Towards total-body J-PET: overview of data correction techniques for image reconstruction

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with contributions from Wojciech Krzemień, Szymon Parzych, Jakub Baran, and the J-PET collaboration

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Outline

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Scatter correction

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Normalization correction

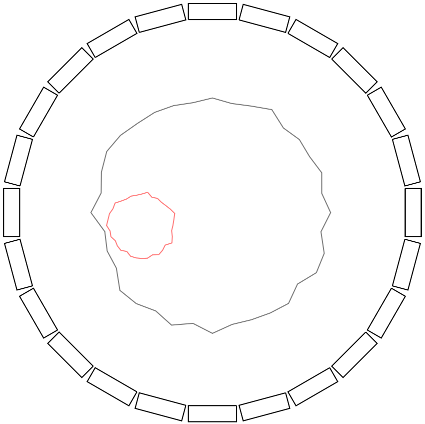
Resolution modeling

Conclusion

Outline

Positron Emission Tomography principles

- The radioisotope is injected into the patient



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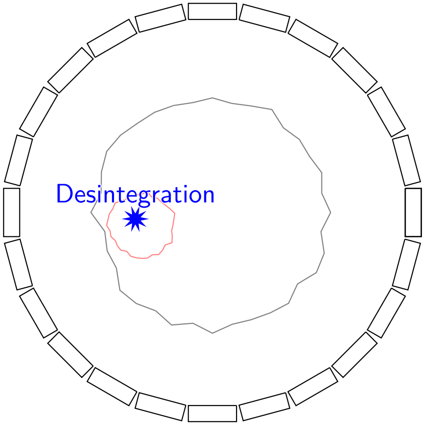

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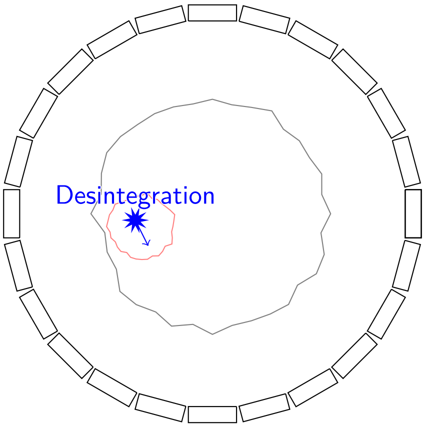

Positron Emission Tomography principles

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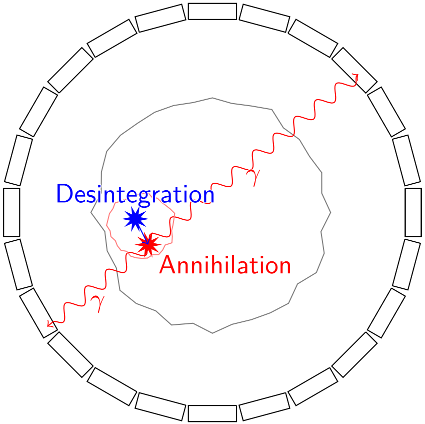
- The positron interacts with an electron, forming a pair of two back-to-back gamma photons



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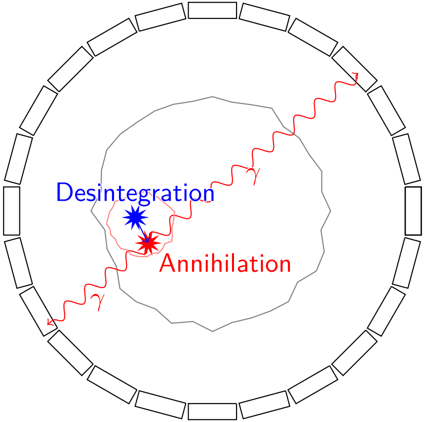
- A list of coincidence events is constructed based on time window



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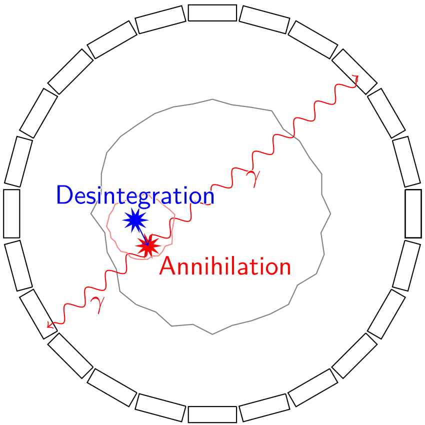
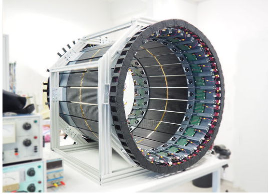
- A list of coincidence events is constructed based on time window
- Coincidences form LORs that hint at where the initial annihilation happened



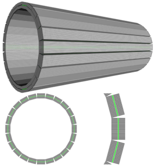
J-PET

Modular Jagiellonian PET (J-PET)



- 24 arrays of 13 plastic scintillator strips
- Length of 50 cm
- Radius of 40 cm

Total-body (TB) J-PET


[1]

- 7 rings composed of 2 layers of scintillator strips
- Layers separated by wavelength shifters
- Total length of more than 2 m

[1] P Moskal et al. "Simulating NEMA characteristics of the modular total-body J-PET scanner—an economic total-body PET from plastic scintillators". In: *Physics in Medicine & Biology* 66.17 (Sept. 2021), p. 175015.

PET image correction

- PET images are degraded due to several effects
- Those effects can be compensated using different techniques:
  - Attenuation correction
  - Scatter correction
  - Random correction
  - Normalization correction
  - Resolution modeling

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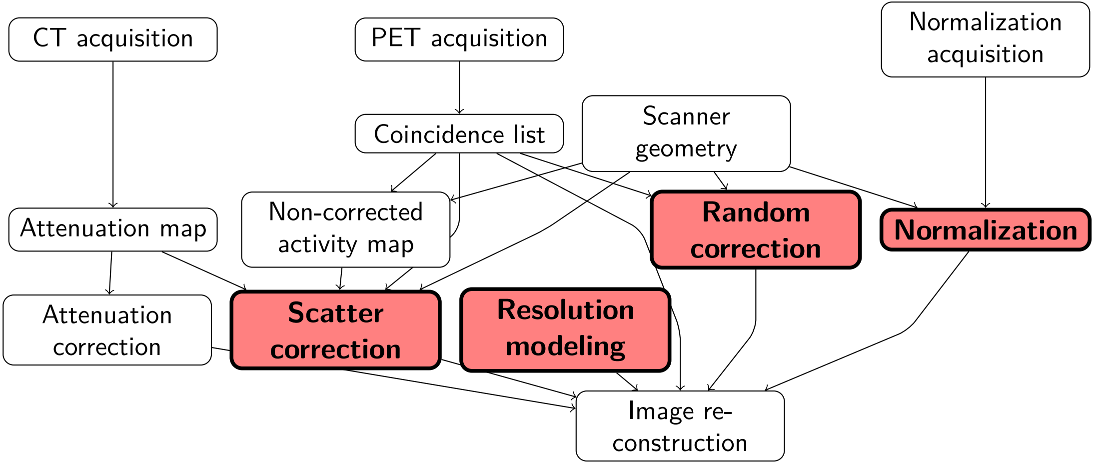
Overview of PET corrections for image reconstruction



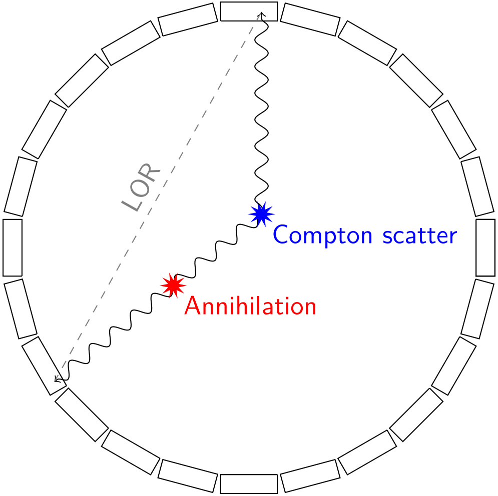
Maximum-Likelihood Expectation-Maximization

Update equation of Maximum-Likelihood Expectation-Maximization (MLEM):

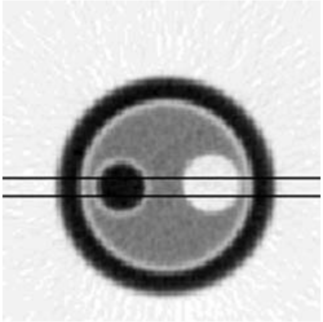
$$x_q^{(k+1)} = \frac{x_q^{(k)}}{S_q} \sum_{p=1}^{P} A_{pq} \frac{y_p}{\eta_p \left(\sum_{q'=1}^{Q} A_{pq'} x_{q'}^{(k)} \right) + s_p + r_p} \qquad (1)$$

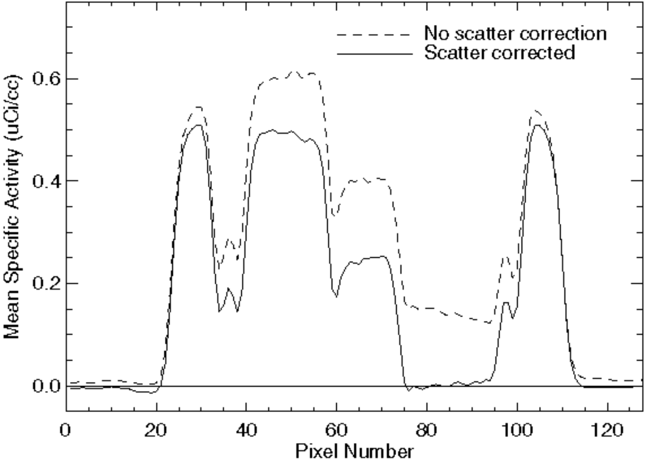
Outline

The problem with scatter coincidences



Importance of scatter correction





2

After simulation based scatter correction.

[2] Dale L. Bailey, ed. *Positron emission tomography: basic sciences*. New York: Springer, 2005.

Scatter correction

- Scattered coincidences correspond from 20 % to 50 % of all coincidences[3]
- Various corrections exist:
  - Empirical approaches (tail fitting)
  - Two (or more) energy windows
  - Convolution/deconvolution
  - Modeling of the scatter distribution during forward projection
    - Analytic methods (single scatter simulation (SSS))
    - Monte Carlo (MC) methods
  - Machine-learning-based approaches

[3] Bailey, *Positron emission tomography*.

Single scatter simulation

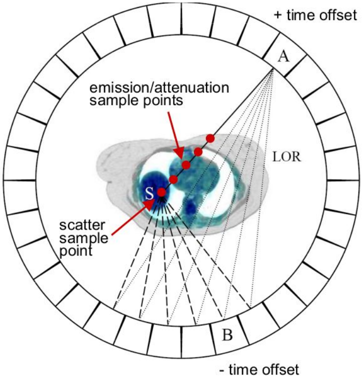


Fig. 1. The single scatter simulation model.

Single-scatter coincidence rate along LOR (A, B) is estimated as the volume integral of a scattering kernel over the scattering medium[4]:

$$S^{AB} = \int_{V_s} \mathrm{d}S \left(\frac{\sigma_{AS}\sigma_{BS}}{4\pi R_{AS}^2 R_{BS}^2} \right) \frac{\mu}{\sigma_c} \frac{\mathrm{d}\sigma_c}{\mathrm{d}\Omega} \left[I^A + I^B \right] \tag{2}$$

[4] C C Watson. "New, Faster, Image-Based Scatter Correction for 3D PET". In: *IEEE Transactions on Nuclear Science* (2000).

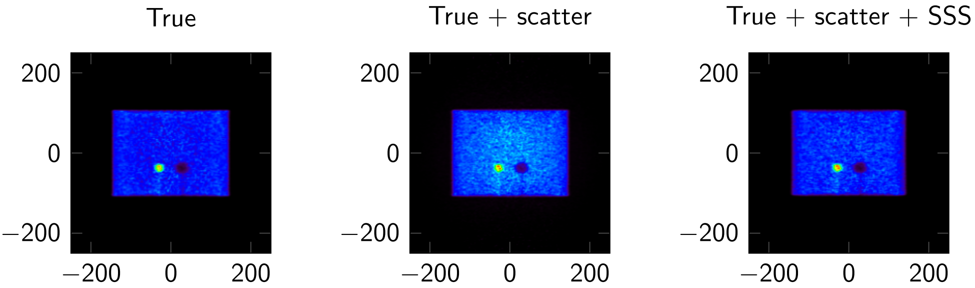
Reconstructions (courtesy of Jakub Baran)

- Use of STIR[5] SSS implementation
- Reconstructions of standard NEMA IEC phantom
- Reconstruction by MLEM (from Customizable and Advanced Software for Tomographic Reconstruction[6])

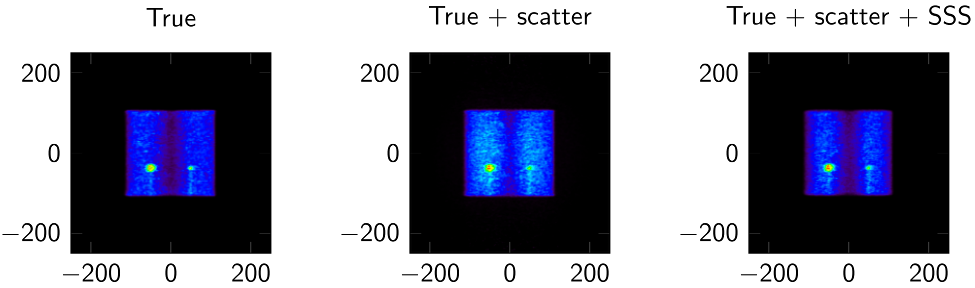
[5] Kris Thielemans et al. "STIR: software for tomographic image reconstruction release 2". In: *Physics in Medicine and Biology* 57.4 (Feb. 2012), pp. 867–883.

[6] Thibaut Merlin et al. "CASToR: a generic data organization and processing code framework for multi-modal and multi-dimensional tomographic reconstruction". In: *Physics in Medicine & Biology* 63.18 (Sept. 2018), p. 185005.

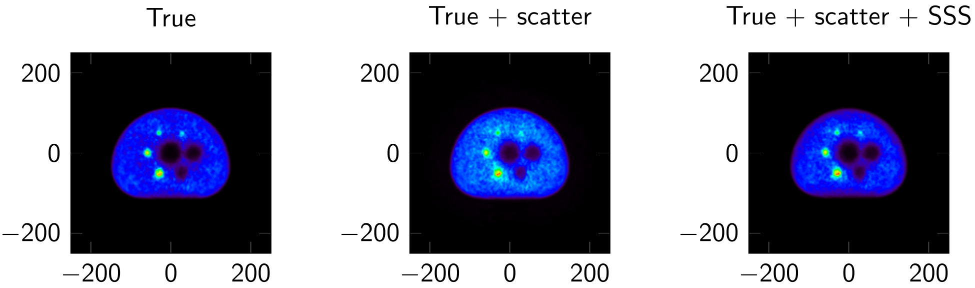
Reconstruction results (x profiles)



Reconstruction results (y profiles)



Reconstruction results (z profiles)



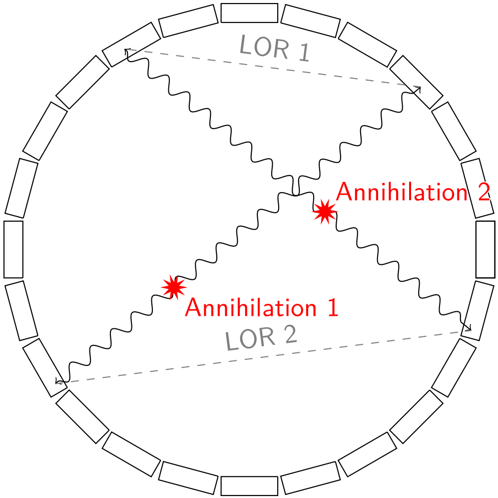
Scatter correction conclusions

- Scatter correction is an important step in PET image reconstruction
- For J-PET: extend SSS to take into account time-of-flight information[7]

[7] Charles C Watson. "Extension of Single Scatter Simulation to Scatter Correction of Time-of-Flight PET". In: *IEEE Nuclear Science Symposium* (2005).

Outline

The problem with random coincidences



Random correction

- Unlike true coincidences, random coincidences tend to be somewhat uniformly distributed across the field-of-view[8]
- Various corrections exist:
  - Tail-fitting methods
  - Single rate
  - Singles-prompts
  - Delayed time window

[8] Bailey, *Positron emission tomography*.

Overview of selected random correction techniques

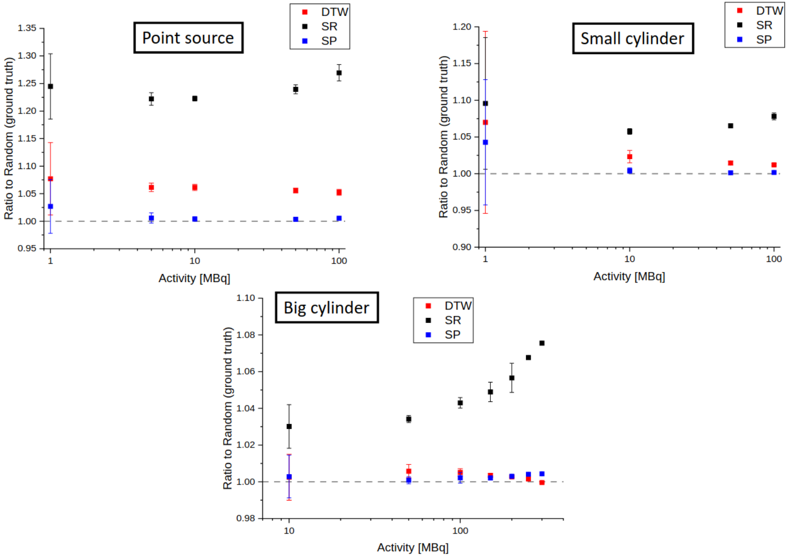
- Single rate: $R_{i,j}^{SR} = 2\tau R_i R_j$
- Singles-prompts: extension to the conventional single rate approach using information from singles and prompts rate
- Delayed time window
  - Timing signals from one detector are delayed by a time significantly greater than the time window (τ)
  - Number of coincidences found estimate the number of random coincidences
  - This estimate is then subtracted to the total number of coincidences

Simulations set-up (courtesy of Szymon Parzych)

- MC simulations conducted with GATE 9.0[9]
- Phantoms:
  - Point source at the center
  - Small water-filled cylinder (radius of 15 cm, length of 22 cm)
  - Large water-filled cylinder (radius of 10.555 cm, length of 168 cm)
  - NEMA IEC
- Coincidence time window: $\tau = 3\,\text{ns}$

[9] David Sarrut et al. "Advanced Monte Carlo simulations of emission tomography imaging systems with GATE". In: *Physics in Medicine & Biology* 66.10 (May 2021), 10TR03.

Preliminary results (courtesy of Szymon Parzych)



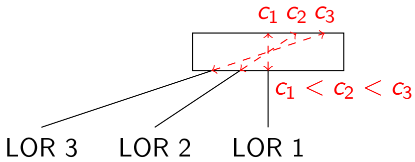
Conclusions for random correction (courtesy of Szymon Parzych)

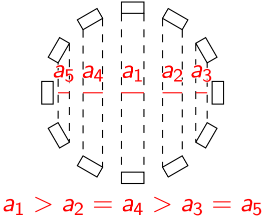
- Singles-prompts method provides the best estimation of total random coincidences
- However, the delayed time window method provides the best distribution of random coincidences
- Delayed time window seems adapted to J-PET due to its triggerless acquisition
- More investigations to be done, especially for TB J-PET

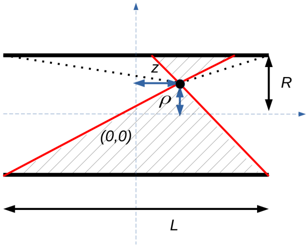
Outline

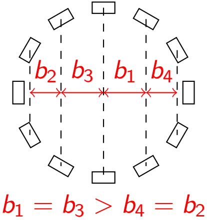
Why is normalization needed?

Several effects can affect LOR sensitivity









The problem of normalization

- Assuming a "perfect" source of activity A, we have

$$C_{\mathrm{LOR}} = A \tag{3}$$

- In practice, a number of effects affect the count rate:

$$C_{\mathrm{LOR}} = F_{\mathrm{LOR}} \times A \tag{4}$$

- Goal of normalization: find η_{LOR} such that

$$C_{\mathrm{LOR}} \times \eta_{\mathrm{LOR}} = A \tag{5}$$

- Two approaches:
  - Direct normalization
  - Component-based normalization

Notations taken from Theodorakis et al.[10].

[10] Lampros Theodorakis et al. "A review of PET normalization: striving for count rate uniformity". In: *Nuclear Medicine Communications* 34.11 (Nov. 2013), pp. 1033–1045.

Direct normalization

- We want

$$C_{\mathrm{LOR}} \times \eta_{\mathrm{LOR}} = A \tag{5}$$

- Therefore,

$$\eta_{\mathrm{LOR}} = \frac{A}{C_{\mathrm{LOR}}} \tag{6}$$

Direct normalization

- We want

$$C_{\mathrm{LOR}} \times \eta_{\mathrm{LOR}} = A \tag{5}$$

- Therefore,

$$\eta_{\mathrm{LOR}} = \frac{A}{C_{\mathrm{LOR}}} \tag{6}$$

- Problem: statistics
  - Modular J-PET has $24 \times 13 \times 25 = 7800$ “detector pixels”
  - ...hence $\frac{7800 \times (7800-1)}{2} = 30\,416\,100$ possible LORs
  - 1% error $\rightarrow$ 10 000 counts per LOR
  - Thus we need about 304 161 000 000 coincidences!
  - TB J-PET requires 49 times more coincidences!

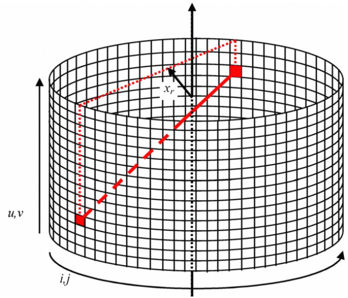
Component-based normalization

General idea

Improve statistics and decrease variance by considering several LORs for normalization computation[11]:

$$\eta_{uivj} = g^{\mathrm{ax}}_{uv} \times g^{\mathrm{tr}}_{ij} \times \epsilon_{ui} \times \epsilon_{vj} \tag{7}$$

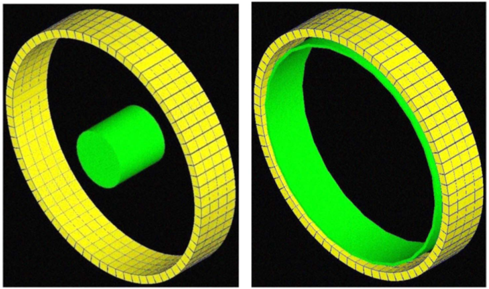
- g^{ax} Axial geometric factors
- g^{tr} Transverse geometric factors
- ϵ Intrinsic detector efficiency



[11] Audrey Pépin et al. "Normalization of Monte Carlo PET data using GATE". In: *2011 IEEE Nuclear Science Symposium Conference Record*. Valencia, Spain: IEEE, Oct. 2011, pp. 4196–4200.

Simulations

Normalization scans



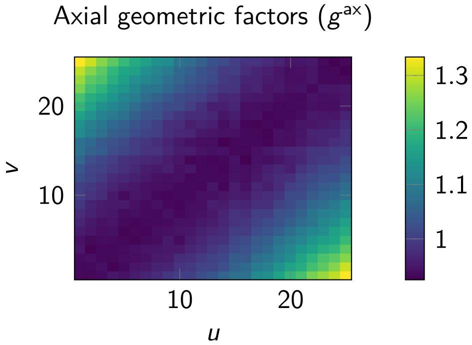
Courtesy of Pépin et al.[12]

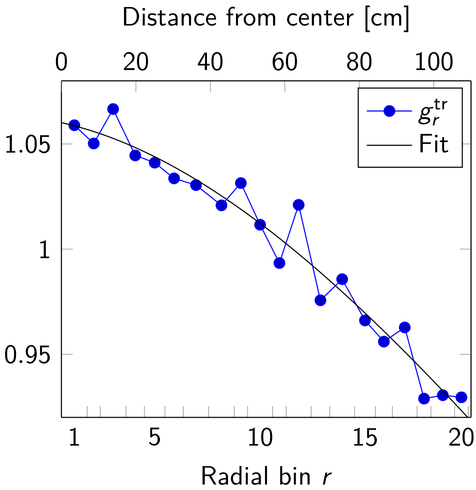
Reconstruction phantom

- Uniform cylinder
- Length: 40 cm (Modular J-PET: 50 cm)
- Radius: 10 cm (Modular J-PET: 40 cm)

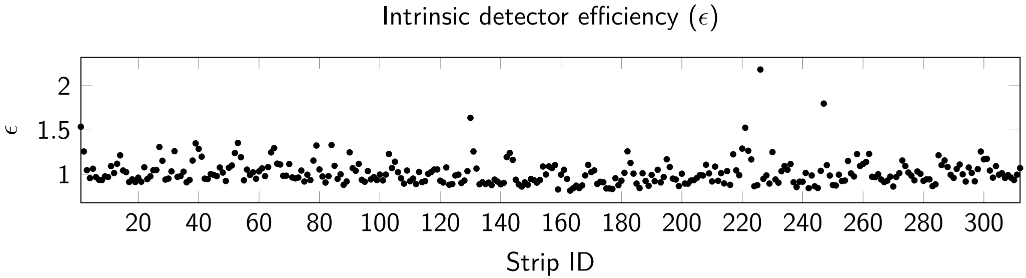
[12] Pépin et al., "Normalization of Monte Carlo PET data using GATE".

Computed normalization factors

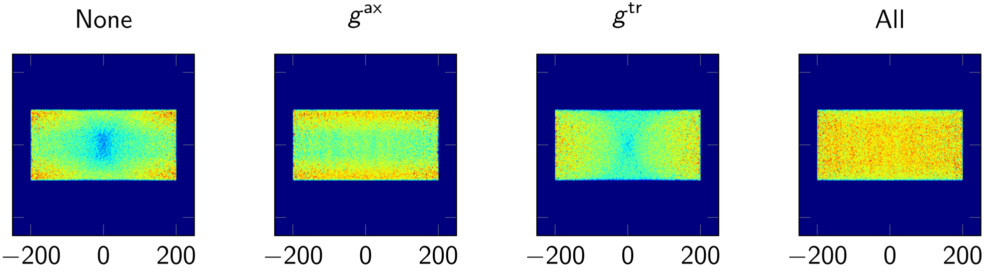




Computed normalization factors (cont.)

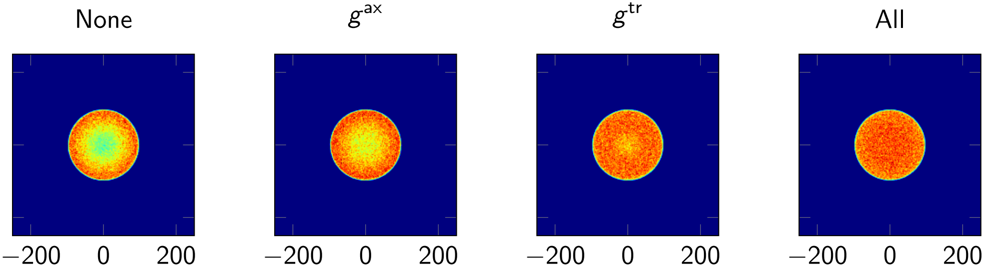


Reconstructions (x profiles)



	Axial uniformity	Radial uniformity
None	9%	24%
All	1%	12%

Reconstructions (z profiles)



	Axial uniformity	Radial uniformity
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All	1%	12%

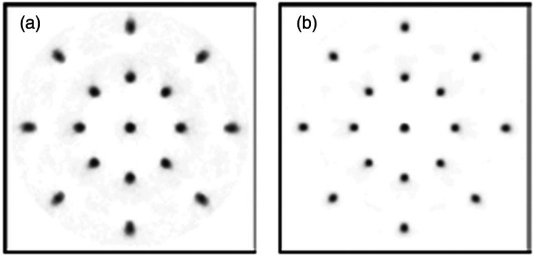
Normalization conclusion

- Normalization favorably compensates for several effects, including some geometrical effects or intrinsic detector efficiencies
- Normalization implemented for Modular J-PET
- Must be investigated for TB J-PET, especially due to its length

Outline

The problem

- Resolution degrading factors translate to undesired cross-contamination between adjacent functional regions
  - Positron range
  - Photon noncollinearity
  - Detector-related effects
    - Intercrystal scattering
    - Intercrystal penetration



Kisung Lee et al. "Pragmatic fully 3D image reconstruction for the MiCES mouse imaging PET scanner". In: *Physics in medicine & biology* 49.19 (2004), p. 4563

Solutions to resolution degradation

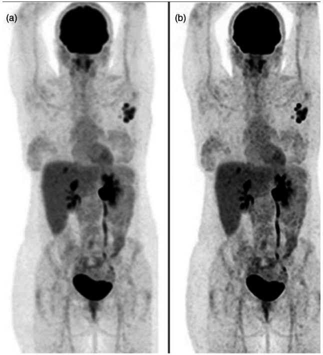
- Post-processing techniques
  - ROI-based techniques (from segmented MRI images)
  - Voxel-based techniques
- Incorporation of anatomical information within the reconstruction algorithm
  - Typically superior to post-processing techniques
  - Drawback: simplifying assumptions
- Resolution modeling

Resolution modeling techniques

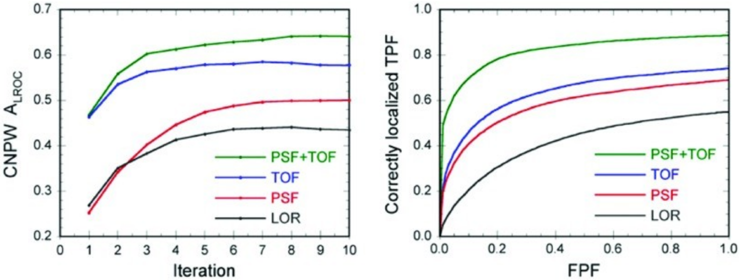
- Idea: incorporate the resolution modeling directly within the system matrix
- The system matrix is modeled as $\mathbf{A}$ when a_{ij} is the probability that an event generated in voxel j is detected along a LOR i
- Example of system matrix decomposition:

$$\mathbf{A} = \mathbf{A}_{\text{det.sens}}\mathbf{A}_{\text{det.blur}}\mathbf{A}_{\text{attn}}\mathbf{A}_{\text{geom}}\mathbf{A}_{\text{positron}} \quad (8)$$

Some results from the literature



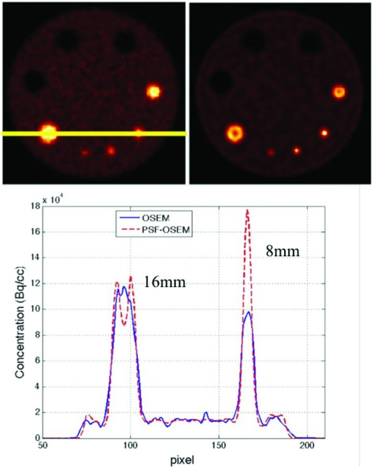
Alain P Pecking, Dominique Bellet, and Jean Louis Alberini. "Immuno-SPET/CT and immuno-PET/CT: a step ahead to translational imaging". In: *Clinical & experimental metastasis* 29 (2012), pp. 847–852



Dan J Kadrmas et al. "Impact of time-of-flight on PET tumor detection". In: *Journal of Nuclear Medicine* 50.8 (2009), pp. 1315–1323

Limitations of resolution modeling

- Resolution modeling can lead to notable edge artifacts, reminiscent of the Gibbs phenomenon
- Some solutions exist
  - Use a reconstruction filter that underestimates the true resolution
  - Amplify a frequency band in the Fourier domain



Bing Bai and Peter D Esser. "The effect of edge artifacts on quantification of positron emission tomography". In: *IEEE Nuclear Science Symposium & Medical Imaging Conference*. IEEE. 2010, pp. 2263–2266

Resolution modeling conclusions

- Resolution modeling results in significant improvements in image resolution and contrast
- Effects on noise is less straightforward to assess
- Main drawback is the edge artifacts, that are not yet fully understood
- Still an open topic in the context of J-PET!

Outline

Corrections matter

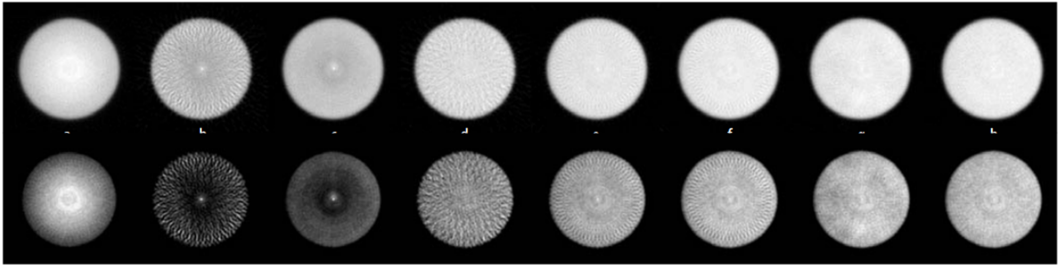


Figure 5.10. Effects of normalisation on image uniformity. Images (summed over all axial planes) from a low-variance 20 cm cylinder acquisition, performed in 3D mode on a Siemens/CTI ECAT 951. (From [15], with permission.)

(Upper row) linear grey scale covering entire dynamic range.
(Lower row) linear grey scale, zero-point set to 70% of image maximum.

(a) no scatter correction;
(b) no normalisation;
(c)no correction for the radial profile;
(d) no crystal efficiency correction;
(e) no transaxial block profile correction;
(f) no crystal interference correction;
(g) no time alignment correction;
(h) fully normalised and scatter corrected.

Dale L. Bailey, ed. *Positron emission tomography: basic sciences*. New York: Springer, 2005

General conclusions

- PET imaging requires several corrections to become quantitative
- A final calibration is required to convert reconstructed values to physical units
- Currently only partially implemented in the context of J-PET
  - Current study focus on Modular J-PET
  - ...but TB J-PET is kept as a goal
- Moving from MC simulations to real data
- Work is ongoing!

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Thanks for your attention!