KU LEUVEN

Opportunities and Challenges for AI/DL/ML in Positron Emission Tomography (PET)

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AI in the wild west workshop
Rennes 29 Jan 2026

Positron Emission Tomography basics

Challenges in PET imaging

AI/ML in PET imaging

Opportunities enabled by new PET scanners

Taming AI in the wild west

Medical Imaging Research Center @ University Hospital Leuven, Belgium

Positron Emission Tomography (PET) - Basics

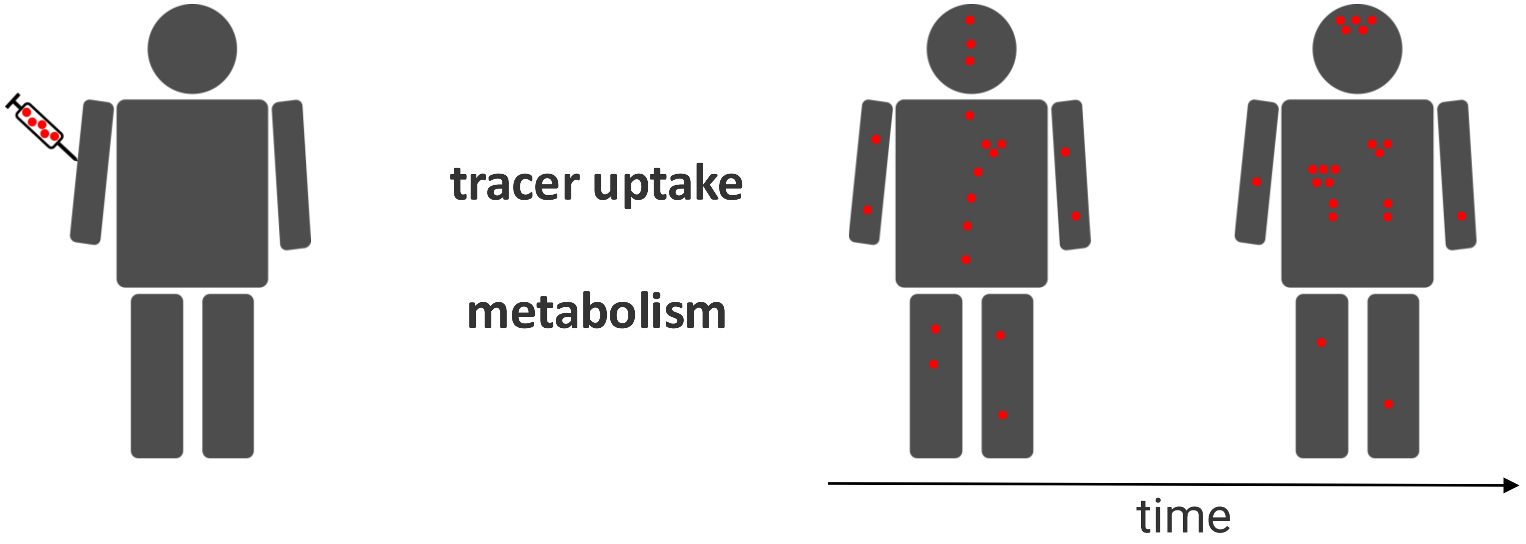
Positron Emission Tomography in a nutshell

tracer injection

120 - 300 MBq (e.g. [^{18}F]FDG)

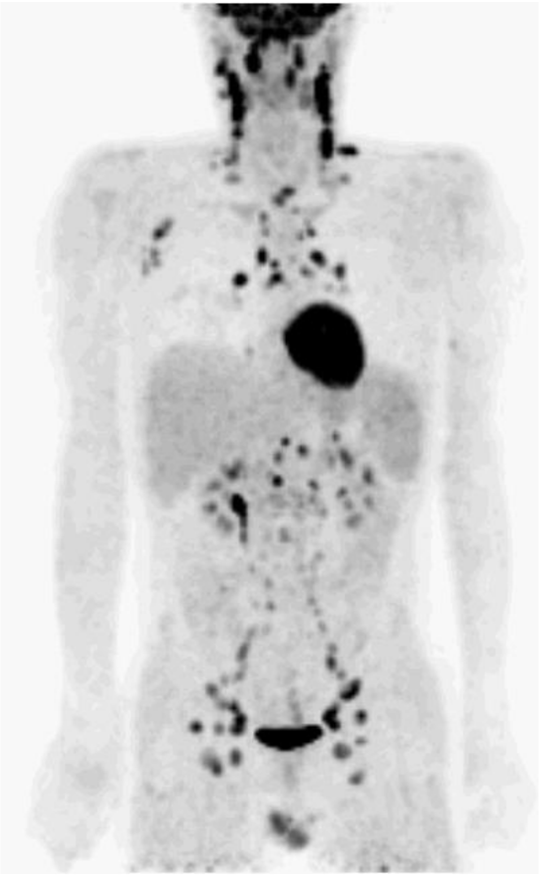
10^{12} molecules (ca 10^{-6} g)

^{18}F half-life 2h



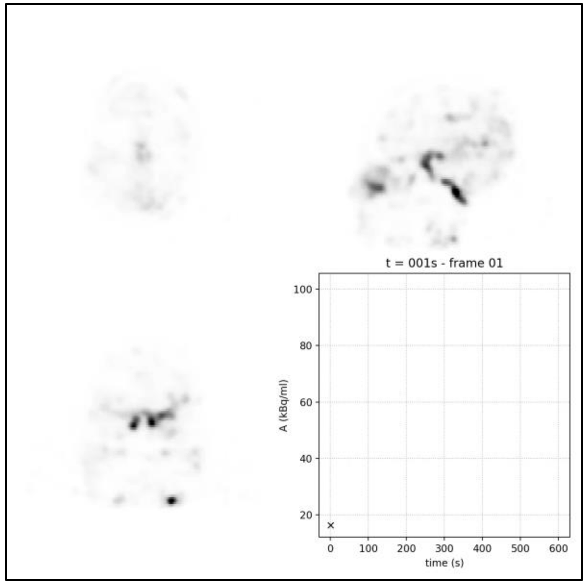
5s p.i.	10s p.i.	15s p.i.	20s p.i.	40min p.i.	50min p.i.

PET image contrast determined by radiotracers



$[^{18}F]$**FDG** PET
malign lymphoma

$[^{18}F]$**NaF** PET
bone metastases

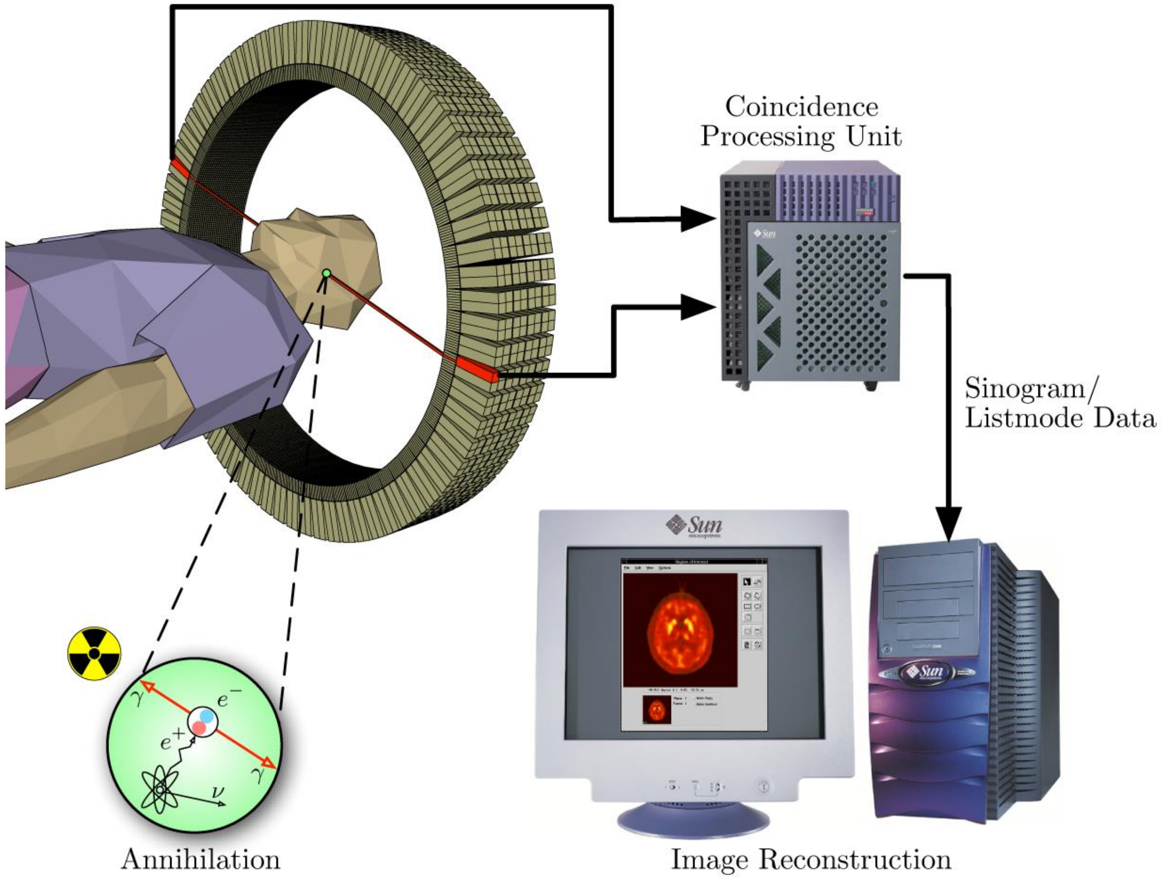


$[^{15}O]H_2O$ PET
brain perfusion

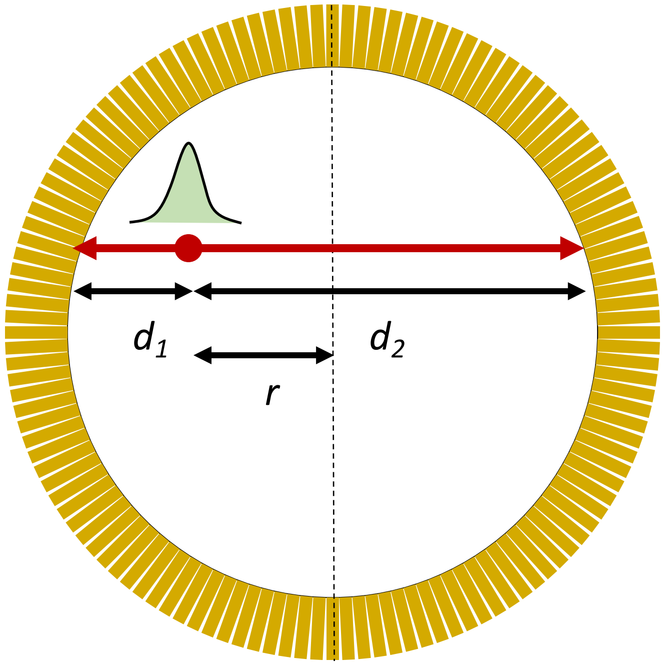
key factors for diagnostic image quality

- tracer specificity + sensitivity
- photon detection system (scanner)
- **image reconstruction**
- **image analysis**

PET data acquisition principle



measurement of "attenuated (TOF) X-ray transform"



$$\Delta t = \frac{d_2 - d1}{c}$$

$$r = \frac{c}{2}\Delta t$$

$$\sigma_r = \frac{c}{2}\sigma_{\Delta t}$$

Time-of-Flight (TOF)

- detection and localization of **annihilation photon pairs** including **arrival time difference (TOF)**
  → **SOTA: 3-6cm FHWM**
  → leads to **variance reduction** in reconstruction
- **(optional) histogramming** of data into "TOF sinograms"

PET coincidences types

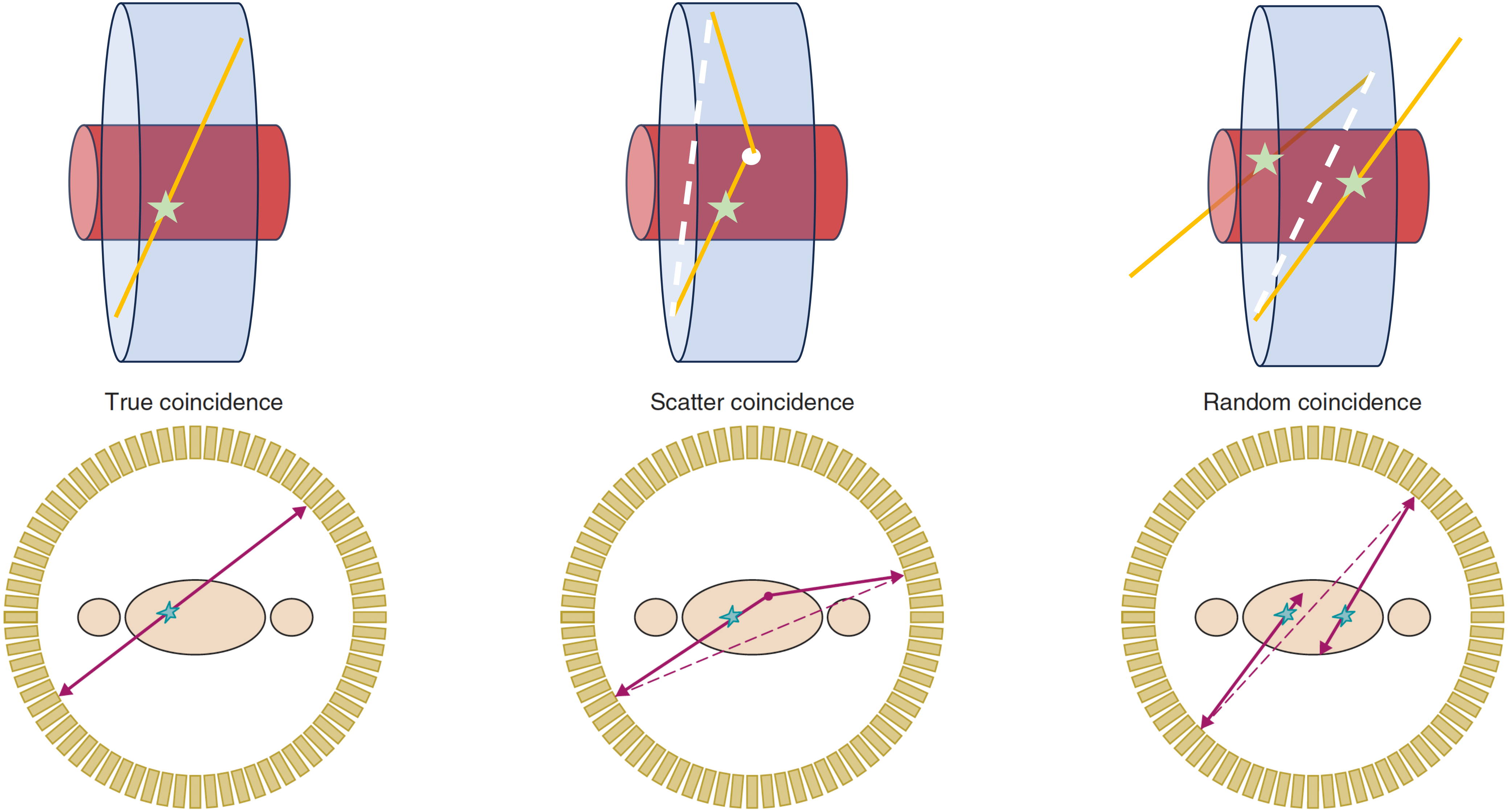


Figure adapted from Cherry: “Physics in Nuclear Medicine”

PET reconstruction as an inverse problem

$$x_{recon} = \mathrm{argmin}_x \left(\sum_i \bar{y}_i(x) - y_i \log \bar{y}_i(x) \right) + \beta R(x)$$

data fidelity
neg. Poisson logL

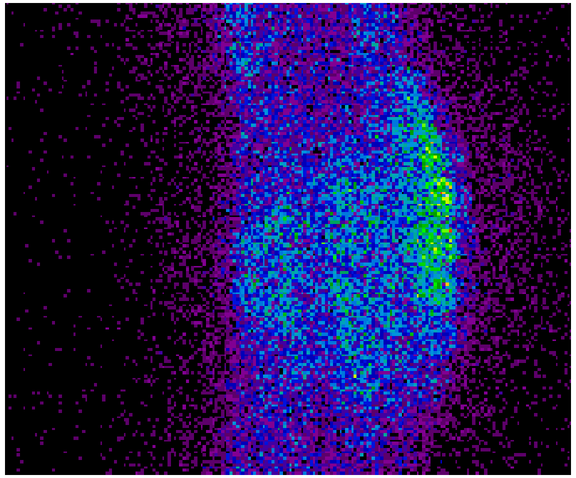
prior knowledge
about solution

$$\bar{y}(x) = \bar{t}(x,\mu) + \bar{s}(x,\mu) + \bar{r}(x,\mu)$$

$$\bar{y}(x) \approx \bar{t}(x,\mu) + \bar{s} + \bar{r} = A(\mu)\,x + b$$

forward model of acquisition physics
object dependent because of attenuation
scatter and random usually "pre-estimated"

acquired emission data y



reconstructed image x

Fundamental recon challenges

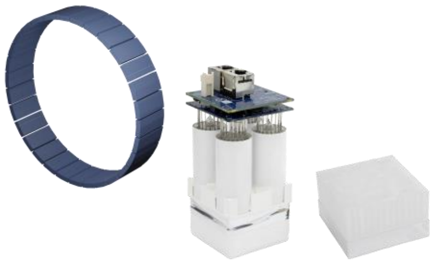
- high data **noise** levels
- **limited resolution** of data
- **accurate modelling** of acquisition **physics** (e.g. **scatter** and resolution effects)
- **data size** and recon speed
- expressing prior knowledge

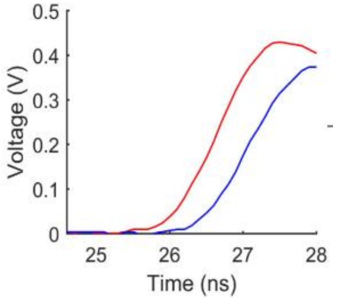
PET compared to CT and MRI

	(TOF) PET	(proton) MRI at 1.5/3T	(energy integrating helical) CT
data SNR	**“low”**	“high”	“high”

From signals to images to decisions

raw signals / data





Listmode file
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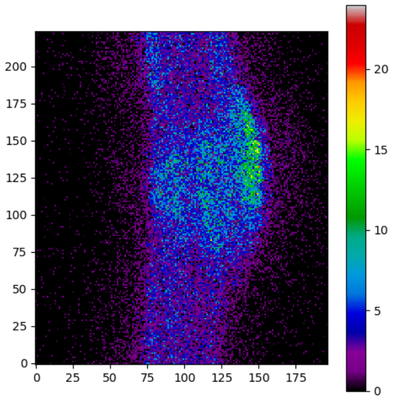
- det 432, det 17, dt = -340ps



reconstruction

images

image processing

feature extraction

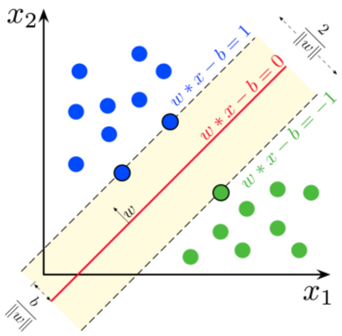
features

symmetry
pattern
intensity
texture
…

decisions

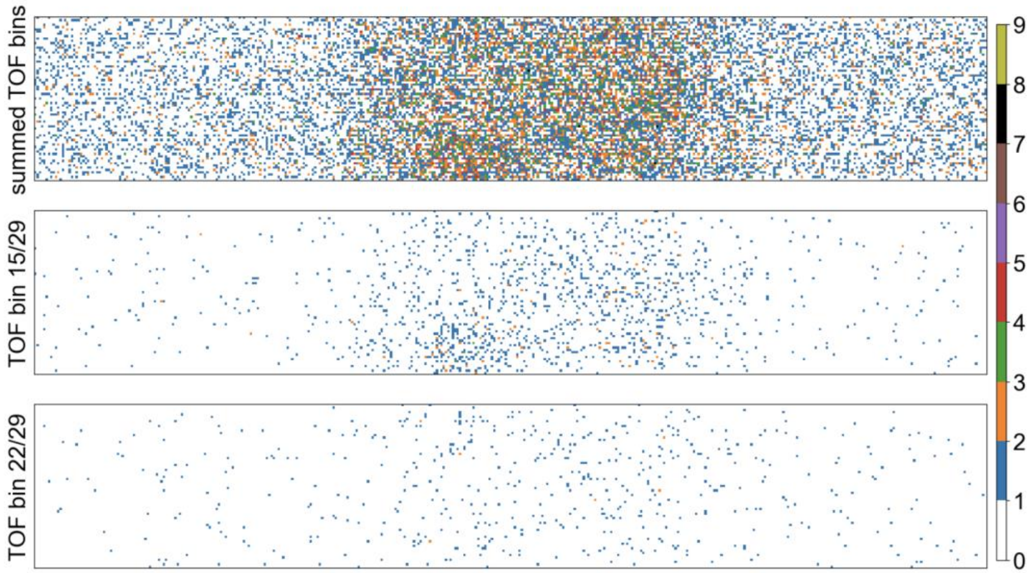
Diseased / healthy?
Apply / change / stop therapy?
…

observer

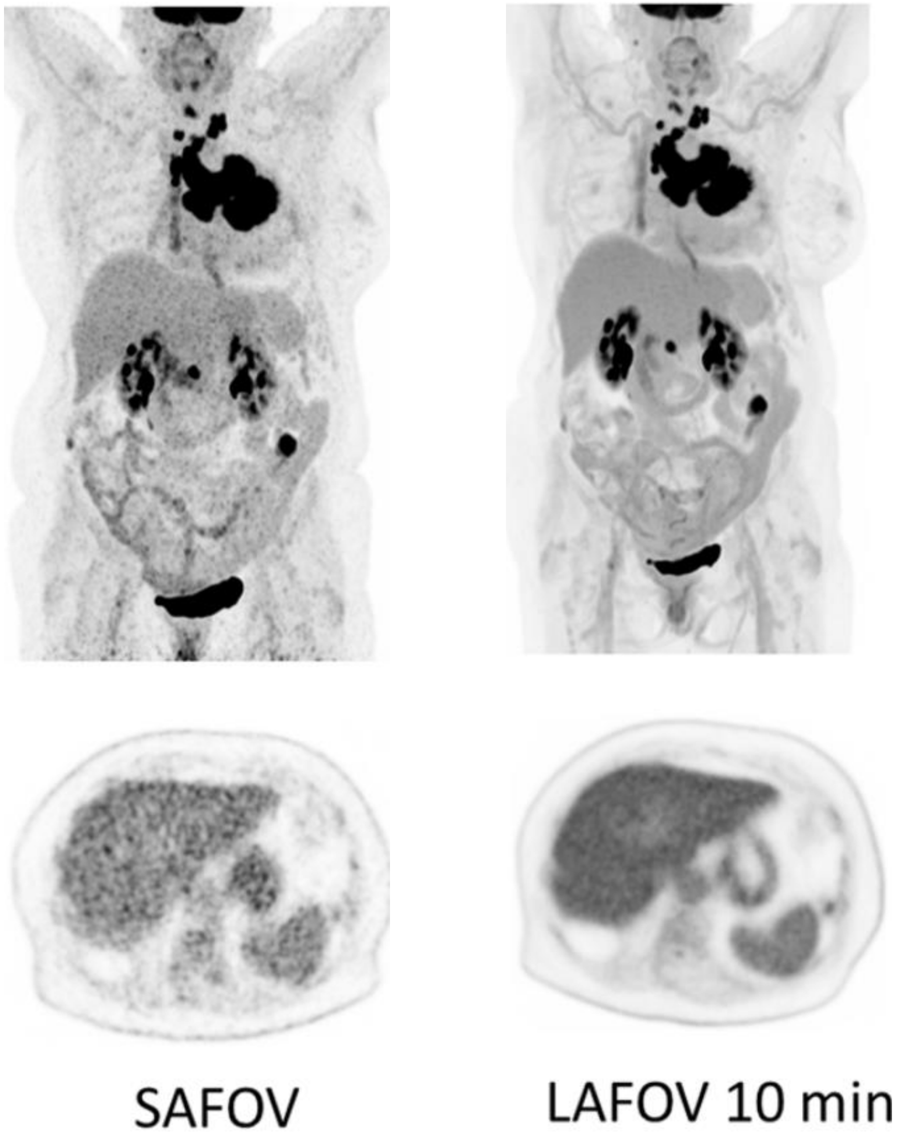


Challenges in PET imaging

Noise / Data size / Data sparsity

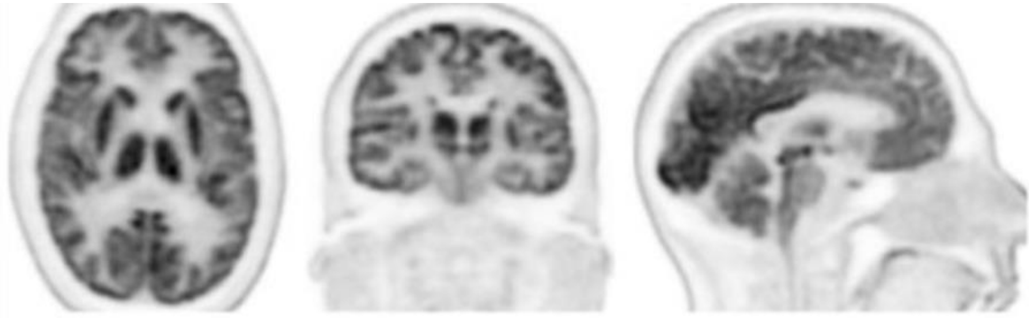


- **high noise levels** because of limits in
  injected activity
  acquisition time
  detection sensitivity
- TOF histogrammed **data is huge** (10-100 GB) but **extremely sparse**
- evaluation of full **forward model** can be extremely **slow** (several minutes)



Alberts *et al.* Clinical performance of long axial field of view PET/CT: a head-to-head intra-individual comparison of the Biograph Vision Quadra with the Biograph Vision PET/CT. *Eur J Nucl Med Mol Imaging* **48**

Resolution



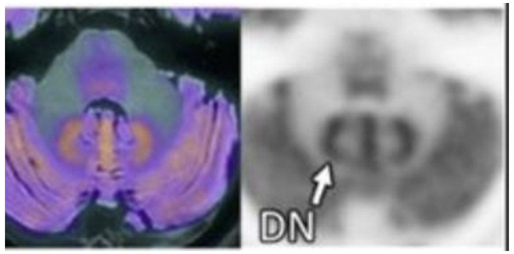
Vision600
ca 4mm res.

PET spatial resolution is "low" because

- Finite detector size
- scanner radius (photon acolinearity)
- parallax effect
- (positron range)

FLAIR MRI

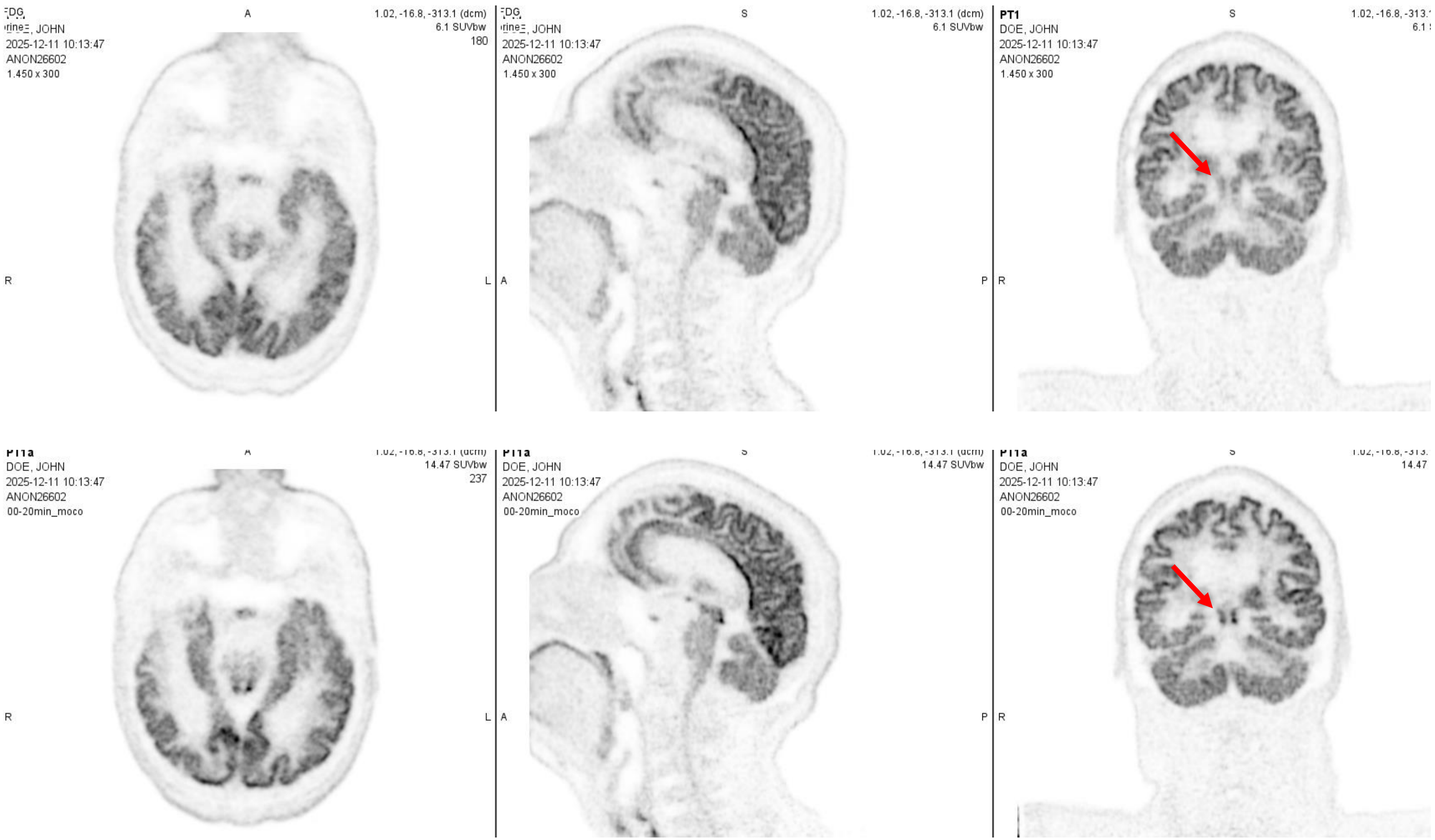
Vision600



Carson et al. "Exceptional PET Images from the First Human Scan on the NeuroEXPLORER, a next-generation ultra-high performance brain PET imager", JNM 2023

Motion

(static) 00-20min **no motion correction**



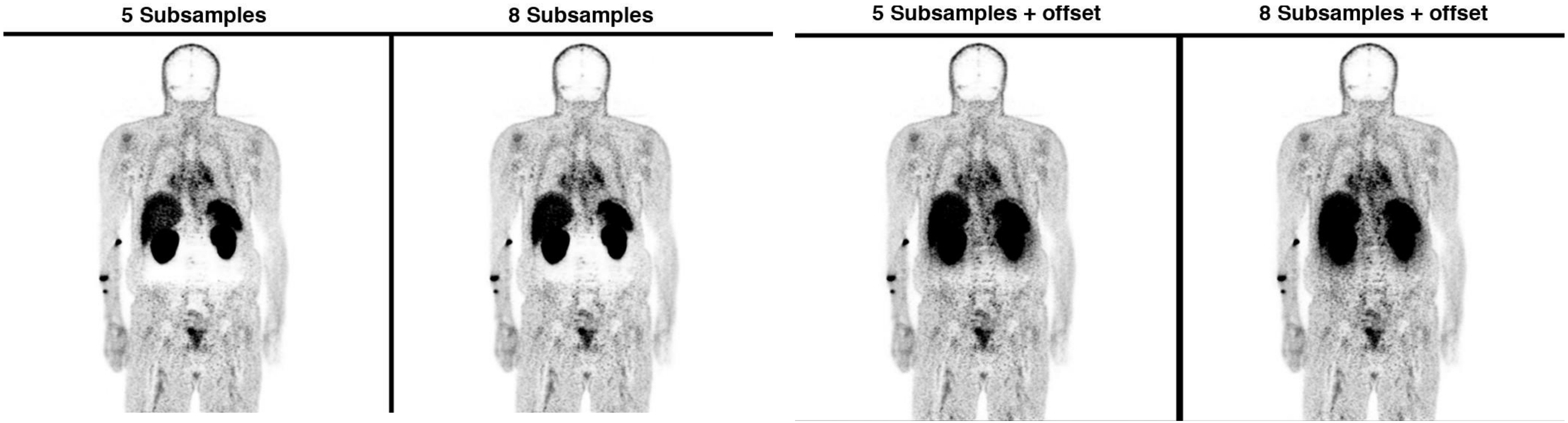
(static) 00-20min UI camera-based **motion correction**

- PET needs **long acquisition times** 5 – 90min
- **motion** → resolution degradation
- true “high-resolution” PET needs **motion tracking and compensation**
- same for **respiratory and cardiac motion**

Quantitative ”corrections” in the forward model

“Improving scatter estimation in PET will bring our kids through college.”
C. Stearns GE Healthcare

$$\bar{y}(x) = \bar{t}(x, \mu) + \bar{s}(x, \mu) + \bar{r}(x, \mu)$$

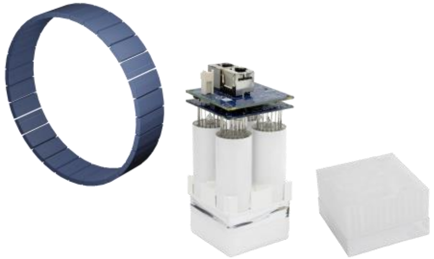


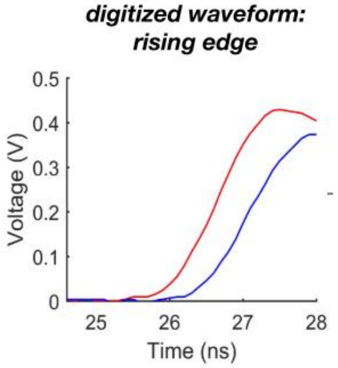
Wangerin et al. “Clinical Evaluation of 68Ga-PSMA-II and 68Ga-RM2 PET Images Reconstructed With an Improved Scatter Correction Algorithm”, Am J Roent, 2018

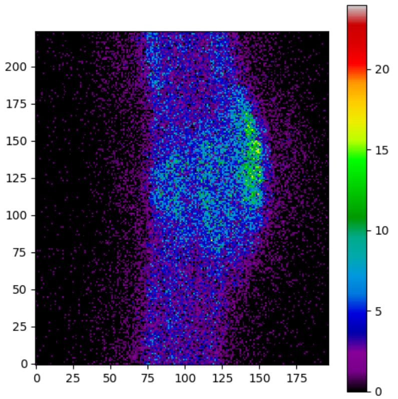
AI/DL/ML in PET imaging

From signals to images to decisions – with AI/DL/ML?

raw signals / data







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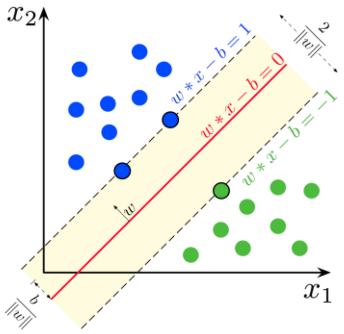
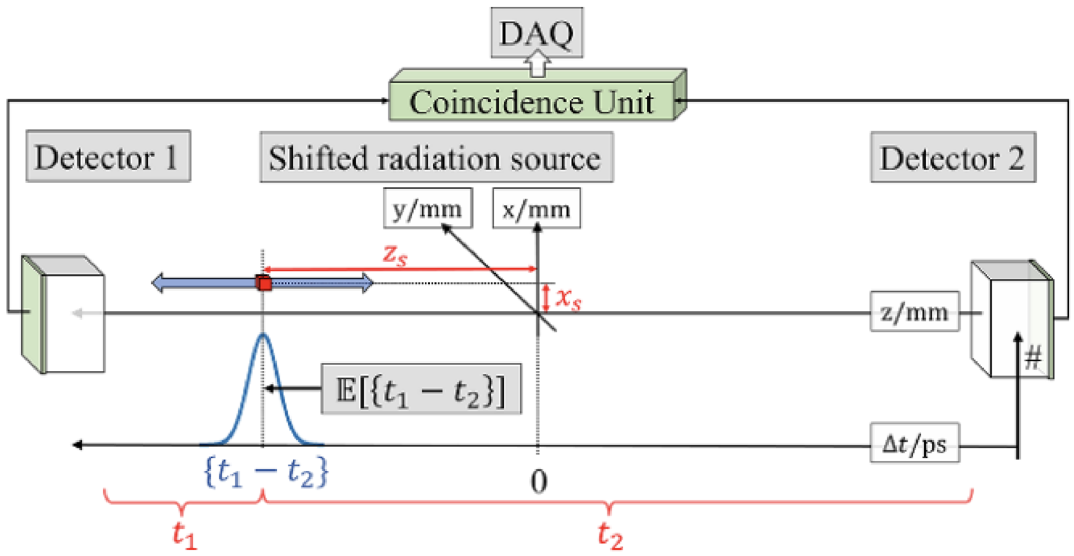


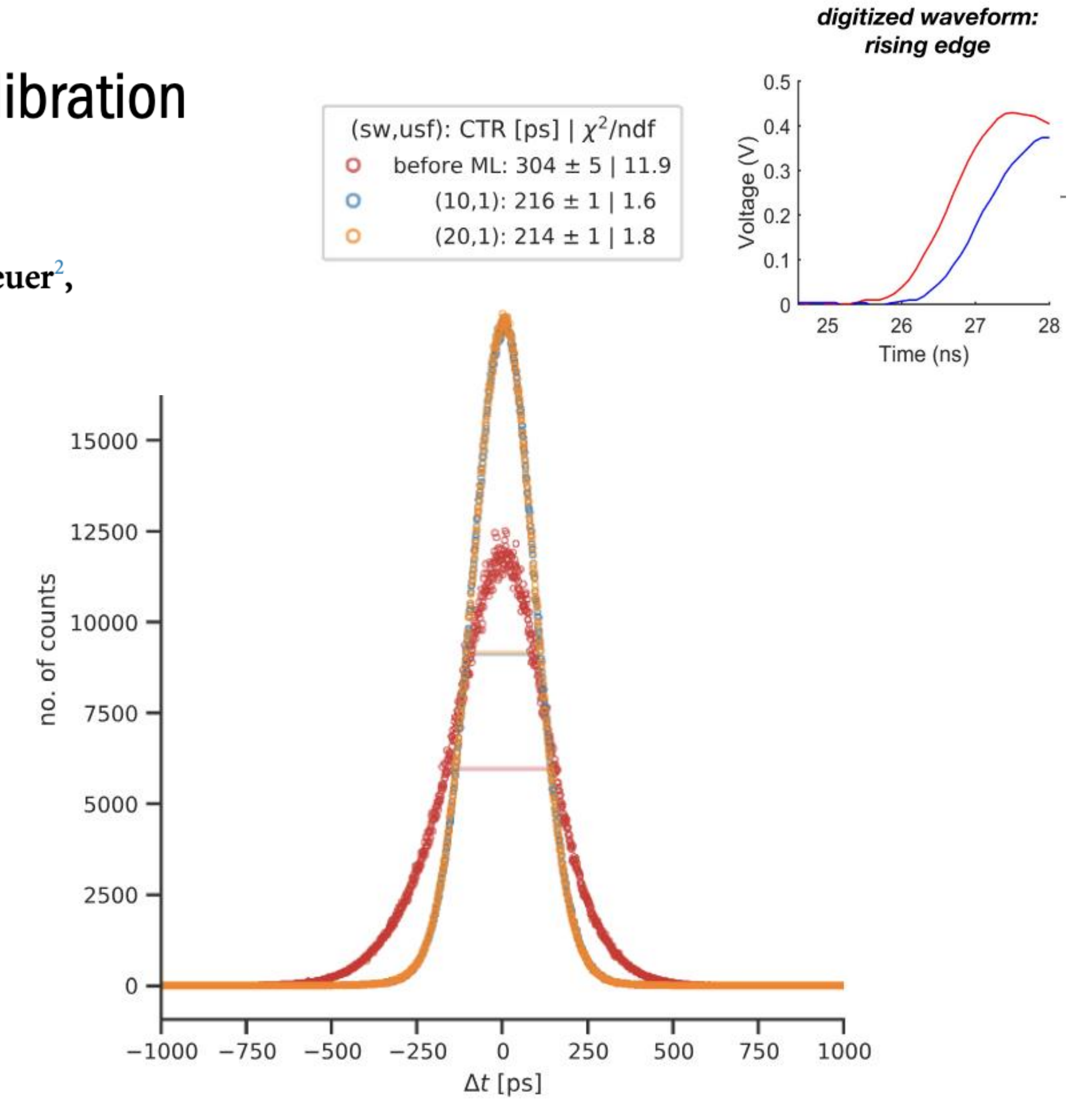
Detector level signal processing

Phys. Med. Biol. **69** (2024) 155026

Holistic evaluation of a machine learning-based timing calibration for PET detectors under varying data sparsity

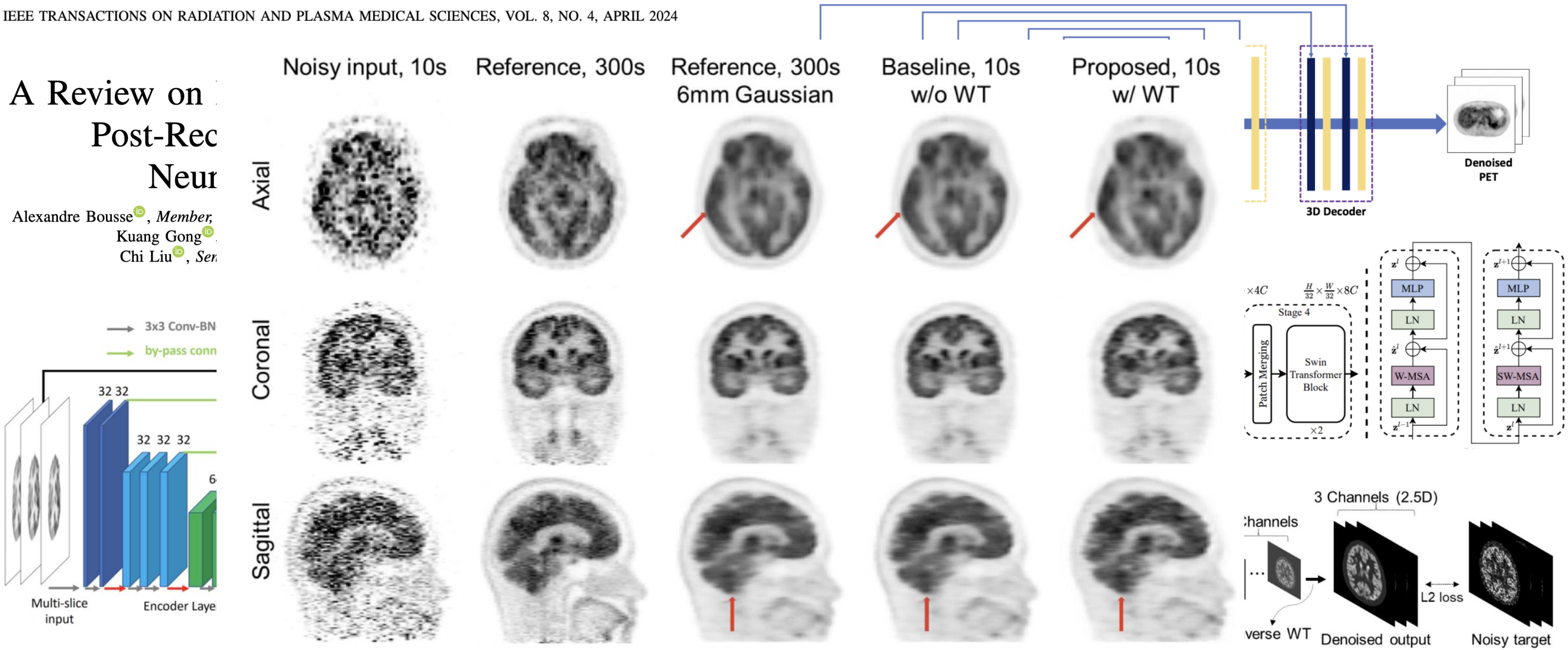
Stephan Naunheim[1,*], Florian Mueller[1], Vanessa Nadig[1], Yannick Kuhl[1], Johannes Breuer[2], Nan Zhang[3], Sanghee Cho[3], Maciej Kapusta[3], Robert Mintzer[3], Martin Judenhofer[3] and Volkmar Schulz[1,4,5,6,*]





use of photon properties + gradient-boosted decision trees to improve coincidence time resolution

Denoising


IEEE TRANSACTIONS ON RADIATION AND PLASMA MEDICAL SCIENCES, VOL. 8, NO. 4, APRIL 2024
A Review on
Post-Rec
Neur
Alexandre Bousse, Member,
Kuang Gong
Chi Liu, Sen
3x3 Conv-BN
by-pass conn
32 32
32 32 32
Multi-slice input
Encoder Laye
Noisy input, 10s
Reference, 300s
Reference, 300s 6mm Gaussian
Baseline, 10s w/o WT
Proposed, 10s w/ WT
Axial
Coronal
Sagittal
Denoised PET
3D Decoder
Stage 4
Patch Merging
Swin Transformer Block
×2
MLP
LN
W-MSA
SW-MSA
3 Channels (2.5D)
Denoised output
L2 loss
Noisy target

ML during PET reconstruction

JOURNAL ARTICLE

AI for PET image reconstruction

Andrew J Reader, PhD, Bolin Pan, PhD

British Journal of Radiology, Volume 96, Issue 1150, 1 October 2023, 20230292, https://doi.org/10.1259/bjr.20230292

Published: 04 September 2023 **Article history** ▾

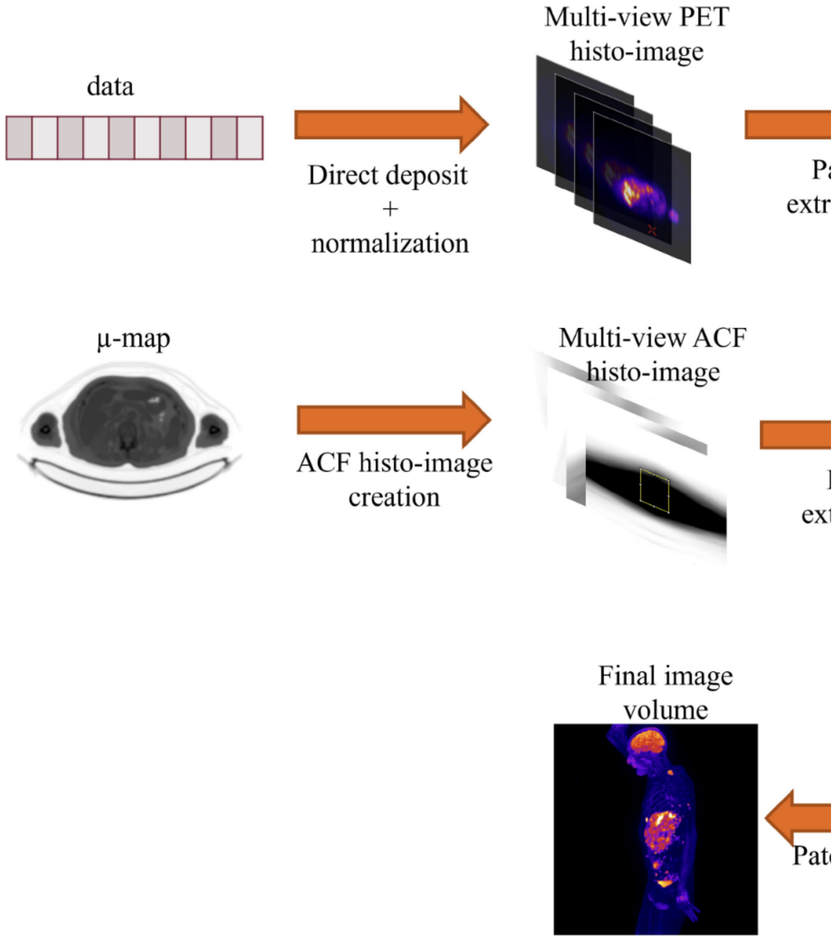
16:05 – 16:55	**Generative AI for medical image reconstruction in positron emission tomography (PET)** *Andrew Reader*

FastPET

Improved Quantification in End-to-End Deep Learning FastPET Reconstruction Using Multiview Histo-Images of Attenuation Correction Factors

Maël Millardet, Deepak Bharkhada, *Member, IEEE*, Juhi Raj, Josh Schaefferkoetter, *Member, IEEE*, Vladimir Panin, *Member, IEEE*, Maurizio Conti, *Member, IEEE*, and Samuel Matej, *Senior Member, IEEE*

IEEE TRANSACTIONS ON RADIATION AND PLASMA MEDICAL SCIENCES, VOL. 10, NO. 1, JANUARY 2026



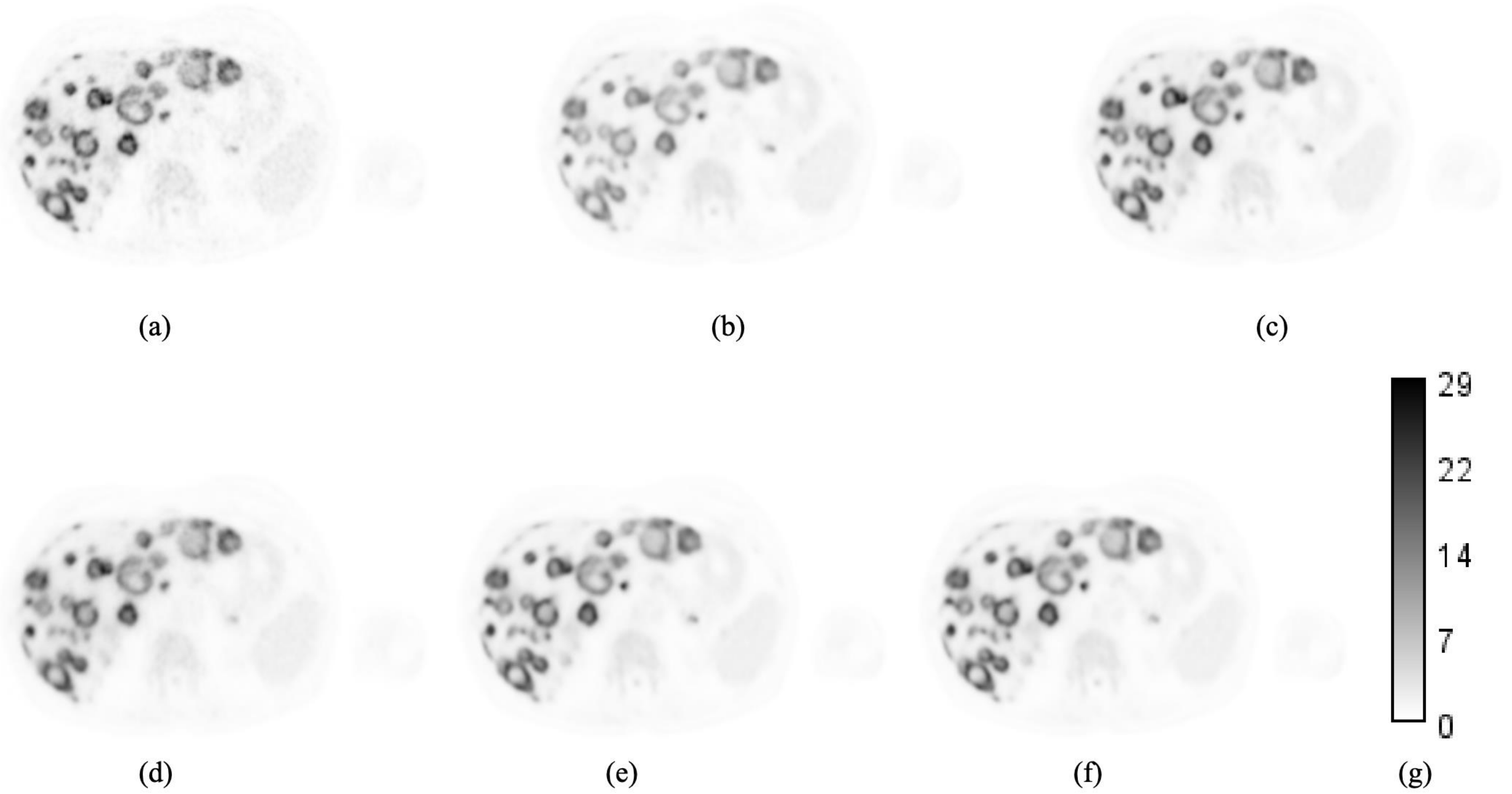


Fig. 10. Reconstruction of the diseased liver of validation patient 2 (4 min scan, 1.2×10^9 prompts, 70 kg) reconstructed with the clinical OSEM, the target MLEM, and the four different FastPET techniques. This liver exhibits lesion shapes that have not been seen during training. The image is acquired on the biograph vision quadra. All subfigures use the same unsaturated colormap. (a) Target MLEM (50×1). (b) FastPET-μ-map. (c) FastPET-pre-corr. (d) Clinical OSEM (4×5). (e) FastPET-ACF. (f) FastPET-all. (g) Colormap (SUV).

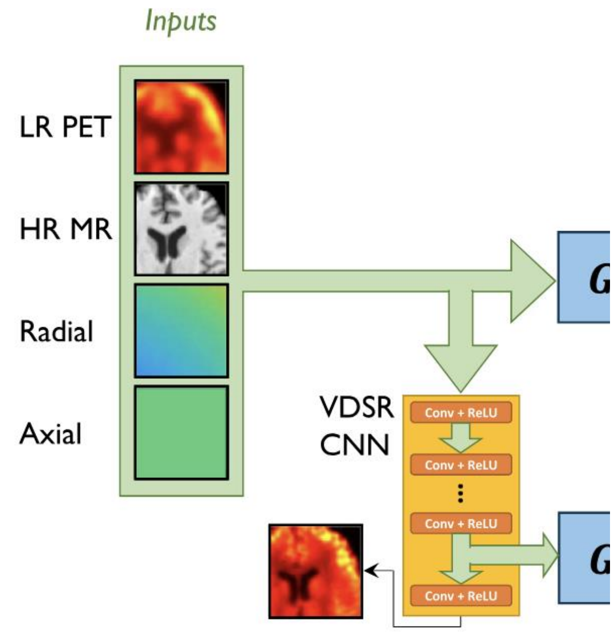
Super resolution

Neural Networks 125 (2020) 83–91

PET image super-resolution using generative adversarial networks

Tzu-An Song [a,1], Samadrita Roy Chowdhury [a,1], Fan Yang [a], Joyita Dutta [a,b,c,*]

[a] Department of Electrical and Computer Engineering, University of Massachusetts Lowell, Lowell, MA, United States of America
[b] Gordon Center for Medical Imaging, Massachusetts General Hospital and Harvard Medical School, Boston, MA, United States of America
[c] Geriatric Research, Education and Clinical Center, Edith Nourse Rogers Memorial Veterans Hospital, Bedford, MA, United States of America



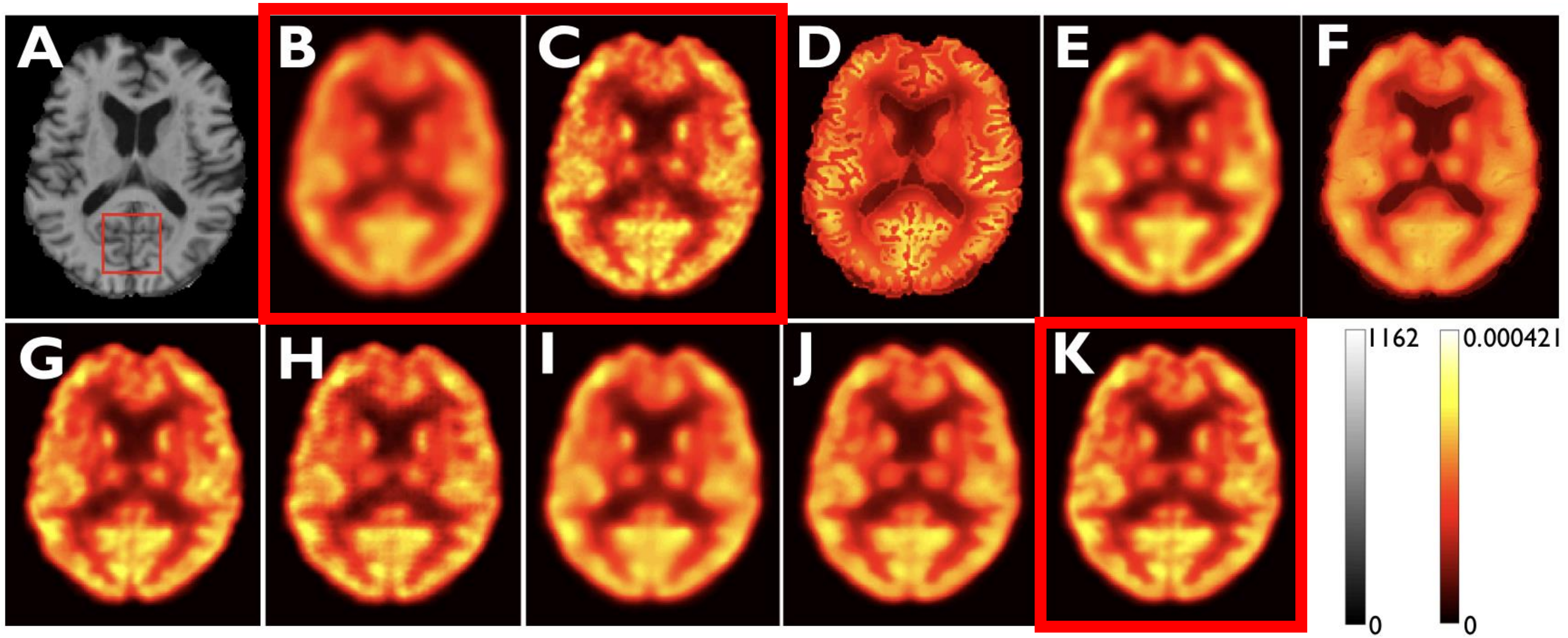


Fig. 5. Transverse image slices from a human subject showing: (A) HR MR, (B) LR PET, (C) HR PET, (D) RBV, (E) TV, (F) JE, (G) VDSR, (H) Lin et al. (2018), (I) SSSR-SVPSF (G_2 replaced by SVPSF), (J) SSSR-NoSim (no simulation guidance), and (K) SSSR-Sim (the proposed method with simulation guidance). The red box in the MR image indicates the region that is magnified for closer inspection in Fig. 6.

Supervised vs self supervised?

Supervised PET DL possible for

- denoising if high count scan is available
  → **subsample LM** file for **virtual lower count scan**
- **paired scans** of same subject (e.g. on different scanners) available
  → **very rare**

Need for self-supervised DL

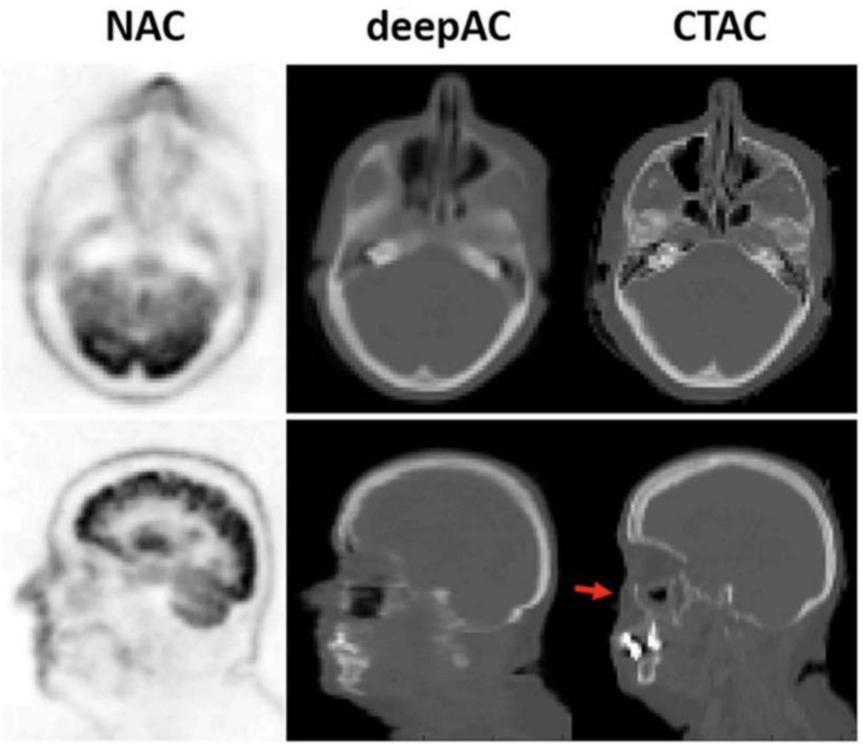
- **“high count”** scans also contain **noise** (depending on scanner / acq. type)
- ”**paired** acquisitions” suffer from **motion** / differences in **tracer kinetics** …
- the **amount of PET scans** is very **small** compared to CT and MR scans (**foundational models**?)

Attenuation correction

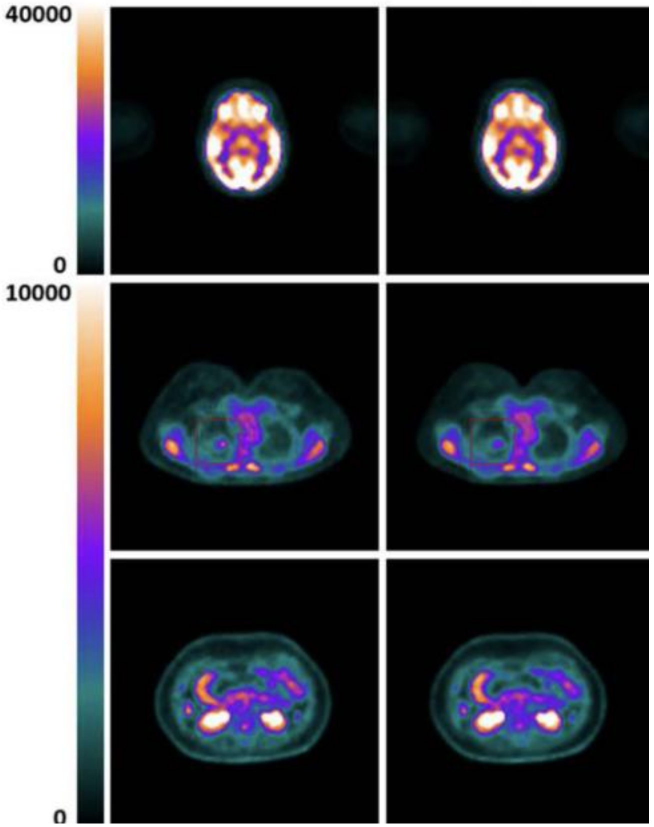
IEEE TRANSACTIONS ON RADIATION AND PLASMA MEDICAL SCIENCES, VOL. 5, NO. 2, MARCH 2021

A Review of Deep-Learning-Based Approaches for Attenuation Correction in Positron Emission Tomography

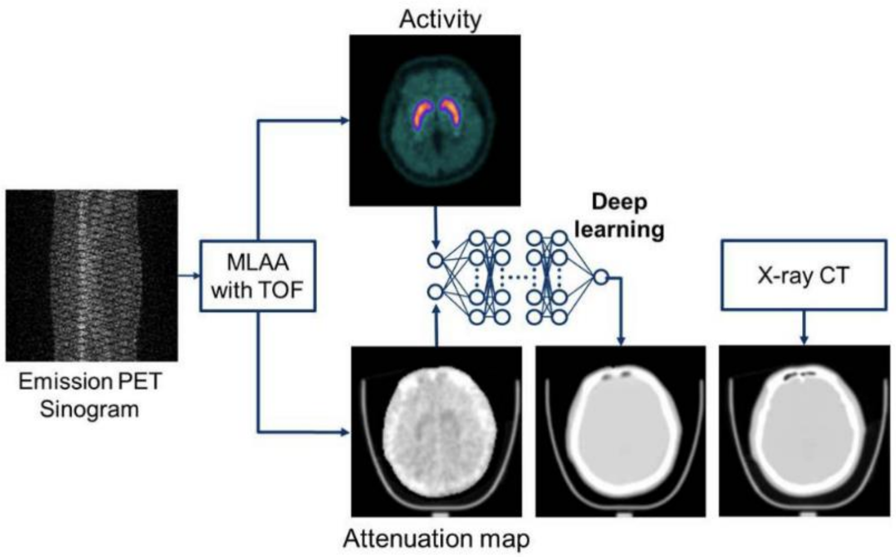
Jae Sung Lee, *Senior Member, IEEE*



DL NAC PET to pCT



DL NAC PET to AC PET



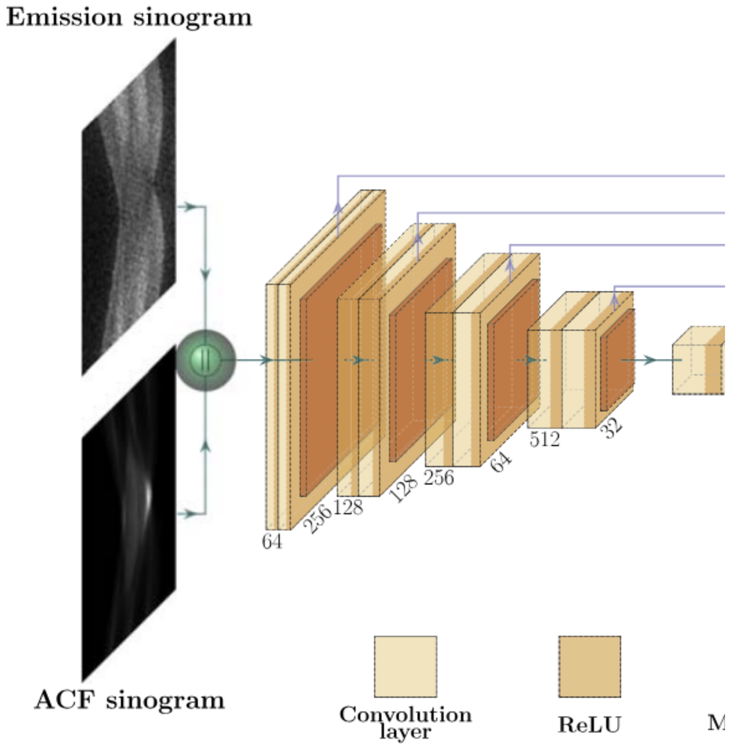
DL-aided joint estimation of activity and attenuation

DL-based scatter estimation

Phys. Med. Biol. **68** (2023) 065004

PET scatter estimation using deep learning U-Net architecture

Baptiste Laurent[1,*], Alexandre Bousse[1], Thibaut Merlin[1], Stephan Nekolla[2] and Dimitris Visvikis[1]



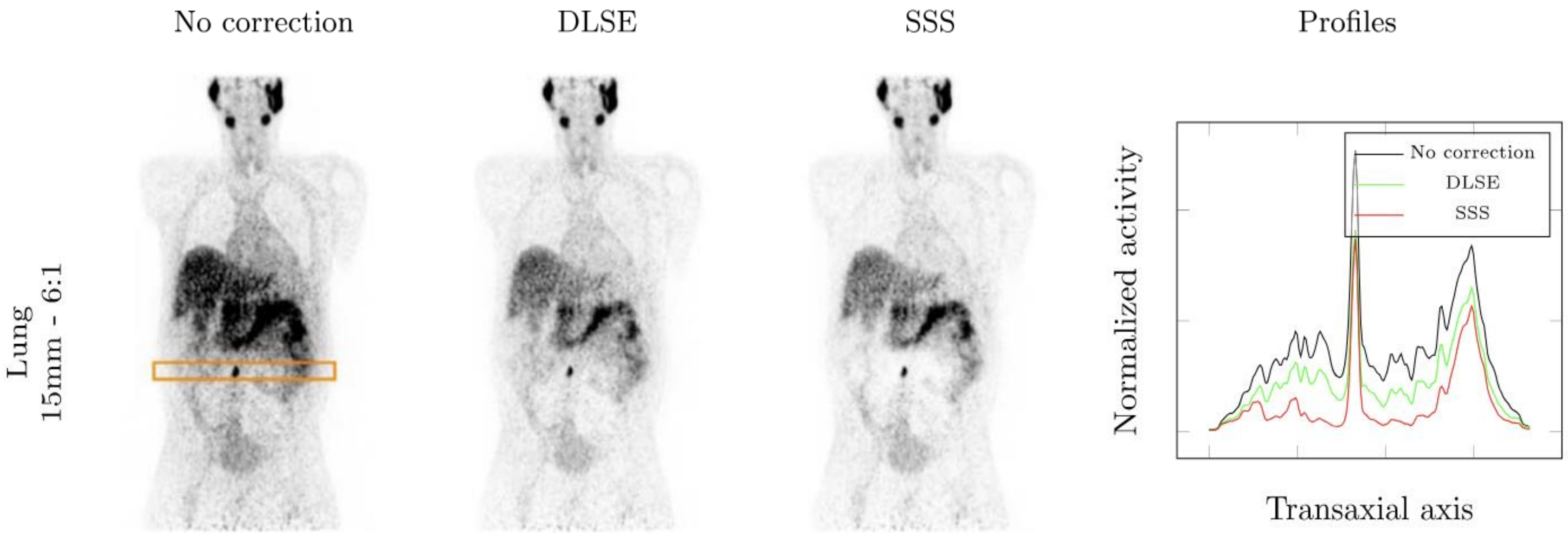


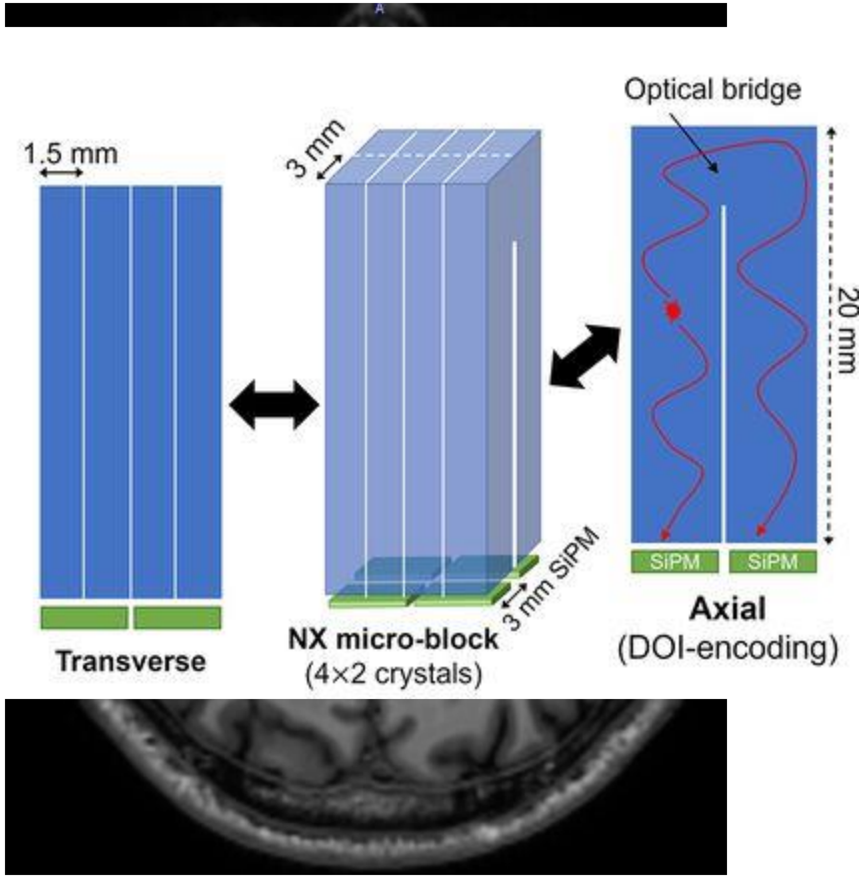
Figure 10. Clinical mMR images reconstructed without scatter correction, and with SSS and DLSE corrections. Display contrast is kept the same for all methods. Profiles along the transaxial axis show the mean activity within orange rectangles.

Opportunities enabled by new PET scanners

New “high-resolution” PET scanners (NeuroExplorer)

standard of care PET
(ca 4mm resolution)

T1 weighted MR

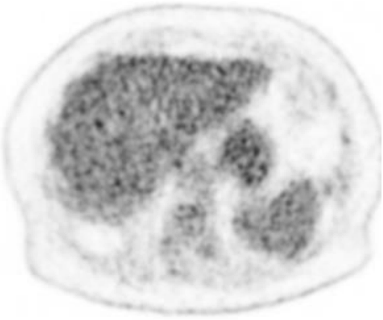


unique opportunities for super-resolution research

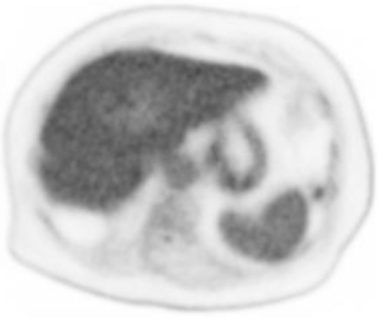
New high-sensitivity PET scanners (large axial FOV)

High sensitivity PET scanners

- **PET** systems with high **solid angle coverage** ”long scanners (>1m)” and detectors with “decent” stopping power (large axial FOV)
- **ca. 3-12x higher noise equivalent count rate for 70cm phantom**
- drawback: high price



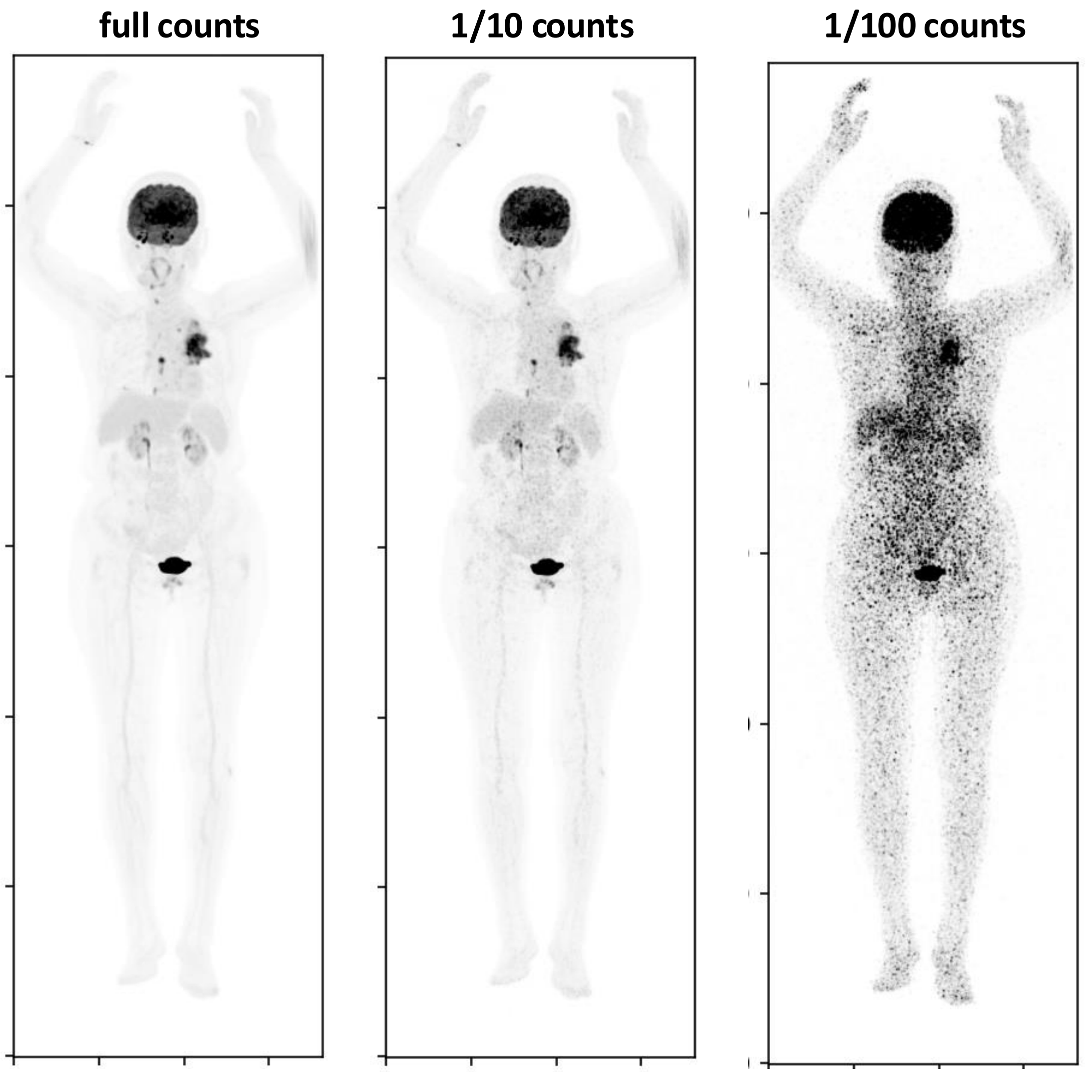
SAFOV



LAFOV 10 min

unique opportunities for denoising research!

Large axial FOV data for denoising



- high count scans (e.g. 3 MBq/kg + 10min) from WB systems are **unique source of low noise and high resolution data sets for supervised learning**
- allows critical evaluation of denoising / processing algorithms with true **"ground truth / gold standard" images**
- **data of immense values for data-driven research**
- **see Ultra-Low Dose PET Imaging Challenge 2025** https://udpet-challenge.github.io/

unique opportunities for denoising research

Taming the wild west (AI in PET / nuclear medicine)

Taming AI in medical imaging in the **wild west** according **to chat GPT 5.2**

Recommendations by German radiation protection commission

SSK

Application of artificial intelligence in image reconstruction and processing in radiology and nuclear medicine

Recommendation of the Radiation Protection Commission (2026)

- AI methods **must not remove or distort diagnostically relevant structures**, must not generate artificial structures, and must **preserve quantification**
- **dose reduction** only if diagnostic **performance is preserved**
- (also) **validate** performance with **export human observers**

- **independent** and **external validation** of methods
- strong developer disclosure obligations to better define training distribution + methods
- **keep conventional (non-AI)** methods available as a **fallback/reference**

Which image quality metrics matter?

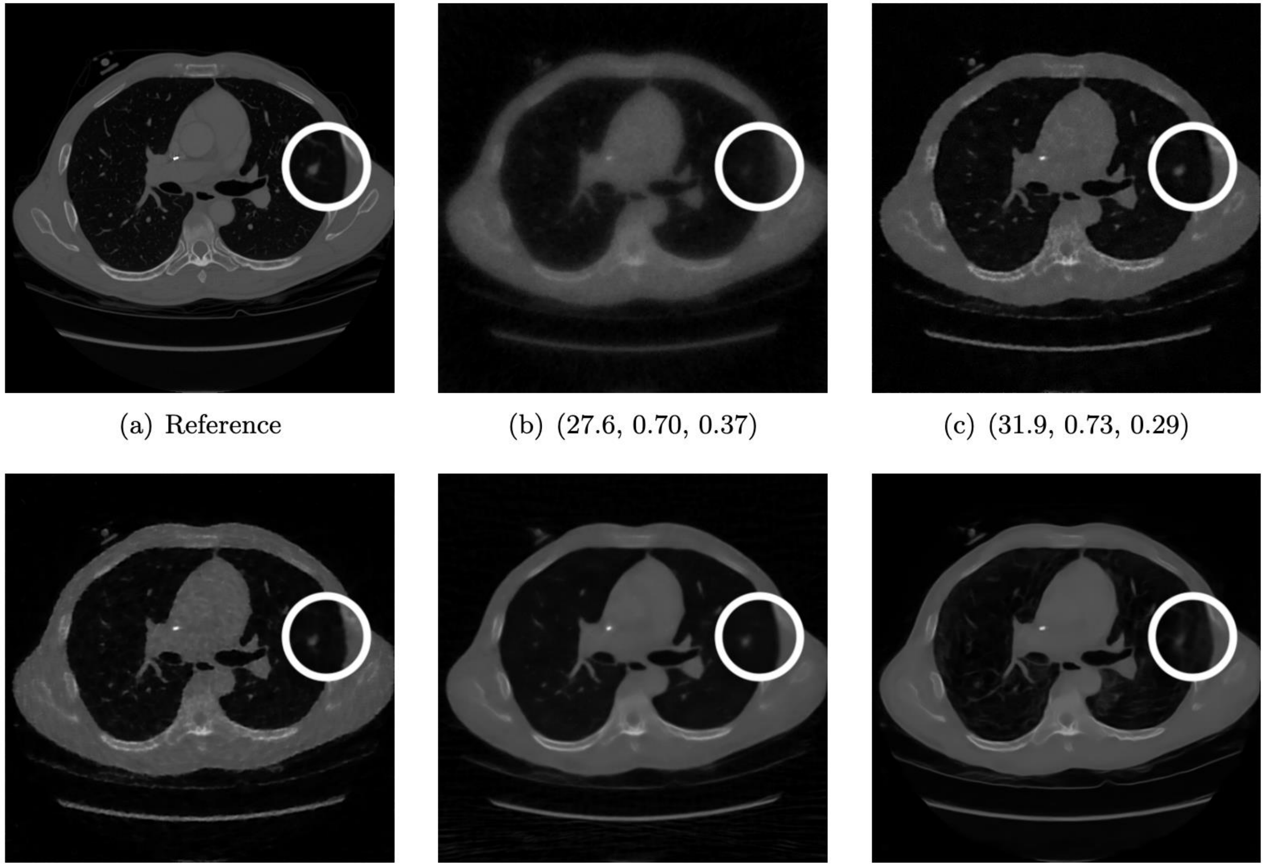
Journal of Imaging Informatics in Medicine (2025) 38:3444–3469

A Study of Why We Need to Reassess Full Reference Image Quality Assessment with Medical Images

Anna Breger[1,2] · Ander Biguri[1] · Malena Sabaté Landman[3] · Ian Selby[4] · Nicole Amberg[5] · Elisabeth Brunner[2]
Janek Gröhl[6,7] · Sepideh Hatamikia[8,9] · Clemens Karner[2] · Lipeng Ning[10] · Sören Dittmer[1] · Michael Roberts[1] ·
A.I.X.-C.O.V.N.E.T. Collaboration · Carola-Bibiane Schönlieb[1]

Problems of PSNR/SSIM/LPIPS IQ metrics

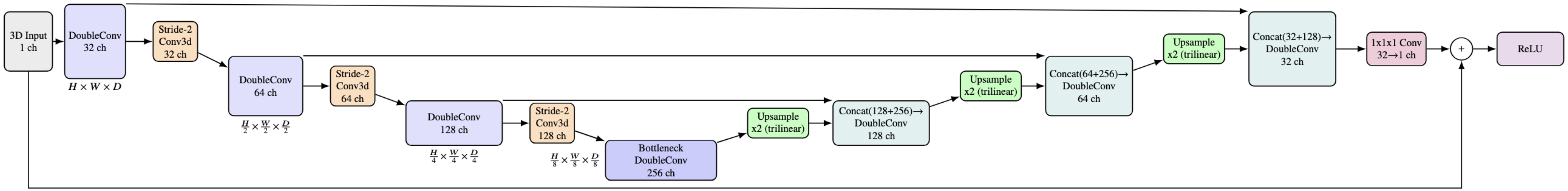
- penalization of **task-irrelevant** perceptual **information**
- inability to detect **local errors** and structural details
- misjudgement of overall visual appearance
- undesired sensitivity to small spatial changes (PSNR, SSIM)

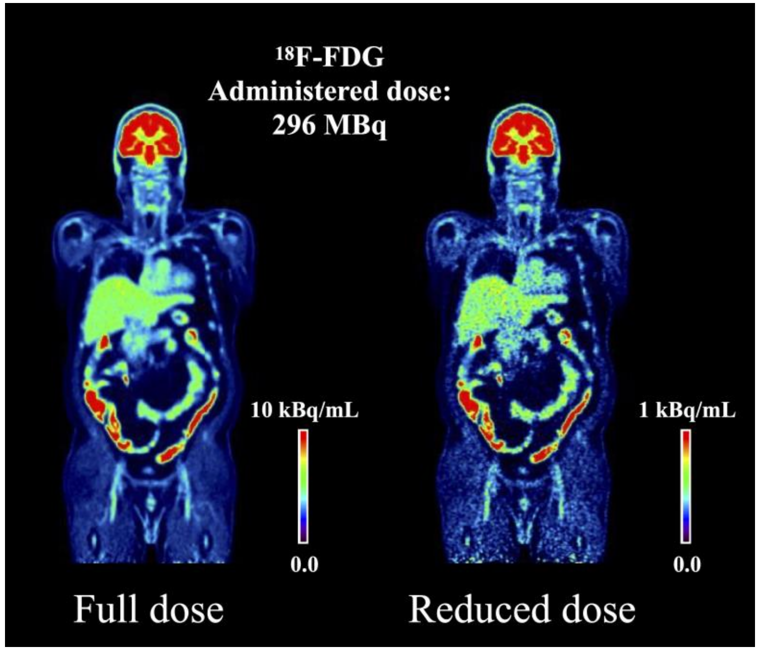


(a) Reference (b) (27.6, 0.70, 0.37) (c) (31.9, 0.73, 0.29)
(d) (32.5, 0.84, 0.19) (e) (32.5,0.77, 0.20) (f) (33.0, 0.89, 0.12)

Figure 3: Reference image (a) and outputs of different reconstruction methods (b)-(f) applied to dose simulated data. PSNR/SSIM/LPIPS are unable to identify the best reconstruction (c), where also the tumour is visualized well.

Experience from 2025 low dose denoising challenge (logSUV)





Balancing / weighting of training data set

(sub selection of 300 / 1000 cases)

interpolation to 1.65 isotropic voxels + RAS orientation

conversion to SUV units

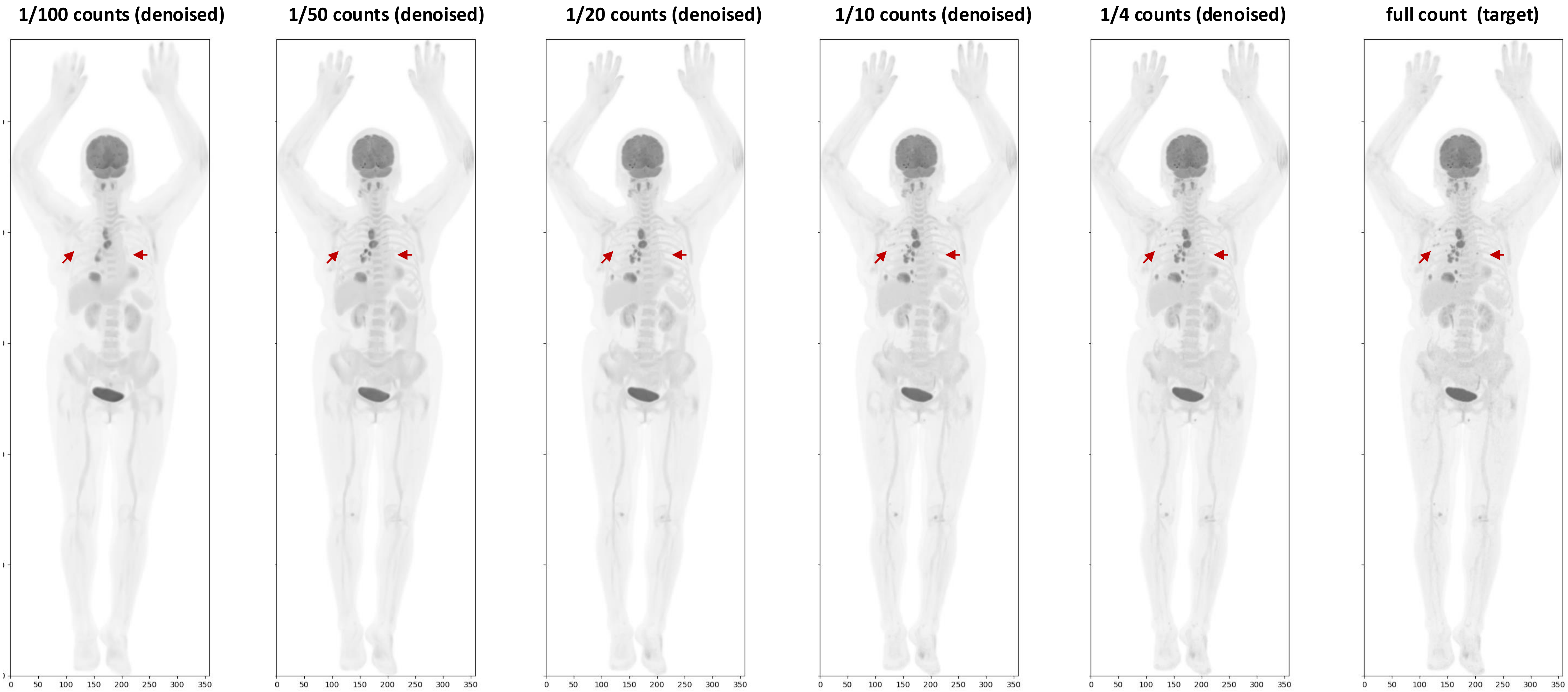
compression of high dynamic range

log(1 + SUV)

creation of sampling map to exclude background

Simplistic and fast 3D Unet + clever data preprocessing + classification of training data **enough for 2d place**!
→ **data curation** probably more important that DL method / architectures

Experience from 2025 low dose denoising challenge



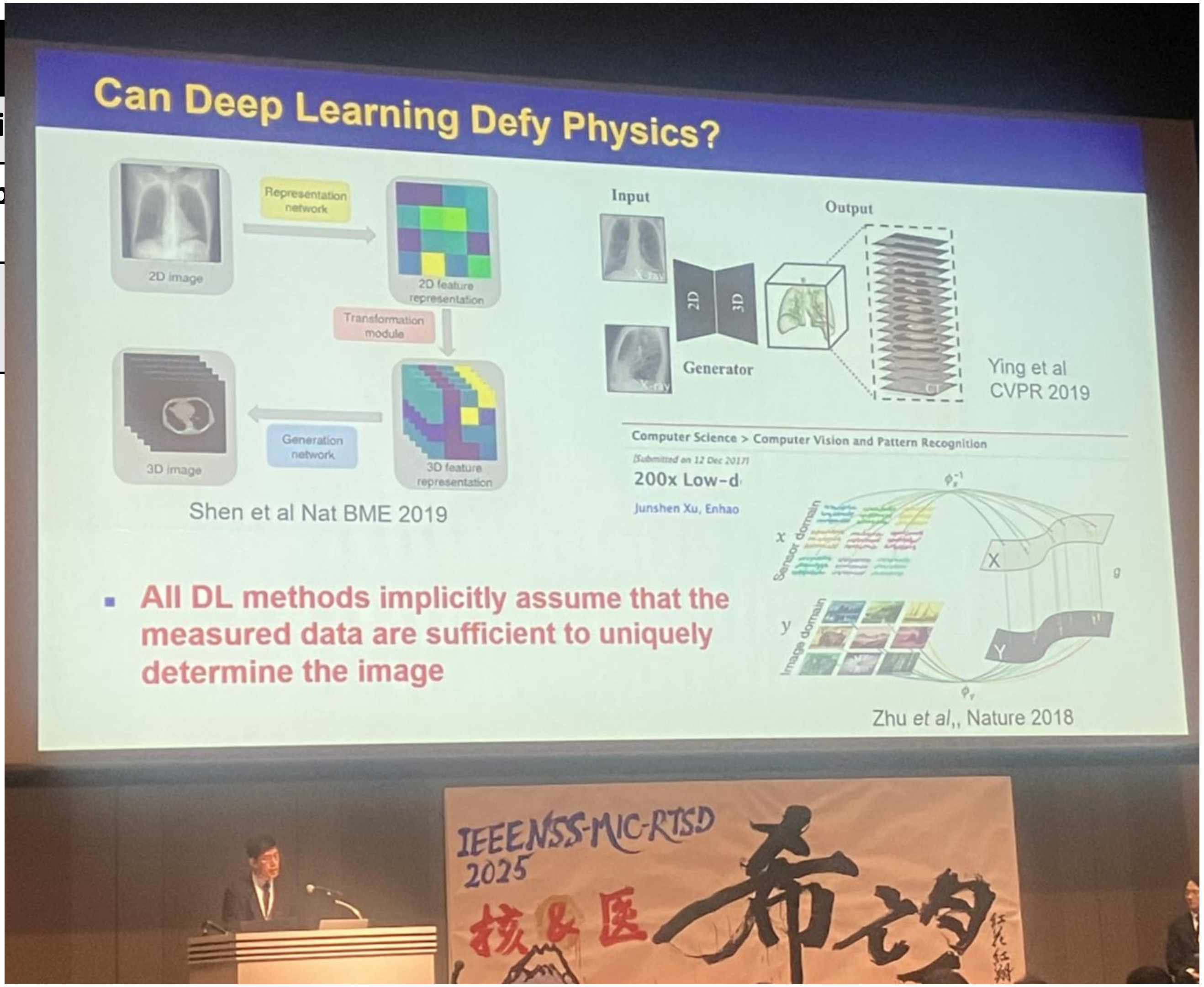
results from runner-up contribution of 2025 low dose challenge

You cannot beat physics / Poisson statistics …

small lesion: A = 2 kBq/ml = 2000 Bq/ml at full dose

V = 0.08 ml (sphere with diameter 0.53cm)

Total lesion activi
Emitted photon p in 10min
Detected true coincidences

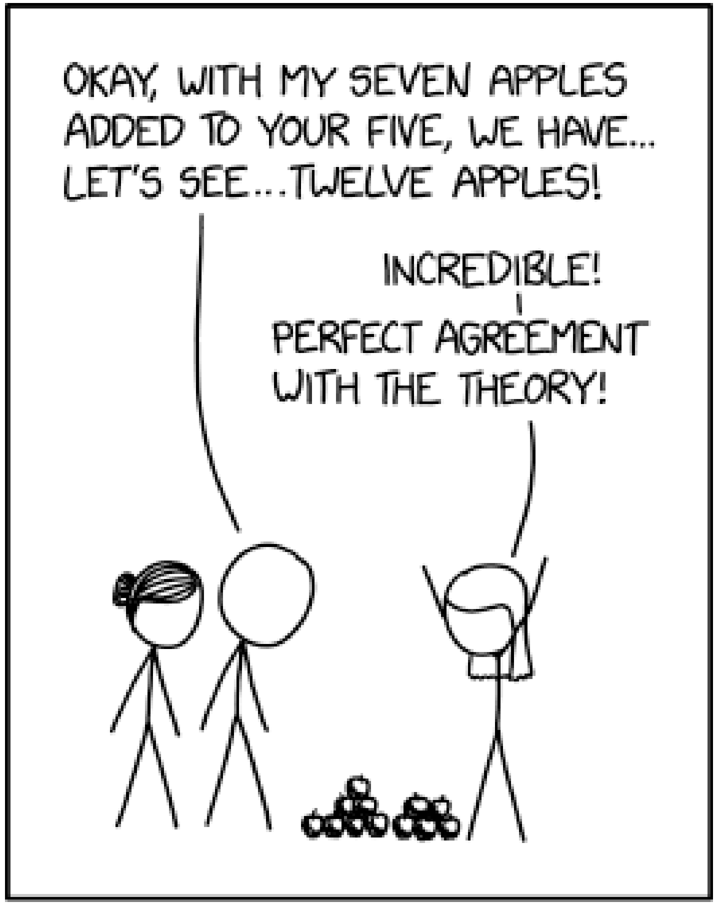


Summary

Discussion, Summary, Thoughts

- **PET imaging** challenges somehow similar, but also very **different MR and CT**
- **PET images can be very diverse** (many different tracers, contrasts, short or long acquisitions …)
  noise is usually main problem
- **AI / DL / ML** is applied in a**ll steps of the PET image** (decision) **pipeline** – at least in research

- **methods** / creativity is **not** the **bottle neck**
  → high quality big open **data** sets and careful **validation is**
- **understanding** where benefit comes from (new methods or better data) is **hard**
- **taming AI** (meaningful regulation / QC) is **hard**
- **"robustness over peak performance"** for clinical use (problem for academia)
- **outliers and incidental findings matter!**



EXPERIMENTAL MATHEMATICIANS

https://xkcd.com/3180/

For all experts in convex optimization

PETRIC 2: Second PET Rapid Image reconstruction Challenge

announcement website | participate register | rankings leaderboard | chat discord

> Main organisers: Matthias Ehrhardt (U Bath), Christoph Kolbitsch (PTB), Charalampos Tsoumpas (RU Groningen), Kris Thielemans (UCL).
>
> Technical support (CoSeC, UKRI STFC): Casper da Costa-Luis, Edoardo Pasca

- Time frame: 17 November 2025 - 15 February 2026

Time for questions