PET/CT QA and Acceptance Testing

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Learning Objectives:

- Summarize the signal processing steps for coincidence detection
- Understand the components of daily a QA
- Identify and troubleshoot sources of failure in daily QA
- List the recommended frequency of QA/QC tests.
- Describe the process of scanner calibration
- Name the different components of the NEMA tests used for PET acceptance testing
- Understand the meaning of the NEMA test results

PET NEMA Acceptance Testing

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Disclosures

- ACR reviewer for NM and PET

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Learning Objectives

- Describe the PET NEMA acceptance tests
- Understand the results of the NEMA acceptance tests for PET scanners.
- Describe the recommended QA/QC tests for PET imaging and their frequency.
- Troubleshoot potential problems with PET images.

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What is NEMA?

The acronym stands for: National Electrical Manufacturers Association

- In 1991 a task group from the SNM published a set of measurements to standardize the *performance characterization of PET scanners*.
- At the same time, NEMA formed its own committee to address the same issue and ended up publishing a standard that adopted the SNM publication however with some refinements. That standard became the NU 2-1994.
- Also at the same time, the European Economic Community underwent a similar process which resulted in an International Electrotechnical Commission (IEC) standard.
- The NEMA and IEC are two different standards although similar in purpose.
- Recently, the NEMA standard has been updated. The new document is known as the NU 2-2001 which is still different from the IEC standard.

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Three NEMA Standards:

• NU2-94: Mainly used for neuroimaging (2D).

• NU2-01: Mainly used for whole Body imaging (2D/3D).

•NU2-07: Mainly to account for radioactive detectors (2D/3D)

The original NEMA standard (NU 2-94) was developed for PET scanners that were used in 2D mode and had a limited axial FOV.

New scanner developments which acquire data in 3D and have large axial FOVs, as well as the major shift in the use of PET from neuroimaging to whole body imaging necessitated updating the first NEMA standard.

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Three NEMA Standards:

- The latest NEMA standard (NU2-07) takes into consideration intrinsically radioactive detectors.
  - This will have impact on measurements of Count losses and randoms, as well as sensitivity
  - Additionally, spatial resolution has been expanded to include the measurement and reporting of the source position.

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Performance Characterization Measurements:

NEMA NU2-94 (2D)
- Transverse/Axial Resolution
- Sensitivity
- Scatter Fraction
- Count Rate and deadtime
- Uniformity
- Accuracy of count rate, scatter & attenuation correction

NEMA NU2-01 and 07 (2D/3D)
- Spatial Resolution
- Sensitivity
- Scatter Fraction/Count Rate Performance
- Image Quality
- Accuracy of count losses and randoms correction

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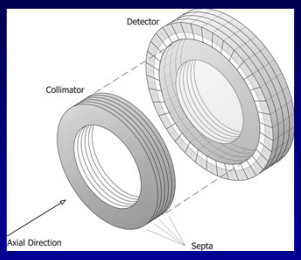
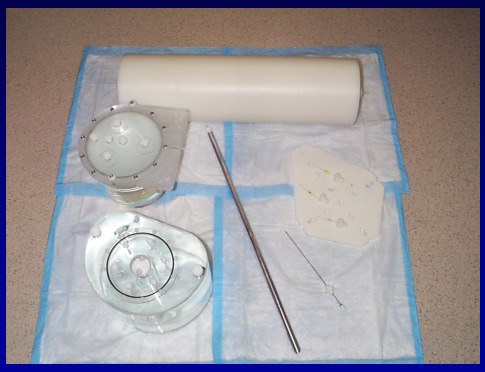
2D and 3D imaging capability using septa



For systems with 2D and 3 D capabilities, Acceptance testing should be performed in both modes

NEMA 94 & 2001/2007 Phantoms



Performance Characterization we will discuss:

NEMA NU2-07 (2D/3D)

- Spatial Resolution
- Sensitivity
- Scatter Fraction/Count Rate Performance
- Image Quality
- Accuracy of correction for count losses and randoms

Test results are compared with manufacturer specifications

Additional tests such as scanner alignment and accuracy of SUV are NOT part of NEMA tests

Daube-Witherspoon M. et al JNM, 43(10) 1398-1409, 2002

Spatial Resolution:

This test measures the capability of the PET system to localize the position of a point source of activity after image reconstruction. The measurement is done using Multiple point sources suspended in air at different locations.

- 3 point sources are made from a solution with an activity concentration of 5mci/cc
- The point sources are positioned at (0,1), (0,10), and (10,0) in center of axial FOV
- Data is acquired for 1 min in 2D and 3D modes.
- Images were reconstructed using FBP (2D) and FORE +FBP (3D)
- Use 256*256 matrix, 25cm FOV, centered at (5,-5), with ramp filter at 4mm cutoff
- No correction for dead time
- Repeat with sources positioned at 4cm from edge of axial FOV.
- Final results are the average of the two measurements.

- Analysis is done by measuring the FWHM and FWTM in the radial and tangential directions

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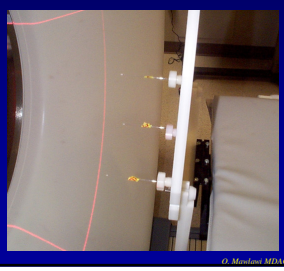
NU2-01/7 Spatial Resolution setup



6 mCi/cc, pipette three 1ul drops onto a slide. Recon (FBP, FORE) 256*256 over a 25 cm FOV. Point Sources are located at (0,1), (0,10), (10,0).

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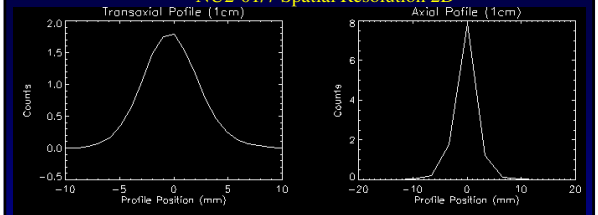
NU2-01/7 Spatial Resolution 2D



Results for 1 cm source

Trans FWHM:	6.13198 (mm)
Trans FWTM:	11.5838 (mm)
Axial FWHM:	5.18200 (mm)
Axial FWTM:	9.88173 (mm)

Results for 10 cm source

Radial FWHM:	6.99282 (mm)
Radial FWTM:	13.0039 (mm)
Tang. FWHM:	6.72525 (mm)
Tang. FWTM:	12.3854 (mm)
Axial FWHM:	6.12650 (mm)
Axial FWTM:	12.3992 (mm)

MDA resolution

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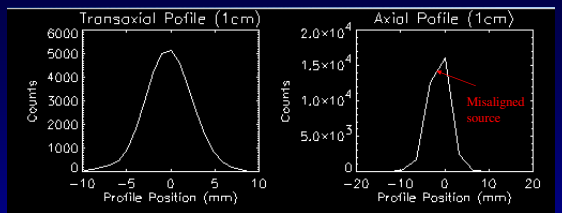
NU2-01/7 Spatial Resolution 3D



Results for 1 cm source

Trans FWHM:	6.11409 (mm)
Trans FWTM:	11.6839 (mm)
Axial FWHM:	5.97538 (mm)
Axial FWTM:	10.9906 (mm)

Results for 10 cm source

Radial FWHM:	6.78070 (mm)
Radial FWTM:	12.8040 (mm)
Tang. FWHM:	6.77996 (mm)
Tang. FWTM:	12.3961 (mm)
Axial FWHM:	6.69178 (mm)
Axial FWTM:	12.3631 (mm)

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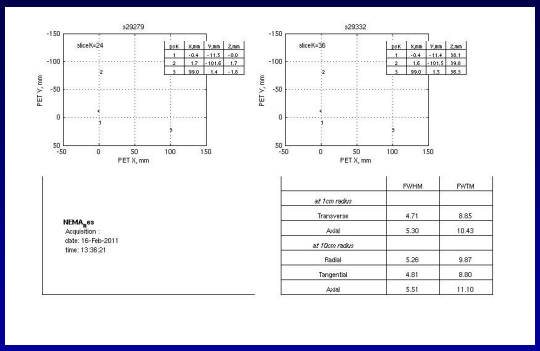
NU2-2007



	FWHM	FWTM
at 1cm radius		
Transverse	4.71	8.85
Axial	5.30	10.43
at 10cm radius		
Radial	5.26	9.87
Tangential	4.81	8.80
Axial	5.51	11.10

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Sensitivity:

This test measures the number of detected coincidence events per second for every unit of activity in the FOV. The test is performed with very low activity levels to minimize the effect of count losses. Measurements of sensitivity are made with increasing amounts of attenuating material, the results are then plotted and extrapolated to give the scanner sensitivity with no attenuation.

- A line source is filled with ~0.1 mCi of F-18 and threaded into an aluminum sleeve
- Setup is suspended in center FOV, data is acquired for 1min in 2D and 3D modes.
- Add a second aluminum sleeve, repeat acquisition.
- Repeat process for 5 aluminum sleeves
- Repeat all the process after repositioning setup at R=10cm

- Analysis is done by fitting sensitivity values and extrapolating to zero attenuation.

$$R_j = R_0 \exp[-2\mu X_j]$$

- Slice sensitivity is calculate by: $S_i = \frac{R_{i,i}}{R_{tot}} S_{tot} \qquad R_{tot} = \sum_i R_{i,i}$

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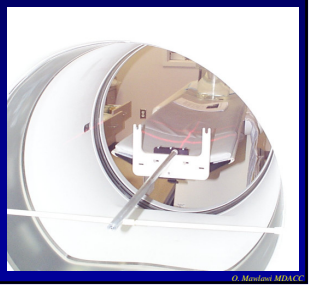
NU2-01/7 Sensitivity Setup



250 uci in the line (2.2 cc)

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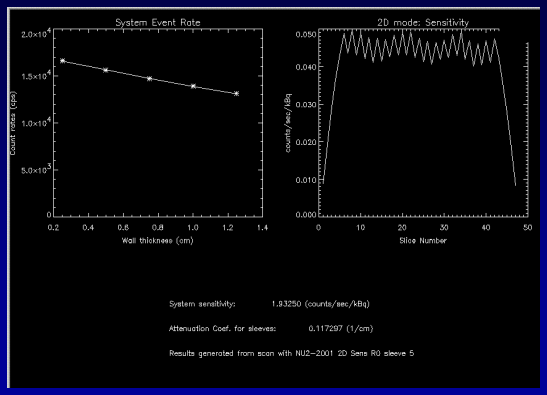
NU2-01/7 Sensitivity R=0 2D



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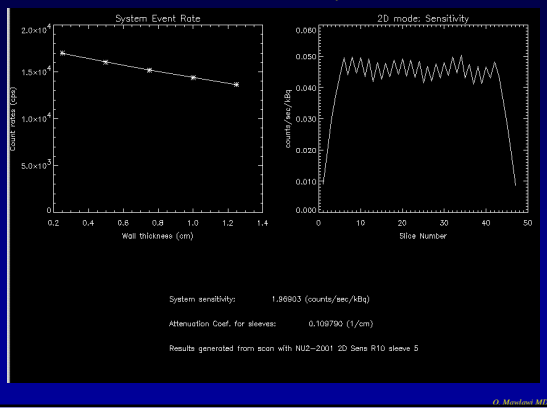
NU2-01/7 Sensitivity R=10 2D



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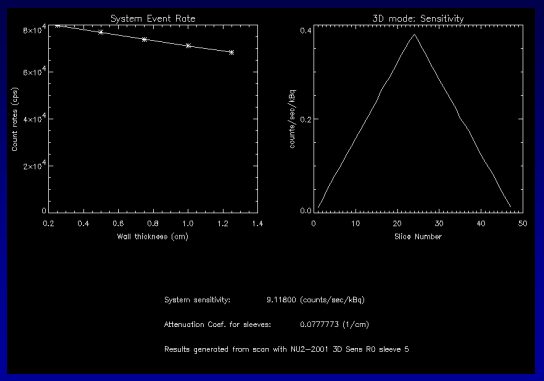
NU2-01/7 Sensitivity R=0 3D



System sensitivity: 9.11800 (counts/sec/kBq)

Attenuation Coef. for sleeves: 0.0777773 (1/cm)

Results generated from scan with NU2-2001 3D Sens R0 sleeve 5

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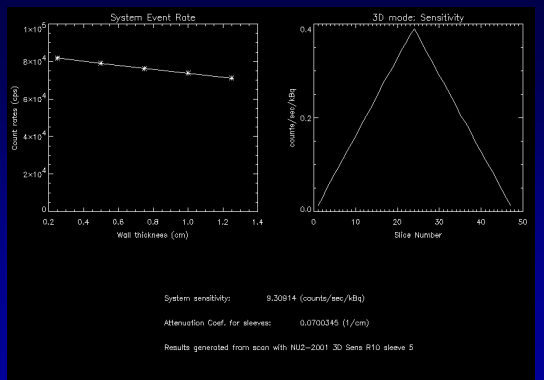
NU2-01/7 Sensitivity R=10 3D



System sensitivity: 9.30914 (counts/sec/kBq)

Attenuation Coef. for sleeves: 0.0700345 (1/cm)

Results generated from scan with NU2-2001 3D Sens R10 sleeve 5

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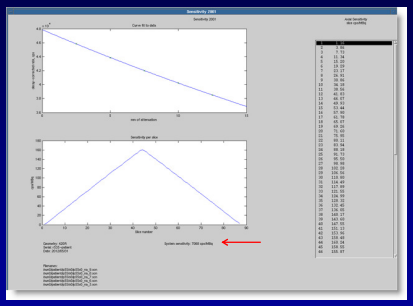
NU2-01/7 Sensitivity R=0 3D



Example from a Philips system

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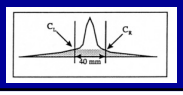
Count Rate and Scatter Fraction

The scatter fraction (SF) portion of this test measures the sensitivity of the scanner to coincidence events caused by scatter while the count rate test measures the performance of the PET scanner across a range of radioactivity levels. The SF measurement is done at activity levels where system dead time and randoms are negligible.

- Fill line source (70mCi 2D, 40mCi 3D) of F-18 and thread it into the scatter phantom.
- setup is placed on the couch in the center FOV with the line source close to couch.
- Data is acquired in dynamic mode as 4*15min, 14*25min with 25 min delays.
- Total time is ~13hrs.

- Analysis is done on sinograms with no corrections applied.
- 3D data was processed using SSRB.
- SF was measured using the last frame of the dynamic data.
- Scatter was calculated within a radius of 12cm from center of phantom.
- Scatter under the peak was estimated by interpolation between ±2cm from center.



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Count rate analysis was done in a 24 cm FOV using the following formulas where i and j are the slice number and acquisition number respectively.

$$R_{tot_j} = \sum_i C_{tot_i} / T_{acq_j} \qquad R_{t_j} = \sum_i (C_{tot_{i,j}} - C_{r+s_{i,j}}) / T_{acq_j}$$

$$R_{r_j} = \sum_i \{R_{tot_{i,j}} - (R_{t_{i,j}} / (1 - SF_i))\} \qquad R_{s_j} = \sum_i (SF_i / 1 - SF_i) R_{t_{i,j}}$$

$$R_{NECR_j} = \sum_i R^2_{t_{i,j}} / \sum_i (R_{tot_{i,j}} + R_{r_{i,j}}) \qquad R_{NECR_j} = \sum_i R^2_{t_{i,j}} / \sum_i R_{tot_{i,j}}$$

C: counts
T: Time
R: Rate

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NU2-01/7 Scatter Fraction/Count Rate Setup

70 mCi in 5.2 cc line

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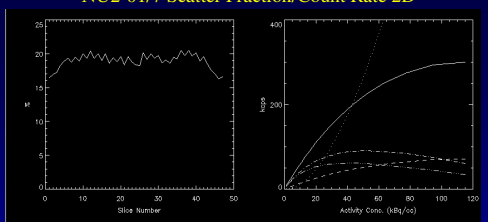
NU2-01/7 Scatter Fraction/Count Rate 2D



ANALYSIS RESULTS

System scatter fraction: 19.1488 (%)

Peak trues rate: 300.453 (kcps) @ 115.203 (kBq/cc)

Peak randoms rate: 1127.30 (kcps) @ 115.203 (kBq/cc)

Peak scatter rate: 71.1656 (kcps) @ 115.203 (kBq/cc)

Peak NEC rate: 90.2195 (kcps) @ 52.4744 (kBq/cc)

Peak NEC rate (2R): 61.5242 (kcps) @ 43.1114 (kBq/cc)

Results generated from scan with 2001_decay_20

K=2: randoms from delays; noisy
K=1: randoms from singles; noise free

RATE PLOT LEDGEND

Trues: solid

Randoms: dotted

Scatter: dashed

NECR: dash dot

NECR (2R): dash dot dot

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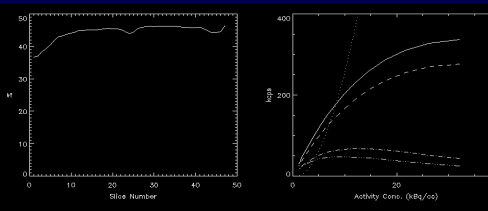
NU2-01/7 Scatter Fraction/Count Rate 3D



ANALYSIS RESULTS

System scatter fraction: 45.1161 (%)

Peak trues rate: 336.336 (kcps) @ 32.0870 (kBq/cc)

Peak randoms rate: 2033.29 (kcps) @ 32.0870 (kBq/cc)

Peak scatter rate: 276.151 (kcps) @ 32.0870 (kBq/cc)

Peak NEC rate: 67.8688 (kcps) @ 12.0064 (kBq/cc)

Peak NEC rate (2R): 47.2708 (kcps) @ 9.86202 (kBq/cc)

Results generated from scan with 2001_decay_3D

RATE PLOT LEDGEND

Trues: solid

Randoms: dotted

Scatter: dashed

NECR: dash dot

NECR (2R): dash dot dot

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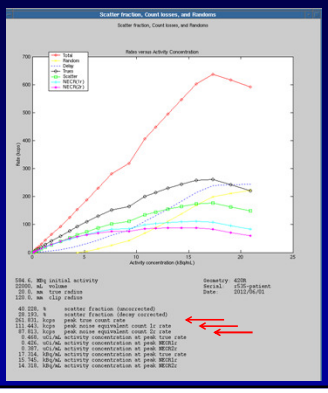
Count Rate Performance

Example from a Philips system



Used 15.8 mCi at 18:05

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Image Quality:

This test attempts to measure the performance of the scanner in a condition that simulates a whole body clinical scan. The test uses hot and cold spheres of different sizes in a volume of non-uniform attenuation. Activity is also placed outside the FOV. Image quality is reported in terms of image contrast and SNR of hot and cold spheres.

- The IEC background is filled with ~5.3 kBq/cc
- The 4 smallest spheres of the IEC phantom are filled with 4 times background
- Two largest spheres are filled with regular water
- Scatter phantom was filled with total activity of 116 MBq/cc (~ background)
- Both phantoms were positioned behind one another in the center FOV
- Data was acquired for 8.5 min (2D) and 7.5 min (3D) since CT was used for atten.
- Repeat with 4 smallest spheres of IEC phantom filled with 8 times background

- Analysis is done on images reconstructed using clinical protocols.
- ROIs are drawn on spheres an background.
- 12 background ROIs are drawn on central,±1cm,±2cm slices (total 60 rois).

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The following parameters are calculated on the ROI values:

- Hot and cold sphere contrast for each sphere (j):

$$Q_{Hot_j} = ((C_{Hot_j} / C_{Bkg_j}) - 1) / ((a_{Hot} / a_{bkg}) - 1) \qquad Q_{Cold_j} = (1 - (C_{Cold_j} / C_{Bkg_j})$$

- The percent background variability for each sphere (j):

$$N_j = SD_j / C_{Bkg_j}$$

- The average residual lung error summed over all slices (i):

$$\Delta C_{lung} = \sum_i C_{lung} / \sum_i C_{Bkg}$$

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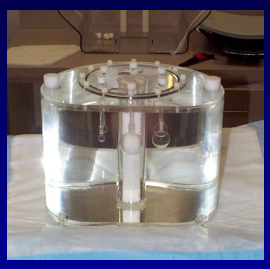
NU2-01/7 Image Quality Setup



- 0.206 uci/cc in 10 Liter background
- 0.88 uCi/cc sphere concentration
- 4.7 mCi in the scatter phantom

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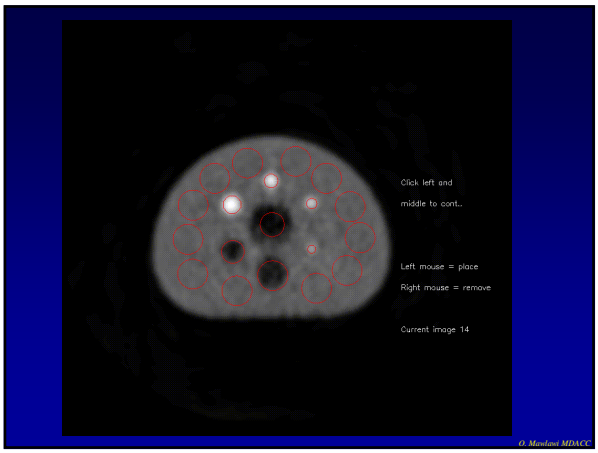
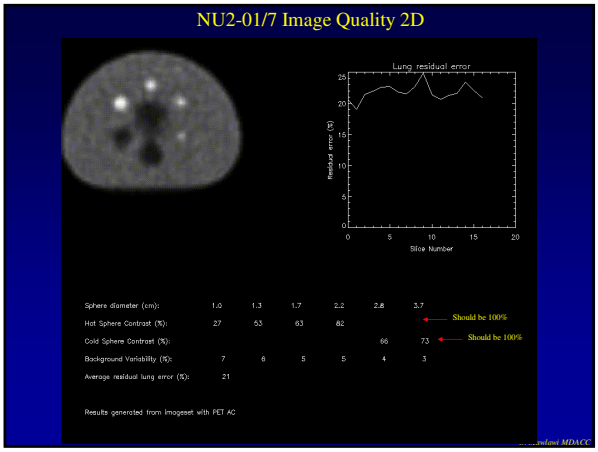
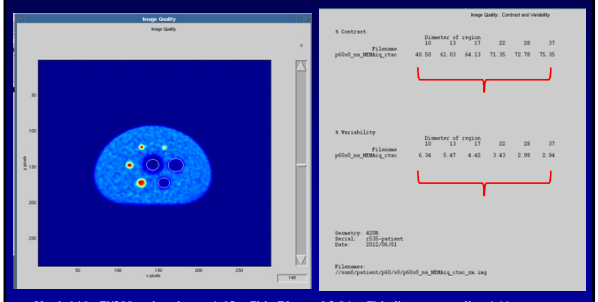


NU2-01/7 Image Quality 2D



NU2-01/7 Image Quality 3D

Example from a Philips system



Used: 146 uCi/200 cc in spheres, 1.65 mCi in Bkg, and 3.04 mCi in line source, all at 4:11

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Accuracy for correction of count losses and randoms:

The accuracy of count losses and randoms corrections is measured by comparing The trues rate calculated using count losses and randoms corrections with the trues Rate extrapolated from measurements with negligible count losses and randoms.

The test uses the data acquired during the count rate and scatter fraction test.

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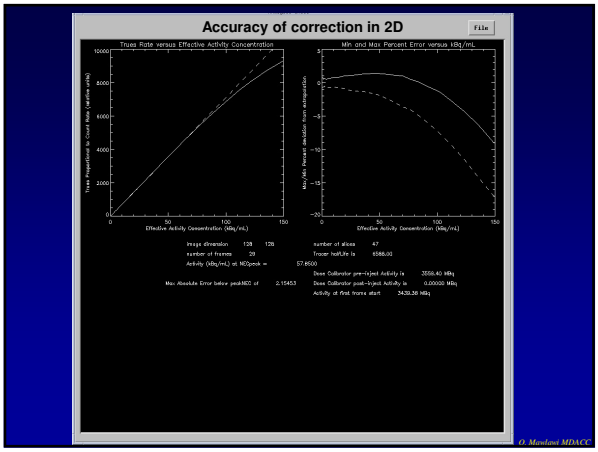

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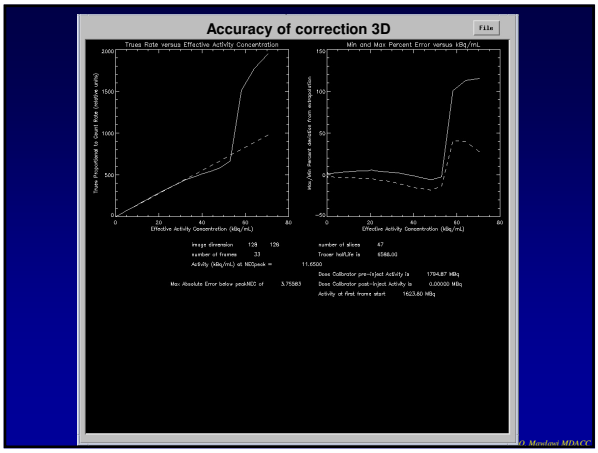

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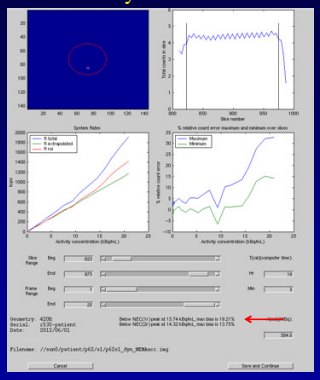
Accuracy of Corrections



Example from a Philips system

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NEMA Acceptance testing

- Results should be compared to manufacturers specification.
- Each system from each manufacturer has specifications for each of the NEMA tests
- These specifications are available upon request from the manufacturer.

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Quality Control Schedule

- Daily:
  - Check singles, coincidences, timing, energy
  - Sinograms
- Weekly:
  - Update gains
- Quarterly
  - Normalization and well counter calibration
- Annually
  - ACR or NEMA tests, TG126.

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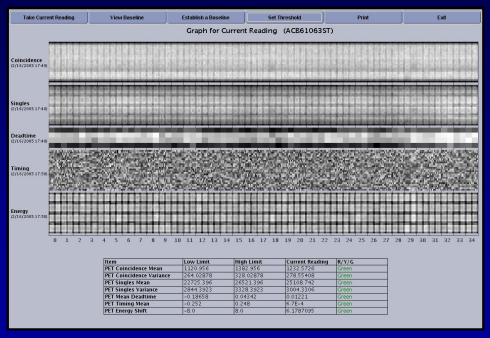
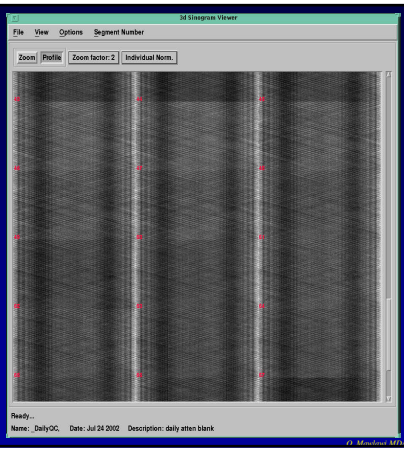
PET Daily QA Scan



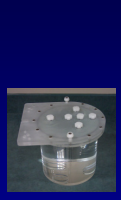
Daily QC

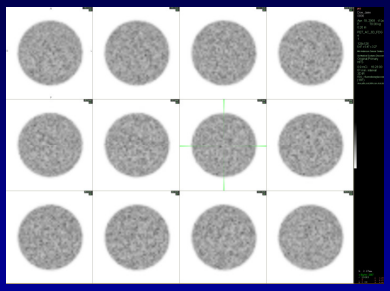
Sample Sinograms



Daily Quality Control

- Pre-calibrated Phantom





Assess quantification accuracy using SUV measurement

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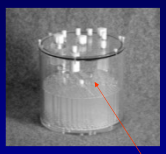
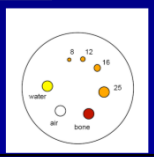
Annual ACR Phantom Images

- Uses the ACR (Esser phantom)





Take OFF the spheres

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Phantom Images - Procedure

From the column on the right, select the administered FDG whole-body dose.

1) Measure F-18 doses and enter values with times on work sheet (next page).
2) Add **Dose A** to a 1000 ml container. Mix and withdraw a 60 ml test **dose #1**. Set aside.
3) Withdraw 40 ml using a second 60 ml syringe and fill the 4 appropriate chambers in the phantom top.
4) Thoroughly mix **Dose B** in phantom background.
5) Remove 60 ml test **dose #2** from the phantom background.
6) Measure activity of test **dose #1 and #2** in dose calibrator; record in sheet.
7) Inject **dose #2** back in phantom. Fill remaining space with water and mix.
8) Scan at the specified time.

Phantom Dose Chart

Patient Dose	Dose A mCi	Dose B mCi
4 mCi	0.140	0.330
6 mCi	0.210	0.495
8 mCi	0.280	0.660
10 mCi	0.350	0.825
12 mCi	0.420	0.990
14 mCi	0.490	1.154
16 mCi	0.560	1.319
18 mCi	0.630	1.484
20 mCi	0.700	1.649

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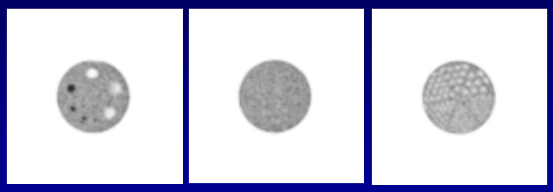
Annual ACR phantom images



Contrast | Uniformity | Resolution

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NEMA Performance Characterization :

NEMA NU2-01/7 (2D/3D)

- Spatial Resolution
- Sensitivity
- Scatter Fraction/Count Rate Performance
- Image Quality
- Accuracy of count losses and randoms correction

Additional tests such as scanner alignment and accuracy of SUV are NOT part of NEMA tests

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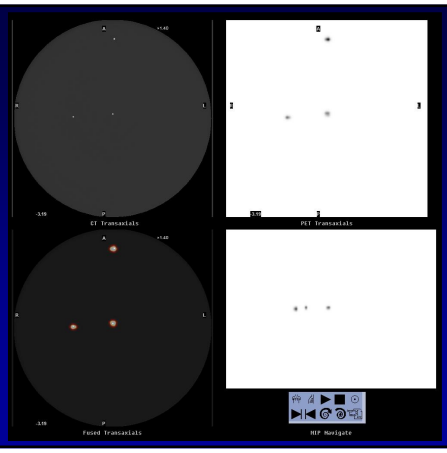
No load



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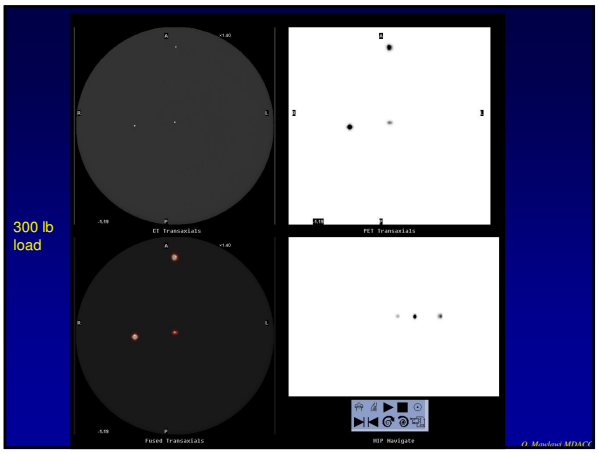
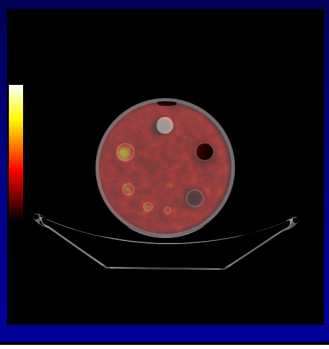
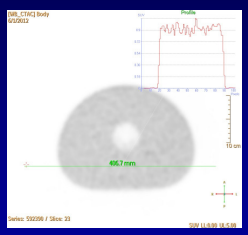


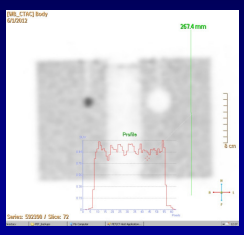
PET/CT scanner alignment



Uniformity



Uniformity within slice



Uniformity across slices

Additional tests

- Timing resolution for TOF systems
- Energy resolution
- Gating functionality
- List mode recording

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CT Daily QA Scan

Normal operations include the following 3 tasks (in order):

- Tube Warmup- A built-in prep scan that gradually increases heat loading in the X-ray tube in order to prevent thermal cracking and eliminate the potential for an arc to occur. It includes a series of exposures made at incrementing kVp
- Daily Air Cals- A built-in prep scan that performs a series of exposures at varying techniques in order to normalize the detector response using *air* as the attenuating media. These scans essentially adjust the detector gains to achieve a uniform response
- Daily QC Phantom scan- Provides data for 3 areas of concern in daily quality assurance: Linearity, Uniformity, Artifact analysis.

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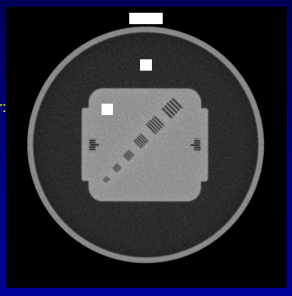
CT Daily QC Scan

- Linearity
  - Linear attenuation coefficients track linearly with material density
  - Remember that CT numbers are defined WRT the attenuation coefficient of water:

$$CT(x,y) = 1000\left(\frac{\mu_{(x,y)} - \mu_{water}}{\mu_{water}}\right)$$

  - The mean CT numbers of air (-1000 HU), water (0 HU), and acrylic (120 HU) displayed within an ROI should be consistent with the defined value +/- manufacture specified tolerance



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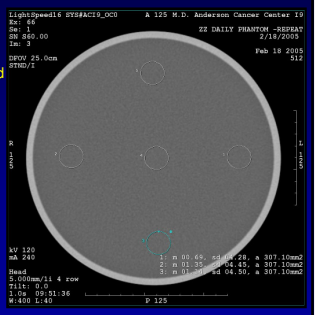
CT Daily QC Scan

- Uniformity
  - ROIs distributed in homogeneous material should indicate consistent signal (HUs) and noise

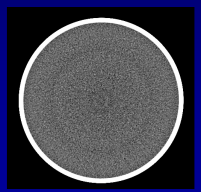


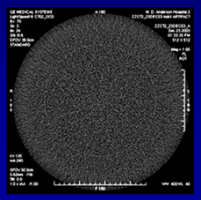
CT Daily QC Scan

- Low Contrast Resolution
  - Qualitative assessment of smallest resolvable hole in a membrane with a CT number similar to that of water

CT Daily QC Scan

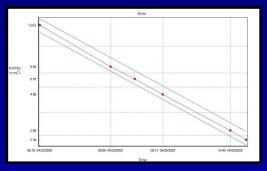
- Artifact Analysis
  - Looking for the presence of artifact
  - *Ring artifact* is the most clinically prevalent in QA scans
  - Caused by non-uniformity in detector response due to gain imbalance or beam obstruction





Dose Calibrator

- D.C. Quality Control Tests
  - Linearity
    - "The proportionality of the measurement result to the activity measured, as determined over the intended range of use for the dose calibrator"
    - A known activity of FDG is assayed at a particular time and then assayed again subsequently on the hour.



http://www.biodex.com/radio/dosecal/pdf/quality_testing.pdf

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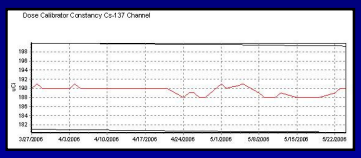
Dose Calibrator

- D.C. Quality Control Tests
  - Constancy
    - "Reproducibility in measuring the same source, over a period of time, with decay correction"
    - Assay a relatively long-lived source (such as Cs-137) each day before using the calibrator



http://www.biodex.com/radio/dosecal/pdf/quality_testing.pdf

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Dose Calibrator

- D.C. Quality Control Tests
  - Accuracy
    - "Determination of the dose calibrator's absolute error resulting from a measurement of a suitable NIST traceable radionuclide activity"
    - Assay 2 calibrated reference sources, decay correct, and determine % error
  - Geometry
    - "Indicated activity does not change with volume or configuration of the source material"

http://www.biodex.com/radio/dosecal/pdf/quality_testing.pdf

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TG 126

- TG126: PET/CT QA/QC and testing
  - Chair: Osama Mawlawi
  - Charge: to develop a report describing procedures for acceptance testing and routine quality assurance of PET scanners.
  - Representation: Academia, industry, consulting, hospitals.
  - Sources: NEMA, IAEA (QA for PET and PET/CT systems)
  - Current issues:
    - Acceptance testing: NEMA standard + alignment as well other aspects ie TOF, Cardiac, dynamic, gated.
    - Annual testing: NEMA-lite; issues with some vendors
  - Meetings: SNM, AAPM, RSNA, (IEEE – MIC)
  - Expected draft date: 2012

http://www-pub.iaea.org/MTCD/publications/PDF/Pub1393_web.pdf

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Artifacts

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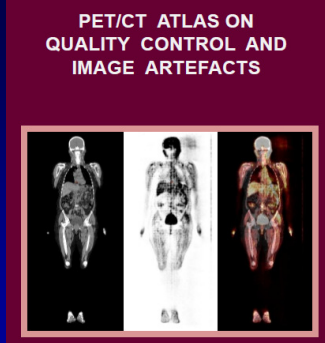

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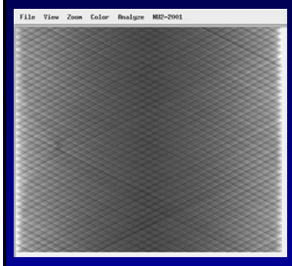
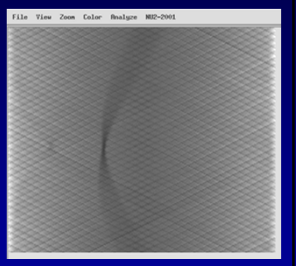
Normalization effects

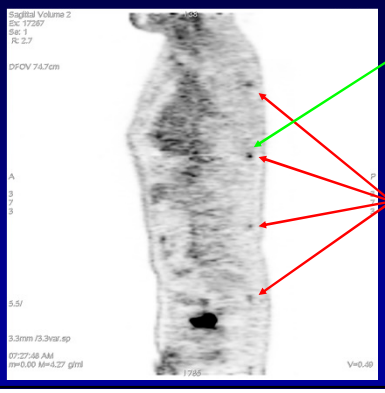


Good Norm

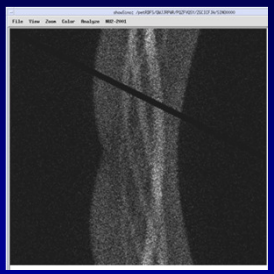


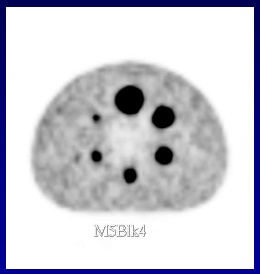
Bad Norm

Effect of bad Normalization

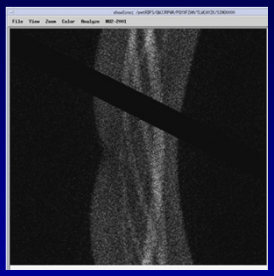


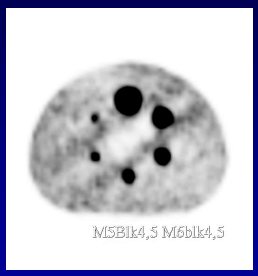
Effects of Bad Blocks

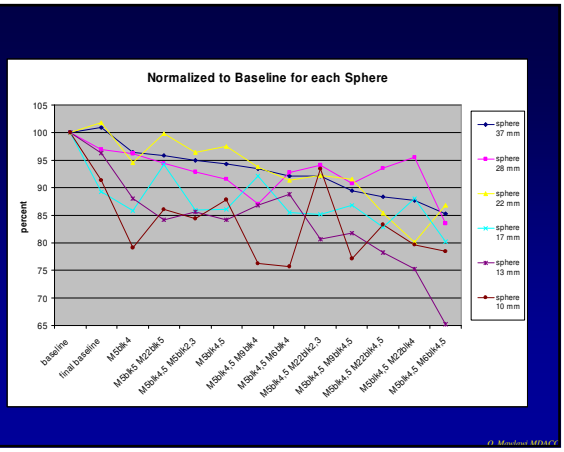




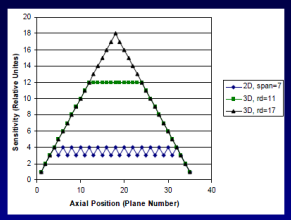
Effects of Bad Blocks

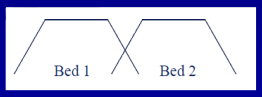




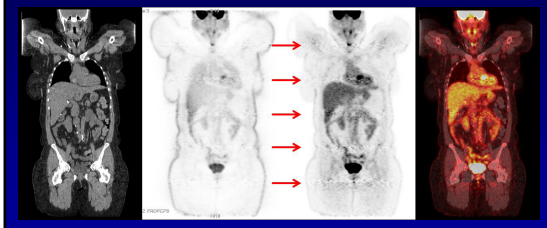


Bed overlap





Insufficient Bed overlap



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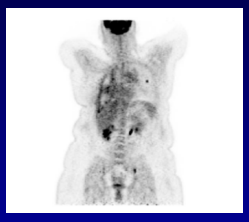
Patient entries



SUVmax	Weight	Unit of weight	Dose (MBq)	Injection time
4.6	109	kg	359	14:08
4.2	99	kg	359	14:08
2.1	109	lb	359	14:08
3.8	109	kg	433	14:08
3.2	109	kg	359	15:08

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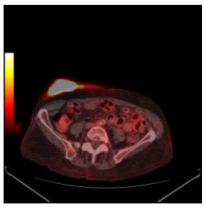
Contamination



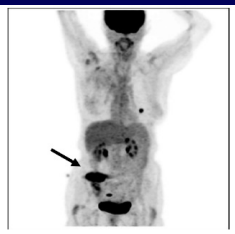


Fig. 1: Transaxial fused AC PET/CT (left) demonstrating extensive tracer contamination of the blanket, which can be falsely interpreted as a malignant uptake on AC PET images (arrow right)

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Thank you