Nuclear Medicine Imaging

Principles of Medical Imaging

Prof. Dr. Philippe Cattin

MIAC, University of Basel

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Introduction

The methods of Nuclear Medicine are a coalition of

- Physics
  - To produce the radio nuclei (radiotracers)
- Chemistry
  - Synthesising radiopharmaceuticals from the tracers
- Physiology/Medicine
  - To understand and interpret the radionuclide distribution
- Engineering
  - To operate/maintain and process the acquired data

Nuclear medicine differs from most other imaging modalities in that the tests primarily show the physiological function of the system being investigated as opposed to traditional anatomical imaging such as CT or MRI.

The Washington University in St. Louis has a nice collection of nuclear medicine cases split by study type and diagnosis.
Scintigraphy or planar imaging is a nuclear medicine imaging modality often used in diagnosis. It consists of the following main steps:

- The radionuclides are combined with chemical compounds → radiopharmaceuticals.
- The radiopharmaceutical is administered to the patient.
- Wait for the radiopharmaceutical to distribute in the body.
- External gamma cameras capture the photons and form an image representing the distribution of the radionuclides i.e. the radiopharmaceuticals.
- Since the energy of the photons is known, scattered photons can be rejected.

Scintigraphy is used to diagnose:

- Cancer and metastases
- Bone fractures caused e.g. by fatigue and are difficult or impossible to see under planar X-ray.
- Myocardial ischemia
- ...

![Fig. 7.1: Principle of scintigraphy](image1)

![Fig. 7.2: Gamma camera of the scintigraph](image2)
Radiopharmaceuticals

Although multiple radionuclides are available for nuclear medicine, the predominant nucleus is $^{99m}$Tc as its generator can be stored for weeks and is immediately available.

All the radiopharmaceuticals are constructed such that they mimic a certain functional compound of the human physiology.

Depending on the age of the patient, the type of investigation and the applied radiopharmaceutical one has to wait for several minutes and up to an hour before scanning the patient.

99mTc Radiopharmaceuticals in Routine Applications

The table below shows some $^{99m}$Tc based radiopharmaceuticals and their use in routine clinical applications on adults in Scintigraphy and SPECT.

<table>
<thead>
<tr>
<th>Organ</th>
<th>Agent</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone</td>
<td>MDP</td>
<td>Metastases</td>
</tr>
<tr>
<td></td>
<td>HMDP</td>
<td>Fractures</td>
</tr>
<tr>
<td>Brain</td>
<td>DTPA</td>
<td>Tumour</td>
</tr>
<tr>
<td></td>
<td>HMPAO</td>
<td>Perfusion</td>
</tr>
<tr>
<td>Cardiac</td>
<td>MIBI</td>
<td>Myocardium</td>
</tr>
<tr>
<td></td>
<td>Terfosmin pyrophosphate</td>
<td>Infarct</td>
</tr>
<tr>
<td>Kidney</td>
<td>DTPA</td>
<td>GFR</td>
</tr>
<tr>
<td></td>
<td>MAG3</td>
<td>Function</td>
</tr>
<tr>
<td></td>
<td>DMSA</td>
<td>Function</td>
</tr>
<tr>
<td>Lung</td>
<td>MAA</td>
<td>Perfusion</td>
</tr>
<tr>
<td>Liver/spleen</td>
<td>Aerosols</td>
<td>Ventilation</td>
</tr>
<tr>
<td></td>
<td>EHIDA</td>
<td>Function</td>
</tr>
<tr>
<td></td>
<td>Colloid</td>
<td>Biliary</td>
</tr>
<tr>
<td>Bone marrow</td>
<td>Colloid</td>
<td>Metastases</td>
</tr>
<tr>
<td>Lymph</td>
<td>Colloid</td>
<td>Function</td>
</tr>
<tr>
<td>Whole body</td>
<td>HMPAO</td>
<td>Infection</td>
</tr>
<tr>
<td>Whole body</td>
<td>White cells Tc-DMSA</td>
<td>Tumour sites</td>
</tr>
</tbody>
</table>
**Bone Scintigraphy Examples** (11)

Fig. 7.8: (20.8 mCi Tc-99m MDP i.v), 30 year old female, four weeks post motor vehicle accident with continued pain in the sternum, back, and right ribs.

Fig. 7.9: Scintigraphy of a patient with advanced stages of bone cancer (black areas).

[http://gamma.wustl.edu/bs116te144.html]

**Causes of Image Degradation** (12)

In nuclear imaging, the photons are emitted isotropically. Figure 7.10 shows possible fates of these photons:

- Photons can be absorbed or scattered within the tissue of the patient.
- Many of the photons escaping the patient are not detected because they are emitted in directions away from the detector.
- The collimator absorbs the vast majority of the photons that reach it → only 1 or 2 in 10,000 reaches the detector.
- Well over 99.9% of the emitted photons are wasted.

**Fig. 7.10: Photon fates in nuclear medicine**

Photons can penetrate the collimator septa without interaction.
- Photons reaching the detector crystal can scatter or pass through without interacting.
- Multiple scattered photons can also mimic a single photon within the allowed energy window.

The relative probability of these resolution limiting events depends on the photon energy.
Collimator

The Collimator is at the heart of any Scintigraphy and/or SPECT system:

- The collimator has the **biggest impact** on the SNR (signal-to-noise ratio) and image **blur**
- The collimator **defines the direction** along which the γ-rays are allowed to propagate
- Lens systems similar to visible light are not possible with γ-rays
- Absorbing lead collimators are typically used

**Collimator Designs**

- **Fig. 7.11:** Design of a parallel hole collimator
- **Fig. 7.12:** Highly sensitive collimator with a lower spatial resolution
- **Fig. 7.13:** High spatial resolution collimator
- **Fig. 7.14:** Converging collimator
- **Fig. 7.15:** Diverging collimator
Collimator Examples (16)

Fig. 7.16: Example parallel (cast) collimator after repair (scratches)

Fig. 7.17: Example parallel (foil) collimator

Fig. 7.18: Cast vs. foil design. Whereas the cast design has an even thickness, the foil design has an uneven septa thickness

Resolution and Efficiency (17)

The spatial resolution of a parallel hole collimator is approximately given by

\[ R \approx \frac{h}{L} + \frac{d}{L} \quad (7.1) \]

and the Efficiency is approximately

\[ \eta \approx \frac{h^2}{16d^2} \quad (7.2) \]

We can state that

- spatial resolution improves when the diameter of the hole \( h \) is reduced but the efficiency of the collimator decreases with \( h^2 \)
- spatial resolution and efficiency is best for objects close to the collimator, thus small \( d \)
- the efficiency decreases rapidly with collimator-to-object distance
- spatial resolution decreases with increasing gamma energy because of septal penetration!

We have to find good compromise between resolution, efficiency, applied dose.
Resolution vs Depth (18)

Fig. 7.20: Resolution vs depth in dependence of the collimator depth $L$, the hole diameter $h$ and the distance to the object $d$.

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Single Photon Emission Tomography (20)

Similar to planar X-ray and CT, Single Photon Emission Tomography (SPECT) is the 3-dimensional version of the 2-dimensional Scintigraphy.

Because SPECT acquisition is very similar to the planar Scintigraphy, the same radiopharmaceuticals may be used.

The concept of SPECT was introduced by David E. Kuhl and Roy Edwards in the late 1950’s. This was even before the development of X-ray computed tomography (CT) in 1970’s.

SPECT combines Scintigraphy with reconstruction methods as used in Computed Tomography (CT) to get the 3D distribution of the radionuclide.

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Fig. 7.21: Multipurpose SPECT scanner

Fig. 7.22: SPECT scanner for mainly cardiac applications
Single Photon Emission Tomography (21)
(2)

- The gantry allows to rotate the gamma camera 360° around the patient.
- The camera takes a series of images (projections) in a step-and-shoot mode.
- The non-circular gantry rotation reduces the patient/camera distance and thus improves image quality.
- Sensitivity can be significantly improved by using 2 or 3 camera heads or even a ring of detectors.
- An angular sampling interval of ≈ 3° is typical.
- Image acquisition time can range from minutes to an hour or more.

SPECT Applications (22)

- Brain
  - Perfusion (stroke, epilepsy, schizophrenia, dementia,...)
- Heart
  - Coronary artery disease
  - Myocardial infarcts
- Respiratory problems
- Liver
- Kidney
- Cancer/Metastases
- Bone fractures
- ...
Early Clinical SPECT Systems

Fig. 7.25: Clinical SPECT imaging system from General Electric ca 1980s

Today's Clinical SPECT Systems

Fig. 7.26: (a) General Electric Millennium VG, (b) Philips Cardio 60, (c) Siemens
Attenuation Correction

Attenuation of the gamma rays within the patient can lead to significant underestimation of activity in deep tissues, compared to superficial tissues or even to a wrong diagnosis.

The attenuations are not always easily recognisable and could thus be mistaken as a pathology.

Approximate correction is possible, based on relative position of the activity and assuming attenuation values $\mu$ e.g. a constant value.

Modern SPECT equipment has a possibility for a transmission scan or even an integrated CT scanner to measure the attenuation coefficients. This data can be incorporated into the SPECT reconstruction to correct for attenuation.

Fig. 7.27: Some $\gamma$ photons are already absorbed within the patient. Although source 'B' has twice the activity than 'A' it only appears as half as active due to absorption in the tissue

Attenuation Correction (2)

The photon attenuation in tissue causes significant problems when reconstructing SPECT images.

Figure 7.28 shows a simulation for 140 keV photons in water with an attenuation of $\mu = 0.15 \text{ cm}^{-1}$ and homogeneous objects of varying diameter.

Attenuation produces distortions that increase with object size.

Fig. 7.28: Effect of attenuation on homogeneous discs (of varying diameter) in water
Having the gamma camera and CT scanner on the same gantry allows straightforward fusion of the two data sets. The CT provides accurate anatomical localisation of the functional information within the gamma camera scan. In addition, the CT data can be used for generating attenuation correction maps to increase the accuracy of the gamma camera data. It is claimed that the accuracy of radionuclide therapy planning can be increased by using the CT attenuation corrected SPECT data. Applications in development include combined coronary CT angiography and myocardial perfusion imaging.
Positron Emission Tomography

Positron Emission Tomography (PET) relies on $\beta^+$-decay that produces two $\gamma$-photons (511 keV) in opposite direction when the positron annihilates with a nearby electron.

As the two photons hit the gamma camera quasi simultaneously, no collimation is required.

PET offers the highest sensitivity of all nuclear medicine imaging techniques as

- it does not require a collimator and
- tissue absorption is less due to the higher energy photons.

The spatial resolution of PET is higher than in SPECT and modern systems often achieve a resolution of $\approx 2 - 3$ mm

PET Radiopharmaceuticals

In contrast to the radionuclei used for Scintigraphy and SPECT, radionuclei for PET must undergo $\beta^+$-decay and thus emit a positron. The most common isotopes used in PET investigations are

<table>
<thead>
<tr>
<th>Element</th>
<th>Half-life ($t_{1/2}$ [min])</th>
<th>$\beta^+$ Energy [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{15}$N</td>
<td>$\approx 10$</td>
<td>1.19</td>
</tr>
<tr>
<td>$^{18}$F</td>
<td>$\approx 110$</td>
<td>0.65</td>
</tr>
<tr>
<td>$^{11}$C</td>
<td>$\approx 20$</td>
<td>0.96</td>
</tr>
<tr>
<td>$^{15}$O</td>
<td>$\approx 2$</td>
<td>1.74</td>
</tr>
</tbody>
</table>

Due to their short half-lifes, they must be produced in an on-site cyclotron.

Before the $\beta^+$ positron annihilates, it has to lose its kinetic energy through collisions. The end-to-end distance of this random walk can be up to 3 mm away from where it was emitted, limiting the achievable resolution.
PET Radiopharmaceuticals (2)  (32)

The most common radiopharmaceutical used in PET is $^{18}$F-labelled fluorodeoxyglucose of FDG. It is extensively used in tumour, brain and heart imaging studies.

In the example below e.g. the lung nodule (arrow) shows an increased uptake of FDG which turned out to be lung cancer.

PET Scanning Principle  (33)

Fig 7.37: Animation of the PET scanning principle
PET Projections

As the co-registration of the functional PET and the anatomical CT images is not trivial, PET scans are increasingly read alongside CT (or MR) scans, giving both the anatomic and metabolic information in immediate sequence without moving the patient → more-precisely registered data.

Fig. 7.39: Philips Gemini TF PET/CT scanner
PET/CT Scan Protocol

The bright red/yellow masses show hypermetabolic areas of the pelvis with metastases of a previous, surgically removed colon carcinoma in a 69-yrs old woman. Photo: Renato M.E. Sabbatini, PhD, Cancer Hospital of São Paulo, Brazil