Joint Emission-Based Patient and Hardware Attenuation Correction for non-TOF PET/MR Imaging

Thorsten Heußer, Christopher M. Rank, Yannick Berker, Martin Freitag, and Marc Kachelrieß

**German Cancer Research Center (DKFZ)
Heidelberg, Germany**

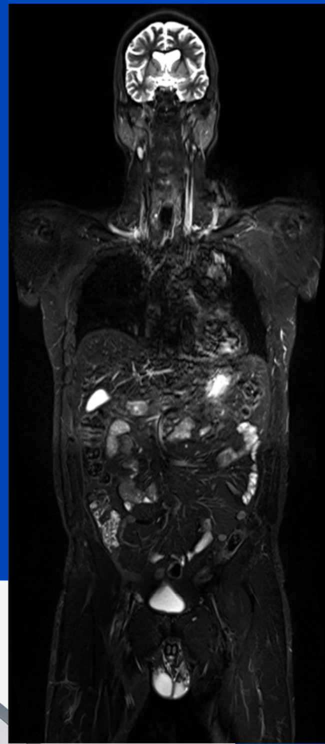
Outline

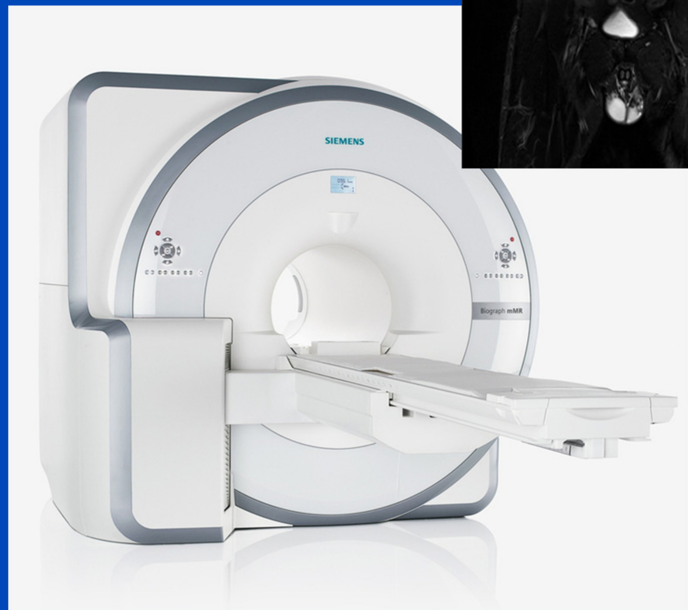
- MR-MLAA
  - Emission-based patient AC for PET/MR
- xMLAA
  - Emission-based hardware AC for PET/MR
- xMR-MLAA
  - Combination of MR-MLAA and xMLAA

Siemens Biograph mMR[1]

MR-Component

- **Field strength: 3T**
- **Bore size: 60 cm**
- **Transversal FOV: 50 cm (max.)**
- **Magnet length: 163 cm**
- **Gradient coil system**
  - **Length: 159 cm**
  - **Amplitude: 45 mT/m**
  - **Slew rate: 200 T/m/s**



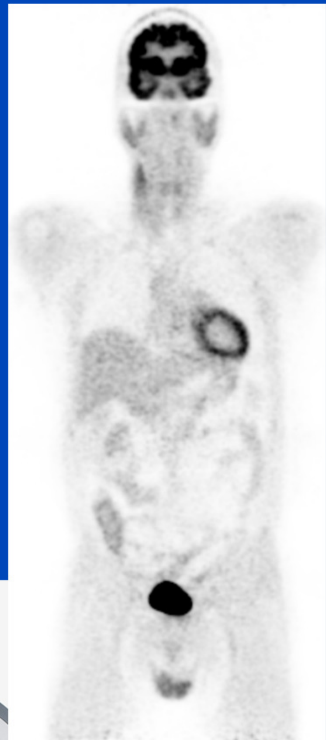


[1] G. Delso, S. Fürst, B. Jakoby, R. Ladebeck, C. Ganter, S.G. Nekolla, M. Schwaiger, and S.I. Ziegler, "Performance Measurements of the Siemens mMR Integrated Whole-Body PET/MR Scanner," *J. Nucl. Med.* 52(12), 1914-1922 (2011).

Siemens Biograph mMR[1]

PET-Component

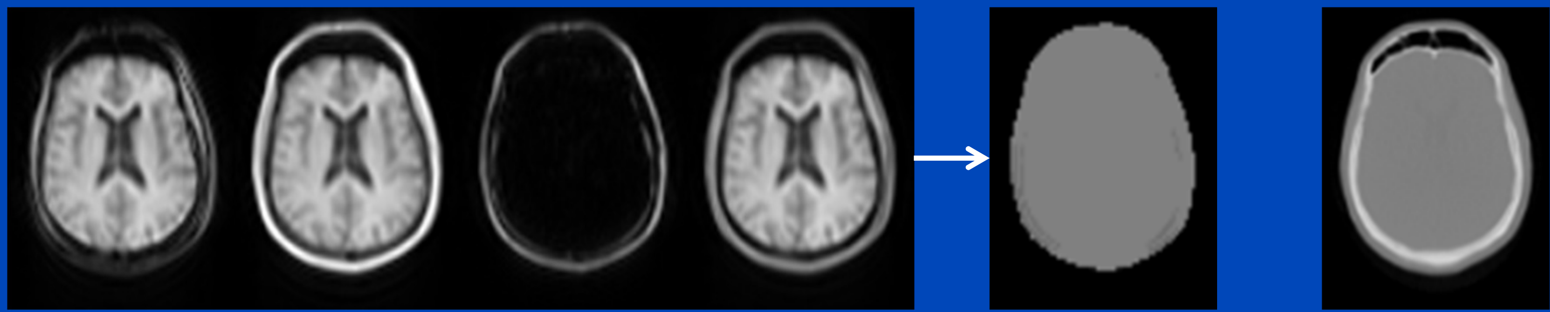
- Scintillator material: LSO
- Photon detectors: APD
- Timing resolution: ≈ 3.0 ns
- TOF-capability: no
- Crystal size: $4 \times 4 \times 20\ \text{mm}^3$
- Ring radius: 65.6 cm
- Transversal FOV: 59.4 cm
- Axial FOV: 25.8 cm
  (127 planes at 2.03 mm)



[1] G. Delso, S. Fürst, B. Jakoby, R. Ladebeck, C. Ganter, S.G. Nekolla, M. Schwaiger, and S.I. Ziegler, “Performance Measurements of the Siemens mMR Integrated Whole-Body PET/MR Scanner,” *J. Nucl. Med.* 52(12), 1914-1922 (2011).

MR-MLAA

Introduction



- **Motivation**
  - Standard MR-based attenuation correction (AC) neglects bone and hardware attenuation and thus underestimates the activity distribution.
- **Aim**
  - To improve patient AC for non-TOF PET/MR.
- **Proposed algorithm**
  - Extension of the maximum-likelihood reconstruction of attenuation and activity (MLAA)[1] for non-TOF PET/MR, called MR-MLAA.

[1] J. Nuyts, P. Dupont, S. Stroobants, R. Benninck, L. Mortelmans, and P. Suetens, "Simultaneous maximum a posteriori reconstruction of attenuation and activity distributions from emission sinograms.," IEEE Trans. Med. Imaging 18(5), 393–403 (1999).

MR-MLAA[1]

Algorithm

- **Joint estimation of attenuation and activity**
  - Using PET emission data
  - Incorporating MR-based prior information
- **Iterative approach**
  - Update attenuation and activity in an alternating manner
- **Objective function**

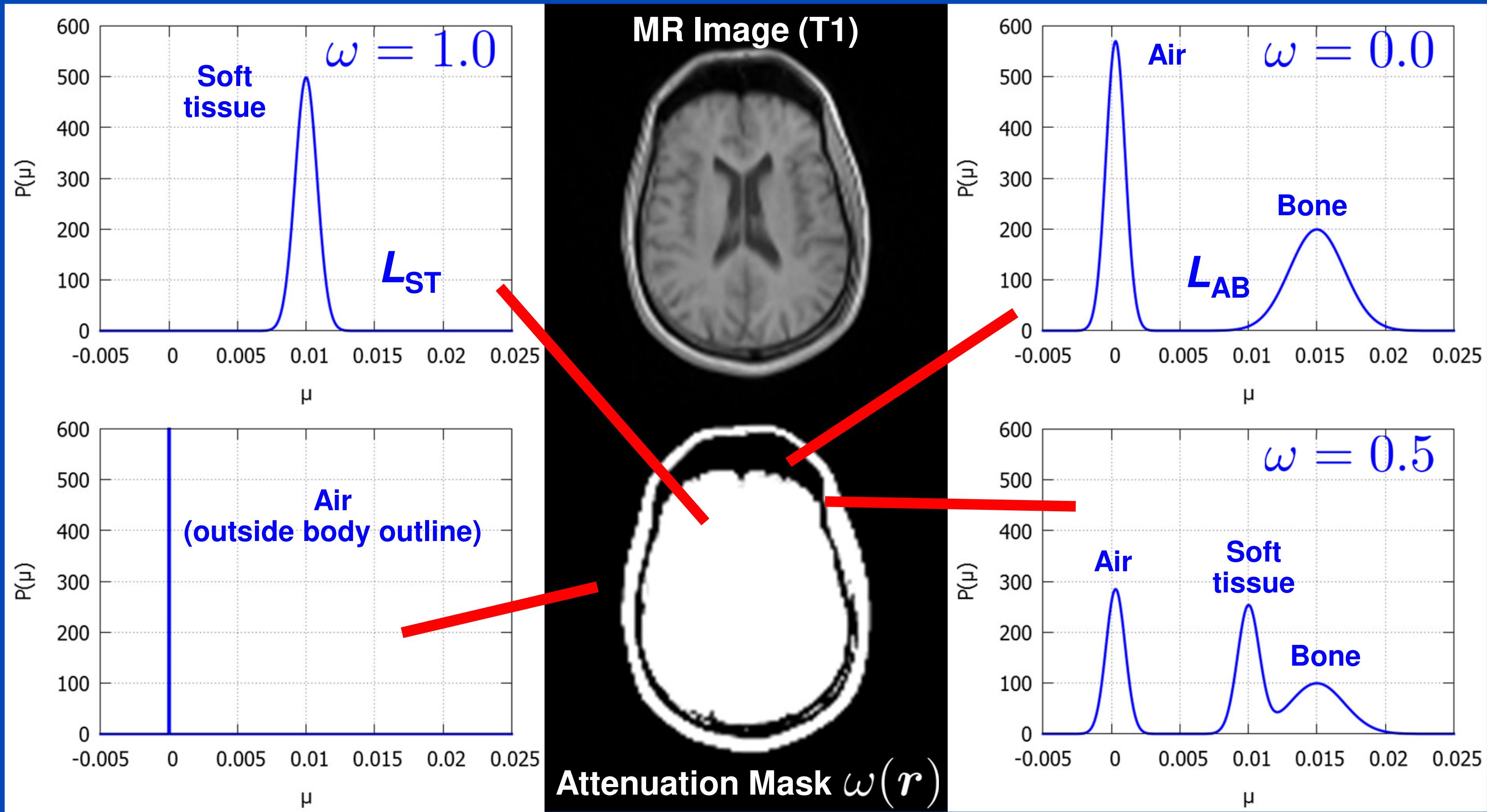
$$Q(\boldsymbol{\lambda}, \boldsymbol{\mu}) = \underbrace{L(\boldsymbol{\lambda}, \boldsymbol{\mu})}_{\text{Log-likelihood}} + \underbrace{L_{\mathrm{S}}(\boldsymbol{\mu}) + L_{\mathrm{I}}(\boldsymbol{\mu})}_{\text{Prior terms}}$$

λ = activity
μ = attenuation

- **Intensity prior L_I**
  - Voxel-dependent Gaussian-like probability distribution of pre-defined attenuation coefficients, e.g., for soft tissue, air, bone
  - Derived from diagnostic T1-weighted MR images

[1] T. Heußer, C.M. Rank, M.T. Freitag, A. Dimitrakopoulou-Strauss, H.-P. Schlemmer, T. Beyer, and M. Kachelrieß, "MR-Consistent Simultaneous Reconstruction of Attenuation and Activity for non-TOF PET/MR," *IEEE Trans. Nucl. Sci.* 63(5):2443-2451 (2016).

MR-MLAA
Intensity Prior L_I

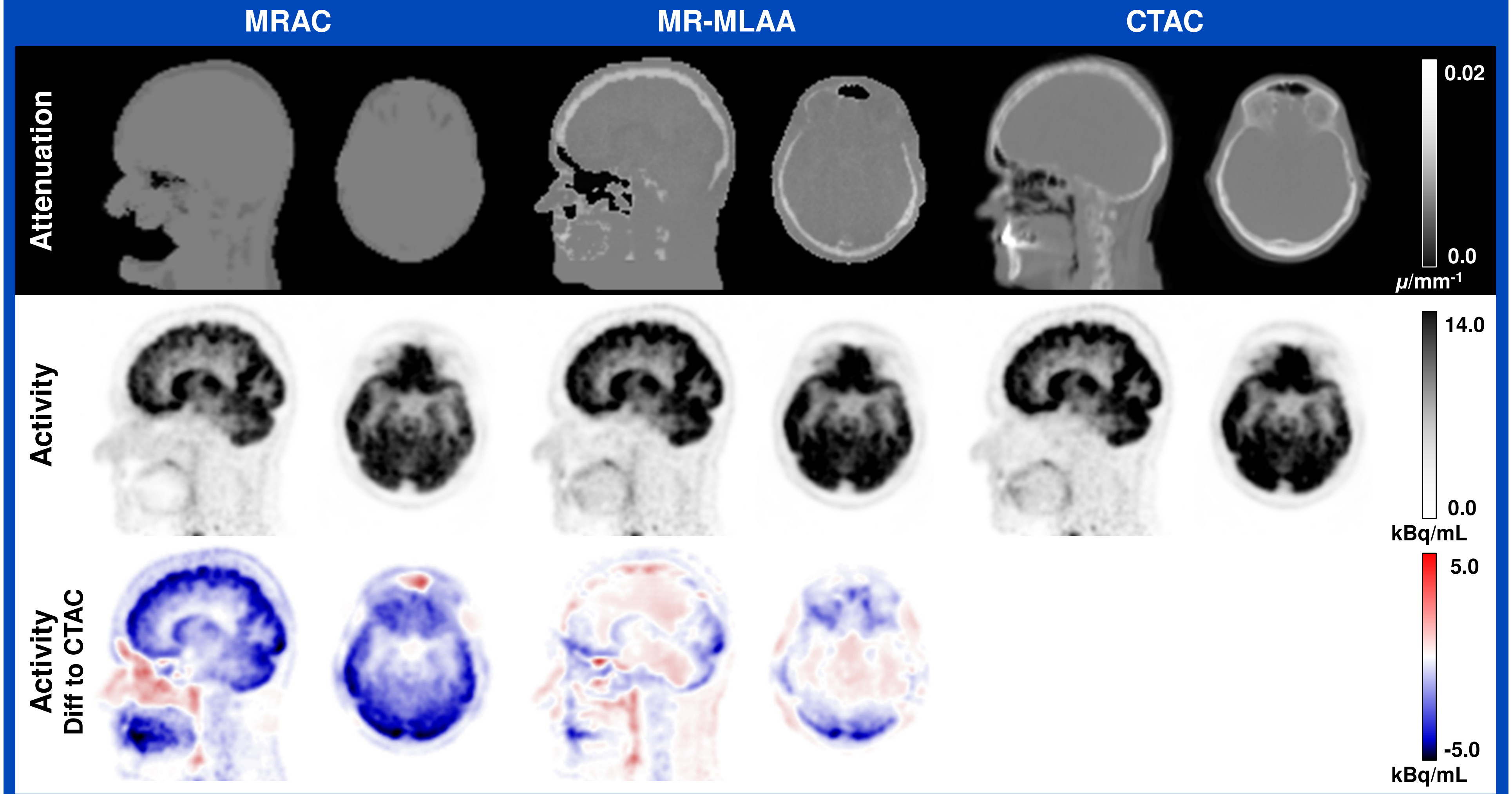


$$L_{\mathrm{I}}(\boldsymbol{\mu}) = \omega(\boldsymbol{r})\beta_{\mathrm{ST}}L_{\mathrm{ST}}(\boldsymbol{\mu}) + (1-\omega(\boldsymbol{r}))\beta_{\mathrm{AB}}L_{\mathrm{AB}}(\boldsymbol{\mu})$$

We use β_{ST} = 0.1 and β_{AB} = 0.6 throughout this presentation.

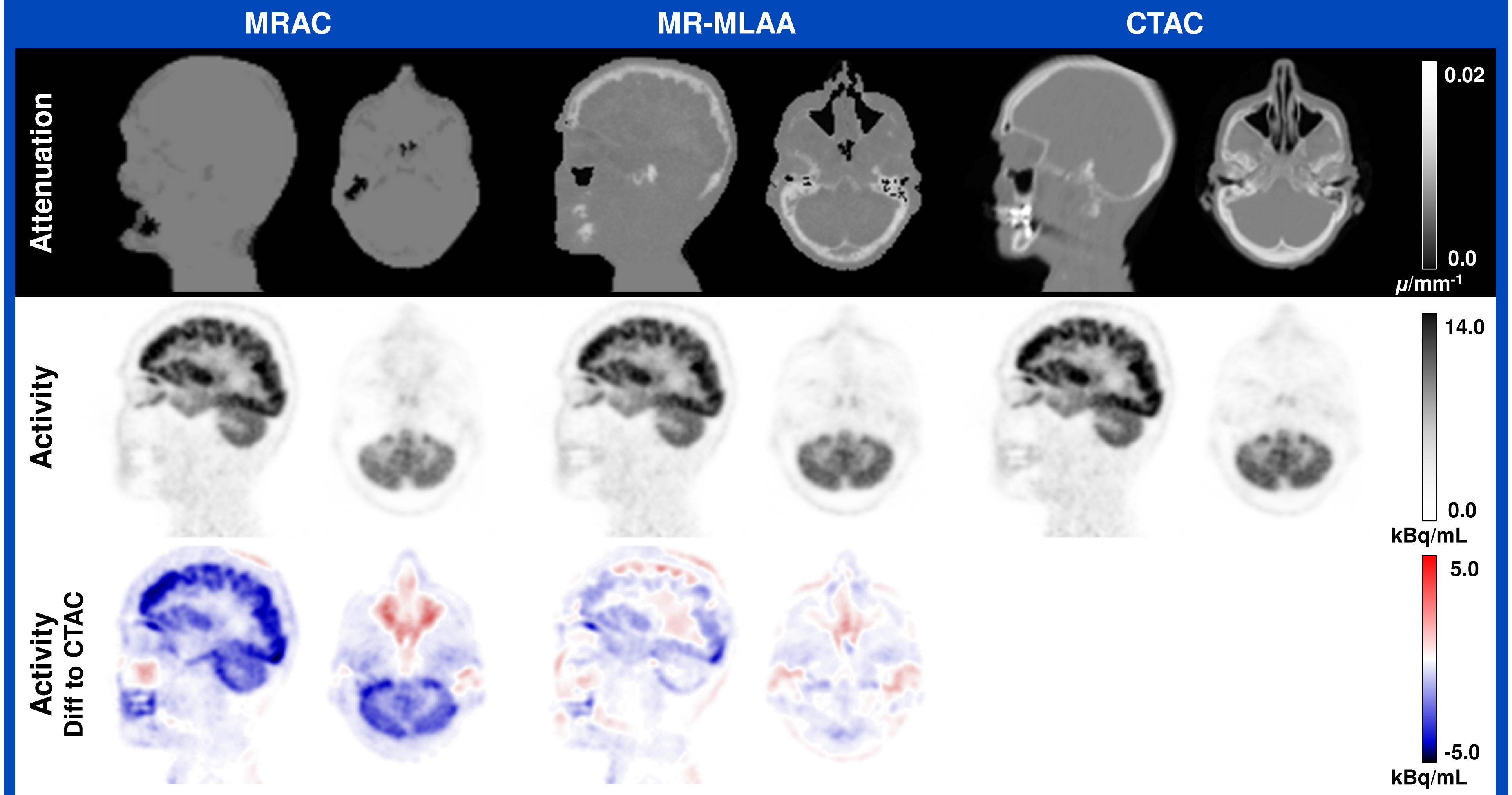
MR-MLAA

Results: Patient 1



MR-MLAA

Results: Patient 2

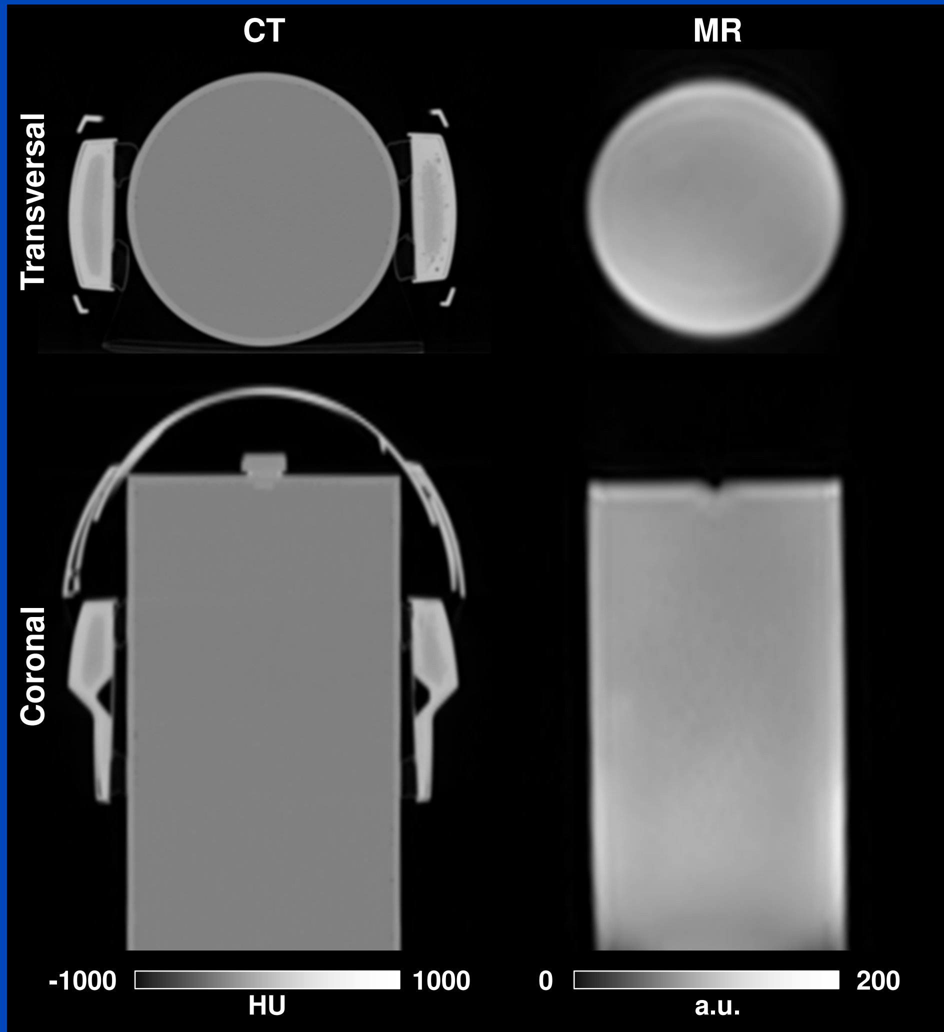


dkfz.

xMLAA

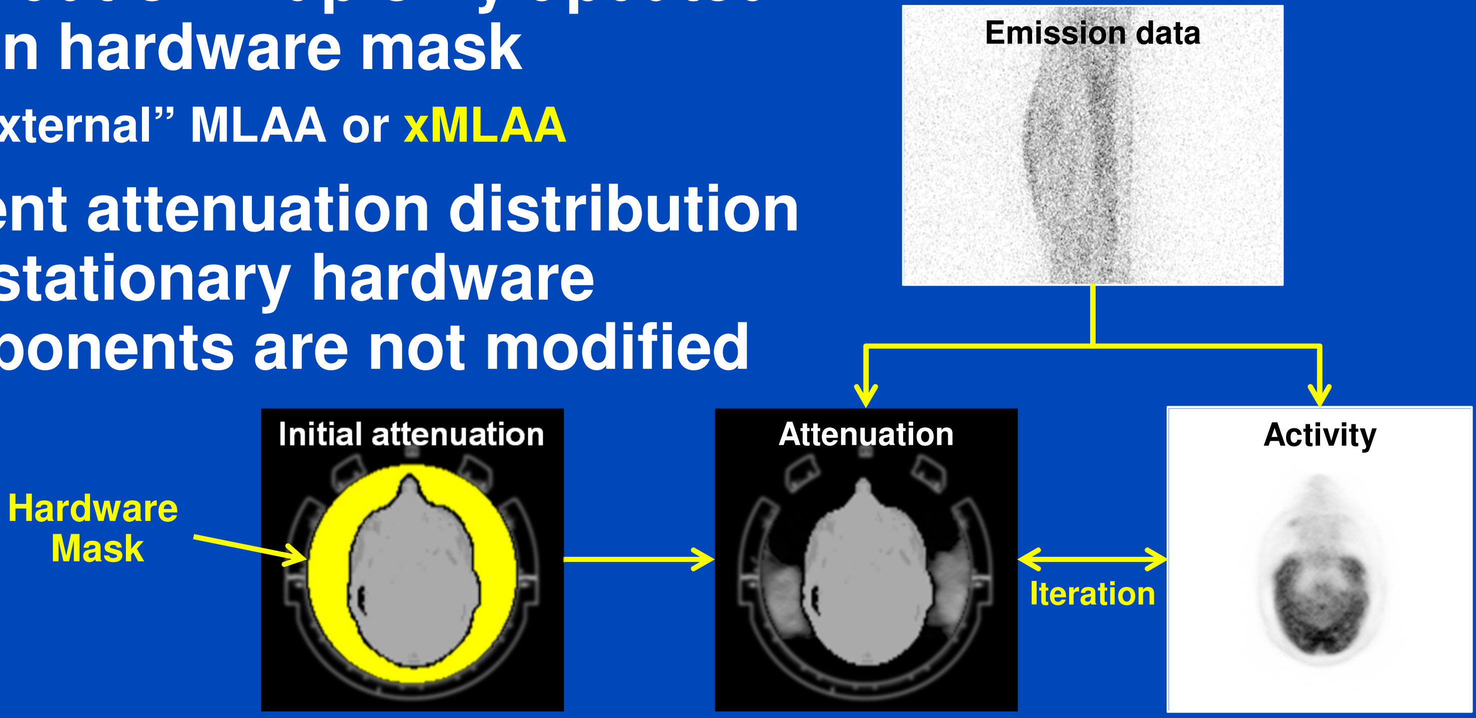
Introduction

- **Flexible hardware components are currently neglected in MR-based AC**
  - MR-safe headphones
  - Radiofrequency torso surface coils
  - Positioning aids
  - ...
- **Aim**
  - Estimate attenuation of flexible hardware components from the PET emission data



xMLAA[1]
Algorithm

- Joint estimation of attenuation and activity
  - Based on the MLAA algorithm
- Attenuation map only updated within hardware mask
  - "External" MLAA or xMLAA
- Patient attenuation distribution and stationary hardware components are not modified

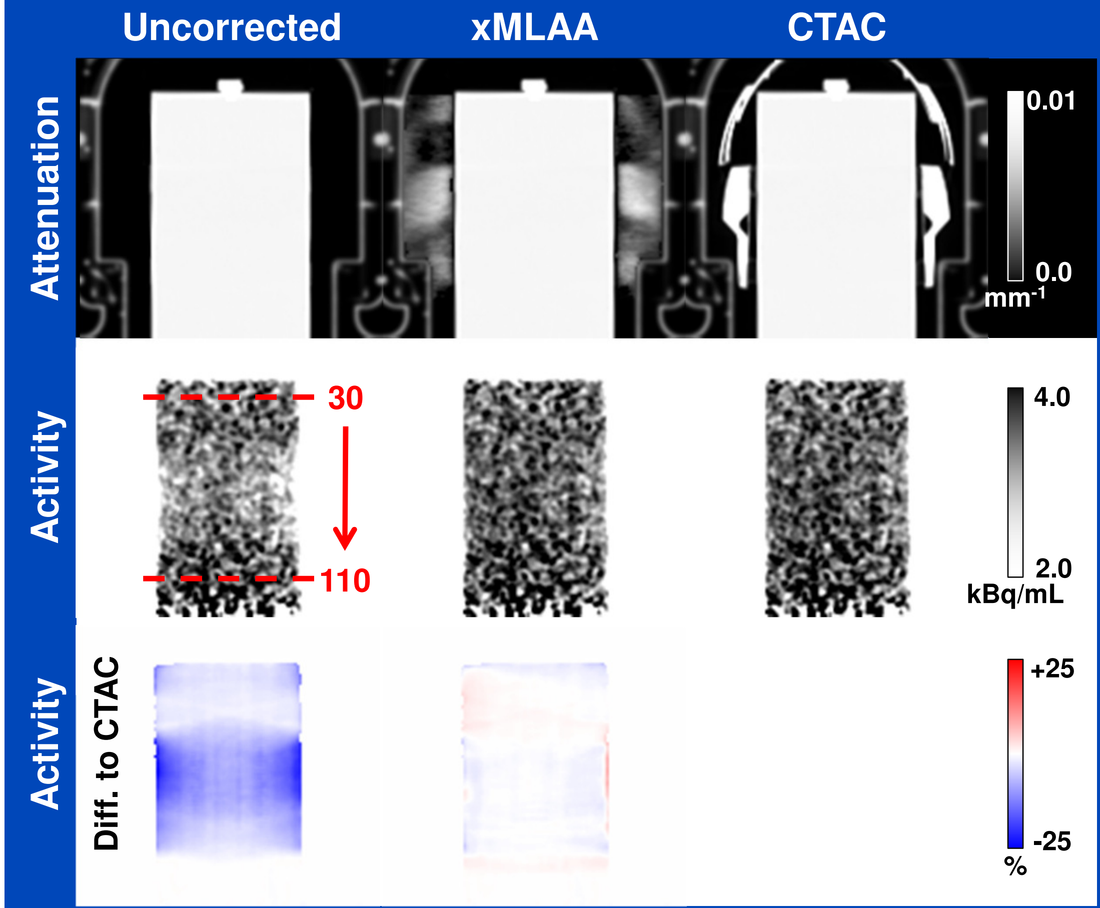


[1] T. Heußer, C.M. Rank, Y. Berker, M.T. Freitag, and M. Kachelrieß, "MLAA-based Attenuation Correction of Flexible Hardware Components in Hybrid PET/MR Imaging," *EJNMMI Physics* 4:12 (2017).

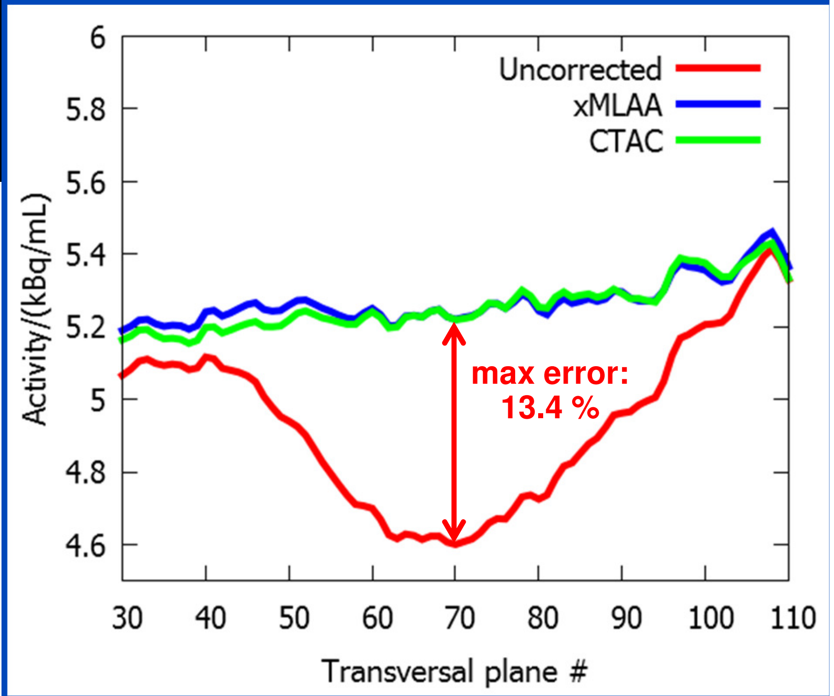
dkfz.

xMLAA

Results Headphones



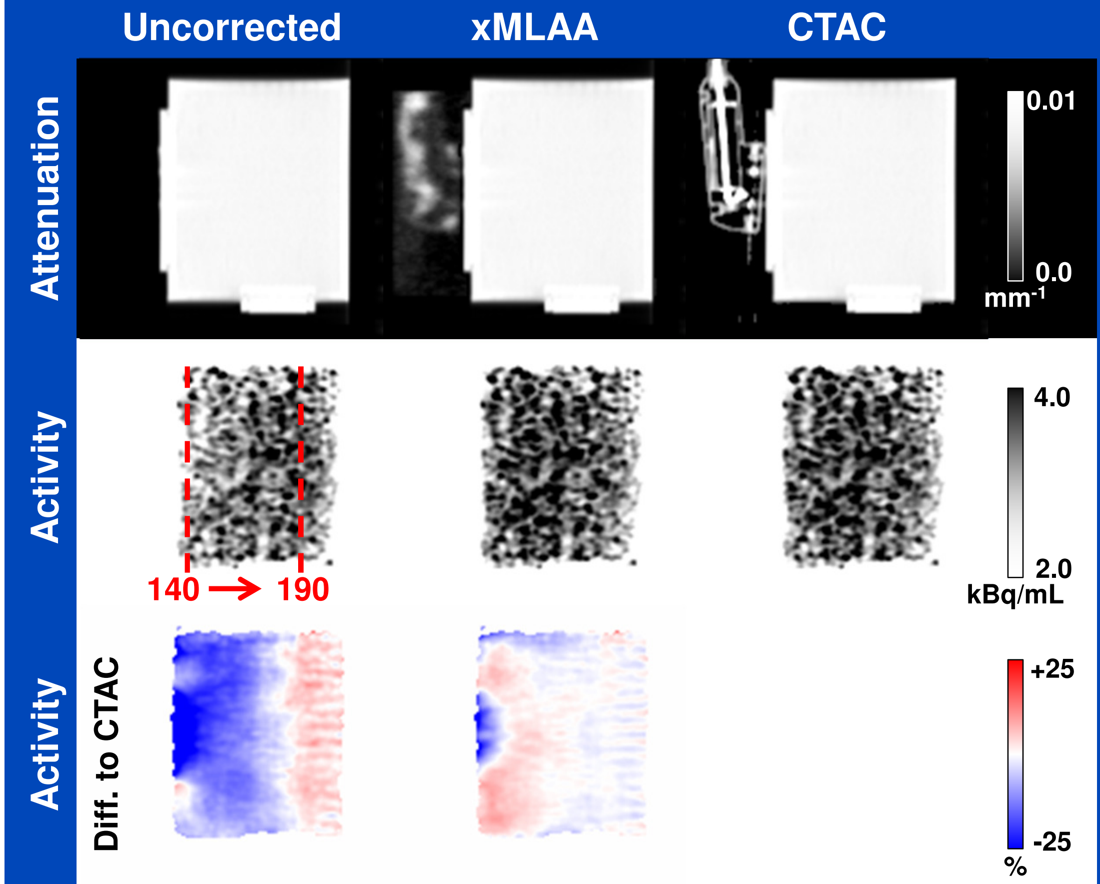
Average Activity in Transversal Planes



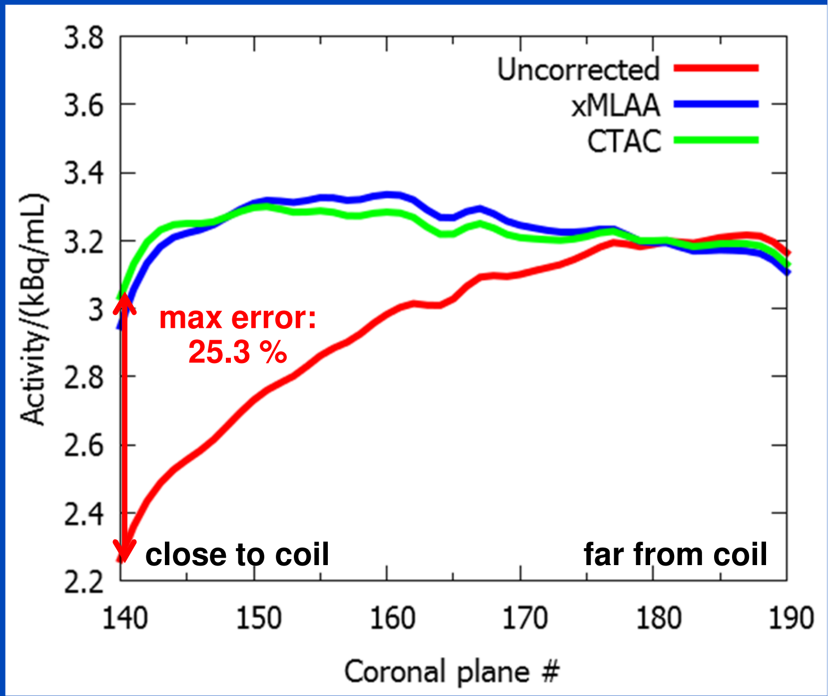
dkfz.

xMLAA

Results Torso Coil

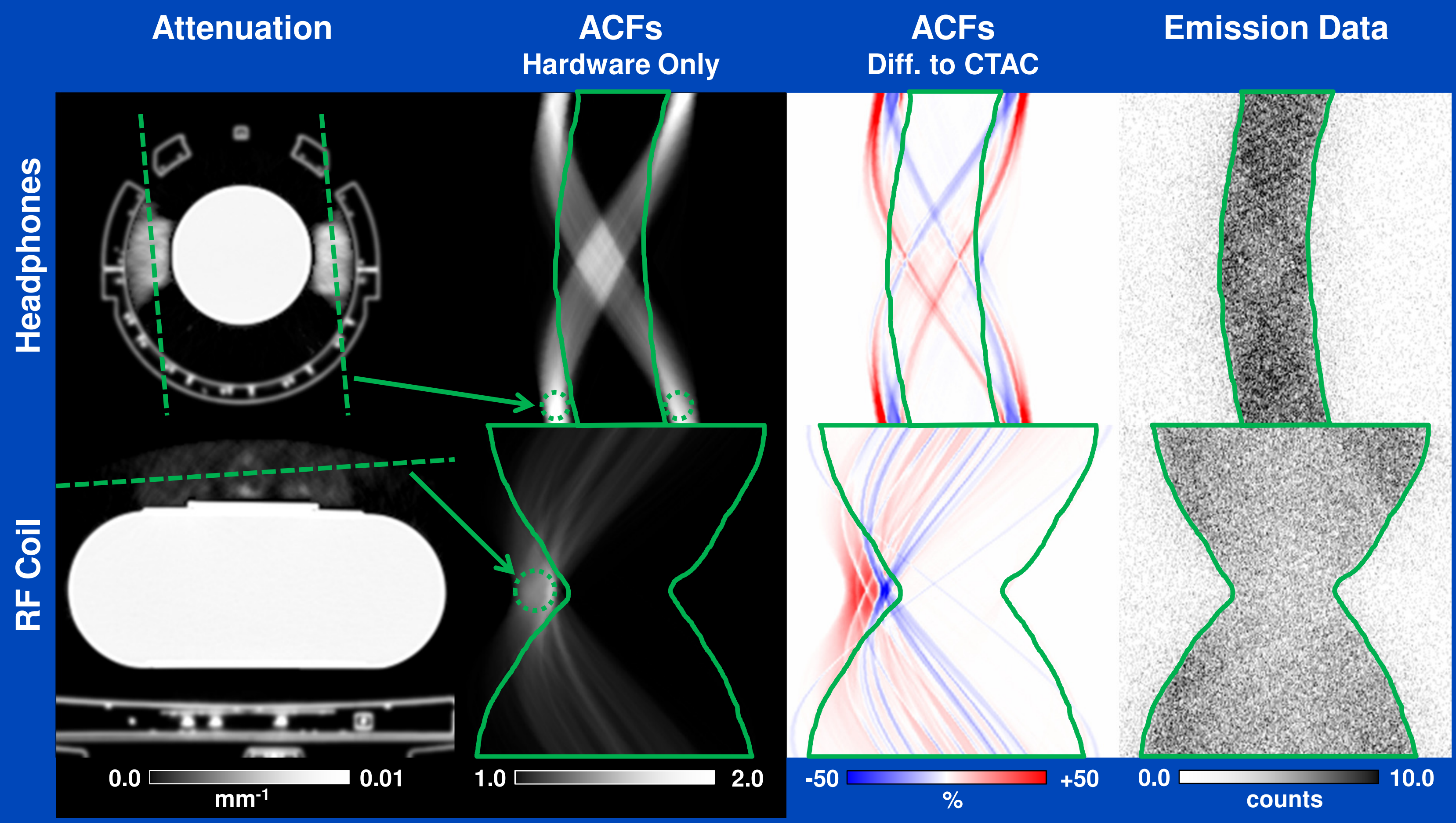


Average Activity in Coronal Planes



dkfz.

xMLAA
Attenuation Correction Factors



dkfz.

xMR-MLAA

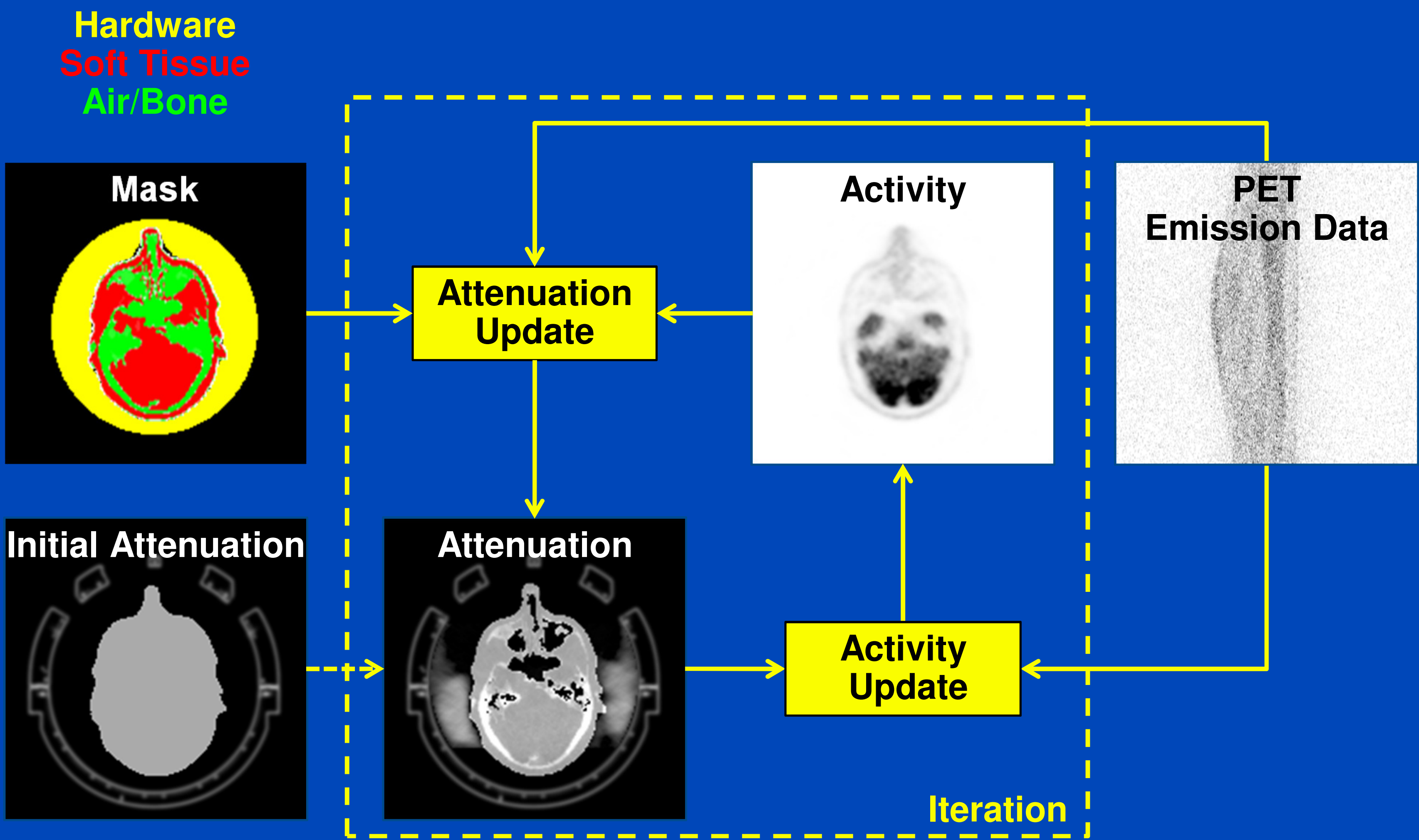
Introduction

- Both MR-MLAA and xMLAA
  - are based on the MLAA algorithm
  - exploit the fact that the PET emission data contain information about both activity and attenuation
  - have been treated separately in our previous studies

- Aim: Jointly estimate patient and hardware attenuation by combining MR-MLAA and xMLAA to xMR-MLAA

xMR-MLAA

Workflow



xMR-MLAA

Objective Function

- Objective function *Q*

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

- 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
- Intensity prior L_I

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

i	Voxel index
j	LOR index
p_j	Measured projections
$\hat{p}_j$	Estimated projections
a_j	Attenuation factor
n_j	Normalization factor
s_j	Scatter
r_j	Randoms
M_{ij}	System matrix element
l_{ij}	Intersection length

xMR-MLAA

Update Equations

- **Activity update (MLEM)[1,2]**

$$\lambda_i^{(n+1)} = \lambda_i^{(n)} \frac{1}{\sum_j M_{ij} a_j^{(n)}/n_j} \sum_j M_{ij} \frac{p_j}{\sum_k M_{kj}\lambda_k^{(n)} + (s_j + r_j n_j)/a_j^{(n)}}$$

- **Attenuation update (MLTR)[3]**

$$\mu_i^{(n+1)} = \mu_i^{(n)} + \alpha \frac{\sum_j \left(l_{ij}(\hat{p}_j^{(n)} - p_j) \frac{\hat{p}_j^{(n)} - s_j/n_j - r_j}{\hat{p}_j^{(n)}} \right) + \frac{\partial}{\partial \mu_i}(L_\mathrm{S} + L_\mathrm{I})}{\sum_j \left(l_{ij}(\hat{p}_j^{(n)} - \frac{s_j}{n_j} - r_j) \left(1 - \frac{p_j(s_j/n_j + r_j)}{\hat{p}_j^{2(n)}}\right) \sum_k l_{kj} \right) - \sum_k \frac{\partial^2}{\partial \mu_i \partial \mu_k}(L_\mathrm{S} + L_\mathrm{I})}$$

i	Voxel index	λ	Activity	n	Iteration number
j	LOR index	μ	Attenuation	α	Relaxation parameter

[1] Shepp and Vardi. "Maximum likelihood reconstruction for emission tomography," *IEEE Trans. Med. Imaging*, 1(2), 113-22, 1982..
[2] Lange and Carson. "EM reconstruction algorithms for emission and transmission tomography," *J. Comput. Assist. Tomogr.*, 8(2), 306-16, 1984.
[3] Nuyts *et al.*, "Iterative reconstruction for helical CT: a simulation study," *Phys. Med. Biol.*, 43(4), 729–37, 1998.

dkfz.

xMR-MLAA

Algorithm

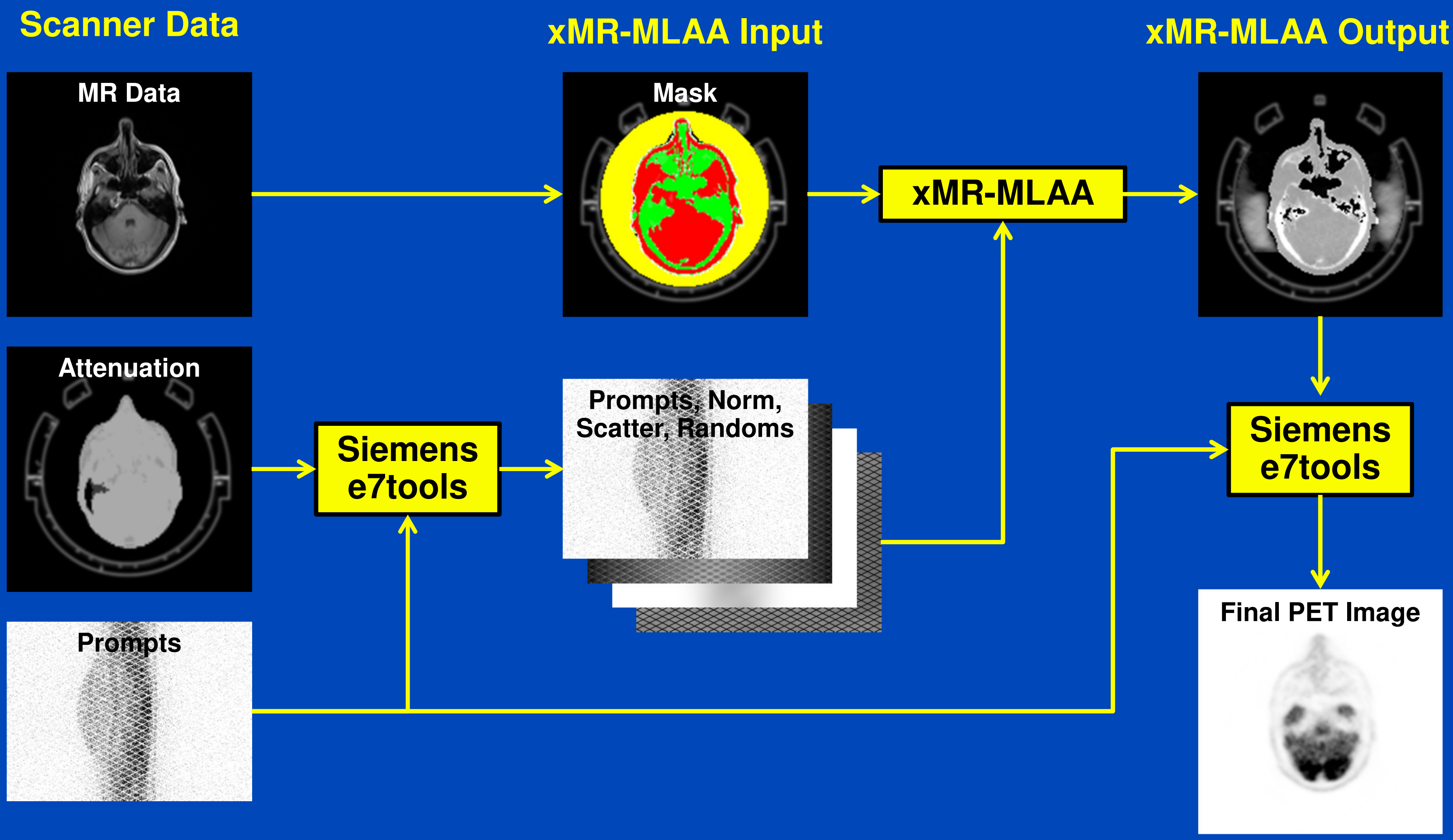
- Hardware and patient attenuation are updated sequentially
- Hardware update
  - xMLAA
  - 2 iterations, 21 subsets
- Patient update
  - MR-MLAA
  - 3 Iterations, 21 subsets
- Intensity prior

Hardware
Soft Tissue
Air/Bone

$$L_{\mathrm{I}}(\boldsymbol{\mu}) = \omega_{\mathrm{X}}(\boldsymbol{r})\beta_{\mathrm{X}}L_{\mathrm{X}}(\boldsymbol{\mu}) + (1-\omega_{\mathrm{X}}(\boldsymbol{r}))L_{\mathrm{MR}}(\boldsymbol{\mu})$$

$$L_{\mathrm{MR}}(\boldsymbol{\mu}) = \omega(\boldsymbol{r})\beta_{\mathrm{ST}}L_{\mathrm{ST}}(\boldsymbol{\mu}) + (1-\omega(\boldsymbol{r}))\beta_{\mathrm{AB}}L_{\mathrm{AB}}(\boldsymbol{\mu})$$

xMR-MLAA
Data Processing



dkfz.

xMR-MLAA

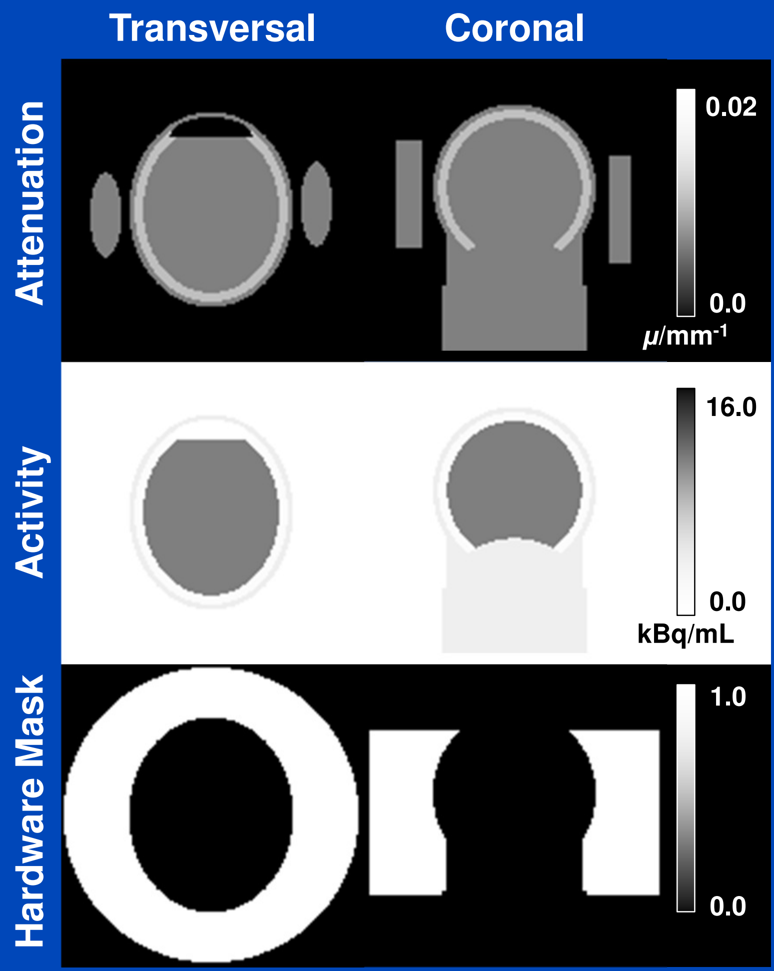
Parameters

- PET system
  - Siemens Biograph mMR
- Detector
  - # of rings: 64
  - # of elements per ring: 448
- LORs
  - # of LORs per view: 344
  - # of views: 252
  - # of planes: 837 (span 11)
- Volume dimensions
  - $344 \times 344 \times 127$
- Voxel size
  - $2.09 \times 2.09 \times 2.03$ mm^3
- Same parameters used for attenuation and activity distribution

dkfz.

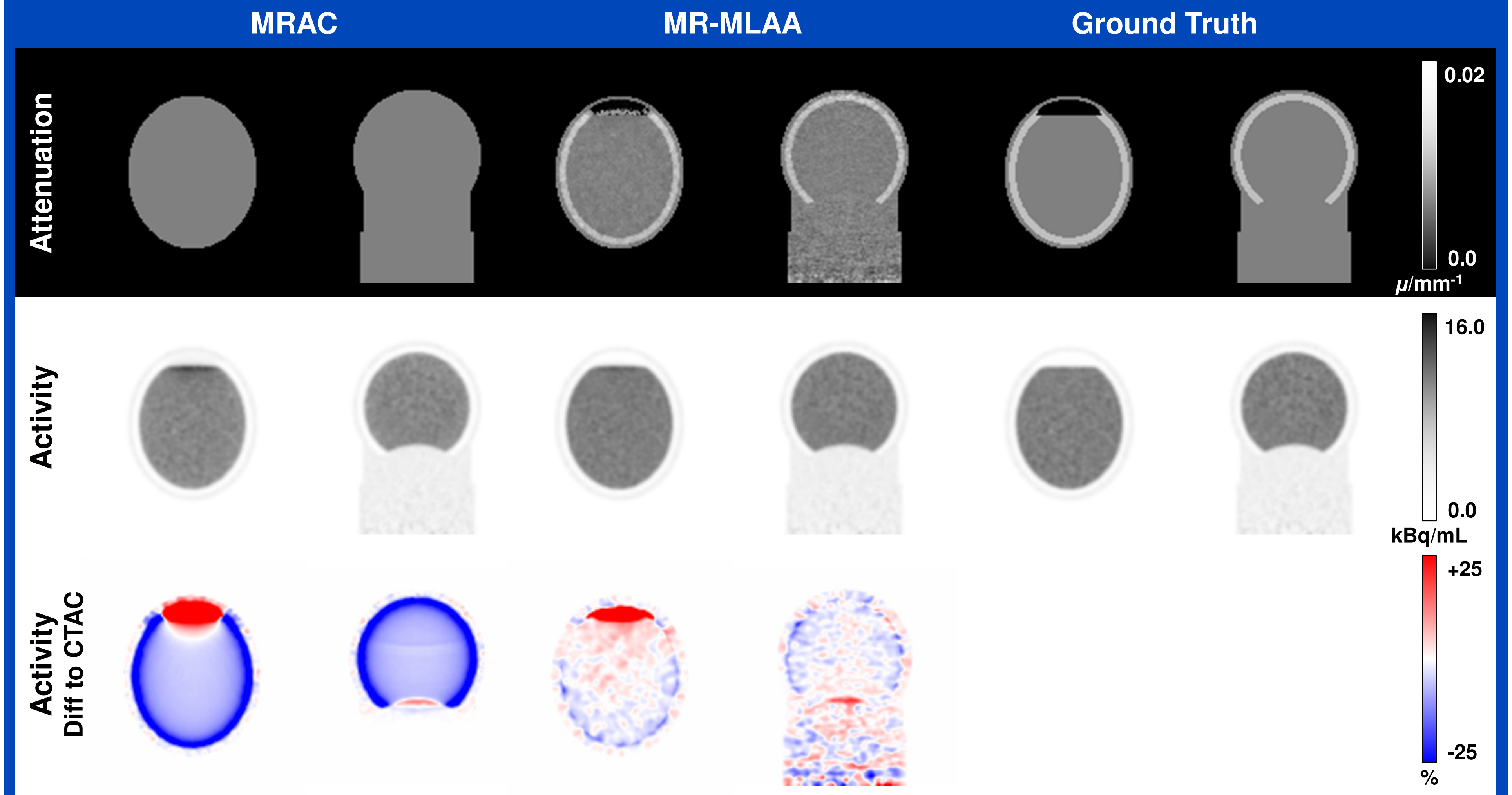
xMR-MLAA
Simulation Study

- **Phantom**
  - Head phantom with skull bone and air cavity (frontal sinus)
  - Two headphone-like objects to each side of the phantom
- **PET simulation**
  - Siemens Biograph mMR geometry
  - Simulating Poisson noise (54×10^6 counts)
  - Considering attenuation
  - No scatter or randoms simulated



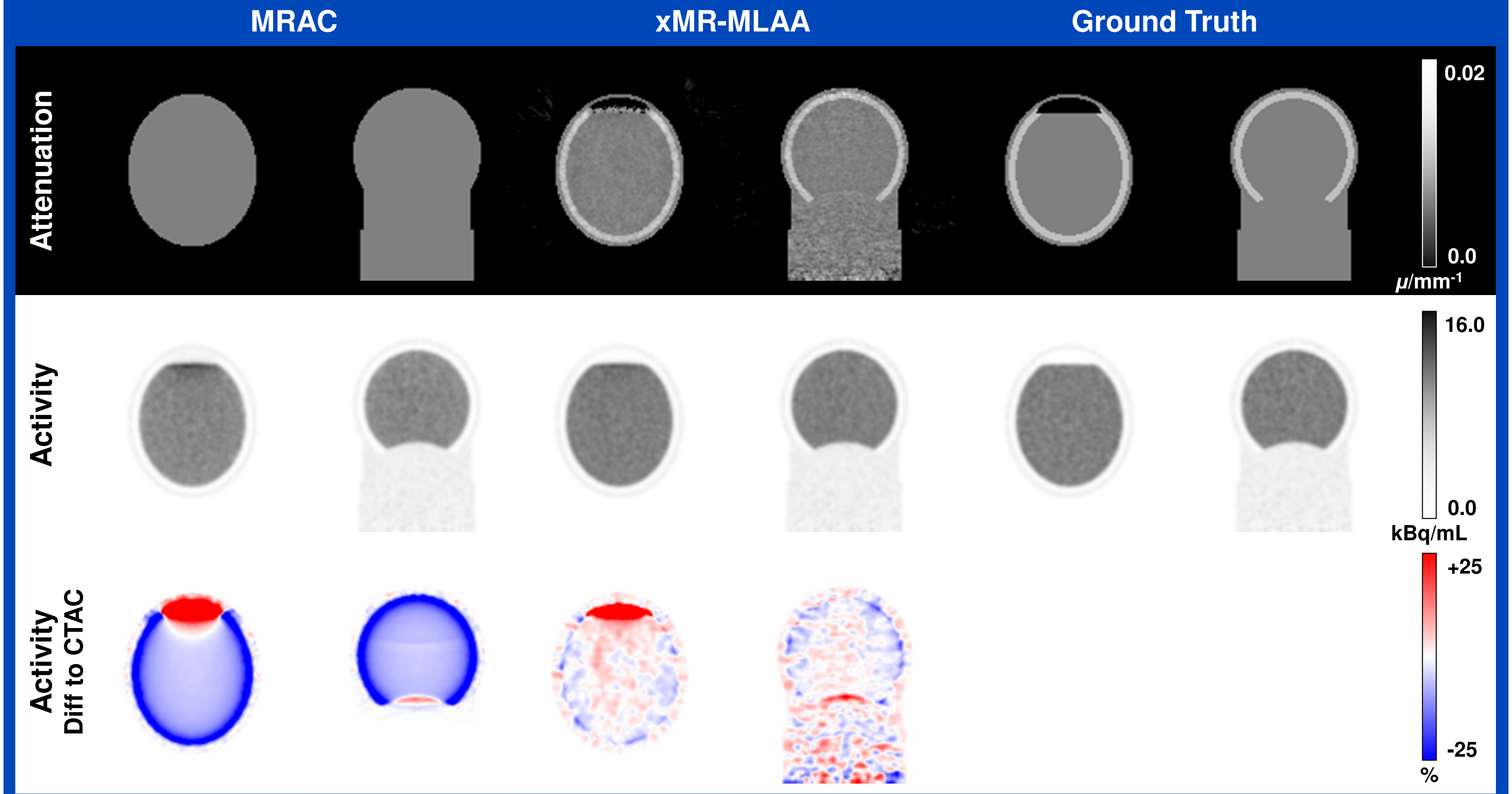
xMR-MLAA: Simulation Study

Without Hardware



dkfz.

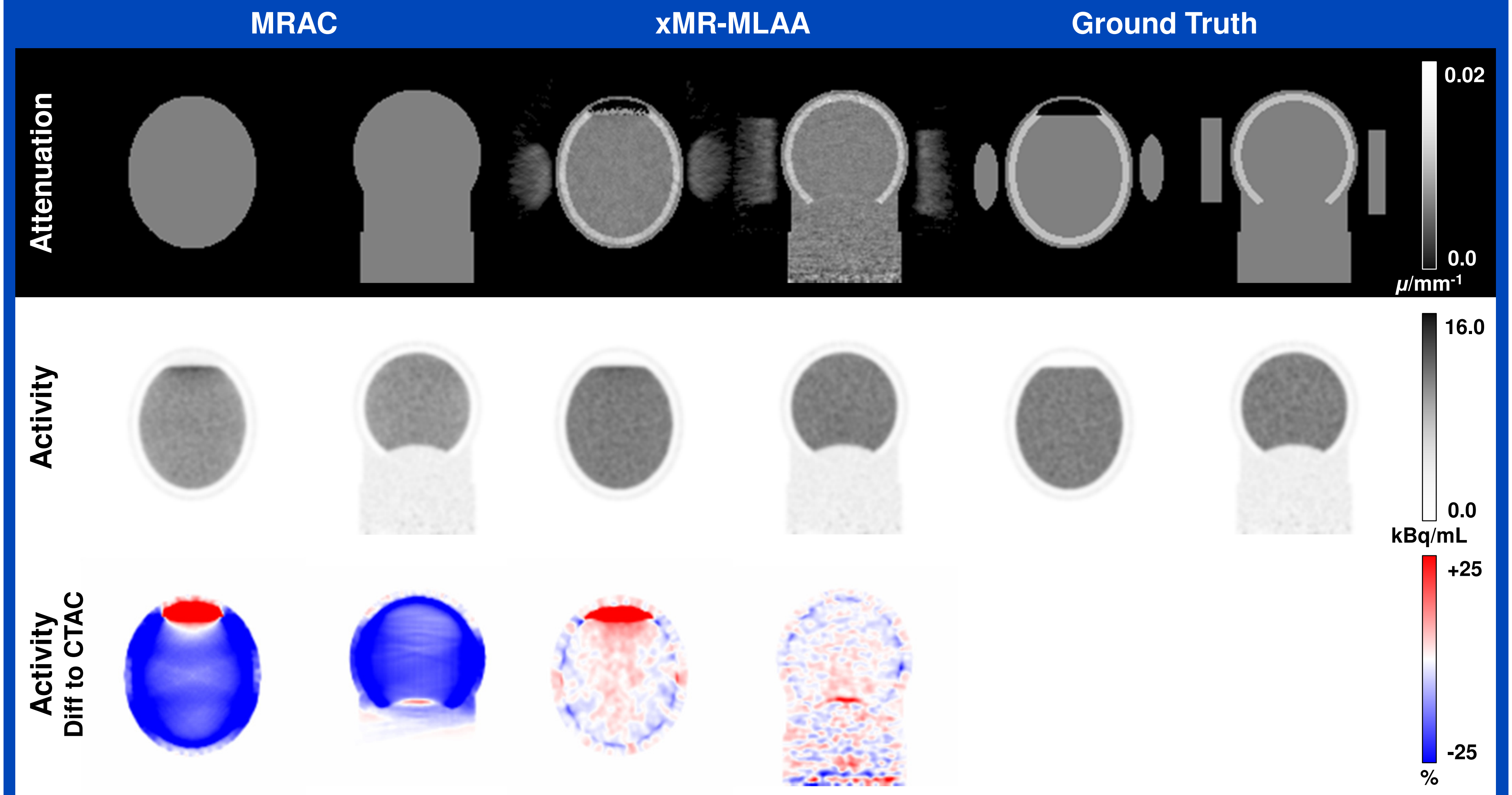
xMR-MLAA: Simulation Study
Without Hardware



dkfz.

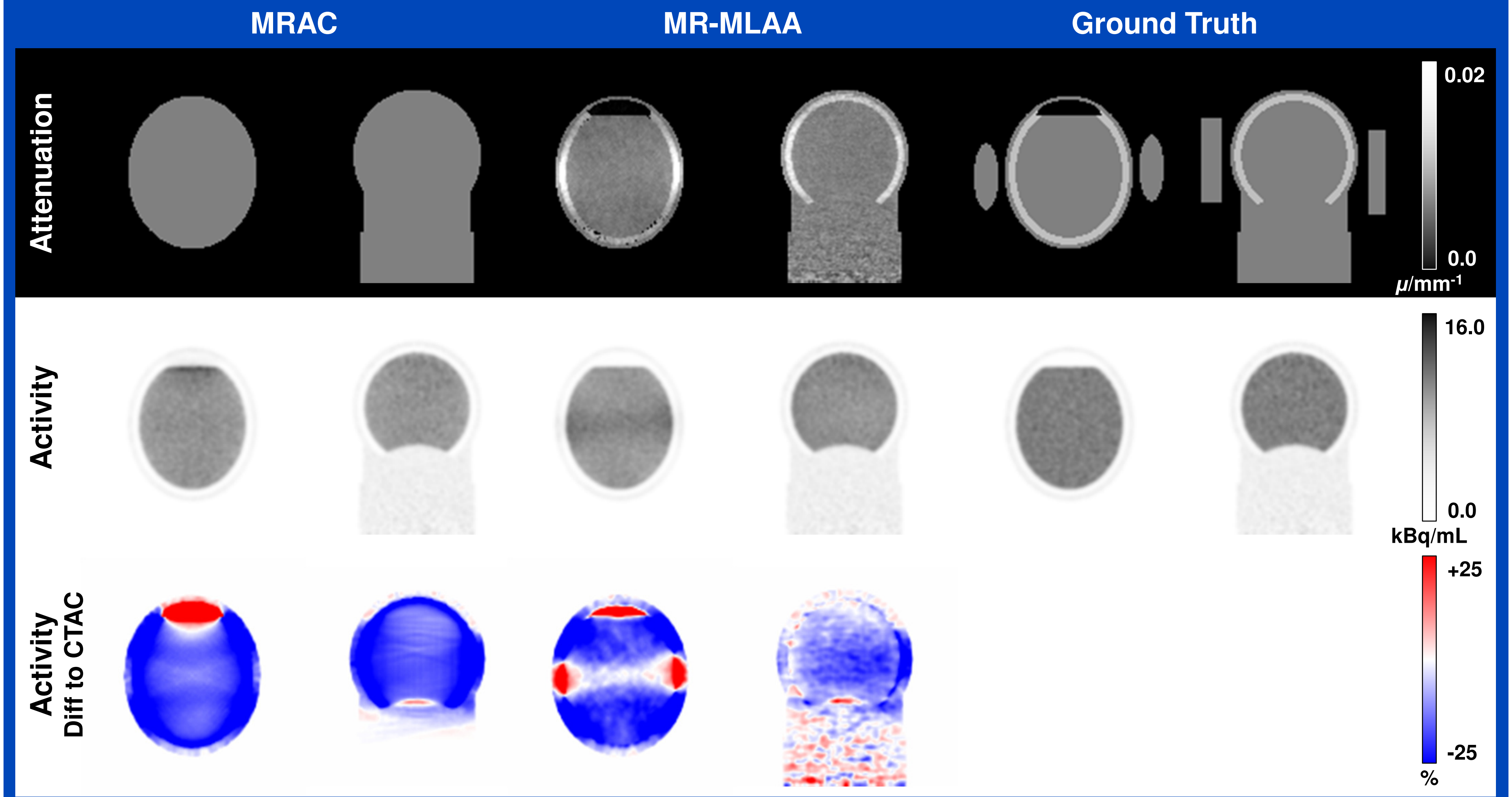
xMR-MLAA: Simulation Study

With Hardware



xMR-MLAA: Simulation Study

Neglecting Hardware in MR-MLAA



dkfz.

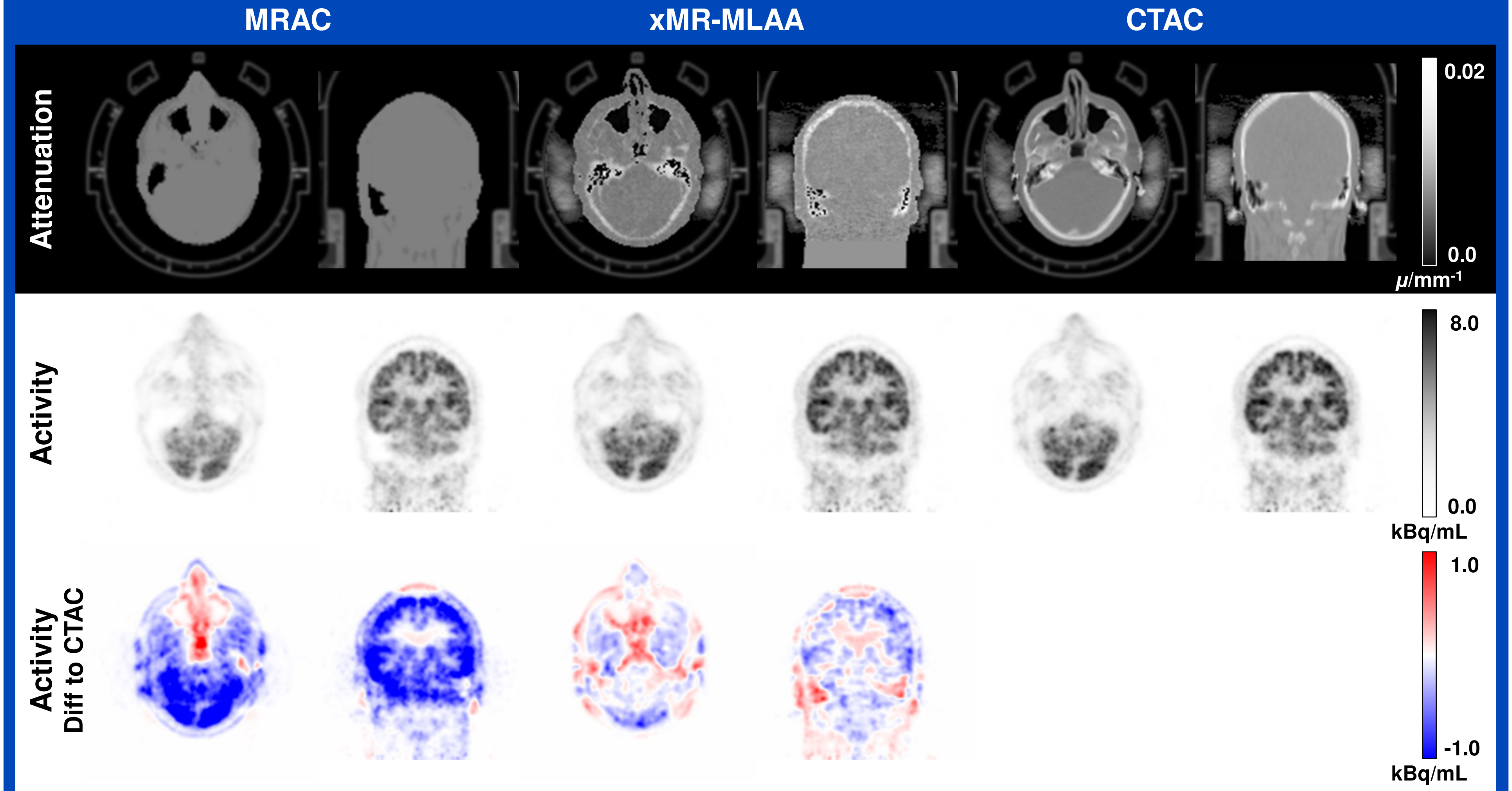
xMR-MLAA

Patient Data

- Clinical non-TOF ^{18}F-FDG-PET/MR data of the head region acquired with a Siemens Biograph mMR
- Attenuation correction
  - MRAC: standard MR-based AC
  - xMR-MLAA: proposed method
  - CTAC: CT-derived AC
- Perform OSEM reconstructions using
  - 3 iterations
  - 21 subsets
  - Gaussian post-smoothing (σ = 2.0 mm)
- Limitation
  - MR hardware components are not present in the CT-based attenuation maps. Therefore, we added the xMLAA-based hardware estimates to the CT-based attenuation maps.

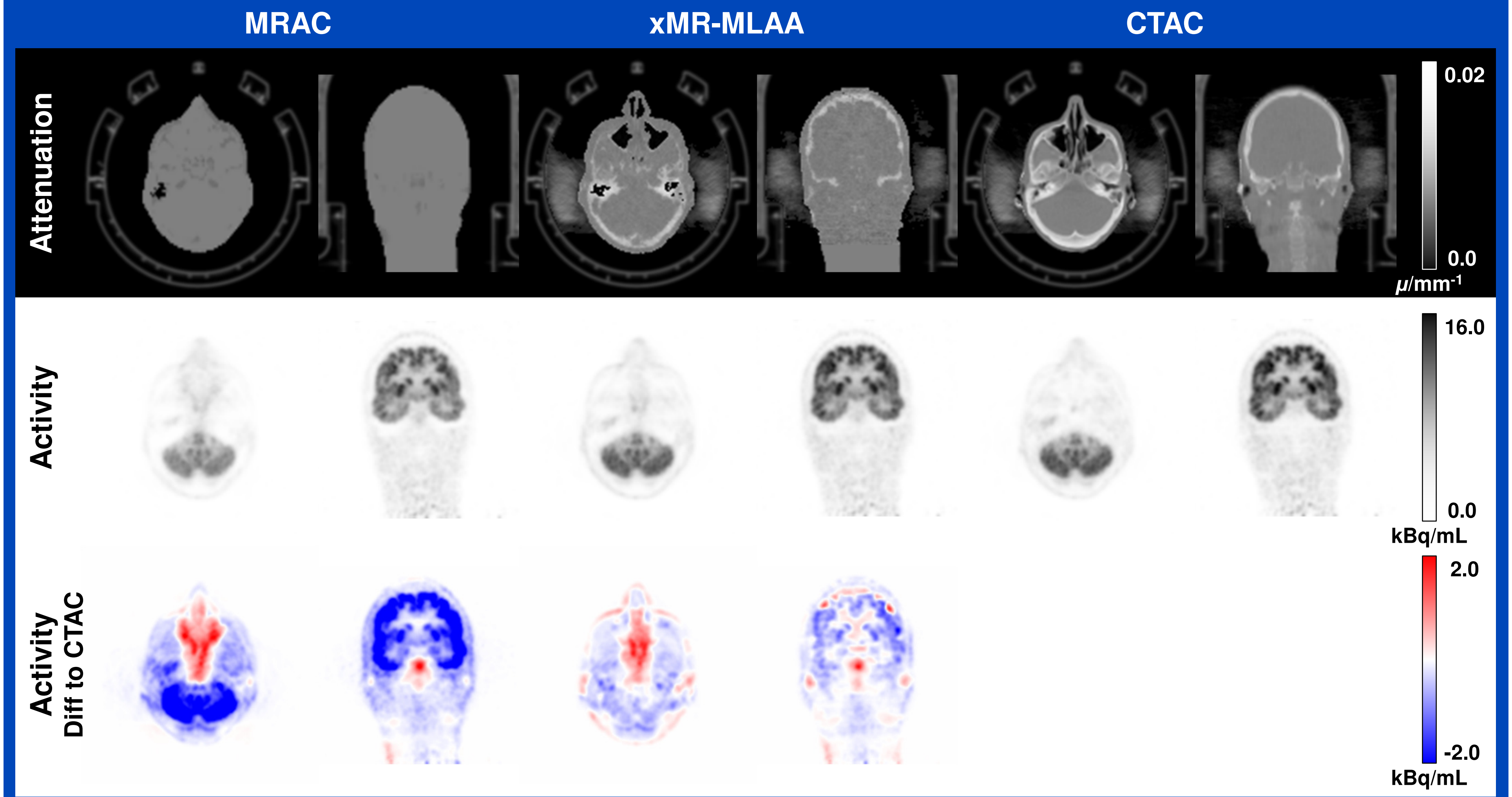
xMR-MLAA

Results: Patient 1



xMR-MLAA

Results: Patient 2



xMR-MLAA

Conclusion

- xMR-MLAA can be employed to jointly estimate both hardware and patient attenuation from the non-TOF PET emission data.
- Patient data show that standard MRAC may result in severe activity underestimation, e.g., around 15% on average for the entire brain if patients wear headphones.
- xMR-MLAA has the potential to reduce the activity underestimation to below 5%.
- TOF information, that was not available for this study, can potentially be incorporated into xMR-MLAA and should yield even better performance.


• Job opportunities through DKFZ's international PhD or Postdoctoral Fellowship programs (www.dkfz.de), or directly through marc.kachelriess@dkfz.de.
• This work was supported by the Helmholtz International Graduate School for Cancer Research, Heidelberg, Germany. Parts of the reconstruction software were provided by RayConStruct® GmbH, Nürnberg, Germany.
Thank You!