AAPM 2019 JUL 14–18
61ST ANNUAL MEETING & EXHIBITION | SAN ANTONIO, TX
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Adaptive Imaging Session

Patient Specific Adaption of Imaging Technique for PET

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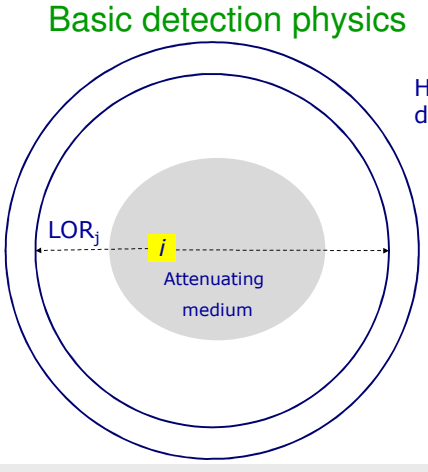
Introduction

- Image quality in PET can be affected by a variety of factors:
  - Physical
  - Technical
  - Biological
- Overall, image quality is determined by **counting statistics**.

Basic detection physics



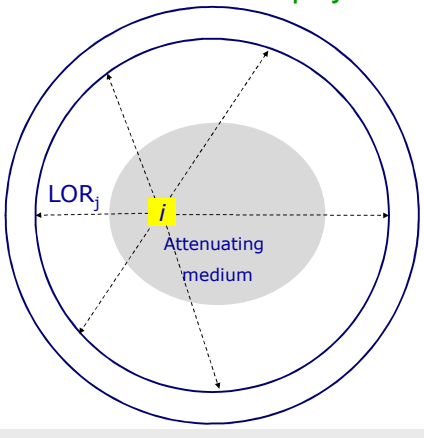
How many (true) coincidences will be detected?

Pairs of annihilation photons from voxel *i*

$$p_j = \sum_i \mathbf{S}_{ij} x_i$$

Counts at LOR$_j$ Sensitivity matrix

Basic detection physics



How many (true) coincidences will be detected?

Pairs of annihilation photons from voxel *i*

$$total\ counts = \sum_j p_j = S_i\, x_i$$

(all LORs)

Counts at LOR$_j$

Sensitivity matrix

Basic physics

To estimate the total number of (true) detected coincidences from a source we need the following information:

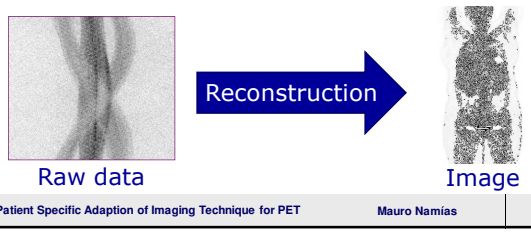
- Source:
  - Activity concentration *[A]* [Bq/ml]
  - Volume *v* [ml]
- Sensitivity *S* at the position of the source:
  - Scanner sensitivity [counts/sec/Bq]
  - Patient / object attenuation
- Acquisition time *t* [s]

$$total\ counts = [A]\left[\frac{Bq}{ml}\right] * v\ [ml]\ * S\left[\frac{counts}{secBq}\right] * t[sec]$$

Uncertainties

- Detected counts ≈ Poisson –> variance = $\sigma^2 = \mu$
- Relative error (CV) = 1/sqrt(N)

Poisson statistics (raw data) impose a **lower limit** for the uncertainties / **noise** in the reconstructed image



Raw data Image

Example: liver

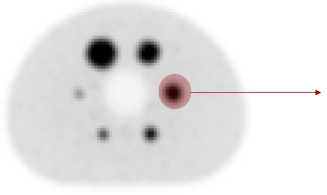
- Source with 6000 Bq/ml (e.g.: liver)
- Scanner sensitivity = 300 counts/sec/MBq
- Average transmission factor = 0.1
- Acquisition time = 2 min = 120 sec

Total counts / ml =

= 6000 Bq/ml * 300E-6 counts/sec/Bq * 0.1 * 120
≈ **21,6 c/ml**

Example: lesion SUV_{mean}

- QIBA lower limits:
  - 4.19 ml lesion (d = 2 cm)
  - SUV = 4 g/ml ≈ **2:1** lesion-to-liver ratio



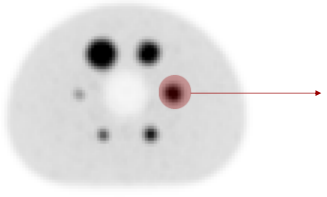
Total counts ≈

≈ 6000 Bq/ml * 2 * 4.19 ml * 300E-6 c/s/Bq * 0.1 * 120 sec =

≈ 180 counts → CV = 1/sqrt(180) = 7.4%

Example: lesion SUV_{max}

What about a **single voxel** from the same lesion?
- v = 0.0434 ml (typical voxel volume)
- SUV = 4 g/ml ≈ 2:1 lesion-to-background (liver) ratio



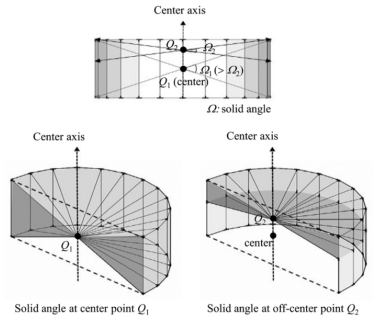
Total counts ≈

6900 Bq/ml * 2 * 0.0434 ml * 300E-6 c/s/Bq * 0.1 * 120 sec =

2 counts → CV = 1/sqrt(2) = 71%

Scanner sensitivity

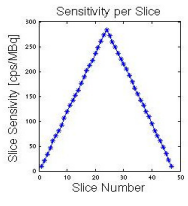
Sensitivity in 3D PET is determined by **geometry**:



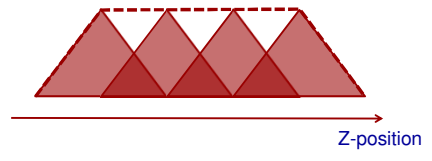
Kim J H *et al* 2015 *IEEE Trans. Nucl. Sci.* **62** 137–47

Scanner sensitivity

NEMA PET sensitivity phantom → Axial sensitivity (in air)



Resulting overlapped sensitivity (e.g.: 6.8 cps/kBq)



Time-activity products

FDG PET/CT: **EANM / SNMMI** procedure guidelines for tumour imaging: version 2.0:

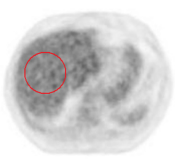
Minimum values

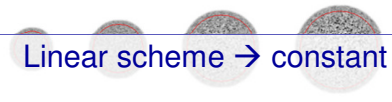
Linear $FDG(MBq) = 7(MBq.min^{-1}.kg^{-1}) \times w/T_{bed}$

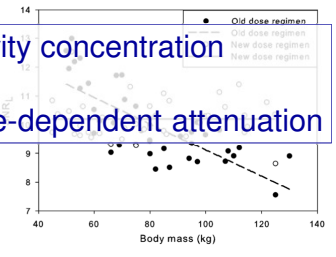
Quadratic $FDG(MBq) = 525(MBq.min^{-1}.kg^{-2}) \times \left(\frac{w}{75}\right)^2/T_{bed}$

Boellaard *et al* 2014. *Eur. J. Nucl. Med. Mol. Imaging* **42** 328–54

Linear vs. quadratic schemes







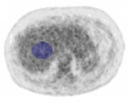
Linear scheme → constant activity concentration

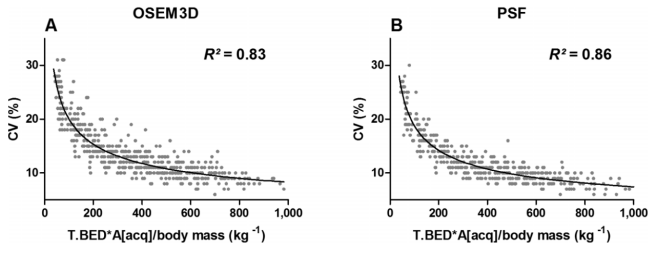
Quadratic scheme → compensates size-dependent attenuation

Simulation with linear dose vs. weight

de Groot *et at* 2013 *EJNMMI Res.* **3** 63

Other weight-based protocols





$$CV = 1.25 * (T.BED * A[acq]/w)^{-0.41}$$

Menezes *et al* 2016 *Med. Phys.* **43** 930–8

Other weight-based protocols

TABLE V. Dose regimen and acquisition parameters adjustments.

Recon method	OSEM3D	PSF	OSEM3D	PSF	OSEM3D	PSF
Body mass (kg)	<60	<60	60–90	60–90	>90	>90
Dose regimen (MBq/kg)	T.BED (min)	T.BED (min)	T.BED (min)	T.BED (min)	T.BED (min)	T.BED (min)
3.0	2.5	2.2	3.3	2.5	4.3	3.0
3.7	2.0	1.8	2.6	2.0	3.4	2.4
5.2	1.5	1.3	1.9	1.4	2.5	1.7

23% reduction in time using PSF

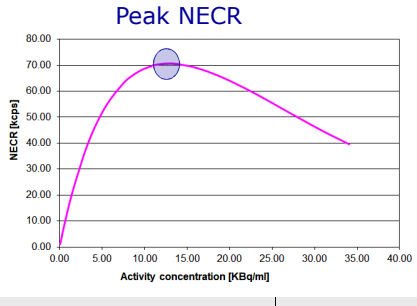
Menezes *et al* 2016 *Med. Phys.* **43** 930–8

Count rates

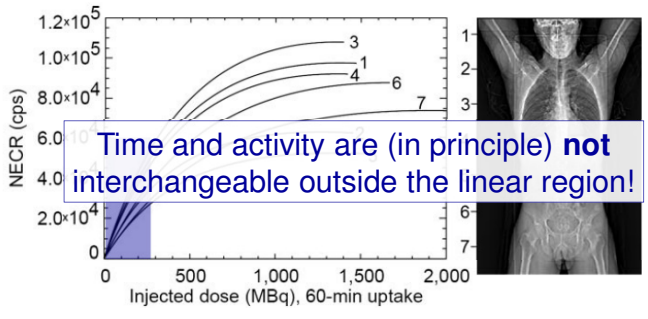
If the administered activity becomes too high, the noise equivalent counts (NEC) can be decreased due to:

- Dead time
- Random coincidences

$$NEC = \frac{T^2}{T + S + kR}$$



Patient-specific count rates



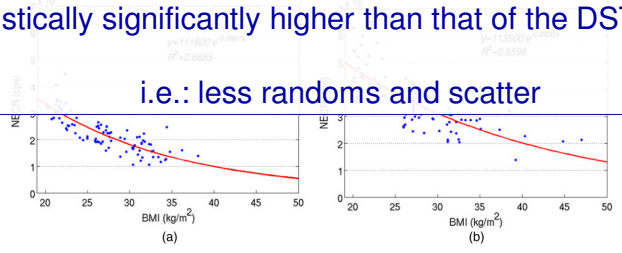
Time and activity are (in principle) **not** interchangeable outside the linear region!

Watson *et al* 2005. *J. Nucl. Med.* **46** 1825–34

NECR vs image noise

"…the **NECR** value for the DRX PET/CT scanner (LSO) is statistically significantly higher than that of the DSTE (BGO)"

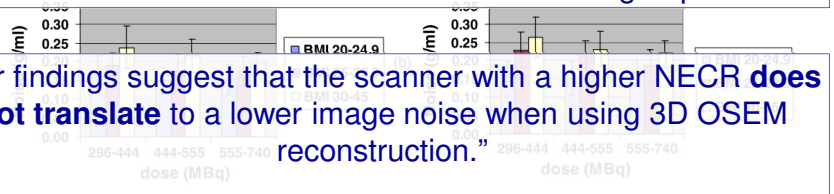
i.e.: less randoms and scatter



Chang *et al* 2011 *Phys. Med. Biol.* **56** 5275–85

NECR vs image noise

"…there was no significant difference in image noise between the two scanners for each BMI and ID subgroup."



"Our findings suggest that the scanner with a higher NECR **does not translate** to a lower image noise when using 3D OSEM reconstruction."

(since randoms and scatter are corrected during reconstruction)

Chang *et al Phys. Med. Biol.* **56** 5275–85

Variable acquisition times

4 weight groups

"…the variability of the PNECR with axial position, independent of weight, is of a similar magnitude."

i.e.: the curve shape is similar

"…a protocol that aims to **equalize total acquired PNEC** for all bed positions by varying imaging times may be **undesirable** as the effect of increased PNECR due to **clinically uninteresting** counts from heart uptake or bladder accumulation may be dominant."

Carney *et al* 2004 *IEEE Symp. Conf. Rec. Nucl. Sci. 2004.* **5** 2910–4

Variable acquisition times

4 weight groups

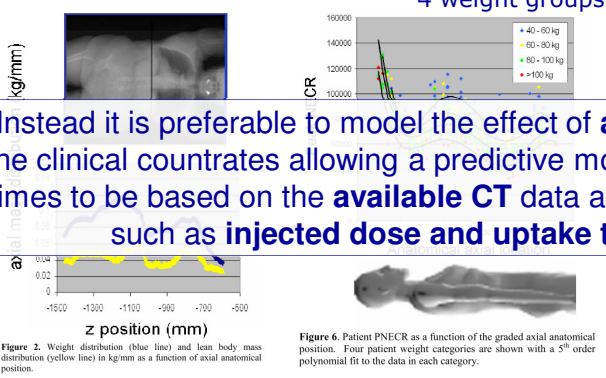


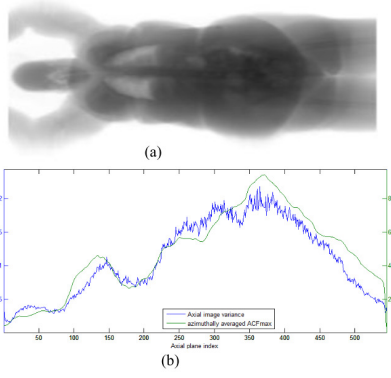
Figure 2. Weight distribution (blue line) and lean body mass distribution (yellow line) in kg/mm as a function of axial anatomical position.

Figure 6. Patient PNECR as a function of the graded axial anatomical position. Four patient weight categories are shown with a 5th order polynomial fit to the data in each category.

"Instead it is preferable to model the effect of **attenuation** on the clinical countrates allowing a predictive model of imaging times to be based on the **available CT** data and parameters such as **injected dose and uptake time**."

Carney *et al* 2004 *IEEE Symp. Conf. Rec. Nucl. Sci. 2004.* **5** 2910–4

Patient attenuation



Noise levels follow the average attenuation correction factor (ACF).

Panin *et al* 2016 *IEEE Nucl. Sci. Symp. Med. Imaging Conf. NSS/MIC 2014* 1–5

Patient attenuation

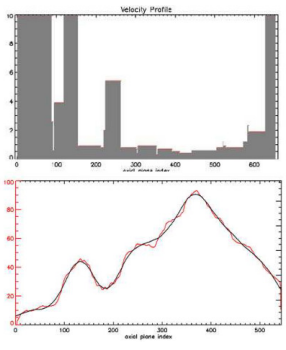


Table speed inversely proportional to attenuation.

What about absolute signal levels?

Panin *et al* 2016 *IEEE Nucl. Sci. Symp. Med. Imaging Conf. NSS/MIC 2014* 1–5

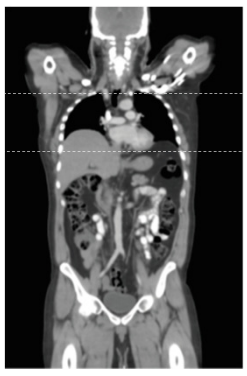
Our most recent contribution:

M. Namías & R. Jeraj. "Patient and scanner-specific variable acquisition times for whole-body PET/CT imaging". Submitted to PMB, June 2019.

Workflow

CT

1 PET bed Position / axial FOV



Sensitivity matrix

Sensitivity image [cps/MBq]

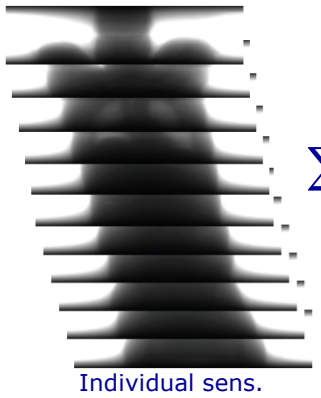
M. Namías & R. Jeraj. 2019. *Phys. Med. Biol.* (under review)

Workflow

HU

CT

cps/MBq



Individual sens.

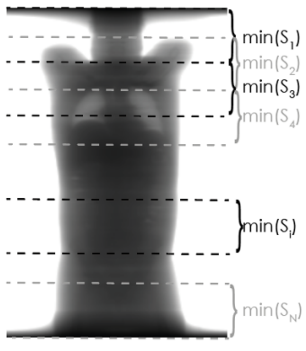
$\sum \rightarrow$

cps/MBq

Whole body sens.

Workflow

- Lesion location not know *a priori*
- Worst case: minimum sensitivity



M. Namías & R. Jeraj. 2019. *Phys. Med. Biol.* (under review)

Workflow

- Weight
- Height
- Injected activity
- Uptake time

→ Model → Liver activity concentration [Bq/ml]

M. Namías & R. Jeraj. 2019. *Phys. Med. Biol.* (under review)

Workflow

Target counts/ml (overall IQ, user-selectable)

Decay from previous bed positions

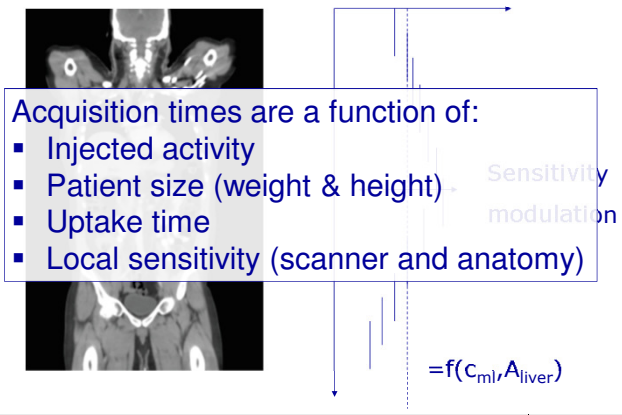
$$T_i = \frac{C_{ml}}{A_{liver} \cdot \min(S_i)} \cdot \exp\left(\frac{\ln(2)}{\tau_{1/2}} \sum_{j=1:i-1} T_j\right)$$

Liver activity concentration (reference region)

Minimum voxel sensitivity

M. Namías & R. Jeraj. 2019. *Phys. Med. Biol.* (under review)

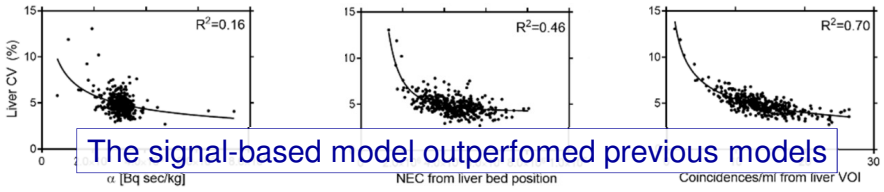
Workflow



Acquisition times are a function of:

- Injected activity
- Patient size (weight & height)
- Uptake time
- Local sensitivity (scanner and anatomy)

Results: noise in liver (retrospective)



The signal-based model outperfomed previous models

$$\alpha = \frac{TA}{w}$$

$$NEC = \frac{T^2}{T+R+S}$$

Weight-based prescription (i.e.: EANM/SNMMI)

NEC-based prescription (i.e.: Watson *et al* 2005)

Signal-based prescription (i.e.: Namías *et al* 2019)

M. Namías & R. Jeraj. 2019. *Phys. Med. Biol.* (under review)

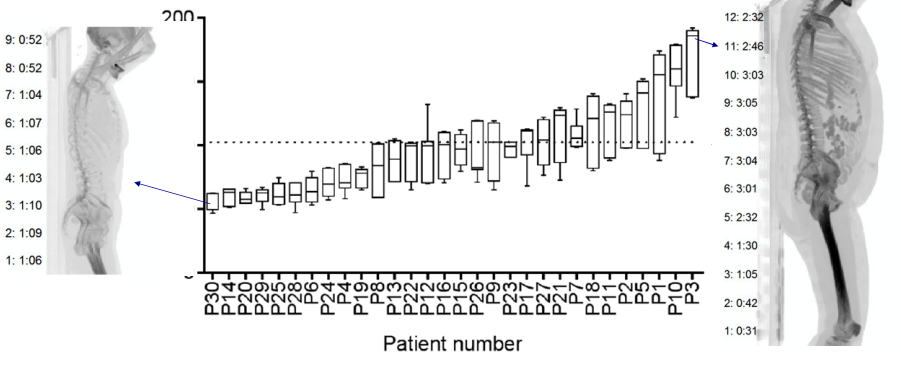
Prospective study

- 30 ^{18}F-FDG patients.
- GE Discovery 710 PET/CT scanner.
- 0.11 mCi/kg & 60 min uptake time (standard of care).
- The target signal level was selected to match the clinical average (7.5 counts/ml).

- List-mode PET acquisition + unlisting:
  - Clinical (standard fixed time)
  - Adaptive

M. Namías & R. Jeraj. 2019. *Phys. Med. Biol.* (under review)

Results: prospective study



M. Namías & R. Jeraj. 2019. *Phys. Med. Biol.* (under review)

Results: liver noise

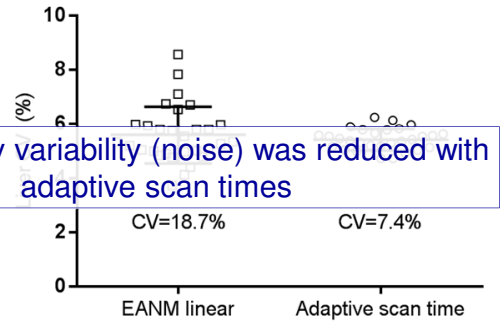


Image quality variability (noise) was reduced with adaptive scan times

M. Namías & R. Jeraj. 2019. *Phys. Med. Biol.* (under review)

Results: bone marrow noise

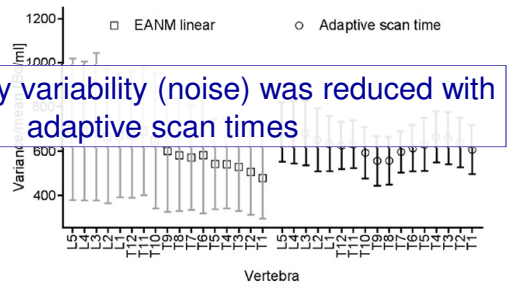


Image quality variability (noise) was reduced with adaptive scan times

M. Namías & R. Jeraj. 2019. *Phys. Med. Biol.* (under review)

Discussion

- Adaptive acquisition times can achieve lower image quality variability across different anatomical regions:
  - Intra-patient
  - Inter-patient.
- This technology is ideally suited to be included in the scanner console.

Thank you!

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