Simultaneous Reconstruction of Attenuation and Activity for non-TOF PET/MR Using MR Prior Information

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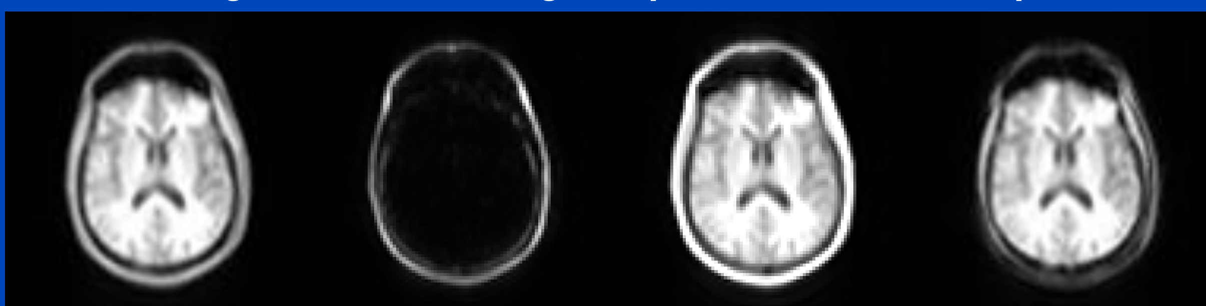
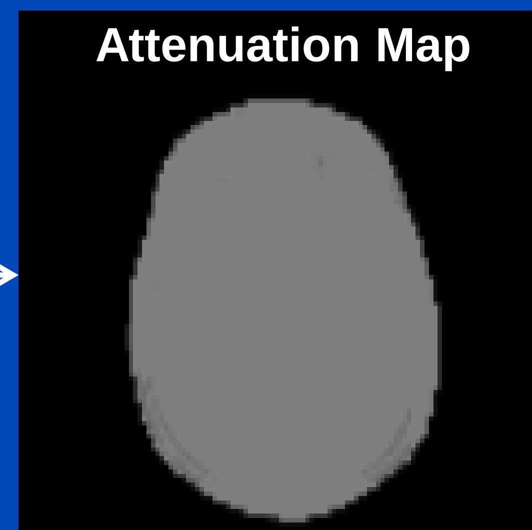
Introduction
Motivation

- Quantitative PET imaging requires accurate attenuation correction (AC).
- Standard MR-based attenuation correction (MRAC) neglects bone attenuation.

MR images obtained using two-point Dixon VIBE sequence





- Neglecting bone yields activity underestimation values of up to 30%[1].

[1] Samarin *et al.*, “PET/MR imaging of bone lesions - implications for PET quantification from imperfect attenuation correction,” *Eur. J. Nucl. Med. Mol. Imaging*, 39(7), 1154–60, 2012.

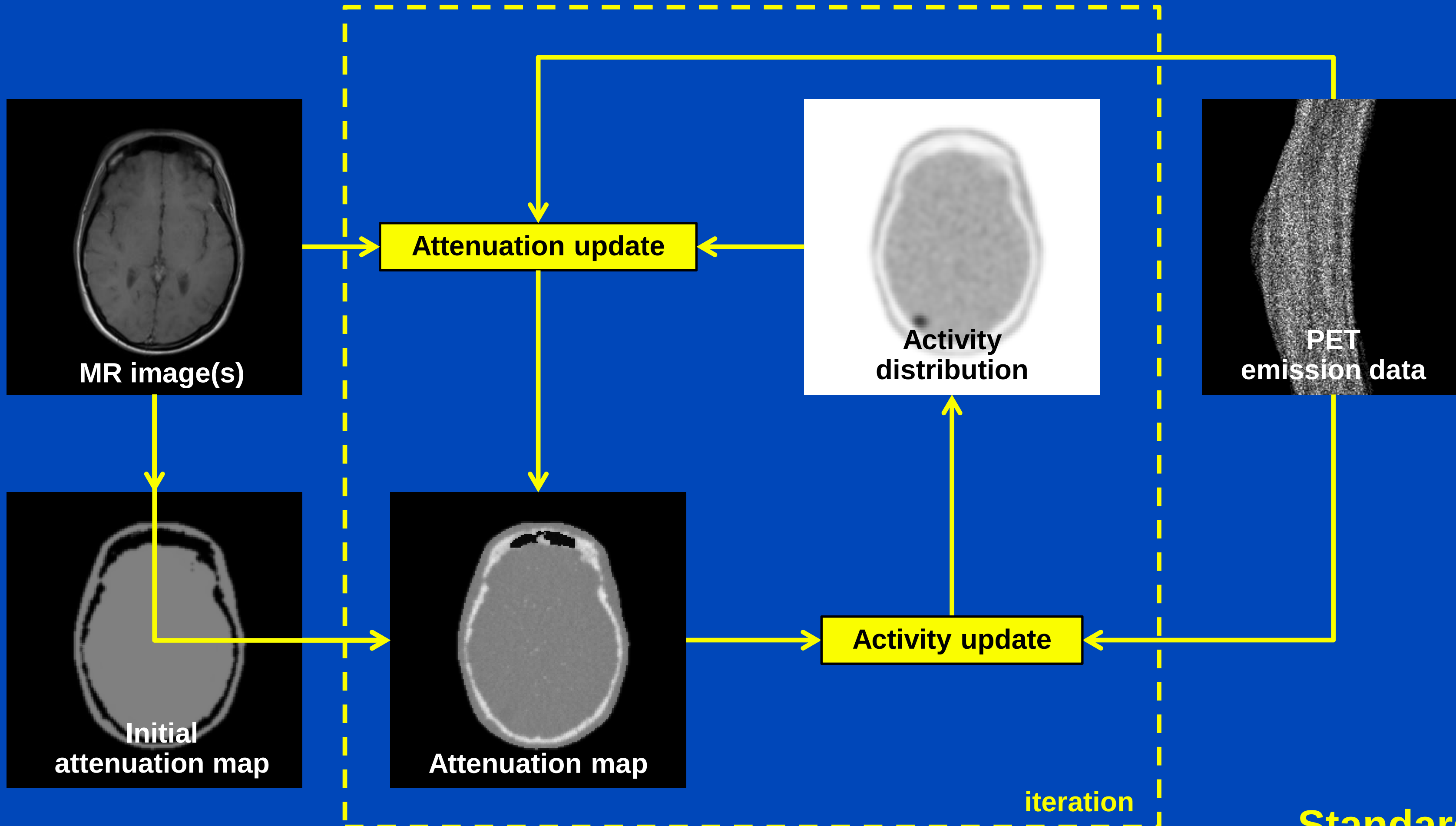
Introduction
Aim

- Improve AC for non-TOF PET/MR by simultaneous reconstruction of attenuation and activity distributions from PET emission data using MR prior information.

- The presented algorithm is an extension of the maximum-likelihood reconstruction of attenuation and activity (MLAA)[1] for non-TOF PET/MR, called **MR-MLAA**.

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

Algorithm
Workflow



Standard
MR-based AC
MLAA

Algorithm
Cost Function

- Cost function *C*

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

- Log-likelihood *L*

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

with $\hat{p}_j = e^{-\sum_i \mu_i l_{ij}} \sum_i \lambda_i M_{ij}$

- Smoothing prior L_S
- Intensity prior L_I

$\boldsymbol{\lambda}$ Activity

$\boldsymbol{\mu}$ Attenuation

p_j Measured projections along LOR *j*

l_{ij} Intersection length of voxel *i* and LOR *j*

M System matrix

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Algorithm

Update Equations

- **Activity Update (AW-MLEM)**

$$\lambda_i^{(n+1)} = \lambda_i^{(n)} \frac{1}{\sum_j M_{ij}\, a_j^{(n)}} \sum_j M_{ij} \frac{p_j}{\sum_i \lambda_i^{(n)} M_{ij}}$$

- **Attenuation Update[1]**

$$\mu_j^{(n+1)} = \mu_j^{(n)} + \alpha \frac{\sum_j \left(M_{ij}\left(a_j^{(n)} \sum_i \lambda_i^{(n)} M_{ij} - p_j\right)\right) + \frac{\partial}{\partial \mu_i}(L_\mathrm{S} + L_\mathrm{I})}{\sum_j \left(M_{ij} a_j^{(n)} \sum_i \lambda_i^{(n)} M_{ij} \sum_i l_{ij}\right) - \frac{\partial^2}{\partial \mu_i^2}(L_\mathrm{S} + L_\mathrm{I})}$$

Prior

with attenuation factor $a_j^{(n)} = e^{-\sum_i \mu_i^{(n)} l_{ij}}$

i	Voxel index	λ	Activity	n	Iteration number	l_{ij}	Intersection length of voxel *i* and LOR *j*
j	LOR index	μ	Attenuation	M	System matrix	α	Relaxation parameter

[1] Nuyts *et al.*, "Iterative reconstruction for helical CT: a simulation study," *Phys. Med. Biol.*, 43(4), 729–737, 1998.

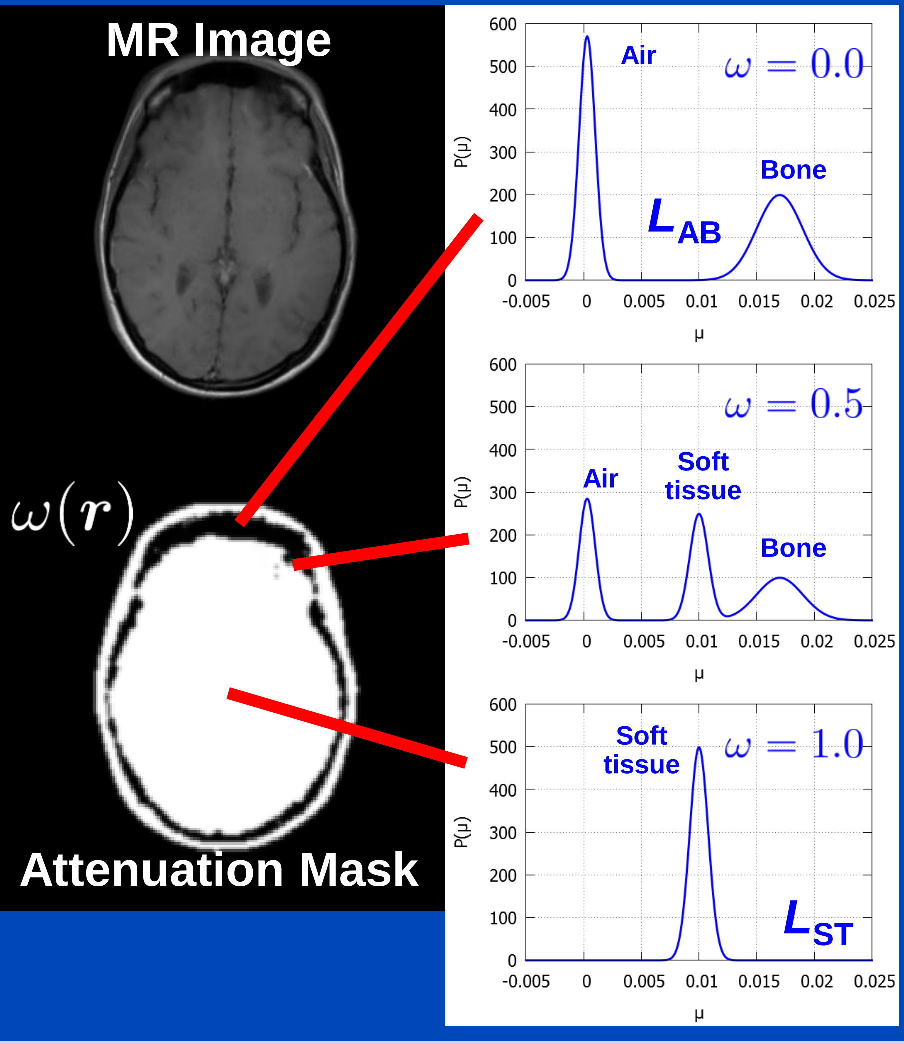
Algorithm

Prior Information

- Optimizing the cost function $C(\lambda, \mu)$ with both the activity and attenuation distribution unknown is an ill-conditioned problem.
- Prior information can help to drive the algorithm towards a ‘desired’ solution.
- Smoothing prior L_S
  - Favors smooth attenuation map
  - Defined as logarithm of a Gibbs probability distribution
- Intensity prior L_I
  - Voxel-dependent Gaussian-like probability distribution of pre-defined attenuation coefficients (e.g., for soft tissue, air, bone)
  - Voxel-dependency is based on the MR information

Algorithm

Intensity Prior I



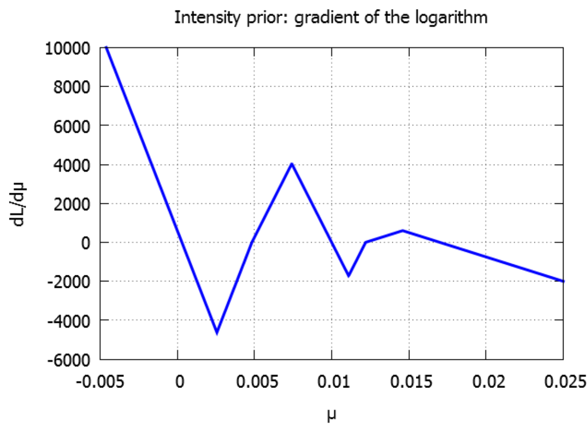
- **Use the MR image to create a mask defining air/bone and soft tissue**
- **Smooth mask**
- **Define intensity prior L_I as linear combination of air/bone intensity prior L_{AB} and soft tissue intensity prior L_{ST}:**

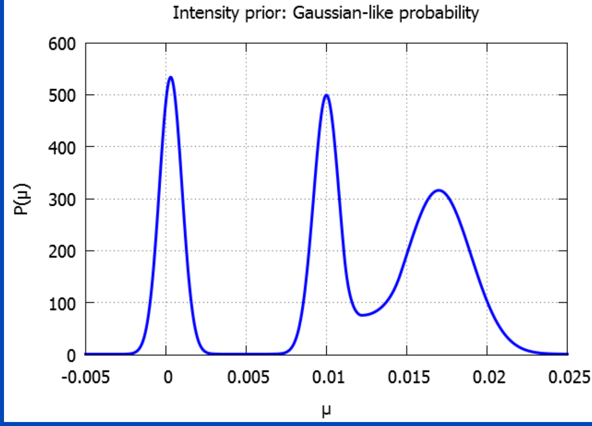
$$L_{\mathrm{I}} = (1-\omega)\beta_{\mathrm{AB}} L_{\mathrm{AB}} + \omega \beta_{\mathrm{ST}} L_{\mathrm{ST}}$$

$\omega(\boldsymbol{r})$ **Voxel-dependent weighting factor, given by the attenuation mask**

$\beta_{\mathrm{AB}},\ \beta_{\mathrm{ST}}$ **Global weighting factors**

Algorithm
Intensity Prior II





- **Express the priors L_{AB} and L_{ST} as a combination of Gaussian-like functions and choose S pre-defined attenuation coefficients for each prior.**
  - **Air/Bone:** $S = 2;\ \bar{\mu}_{\text{air}} \pm \sigma_{\text{air}},\ \bar{\mu}_{\text{bone}} \pm \sigma_{\text{bone}}$
  - **Soft tissue:** $S = 1;\ \bar{\mu}_{\text{soft tissue}} \pm \sigma_{\text{soft tissue}}$
- **Define the gradient of the logarithm**

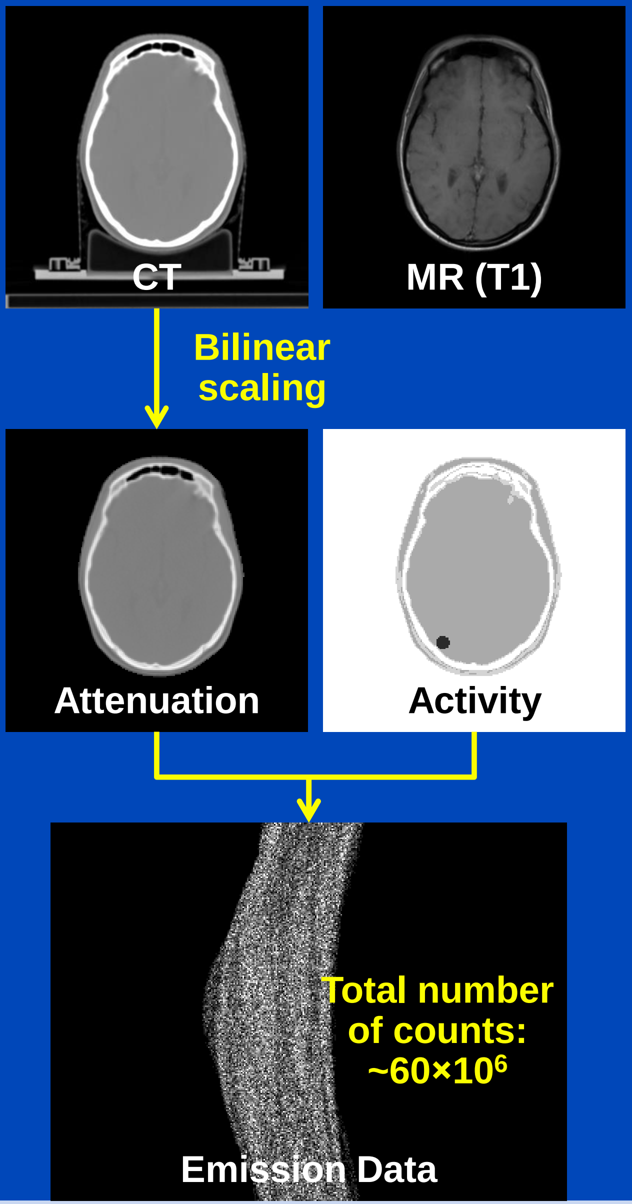
$$\frac{\partial L_{\text{AB/ST}}(\mu, \bar{\mu}_s; s=0,\cdots,S-1)}{\partial \mu} = \begin{cases} \frac{\mu - t_s}{\sigma_s^2} & \text{if } t_s < \mu \leq \frac{t_s + \bar{\mu}_s}{2} \\ -\frac{\mu - \bar{\mu}_s}{\sigma_s^2} & \text{else if } \frac{t_s + \bar{\mu}_s}{2} < \mu \leq \frac{t_{s+1} + \bar{\mu}_s}{2} \\ \frac{\mu - t_{s+1}}{\sigma_s^2} & \text{else if } \frac{t_{s+1} + \bar{\mu}_s}{2} < \mu \leq t_{s+1} \end{cases}$$

$\bar{\mu}_{s-1} < t_s < \bar{\mu}_s$ **Intersection points t_s between neighboring Gaussians**

Experiments

Data

- Use pair of co-registered MR/CT head patient data
- Simulate 3D activity distribution:
  - Fat/Soft tissue: 5-10 kBq/mL
  - Air/bone: 0 kBq/mL
  - Lesions: 25 kBq/mL
- Simulate 3D PET emission data accounting for
  - Poisson noise
  - attenuation
- Use Siemens Biograph mMR Geometry



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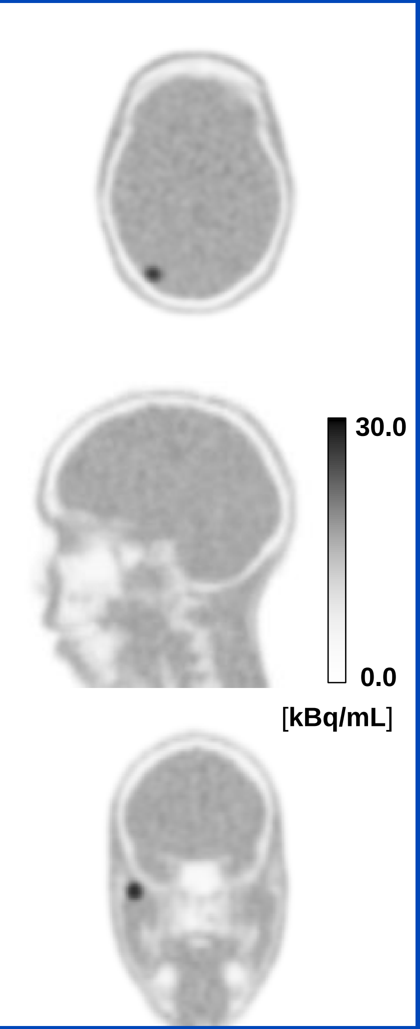
Experiments

Reconstructions

- **AW-OSEM reconstructions using**
  - the true attenuation for AC (ground truth)
  - standard MR-based AC (MRAC)
  - the final attenuation map from MR-MLAA for AC
    - » Mask derived from MR image (standard)
    - » Mask derived from attenuation image (idealized)
- **Reconstruction parameters:**
  - Iterations: 3
  - Subsets: 21
  - Gaussian post-smoothing: FWHM = 5 mm
- **Quantitative Evaluation**
  - Measure relative mean activity in ROIs corresponding to simulated lesions
  - Calculate activity difference to ground truth

Ground Truth



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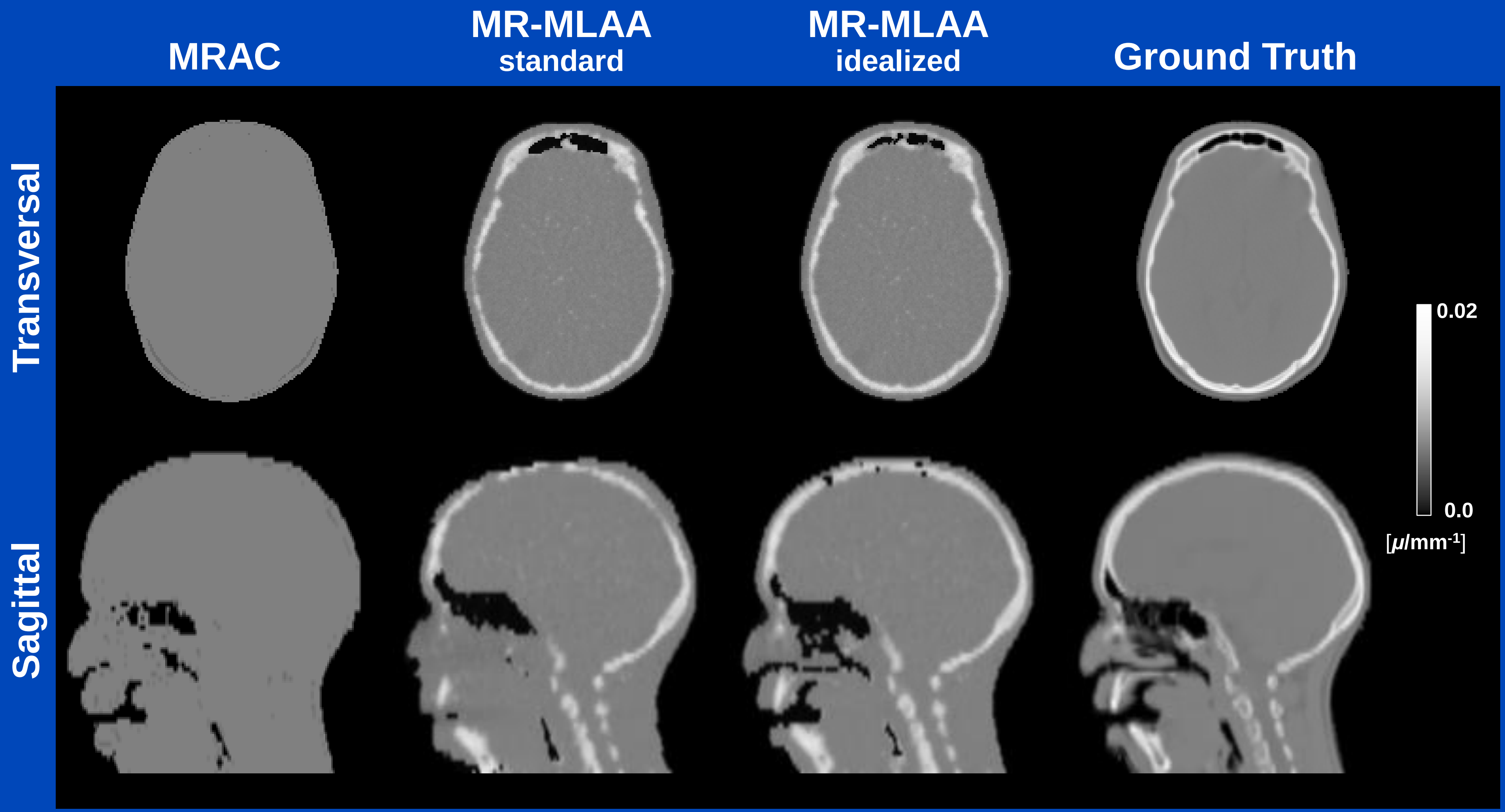
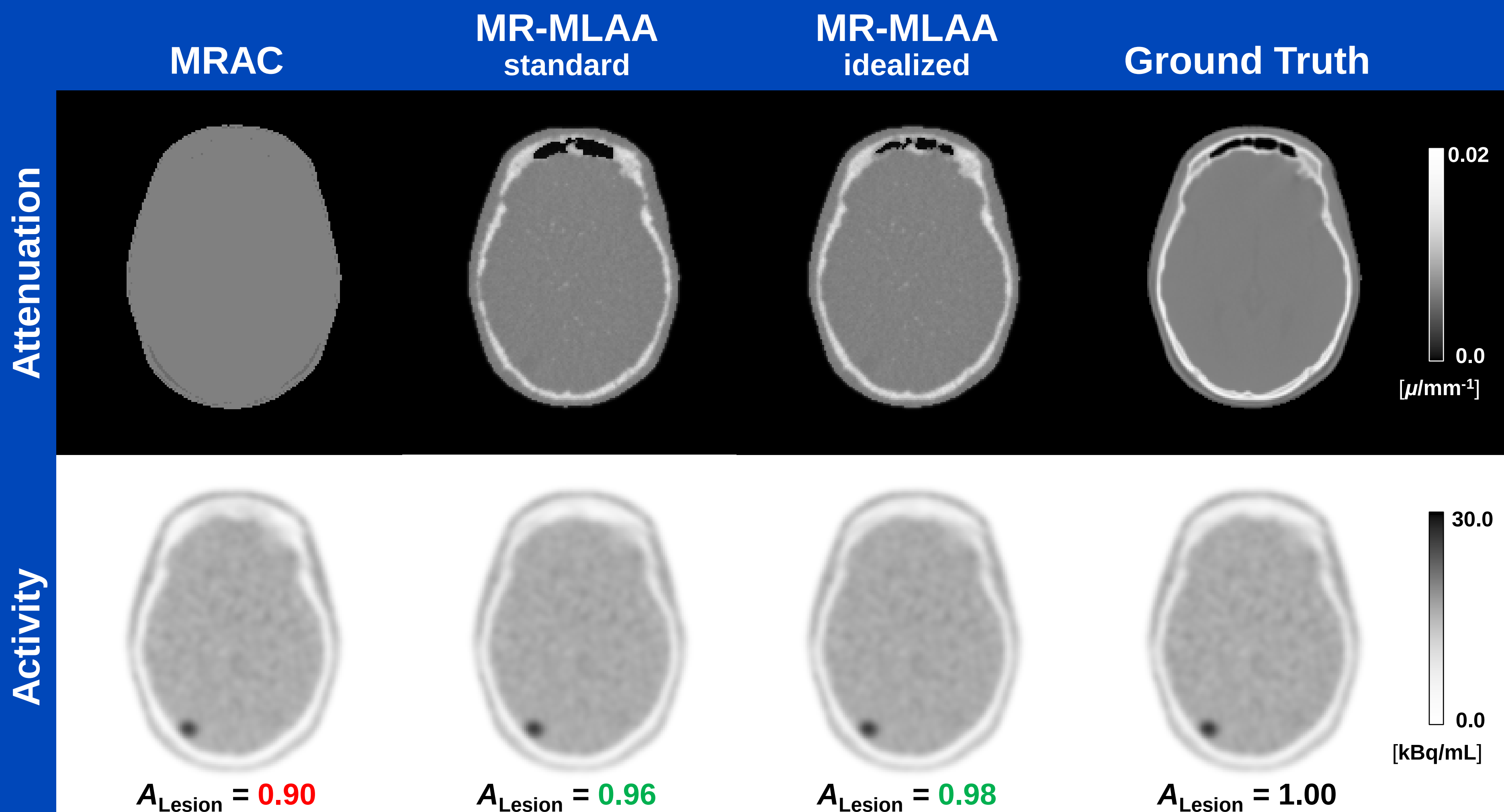
Results

Attenuation



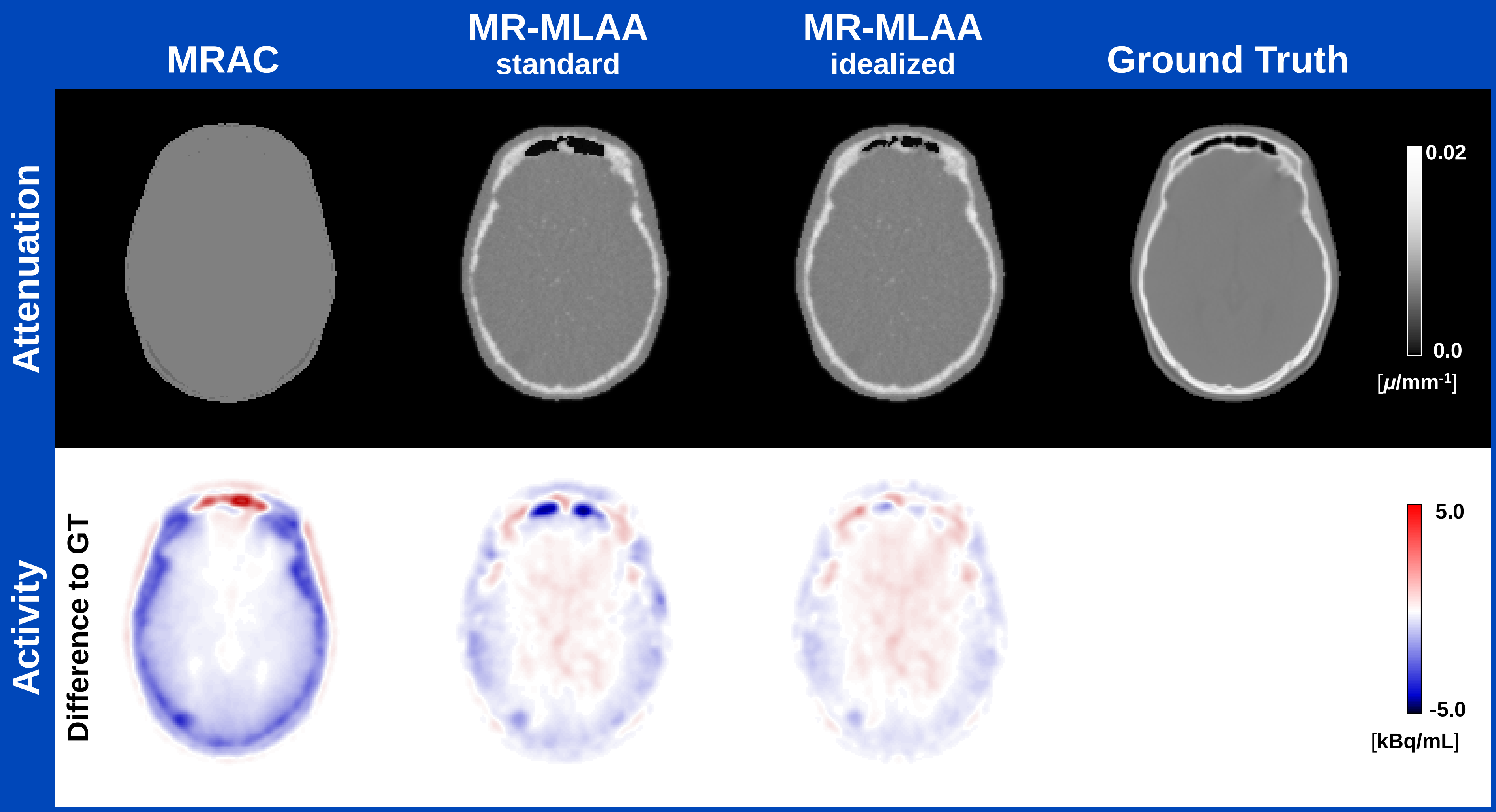
Results

Attenuation and Activity (Slice A)



Results

Attenuation and Activity (Slice A)



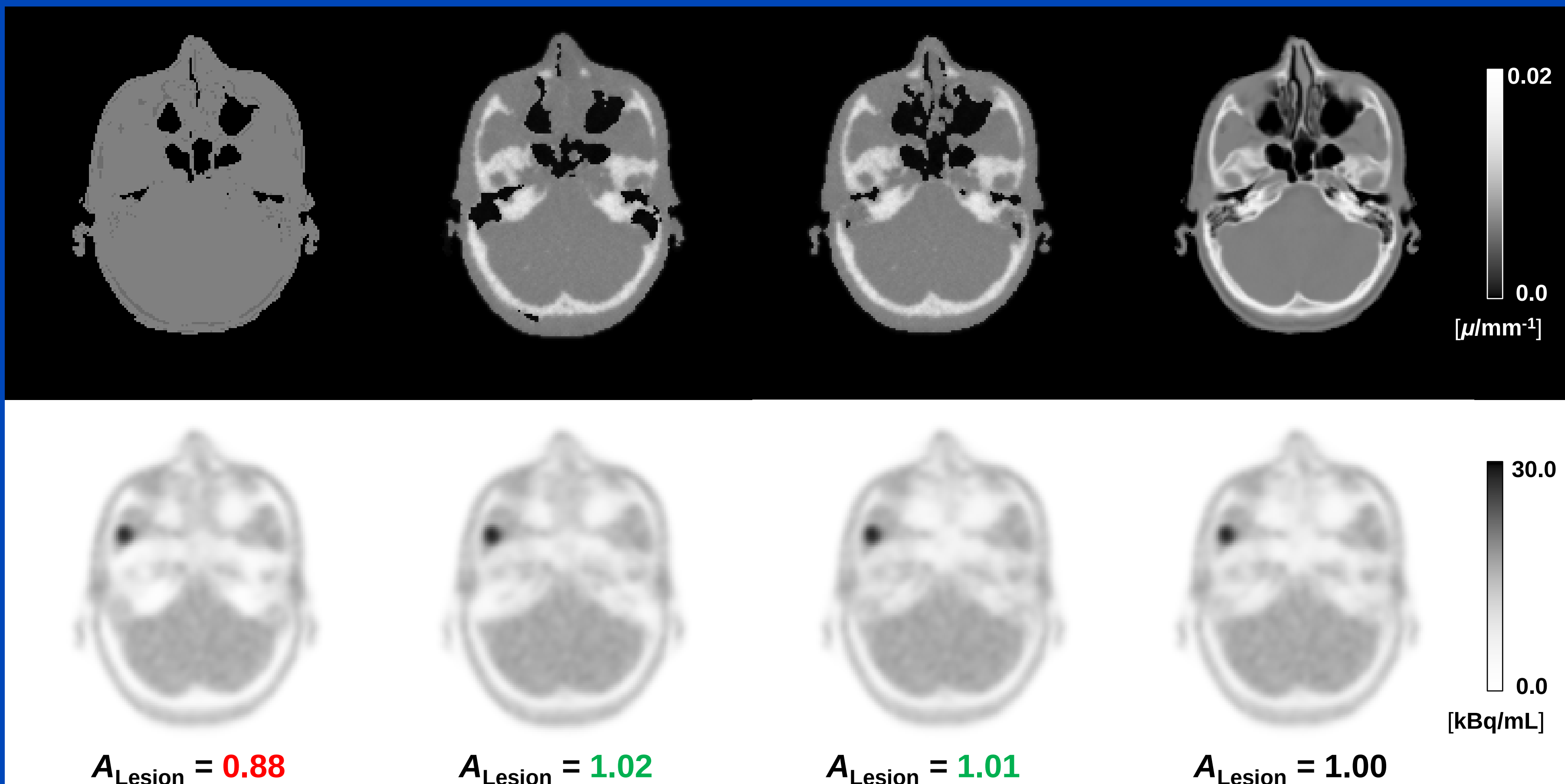
Results

Attenuation and Activity (Slice A)

MRAC	MR-MLAA standard	MR-MLAA idealized	Ground Truth

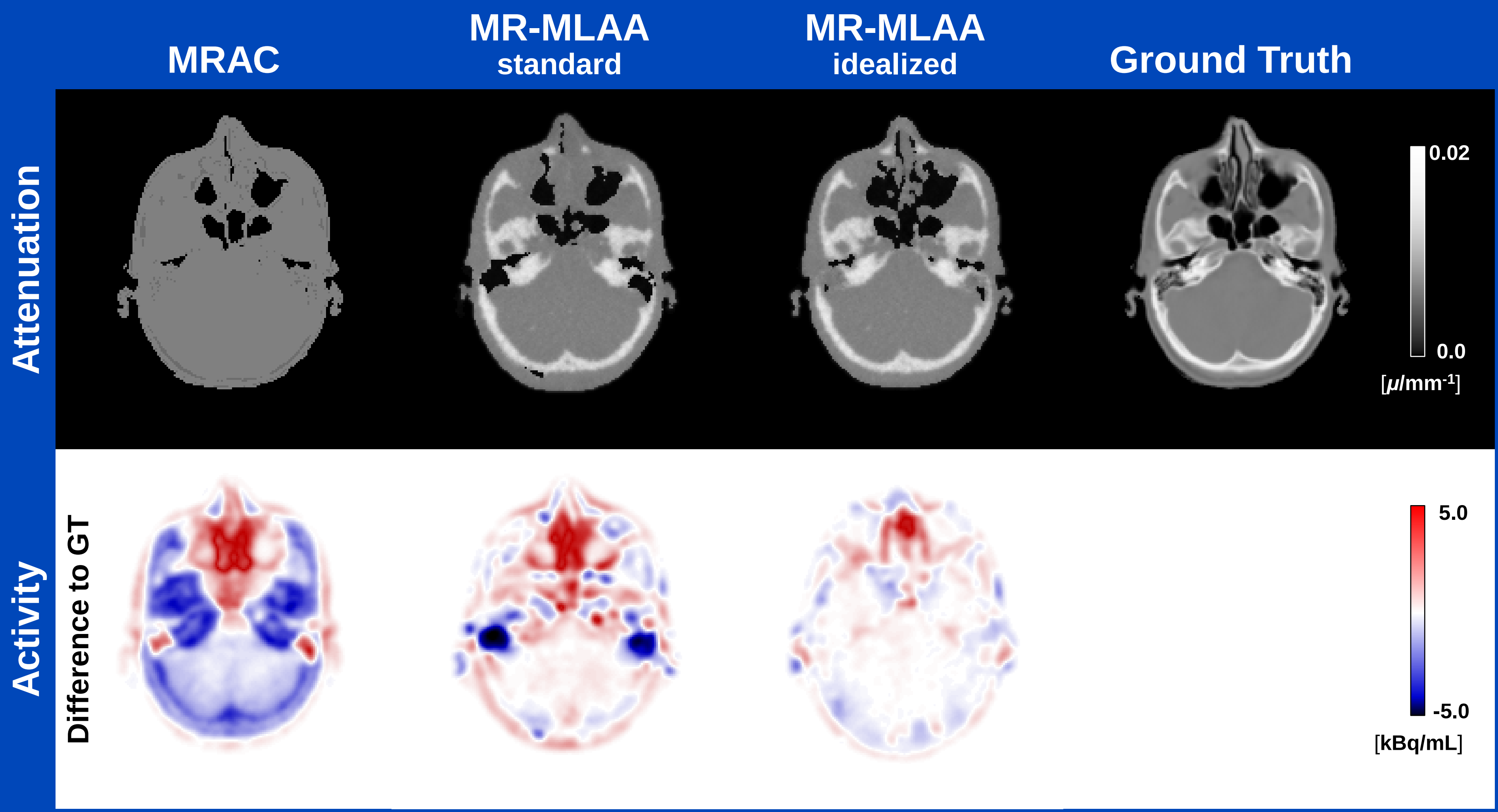
Attenuation

Activity



Results

Attenuation and Activity (Slice A)



Conclusion

- MR-MLAA significantly improves bone attenuation estimation compared to MRAC.
- MR-MLAA improves PET quantification compared to MRAC, especially for regions close to bone tissue.
- Challenges
  - Small air cavities (e.g., nasal sinuses)
  - Misclassification of air as bone or soft tissue leads to increased activity values
  - Thin bone structures

Outlook

- Clinical data coming soon.
- Potential improvements
  - Sophisticated segmentation technique to create attenuation mask from MR image(s) (e.g., based on UTE images)
  - Additional prior information from non attenuation-corrected (NAC) images
  - Time-of-flight (TOF) information
- Adaption to whole-body PET/MR requires
  - additional tissue classes (e.g., fat)
  - proper handling of truncated MR data

Thank You!

This presentation will soon be available at www.dkfz.de/ct.

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