Chapter 8: Generic performance measures

Set of 76 slides based on the chapter authored by
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Review of Nuclear Medicine Physics:
A Handbook for Teachers and Students

Objective:

To familiarize the student with the generic performance measures used to evaluate nuclear medicine imagers.

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TABLE OF CONTENTS

8.1 INTRINSIC AND EXTRINSIC MEASURES

8.1.1 Generic nuclear medicine imagers

8.1 INTRINSIC AND EXTRINSIC MEASURES

8.1.1 Generic nuclear medicine imagers

Main components of generic nuclear medicine imagers

- Detection system.
- Collimation system (to select gamma rays at specific angles).
- Electronics.
- Computing system (to create the map of the radiotracer distribution).

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8.1 INTRINSIC AND EXTRINSIC MEASURES

8.1.1 Generic nuclear medicine imagers

Detection system

- Scintillators
  - Sodium iodide activated with thallium (NaI(Tl)).
  - Bismuth germanate (BGO).
  - Lutetium oxyorthosilicate (LSO).
- Semiconductors
  - Cadmium zinc telluride (CZT).

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8.1 INTRINSIC AND EXTRINSIC MEASURES

8.1.1 Generic nuclear medicine imagers

Detection process in scintillators

- Gamma ray interacts with crystal and energy is partially or totally transferred to crystal.
- Light is emitted, with wavelength depending on crystal material, not on gamma ray energy.
- The intensity of the light depends on the energy deposited in the crystal.

Detection process in scintillators (cont.)

- Scintillation light strikes the cathode of the photomultiplier tube and electrons are emitted.
- Electrons are accelerated in the photomultiplier and strike a series of dynodes (9-11), producing a secondary emission of electrons.
- The number of electrons increases and a signal is obtained at the output, whose amplitude is proportional to the energy transferred to the crystal.

Detection process in semiconductors

- The gamma ray still deposits some or all of its energy in the crystal through photoelectric absorption or, more likely, Compton scattering interactions.
- Energy creates electron–hole (e–h) pairs that are then collected by application of an electric field to create a measurable signal.

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Electronic functions

- Determine the location of interaction of the gamma ray in the detector.
- Calculate the energy deposited in the crystal and ascertain whether that energy falls within a prescribed range of desirable energies.
- For PET systems, measure the times that the two annihilation photons interacted and evaluate whether the difference in those times falls within a desired timing window to have both come from the same annihilation event.

Electronic functions

Image formation

- 2-D – Planar imaging
  - Display the number of events at each detector position.
- 3-D – SPECT or PET imaging
  - Detector data must be combined through a reconstruction algorithm:
    - Analytical methods: e.g. filtered back projection.
    - Iterative methods: e.g. OSEM.

8.1 INTRINSIC AND EXTRINSIC MEASURES

8.1.1 Generic nuclear medicine imagers

Performance measures

- Performance measures aim to test one or more of the components, including both hardware and software, of a nuclear medicine imager.
- There are two general classes of measurements of scanner performance: intrinsic and extrinsic.

8.1 INTRINSIC AND EXTRINSIC MEASURES

8.1.2 Intrinsic performance

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- Intrinsic measurements reflect the performance of a sub-part of the imager under ideal conditions.
- On a gamma camera, measurements without a collimator will describe the best possible performance of the detector without the degrading effects of a collimator.
- On a PET scanner, intrinsic performance is often determined for a pair of detectors, rather than for the entire system.

These measurements are typically performed under non-clinical conditions and will not reflect the performance of the nuclear medicine imager for patient studies.

8.1 INTRINSIC AND EXTRINSIC MEASURES

8.1.3 Extrinsic performance

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8.1 INTRINSIC AND EXTRINSIC MEASURES

8.1.3 Extrinsic performance

- Extrinsic, or system, performance measures are made on the complete nuclear medicine imager under conditions that are more clinically realistic.
  - On a gamma camera, extrinsic measurements are made with the collimator in place.
  - For SPECT and PET systems, the performance is often measured on the reconstructed image.
- The extrinsic performance of a system gives an indication of how well all of the components of the imager work together to yield the final image.

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8.2 ENERGY RESOLUTION

8.2.1 Energy spectrum

Energy spectrum

The number of measured events with a given energy plotted as a function of energy is the energy spectrum.

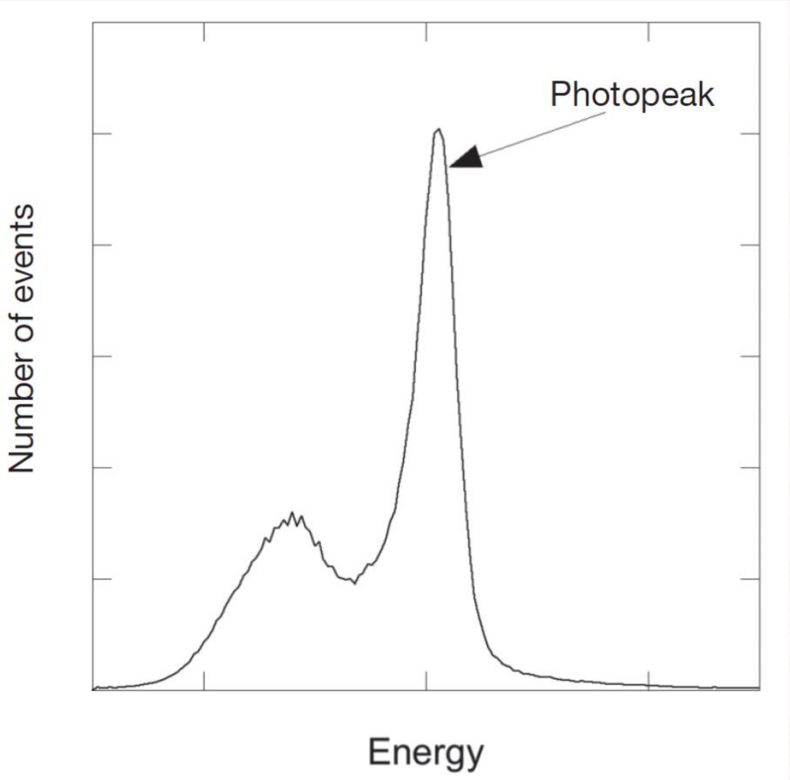
Energy spectra characteristics

All energy spectra have some common features:

- The photopeak, where the gamma ray deposited all of its energy in the detector through one or more interactions.
- The broad, lower energy region that reflects incomplete deposition of the gamma ray's energy in the detector and/or Compton scattering of the gamma rays.

8.2 ENERGY RESOLUTION

8.2.1 Energy spectrum



Energy spectrum

- The photopeak is not a sharp peak but is blurred.
- This broadening is due to statistical fluctuations in the detection of photons and conversion of the energy deposited in the crystal into an electrical signal.
- This is a larger effect for scintillation detectors than for semiconductors.

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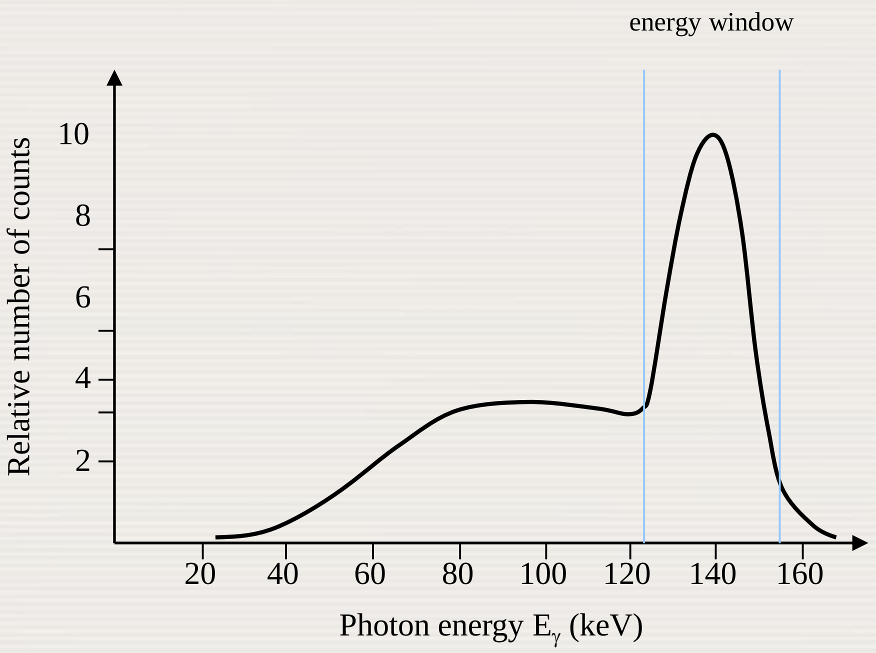
Radiotracer distribution

The goal of nuclear medicine imaging is to map the distribution of radiotracers.

- Only gamma rays that do not interact in the tissue before reaching the detectors are useful.
- Any gamma rays that scatter in the body first change their direction and do not provide an accurate measurement of the original radionuclide's location.

8.2 ENERGY RESOLUTION
8.2.1 Energy spectrum



Nuclear medicine imagers accept events whose energies lie in a 'window' around the photopeak energy

- PET scanners:
  - 40–650 keV for LSO detectors
- Gamma cameras:
  - 129.5–150.5 keV NaI(Tl) detectors, for ^{99m}Tc (15% of 140 keV).

8.2 ENERGY RESOLUTION

8.2.2 Intrinsic measurement- energy resolution

8.2 ENERGY RESOLUTION

8.2.2 Intrinsic measurement- energy resolution

Energy resolution

- The intrinsic ability of a detector to distinguish gamma rays of different energies is reflected in its energy resolution.
- The energy resolution of a detector is defined as the full width of the photopeak at one half of its maximum amplitude (FWHM), divided by the energy of the photopeak, and is typically expressed as a percentage of the peak energy.

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8.2 ENERGY RESOLUTION

8.2.2 Intrinsic measurement- energy resolution

As the energy resolution worsens, it is necessary to accept more low energy events because the photopeak includes lower energy gamma rays.

Detector material	Energy resolution (%)	Lower energy threshold (keV)
BGO	15 - 20	350-380
LSO	12	440-460
$LaBr_3$	6-7	480-490

8.2 ENERGY RESOLUTION

8.2.3 Impact of energy resolution on extrinsic imager performance

Energy resolution, energy window and scatter fraction

- The energy resolution defines the minimum width of the energy window for a given radiotracer.
- The energy window in turn affects the amount of scattered photons accepted.
- The ratio of scattered events to total measured events is the 'scatter fraction'.
  - The scatter fraction is an extrinsic performance measure that describes the sensitivity of a nuclear medicine imager to scattered events and is extremely relevant for quantitative imaging.

Scatter measurement

- Scatter measurement involves imaging a line source in a uniformly filled phantom of a specified size at a low activity level.
- In this case, scattered and unscattered events can be reasonably well differentiated.

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Scatter fraction and energy window

- Good energy resolution does not lead to a low scatter fraction unless the energy window used is made appropriately narrow.
- A scanner with 7% energy resolution will accept approximately as much scatter as one with 12% energy resolution if both systems have the same lower energy threshold.

8.3 SPATIAL RESOLUTION

8.3.1 Spatial resolution blurring

Spatial resolution

- The spatial resolution of a nuclear medicine imager characterizes the system's ability to resolve spatially separated sources of radioactivity.
- In addition to blurring small structures and edges, resolution losses also lead to a decrease in the contrast measure in these structures and at boundaries of the activity distribution ("partial volume effect").

Multi crystal vs single crystal detectors

- In multi crystal systems, resolution is limited by the size of detector elements.
- In single crystal detectors, the spatial sampling of the crystal determines the best spatial resolution achievable.

8.3 SPATIAL RESOLUTION

8.3.1 Spatial resolution blurring

Other factors affecting spatial resolution

- Stopping power of detector material
  - Higher stopping power detectors have higher resolution than low stopping power ones due to less inter-crystal scatter.
- Photon energy
  - Higher energy photons give rise to bigger signals, thus will be better located than small ones.

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8.3 SPATIAL RESOLUTION

8.3.2 General measures of spatial resolution

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Measures of spatial resolution

Several parameters have been defined to give a quantitative measure of spatial resolution, such as the following:

- Point spread function (PSF).
- Line spread function (LSF).
- Full width at half maximum (FWHM).
- Full width at tenth maximum (FWTM).
- Modulation transfer function (MTF).

Point spread function (PSF)

The point spread function (PSF) is the profile of measured counts as a function of position across a point source.

Line spread function (LSF)

Similarly to the point spread function (PSF), the line spread function (LSF) is the profile of measured counts as a function of position across a line source.

Full width at half maximum (FWHM) and full width at tenth maximum (FWTM)

- Rather than showing the complete profiles, sometimes it is more convenient to characterize them by simple measures.
- The full width at half maximum (FWHM) and full width at tenth maximum (FWTM) are the widths of the profile at the corresponding fraction of its maximum value.

Modulation transfer function (MTF)

- The modulation transfer function (MTF) is one way to more completely characterize the ability of a system to reproduce spatial frequencies.
- The MTF is calculated as the Fourier transform of the PSF and is a plot of the response of a system to different spatial frequencies.

8.3 SPATIAL RESOLUTION

8.3.3 Intrinsic measurement — spatial resolution

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8.3 SPATIAL RESOLUTION

8.3.3 Intrinsic measurement — spatial resolution

Intrinsic measurements

- The intrinsic spatial resolution is a measure of the resolution at the detector level (or detector pair level for PET) without any collimation.
- It defines the best possible resolution of the system, since later steps in the imaging hardware degrade the resolution from the detector resolution.

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Gamma cameras and PET systems

- On gamma cameras, the intrinsic resolution is determined using a bar phantom with narrow slits of activity across the detector.
- On PET systems, the intrinsic resolution is measured as a source is moved between a pair of detectors operating in coincidence.

8.3 SPATIAL RESOLUTION

8.3.4 Extrinsic measurement — spatial resolution

8.3 SPATIAL RESOLUTION

8.3.4 Extrinsic measurement — spatial resolution

Extrinsic resolution measurements

- The intrinsic spatial resolution sets a limit on the resolution but does not translate easily into a clinically useful value because other components of the imager impact the resolution in the image.
- Extrinsic measures of spatial resolution are made under more clinically realistic conditions and include the effects of the collimator (for single photon imaging) and reconstruction processing.

Extrinsic resolution measurements

The extrinsic spatial resolution is distinguished from the intrinsic resolution because it includes many effects not seen with the intrinsic resolution:

- collimator blurring.
- linear and angular sampling.
- reconstruction algorithm.
- spatial smoothing.
- impact of electronics.

Spatial resolution in patient images

The spatial resolution achieved in patient images is typically somewhat worse than the extrinsic spatial resolution, due to:

- The spatial sampling in the extrinsic resolution measurement is finer than occurs clinically.
- The reconstruction algorithm in the performance measurement is often not the technique applied to clinical data.
- Noise in the clinical data necessitates noise reduction through spatial averaging (smoothing), which blurs the image.

8.4 TEMPORAL RESOLUTION

8.4.1 Intrinsic measurement — temporal resolution

Timing resolution and decay time

- The timing resolution, or resolving time, is the time needed between successive interactions in the detector for the two events to be recorded separately.
- The timing resolution is largely limited by the decay time of the crystal.

8.4 TEMPORAL RESOLUTION

8.4.1 Intrinsic measurement — temporal resolution

Decay time ranges

- For scintillators, the decay time can be as high as 250–300 ns or as low as 20–40 ns, depending on the detector material.
- For semiconductor detectors, the decay time is much smaller.

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8.4 TEMPORAL RESOLUTION

8.4.1 Intrinsic measurement — temporal resolution

Coincidence timing window

- The timing of events is critical for PET.
- Coincidence timing window are to be set to <10 ns and >6 ns for a ring diameter of 90 cm.
- For time of flight systems, the coincidence time window is still 4–6 ns but the time of flight difference can be measured with a resolution of 300–600 ps.

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8.4 TEMPORAL RESOLUTION

8.4.2 Dead time

Dead time types

- The consequence of a finite timing resolution is a loss of counts measured at higher activities.
- There are two types of dead time: non-paralysable and paralysable
  - Non-paralysable dead time arises when an event causes the system to be unresponsive for a period of time.
  - For paralysable dead time, any further event is not only not recorded but also extends the period for which the electronics are unresponsive.

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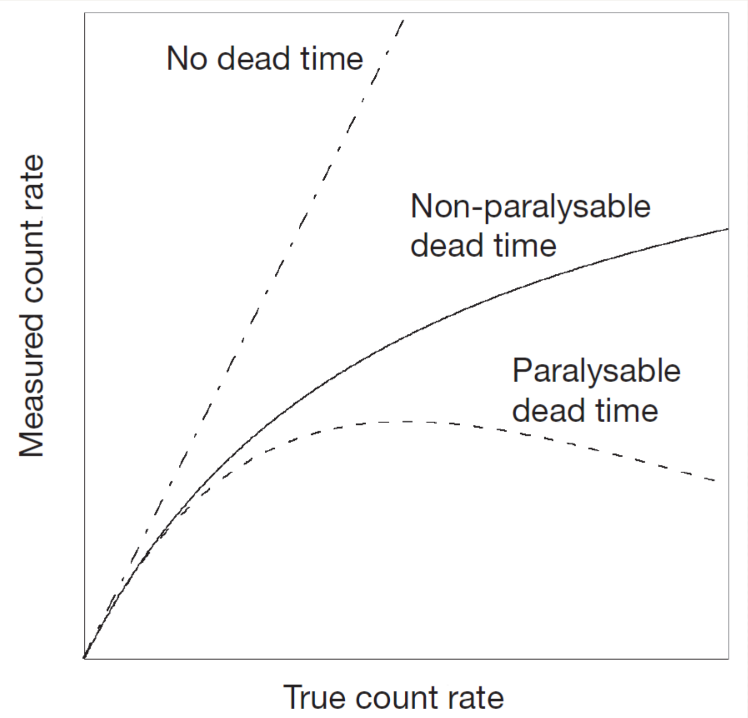
8.4 TEMPORAL RESOLUTION

8.4.2 Dead time



System dead time as a function of count rate

Characteristics of dead times

- At moderate count rates, paralysable and non-paralysable dead times are the same; it is only at high count rates that the two types of dead time differ.
- Systems with non-paralysable dead time saturate at high count rates, while those with paralysable dead time peak and then record fewer events as the activity increases.

Consequences of dead time

- Due to increased dead time, additional activity injected in the patient does not lead to a comparable improvement in image quality or reduction in image noise.
- For imaging studies with a large dynamic range (e.g. cardiac scans), count rate performance is critical.

8.4 TEMPORAL RESOLUTION

8.4.3 Count rate performance measures

Measurement of count rate performance

- The generic measurement of count rate performance involves determining the response of the nuclear medicine imager as a function of activity presented to the system.
- Typically, this requires starting with a high amount of activity and acquiring multiple images over time as the activity decays.
- By comparing the observed events with the counts that would be expected after decay correction of events detected at low activities, the system dead time can be determined as a function of activity level.

Types of count rate performance measurements

- Intrinsic count rate performance measurements are performed with a source in air and without any detector collimation. This is typically performed only on gamma cameras.
- The system, or extrinsic, count rate performance is measured with the complete system, including any collimation or detector motion, and a distributed source with scattering material.

Scatter

- The scatter adds low energy photons that contribute to
  - pile-up
  - and dead time
- These are not present in the intrinsic measurement.

Random coincidences

For PET, random coincidences also increase as the activity increases.

- The true coincidence rate would increase linearly with activity in the absence of dead time losses.
- The random coincidence rate increases quadratically with activity.
- Their impact becomes greater at higher count rates.

Noise equivalent count rate (NECR)

A global measure of the impact of random coincidences and scatter on image quality is given in the noise equivalent count rate (NECR) defined as:

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

where T, S and R are the true, scatter and random coincidence count rates and k is 1 or 2 according to the estimate used for randoms.

8.5 SENSITIVITY

8.5.1 Image noise and sensitivity

Sensitivity

- The relative response of a system to a given amount of activity is reflected in its sensitivity.

8.5 SENSITIVITY

8.5.1 Image noise and sensitivity

Factors that determine sensitivity

The sensitivity of a system is determined by many factors:

- The geometry of the imager.
- The stopping power and depth of the detectors.
- The radionuclide's energy.
- The imager's energy resolution and energy window.
- The source distribution and its position in the imager.

8.5 SENSITIVITY

8.5.2 Extrinsic measure — sensitivity

Characteristics of sensitivity measurements

- All performance measurements of sensitivity are extrinsic.
- For single photon imaging, in particular, the collimator is a major source of loss of events.
- Any measurement of sensitivity is performed under prescribed conditions that do not attempt to replicate patient activity distributions.
- The source configuration and sensitivity definition is different for different systems.

Source configuration and definition of sensitivity

Planar imaging

- A shallow dish source without intervening scatter material is used.
- The sensitivity is reported as a count rate per activity.

Source configuration and definition of sensitivity

SPECT

- A cylindrical phantom is filled uniformly with a known activity concentration.
- The sensitivity is reported as a count rate per activity concentration.

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Source configuration and definition of sensitivity

Whole body PET scanners

- A line source that extends through the axial FOV is imaged with sequentially thicker sleeves of absorbing material.
- The data are extrapolated to the count rate one would measure without any absorber.
- The sensitivity is then reported as a count rate per unit activity.

8.6 IMAGE QUALITY

8.6.1 Image uniformity

8.6 IMAGE QUALITY

8.6.1 Image uniformity

Importance of uniformity for image quality

Image uniformity can be affected by different factors:

- All PMTs of a given type do not respond exactly the same way, and a correction for this difference in gain is applied before the image is formed.
- Collimators can also have defects that lead to non-uniformities in the image.
- For tomographic scanners, corrections for attenuation and unwanted events such as scatter can also affect the uniformity of the image.

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Measures of image uniformity

Intrinsic uniformity

- Intrinsic uniformity is measured without a collimator by exposing the detector to a uniform activity distribution (e.g. from a distant, uncollimated point source).
- Intrinsic uniformity is measured at both low and high count rates, where mis-positioning effects become more pronounced.

Measures of image uniformity

Extrinsic uniformity

- The extrinsic or system uniformity is determined with a collimator in place (for single photon imaging).
- Images are processed or reconstructed as for clinical studies.

8.6 IMAGE QUALITY

8.6.2 Resolution/noise trade-off

Image quality

- Most performance measurements are carried out under non-clinical conditions to isolate an aspect of the imager's performance.
- To include more of the effects seen in clinical data, some performance standards call for a measurement of image quality.
- Phantoms, activities, acquisition time, noise level, data processing and analysis are chosen to have results more comparable to the ones obtained in patient studies.

Characteristics

- The activity distribution is a series of small structures (e.g. spheres of varying diameters) in a background activity typical of the activity levels seen in patient studies.
- Activity, acquisition time and data processing are similar to patient studies.
- Data analysis consists of such measures as sphere to background contrast recovery, noise in background areas and/or signal to noise ratio in the spheres.

8.7 OTHER PERFORMANCE MEASURES

8.7 OTHER PERFORMANCE MEASURES

Other performance measures that reflect a given aspect of a nuclear medicine imager.

- Spatial linearity (planar systems).
- Registration of different imaging modalities (PET-CT, SPECT-CT,PET-MR).
- Multiple energy windows.

Quantitative linearity and calibration is an important measurement for systems such as PET scanners that aim to relate pixel values to activity concentrations.