3D PET list-mode reconstruction including all available information provided by the detector

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PET reconstruction

Coincidences

Line-of-Response (LOR)

Sinogram
PET list-mode reconstruction

List-mode data:

<table>
<thead>
<tr>
<th>ID</th>
<th>T</th>
<th>E</th>
<th>DOI</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID1</td>
<td>T1</td>
<td>E1</td>
<td>DOI1</td>
</tr>
<tr>
<td>ID2</td>
<td>T2</td>
<td>E2</td>
<td>DOI2</td>
</tr>
<tr>
<td>ID3</td>
<td>T3</td>
<td>E3</td>
<td>DOI3</td>
</tr>
<tr>
<td>ID4</td>
<td>T4</td>
<td>E4</td>
<td>DOI4</td>
</tr>
<tr>
<td>ID5</td>
<td>T5</td>
<td>E5</td>
<td>DOI5</td>
</tr>
</tbody>
</table>
...

List-mode VS sinogram [Rahmim2004]:
- Better spatial sampling
- Better temporal sampling (motion correction)
- More information: TOF, DOI, energy…

Quantitative clinical reconstruction

PET list-mode reconstruction

Iterative reconstruction
- LM-OSEM [Reader 1998]
- For each LOR, forward and backward projection

System Matrix (SM)
Probability to detect a positron emission from the voxel $i$ with the LOR $j$

store the “contribution” of each LOR in image space

\[ \text{card}(SM) = (M, N) \]

$M$ is the number of LORs and $N$ the numbers of voxels

\[ \text{card}(SM) = (M, N, t) \]

Huge matrix
- difficult to include additional information
- memory size (specially for GPU)

PET list-mode reconstruction

SM decomposition [Qi1998]

$$\mathbb{R}^{M \times N}$$

$$\mathbb{P} + \mathbb{M}_{po} + \mathbb{M}_{pi}$$

Scanner

Patient

physiology+physics
PET list-mode reconstruction

\[
\text{SM decomposition} \quad [\text{Qi1998}]
\]

\[
\text{SM} = \mathcal{P} + \mathcal{M}_{po} + \mathcal{M}_{pi}
\]

Compute on-the-fly the contribution of the LOR using a projector

Siddon’s algorithm \([\text{Siddon1985, Zao2002}]\)

\[
\text{Voxel’s contribution}
\]
PET list-mode reconstruction

Siddon’s algorithm is a simple projector using only detector IDs

Recent and future detectors are able or will be able to record many kind of information

List-mode data:

- ID1 T1 E1 DOI1
- ID2 T2 E2 DOI2
- ID3 T3 E3 DOI3
- ID4 T4 E4 DOI4
- ID5 T5 E5 DOI5
- ...

How to use this information within the projector
Considering the detector itself

Geometrical effects
- rectangular crystals shape
- cylindrical scanner

Crystal penetration
- photoelectric effect

Intra and inter crystal scattering
- Compton scattering

Does Siddon projector (a simple line) is enough?
Considering the detector itself

PET Philips GEMINI

Resolution: 100 µm

Gaussian
Rectangular

Scattering

FWHM ~2 mm
FWTM ~4 mm

LOR cross section

8 mm
Considering the detector itself

**PET Philips GEMINI**

- **VOR cross section**
- **FWHM ~8 mm**
- **FWTM ~13 mm**
- **Resolution 100 µm²**
Considering the detector itself

Not just a simple line!

Volume-of-response (VOR)
- complex shape
- spatially variant

FWHM ~8 mm
FWTM ~13 mm

resolution 100 µm²
Considering the detector itself

Computes on-the-fly the VOR including the detector effects

Single line  
[Siddon1985]

Multiple rays  
[Chen2007, Moehrs2008]

VOR modeling  
[Ortuño2011, Cui2011]

Geometrical effect
Crystal penetration
Crystal scattering

[Ortuño2011, Cui2011] spatially variant

Siddon, Med. Phys., 1985  
Chen & Glick, IEEE MIC, 2007  
Ortuño et al., IEEE MIC, 2011  
Cui et al., IEEE MIC, 2011
Considering the detector itself

Gaussian VOR modeling [Cui2011a, Cui2011b]

1. From the first slice of the VOR: select $\sigma_{\text{left}}$ and $\sigma_{\text{right}}$ of the gaussian model using the tables of pre-measured data.

2. Render the 2D asymmetrical Gaussian distribution in the current slice.

3. Go to the next slice and back to step 1 until the VOR is fully rendered.

Cui2011a: Cui et al., IEEE MIC, 2011
Considering the detector itself

Gaussian VOR modeling [Cui2011a, Cui2011b]

Gaussian as VOR:
- no rectangular shape
- no scattering
- required interpolation to cover the field-of-view

1. From the first slice of the VOR and \( \sigma \) right of the gaussian tables of pre-measured data.
2. Go to the next slice and back to step 1 until the VOR is fully rendered.

Cui2011a: Cui et al., IEEE MIC, 2011
Computes on-the-fly the VOR including the detector effects

Considering the detector itself

Multiple rays
[Chen2007, Moehrs2008]

VOR modeling
[ortuño2011, Cui2011]

Multiple rays VOR modeling
[Autret2012]

Geometrical effect
Crystal penetration
Crystal scattering

Geometrical effect
Crystal penetration
Crystal scattering

Geometrical effect
Crystal penetration
Crystal scattering

[Cui2011] spatially variant

Spatially variant

References:
Chen & Glick, IEEE MIC, 2007
Ortuno et al., IEEE MIC, 2011
Cui et al., IEEE MIC, 2011
Autret et al., IEEE MIC, 2012
Considering the detector itself

Intrinsic Detector Response Function (IDRF)

Relationship between the VOR and the IDRFs of both detectors [Gonzalez2011]:

$$X = \frac{1}{2} (1 - t) X_1 + \frac{1}{2} (1 + t) X_2$$

VOR IDRF IDRF
Considering the detector itself

Full IDRF modeling based on Monte Carlo simulation [Awen2012]

Analytical model
- Geometrical effect
- Crystal penetration
- Crystal scattering
- Spatially variant
- Easy to extend with other information (DOI, TOF, etc)
Considering the detector itself

Iterative Random IDRF Sampling (IRIS) [Autret2012, Autret2013a]

1. Select both IDRF models related to both crystal detectors of the LOR.

2. Generate a pair of random points using the IDRF models.

3. Render and accumulate the line connecting the generated pair points with the DDA algorithm [Bert2011].

\[ X = \frac{1}{2} (1 - t) X_1 + \frac{1}{2} (1 + t) X_2 \]

VOR \hspace{1cm} IDRF \hspace{1cm} IDRF

Autret et al., IEEE MIC, 2012
Autret et al., Fully3D, 2013
Bert & Visvikis, IEEE MIC, 2011
Considering the detector itself

IRIS is easy to use on GPU [Autret2012]

Bloc de threads = VOR

threads = Line

Lines or LOR
Evaluation study

Philips PET GEMINI scanner
- Monte Carlo Simulation [Lamare2006] performed with GATE [Jan2011]
- TOF resolution of 500 ps FWHM
- DOI resolution of 1 mm FWHM
Evaluation study

NEMA IEC NU2-2001 phantom
- 12x10^6 true coincidences

Miniature Derenzo phantom
- One centered inside the FOV
- One 200 mm shifted from the center
- 4x10^6 true coincidences
Evaluation study

Contrast Recovery Coefficient (CRC)

\[ CRC = \frac{r_h - r_b}{r_b} \]

Signal-to-noise ratio (SNR) [Lodge2010] (background)

\[ m_j = \frac{(v1_j + v2_j)}{2} \]
\[ d_j = v1_j - v2_j \]
\[ a_i = \text{mean}(m) \]
\[ dsd_i = \text{std}(d) \]

\[ SNR = \frac{\sqrt{2}}{S} \sum_{i}^{S} \frac{a_i}{dsd_i} \]
Results

PET Philips GEMINI

resolution 100 µm²

Gaussian
Rectangular
Scattering

Gaussian
IRIS
Results

PET Philips GEMINI

VOR cross section

resolution 100 µm²

Gaussian

IRIS
Results

CRC/SNR (LM-OSEM 1 subset 70 iterations) [Awen2013a]

CRC in the biggest hot sphere

CRC in the smallest hot sphere
Results

Image Quality

Reconstructed image for the same SNR (=4.5)
Results

Image Resolution

Centered miniature Derenzo (LM-OSEM 1 subset 15 iterations)

Shifted miniature Derenzo (LM-OSEM 1 subset 15 iterations)
Results

Image Resolution

Centered miniature Derenzo (LM-OSEM 1 subset 15 iterations)

Siddon

IRIS is better in term of contrast

How to improve that?

Include more information from the list-mode data

Shifted miniature Derenzo (LM-OSEM 1 subset 15 iterations)

Siddon

Gaussian

IRIS
Considering time-of-flight (TOF)

In conventional PET imaging, it's possible only to know that a coincident event has taken place on the line of response, but not the actual location of the event.

www.healthcare.philips.com

TruFlight technology uses the actual time difference between the detection of coincident events to more accurately identify the origin of the annihilation. Better identification leads to a quantifiable improvement in image quality.

Typical TOF resolution is 500 ps FWHM (7.5 cm)

Along the LOR

Along a small part of the LOR
Considering time-of-flight (TOF)

Gaussian projector

IRIS projector

FWHM given by the TOF resolution

TOF weighting can be used on every projector
Results TOF

CRC/SNR (LM-OSEM 1 subset 70 iterations) [Awen2013b]

CRC in the biggest hot sphere

CRC in the smallest hot sphere

Improve convergence, SNR and contrast

Autret et al., IEEE MIC, 2013
Results TOF

Image Quality

Reconstructed image for the same SNR (=4.5)
Results TOF

Image Resolution

Centered miniature Derenzo (LM-OSEM 1 subset 15 iterations)

Siddon

Gaussian

IRIS

Shifted miniature Derenzo (LM-OSEM 1 subset 15 iterations)

Siddon

Gaussian

IRIS
Results TOF

Image Resolution

Centered miniature Derenzo (LM-OSEM 1 subset 15 iterations)

Diameter of the miniature Derenzo phantom: 5 cm

Shifted miniature Derenzo (LM-OSEM 1 subset 15 iterations)

TOF resolution 500 ps ~7.5 cm

Include more information!
Considering Depth-of-Interaction (DOI)

- Crystal depth where the photon was detected
- Improve LOR location for a given resolution (FWHM 1 mm)

Only available on prototype detector

Crystal

DOI

Detector

Without DOI

With DOI
Considering Depth-of-Interaction (DOI)

Easy to use with ray or multi-ray projectors (Siddon, Chen, IRIS, etc.)

Difficult for VOR modeling projector (especially Gaussian)

Gaussian model + DOI = Not a Gaussian anymore!
Results DOI

CRC/SNR (LM-OSEM 1 subset 70 iterations)

CRC in the biggest hot sphere

CRC in the smallest hot sphere

Not really improve the contrast
Results DOI

Image Quality

Reconstructed image for the same SNR (=4.5)
Results DOI

Image Resolution

Centered miniature Derenzo (LM-OSEM 1 subset 15 iterations)

Shifted miniature Derenzo (LM-OSEM 1 subset 15 iterations)
Results DOI

- Center of the FOV
- Far to the center
Results TOF+DOI

CRC/SNR (LM-OSEM 1 subset 70 iterations)

CRC in the biggest hot sphere

CRC in the smallest hot sphere
Results TOF+DOI

Image Quality

Reconstructed image for the same SNR (=4.5)
Results TOF+DOI

Image Resolution

Centered miniature Derenzo (LM-OSEM 1 subset 15 iterations)

Shifted miniature Derenzo (LM-OSEM 1 subset 15 iterations)
Results TOF+DOI

Final reconstruction

Siddon

IRIS

2.4 mm

8.0

0.0

Siddon

IRIS
Conclusion

New IRIS projector including geometry, TOF and DOI:

- Accurate detector modeling
- Improved image quality and resolution
- TOF: improve image quality (SNR, contrast and convergence)
- DOI: improve image resolution (specially off center)
- Easy to perform on GPU (only need to draw simple lines)

Perspectives:

- Evaluation with different scanner geometry and resolutions of TOF and DOI
- Include other detector information (energy, …)
Thank for your attention

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