IAEA Post Graduate Educational Course on Radiation Protection and Safety of Radiation Sources
Greek Atomic Energy Commission, Athens 2003

Justification and Optimization in Nuclear Medicine (Radiation Protection of the patient)



P. Dimitriou

OBJECTIVE

To be able to apply the principles of radiation protection including operational considerations, calibration, and quality control for diagnostic procedures using these major equipment: Activity meter, monitoring equipment, probes, scanners, gamma cameras, SPECT-system including coincidence option, and PET.

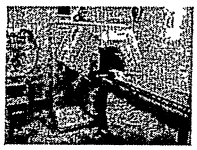


Content

- Activity meter and calibration of sources
- Probes and counters
- Equipment for morphological and functional studies
  - Scanner
  - Gammacamera
  - PET
- Clinical dosimetry

Optimization (BSS II.17)

(b) (iii) appropriate image acquisition and processing;



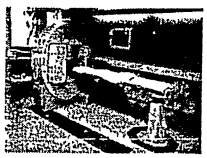
QUALITY ASSURANCE (BSS)

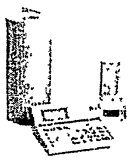
II.23. Quality assurance programmes för medical exposures shall include:

(a) Measurements of the radiation generators, imaging devices and irradiation installations at the time of commissioning and periodically thereafter.

OPTIMIZED USE OF EQUIPMENT

- Well trained staff with access to relevant manuals
- Quality control programme
- Regular maintenance





IAEA Training Course on Radiation Protection in Nuclear Medicine

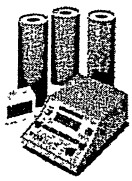
Part 7
Optimization of Protection in Medical Exposure

Module 7.1. Activity meter and calibration of sources

ACTIVITY METER DOSE CALIBRATOR



CRC-15W
Item # 6130-3113



CRC®- 712M
Dose Calibrator
Item # 5130 - 3054

Nuclear Medicine Part 7 Medical Exposure Diagnostic Procedures 6

CALIBRATION OF SOURCES BSS II.19

Registrants and licensees shall ensure that:

(a) the calibration of sources used for medical exposure be traceable to a Standards dosimetry laboratory

(d) unsealed sources for nuclear medicine procedures be calibrated in terms of activity of the radio-pharmaceutical to be administered, the activity being determined and recorded at the time of administration;

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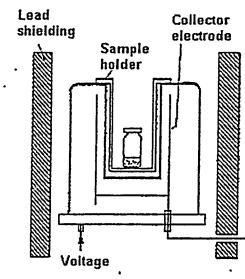
Activity meter



Well-shaped ionization chamber filled with a gas of high atomic number (e.g. Xenon) and kept under pressure

Electrometer — Display

Radionuclide selector

Proportionality between the number of photons emitted and the ionization current

Nuclear Medicine Part 7 Medical Exposure Diagnostic Procedures 10 SC97

Activity meter

The response of the detector will depend on:

- Radionuclide (energy and abundance of photons).
- Geometry of the detector.
- Geometry of the source.
- The condition of the instrument (QC).

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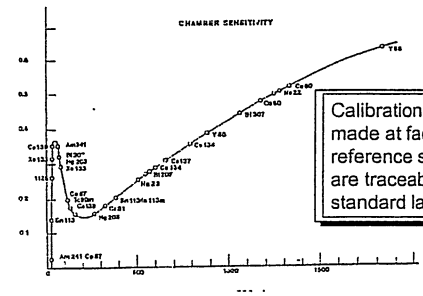
Activity meter



Calibration should be made at factory using reference sources that are traceable to a standard laboratory

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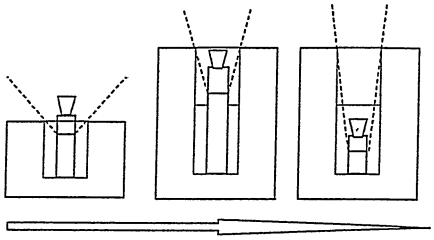
ACTIVITY MEASUREMENT

Setting	Measured activity
Tc-99m	1.00
Co-57	1.19
In-111	2.35
Tl-201	1.76
Ga-67	1.12
I-123	2.19
I-131	1.43

Measured activity/True activity of Tc.99m if the indicated settings are used

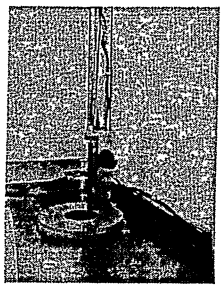
Geometric efficiency

The quotient: number of photons reaching the detector over the number of photons emitted from the sample



Increasing geometric efficiency

SAMPLE HOLDER
(reproducible geometry)



Activity meter

Operational considerations

Radionuclide settings
Background
Reproducibility

QUALITY CONTROL OF ACTIVITY METER
(what should be done and who should do it)

	Acceptance	Daily	Monthly	Yearly
High voltage/display	P	T	T	P
Zero adjust	P	T	T	P
Background	P	T	T	P
Accuracy	P			P
Precision	P		T	P
Relative responses	P		T	P
Subsidiary calibrations	P			
Linearity	P			P
Electrical safety	P			P
Leakage radiation	P			P

P: physicist
T: technician

The accuracy should be +/- 5%
Traceability to a national standard.
Interlaboratory comparisons.

Sealed sources for calibration of activity meters

- Long half-life
- Range of photon energies
- Range of activities
- Calibrated within 5%



Co57, Ba133, Cs137, Co60

Sealed sources for calibration of activity meters

Radionuclide	Photon energy (keV)	Half-life	Activity (MBq)
Co-57	122	271 d	185
Ba-133	81, 356	10.7 y	9.3
Cs-137	662	30 y	7.4
Co-60	1173, 1332	5.27 y	1.9

Measurement of precision and accuracy

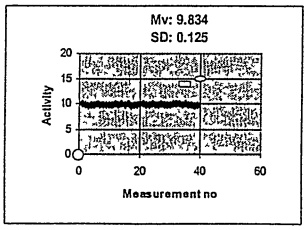
Source (sealed): Cs-137 or Co-57

Procedure: Select settings for the radionuclide and adjust background. Insert source in holder and make 10 measurements.

Data analysis: To assess *precision*, calculate for each source (i) the percentage difference between the measured activity A_i and their mean A_{mv}. (+/-5%)
To assess *accuracy*, calculate the percentage difference between the mean activity and the certified activity. (+/- 10%).

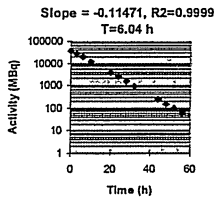
Measurement of reproducibility

Measure the activity of a sealed reference source e.g. every morning. Use Tc-99m settings.



Measurement of linearity

Use a radionuclide with short half-life e.g. Tc-99m
Make repeated measurements during several half-lives.



Measurement of linearity

Graded source method

Pipette into a series of sample vials by means of the remote pipetting device decreasing volumes of the radionuclide solution, with activities covering the range of interest (e.g. 10, 5, 2, 1, 0.5, .2, 0.1 ml of a solution having an activity about 370 MBq/ml). Bring up the total volume in each vial to constant volume (e.g. 20 ml). Measure and record the activity.

Attenuators

Use a set of lead attenuators calibrated to to reduce the photon fluence from Tc-99m in a known way and hence simulating different activities. Measure and record the activity.

$A=A_0 \exp(-\mu d)$

IAEA Training Course on Radiation Protection in Nuclear Medicine

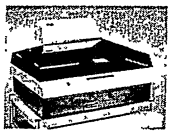
Part 7
Optimization of Protection in Medical Exposure

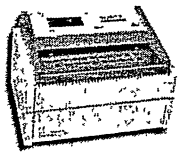


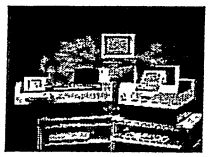
Module 7.2. Sample counters and probes

Sample counters

Gamma counter
Liquid scintillation counter



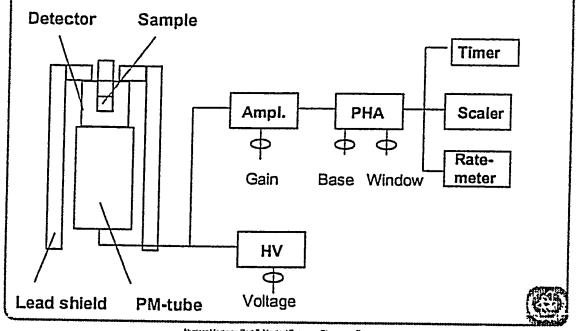




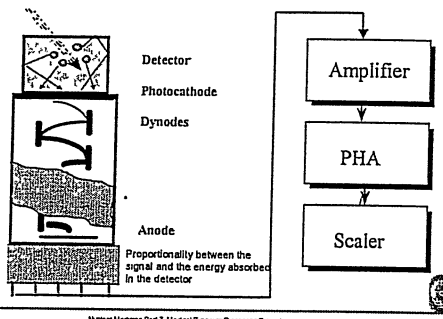
Examples of use of sample counters

RIA	^{125}I
Kidney clearance	^{51}Cr
Vitamin B12 deficiency	^{57}Co, ^{58}Co
Ferrokinetic studies	^{59}Fe
Total body water	^{3}H
Blood volume	^{125}I, ^{51}Cr, ^{99m}Tc
Biomedical reasearch	^{3}H, ^{14}C

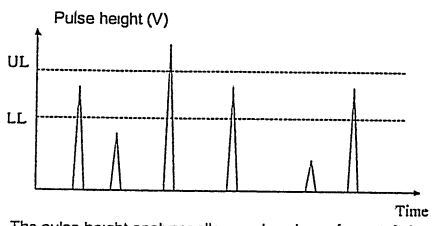
Gamma counter



Scintillation detector



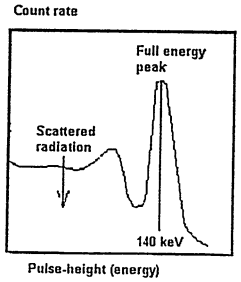
Pulse height analyzer



The pulse height analyzer allows only pulses of a certain height (energy) to be counted.

○ counted ○ not counted

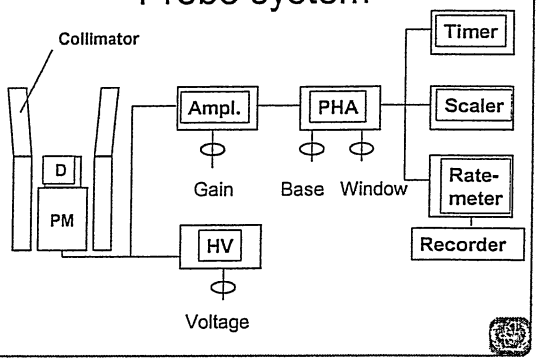
Pulse-height distribution
NaI(Tl)



PROBE SYSTEM

- Thyroid uptake measurements
- Radionuclide angiography
- Renography

Probe system



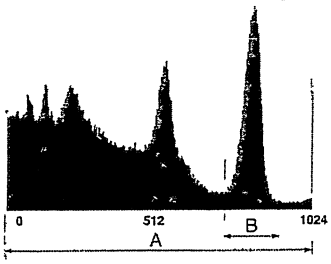
GAMMACOUNTER PROBE

Operational considerations

- Window setting
- Geometry
- Reproducibility
- Count losses
- Background



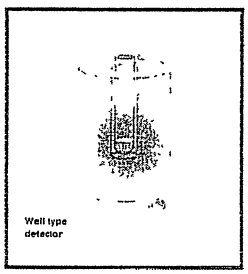
Window setting

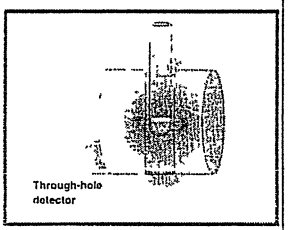


Energy window setting depends on the energy resolution of the detector and the photon energies

Gamma counter

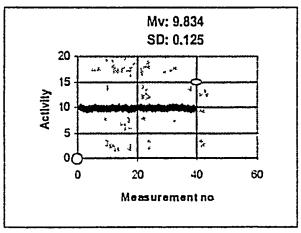
Different design of the detector





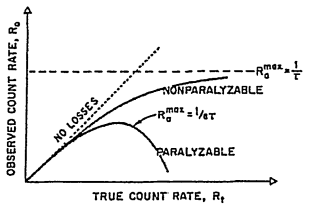
REPRODUCIBILITY

Measure the activity of a reference source
e.g. every morning or every week. Use window settings corresponding to the radionuclide

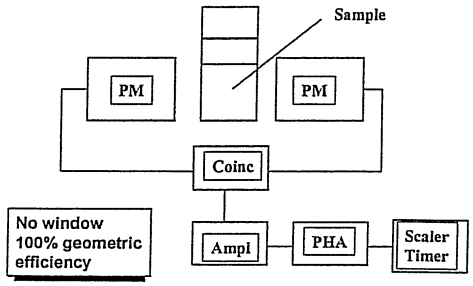


COUNT LOSSES
(LINEARITY OF ACTIVITY RESPONSE)

- Decaying source method
- Graded source method



Liquid scintillation counter



Liquid scintillation counter

Operational considerations

- Counting efficiency
- Quenching
- Sample preparation
- Window setting
- Reproducibility
- Background

QUALITY CONTROL

- Scaler/timer/ratemeter function
- Energy calibration
- Energy resolution
- Preset analyser facilities
- Sensitivity, counting efficiency
- Counting precision
- Count rate losses
- Linearity of energy response
- Background
- Linearity of activity response
- Geometrical response
- Quench correction methods (LSC)

IAEA-TECDOC-602

Quality control of Nuclear medicine instruments 1991

INTERNATIONAL ATOMIC ENERGY AGENCY IAEA

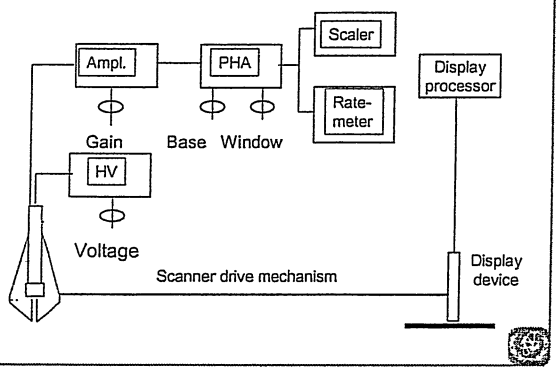
May 1991

IAEA Training Course on Radiation Protection in Nuclear Medicine

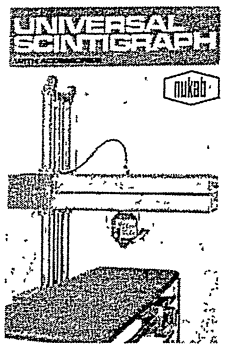
Part 7
Optimization of Protection in Medical Exposure

Module 7.3. Equipment for morphological and functional studies

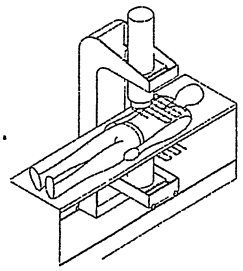
RECTILINEAR SCANNER



RECTILINEAR SCANNER

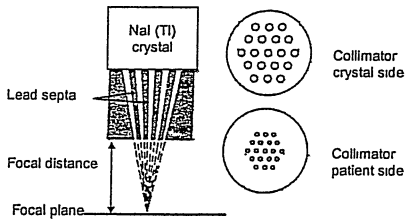


Used to measure the spatial distribution of a radiopharmaceutical

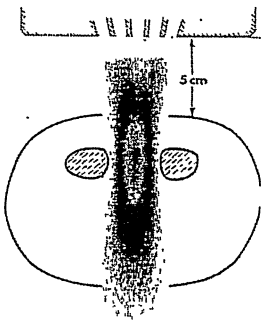


Rollo 1977

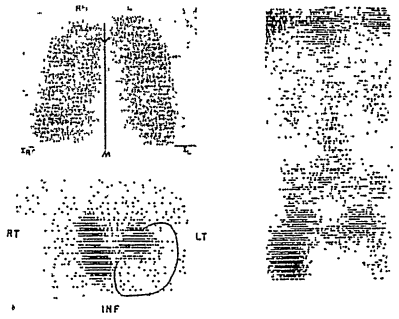
COLLIMATOR



COLLIMATOR



SCANNER IMAGES



SCANNER

Operational considerations:

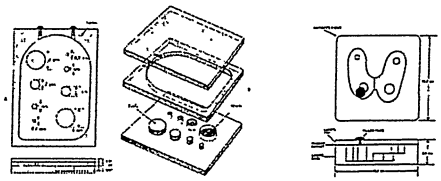
- Scanning speed (optimum count density)
- Collimator
- Collimator mounting
- Tapper function
- Window setting
- Background

SCANNER QUALITY CONTROL

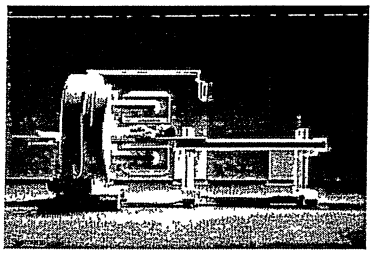
	Acceptance	Daily	Weekly	Yearly
Energy window	P	T	T	P
Energy resolution	P			P
Sensitivity	P		T	P
Counting precision	P			P
Linearity of energy response	P			P
Test of integral background	P		T	P
Test of preset analyzer facilities	P			P
System linearity	P		T	P
Background subtraction	P			P
Contrast enhancement	P			P
Scanner drive	P			P
Total performance	P		T	P

P: physicist T:technician

TOTAL PERFORMANCE PHANTOM

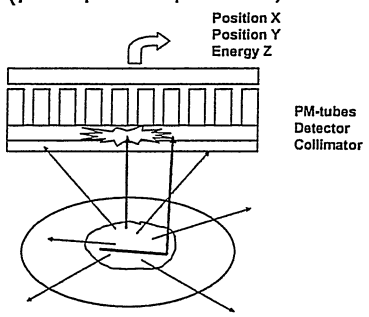


Gamma camera

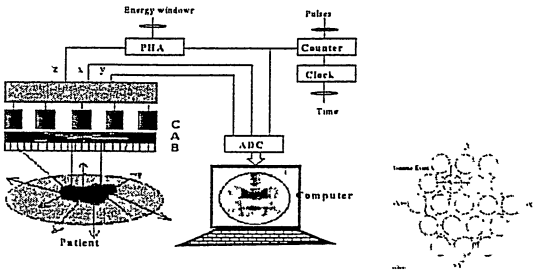


Used to measure the spatial and temporal distribution of a radiopharmaceutical

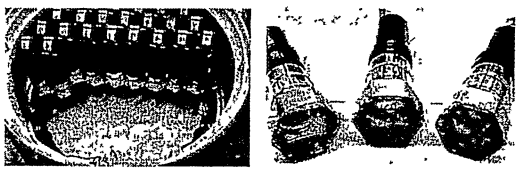
Gamma camera (principle of operation)



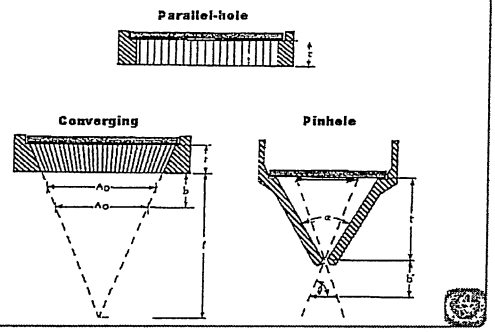
GAMMA CAMERA



PM-tubes

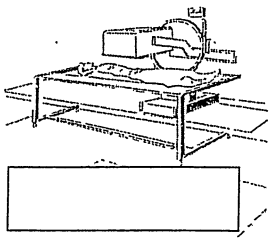


Gammacamera collimators

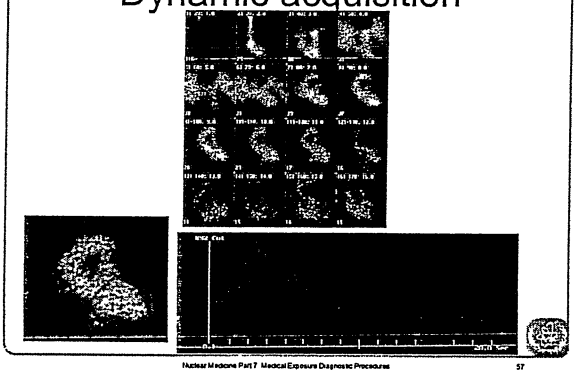


Gammacamera Data acquisition

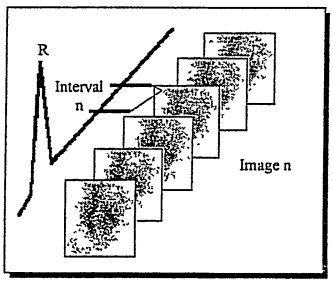
- Static
- Dynamic
- ECG-gated
- Wholebody scanning
- Tomography
- ECG-gated tomography
- Wholebody tomography



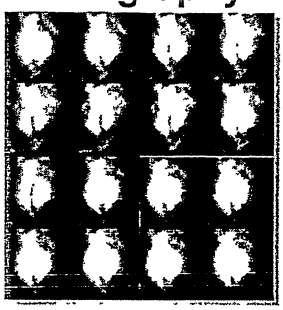
Dynamic acquisition



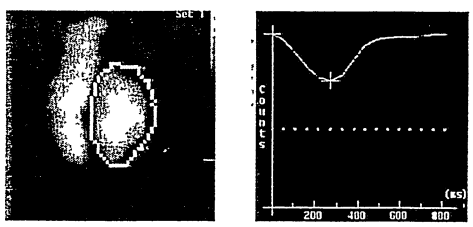
ECG-gated acquisition



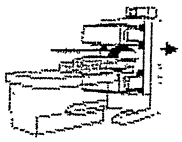
ECG-gated bloodpool scintigraphy

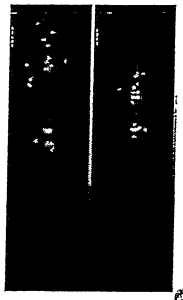


Left ventricle time-activity curve

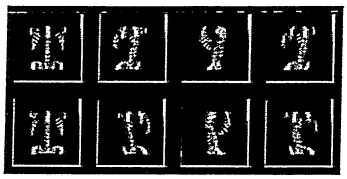


Whole body scanning

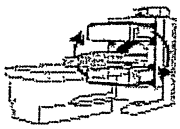




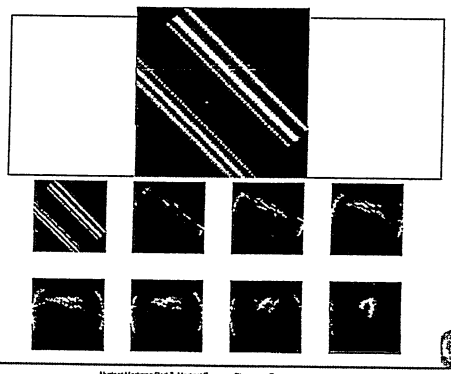
Tomographic acquisition



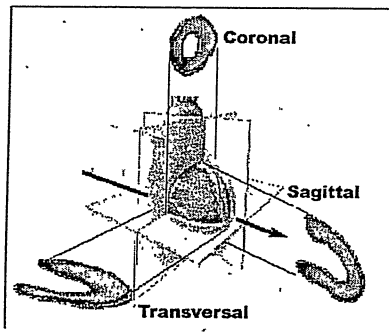




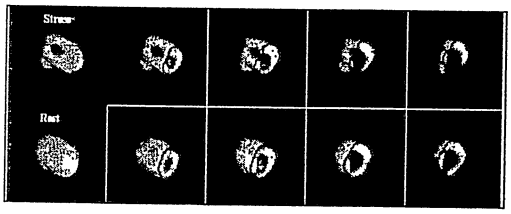
Tomographic reconstruction



Tomographic planes

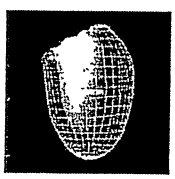


Myocardial scintigrafi



ECG GATED TOMOGRAPHY

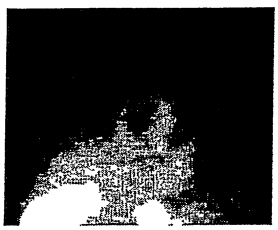




Factors affecting image formation

- Distribution of radiopharmaceutical
- Collimator selection and sensitivity
- Spatial resolution
- Energy resolution
- Uniformity
- Count rate performance
- Spatial positioning at different energies
- Center of rotation
- Scattered radiation
- Attenuation
- Noise

Distribution of radiopharmaceutical



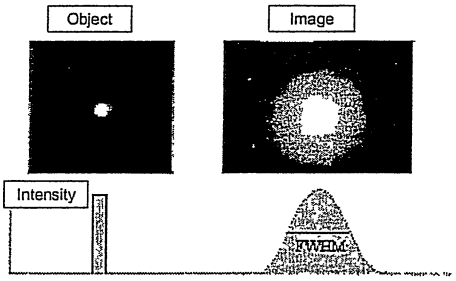
SPATIAL RESOLUTION

Sum of intrinsic resolution and the collimator resolution

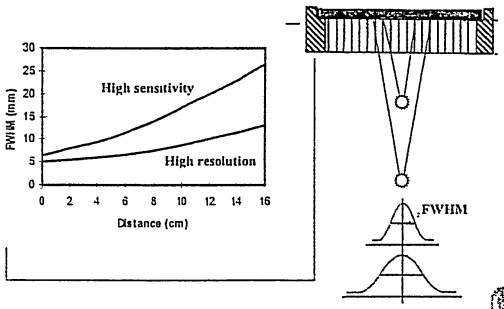
Intrinsic resolution depends on the positioning of the scintillation events (detector thickness, number of PM-tubes, photon energy)

Collimator resolution depends on the collimator geometry (size, shape and length of the holes)

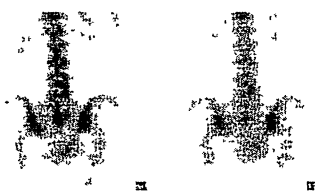
SPATIAL RESOLUTION



Resolution - distance

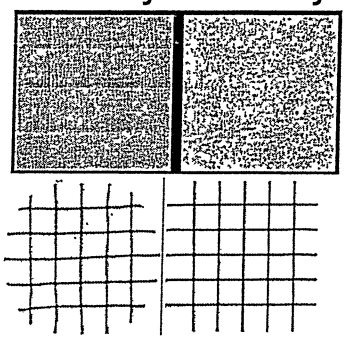


SPATIAL RESOLUTION - DISTANCE

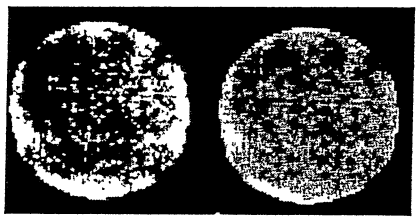


Optimal Large distance

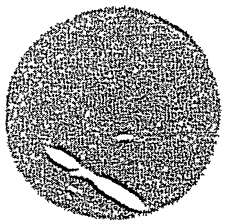
Uniformity & Linearity



NON UNIFORMITY

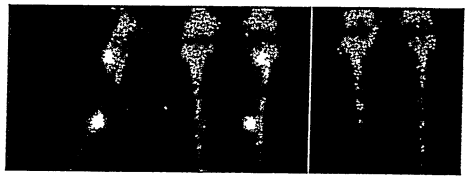


NON UNIFORMITY



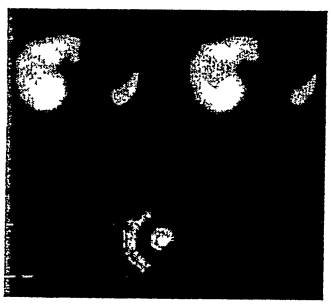
Cracked crystal

NON-UNIFORMITY

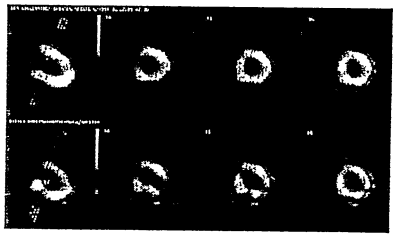


(Contamination of collimator)

NON UNIFORMITY
RING ARTIFACTS

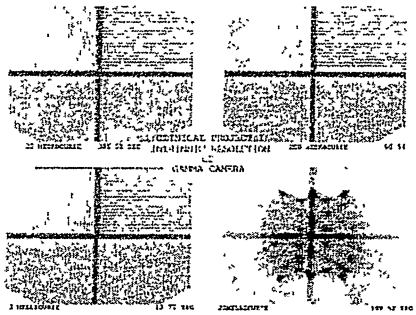


NON-UNIFORMITY



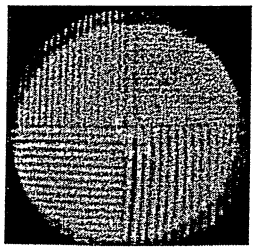
Defect collimator

COUNT RATE PERFORMANCE



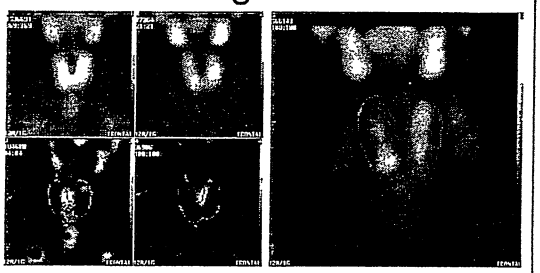
(IAEA QC Atlas)

Spatial positioning at different energies

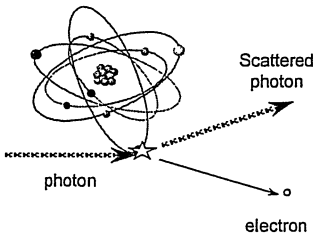


Intrinsic spatial resolution with Ga-67 point source (count rate < 20k cps); quadrant bar pattern; 3M counts; preset energy window widths; summed image from energy windows set over the 93 keV, 183 keV and 296 keV photopeaks.
(IAEA QC Atlas)

Spatial positioning at different energies



Scattered radiation

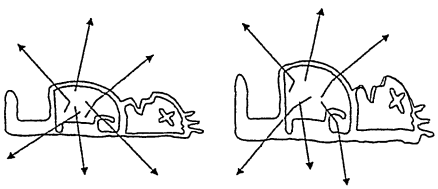


The amount of scattered photons registered

Patient size
Energy resolution of the gammacamera
Window setting

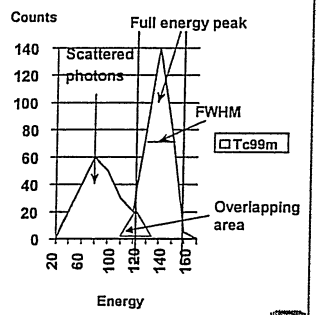


PATIENT SIZE

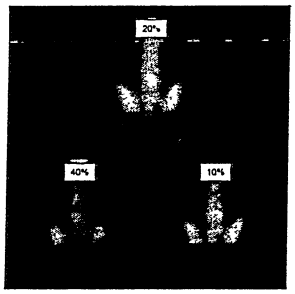


Pulse height distribution

The width of the full energy peak (FWHM) is determined by the energy resolution of the gamma camera. There will be an overlap between the scattered photon distribution and the full energy peak, meaning that some scattered photons will be registered.

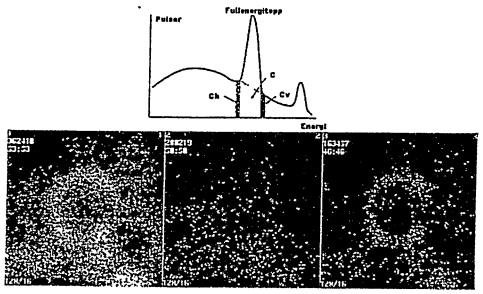


Window width

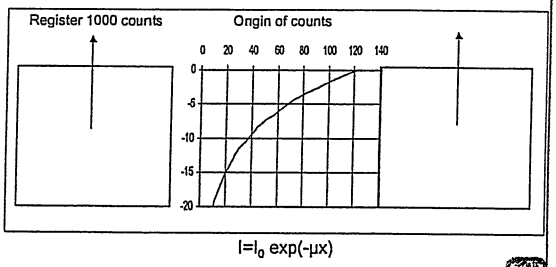


Increased window width will result in an increased number of registered scattered photons and hence a decrease in contrast

SCATTER CORRECTION



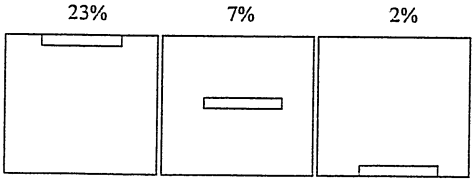
ATTENUATION



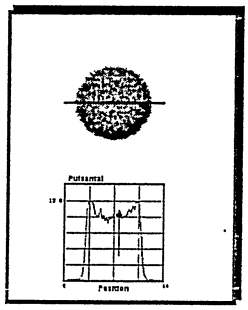
$I = I_0 \exp(-\mu x)$

ATTENUATION

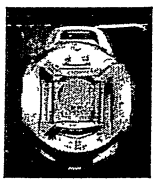
Contrast (2cm object)

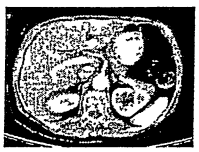


ATTENUATION CORRECTION



ATTENUATION CORRECTION





Transmission measurements
- Sealed source
- CT

NOISE



Count density

Gammacamera

Operational considerations

- **Collimator selection**
- **Collimator mounting**
- **Distance collimator-patient**
- **Uniformity**
- **Energy window setting**
- **Corrections (attenuation, scatter)**
- **Background**
- **Recording system**
- **Type of examination**

QC GAMMACAMERA

	Acceptance	Daily	Weekly	Yearly
Uniformity	P	T	T	P
Uniformity, tomography	P			P
Spectrum display	P	T	T	P
Energy resolution	P			P
Sensitivity	P		T	P
Pixel size	P		T	P
Center of rotation	P		T	P
Linearity	P			P
Resolution	P			P
Count losses	P			P
Multiple window pos	P			P
Total performance phantom	P			P

P: physicist T:technician

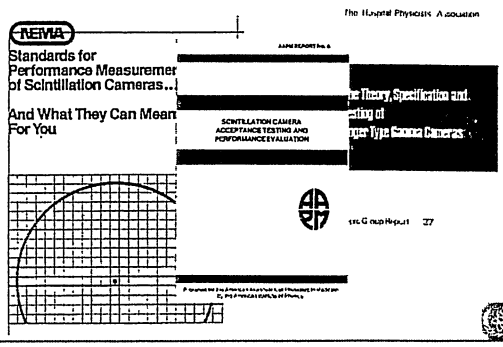
IAEA-TECDOC-602

Quality control of Nuclear medicine instruments 1991

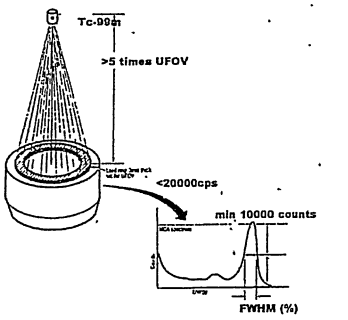
INTERNATIONAL ATOMIC ENERGY AGENCY IAEA

May 1991

QC Gamma camera



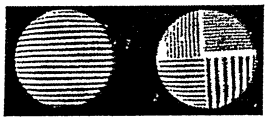
Energy resolution



Nuclear Medicine Part 7 Medical Exposure Diagnostic Procedures 97

Linearity

Flood source or point source (Tc-99m)
Bar phantom or orthogonal-hole phantom



1. Subjective evaluation of the image.
2. Calculate absolute (AL) and differential (DL) linearity.

AL: Maximum displacement from ideal grid (mm)
DL: Standard deviation of displacements (mm)

Nuclear Medicine Part 7 Medical Exposure Diagnostic Procedures 98

UNIFORMITY

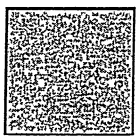
Flood source (Tc-99m, Co-57)
Point source (Tc-99m)

Intrinsic uniformity: Point source at a large distance from the detector. Acquire an image of 10.000.000 counts.

With collimator: Flood source on the collimator. Acquire an image of 10.000.000 counts.

Nuclear Medicine Part 7 Medical Exposure Diagnostic Procedures 99

Uniformity



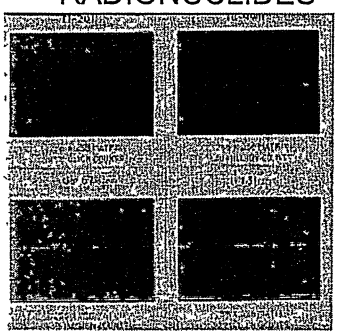
1. Subjective evaluation of the image
2. Calculate
   - Integral uniformity (IU)
   - Differential uniformity (DU)

IU=(Max-Min)/Max+Min)*100, where Max is the the maximum and Min is the minimum counts in a pixel.

DU=(Hi-Low)/(Hi+Low)*100, where Hi is the highest and Low is the lowest pixel value in a row of 5 pixels moving over the field of view.
Matrix size 64x64 or 128x128

Nuclear Medicine Part 7 Medical Exposure Diagnostic Procedures 100

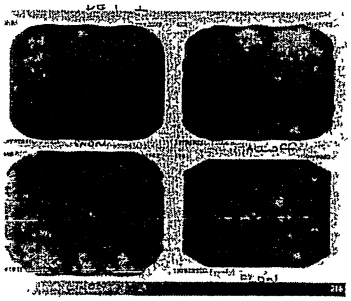
UNIFORMITY/DIFFERENT RADIONUCLIDES



D BOULFELFEL
Dubai Hospital

Nuclear Medicine Part 7 Medical Exposure Diagnostic Procedures 101

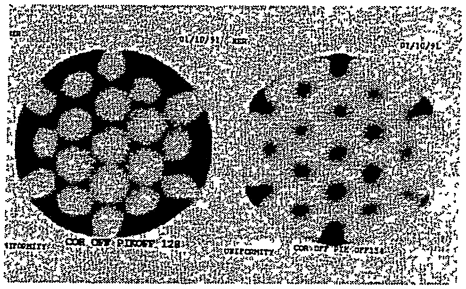
LINEARITY AND UNIFORMITY CORRECTIONS



Dogan Bor, Ankara

Nuclear Medicine Part 7 Medical Exposure Diagnostic Procedures 102

OFF PEAK MEASUREMENTS



Dogan Bor, Ankara

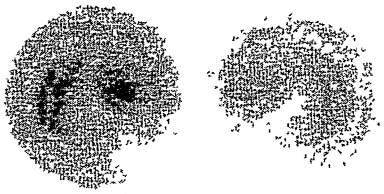
TOMOGRAPHIC UNIFORMITY



Tomographic uniformity is the uniformity of the reconstruction of a slice through a uniform distribution of activity.

SPECT phantom with 200-400 MBq Tc99m aligned with the axis of rotation. Acquire 250k counts per angle. Reconstruct the data with a ramp filter.

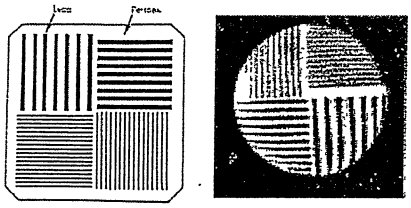
INCORRECT MEASUREMENT



Two images of a flood source filled with a solution of Tc-99m, which had not been mixed properly

Spatial resolution

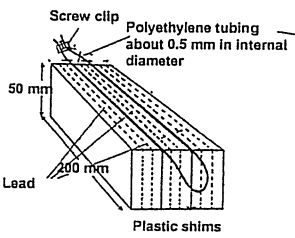
Flood source or point source.
Bar phantom



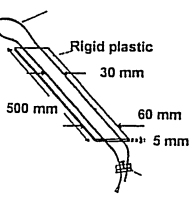
Subjective evaluation of the image

SPATIAL RESOLUTION

Intrinsic resolution



System resolution

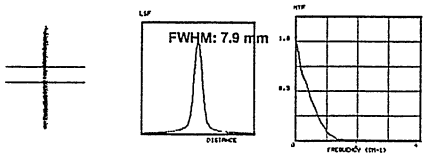


IAEA TECDOC 602

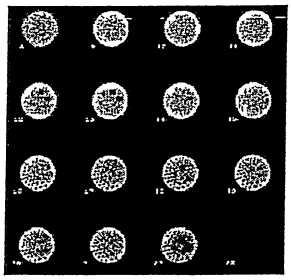
SPATIAL RESOLUTION

Tc-99m or other radionuclide in use
Intrinsic: Collimated line source on the detector
System: Line source at a certain distance

Calculate FWHM of the line spread function



TOMOGRAPHIC RESOLUTION



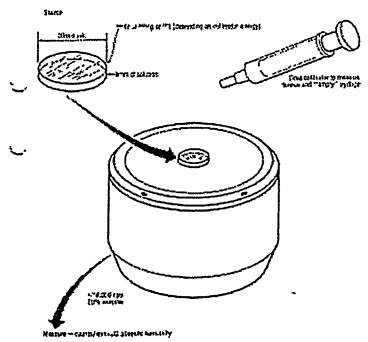
Measurements should be made with and without scatter.

1. Point or line source free in air
2. Point or line source in a SPECT phantom

Sensitivity

- Expressed as counts/min/MBq and should be measured for each collimator
- Important to observe with multi-head systems that variations among heads do not exceed 3%

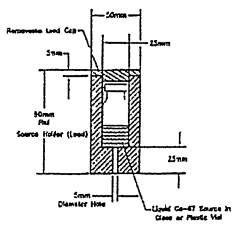
SENSITIVITY



Multiple Window Spatial Registration

- Performed to verify that contrast is satisfactory for imaging radionuclides, which emit photons of more than one energy (e.g. Tl-201, Ga-67, In-111, etc.) as well as in dual radionuclides studies

Multiple Window Spatial Registration

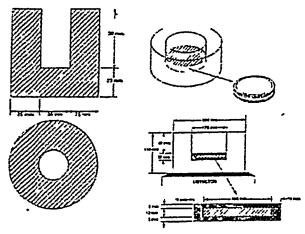


- Collimated Ga-67 sources are used at central point, four points on the X-axis and four points on the Y axis
- Perform acquisitions for the 93, 184 and 300 keV energy windows
- Displacement of count centroids from each peak is computed and maximum is retained as MWSR in mm

Count Rate Performance

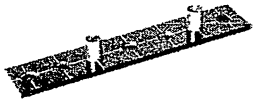
- Performed to ensure that the time to process an event is sufficient to maintain spatial resolution and uniformity in clinical images acquired at high-count rates

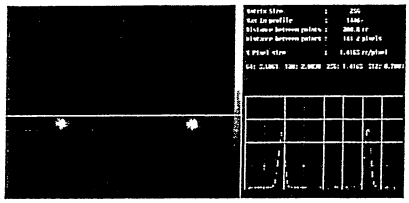
Count Rate Performance



- Use of decaying source or calibrated copper sheets to compute the observed count rate for a 20% count loss and the maximum count rate without scatter

Pixel size





Center of rotation

Point source of Tc-99m or Co-57
Make a tomographic acquisition

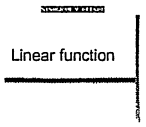
In x-direction the position will describe a sinus-function. In y-direction a straight line.

Calculate the offset from a fitted cosine and linear function at each angle.

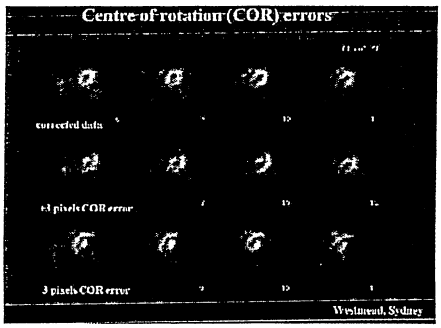
Cosine function



Linear function

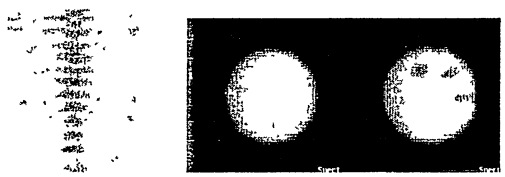


CENTER OF ROTATION

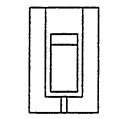


Total performance

Total performance phantom. Emission or transmission.
Compare result with reference image.



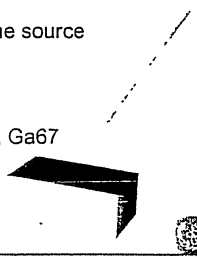
SOURCES FOR QC OF GAMMA-CAMERAS





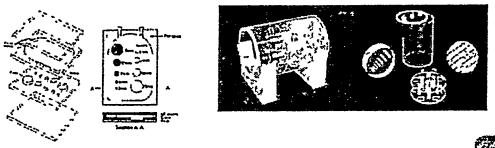
- Point source
- Collimated line source
- Line source
- Flood source

Tc99m, Co57, Ga67

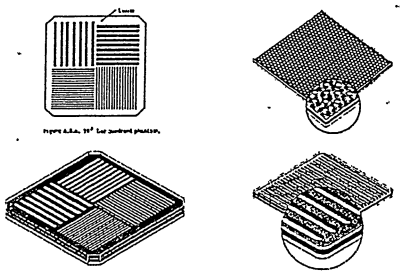


Phantoms for QC of gamma-cameras

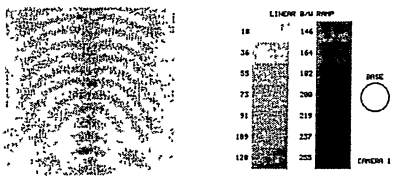
- Bar phantom
- Slit phantom
- Orthogonal hole phantom
- Total performance phantom



Phantoms for QC of gamma-cameras

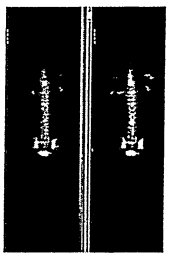


QUALITY CONTROL ANALOGUE IMAGES



Quality control of film processing: base & fog, sensitivity, contrast.

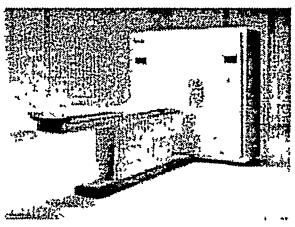
QUALITY ASSURANCE COMPUTER EVALUATION



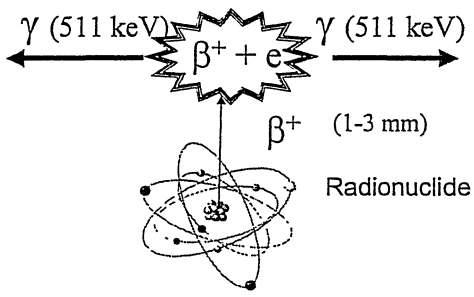
Efficient use of computers can increase the sensitivity and specificity of an examination.

* software based on published and clinically tested methods
* well documented algorithms
* user manuals
* training
* software phantoms

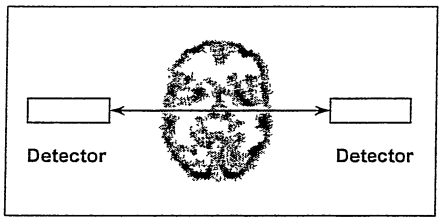
PET
Positron Emission Tomography



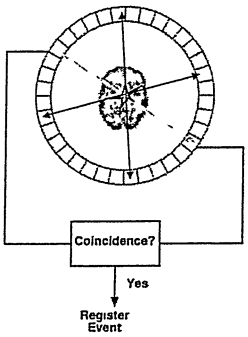
ANNIHILATION



PET-scanner principle

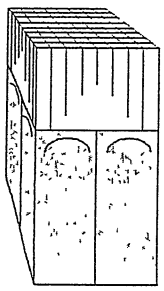


PET-SCANNER

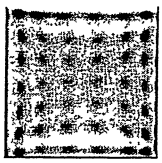


M Dahlbom, UCLA

PET DETECTORS



A large number of scintillation crystals are coupled to a smaller number of PM-tubes. In the block detector, a matrix of cuts are made to define the detector elements. The light produced in each crystal will produce a unique combination of signals, which will allow the detector to be identified.



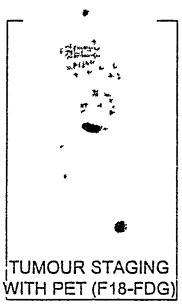
Flood response for a block detector

M Dahlbom, UCLA

Radionuclides

Radionuclide	*Halftime*	*Particle energy (mean)*
C-11	20.4 min	0.39 MeV
N-13	10 min	0.50 MeV
O-15	2.2 min	0.72 MeV
F-18	110 min	0.25 MeV
Cu-62	9.2 min	1.3 MeV
Ga-68	68.3 min	0.83 MeV
Rb-82	1.25 min	1.5 MeV

CLINICAL USE



TUMOUR STAGING
WITH PET (F18-FDG)

FACTORS AFFECTING IMAGE FORMATION

- Detector efficiency
(the probability that the detector registers an event when a gamma ray path intersects the detector. Depends on detector size and material)
- System sensitivity
(the number of events registered by the scanner per unit activity. Depends on detector efficiency and system geometry)
- Time resolution
(the ability to accurately determine coincidence events.)
- Count-rate capability
(the ability of the scanner to record events a high count rates. Depends on detector material and the properties of the electronic components)
- Spatial resolution
(the ability to separate closely spaced objects. Depends on detector size, physics of positron decay, system geometry and detector material)

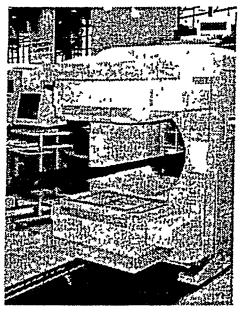
OPERATIONAL CONSIDERATIONS

- Calibration check
- Normalization
- Blank scan
- Scanner cross calibration

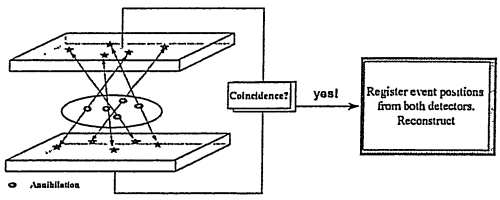
QUALITY CONTROL

- Calibration check
- Uniformity
- Spatial Resolution
- Scatter fraction
- Sensitivity
- Count rate losses and randoms
- Scanner cross calibration
- Drifts in coincidence timing
- Drifts in energy thresholds
- Mechanical movement of detector rings
- Removable septa positioning
- Laser alignment
- Attenuation correction accuracy
- Dead time correction accuracy
- Scatter correction accuracy
- Random coincidence correction accuracy

PET with gammacamera



Principle of operation

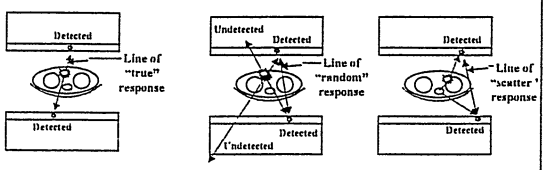


(Gerd Muehllehner et al 1994)

Types of Coincidence Events

"True" events result from coincidence between 2 photons from the same annihilation. Such events provide valid data.

"Random" and "Scatter" events represent invalid data. These events are recorded by the system as misplaced "trues", resulting in background noise that reduces image contrast and resolution.



Metabolic Image Information

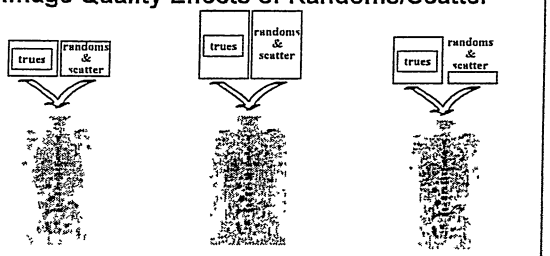
Background Noise

Siemens

Factors affecting image formation

- Random/scatter events
- Crystal thickness
- Dead time losses (fast electronic)

Image Quality Effects of Randoms/Scatter



Typical coincidence image* containing a high percentage of randoms and scatter

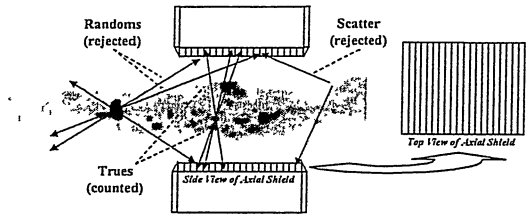
Same image with increased counts but no change in the ratio of trues to randoms & scatter

Same image with same number of counts but a positive change in the ratio of trues to randoms & scatter

Superior Image Quality is the result of superior Count Quality

Siemens

Contrast Enhancing Axial Shields



Primary Objective:
Reduce randoms and scatter originating from high activity organs outside the scan FOV (e.g. brain, heart, bladder)

Design Concept:
Specially designed lead strips equally spaced perpendicular to the axis of rotation. Similar to PET septa, but optimized for NaI coincidence

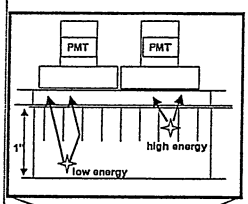
Clinical Benefit:
Higher image contrast for improved lesion detectability

Siemens

CRYSTAL THICKNESS

- The probability of photon interaction increases with the crystal thickness
- The spatial resolution decreases with the thickness of the crystal
- Can this be optimized?

StarBrite™



Tracks
- 12.5 mm deep
- 5940 squares à 7x7 mm
- Reduce light scattering in the crystal
- Reflect light towards the PM-tubes



StarBrite™ is a Registered Trademark of BICRON

The main problem to solve is to be able to manage the very high count rates, which cause problems such as:

- Dead time losses and pile up of pulses
- Many random coincidences
- Instable energy window

IAEA Training Course on Radiation Protection in Nuclear Medicine

Part 7
Optimization of Protection in Medical Exposure

Module 7.4. Clinical dosimetry

CLINICAL DOSIMETRY (BSS)

II.20. Registrants and licensees shall ensure that the following items be determined and documented:

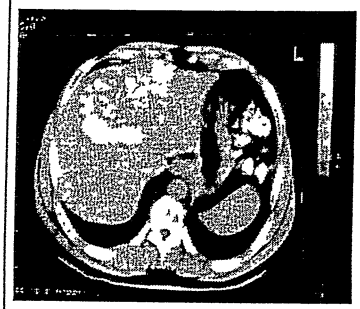
(d) In diagnosis or treatment with unsealed sources, representative absorbed doses to patients;

Conception of absorbed dose in NM

The calculation of the absorbed dose - a tricky problem, because of several factors:

- 1. the distribution of the radionuclide within the body and its uptake in certain critical organs
- 2. inhomogeneous distribution of the nuclide even within the critical organ
- 3. the biological half-life of the nuclide, which may vary with patients' ages and may be modified by disease or pathological conditions.

Treatment of Hepatocellular Carcinoma with ^{131}I-Lipiodol



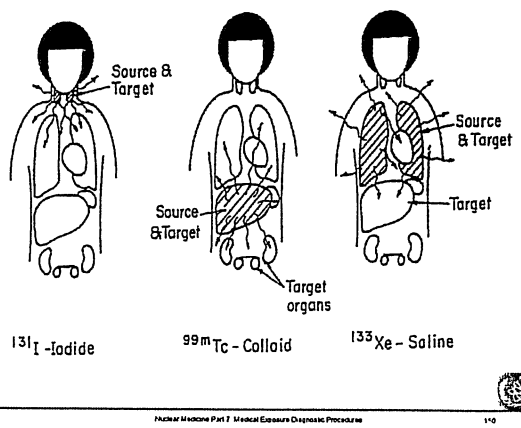
CT scan demonstrating non-homogenous distribution of Lipiodol. Tumour can not be treated as a homogenous sphere.

Absorbed dose to an organ is determined by:

- Radionuclide
- Activity administered
- Activity in the organ
- Size and shape of the organ
- Activity in other organs
- Kinetics of radiopharmaceutical
- Quality of radiopharmaceutical

The MIRD System of Internal Absorbed Dose Calculation

- MIRD - Medical Internal Radiation Dosimetry developed by the Society of Nuclear Medicine
- The organ containing the radionuclide is called the *source* organ
- We wish to calculate the absorbed dose to the *target* organ
- The source and target organs may be the same
- The amount of radiation from the source reaching the target must be known



Derivation of the General MIRD Equation

- Let E be the mean energy per particle (photon or electron)
- If n is the number of particles emitted per disintegration
- then nE is the mean energy emitted per disintegration

Mean energy per nuclear transition

Type i radiation

$$\Delta_i = K \cdot n_i \cdot E_i$$

Total energy/disintegration

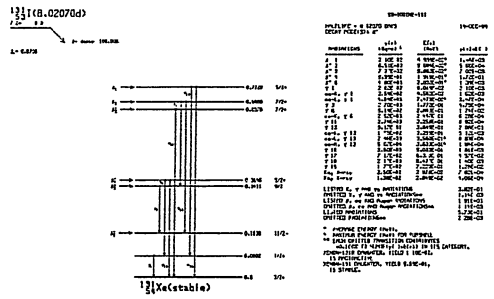
$$\Delta = \sum_i \Delta_i = K \sum_i n_i \cdot E_i$$

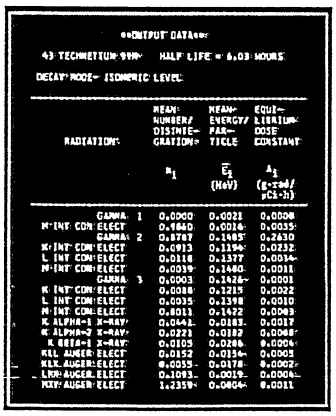
Emitted energy

Radionuclide	*MeV/disintegration*	
	particles	*photons*
Ga-67	0.0047	0.016
Se-75	0.0143	0.391
Tc-99m	0.0149	0.127
In-111	0.0030	0.405
I-123	0.0236	0.172
I-125	0.0045	0.042
I-131	0.1910	0.382
Tl-201	0.0303	0.093

Decay data

http://iaeand.iaea.or.at/formmird.html





^{99m}Tc

Required information for dosimetry calculations

Absorbed Dose

- Energy absorbed in a material per unit mass
- has unit of the gray (1 Gy = 1 J/kg)

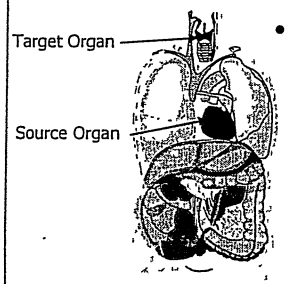
Absorbed Dose in the Target Organ

The absorbed dose will be equal to the total amount of energy that is emitted by the source organ X the fraction of that energy that is absorbed in the target organ
divided by the mass of the target organ

Absorbed Fraction

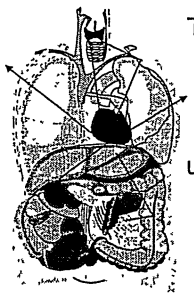
- The absorbed fraction, Φ, is the fraction of the energy emitted by the source organ that is absorbed in the target

Absorbed Fraction



- Depends on
  - the size of the source organ
  - the size of the target organ
  - the relative positions in the body of these organs
  - the energy of the photons
  - the attenuation properties of the tissues between the source and target organs

Determination of the Absorbed Fraction



The only method available is

CALCULATION

using Monte Carlo modelling

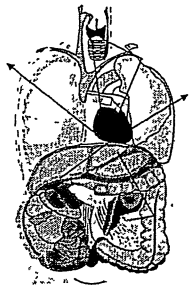
What is Monte Carlo Modelling?

- Essentially a ray tracing method, in which the fates of individual particles are determined
- The method is based on randomly sampling a probability distribution for each successive interaction
- Typically, the history of 10 million photons will be modeled

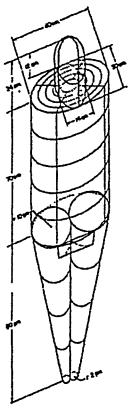
Monte Carlo Modelling

- Requires detailed knowledge of the absorption and scattering coefficients for the specific energies and for the various types of tissues.
- The name *Monte Carlo* was invented in 1947 by mathematicians Ulam and von Neumann who were working on nuclear weapons.

Determination of the Absorbed Fraction



- Radiation will be emitted randomly by the source in all directions
- Some photons will escape from the body without interaction
- Some photons will deposit their energy by photo electric interactions
- Some photons will undergo Compton scattering

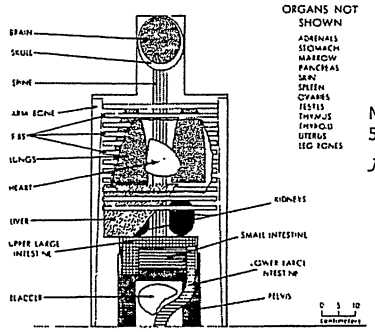


The MIRD Standard Man

MIRD Pamphlet No. 5 Revised.

J Nucl Med Jan 1978

ANTERIOR VIEW OF THE PRINCIPAL ORGANS IN THE HEAD AND TRUNK OF THE PHANTOM



The MIRD Standard Man

MIRD Pamphlet No. 5 Revised.

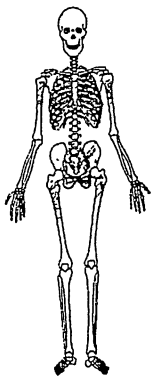
J Nucl Med Jan 1978



SKULL	13.1%
VERTEBRAE	28.4%
RIBS + STERNUM	10.2%
SCAPULAE	4.8%
HEAD AND NECK OF BOTH ARMS	1.9%
BOTH CLAVICLES	1.6%
HEAD AND NECK OF BOTH LEGS	3.8%
PELVIS	36.2%

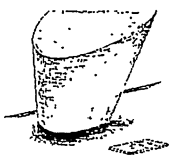
TOTAL AMOUNT OF RED BONE MARROW: 1500 g

RED BONE MARROW



MIRD Standard Man

The liver is defined by an elliptical cylinder cut by a plane:



$$\left(\frac{x}{16.5}\right)^2 + \left(\frac{y}{8}\right)^2 \le 1$$

$$\frac{x}{35} + \frac{y}{45} - \frac{z}{43} \le -1$$

$$27 \le z \le 43$$

TABLE 1. ELEMENTAL COMPOSITION OF DIFFERENT TISSUES OF THE PHANTOM* (% BY WEIGHT)

Element	Skeletal tissue†	Lung tissue‡	Total body minus skeleton and lungs§
H	7.04	10.21	10.47
C	22.79	10.01	23.02
N	3.82	2.59	2.34
O	48.56	75.96	43.23
Na	0.22	0.19	0.15
Mg	0.11	7.4×10^{-3}	0.015
P	9.94	0.081	0.24
S	0.17	0.23	0.22
Cl	0.14	0.27	0.14
K	0.15	0.20	0.21
Ca	9.91	7.0×10^{-3}	0
Fe	8.8×10^{-3}	0.037	6.3×10^{-3}
Zn	4.3×10^{-3}	1.1×10^{-3}	3.2×10^{-3}
Br	0	3.7×10^{-3}	5.7×10^{-4}
Sr	33×10^{-3}	5.9×10^{-3}	3.4×10^{-3}
Zr	0	0	8.0×10^{-4}
Pb	1.1×10^{-3}	4.1×10^{-3}	1.6×10^{-3}

* Reference 13 and 14.
† Density 1.3868 g/cm³.
‡ Density 0.3746 g/cm³.
§ Density 0.9748 g/cm³.

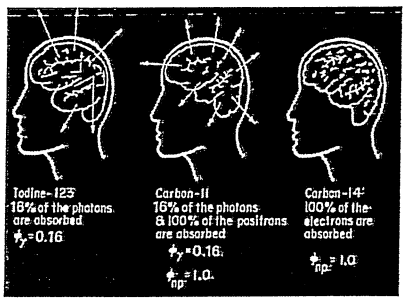
The MIRD Standard Man

Mird Pamphlet No. 5 Revised.

J Nucl Med Jan 1978

Examples of Absorbed Fractions

Note: $\phi = 1$ for charged particles



Derivation of the General MIRD Equation

- If A is the activity of the source, the *cumulated activity* $\tilde{A}$ is the sum, or accumulation, of all the nuclear transitions occurring in the source over a period of time
- then $\tilde{A}nE$ is the total radiation energy emitted by the source

Derivation of the General MIRD Equation

- $\tilde{A}nE\phi$ is the energy absorbed in the target during the time interval of interest (ϕ is the absorbed fraction)
- $D = \tilde{A}nE\phi/m$ is the absorbed dose, where m is the mass of the target organ

Derivation of the General MIRD Equation

$$D = \tilde{A}S \quad (S = nE\phi/m)$$

S is dependent on the radionuclide and the geometry. S-values for different radionuclides and source/target organs can be found in MIRD publications

Derivation of the General MIRD Equation

Generally each radionuclide will emit more than one type of "particle"

$D = \tilde{A}\Sigma S_i$ where S_i is the S factor of the ith particle

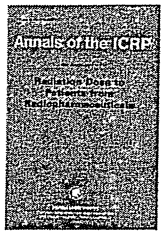
Derivation of the General MIRD Equation

Generally there will be many source organs r_h contributing to the target organ r_k, and all these contributions must be added to give the total dose to the target organ.

$$D(r_k) = \Sigma D(r_k \leftarrow r_h)$$

ICRP

ICRP publications 53, 62 & 80 give the absorbed dose per unit activity administered (mGy/MBq) for different radiopharmaceuticals and different organs as well as the effective dose.



Calculation of the cumulated activity

The Cumulated Activity, $\tilde{A}_h$ is simply the sum of all the nuclear transitions in organ h during the time interval of interest. Therefore

$$\tilde{A}_h = \int A_h(t)\, dt$$

Determination of cumulated activity

- Numerical integration of time-activity curves
- Assuming exponential outflow from an organ
- Using a biokinetic model

Use of the General MIRD Equation

- Often the activity function $A_h(t)$ can be approximated by a sum of exponentials

$$A_h(t) = \Sigma A_j e^{-\lambda t}$$

where λ is the "effective" clearance constant, combining both the physical decay constant and the biological clearance constant.

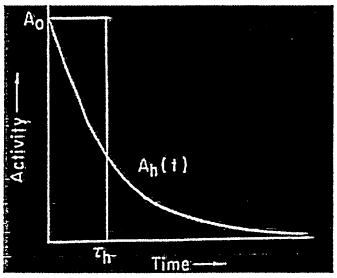
$$\frac{1}{T_{eff}} = \frac{1}{T_{phys}} + \frac{1}{T_{biol}}$$

Cumulated Activity

- Usually the integration limits for the calculation of the cumulated activity are zero to infinity.
- In which case:

$$\tilde{A} = \Sigma A_j / (\lambda_j)_e = 1.443 \Sigma A_j (T_j)_e$$

Example Plasma Clearance Curve showing Residence Time



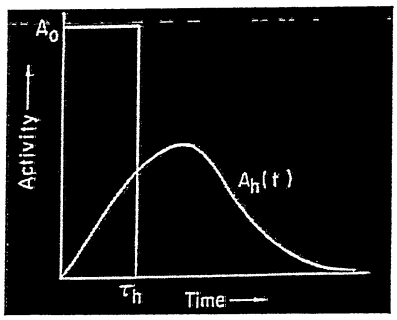
The Residence Time

The ratio τ in a source organ

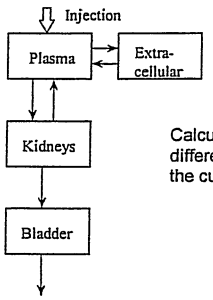
$$\tau = \tilde{A}_h / A_0$$

is defined as the residence time, where A_0 is the administered activity at zero time.

Example Organ Activity-Time Curve showing Residence Time



Biokinetic models



Calculate time-activity curves for the different compartments and calculate the cumulated activity.

Data Acquisition for Radiopharmaceutical Dosimetry (Biodistribution) Studies.

To determine the time-activity profile of the radioactivity in the source regions, four questions must be answered:

- What regions are source regions?
- How fast does the radioactivity accumulate in these source regions?
- How long does the activity remain in the source regions?
- How much activity is in the source regions?

Details of the appropriate measurement techniques can be found in MIRD Pamphlet No. 16 (J Nucl Med 1999, 40:37S-61S)

Data Acquisition for Radiopharmaceutical Dosimetry (Biodistribution) Studies.

Pharmacokinetics – biodistribution in humans and animals (when insufficient human data)

1. Human studies limited number of measurements, biodistribution and elimination only for few organs and tissues

   Methods -whole body measurements. sample collection (blood, urine, feaces..)

   Equipment – scintillation camera. SPECT

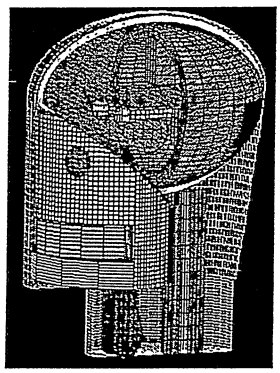
2. Animal studies – whole body activity retention (blood samples, urine) dissection of the body and collection of organs and tissues

Data Acquisition for Radiopharmaceutical Dosimetry (Biodistribution) Studies.

3. Compartmental analysis – mathematical models for describing the biokinetics of RF , transfer coefficients between compartments, calculation of residence time and cumulated activities

Assumptions in Standard MIRD Dosimetry

- Entire organs taken as sources and targets
- Homogeneous absorbing material
- Uniform activity distribution
- Constant mass
- Edge effects are negligible



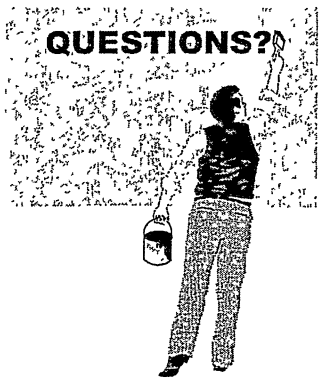
MIRD Pamphlet No. 15

J Nucl Med 1999, 40:62S-101S

Improved mathematical model of the brain and skull.

Patient-Specific Dosimetry

- The MIRD approach provides estimates of organ doses and Effective Dose to the standard phantoms. This can be used for dosimetry of diagnostic radiopharmaceuticals.
- For radionuclide therapy, a patient-specific approach must be taken to determine the tumour and non-tumour tissue doses.



DISCUSSION

Discuss levels of acceptance for parameters such as uniformity, energy resolution, spatial resolution, center of rotation etc.

DISCUSSION

Discuss who should do the quality control of the equipment in a nuclear medicine department

DISCUSSION

Discuss the different factors that will affect the magnitude of the uncertainty between the equivalent dose to an organ and the effective dose calculated according to MIRD and the doses actually received by the patient.

Is it important if the uncertainty is e.g. a factor of 2?

Where to Get More Information

- Other sessions
  - Part 2 Radiation Physics
  - Part 6 Medical exposure
- Further readings
  - NEMA publications
  - MIRD publications
  - ICRP Publications (53, 62)
  - IAEA TECDOC 602
  - IAEA Basic Safety Standards
  - WHO/IAEA Manual on Radiation Protection in Hospitals and general practice. Volume 4. Nuclear medicine, (draft manuscript)
  - IAEA. Model Regulations on Radiation Safety in Nuclear Medicine. (in preparation).
  - Publications from HPA and AAPM regarding QC
- Practical sessions
  - QC activity meter
  - QC gammacamera