PET Scanner Performance: Quality Assurance and Acceptance Testing

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Introduction

Quality Control

Procedures required to ensure that the distribution of radiation emitted from a patient is accurately reflected in the measured raw data.

Facets

- Quality assurance:
  - verify scanner is operating properly
  - identify problems prior to scanning patients
- Acquisition of corrections to compensate for known imperfections in data measurement

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Quality Assurance

Quality Assurance Test Requirements

- Well defined regimen of measurements
  - Quick and easy to conduct
  - Sensitive to modes of failure of the scanner
  - Preferably quantitative, not qualitative

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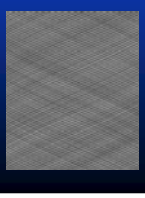
Quality Assurance Data

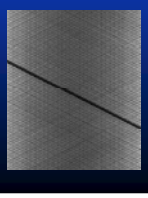
- Blank Scan Sinograms: On stand-alone PET systems, used with transmission sinograms to create attenuation correction factors
- Emission Sinograms: Scans of uniform cylinder

Blank Scan Sinograms

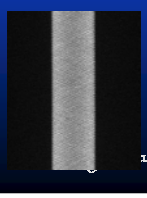
Good blank



Bad block



Sinogram of a Uniform Cylinder



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Quantitative Analysis of QA Data

- Quantitative analysis is an important aspect of the QA of a PET scanner
- Quantitative analysis of QA data:
  - validates system calibration
  - provides information on crystal, block or module (bucket) efficiencies with respect to system average
  - compare to baseline data - monitor system stability
  - ensures validity of normalization

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Quality Assurance

Detector and Electronics Characterization

- Singles mode detector calibration
  - Crystal map
  - PMT gain adjustment
  - Energy map
- Coincidence timing calibration

Did the engineer calibrate the scanner properly?

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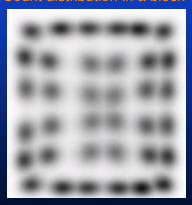
Crystal Map

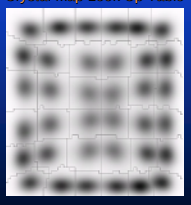
Purpose:

- Map the position of the detected event to a specific crystal
- Obtained quarterly or after detector maintenance

Count distribution in a block



Crystal Map Look Up Table



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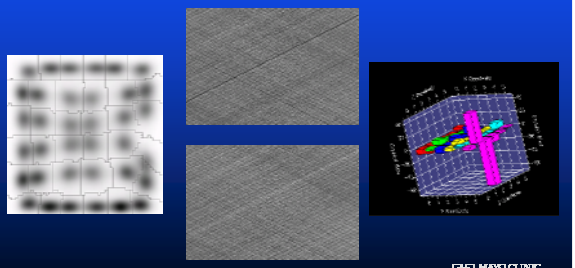
Verification of Crystal Map

QA of crystal maps created during calibration of the scanner



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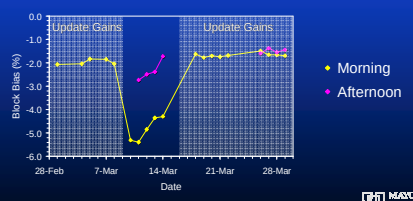
PMT Gain Adjustment

Purpose:

- Balances the gain characteristics of the PMTs in a block
- Compensates for PMT gain drift with temperature, age, …
- Acquired weekly (daily) or after detector maintenance



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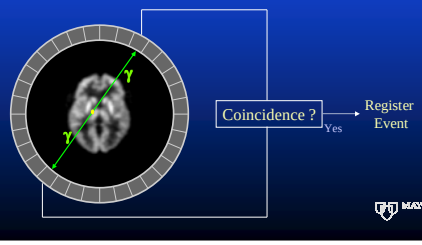
Coincidence Timing Calibration

Purpose:

- Adjust for timing delays so events from all blocks are timestamped equivalently
- Acquired weekly or after detector maintenance



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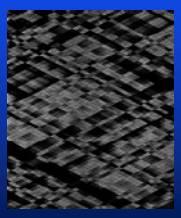
Coincidence Timing Calibration

Blank scan created with incorrect CTC calibration



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Daily Quality Assurance

Can the Scanner be Used Today?

Potential Problems

- System stability, drifts
- Detector module / PMT/ preamp failure
- Loose cables, connectors
- Inoperable gantry motors, source loader

Daily QA Regimen

- Automatic PMT gain adjustment
- Blank scan

- QA will detect but not prevent these problems

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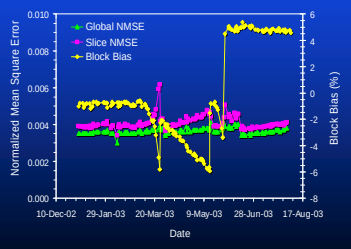
Example: NMSE and Block Bias

QA must be sensitive to modes of failure of the scanner

NMSE: Error with respect to baseline scan



NEMA NU 2-2001

PET Performance Measurements

National Electrical Manufacturers Association. *NEMA Standards Publication NU 2-2001: Performance Measurements of Positron Emission Tomographs*

NEMA NU 2-2001

Acceptance Testing

Can we use our new scanner?

Annual QA

Is the scanner still performing within specification?

NEMA NU 2-2001

- Measures performance of PET scanners under conditions that attempt to represent whole body studies
  - Phantom of length greater than axial FOV
  - Out of field activity
- Standardizes oblique LOR manipulation in 3D acquisitions
- Daube-Witherspoon ME, et al. PET Performance Measurements Using the NEMA NU 2-2001 Standard. *J Nucl Med* 2002:1398-1409.

Phantoms for NU 2-2001

NEMA NU 2-2001

Three phantoms:

Scatter phantom

203x700mm phantom with activity in line source

Sensitivity phantom

Image quality phantom

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NEMA NU 2-2001

Performance Measures:

- Spatial Resolution (Transaxial, axial)
- Sensitivity
- Scatter Fraction
- Count Losses
- Count Rate Correction Accuracy
- Image Quality

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Spatial Resolution

- Spatial resolution of a system represents its ability to distinguish between two points of radioactivity
- F-18 point sources in air at six locations:
  - (0,1), (0,10) and (10,0) cm
  - Center of axial FOV and ¼ axial FOV from center
- Reconstruct: image pixel < ⅓ expected FWHM
- Profile width ~ 2 times FWHM
- Report FWHM and FWTM in radial, tangential and axial directions

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Spatial Resolution

Transaxial Resolution

	FWHM @ 1cm	FWHM @ 10cm
Philips Allegro	5.5 mm	5.6 mm
GE DST	6.2	6.7
CTI HiREZ	6.5 4.6	7.5 5.8

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Sensitivity

- Sensitivity of a scanner represents its ability to detect annihilation radiation
- Rate of true coincidence counts per unit radioactivity (expressed in cps/kBq) in absence of attenuating media

- Rationale: need material around source to ensure annihilation of positrons, but this material also attenuates the annihilation photons
- Based on technique by Bailey DL, Jones T, et al. *Eur J Nucl Med* 1991;18:374-379.

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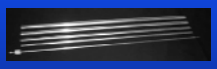
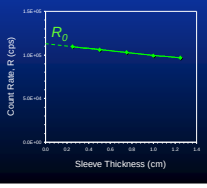
Sensitivity

- Successive measurements with a 700 mm line source with a known amount of F-18 surrounded by nested, known absorbers



- The count rate with no absorber is extrapolated from these measures



$$System\ Sensitivity = \frac{R_0}{Activity}$$

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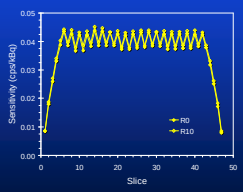
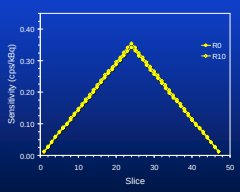
Sensitivity

- Measure at radial locations of 0 and 10cm
- Report system sensitivity and slice sensitivity profile

2D



3D



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Sensitivity

		Sensitivity (cps/kBq)
GE DST	2D	2.0
	3D	9.3
Philips Allegro		4.4
CTI HiRez		4.5

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Scatter Fraction

- Scatter fraction is a measure of the system sensitivity to scatter

$$SF = \frac{Scatter}{Scatter + Trues}$$

- Use 203 mm diameter polyethylene cylinder of length 700 mm, with activity located in a line source of diameter 2.3mm that is 4.5mm off axis
- Measured with low activity (Randoms:Trues < 1%) to avoid random coincidences, deadtime and pulse pileup.

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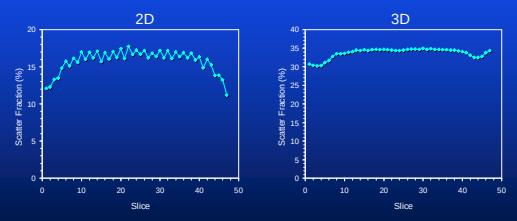
Scatter Fraction

Scatter Fraction vs Slice



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Scatter Fraction

	Scatter Fraction	LLD (keV)
GE DST 2D	19%	375
3D	44%	375
Philips Allegro	40%	410
CTI HiRez	36%	425

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Count Rate Performance

- Measurement of count rate performance gives an indication of scanner performance as a function of activity
- Use 700 mm long polyethylene cylinder
- Measured with high initial activity of F-18
  3D: 800 MBq; 2D: 5 GBq
- Acquire data until randoms and deadtime losses are negligible (14 to 18 hrs)

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Count Rate Performance

- Calculate Noise Equivalent Count Rate

$$R_{NEC} = \frac{R_{Trues}^2}{R_{Trues} + R_{Scatter} + k \cdot R_{Randoms}}$$

R_{NEC}: Figure of merit relating scanner performance to sinogram SNR after randoms and scatter corrections.

For NEMA, k = 1 (calculated Randoms); R_{NEC} (1R)

- Report peak NEC and effective activity concentration at peak

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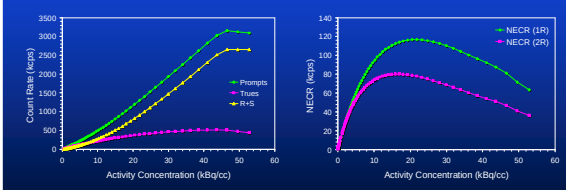
3D Count Rate Performance

Peak R_{Trues}: 515 kcps @ 44 kBq/ml

Peak R_{NEC} (1R):117 kcps @ 20 kBq/ml



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Count Rate Performance

Count Rate Performance

	Peak R_{NEC} (kcps)	Activity (kBq/ml)
CTI HiREZ	85	21
GE DST 2D	84	49
3D	63	12
Philips Allegro	30	9

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Image Quality Measurement

- Standardized imaging situation that simulates a clinical whole body imaging condition
- Phantom consists of a torso phantom with hot and cold lesions in a warm background
- Scatter phantom abutted to image quality phantom

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Image Quality Measurement

- Hot spheres: 10, 13, 17, 22 mm id
- Cold spheres: 28, 37 mm id
- Lung insert
- Activity in hot spheres 8 and 4 times that of background
- Activity in background 5.3 kBq/ml
- Simulated acquisition 100cm in 60min

$$T_{acq} = \frac{60\,\text{min}}{100\,\text{cm}}\,\Delta z \approx 7\,\text{min}$$

- Repeat acquisition three times
- Reconstruct using clinical protocol

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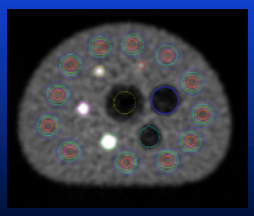
Image Quality Measurement

- Report image contrast and SNRs for hot and cold lesions, residual error in lung, variability in background
- Visual inspection for artifacts



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NEMA and Lutetium-176

- LSO is inherently radioactive
- Background radiation gives rise to Randoms, some Trues

- Implications for NEMA: cannot obtain Randoms:Trues ratio of < 1%
- For count rate and sensitivity measurements – acquire background scan to estimate intrinsic true and random rates

- Watson CC, et al. *J Nucl Med* 2004;45:822-826.
- Erdi YE, et al. *J Nucl Med* 2004;45:813-821.

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Summary

- Need for QA regimen
- Quantitative analysis of QA data
- NEMA NU 2-2001 Performance Standard procedures

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