Positron Emission Tomography
Quality control and Quantification

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Introduction

What is "Quality Control for PET" ?

Introduction

- **Quality management system**

Programme that controls how quality is maintained and ensured throughout an organization

- **Quality Assurance**

General concepts of actions that ensure that a delivered service meets the requirements

- **Quality control**

A specific set of measurements focused on monitoring the performance of a system.

IAEA Human Health Series No. 1

Introduction

The product, which is offered is an evaluation of metabolic activity and the corresponding conclusion

In other words:

a diagnosis

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In other words:

a diagnosis

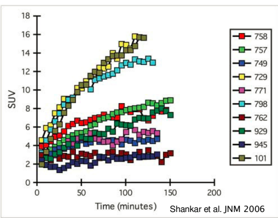
This can be influenced by various factors!

Quality Assurance

For a proper „quantitative“ evaluation the whole work flow must be taken into account

Quantification

What is quantification?



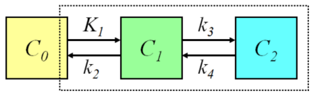
Most interesting part is the metabolism -> the uptake rates

Tracer uptake is a dynamic process

Quantification

Description of the process with differential equations:

Kinetic modeling



$$\frac{dC_1}{dt} = C_0 * K_1 - (k_2 + k_3)C1 + k_4 * C_2$$

Requires: Arterial blood sampling, Dynamic measurements, post-processing….

Kinetic modelling is the gold standard

Quantification

Measured Activity is normalized to Injected Activity

$$SUV = \frac{Act_{VOL}\left[\frac{kBq}{ml}\right]}{\frac{Act_{administrated}[MBq]}{BW[kg]}}$$

Can be normalized to:

- Body weight
- Body surface area
- Lean Body mass

SUV is an easy solution to a complicated problem

Quantification

Standards for PET Image Acquisition and Quantitative Data Analysis

Technical factors

- Relative calibration between PET scanner and dose calibrator (10%)
- Residual activity in syringe (5%)
- Incorrect synchronisation of clocks (10%)
- Injection vs calibration time (10%)
- Quality of administration (50%)

Σ: 85%

R. Boellaard 2009, J Nucl Med Supplement Issue 50: 11S

Small mistakes can add up

Quantification

Standards for PET Image Acquisition and Quantitative Data Analysis

Physics related factors

- Scan acquisition parameters (15%)
- Image reconstruction parameters (30%)
- Use of contrast agents (15%)
- ROI (50%)

Σ: 110%

Biological factors

- Uptake period (15%)
- Patient motion and breathing (30%)
- Blood glucose levels (15%)

Σ: 60%

R. Boellaard 2009, J Nucl Med Supplement Issue 50: 11S

Small mistakes can add up

Quantification: Patient preparation

Main purpose:

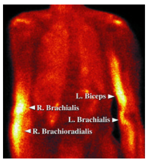
- reduction of tracer uptake in normal tissue
  - Kidneys, bladder, skeletal, muscle, myocardium, brown fat
- Optimized tracer uptake in target structures
- **Reproducible results !!!!**

Quantification: Patient instructions

Patients instructions

Example:

(No) exercise before a study

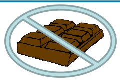


Pappas et al. J Appl Phyiol 2001

Ensure clear patient instructions

Quantification: Patient instructions

- No food or sugar for at leas 6h prior injection
  - To keep blood glucose level low



- Adequate pre hydration (e.g. 1l water in the 2h prior injection)
  - To ensure sufficiently low FDG in urine (less artefacts)
  - Radiation safety

- Good practice: Check blood glucose level on arrival to obviate an unnecessary wait
- Keep patient warm 30-60 min prior FDG administration
  - avoid uptake in brown fat

Ensure clear patient instructions

Quantification: Patient instructions

- Blood glucose level must be measured prior to FDG administration
  - < 120 mg/dl
- Check body weight prior the examination
  - Can change during a treatment
  - Patient may not know the exact weight
  - Mistakes contribute directly in wrong SUV

- Measure residual activity in syringe
  - Avoid wrong dose

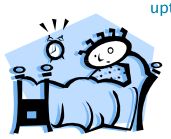
Avoid accumulation of small mistakes

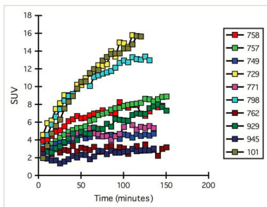
Quantification: Patient preparation

Patients instructions → Preparation/ administration

Example:

Different uptake times



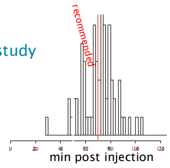


Shankar et al. JNM 2006

Mind variability of tracer uptake time

Quantification: Patient preparation

- Keep patient comfortable post FDG administration
  - Low uptake in brown fat, muscles
- For brain studies no reading, TV, talking and a dimmed light
  - ➢ Avoid activating brain regions
- Send patient to toilet 5 min before start of the PET study
  - ➢ Avoid activity in bladder
- Acquisition should start 60 ± 5 min after FDG administration (EANM: ± 10 min)



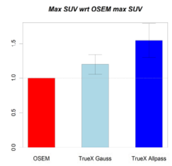
Tracer specific metabolism during tracer uptake period

Quantification: Acquisition

Patients instructions ➔ Preparation administration ➔ PET/CT Examination

Example:

Different algorithms



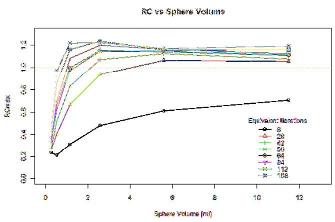
Rausch 2011

Reconstruction parameters effect PET quantification

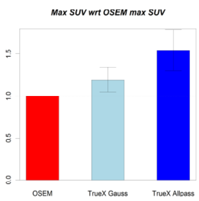
Quantification: Reconstruction

- Algorithm, parameter settings and post filtering influence the outcome

Different Iterations and Subsets



Different Algorithms



Reconstruction settings strongly influence quantification

Quantification: Acquisition

- **Scan duration dose not have a significant effect on SUV accuracy, except possibly for extremely short scans**
  (Kinahan P.E. et al. Positron Emission Tomography-Computed Tomography Standardized Uptake Values in Clinical Practice and Assessing Response to Therapy, Semin Ultrasound CT MR 2010)

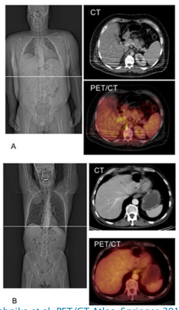
BUT:

- **"PET acquisition parameters, such as acquisition mode, scan duration per bed position, and amount of bed overlap in subsequent bed positions, in combination with patient weight and ^{18}F-FDG dose, affect PET image quality"**
  (Boellaard R. Standards for PET Image Acquisition and Quantitative Data Analysis, JNM 2009)

Scan duration may influence quantification in PET

Quantification: Beam Hardening

- Bone attenuates low energy photons more than the higher energy photons
  - Overestimation of the attenuation for 511 keV photons
  - Hardening artefacts
  - Avoid by placing arms over the head
- Metal implants lead to serious hardening artefacts
  - Especially a problem in head and neck cancer
- In some cases the CT FOV is smaller than the PET FOV
  - Leads to truncation artefacts and wrong quantification
  - Most systems have correction algorithms



Mohnike et al. PET/CT Atlas, Springer 2011

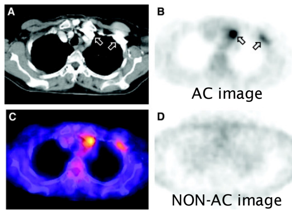
Avoid beam hardening effects by proper patient positioning

Quantification: Contrast agents

- Attenuation for positive contrast agents for X-ray beams similar to bone
- Attenuation for contrast agents for 511 keV Photons similar to water

Solution:

- Low dose CT for AC before administration of IV Contrast agents
- Use of negative oral contrast agents
- Use of specific protocols

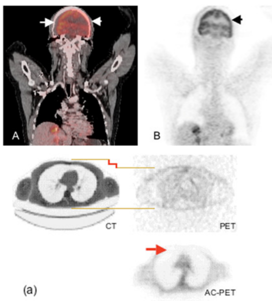


Antoch et al. JNM 2004

Contrast agents can cause artifacts in AC corrected images

Quantification: Breathing

- Movement between CT and PET can lead to miss-registration
  - Mistakes in attenuation correction
- PET study is average over multiple breathing cycles
  - for 1 and 2 line CTs AC CT ask patient to exhale and hold breath
  - For 6 or more lines the AC CT can be done wile the patient is exhaling



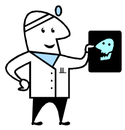
Mohnike et al. PET/CT Atlas, Springer 2011

Miss-registration of AC-CT leads to mistakes in AC PET image

Quantification: Interpretation

Patients instructions → Preparation administration → PET/CT Examination → Evaluation & Interpretation

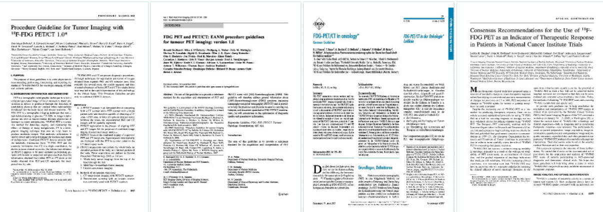
Example:



- Different SUV values can be used:
  - Maximum SUV
  - Mean SUV (Threshold segmented)
  - Peak SUV
  - Lean body mass SUV

Need to standardize image interpretation

Guidelines: FDG PET/CT



Delebeke, JNM 2006 | Boellaard, EJNM 2010 | Krause, Nukmed 2007 | Shankar, JNM 2006

"Guide us through the guidelines !"

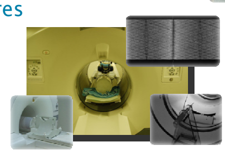
Many guidelines – large variability

Quality Control

Consists of:

•Acceptance testing

•Routine QC procedures



QC = Acceptance testing + Routine tests

Acceptance testing

"After installation,..., a nuclear medicine instrument must undergo thorough and careful acceptance testing, the aim being to verify that the instrument performs according to its specifications and its clinical purpose."

Busemann S. et al. EJNMMI 2010; 37:662-671

Testing

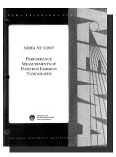
•Standards like NEMA NU2 or IEC performance standards

•Clinical Settings (!?)

•Additional tests for individual components

•Reference data for future QC tests

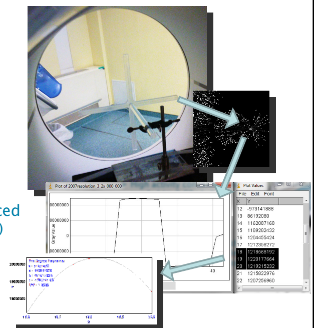
Basically the same at end of warranty



Prerequisite for clinical operation

Acceptance: Spatial Resolution

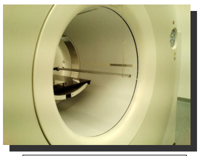
- Point source in air
  - best possible performance
- Collect at least 1 M counts
  - High activity concentration needed (≥ 2 GBq/ml)
- Reconstruction using FBP
  - Comparability
- Can be reconstructed using advanced reconstructions (e.g. PSF modeling)
  - Enhanced special resolution
- Report FWHM and FWTM

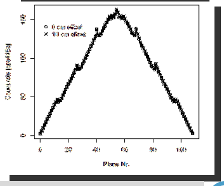


Resolution is measured in an ideal scenario

Acceptance: Sensitivity

- Count rate of true events for a given activity
- Line source (~6 MBq) surrounded by aluminium tubes (ensure annihilation) with known thickness
- Acquisition of 5 images (>10 k counts; ~ 5 min each) with different numbers of Al-tubes @ centre of FOV and 10 cm radial offset
- Extrapolation of the data to a zero-thickness Al-tubing
- Sensitivity = Σ count rate / activity

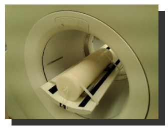


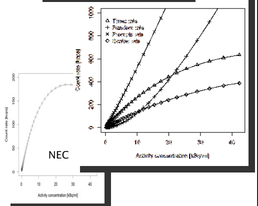


Rate of true coincidences for a give source

Acceptance: Count rate performance

- Scatter fraction: the systems sensitivity to scattered radiation (**energy resolution**)
- Count losses and random rate: the systems ability to measure highly radioactive sources (timing resolution and dead time)
- Noise equivalent count rate (NEC): amount of trues (no scatter and randoms) for similar SNR as with scatter and randoms
- Starting activity to be beyond NEC peak (>1 GBq in ~ 5ml)
- Evaluation described in NEMA NU2

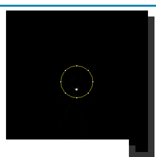


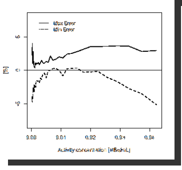


Count rate performance to asses system behavior with high activities

Acceptance: Accuracy

- To assess the accuracy of dead time looses and random event.
- Count rate performance measurements are used
- Reconstruction using “clinical standard settings” (FBP ?)
- Report “relative count rate error”: differences of measured count rate to expected count rate in [%]

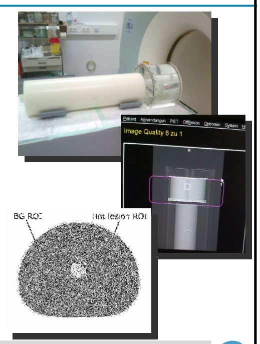




Systems ability to replicate the true activity

Acceptance: Image Quality

- To compare image quality of different systems in a standardized way
- Simulating a total body imaging study: cold- and hot lesions, non uniform attenuation; scatter form outside the FOV
- Scanned three times for more stable values
- Acquisition time axial FOV dependent !!!
  - ➢ $T = \frac{30min}{100cm} * axial\ step$
- Report: contrast recovery; BG variability and Lung residual



Standardized evaluation of image quality

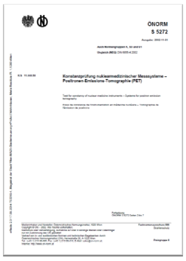
Routine Quality Control

- Simple routine tests specific to imaging system
- Sensible to system changes
- Detailed SOPs should be available on-site
- Proper documentation to estimate long time behavior
- Thresholds (manufacturers recommendations) and corresponding actions if exceeded in SOP
- Define a responsible person

Busemann S. et al. EJNMMI 2010; 37:662-671

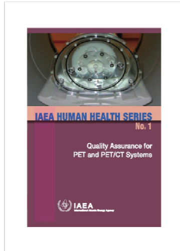
Ensure daily quality in routine operation

Guidelines



National guidelines


EANM guidelines



IAEA guidelines

Several guidelines exist

Routine QC - PET

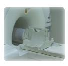
Test	Purpose	Frequency
Physical inspection	Check gantry covers and patient handling system	Daily
Daily QC	Test proper functioning of detector modules	Daily
Uniformity	Axial uniformity across image planes	After maintenance / normalization
Normalization	System response to activity in the FOV	Variable (min 6-monthly)
Calibration	Calibration factor from voxel to true activity	Variable (min 6-monthly)
Spatial resolution	Spatial resolution	Yearly
Sensitivity	Volume response to a source of activity concentration	Monthly
Image quality	check hot and cold lesions	Yearly

Buseman Sokole E. et al. EJNMMI 2010; 37:662-671

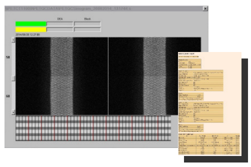
Routine QC – PET: Daily QC

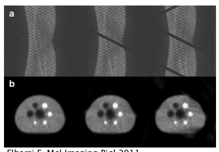
Different vendors – different methods

^{68}Ga/^{68}Ge cylinder



^{22}Na point source





Elhami E. Mol Imaging Biol 2011

Detector failure can be seen in the sinogram as black lines (a)

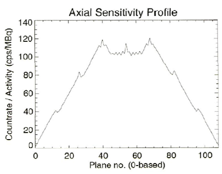
Detector failure impacts image quality (b)

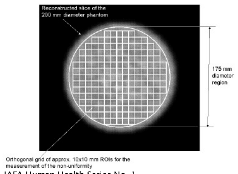
Assess constancy of detector performance to pick up sudden changes

Routine QC – PET: Uniformity

Axial uniformity

In-plane uniformity





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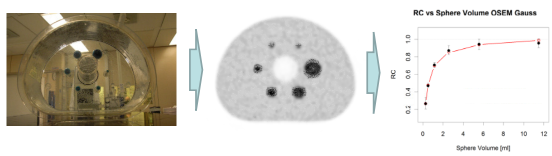
Corrective action: Normalization (+ Calibration)

Test if activity is uniform across all planes / within a plane

Routine QC – PET: Image Quality

Can be done with the NEMA/IEC Image quality phantom

Evaluation of Recovery Coefficients or Contrast



Evaluate image quality in standardized conditions

Routine QC - CT

Test	Purpose	Frequency
X-ray CT – daily	Daily procedures due to manufacturer`s recommendation	Daily
X-ray CT – numbers	Determine CT number accuracy	Monthly
X-ray CT – alignment	Determine 3-D alignment of PET and CT	At least monthly
X-ray CT – performance	Check according to national radiation safety	As advised

Buseman Sokole E. et al. EJNMMI 2010; 37:662-671

QC of hybrid Nuc/CT systems = $QC_{Nuc} + QC_{CT}$

Additional Tests

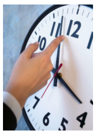
- Clock syncronization
- Cross calibration

(of PET system and on-site dose callibrator)

Extend QC to include quantification

Clock-synchronization

5 minutes offset imply:
- ^{18}F - 3% difference
- ^{68}Ga - 5% difference
- ^{11}C - 16% difference
- ^{15}O - 82% difference



"The clocks within the department, within all instruments and all computers must be synchronized"

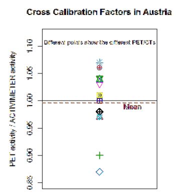
Buseman S. et al. Routine QC recommendations for nuclear medicine instrumentation, EJNMMI 2010

Check clock synchronization at least weakly

Cross-calibration

$$SUV = \frac{Act_{VOL}\left[\frac{kBq}{ml}\right]}{\frac{Act_{administrated}[MBq]}{BW[kg]}}$$

$$SUV = \frac{Act_{VOL}\left[\frac{kBq}{ml}\right]}{\frac{Act_{administrated}[MBq]}{BW[kg]} * CC_{factor}} = \frac{Act_{VOL}\left[\frac{kBq}{ml}\right]}{\frac{Act_{administrated}[MBq]}{BW[kg]}} * CC_{factor}$$



Wrong Cross-calibration contributes direct to SUV

Mistakes in cross-calibration imply mistakes in SUV

Summary

- Regular QC is important
- Proper Quality Assurance is essential
- Don`t be afraid of guidelines
- Adopt standardized procedures and a proper documentation for QC at your site
- Standardized procedures and a proper documentation is essential for QC

Keep your working-horse working

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