PET Scanner Quality Assurance

Brad Kemp, PhD
Department of Radiology
Mayo Clinic

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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

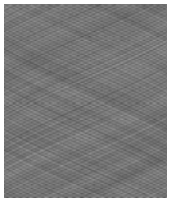
Outline

- Corrections
- System Calibration
- Daily QA
- NEMA NU 2-2001 Performance Standards
- Scanner certification

System Correction: Normalization

Purpose: Corrects for the variations in efficiency in lines of response (LOR) in each slice of the sinogram

- A uniformity correction
- For 2D: Direct Measurement using a low activity source
- For 3D: Indirect Measurement using a uniform phantom
- Acquired quarterly or after system maintenance



System Calibration

Purpose: convert image counts/pixel to activity/volume

- A phantom of known activity concentration is imaged and reconstructed with uniform attenuation correction
- Average counts in a slice are calculated

→From this a system calibration is calculated

- Acquired monthly or after system maintenance

Quality Assurance

Quality Assurance Test Requirements

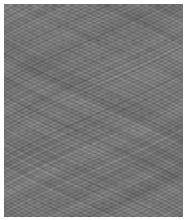
- Well defined regimen of measurements
  - Quick and easy to conduct
  - Sensitive to modes of failure of the scanner
  - Preferably quantitative, not qualitative

Blank Scan

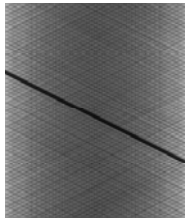
- On stand-alone PET systems, used with transmission sinograms to create attenuation correction factors
- Acquired daily - good source of QA data
- Emission scan of uniform cylinder

Transmission Sinograms

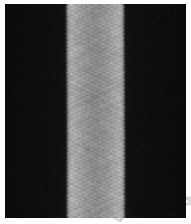
Good blank



Bad block



Sinogram of a Uniform Cylinder



Quantitative Analysis of Blank Scans

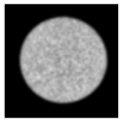
- The quantitative analysis of blank scans is an important aspect of the QA of a PET scanner

- Quantitative analysis of blank scans:
  - validates system calibration
  - provides information on crystal, block or module (bucket) efficiencies with respect to system average
  - compare to baseline - monitors system stability
  - ensures validity of normalization

Quantitative Analysis of Blank Scans

Time Line

Has the system drifted?
Is the normalization valid?



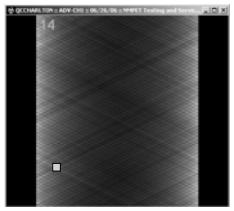
Overview: Daily QA

Daily QA analysis calculates a global and slice normalized mean square error (NMSE) by using a reference scan; the reference scan is defined as the blank scan acquired immediately after normalization

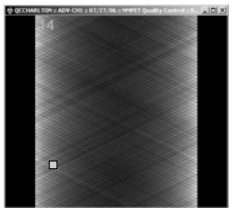
Normalized Mean Square Error

Pixel to pixel comparison

Reference Blank



Daily Blank



$$NMSE = \frac{\sum_i \left(Counts_i^{REF} - Counts_i^{DAY}\right)^2}{\sum_i \left(Counts_i^{REF}\right)^2}$$

Compute global and slice NMSE

Quality Assurance

Detector and Electronics Characterization

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

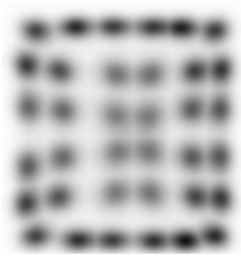
Did the engineer calibrate the scanner properly?

Crystal Map

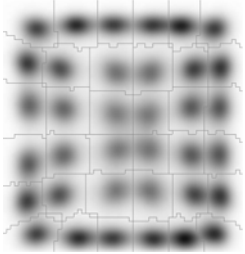
Purpose:

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

Count distribution in a block

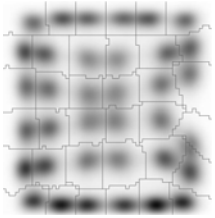


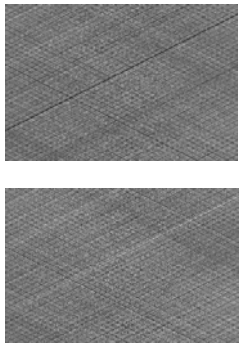
Crystal Map Look Up Table

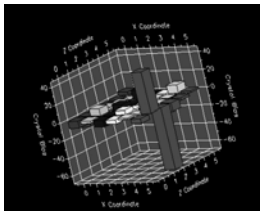


Verification of Crystal Map

QA of crystal maps created during calibration of the scanner



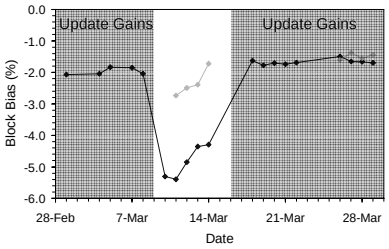




PMT Gain Adjustment

Purpose:

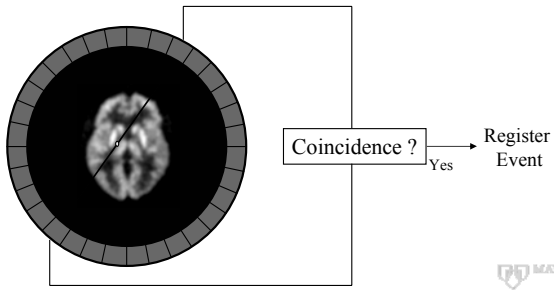
- Balances the gain characteristics of the PMTs in a block
- Compensates for PMT gain drift with temperature, age, …
- Acquired weekly (daily) or after detector maintenance



Coincidence Timing Calibration

Purpose:

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



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

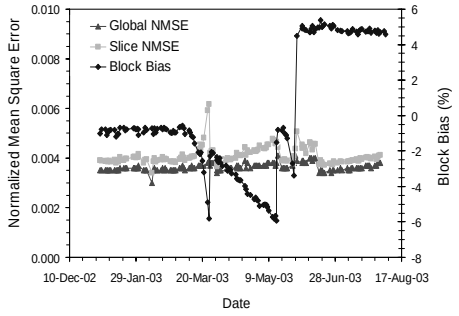
- Automatic PMT gain adjustment
- Blank scan

• QA will detect but not prevent these problems

Example: NMSE and Block Bias

QA must be sensitive to modes of failure of the scanner

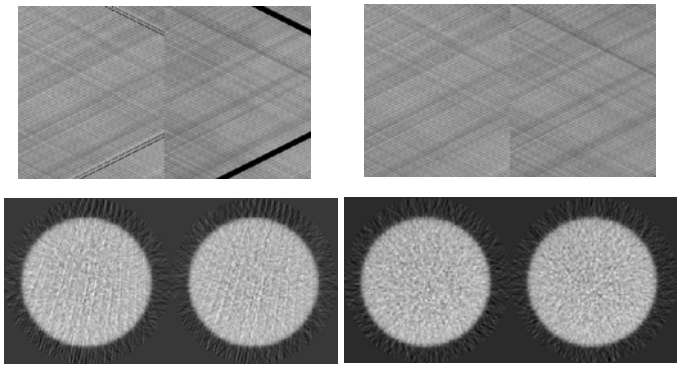
NMSE: Error with respect to baseline scan



Daily QA: Loose Cable

Loose Cable

Better



QA Schedule

Detector and Electronics Characterization	Frequency
– Crystal map	Quarterly
– PMT gain	Weekly (daily)
– Coincidence timing	Weekly (daily)
System Corrections	
– Normalization	Quarterly
– Scanner calibration	Monthly (weekly)
– Blank Scan	Daily

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?

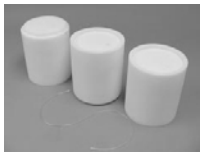
Annual QA

Is the scanner still performing within specification?

Phantoms for NU 2-2001

NEMA NU 2-2001
Three phantoms:

Scatter phantom
203x700mm phantom with activity in line source



Sensitivity phantom

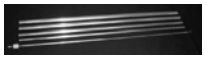
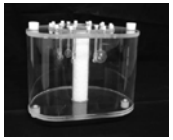


Image quality phantom



NEMA NU 2-2001

<u>Performance Measures:</u>

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

Spatial Resolution

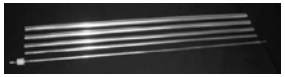
- Spatial resolution of a system represents its ability to distinguish between two points of radioactivity
- F-18 point sources in air at six locations:
  - (0,1), (0,10) and (10,0) cm
  - Center of axial FOV and ¼ axial FOV from center
- Reconstruct: image pixel < ⅓ expected FWHM
- Profile width ~ 2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

Sensitivity

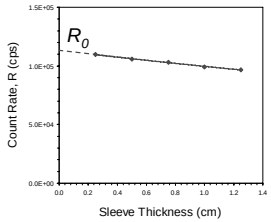
- Sensitivity of a scanner represents its ability to detect annihilation radiation
- Rate of true coincidence counts per unit radioactivity (expressed in cps/kBq) in absence of attenuating media
- Rationale: need material around source to ensure annihilation of positrons, but this material also attenuates the annihilation photons
- Based on technique by Bailey DL, Jones T, et al. *Eur J Nucl Med* 1991;18:374-379.

Sensitivity

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



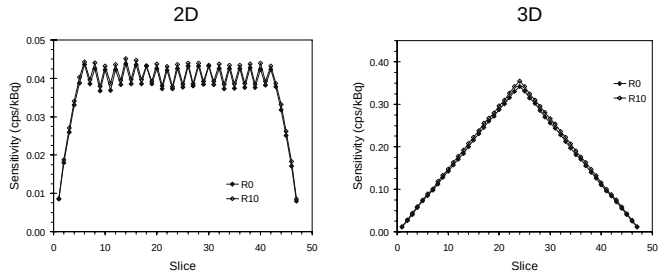
- The count rate with no absorber is extrapolated from these measures



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

Sensitivity

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



Scatter Fraction

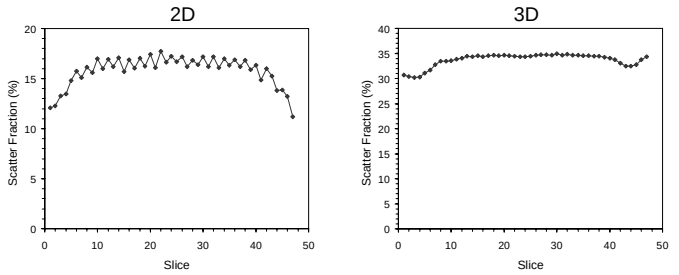
- Scatter fraction is a measure of the system sensitivity to scatter

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

- 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.

Scatter Fraction

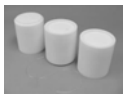
Scatter Fraction vs Slice



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)



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)

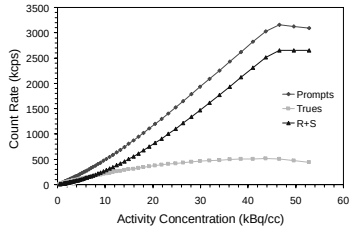
- Report peak NEC and effective activity concentration at peak

Count Rate Performance

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

Peak R_{NEC} (1R):118 kcps @ 22 kBq/ml

Peak R_{NEC} (2R): 80 kcps @ 18 kBq/ml



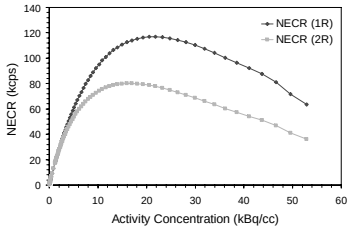


Image Quality Measurement

- 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

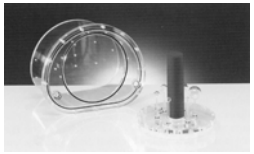


Image Quality Measurement

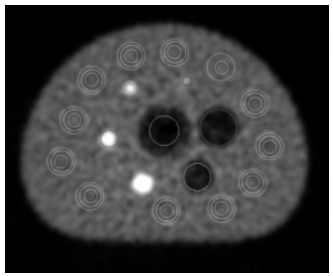
- Hot spheres: 10, 13, 17, 22 mm id
- Cold spheres: 28, 37 mm id
- Lung insert
- Activity in hot spheres 8 and 4 times that of background
- Activity in background 5.3 kBq/ml
- Simulated acquisition 100cm in 60min

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

- Repeat acquisition three times
- Reconstruct using clinical protocol

Image Quality Measurement

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



NEMA and Lutetium-176

- LYSO 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 delayed event to measure intrinsic randoms rates

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