Oxford University Hospitals
NHS Foundation Trust

Clinical Implementation of New PET Reconstruction Methods

Daniel McGowan

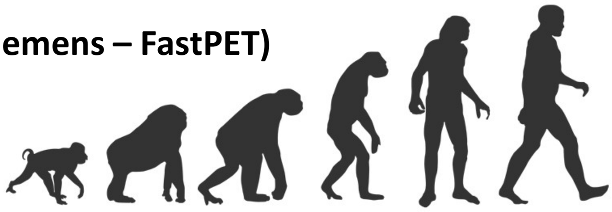
Head of Education and Research, Consultant Clinical Scientist
Department of Medical Physics and Clinical Engineering, Oxford University Hospitals

Honorary Senior Clinical Research Fellow, Department of Oncology, University of Oxford

Oxford University Hospitals
NHS Foundation Trust

PET image reconstruction

- Evolution of image reconstruction methods
  - FBP
  - OSEM
  - OSEM TOF
  - OSEM+PSF TOF
  - **DDG**
  - **MAP (GE – Q.Clear)**
  - **AI (GE – PDL, United – uAI HYPER, Siemens – FastPET)**
  - **Your work!**



NHS
Oxford University Hospitals
NHS Foundation Trust

MAP: GE Implementation

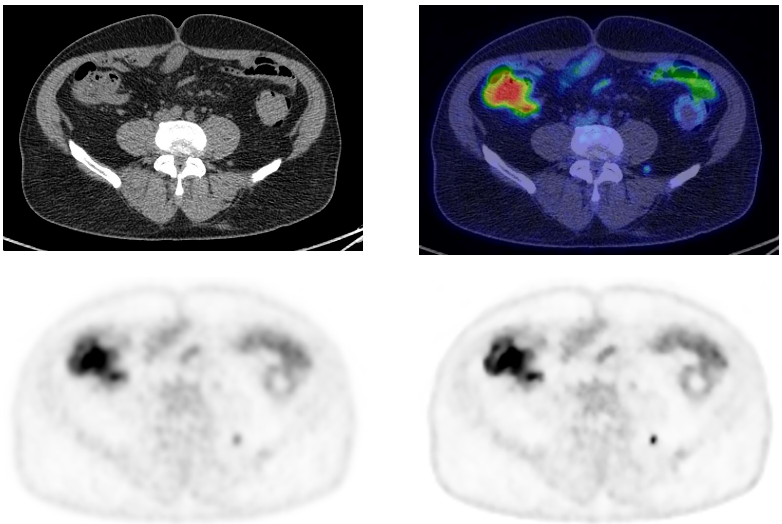
- Marketed as ‘Q.Clear’
- One variable for users to optimise
  - Higher beta gives greater noise suppression

$$\hat{x} = \arg\max_{x\geq 0} \sum_{i=1}^{n_d} y_i \log[Px]_i - [Px]_i - \beta \sum_{j=1}^{n_v} \sum_{k\in N_j} \kappa_{jk}\varphi(x_j - x_k)$$

- What is the impact on clinical images…

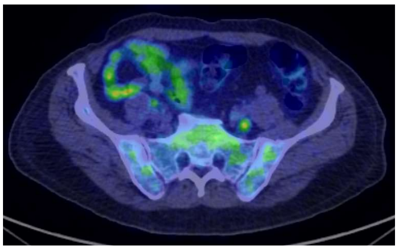
NHS
Oxford University Hospitals
NHS Foundation Trust

62M, FDG



NHS
Oxford University Hospitals
NHS Foundation Trust

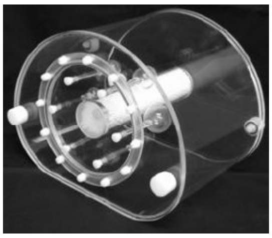
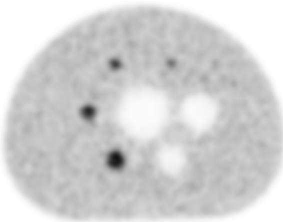
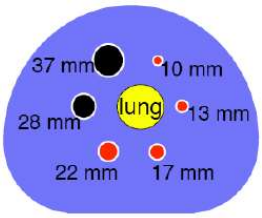
75M, F-choline

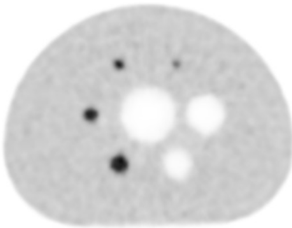



NHS
Oxford University Hospitals
NHS Foundation Trust

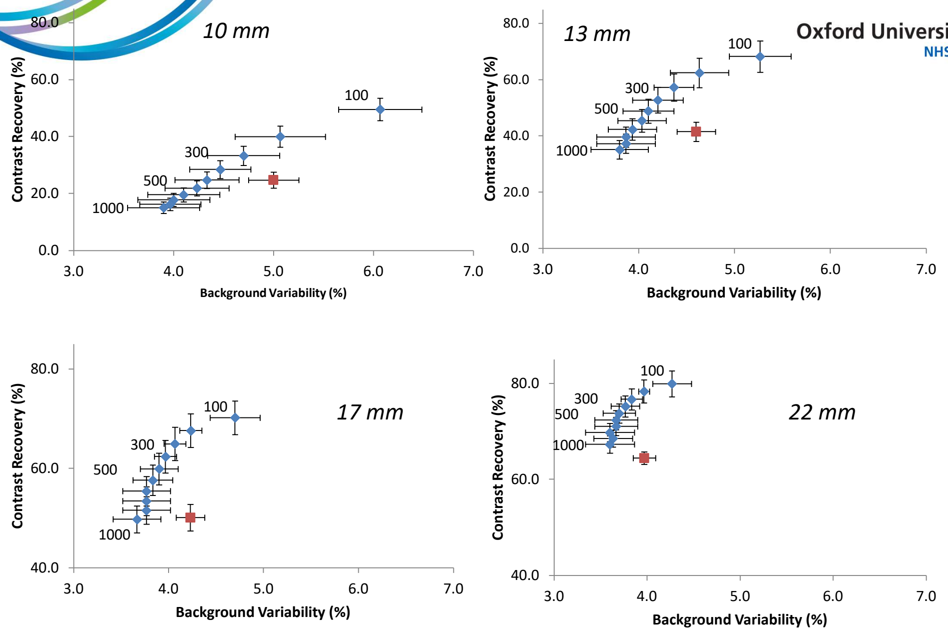
Phantom Testing

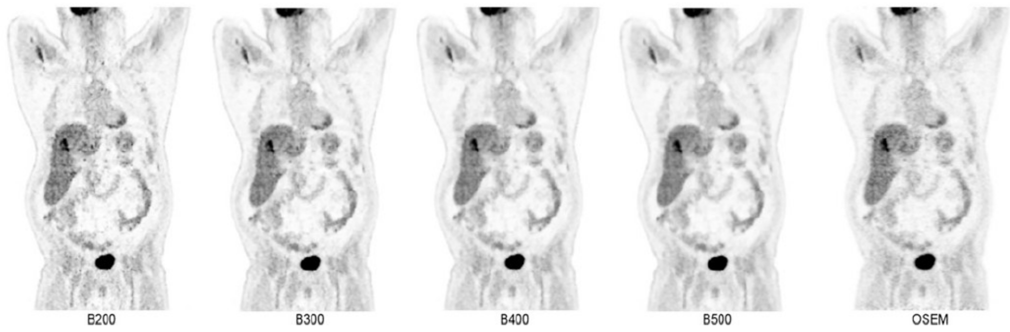
- Use NEMA IQ. Sphere: background 4:1



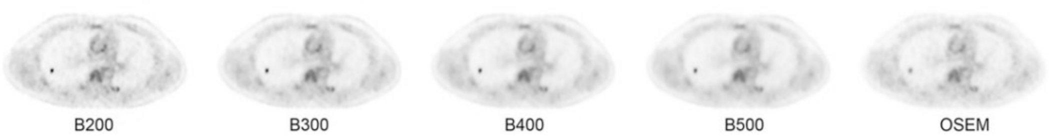
Oxford University Hospitals
NHS Foundation Trust





- Radiologist blind scoring

Parameter	Highest-ranked reconstruction (% of cases) Scorer 1	Scorer 2
Overall IQ	B400 (87%)	B400 (73%)



Oxford University Hospitals
NHS Foundation Trust

Clinical Testing

- Use prior patient sinograms

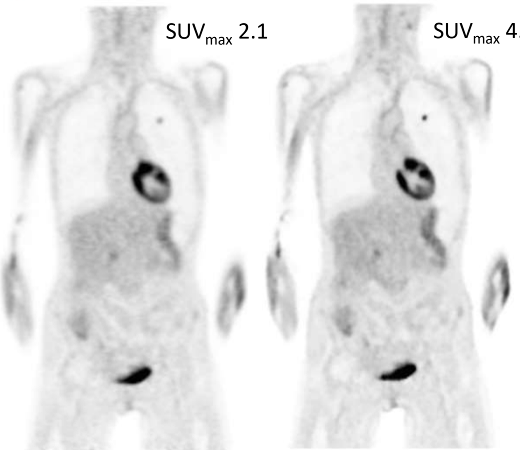
- Series of histological proven cancer types
- **Blind** radiologist scoring

Eur Radiol (2016) 26:576–584
DOI 10.1007/s00330-015-3832-y

NUCLEAR MEDICINE

Oxford University Hospitals
NHS Foundation Trust

Novel penalised likelihood reconstruction of PET in the assessment of histologically verified small pulmonary nodules



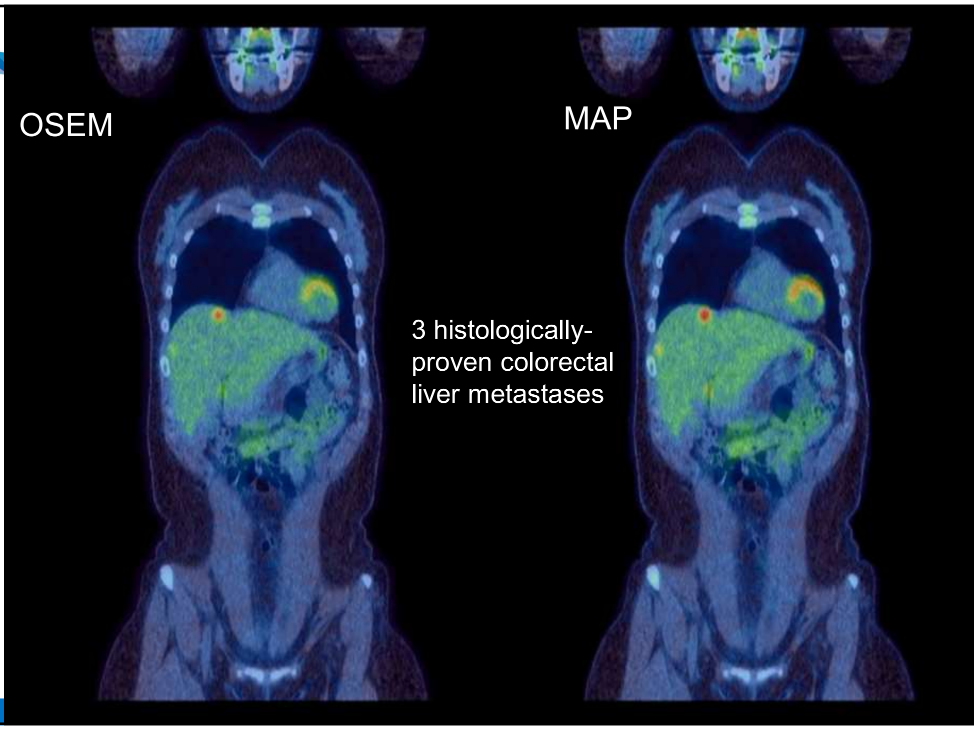
11mm left upper lobe adenocarcinoma

N=121 nodules

Conclusion

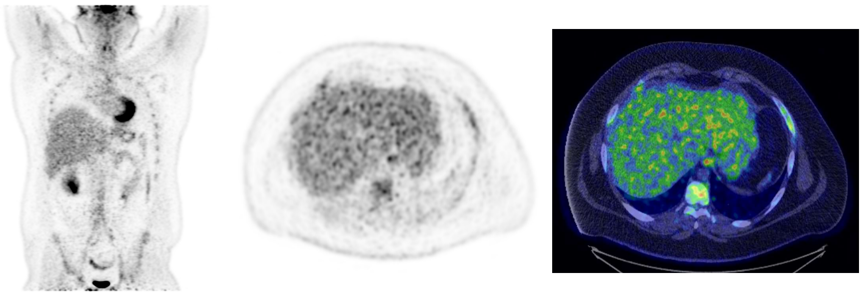
The use of BPL, an iterative reconstruction technique using a Bayesian penalised likelihood reconstruction algorithm, results in a significant increase in signal-to-noise and signal-to-background measures in comparison to conventional OSEM reconstruction. While it does not improve the overall accuracy of 18F-FDG PET/CT for differentiating benign from malignant nodules, it appears to provide a more accurate report on the metabolic activity of the nodules. When a semi-quantitative analysis

NHS
y Hospitals
Foundation Trust



23M…184Kg

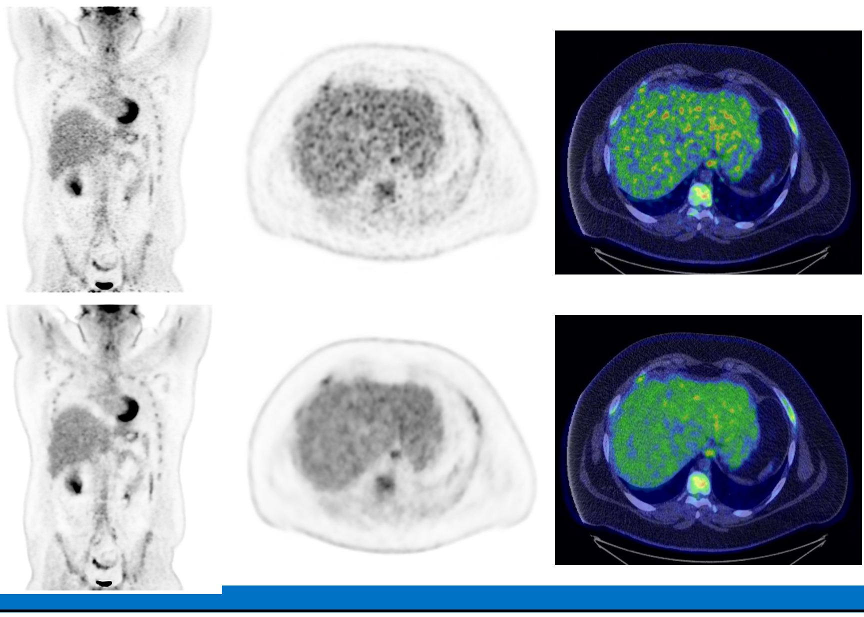
Oxford University Hospitals NHS Foundation Trust



- Patient weight significantly impacts IQ
- Increase in weight leads to increase in noise
- Different dosing regime and bed times have been tested…still poorer IQ for obese patients

23M…184Kg

Oxford University Hospitals NHS Foundation Trust



Clinical Papers

Oxford University Hospitals
NHS Foundation Trust

Eur Radiol (2016) 26:576–584
DOI 10.1007/s00330-015-3832-y
NUCLEAR MEDICINE

Novel p…
in the a…
pulmon…

Eugene J. Teo…
Elizabeth Bel…

Received: 23 Dec…

ELSEVIER

Does a n…
improve…

Nassim Par…
Kevin M. Br…
[a] Department of Clin…
[b] Department of Onc…
[c] Radiation Physics…

Eur Radiol
DOI 10.1007/s00330-…
NUCLEAR ME…

18F-FDG …
mediastin…
using a pe…

Eugene J. Teoh [1,2] · Daniel R. McGow…
Edward Black [4] · Alastair Moore [5] · A…

Received: 27 May 2015 / Revised: 23 Decemb…

Anna K. Chilc…
Kevin M. Brad…
Daniel R. McG…

Nuclear Medicine and Molecular Imaging • Original Research

Effect of a Bayesian Penalized Likelihood PET Reconstruction Compared With Ordered Subset Expectation Maximization on Clinical Image Quality Over a Wide…

Optimization of Image Reconstruction for ^{90}Y Selective Internal Radiotherapy on a Lutetium Yttrium Orthosilicate PET/CT System Using a Bayesian Penalized Likelihood Reconstruction Algorithm

Lisa M. Rowley[1], Kevin M. Bradley[2], Philip Boardman[2], Aida Hallam[1], and Daniel R. McGowan[1,3]

[1]Radiation Physics and Protection, Churchill Hospital, Oxford University Hospitals NHS Foundation Trust, Oxford, United Kingdom; [2]Department of Radiology, Churchill Hospital, Oxford University Hospitals NHS Foundation Trust, Oxford, United Kingdom; and [3]Department of Oncology, University of Oxford, Oxford, United Kingdom

Clinical Papers

Oxford University Hospitals
NHS Foundation Trust

Phantom and Clinical Evaluation of the Bayesian Penalized Likelihood Reconstruction Algorithm Q.Clear on an LYSO PET/CT System

Eugene J. Teoh*[1,2], Daniel R. McGowan*[2,3], Ruth E. Macpherson[1], Kevin M. Bradley[1], and Fergus V. Gleeson[1,2]

[1]Department of Radiology, Churchill Hospital, Oxford University Hospitals NHS Trust, Oxford, United Kingdom; [2]Department of Oncology, University of Oxford, Old Road Campus Research Building, Oxford, United Kingdom; and [3]Radiation Physics and Protection, Churchill Hospital, Oxford University Hospitals NHS Trust, Oxford, United Kingdom

Q.Clear, a Bayesian penalized-likelihood reconstruction algorithm for PET, was recently introduced by GE Healthcare on their PET scanners to improve clinical image quality and quantification. In this work, we determined the optimum penalization factor (beta) for

Key Words: positron emission tomography; image reconstruction; Bayesian penalized likelihood; NEMA; image quality; optimization

J Nucl Med 2015; 56:1447–1452
DOI: 10.2967/jnumed.115.159301

- Evidence in literature
- Many presentations
- Helpful having phantom **and** clinical scoring
- Build diagnostic confidence
- Also used for data driven gating evaluation

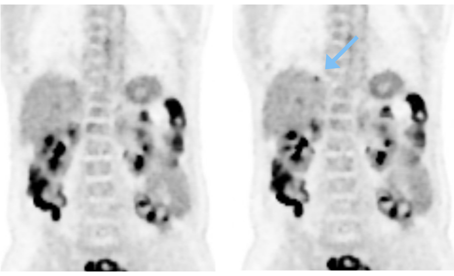
NHS
Oxford University Hospitals
NHS Foundation Trust

Data-Driven Respiratory Gating Outperforms Device-Based Gating for Clinical ^{18}F-FDG PET/CT

Matthew D. Walker[1], Andrew J. Morgan[1], Kevin M. Bradley[2,3], and Daniel R. McGowan[1,4]

[1]*Radiation Physics and Protection, Churchill Hospital, Oxford, United Kingdom;* [2]*Department of Radiology, Churchill Hospital, Oxford, United Kingdom;* [3]*Wales Research and Diagnostic PET Imaging Centre, Cardiff University, Cardiff, United Kingdom; and* [4]*Department of Oncology, University of Oxford, Oxford, United Kingdom*

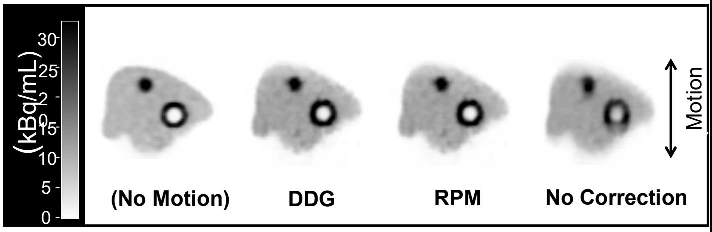
J Nucl Med 2020; 61:1678–1683
DOI: 10.2967/jnumed.120.242248



Ungated 50%
SUV_{max} = 2.4

DDG
SUV_{max} = 3.8

Liver met only clearly visible on respiratory gated images



NHS
Oxford University Hospitals
NHS Foundation Trust

- However, with new technology people need to relearn!
- Perceived issue with lymphoma…

European Journal of Nuclear Medicine and Molecular Imaging (2018) 45:316–317
https://doi.org/10.1007/s00259-017-3893-z

LETTER TO THE EDITOR

All that glitters is not gold - new reconstruction methods using Deauville criteria for patient reporting

Sally F. Barrington[1] · Tom Sulkin[2] · Adam Forbes[3] · Peter W. M. Johnson[4]

Embrace Progress

Kevin M. Bradley, Daniel R. McGowan, Fergus V. Gleeson, Geoffrey B. Johnson, Jason R. Young, Craig S. Levin, Guido A. Davidzon and Andrei H. Iagaru

Journal of Nuclear Medicine July 2018, 59 (7) 1169; DOI: https://doi.org/10.2967/jnumed.118.212761

- Sadly other manufacturers not using MAP, yet
- A range are trying AI enhancement
  - How to implement and trust these?

Oxford University Hospitals NHS Foundation Trust

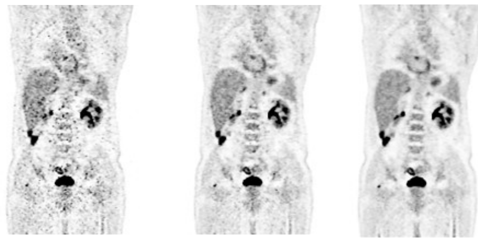
Precision DL – what is it?

- An image enhancement tool using deep learning
  - To make images "ToF-like"
  - Improved quantification
  - Improved lesion detectability
- Three 'strengths' that can be used depending on user preference (similar to beta)

  Low Medium High

Q.Clear Image → PDL Enhanced Image

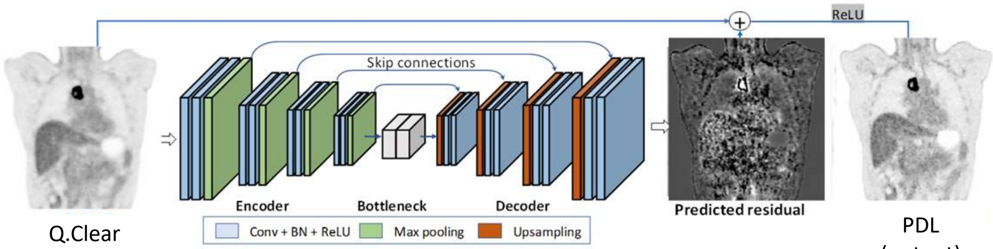
High noise input Low noise input



Oxford University Hospitals NHS Foundation Trust

Precision DL – how was it developed?

- *To trust need to know how developed!*
- 100s of paired FDG images – nonToF Q.Clear and ToF Q.Clear
- Multi-site & multi-scanners
- 3D residual U-net trained for each PDL strength



Q.Clear (input)

PDL (output)

NHS
Oxford University Hospitals
NHS Foundation Trust

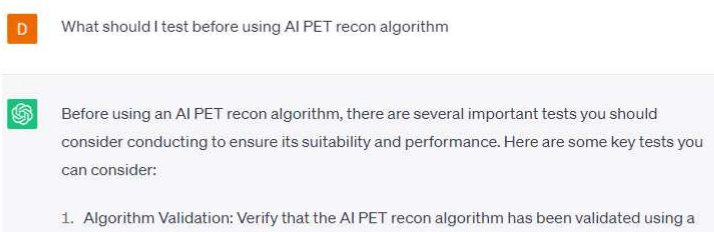
Testing PDL

- Before using an AI PET recon algorithm, there are several important tests you should consider conducting to ensure its suitability and performance. Here are some key tests you can consider:
  - Algorithm Validation
  - Performance Evaluation
  - Robustness Assessment
  - Comparison with standard methods
  - Clinical Validation
  - Generalisation testing
  - Safety and Regulatory Compliance
  - User Interface and Integration Testing

NHS
Oxford University Hospitals
NHS Foundation Trust

Testing PDL

- What did you think of those reasons?
- They were all written by chat GPT!



Oxford University Hospitals
NHS Foundation Trust

Deep Learning PET Algorithms

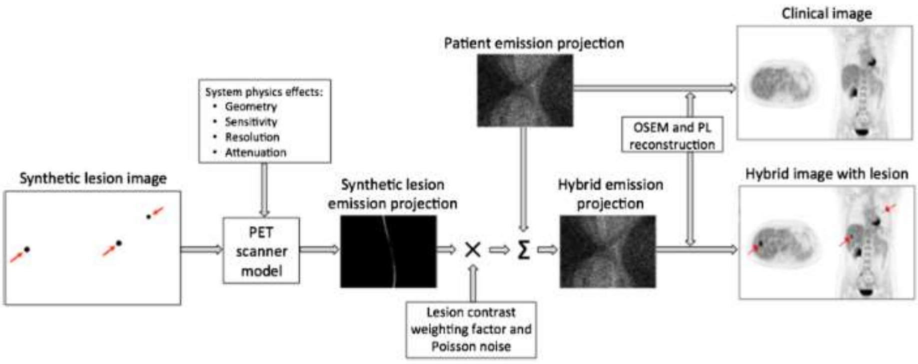
- What do I (with clinical physics hat!) want before using?

- *Knowledge of how developed* ✓
- *Phantom testing*
- *Lesion Quantification*
- *Lesion Detectability*
- *Image Noise*
- *Potential over enhancement*
- *Robustness of algorithm*
- *FDA/CE marked device*

Oxford University Hospitals
NHS Foundation Trust

Testing PDL: Lesion Insertion

- Unable to really use phantoms – lesion insertion technique



NHS
Oxford University Hospitals
NHS Foundation Trust

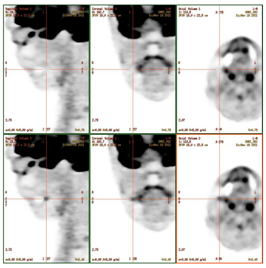
Testing PDL: Lesion Insertion

- Ground truth known!

Q.Clear nonTOF

Without inserted lesion

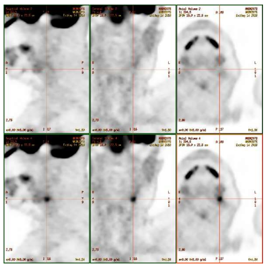
With inserted lesion



Q.Clear ToF

Without inserted lesion

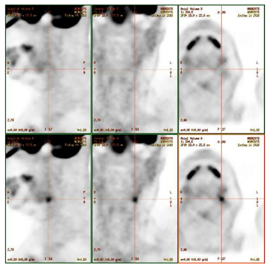
With inserted lesion



M-PDL

Without inserted lesion

With inserted lesion



10 mm, 4:1 contrast lesion in the head/neck area of a DMI 25 cm exam.

NHS
Oxford University Hospitals
NHS Foundation Trust

Testing PDL: Accuracy

- Inserted lesions allow assessment of quantitation accuracy
- Accuracy comparison (n=32) using 10&15mm lesions in **DMI data**

Reconstruction method	Average % Accuracy **SUVmean**	Average % Accuracy **SUVmax**	Average liver noise (std)
Q.Clear nonToF	50	49	0.19
Q.Clear ToF	**60**	63	0.21
PDL-H	**58**	61	0.21

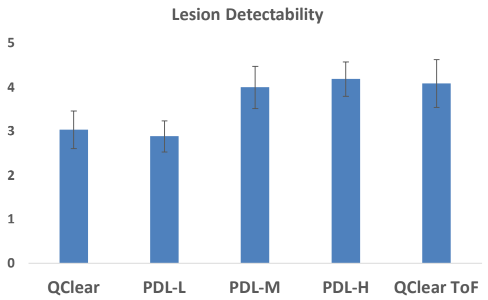
Oxford University Hospitals
NHS Foundation Trust

Testing PDL: Lesion Detectability

- Model Observer Detectability
- Also tested via human (n=3) scoring of patients (n=50)
- Time consuming! 250 PET scans (blinded to recon used) with CT

Likert scale

5 (excellent)
4 (very good)
3 (good)
2 (satisfactory)
1 (poor)
0 (non-diagnostic)



Oxford University Hospitals
NHS Foundation Trust

Testing PDL: Clinical Scoring

- Patient scan review (n=50)
- Diagnostic Confidence and Image noise (as well as Lesion Detectability)

Scores	Diagnostic confidence	Lesion detectability	Image noise/quality
Non-ToF BSREM	3.03 ± 0.40 (<0.001)	3.03 ± 0.43 (<0.001)	3.36 ± 0.40 (1.000)
DL-ToF(L)	2.98 ± 0.34 (<0.001)	2.88 ± 0.35 (<0.001)	**4.52 ± 0.27** (<0.001)
DL-ToF(M)	**4.07 ± 0.47** (<0.001)	3.99 ± 0.48 (1.000)	4.09 ± 0.34 (<0.001)
DL-ToF(H)	3.83 ± 0.38 (0.11)	**4.18 ± 0.39** (1.000)	3.39 ± 0.40 (0.96)
ToF BSREM	3.53 ± 0.53	4.08 ± 0.54	3.08 ± 0.55
ICC	0.67 (0.60, 0.74)	0.68 (0.61, 0.74)	0.58 (0.48, 0.66)

5 (excellent)
4 (very good)
3 (good)
2 (satisfactory)
1 (poor)
0 (non-diagnostic)

European Journal of Nuclear Medicine and Molecular Imaging (2022) 49:3740–3749
https://doi.org/10.1007/s00259-022-05824-7

ORIGINAL ARTICLE

Deep learning–based time-of-flight (ToF) image enhancement of non-ToF PET scans

Abolfazl Mehranian[1] · Scott D. Wollenweber[2] · Matthew D. Walker[3] · Kevin M. Bradley[4] · Patrick A. Fielding[5] · Martin Huellner[6] · Fotis Kotasidis[7] · Kuan-Hao Su[2] · Robert Johnsen[2] · Floris P. Jansen[2] · Daniel R. McGowan[3,8]

Oxford University Hospitals
NHS Foundation Trust

Testing PDL: Quantification

- Lesion SUVmax + VOIs in lung and liver

	Lesion SUV_{max} (%)	Lung SUV_{mean} (%)	Liver SUV_{mean} (%)	Liver noise (SUV)
Non-ToF BSREM	−28.6 ± 18.3 (<0.0001)	7.7 ± 15.0 (<0.0001)	4.3 ± 5.6 (<0.0001)	0.16
DL-ToF(L)	−28.7 ± 19.0 (<0.0001)	0.6 ± 12.1 (0.179)	0.7 ± 4.6 (0.067)	0.10
DL-ToF(M)	−8.0 ± 22.5 (<0.0001)	1.3 ± 13.0 (0.083)	0.8 ± 4.4 (0.016)	0.13
DL-ToF(H)	1.7 ± 23.9 (0.57)	1.4 ± 11.5 (0.50)	0.1 ± 4.5 (0.86)	0.19
ToF-BSREM	–	–	–	0.19

European Journal of Nuclear Medicine and Molecular Imaging (2022) 49:3740–3749
https://doi.org/10.1007/s00259-022-05824-7

ORIGINAL ARTICLE

Deep learning–based time-of-flight (ToF) image enhancement of non-ToF PET scans

Abolfazl Mehranian[1] · Scott D. Wollenweber[2] · Matthew D. Walker[3] · Kevin M. Bradley[4] · Patrick A. Fielding[5] · Martin Huellner[6] · Fotis Kotasidis[7] · Kuan-Hao Su[2] · Robert Johnsen[2] · Floris P. Jansen[2] · Daniel R. McGowan[3,8]

Oxford University Hospitals
NHS Foundation Trust

Deep Learning PET Algorithms

- What do I (with clinical physics hat!) want before using?

- *Knowledge of how developed* ✓
- ~~*Phantom*~~ *Lesion insertion* ✓
- *Lesion Quantification* ✓
- *Lesion Detectability* ✓
- *Image Noise* ✓
- *Potential over enhancement (not shown)* ✓
- *Robustness of algorithm (not shown)* ✓
- *FDA/CE marked device* ✓

Many other tests performed not covered here!

FDA U.S. FOOD & DRUG ADMINISTRATION

April 27, 2023

GE Healthcare
% George Mashour
Senior Regulatory Affairs Manager
GE Medical Systems Israel
4 Hayozma Street
Tirat Hacarmel, 30200
ISRAEL

Re: K223212
Trade/Device Name: Precision DL

Oxford University Hospitals
NHS Foundation Trust

Deep Learning PET Algorithms

- Happy with testing. Now to use with patients for better scans!

- Increasing use of AI in PET (and other modalities)
- Clinical staff may be unsure how to test
- Giving results from these sorts of tests would assist with clinical implementation

Oxford University Hospitals
NHS Foundation Trust

PET image reconstruction

European Journal of Nuclear Medicine and Molecular Imaging (2021) 48:2711–2726
https://doi.org/10.1007/s00259-021-05390-4

CONTROVERSIES - FOR

New PET technologies – embracing progress and pushing the limits

Nicolas Aide[1,2] · Charline Lasnon[2,3] · Adam Kesner[4] · Craig S Levin[5] · Irene Buvat[6] · Andrei Iagaru[7] · Ken Hermann[8] · Ramsey D Badawi[9] · Simon R Cherry[9] · Kevin M Bradley[10] · Daniel R McGowan[11,12]

European Journal of Nuclear Medicine and Molecular Imaging (2021) 48:2696–2710
https://doi.org/10.1007/s00259-021-05403-2

CONTROVERSIES - AGAINST

Moving the goalposts while scoring—the dilemma posed by new PET technologies

Julian M.M. Rogasch[1,2] · Ronald Boellaard[3] · Lucy Pike[4] · Peter Borchmann[5] · Peter Johnson[6] · Jürgen Wolf[7] · Sally F. Barrington[4] · Carsten Kobe[8]

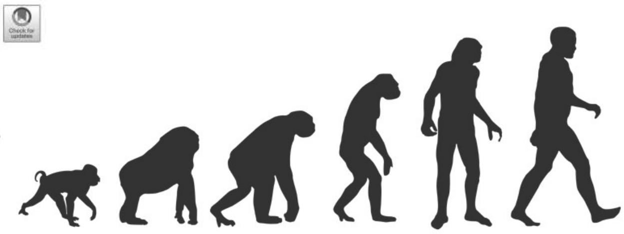
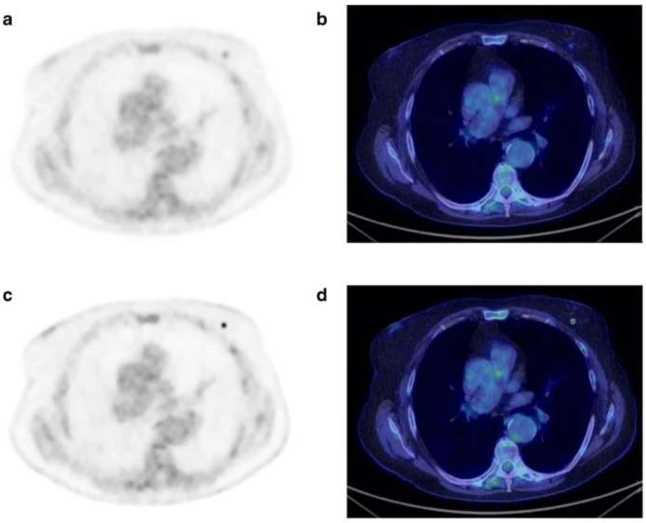


Fig. 2



Incidentally detected tiny, ^{18}F-FDG avid breast nodule in a 70-year-old patient. Triple assessment (mammogram, ultrasound and breast examination) following PET was negative, but 3 months later a small (sub-centimetre) ductal cell breast carcinoma was detected and cured. SUV_{max} 1.8 on OSEM (**a** and **b**) and SUV_{max} 5.0 on BPL (**c** and **d**). PET images on an SUV scale 0–6

NHS
Oxford University Hospitals
NHS Foundation Trust

- We need to get new recons into the clinic
- Important to get clinical staff on board and understanding the underlying recon
- *"We look forward to all users embracing technology, now and in the future, for improved early diagnosis and detection and crucially the benefit of patient care"*
- **Please keep developing!**

European Journal of Nuclear Medicine and Molecular Imaging (2021) 48:2711–2726
https://doi.org/10.1007/s00259-021-05390-4

CONTROVERSIES - FOR

New PET technologies – embracing progress and pushing the limits

Nicolas Aide[1,2] · Charline Lasnon[2,3] · Adam Kesner[4] · Craig S Levin[5] · Irene Buvat[6] · Andrei Iagaru[7] · Ken Hermann[8] · Ramsey D Badawi[9] · Simon R Cherry[9] · Kevin M Bradley[10] · Daniel R McGowan[11,12]

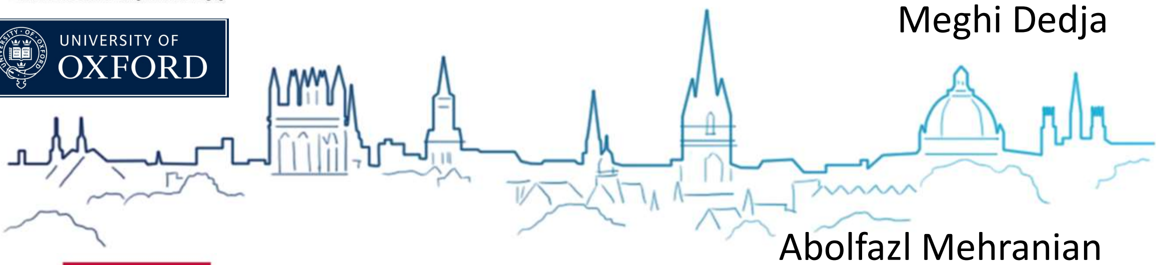
Oxford University Hospitals NHS
NHS Foundation Trust

Acknowledgements

NCIMI
National Consortium of Intelligent Medical Imaging

UNIVERSITY OF OXFORD

Matt Walker
Meghi Dedja



CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

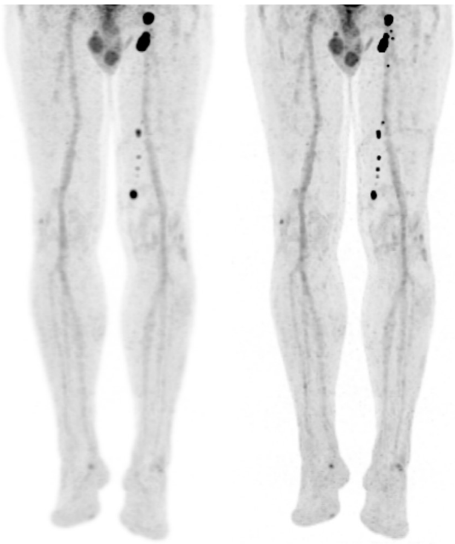
Kevin Bradley
Patrick Fielding

USZ Universitäts Spital Zürich

Martin Hüllner

Abolfazl Mehranian
Rob Johnsen
Scott Wollenweber
Moshe Levy
Floris Jansen
+ Many other staff at GE

NHS
Oxford University Hospitals
NHS Foundation Trust



Thanks for listening

Any Questions?

daniel.mcgowan@oncology.ox.ac.uk

Teoh and Bradley QJM 2017