The Abdus Salam
International Centre for Theoretical Physics

IAEA

JOINT ICTP-IAEA ADVANCED SCHOOL ON
INTERNAL DOSIMETRY FOR MEDICAL PHYSICISTS
SPECIALIZING IN NUCLEAR MEDICINE

12 - 16 April 2010

Miramare, Trieste, Italy

CT-PET calibration : physical principles and operating procedures

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Topics

- Introduction to PET physics
  - F-18 production
  - β^+ decay and annichilation process
  - $\gamma\,\gamma$ coincidence detection
  - true, random and scatter coincidences
  - the NECR, image quality VS patient dose
- PET calibration and QC procedures
  - the sinogram
  - normalization and ECF calibration
  - daily QC
  - uniformity, sensitivity

PET

POSITRON EMISSION TOMOGRAPHY

Positron

The positron (e^+) is emitted in the β^+ decay process:

$$p \rightarrow n + e^+ + \nu_e$$

The β^+ decay is forbidden for a free proton. The process must occur in a nucleus:

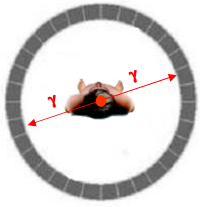
$$(A,Z) \rightarrow (A,Z-1) + e^+ + \nu_e$$

For example:

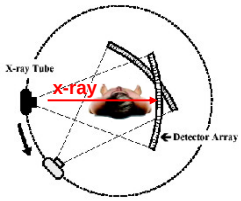
$$^{18}F \rightarrow {}^{18}O + e^+ + \nu_e$$

Emission

Emission (tomography) : the source of radiation is inside the patient:

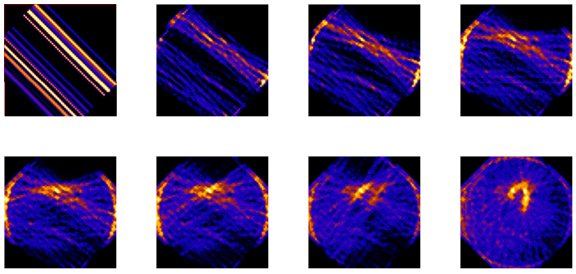


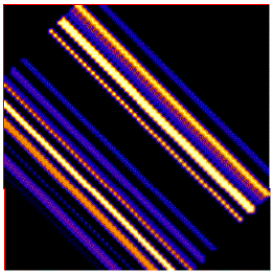
Transmission (tomography) : the source of radiation is outside the patient:



Tomography

Tómos = from Greek = (cross-) section

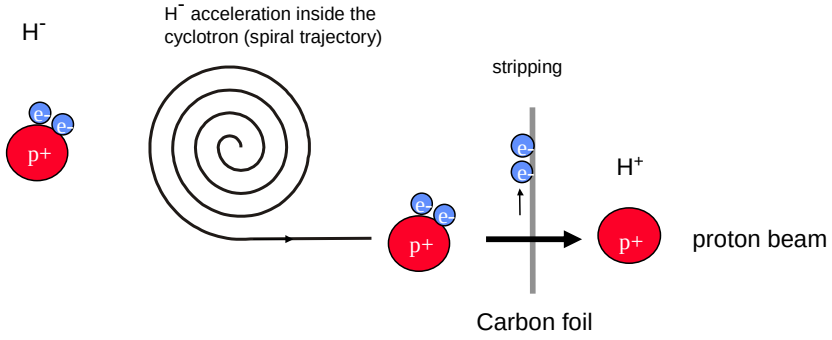




Material from "IAEA Educational Course Radiation Protection in Nuclear Medicine"

Intro to PET physics

How the F-18 is produced?



$$p + {}^{18}O \rightarrow n + {}^{18}F$$

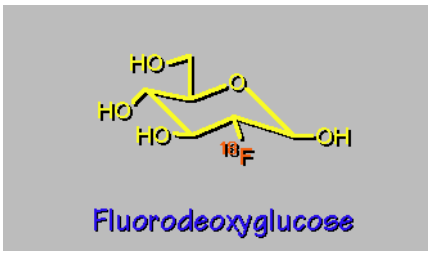
Intro to PET physics

FDG synthesis

FDG

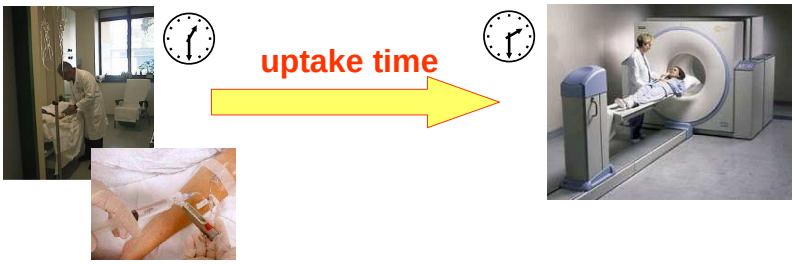
Main applications:

- Oncology (cancer detection and staging)
- Cardiology
- Neurology



Intro to PET physics

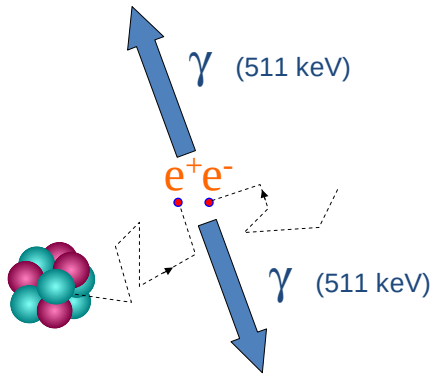
FDG administration



Intro to PET physics

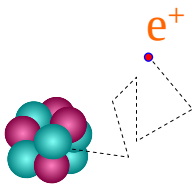
β^+ decays and annnihilation process

$^{18}F \rightarrow {}^{18}O + e^+ + \nu_e$



Intro to PET physics

e^+ range in the patient tissues



Radioisotope	e^+ Range (mm)
^{15}O	8.4
^{13}N	5.4
^{11}C	4.2
^{18}F	2.6

Intro to PET physics

Radioisotope	e^+ E_{max} (keV)	e^+ E_{mean} (keV)	$T_{1/2}$ (min)	e^+ Range (mm)	Decay
^{15}O	1720	740	2.07	8.4	100% β^+
^{13}N	1190	490	9.96	5.4	100% β^+
^{11}C	970	390	20.4	4.2	99% β^+
^{18}F	635	250	110	2.6	97% β^+, 3% E.C.

Fermi's Golden Rule

$$|i\rangle \rightarrow |f\rangle$$

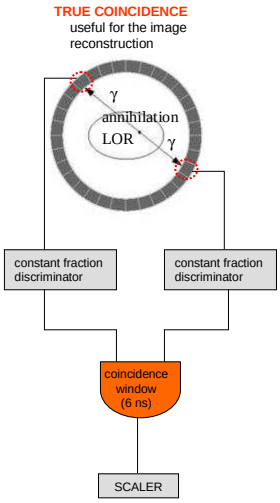
$$p_{i\rightarrow f} = \frac{2\pi}{\hbar} \cdot |M_{if}|^2 \cdot \left|\frac{dn_f}{dE}\right|$$

Transition matrix (dynamics)

density of final states (phase space)

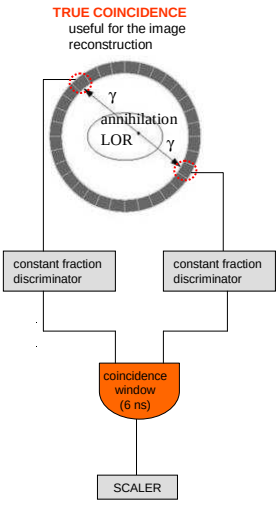
Intro to PET physics

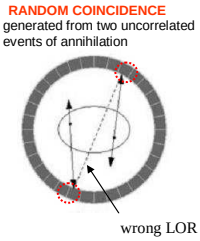
e^+e^- annnihilation process and $\gamma\gamma$ coincidence detection

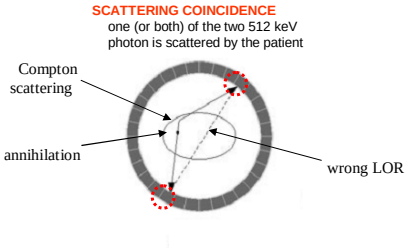


Intro to PET physics

True, random and scatter coincidences



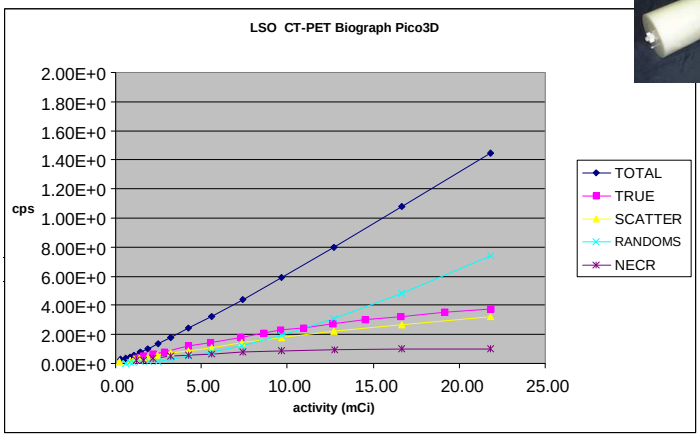




Intro to PET physics

True, random and scatter coincidences

Cylindrical phantom
water + F-18 filled

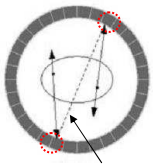


Intro to PET physics

Random coincidences :

- they don't contribute to image
- they increase the noise
- 20 – 50 % of true coincidences

RANDOM COINCIDENCE



How to reduce them?

$C_R = 2 \tau C_S^2$

→ smaller coincidence window
→ less activity

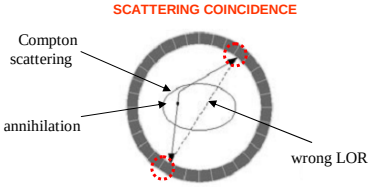
How to take into account?

→ delayed window method

Intro to PET physics

Scatter coincidences :

- don't contribute to image
- in the human thorax, 50% or more of the measured data may be scattered.
- reduce the contrast



How to reduce them?

→ 2D instead of 3D
→ less activity

How to take into account?

→ scatter modelling and compensation algorithms

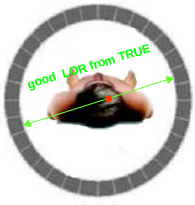
Intro to PET physics

Conventional Nuclear Medicine (planar, SPECT)

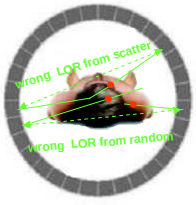
$$SNR \cong \frac{N}{\sqrt{N}} = \sqrt{N}$$

Positron Emission Tomography

TRUE EVENTS contribute to SIGNAL and NOISE



RANDOM AND **SCATTERING** EVENTS contribute only to NOISE



$$\frac{NECR}{\sqrt{NECR}} = \frac{T}{\sqrt{T+S+2R}}$$

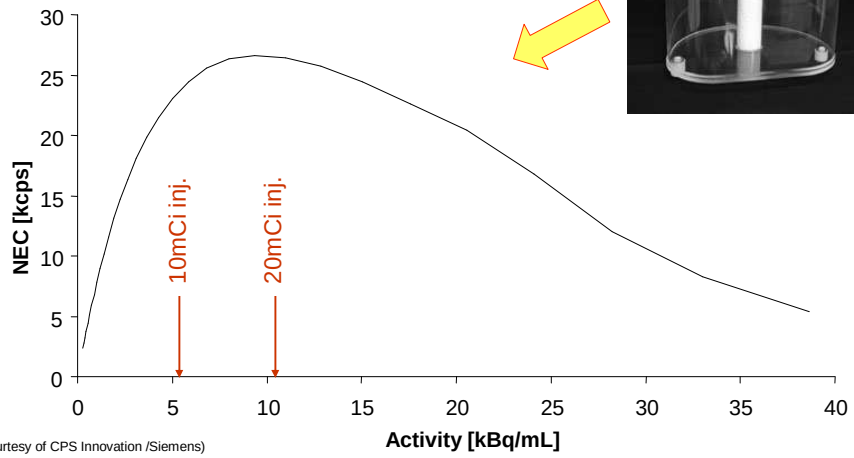
$$NECR = \frac{T^2}{T+S+2R}$$

$$SNR = \frac{T}{\sqrt{T+S+2R}}$$

Intro to PET physics

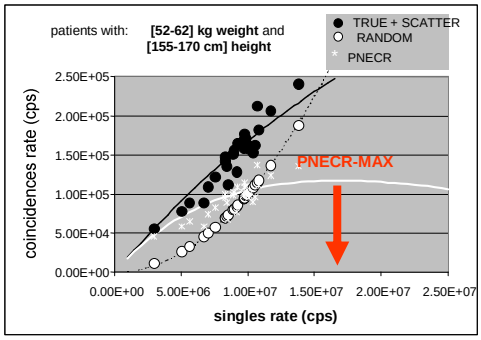
IMAGE QUALITY → NECR

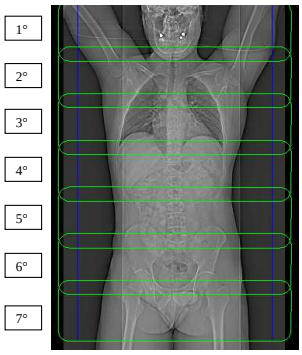
PET phantom for IQ



(courtesy of CPS Innovation /Siemens)

Intro to PET physics

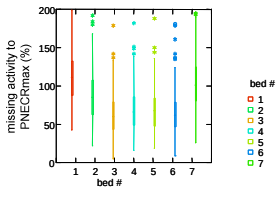




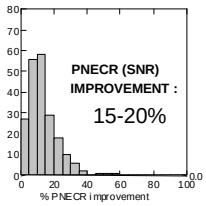
"COUNT-RATE ANALYSIS FROM CLINICAL SCANS IN PET WITH LSO DETECTORS"
F. Bonutti et al, Radiation Protection Dosimetry, (2008)

MISSING ACTIVITY = 70%

(for central beds)



but:

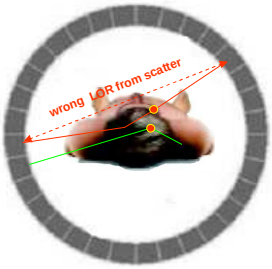


Intro to PET physics

Attenuation correction

Many true coincidences are lost because of

- scatter (Compton or Rayleigh interactions)
- absorption (photoelectric interaction)



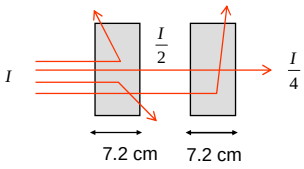
Scattered but detected
⇒"scatter" contribution to data
⇒"attenuation" of the true LOR intensity

Scattered and not detected
⇒"attenuation" of the true LOR intensity

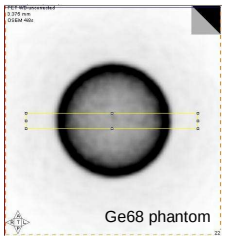
Intro to PET physics

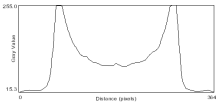
How much is the attenuation ?

@ 511 keV every 7.2 cm of water half radiation intensity is lost:

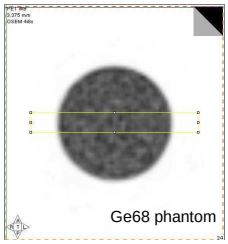


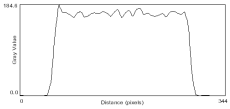
no AC





AC





Intro to PET physics

Attenuation correction

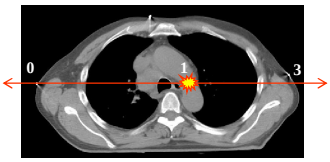
- the emitter distribution is distorted.
- quantification is not possible (SUV)
- lung lesions may not be visible in uncorrected images

Intro to PET physics

Attenuation correction

Attenuation factors range from < 5 in the brain to > 150 in the body.

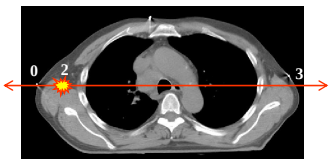
In PET the attenuation doesn't depend on the position of the source point along that LOR:



γ γ detection probability ~

$$e^{-\int_0^1 \mu(\ell)d\ell} e^{-\int_1^3 \mu(\ell)d\ell} = e^{-\int_0^3 \mu(\ell)d\ell}$$

=



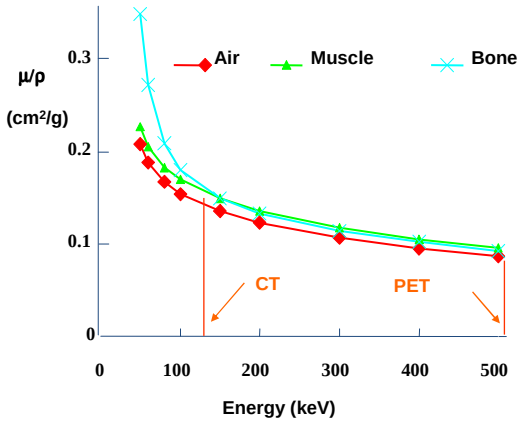
γ γ detection probability ~

$$e^{-\int_0^2 \mu(\ell)d\ell} e^{-\int_2^3 \mu(\ell)d\ell} = e^{-\int_0^3 \mu(\ell)d\ell}$$

Intro to PET physics

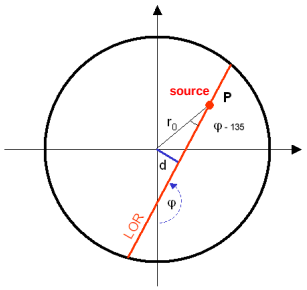
Attenuation correction

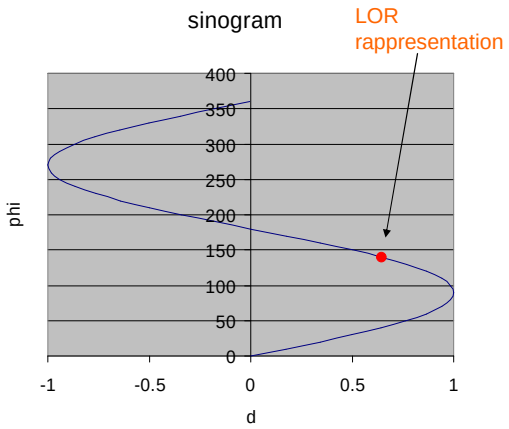
Rescaling the attenuation coefficients μ with energy



PET calibration and QC procedures

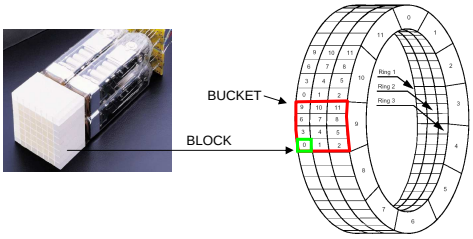
The sinogram





PET calibration and QC procedures

The normalization procedure



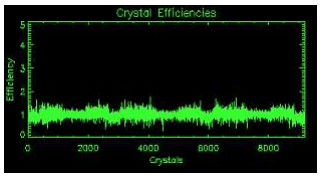
Ge-68 phantom, 1÷2 mCi

Example : Siemens Biograph LSO Pico3D

number of elementary detectors :

(12 buckets) X (12 blocks) X (64 crystals)

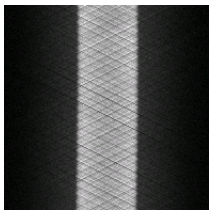
= 9216



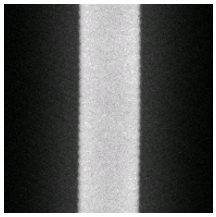
(courtesy of CPS Innovation /Siemens)

PET calibration and QC procedures

uniform phantom sinogram for a un-normalized system



uniform phantom sinogram for a normalized system

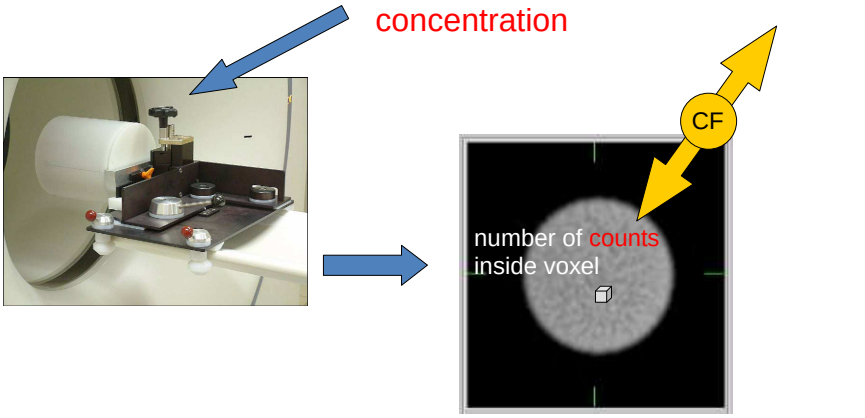


PET calibration and QC procedures

Calibration Factor (CF)

→ make possible quantifications (SUV)

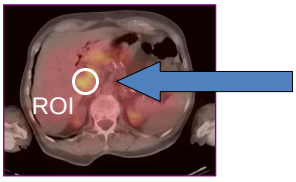
Ge-68 phantom of known activity concentration



PET calibration and QC procedures

Calibration Factor (CF)

→ make possible quantifications (SUV)



$$\text{ROI activity} = \frac{\text{ROI counts}}{0.969} \times \text{ECF}$$

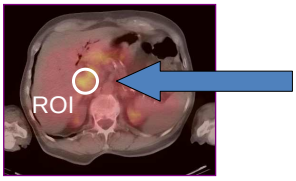
$^{18}F \rightarrow {}^{18}O + \nu_e$

- β^+ : $p \rightarrow n + e^+ + \nu_e$ (branching ratio = 96.9 %)
- E.C. : $p + e^- \rightarrow n + \nu_e$ (branching ratio = 3.1 %)

PET calibration and QC procedures

Calibration Factor (CF)

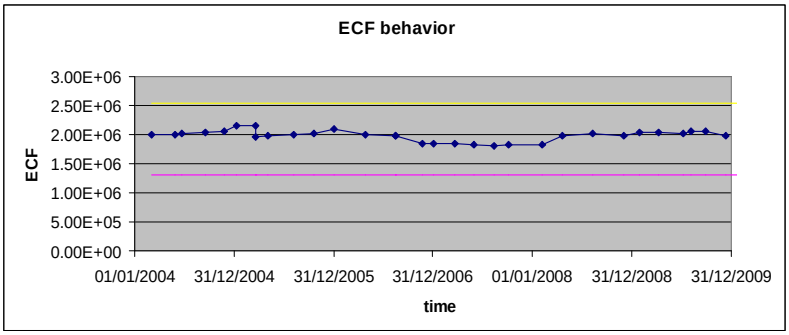
→ make possible quantifications (SUV)



$$SUV = \frac{\text{ROI activity concentration}}{\text{mean (body) activity concentration}}$$

PET calibration and QC procedures

ECF behavior (Emission Calibration Factor)



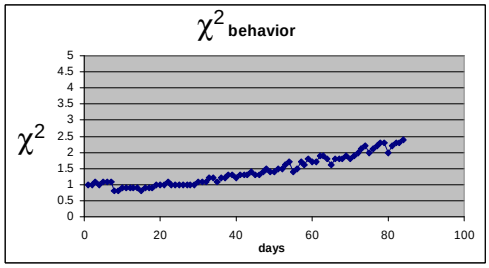
(Siemens Biograph LSO Pico3D)

PET calibration and QC procedures

After normalization, the software gives the χ^2

If you normalize the system every 1-2 months, typical χ^2 are 0.5 ÷ 1.5

If you do it less frequently, the χ^2 goes up



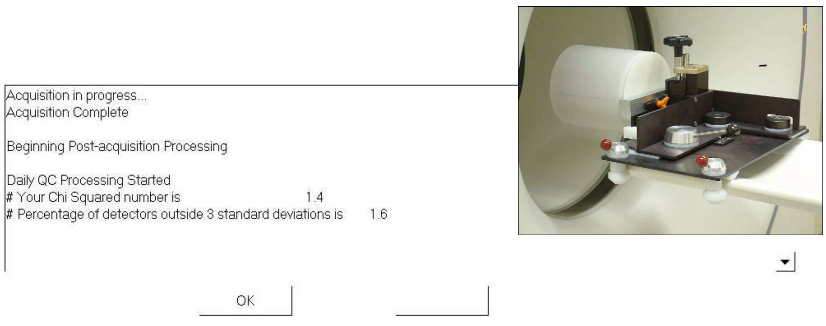
Optimal frequency may depend on the system

In our Departement we do normalization at least every 2 months

PET calibration and QC procedures

The need for normalization come out from the "daily QC" test

For this test, usually a Ge-68 cylindric phantom is used (1-2 mCi)

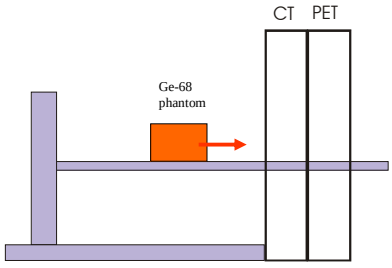


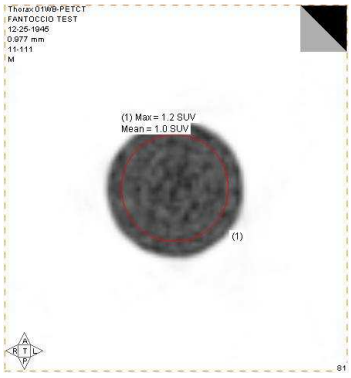
PET calibration and QC procedures

After the “daily QC” test, give a look to the sinograms :

PET calibration and QC procedures

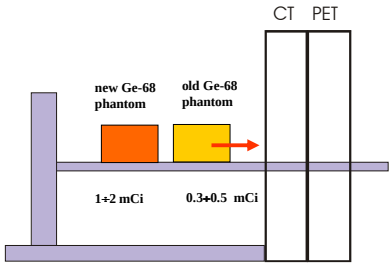
SUV tests : with a single Ge-68 phantom
(we do it monthly)

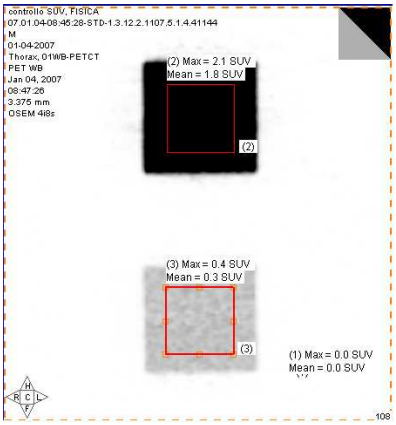




PET calibration and QC procedures

SUV tests : with two single Ge-68 phantom
(we do it every 6 months)

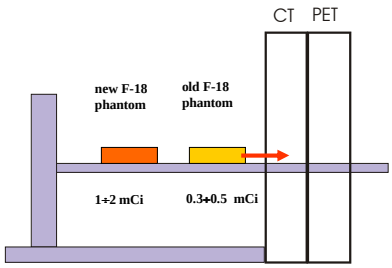




PET calibration and QC procedures

SUV tests : with two F-18 bottles
(we do it yearly)

Check the SUV results on the workstationsd using the different available tools



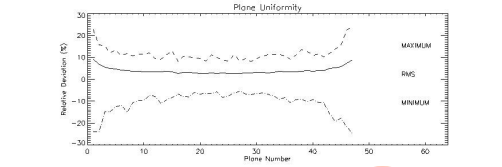
LEO2			
min	max	averg	
1.17	1.26	**1.21**	tool "elissoide"
0.60	0.68	**0.64**	
1.17	1.26	**1.21**	tool "3D isocontour"
0.61	0.68	**0.64**	
1.13	1.26	**1.20**	tool "multiframe polygon"
0.59	0.69	**0.64**	
1.16	1.28	**1.22**	tool "multiframe contour"
0.59	0.69	**0.64**	

LEO3			
min	max	averg	
1.13	1.26	**1.21**	tool "elissoide"
0.59	0.68	**0.64**	
1.15	1.26	**1.21**	tool "3D isocontour"
0.59	0.67	**0.64**	
1.17	1.29	**1.22**	tool "multiframe polygon"
0.59	0.69	**0.64**	
1.16	1.29	**1.22**	tool "multiframe contour"
0.59	0.69	**0.64**	

ESOFT			
min	max	averg	
1.13	1.26	**1.20**	tool "elissoide"
0.59	0.67	**0.64**	
1.20	1.26	**1.22**	tool "3D isocontour"
0.59	0.66	**0.65**	
1.17	1.30	**1.22**	tool "multiframe polygon"
0.59	0.68	**0.64**	
1.18	1.28	**1.22**	tool "multiframe contour"
0.60	0.69	**0.65**	

PET calibration and QC procedures

Uniformity test : with Ge-68 phantom (we do it every 3 months)



Uniformity Test Results
Scanner Model 1024
Thu Jan 04 10:46:07 2007
C:\SERVICE\uniformity.s.hdr
Corrections Applied :
tometric-arc-corr scatter-correction-OK scatter-correction-OK direct-ACF-multiply

SUMMARY OF PERFORMANCE RESULTS
Measured Volume RMS Variation : 4.5 %
Measured System RMS Variation : 1.9 %
Minimum Volume Relative Deviation : -29.2 %
Maximum Volume Relative Deviation : 19.3 %
Minimum System Relative Deviation : -6.8 %
Maximum System Relative Deviation : 2.6 %

PLANE-BY-PLANE PERFORMANCE RESULTS

Plane Index	Minimum Relative Deviation	Maximum Relative Deviation	Relative Standard Deviation	Plane Index	Minimum Relative Deviation	Maximum Relative Deviation	Relative Standard Deviation
1	-24.1	22.656	9.1	25	-7.6	8.4	2.7
2	-24.0	15.749	6.8	26	-8.1	11.2	2.6
3	-14.8	15.235	5.5	27	-5.6	8.3	2.5
4	-15.0	12.103	5.0	28	-6.7	9.5	2.8
5	-12.6	13.326	4.8	29	-7.1	8.2	3.0
6	-11.7	10.645	4.1	30	-6.5	9.3	3.0
7	-15.2	11.802	4.0	31	-6.4	10.4	3.0
8	-10.7	10.673	3.7	32	-8.7	11.3	3.0
9	-9.5	11.394	3.6	33	-7.7	11.3	3.2
10	-9.6	11.395	3.5	34	-9.1	11.3	3.5
11	-7.3	12.085	3.5	35	-8.2	10.7	3.5
12	-7.9	9.371	3.4	36	-10.7	9.2	3.5
13	-11.3	9.249	3.3	37	-9.3	11.0	3.5
14	-8.4	11.295	3.5	38	-9.2	13.6	3.7
15	-8.4	13.173	3.3	39	-10.1	12.6	3.9
16	-6.7	8.189	2.7	40	-9.4	10.9	3.8
17	-7.7	10.535	3.1	41	-10.7	11.6	3.9
18	-8.2	10.086	3.1	42	-10.6	10.1	4.0
19	-6.1	9.639	3.0	43	-15.6	11.8	4.8
20	-6.7	9.463	2.7	44	-19.4	13.8	5.2
21	-6.5	8.232	2.7	45	-17.6	15.3	5.8
22	-6.6	11.268	2.9	46	-21.7	22.5	7.4
23	-5.8	9.970	2.6	47	-25.0	23.9	8.9
24	-8.3	8.791	2.8				

SUMMARY OF PERFORMANCE RESULTS
Measured Volume RMS Variation : 4,5 %
Measured System RMS Variation : 1,9 %
Minimum Volume Relative Deviation : -29,2 %
Maximum Volume Relative Deviation : 19,3 %
Minimum System Relative Deviation : -6,8 %
Maximum System Relative Deviation : 2,6 %

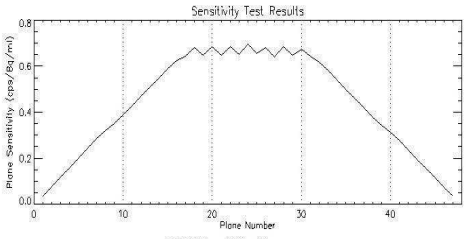
Uniformity Specification (from CPS/Siemens standards):

The measured volume RMS variation will be < 10%

NEMA : $NU_{vol} < 15\%$

PET calibration and QC procedures

Sensitvity test : with Ge-68 phantom (we do it every 3 months)



C:\SERVICE\sensitivity.s.hdr
Thu Jan 04 09:59:11 2007

INPUT
Branching Fraction : 0.8910
Assayed Activity : 8.251e+007 Bq
Assay Time : 11:00:00 29:11:2006
Scan Start Time : 08:44:02 04:01:2007
Scan Duration : 900.00000 sec
Average Activity : 7.526e+007 Bq
Phantom Volume : 6189.00 ml
Average Specific Activity : 1.216e-004 Bq/ml
Mean Dead Time Correction Factor : 1.09081
Average Scatter Fraction : 0.337
Maximum Ring Difference : 17
Span : 7

SUMMARY OF PERFORMANCE RESULTS
Measured Total System Sensitivity : 2.055e+001 cps/Bq/ml
: 2.055e+007 cps/MBq/ml
: 7.605e+005 cps/uCi/ml

Measured Average Plane Sensitivity : 4.373e-001 cps/Bq/ml
STD : 2.173e-001 cps/Bq/ml
Relative STD : 4.969e+001%

Sensitivity Unadjusted for Scatter : 1.262e+006 cps/uCi/ml

Sensitivity Specification (from CPS/Siemens standards):

The measured system sensitivity will be

> 725000 counts/sec/µCi/ml

NEMA : $S_{meas} > 95\% S_{ref}$

CT calibration and QC procedures

Daily :

- X-ray tube check-up and calibration

Every 3 months :

- Noise, constancy and uniformity of CT numbers
- CT numbers linearity, contrast scale
- High and low contrast spatial resolution
- Slice thickness
- Table accuracy movement
- Laser alignement

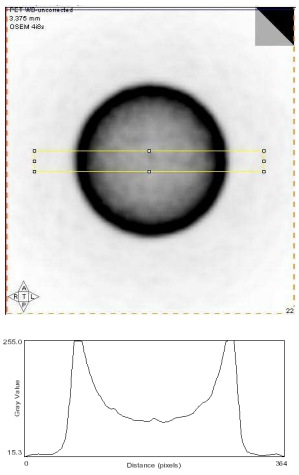
Every 6 months :

- Dose (in head and body CT phantoms)

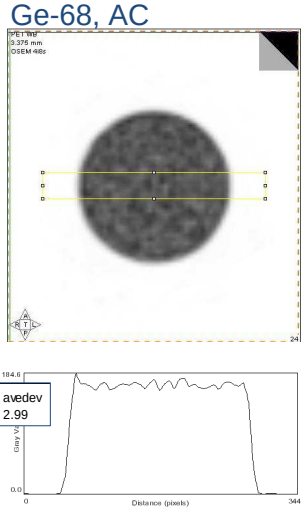
CT-PET calibration and QC procedures

Yearly : attenuation correction check

Ge-68, no AC



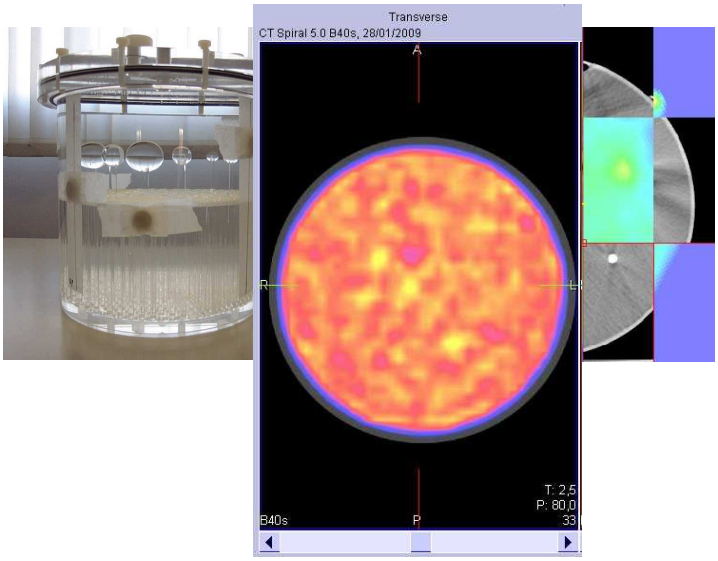
Ge-68, AC



S.D.	average	avedev
5.00	167.47	2.99

CT-PET calibration and QC procedures

Yearly : CT-PET co-registration check



PET/CT UDINE SCAN PROTOCOL