR index
p_j Emission data
$\hat{p}_j$ Estimated emission data
a_j Attenuation factor
n_j Normalization
s_j Scatter
r_j Randoms
M_{ij} System matrix element
l_{ij} Intersection length of voxel *i* and LOR *j*

Results Phantom



Results Patients



Patient Data: We investigated three ^{18}F-FDG patients wearing headphones during data acquisition. Administered activity was 227±16 MBq. Only PET data from the bed position corresponding to the head region were considered. The vendor-provided MR-based attenuation map was used for patient AC. As for the phantom data, the MLAA attenuation update for headphone attenuation estimation was applied outside the patient body outline but within the head coil. Final reconstructions were performed for the uncorrected case neglecting headphone attenuation and for MLAA-based headphone attenuation estimation employing an OSEM algorithm with 3 iterations and 21 subsets. Neither a reference scan nor CT-based attenuation templates were available for comparison.

Results

Phantom Data: Neglecting headphone attenuation estimation resulted in a maximum activity underestimation of 13.3% compared to CTAC and evaluated within entire transversal planes. This severe quantification error could be reduced to 0.8% when applying the proposed MLAA-based approach. The segmentation-based approaches (MLAA Seg 1 and 2), which require only a single MLAA iteration, were found to be less accurate than MLAA without segmentation and performing 50 iterations. However, compared to CTAC, the quantification error evaluated within entire transversal planes was below 2.0% for all investigated planes.

Patient Data: Visual comparison with the phantom data showed similar appearance of the headphones in the MLAA-derived attenuation maps. Across three patients, quantitative evaluation revealed an activity underestimation of 7.7% evaluated in the full brain and of 14.5% evaluated in the cerebellum comparing the uncorrected case neglecting headphone attenuation with MLAA.

Conclusion

This study demonstrates the feasibility of applying MLAA for accurate headphone attenuation estimation. The proposed approach can also be applied for other hardware components located within the PET field-of-view, such as MR surface coils or positioning aids. Since MLAA is already implemented in current clinical PET/MR devices, the proposed approach can, in principle be readily included into clinical workflow.

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