Emission-based Joint Estimation of Patient and Hardware Attenuation Distributions for Hybrid PET/MR Imaging

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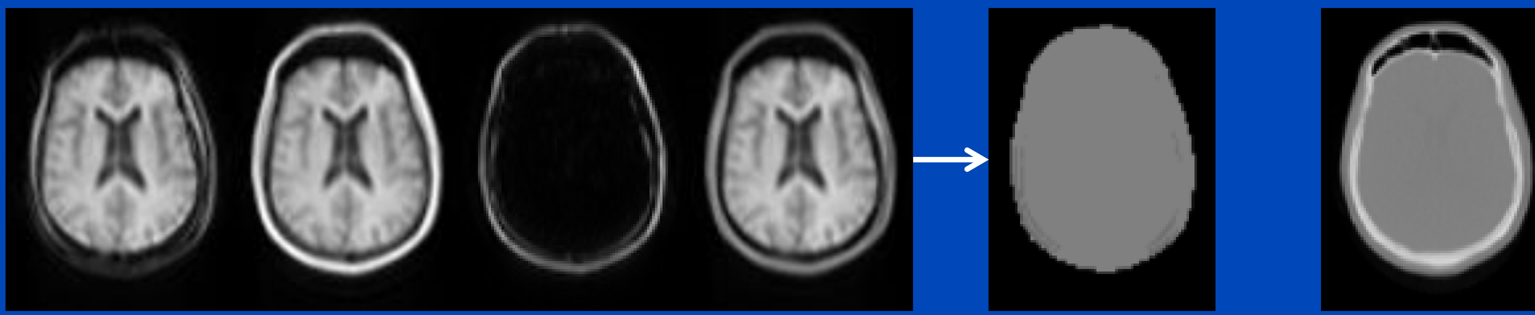
IN DER HELMHOLTZ-GEMEINSCHAFT

xMR-MLAA



- **Motivation**
  - MRAC underestimates hardware and bone attenuation
  - MRAC underestimates patient activity
- **Aim**
  - To improve patient AC for non-TOF PET/MR (e.g., Siemens mMR)
- **Proposed algorithm**
  - Extension of MR-MLAA: MR-based maximum-likelihood reconstruction of attenuation and activity (MLAA[1])

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

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

MR-MLAA[1]

- 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

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

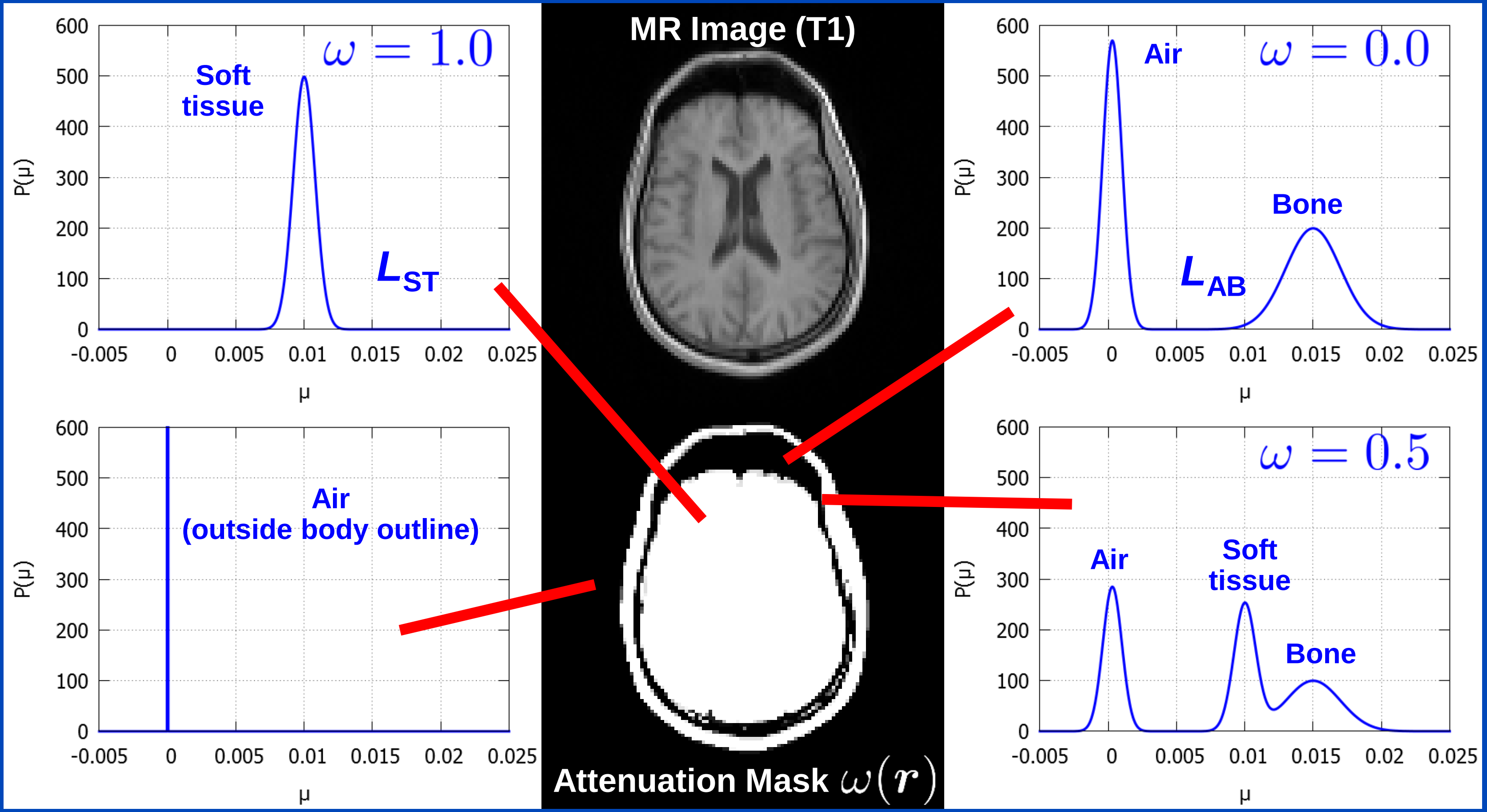
λ = activity
μ = attenuation

- 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] Heußer, Rank, Freitag, Dimitrakopoulou-Strauss, Schlemmer, Beyer, and 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 used β_{ST} = 0.1 and β_{AB} = 0.6 in our experiments.

(x|MR)-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]**

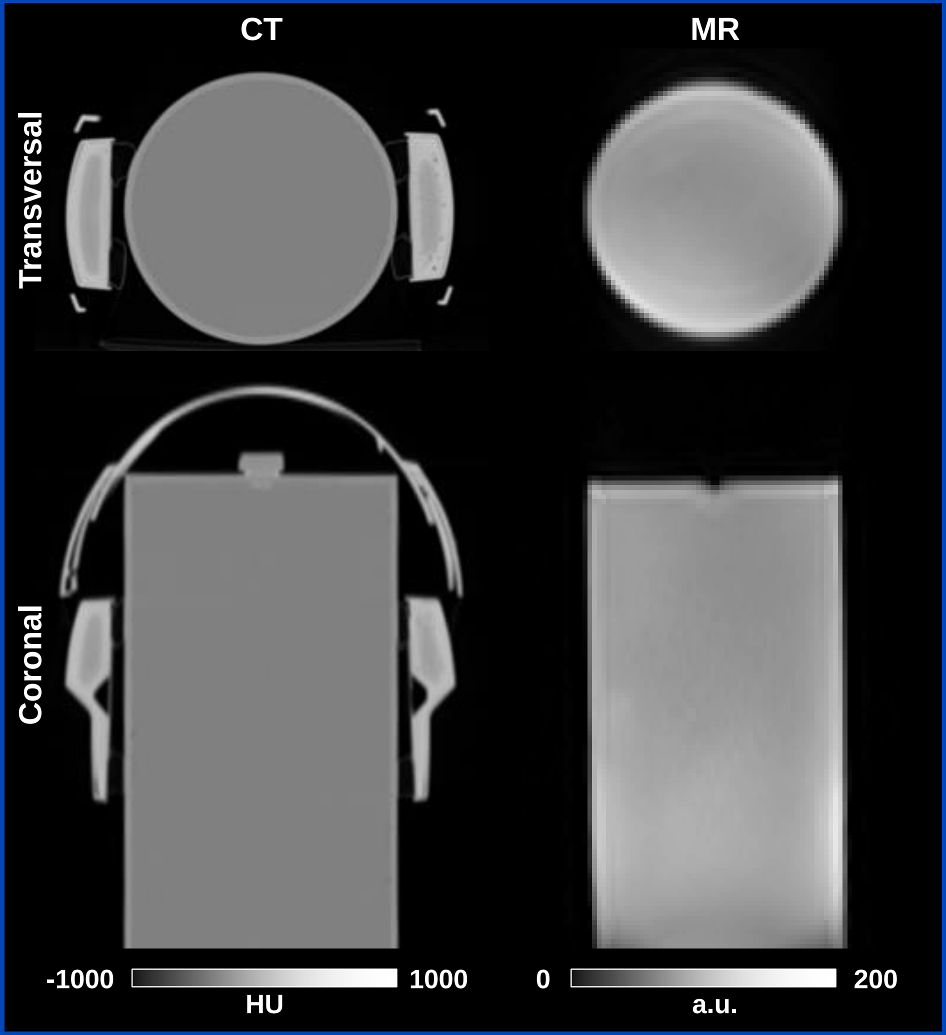
$$\mu_i^{(n+1)} = \mu_i^{(n)} + \alpha \frac{\sum_j \left(l_{ij} (\hat{p}_j^{(n)} - p_j) \frac{\hat{p}_j^{(n)} - s_j/n_j - r_j}{\hat{p}_j^{(n)}} \right) + \frac{\partial}{\partial \mu_i} (L_\mathrm{S} + L_\mathrm{I})}{\sum_j \left(l_{ij} (\hat{p}_j^{(n)} - \frac{s_j}{n_j} - r_j) \left(1 - \frac{p_j (s_j/n_j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

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," JCAT 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).

xMLAA[1]

- **Flexible hardware components are currently neglected in MR-based AC**
  - Headphones
  - Radiofrequency coils
  - Positioning aids
  - …
- **Aim**
  - Estimate attenuation of flexible hardware from the PET emission data

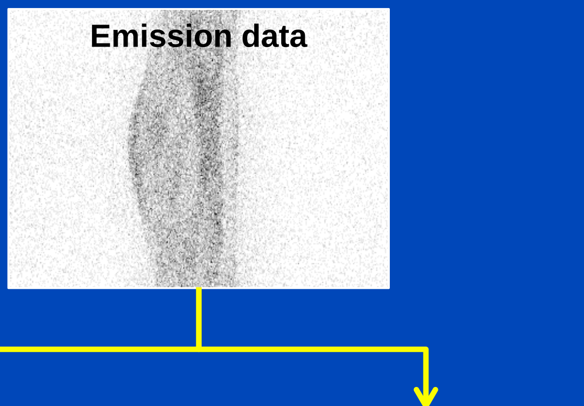


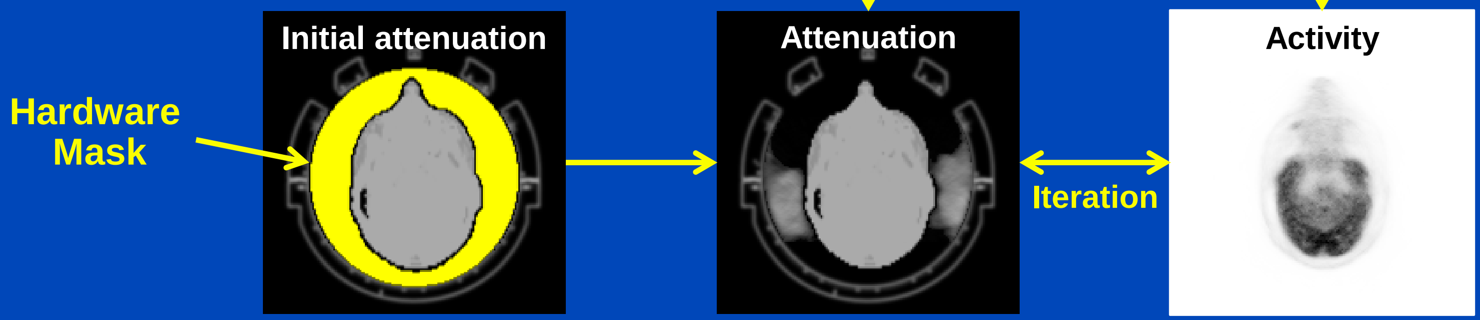
[1] Heußer, Rank, Berker, Freitag, and Kachelrieß, "MLAA-based Attenuation Correction of Flexible Hardware Components in Hybrid PET/MR Imaging," EJNMMI Physics 4:12 (2017).

xMLAA[1]

Algorithm

- **Joint estimation of attenuation and activity**
  - **Based on the MLAA algorithm**
- **Attenuation map updated only within hardware mask**
  - **“External” MLAA or xMLAA**
- **Patient attenuation distribution and stationary hardware components assumed correct**

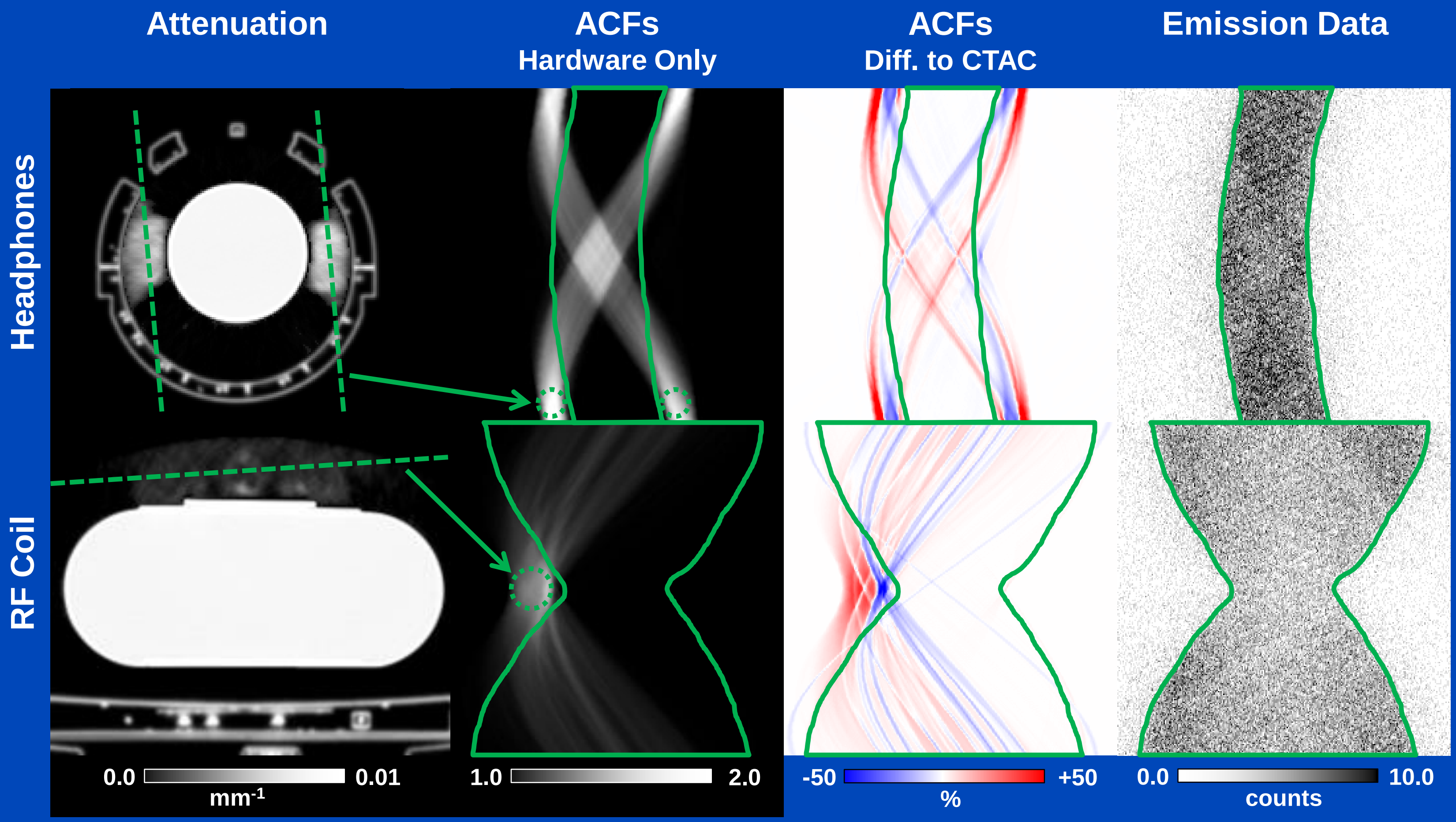




[1] Heußer, Rank, Berker, Freitag, and Kachelrieß, “MLAA-based Attenuation Correction of Flexible Hardware Components in Hybrid PET/MR Imaging,” EJNMMI Physics 4:12 (2017).

xMLAA

Attenuation Correction Factors



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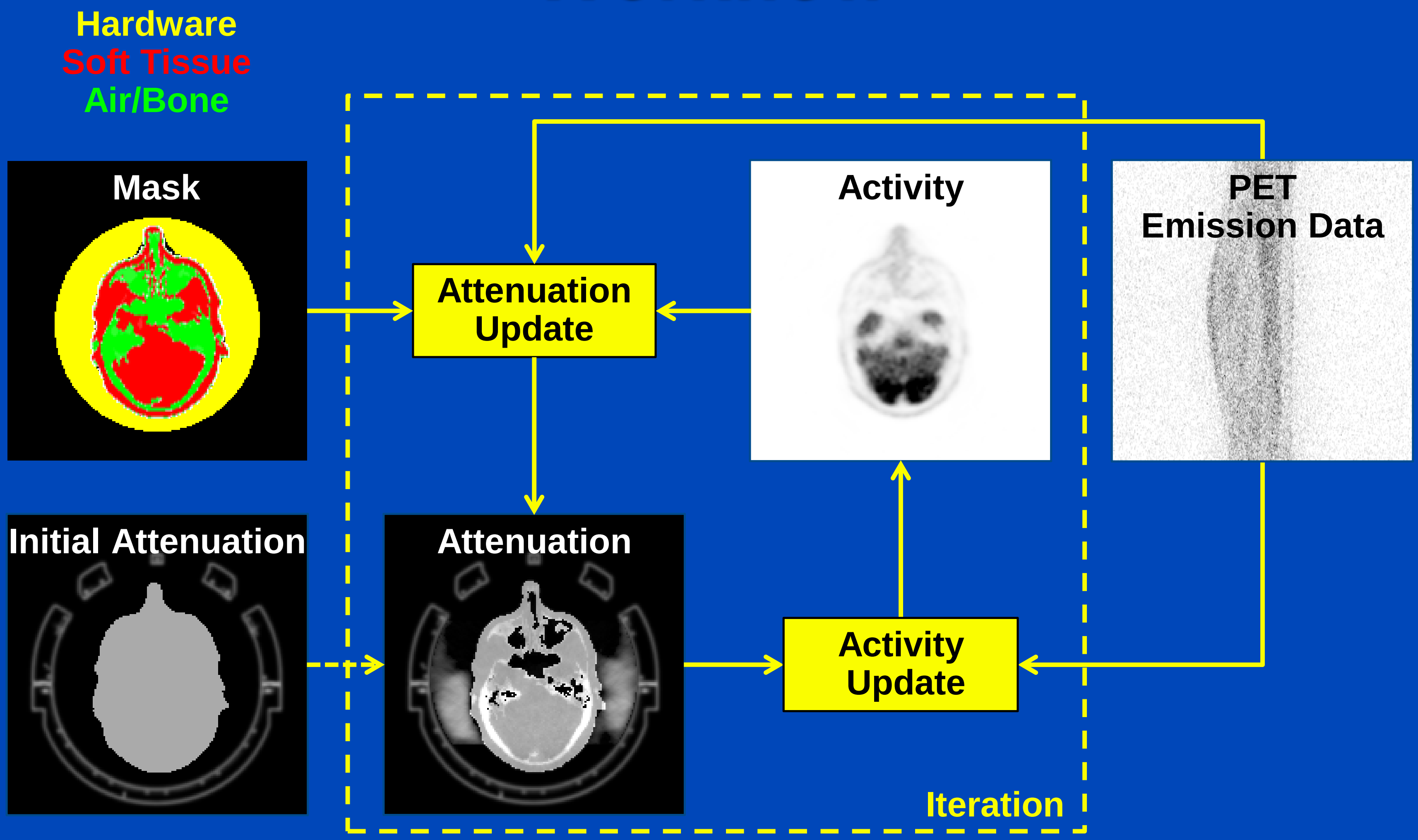
xMR-MLAA

- **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: Estimate patient activity, corrected for patient and hardware attenuation, by combining MR-MLAA and xMLAA to xMR-MLAA**

xMR-MLAA

Workflow



xMR-MLAA

Algorithm

- Hardware and patient attenuation are updated sequentially
- Hardware update
  - xMLAA (MLEM + xPrior-MLTR)
  - 2 iterations, 21 subsets
- Patient update
  - MR-MLAA (MLEM + MR-Prior-MLTR)
  - 3 Iterations, 21 subsets
- Intensity prior

Hardware
Soft Tissue
Air/Bone

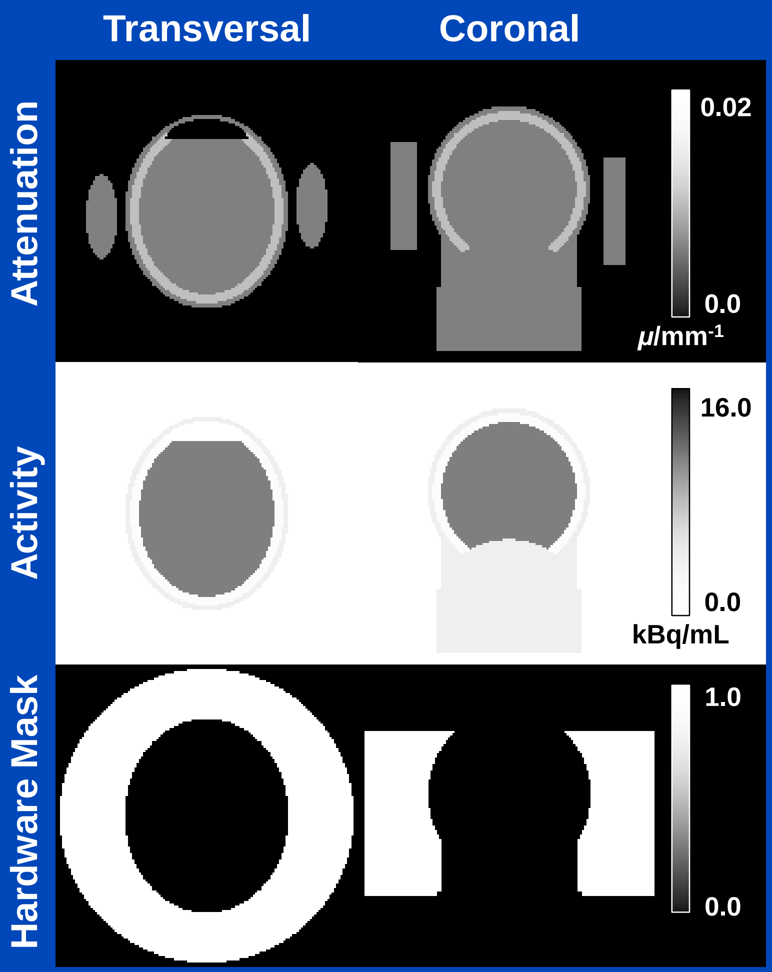
$$L_{\mathrm{I}}(\boldsymbol{\mu}) = \omega_{\mathrm{x}}(\boldsymbol{r})\beta_{\mathrm{x}}L_{\mathrm{x}}(\boldsymbol{\mu}) + (1-\omega_{\mathrm{x}}(\boldsymbol{r}))L_{\mathrm{MR}}(\boldsymbol{\mu})$$

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

xMR-MLAA

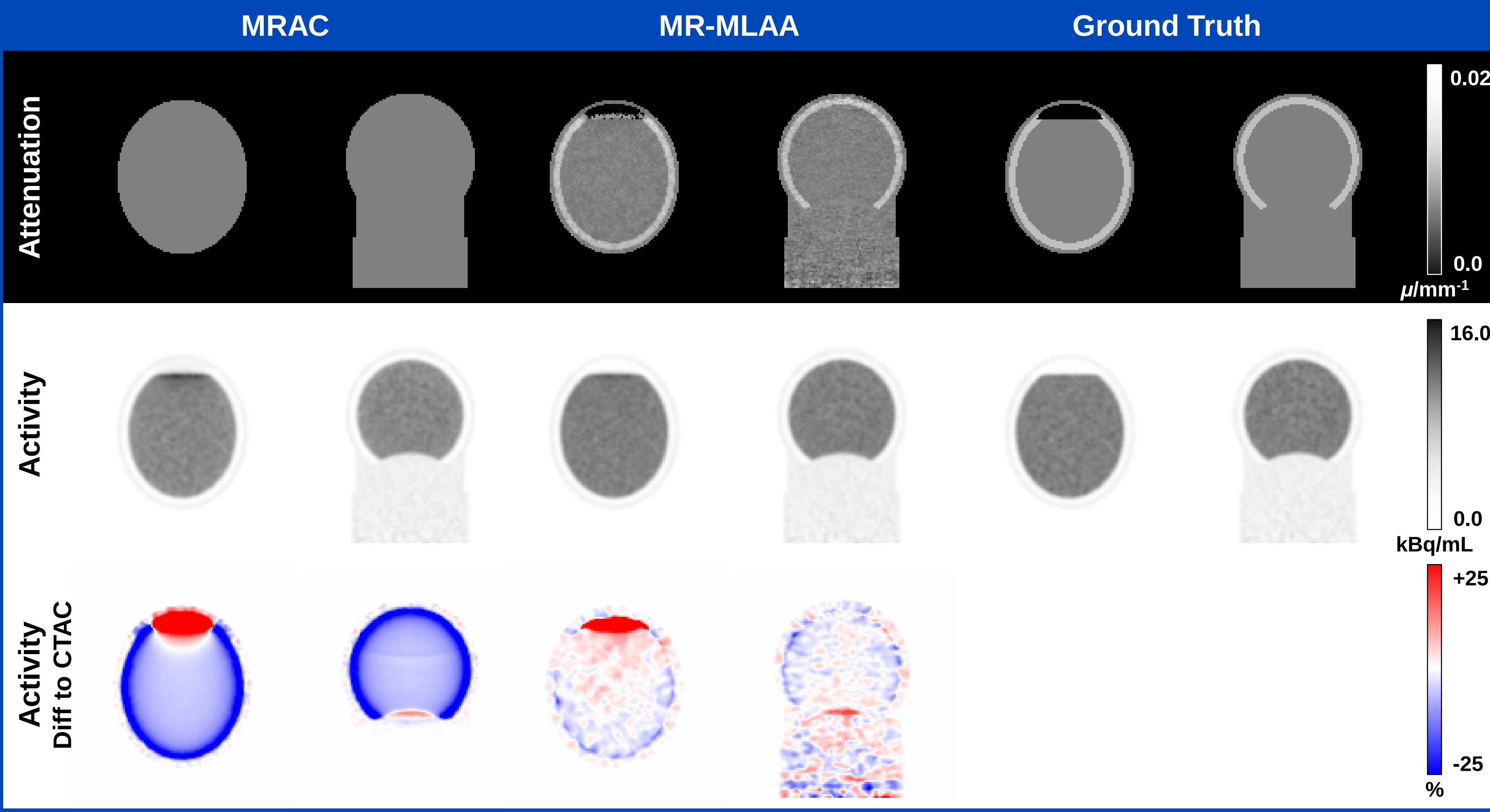
Simulation Study

- 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



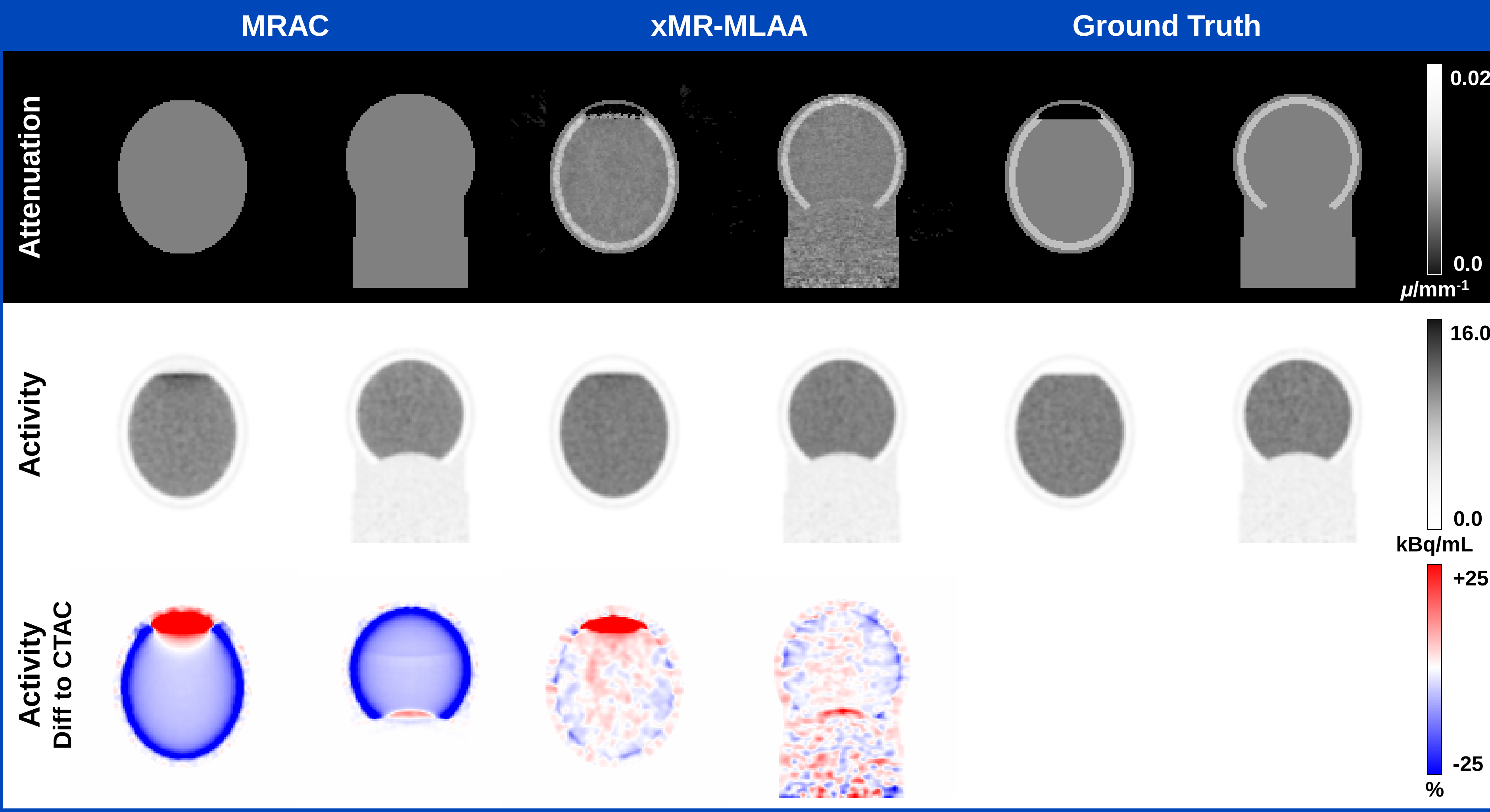
MR-MLAA: Digital Phantom

Without Hardware



xMR-MLAA: Digital Phantom

Without Hardware



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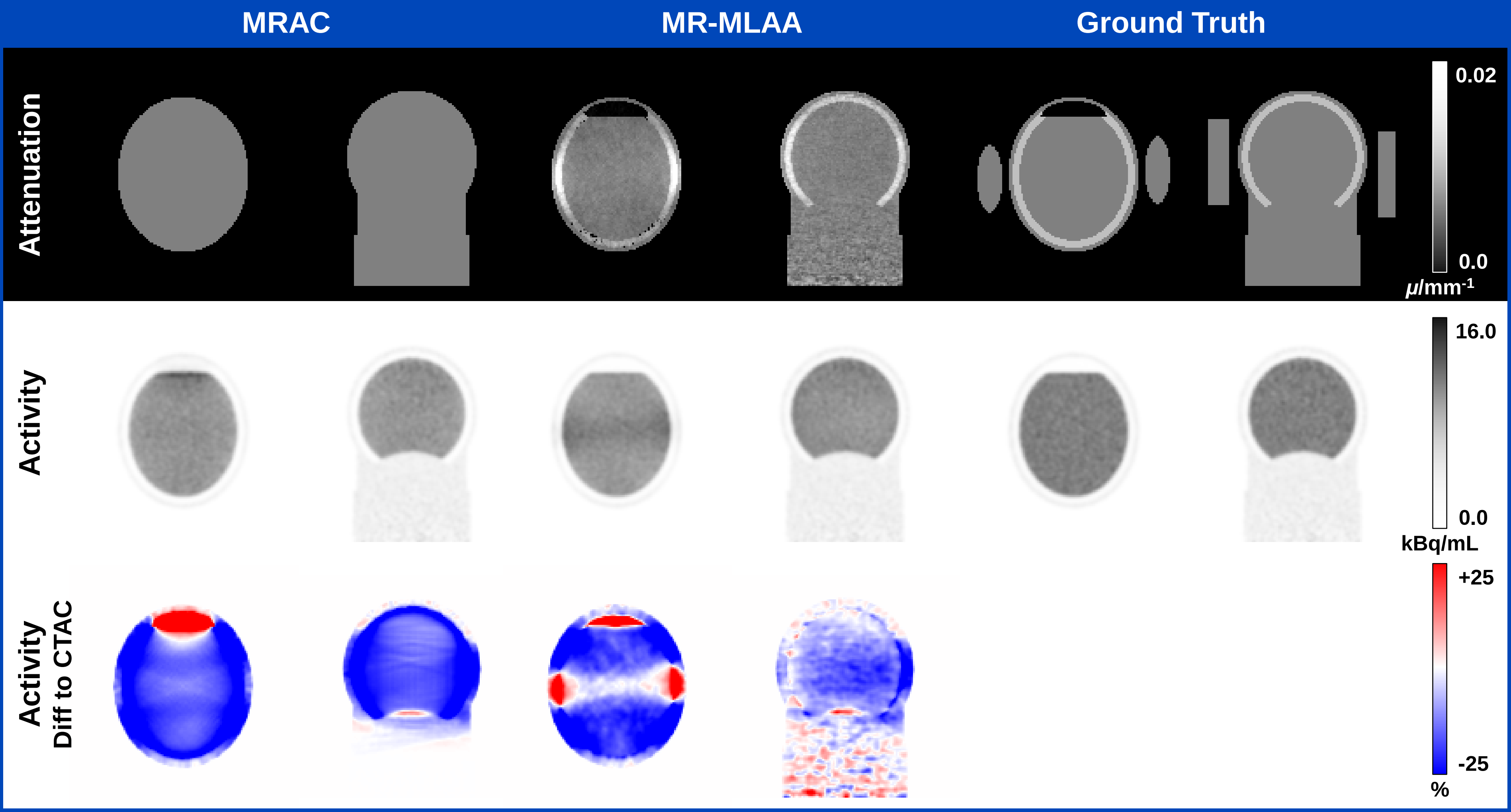
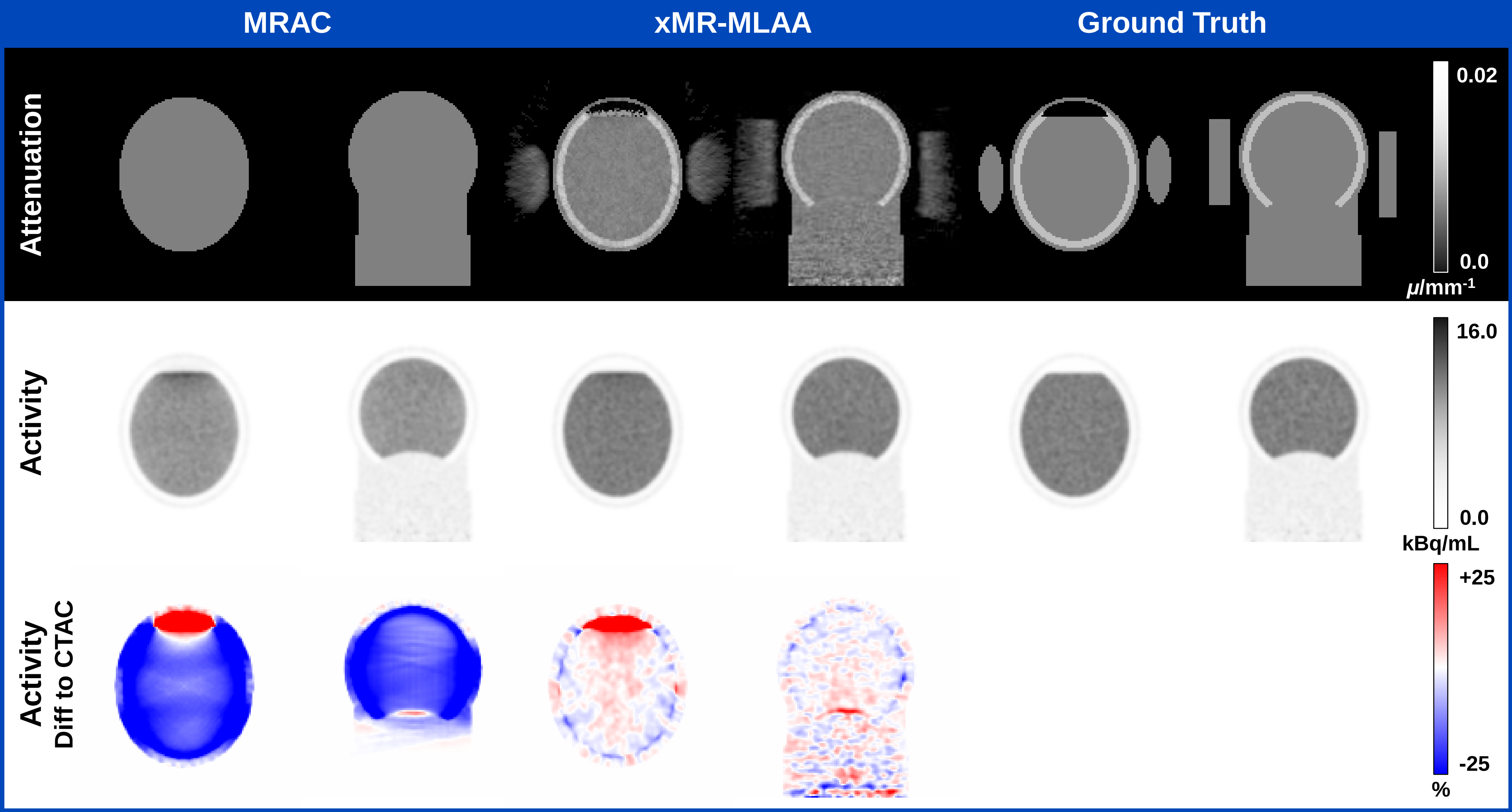
MR-MLAA: Digital Phantom
With Hardware, neglected



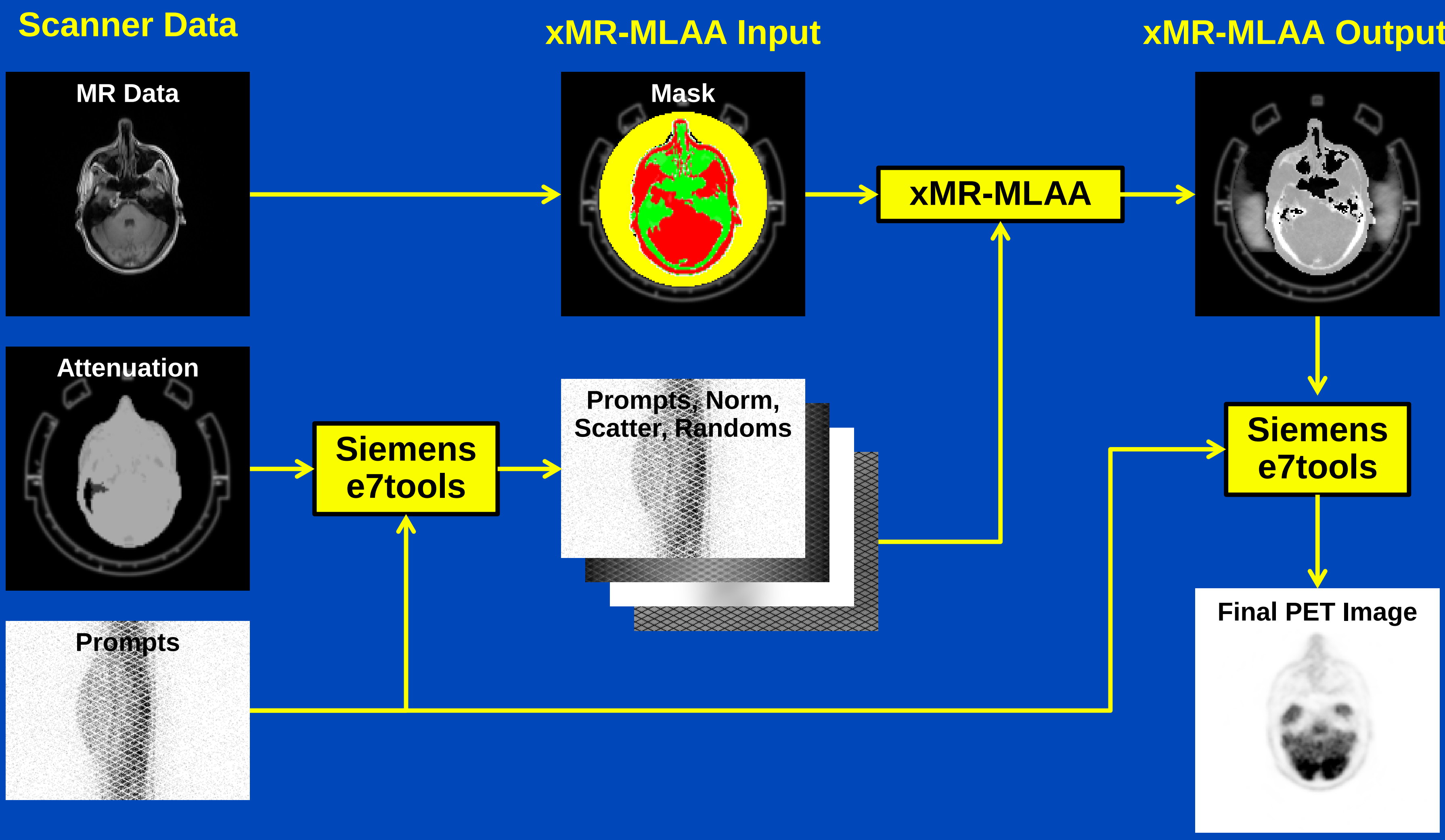
xMR-MLAA: Digital Phantom
With Hardware



xMR-MLAA
Patient Data

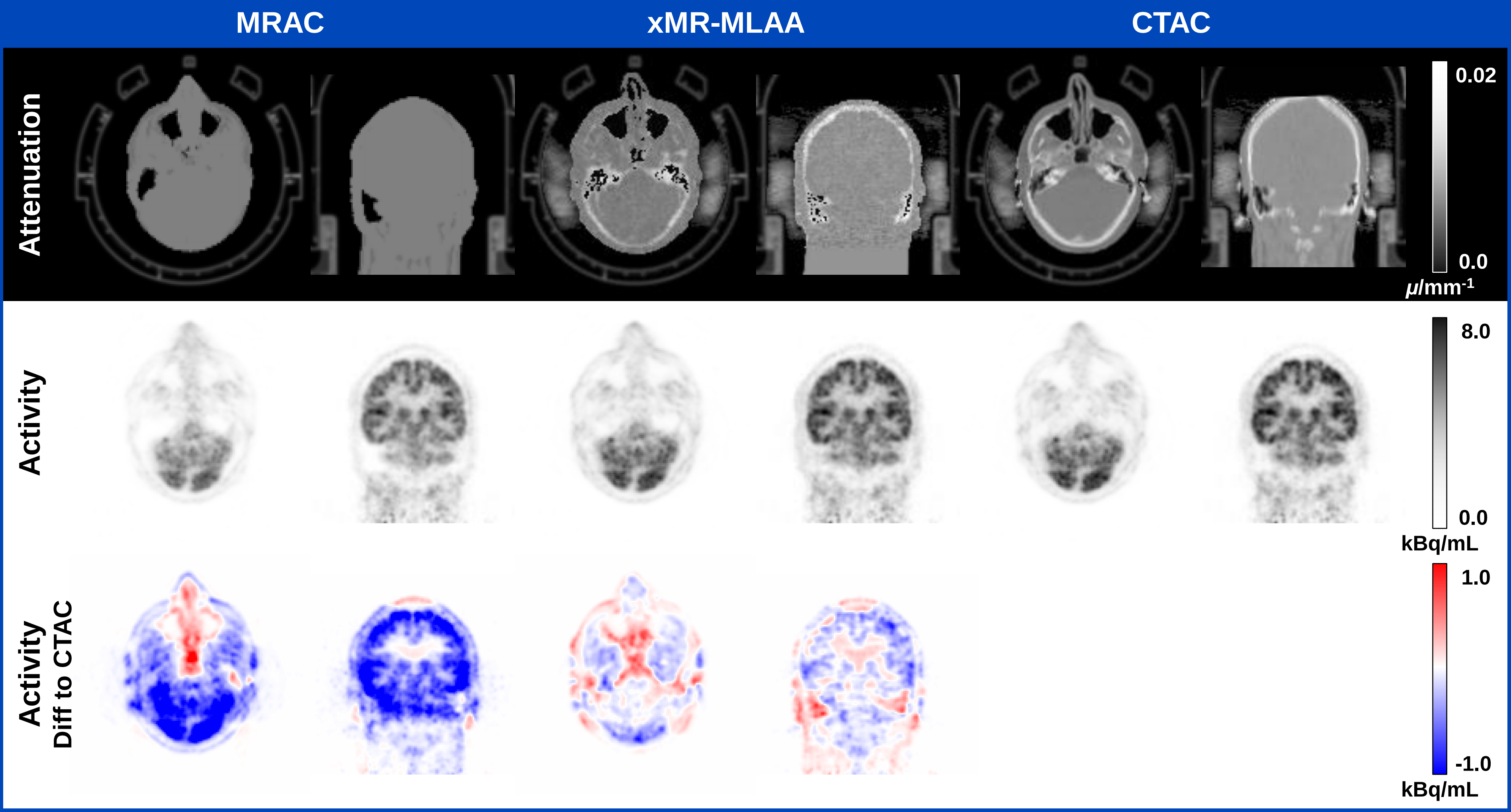
- Clinical non-TOF ^{18}F-FDG-PET/MR data of the head region acquired with a Siemens Biograph mMR
  - OSEM, 3 it., 21 subs., Gaussian smoothing (σ = 2 mm)
- Attenuation correction
  - MRAC: standard MR-based AC
  - xMR-MLAA: proposed method
  - CTAC: CT-derived AC
- Limitation
  - Ground truth CT-AC does not show MR hardware components
  - xMLAA-based hardware estimates added to CTAC

xMR-MLAA
Data Processing



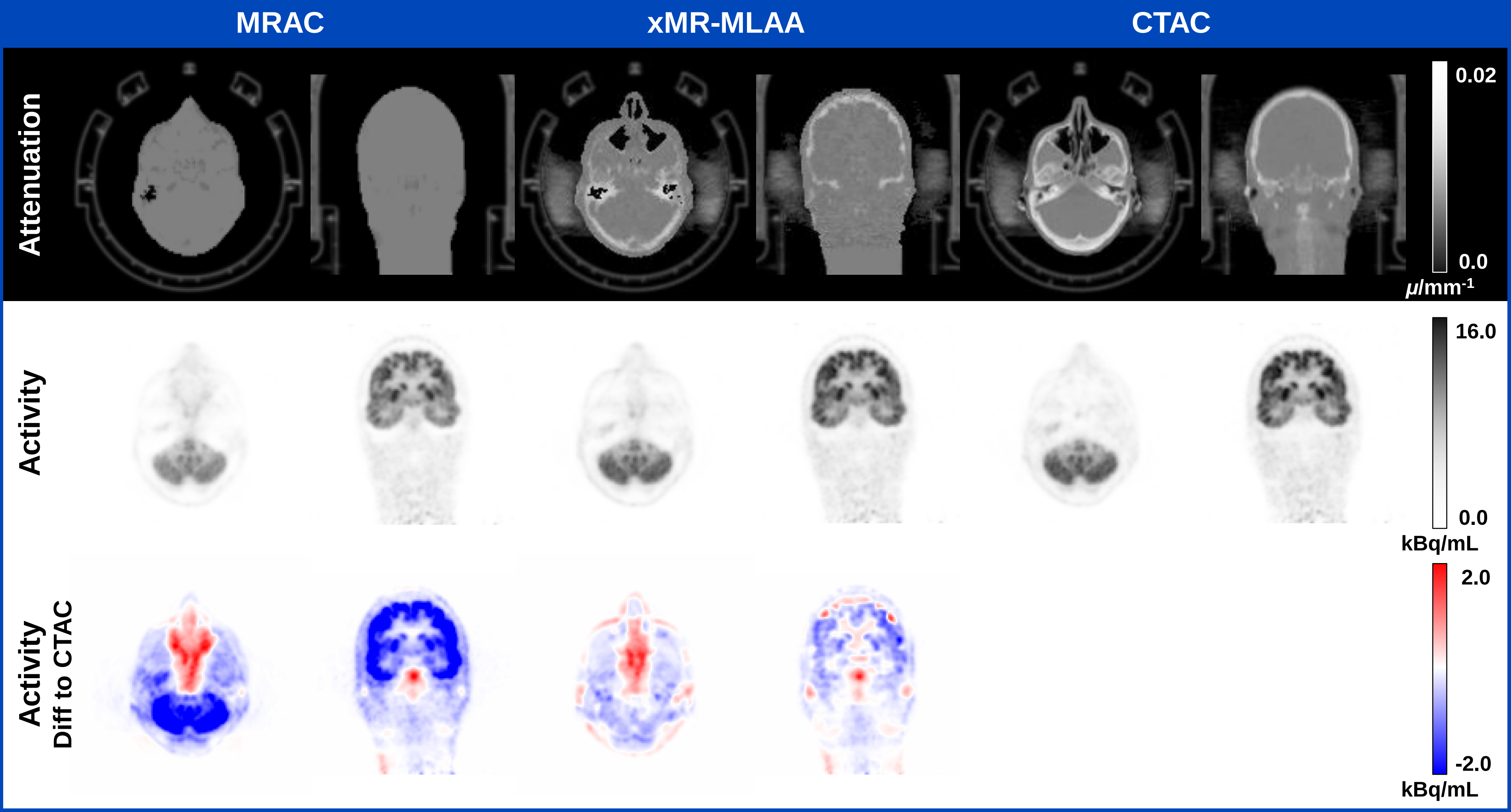
xMR-MLAA

Results: Patient 1



xMR-MLAA

Results: Patient 2



xMR-MLAA

Conclusion

- xMR-MLAA jointly estimates hardware and patient attenuation from non-TOF PET emission data
- Standard MRAC: ~15% patient activity underestimation with headphones
- xMR-MLAA: < 5% patient activity error, despite challenging MR segmentation in paranasal sinuses
- TOF information is expected to improve performance: in particular, in MR-MLAA

Job opportunities through our International PhD or Postdoc programs (www.dkfz.de), or through marc.kachelriess@dkfz.de.

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