Institut "Jožef Stefan" Ljubljana, Slovenija · MGH 1811 MASSACHUSETTS GENERAL HOSPITAL · University of Ljubljana Faculty of Mathematics and Physics · Univerza v Mariboru · UCDAVIS UNIVERSITY OF CALIFORNIA

Panel TOF-PET imager

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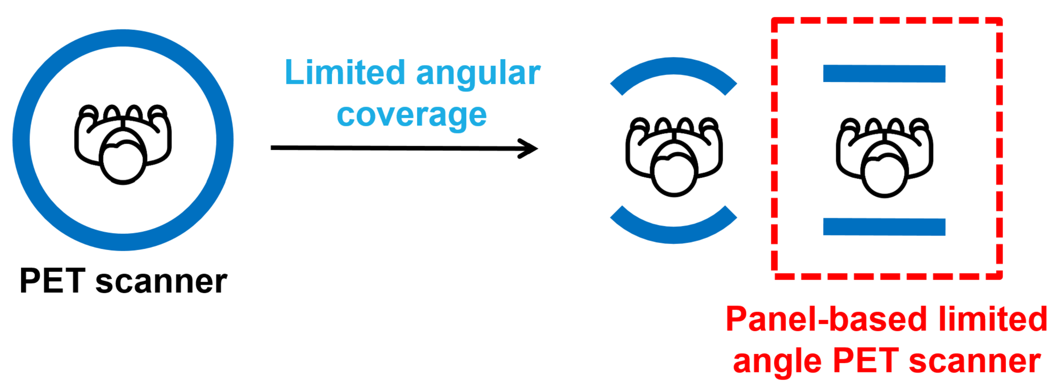
Positron emission tomography (PET) is one of the most important diagnostic tools in medicine, providing three-dimensional imaging of functional processes in the body. The method is based on detecting two gamma rays originating from the point of annihilation of the positron emitted being by radio-labelled agent, and used to follow the human's physiological processes. In Time-Of-Flight PET gamma rays' arrival time is measured in addition to their position. The coincidence timing resolution (CTR) of state-of-the art scanners is between 200 ps and 500 ps FWHM, which can already significantly improve the contrast in imaging large objects. To increase the sensitivity of the next-generation PET scanners timing accuracy should be substantially increased. By using latest advances multichannel system with improved CTR is becoming technologically possible. Generally 3D images from limited angle PET scanners are distorted and have artefacts. Fortunately, with improving timing resolution of PET gamma detectors, artefact free images can be obtained even by a very simplified detector. In the contribution we will show the simulation studies of the simple panel detector using gamma detectors with 50 ps coincidence timing resolution. With this new concept, the price of PET scanners for imaging single or multiple organs can be drastically decreased. We evaluated different panel detector arrangements by imaging different phantoms. We compared the reconstructed images with the image obtained with the Siemens Biograph Vision, state-of-the-art clinical PET scanner. We found comparable image quality parameters of both systems when the CTR approaches 50ps FWHM and also that good CTR can partially compensate for smaller gamma detection efficiency.

Limited angle PET



Potential benefits

Mobility

Portable or bedside PET imaging

Flexibility

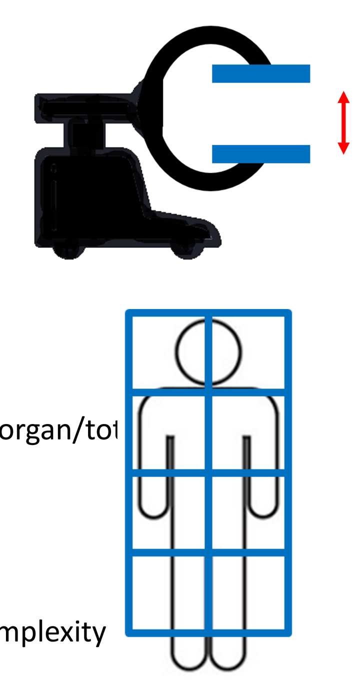
Adjustable FOV and sensitivity

Modularity

Combining multiple panels → multi-organ/total body PET scanner

Accessibility

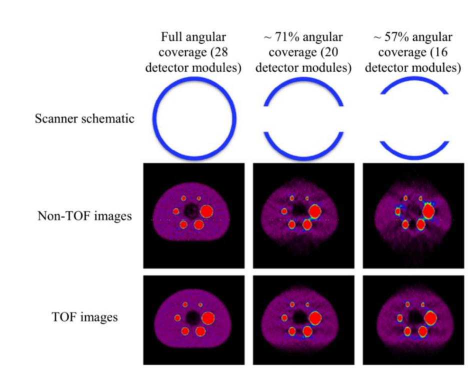
Reduced manufacturing cost and complexity



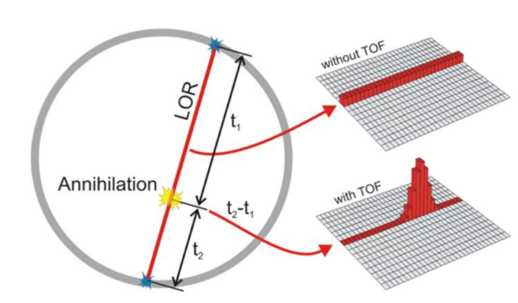
Challenge

Limited angle PET scanners will generally produce distorted images with artefacts unless they have good **time-of-flight** information

As the **coincidence time resolution (CTR)** improves, the angular sampling requirement to obtain distortion-free images decreases



S. Surti, J. S. Karp, Physica Medica 32 (2016) 12–22



The10ps-challenge.org

State-of-the-art in TOF

Clinical scanner:

Siemens Biograph Vision PET/CT → **214 ps**

https://www.siemens-healthineers.com/molecular-imaging/pet-ct/biograph-vision

Laboratory measurement:

Gundacker *et al*, *Phys. Med. Biol.* 65 (2020) 025001 (20pp)

2 x 2 x 3 mm LSO → **58 ps***

2 x 2 x 20 mm LSO → 98 ps*

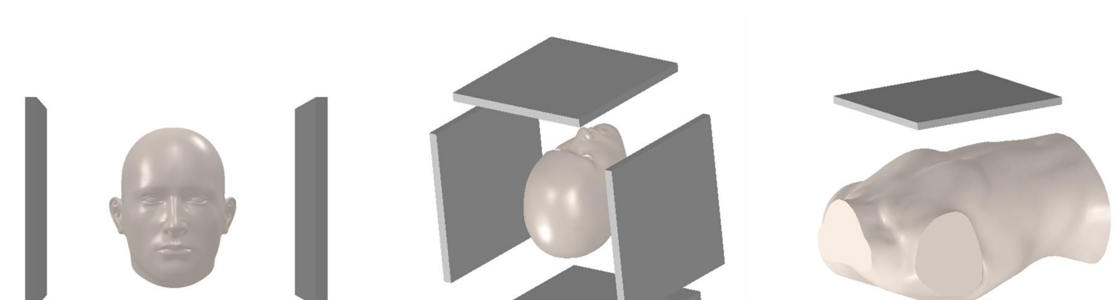
*measured with high power readout electronics that cannot be scaled to large devices

Multi-panel limited angle PET system

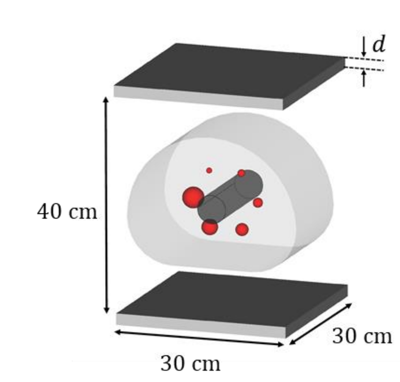
Aim:

Investigate the benefits of coincidence time resolutions down to **50 ps** FWHM in multi-panel limited angle PET systems

Study the performance **two-panel** and **four-panel** designs and gain insight into potential real-world applications



Specification of simulated scanners



	Limited angle scanner	Reference scanner
Scintillator	LSO	LSO
Crystal size	3 x 3 x 5/10/15/20 mm^3	3.2 x 3.2 x 20 mm^3
Panel detector size	30 x 30 cm	/
Axial field of view	30 cm	26.3 cm
Distance between panels	40 cm	
Ring diameter	/	78 cm
Energy resolution	10%	10%
Energy window	435 – 585 keV	435 – 585 keV
Coincidence time resolution	**200 ps, 100 ps, 75 ps, 50 ps**	**214 ps**
Coincidence time window	2 ns	4.1 ns

Notation:
Npanels_$d$mm_$t$ps

Reference system → implemented in simulations following the design of Siemens Biograph Vision PET/CT scanner

Methods

Open-source software **Geant4/GATE** → Monte Carlo simulations of digital phantoms and different scanner designs

Open-source software **CASToR** → image reconstruction with Maximum Likelihood Expectation Maximization (**MLEM**) algorithm

Simulations were performed on a **Grid** → Slovenian national super-computing network (SLING)

Image quality

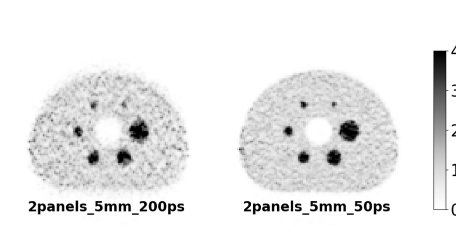
NEMA NU 2-2018 image quality phantom

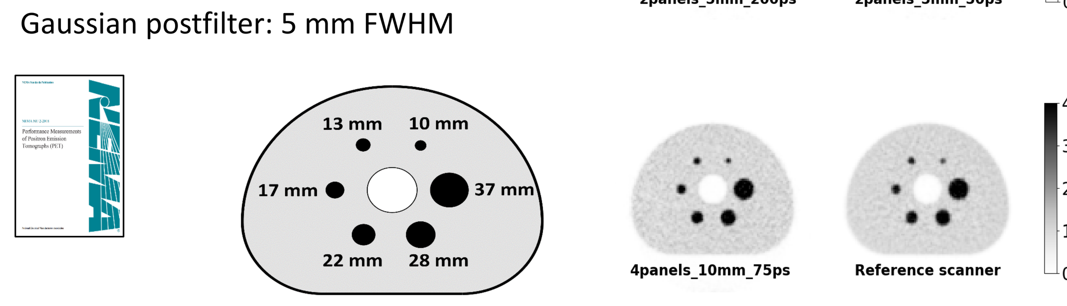
4:1 hot sphere to background activity ratio

Simulated 1 min scans

MLEM: 50 iterations, 3 x 3 x 3 mm^3 voxels

Gaussian postfilter: 5 mm FWHM





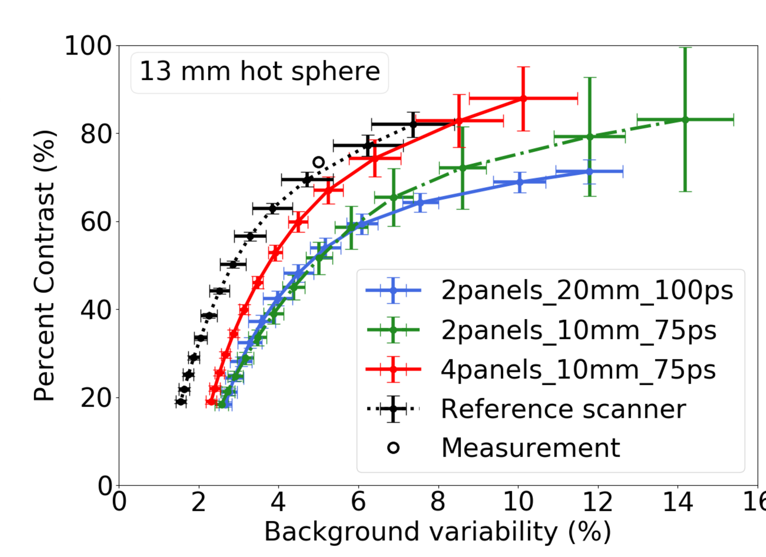
Quantitative measures used to evaluate the image quality

percent contrast

$$Q_{H,j} = \frac{\frac{C_{H,j}}{C_{B,j}} - 1}{\frac{a_H}{a_B} - 1}$$

Backgroud variability

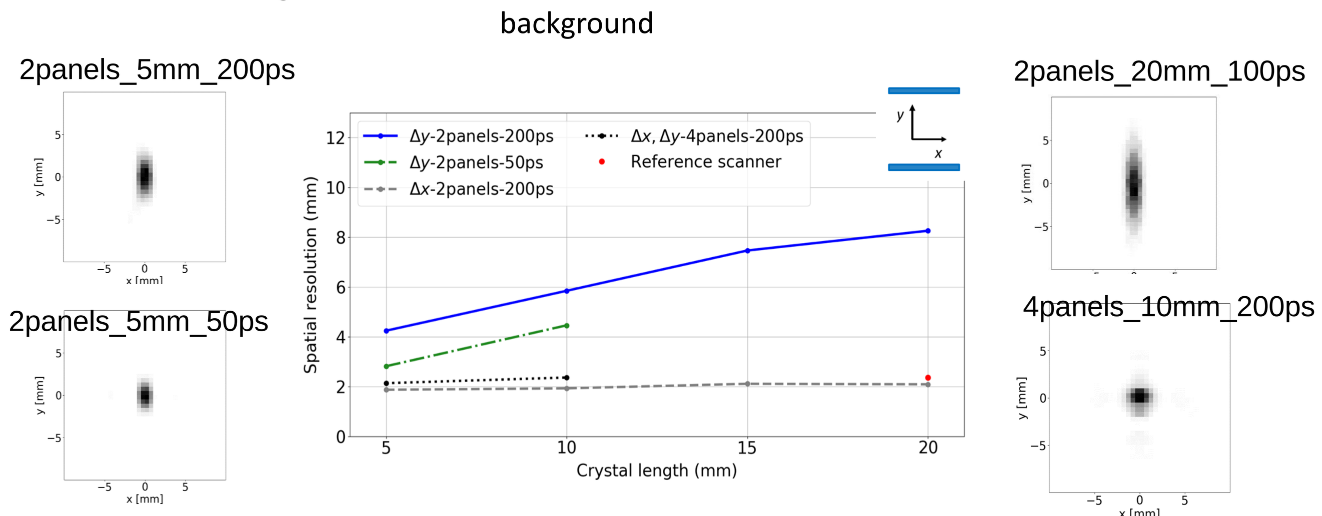
$$N_j = \frac{\sigma_j}{C_{B,j}}$$



Measurement → J. van Sluis, J Nucl Med 2019 60(7) 1031-1036

Spatial resolution

Evaluated images of a hot rod near the center of the field-of-view in warm background

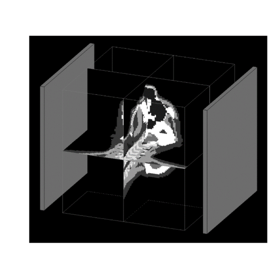


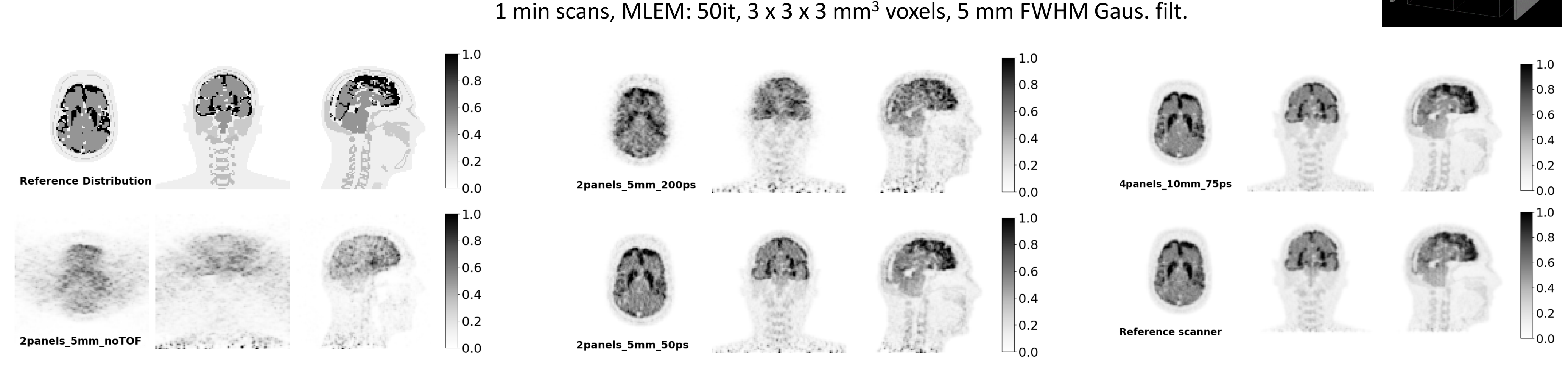
Example of a possible application

XCAT software → generate a highly anatomically detailed phantom

voxelized human head model (3 x 3 x 3 mm^3 voxels)

1 min scans, MLEM: 50it, 3 x 3 x 3 mm^3 voxels, 5 mm FWHM Gaus. filt.





Structural similarity index

$$\mathrm{SSIM}(x,y) = \frac{(2\mu_x\mu_y + C_1)(2\sigma_{xy} + C_2)}{(\mu_x^2 + \mu_y^2 + C_1)(\sigma_x^2 + \sigma_y^2 + C_2)}$$

Normalized root-mean-square error

$$\mathrm{NRMSE} = \frac{1}{\bar{y}}\sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)^2}$$

System	MSSIM	NRMSE
2panels_5mm_200ps	0.221 ± 0.001	0.471 ± 0.001
2panels_5mm_50ps	0.361	0.393
2panels_10mm_75ps	0.436	0.402
2panels_20mm_100ps	0.470	0.422
4panels_10mm_75ps	0.576	0.376
Reference scanner	0.563	0.402

MSSIM → mean SSIM in the head region (true mask used)

Conclusion

- **Good coincidence time resolution** can:
  - compensate for lower detection efficiency or smaller angular coverage
  - enable us to obtain **good image quality with a simple limited angle PET system** without distortions or artifacts
- Spatial resolution substantially degrades with increased crystal length in the two-panel design due to the **parallax error**
- **Four-panel design can produce images of comparable quality, compared to the state-of-the-art reference scanner**

Next steps: build a prototype limited angle PET scanner and experimentally confirm the feasibility of such devices