Neurocam - Gamma Camera

Scintillation Camera

HAL O. ANGER

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A new and more sensitive gamma-ray camera for visualizing sources of radioactivity is described. It consists of a lead shield with a pinhole aperture, a scintillating crystal within the shield viewed by a bank of seven photomultiplier tubes, a signal matrix circuit, a pulse-height selector, and a cathode-ray oscilloscope. Scintillations that fall in a certain range of brightness, such as the photopeak scintillations from a gamma-ray-emitting isotope, are reproduced as point flashes of light on the cathode-ray tube screen in approximately the same relative positions as the original scintillations in the crystal. A time exposure of the screen is taken with an oscilloscope camera, during which time a gamma-ray image of the subject is formed from the flashes that occur. One of many medical and industrial uses is described, namely the visualization of the thyroid gland with I^{131}.
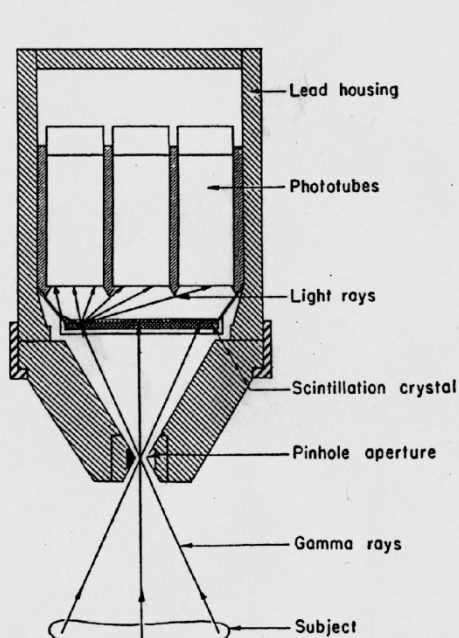
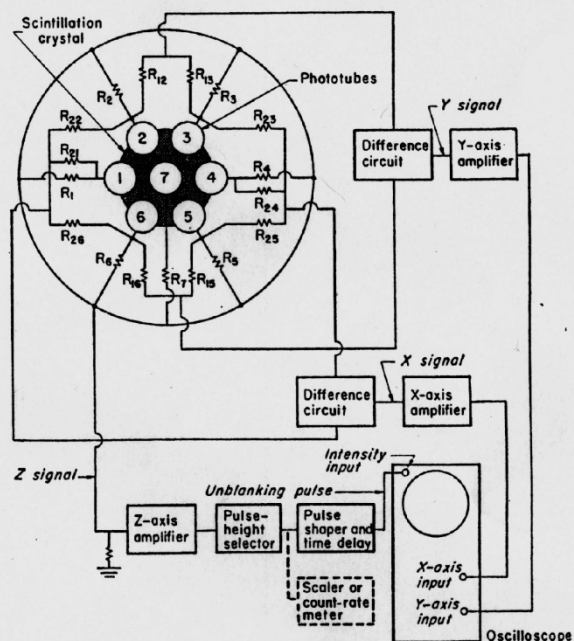FIG. 1. Sectional drawing of scintillation camera.

FIG. 2. Block diagram of electronic circuit.

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Introduction to and the early days of nuclear medicine

Nuclear imaging produces images of distribution of radionuclides in objects. It is a widely used medical imaging modality when a dynamical process of organs of the human body rather than its anatomy is investigated. The method is based on detection of the emitted radiation (emission technique) contrary to imaging when X-rays are used (transmission technique).

A very simple and early application of the emission technique is the measurement of iodine uptake by the thyroid gland. Radioactive iodine is orally ingested and a gamma ray counter placed near the neck measures the increase of activity with time, as the iodine is concentrated in the thyroid. The measurement helps to quantify the function of the thyroid gland. In the early days of nuclear medicine ^{131}I with the rather long half-life, 8 days, was applied, that gave a non-negligible dose contribution to the patient. Nowadays, ^{123}I with the much shorter half-life, 13 hours is used.

To obtain a complete picture of the thyroid from the spatial pattern of the radioactive emissions, one scanned over the area using a scintillation detector. A few mm diameter collimators confined the detector to observe only a small area. By scanning back and forth through a rectangular array the intensity of the radiation was recorded. This type of rectilinear scanning system is the first imaging tool that could provide a functional image of an organ. In figure 1, the principles of a rectilinear scanner and an image recorded in the 50's are displayed.
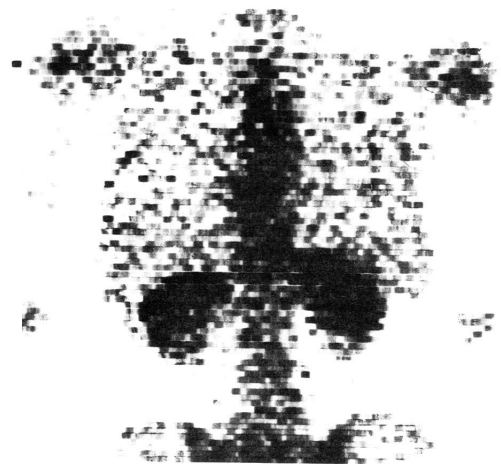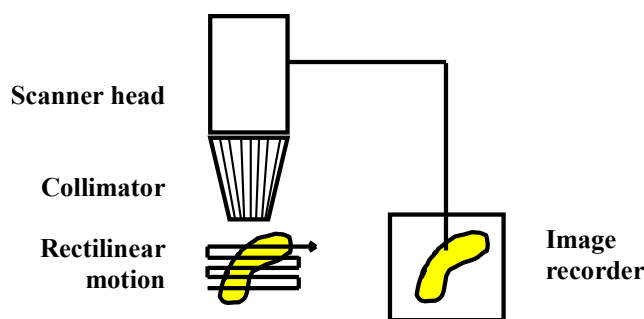
Fig 1
Rectilinear scanner and an image of the upper body.

The development of single large-area crystals of NaI(Tl) led to a radical change in radioisotope imaging with invention developed by Hal O. Anger at Berkeley in the late 50's. The introduction of the Anger Gamma Camera eliminated the disadvantage of the scanning imaging technique, where only a small portion of the decaying activity is being measured at the time. Most of the emitted gamma rays are "wasted" and contributes to an unnecessary radiation dose to the patient.

The more rapid acquisition that was introduced by the use of Anger Gamma Camera enabled dynamic studies that depict the redistribution of radionuclides. The consecutive images make cine of the functional behaviour of the organ like extraction and the excretion of radiopharmaceutical by the kidneys.

Some dynamic processes occur too rapidly to be effectively portrayed by a single sequence of image acquisition. Each image in the sequence would have too few counts to be statistical valid. However, if the dynamical process is repetitive, gated image sequence that accurately depicts the dynamic process. Gated acquisition is most commonly used for evaluating cardiac mechanical performance.

Radionucleide production and radiopharmaceuticals

In the thyroid the radioactive iodine is accumulated in the gland. However, for studying the function and depicting the image of most of other organs where the radioisotope is not directly absorbed, pharmaceutical compounds that are labelled with a radioactive isotope are developed. By choosing a compound that tends to accumulate in a specific organ, a local concentration of the radioisotope can be achieved.

Since the mid 60's ^{99m}Tc has been the most important radionuclide for a variety of radiopharmaceutical applications. This radioisotope is nearly an ideal compound to be used:

- ^{99m}Tc decays without emission of charged particles, no extra dose to the patient
- ^{99m}Tc emits only one gamma-ray and of "optimal" energy (142 keV), low enough to be detected with a thin scintillator and at the same time the energy is sufficiently high and therefore the attenuation of the intensity of photons in the body is limited
- ^{99m}Tc has a short half life, 6 hours, that limits the excess dose to the patient
- ^{99m}Tc can easily be produced at the nuclear medicine clinic by eluting it from the long-lived ($T_{1/2} = 66$ hours) mother isotope ^{99}Mo.
- ^{99m}Tc easily can be attached to specially designed pharmaceutical "kits" to form a radiopharmaceutical for a specific application
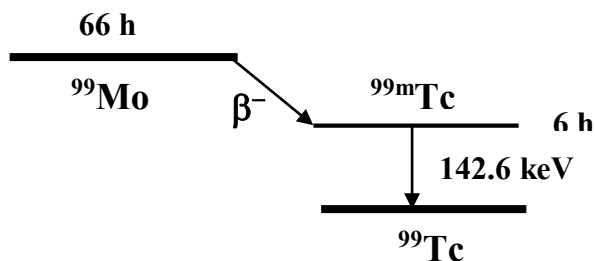

Fig. 2 Decay scheme of ^{99}Mo. The 66 h ground state decays with beta emission to the 6 h isomeric state of technetium, ^{99m}Tc. The isomeric state decays with 142.6 keV gamma emission to the ground state of ^{99}Tc.

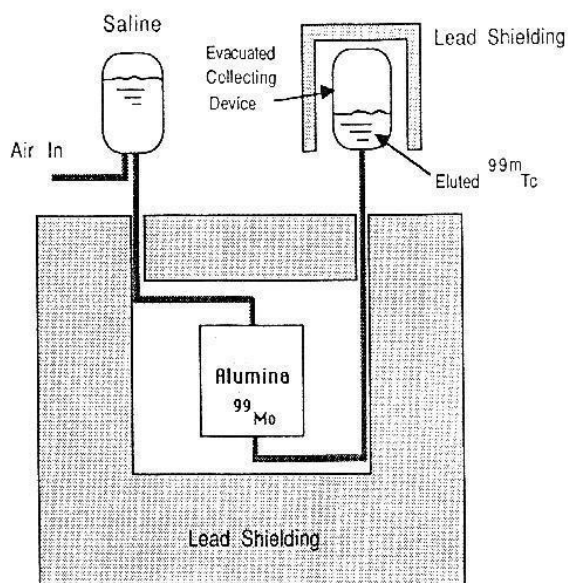*Fig. 3 Basic components of a ^{99m}Tc generator. The technetium is washed off, eluted, as sodium pertechnetate with sterile saline solution.*

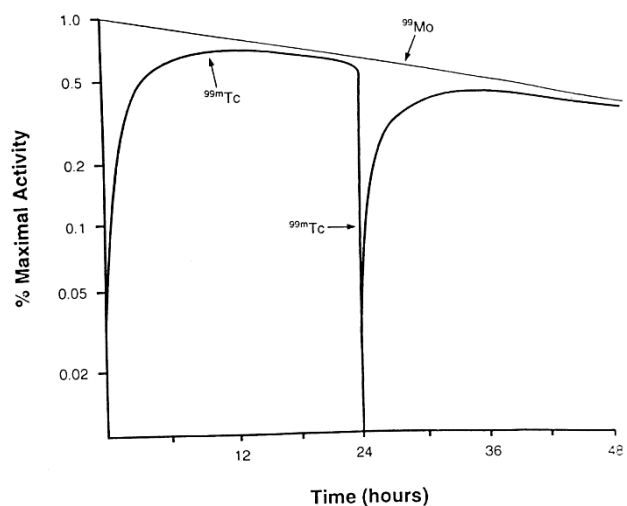*Fig. 4 Decay of activity of ^{99}Mo and growth and re-growth of activity of ^{99m}Tc in a generator, which is, eluted daily.*

The Anger Gamma Camera

The Anger Gamma Camera contains a disk shaped sodium iodine crystal coupled to a large number photomultiplier tubes, PMT's. A preamplifier is connected to the output of each PMT. Between the patient and the crystal is a collimator, usually made of lead, which only allows gamma rays approaching from certain directions to reach the crystal. The collimator is essential; the gamma camera without a collimator does not generate meaningful images.

The radiation enters the camera through the multi-hole collimator and strikes the large NaI(Tl) crystal a flash of light occurring at a particular place in the scintillator is recorded in part by several tubes, but with relative intensities varying with the distance between the tube and the scintillation event. From the relative intensities recorded in different tubes it is possible to determine where the original photon struck the scintillator and thus construct an image after many photons are counted and recorded. The major components of the Anger Gamma Camera are summarised and shown in fig. 5.
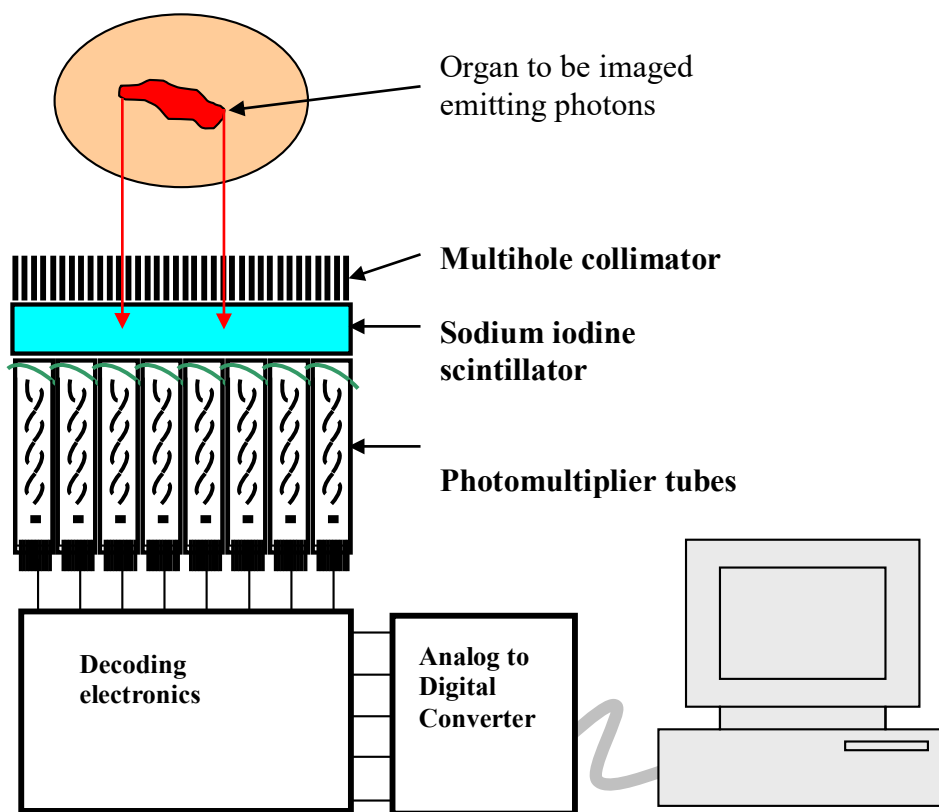
Figure 5. The principal construction of the Anger Gamma Camera

The collimator

The collimator of a scintillation camera forms the projection image by permitting the photons approaching the camera from certain direction to reach the crystal but absorbing most of the other photons. The collimators are made of lead or other material with high absorption. The most frequently used collimator is of the parallel-hole type with several thousands of hexagonal holes. The partitions between the holes must be sufficiently thick to absorb photons incident upon them. Therefore collimators are designed for radionuclides emitting certain energies.

A general-purpose low-energy multi-hole collimator consist of a lead disk, typically 25 mm thick, with closely packed circular or hexagonal holes (~25 holes/cm^2). The holes have a 2.5 mm "diameter" and the lead between them, called septa is 0.3 mm thick. This type of collimator can be used for energies up to 150 keV, e.g. ^{99m}Tc.

The spatial resolution of the gamma camera depends mainly on the electronic readout circuit of the scintillator and on the collimator. The resolution (Full Width Half Maximum, FWHM) of a parallel-hole collimator is defined as the width of the average intensity distribution obtained from a point source placed at a distance *z* from the collimator face.
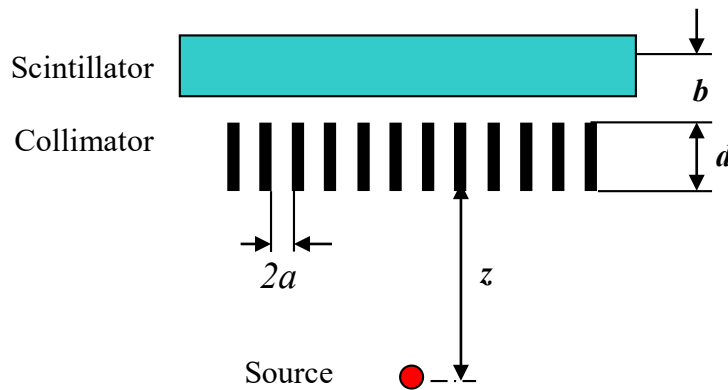

Figure 6. The paralell hole collimator

The resolution is

$$R_s = 2a \, (d + z + b) \, / \, d$$

where R_s is the collimator dependant spatial resolution, *2a* is the diameter of the collimator holes, *d* is the thickness of the collimator and *b* is the gap between the back side of the collimator and the image plane inside the crystal.

A higher resolution collimator would have more and smaller holes per cm^2 and therefore lower sensitivity. The total number of detected photons depends of course also on the amount of radioactivity and the imaging time. A "high-sensitivity" collimator on the other hand, has fewer and larger holes and consequently poorer resolution. This type is used for dynamic imaging where short exposure times are necessary and poorer resolution must be accepted.

A range of collimators is required to image different photon energies and to achieve sufficient compromise between spatial resolution and sensitivity. In addition to the above mentioned parallel-hole type there exist also converging, diverging and pinhole collimators.

The pinhole collimator is used at close distances primarily for high-resolution imaging of small organs (e.g. thyroid). The collimator provides a magnified image of the object see fig.7, and the magnification factor will depend on the ratio $(d+b) / z$. Typically the diameter $2a$ of the pinhole is in the order of a few millimeters and d is 20 – 30 cm.
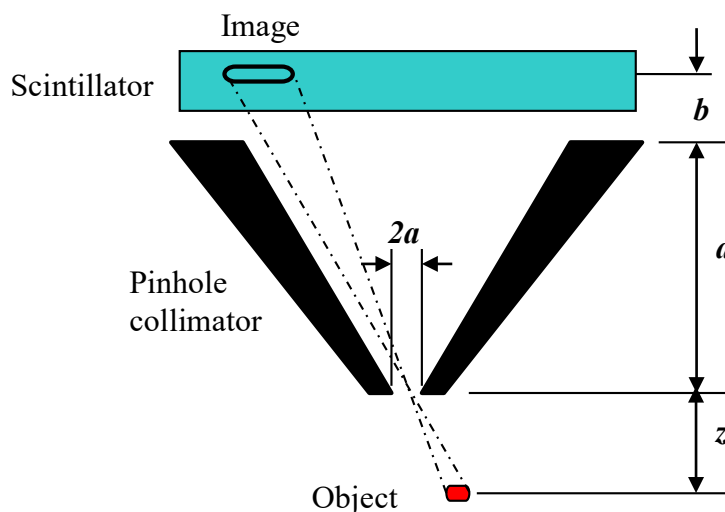

Fig 7. The pinhole collimator

The scintillator and the photomultipliers

The gamma camera contains a disk-shaped or rectangular NaI(Tl) crystal. The size is in the order of 30 – 50 cm. The thickness of the scintillator is a trade-off between the intrinsic resolution of the camera and the detection efficiency of the incident photons. Most modern cameras have crystals 9.5 mm (3/8") thick. The photo-peak efficiency of these crystals is approx. 90% for the 142 keV gamma rays from ^{99m}Tc. In figure 8 the detection efficiency of a NaI(Tl) scintillator is shown for different crystal thickness and energy.
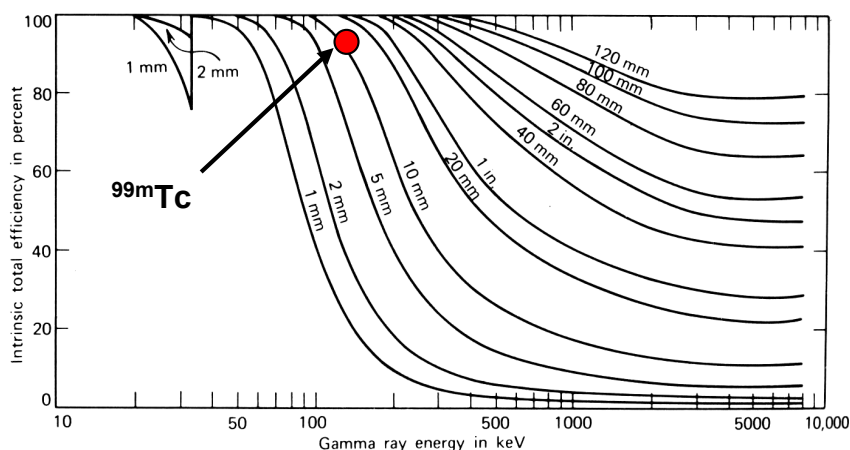

Figure 8. The intrinsic total detection efficiency of gamma rays with perpendicular incidence for various thickness of a NaI(Tl) scintillator. The detection efficiency of a 10 mm thick crystal for 140 – 150 keV photons is indicated

To protect the crystal from light and from atmosphere (NaI is hygroscopic) it is encapsulated in a thin aluminium cylinder with one flat glass window. The scintillation light is detected by an array of photomultiplier tubes, PMT's. Gamma cameras with disk-shaped scintillators are equipped with 37, 61 or 91 hexagonally placed PMT's depending on the diameter of the crystal. To minimize the loss of scintillation light PMT's with hexagonal front –face are used.
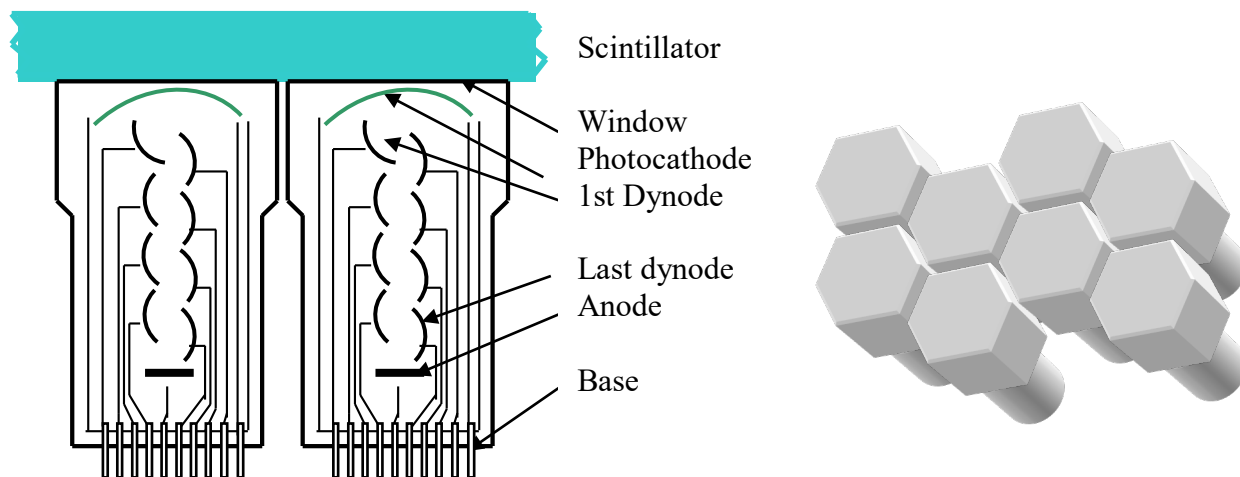
Figure 9. Hexagonal PMT's with scintillator and a cluster of 8 tubes

A photomultiplier tube is a vacuum tube usually made of glass that converts very small light signals into a measurable electric current. Fig 9 shows how the PMT's are built and how several tubes can be assembled to detect the light from a disc shaped scintillator.

Each tube has a transparent window to admit light and a semi-transparent photocathode made of a thin layer of photo-emissive material deposited on the inner surface of the window. The photocathode will emit electrons in response to absorbing photons. The electron multiplier consists of several electrodes, dynodes, covered with a layer of secondary emissive material. For each incident electron, the dynode emits several secondary electrons. These are accelerated to the next dynode by a potential approximately 100 volts producing even more secondary electrons. The number of electrons that reach the anode is multiplied up to 10^6 times depending on the number of dynodes.

The electronic circuit and the position logic

The absorbed photons in the scintillator will create light that is detected in principle by all the photomultipliers. The strongest signal will come from the closest PMT and the signal amplitudes from the PMT's decrease with the distance from original scintillation point.

Hal O. Anger, Berkeley, has as mentioned above suggested a method of determining the position of the light flash in the scintillator. (The abstract with some figures of his original paper is shown on the front page of this document.) The KTH Gamma Camera uses this type of readout. In recently built cameras however, the PMT signals are digitalized immediately after pre-amplification and the position of the detected photon is deduced with a help of front-end processors with dedicated software.

A resistive coupled network used by Anger provides the position information from the analogue outputs of the photomultiplier tubes. The output of each PMT is fed to a preamplifier for pulse amplification and shaping. The signals from the preamplifiers are combined via a resistor matrix into four composite signals X^+, X^-, Y^+ and Y^- before further processing. The total intensity of the signal, Σ, is given by

$$\Sigma = X^+ + X^- + Y^+ + Y^-$$

and the positions by

$$x = k * (X^+ - X^-) / \Sigma \qquad \text{and} \qquad y = k * (Y^+ - Y^-) / \Sigma$$
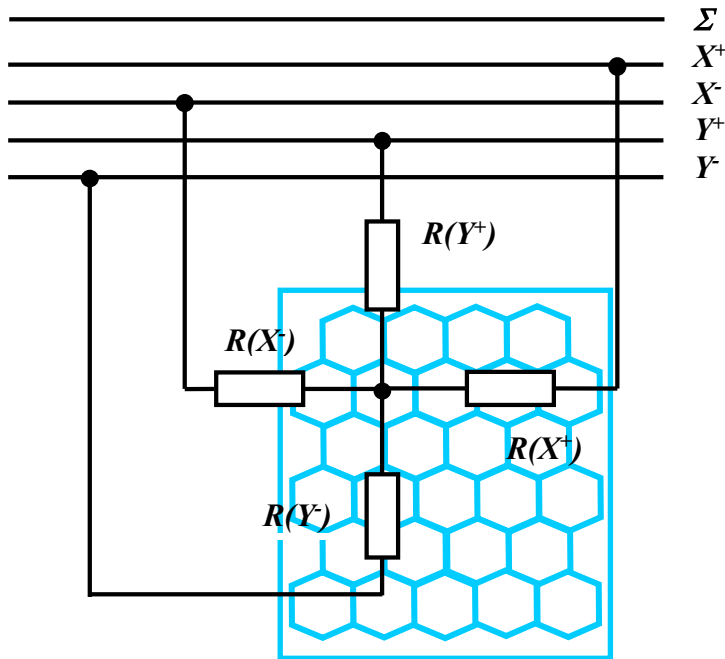
where k is constant.

Figure 10.
Four resistors are connected to each preamplifier output. The resistors are coupled to four outputs to form the composite signals X+, X-, Y+ and Y- . The sum of all PMT outputs is the Σ signal.

Performances, limitations and applications of a Gamma Camera

Performance

Uniformity is a measure of a camera's response to uniform irradiation of the detector surface.

Spatial resolution is a measure of a camera's ability to accurately portray spatial variations in activity concentration and to distinguish as separate radioactive objects in close proximity. The system spatial resolution is evaluated by acquiring an image from a point or line source to determine the full width half maximum, FWHM of the system at a specific distance to the source. The spatial resolution of the gamma camera significantly degrades as the collimator-to-patient distance is increased; see the subsection on collimators above.

Limitations

It should be remembered that the vast majority of the emitted photons never reach the scintillator. Over half of the photons are not detected because they are emitted in direction away from the detector and the collimator absorbs the photons with wrong direction. Only a tiny fraction of emitted photons has trajectories permitting pass through the collimator holes. Over 99,9% of the photons emitted during imaging are wasted. To improve statistics and thus the image quality by increasing the activity is limited. The maximum acceptable-dose restricts the activity administrated to the patient and thus the number of counts in the image.

Another limitation is the imaging technique. Scintillation cameras are operated in pulse-mode contrary to transmission imaging, i e. Computed Tomography where only the photon flux is recorded. In pulse-mode each event is analysed separately so that pulse-height discrimination can be employed. As shown earlier the pulse height discrimination (the use of SCA) is necessary for event localisation.

Applications

As mentioned in the previous chapters the gamma camera is mainly used for functionality studies where the uptake of a radio-pharmaca in an organ is measured. If *static acquisition* is used the single image is acquired for a preset time interval or until the number of counts in the image reaches a preset number.

In addition to this standard 2-dimensional imaging the gamma camera technique is used for a variety of other studies. In *dynamic acquisition,* a series of images is acquired one after another, for a preset time per image. This type of acquisition is used to study dynamic physiological processes, such as the transport of a radiopharmaceutical in the human body.

If the time of the arrival of the signal is registered together with the integral activity of a region a *time-activity curve* for an organ can be recorded. For instance a consecutive observation of both kidneys of a patient reveal quantitative uptake and excretion of the pharmaceutical marked with ^{99m}Tc activity.

Gated acquisition is used to study dynamic processes that occur too rapidly to be effectively portrayed by dynamic acquisition e.g. if each image in the sequence contains too little data to be statically valid. If the dynamic process is repetitive, gated acquisition may permit the acquisition of an image sequence that accurately depicts the dynamic process. Gated acquisition is frequently used for evaluating cardiac mechanical performance and requires a physiologic monitor (ECG) that provides a trigger pulse to the computer at the beginning of each cycle of the process being studied.

3D image reconstruction of an object is made using the Single Photon Emission Computed Tomography (SPECT) method. SPECT is the most widespread technique and is frequently combined with gated acquisition for heart investigation. SPECT requires one or more gamma cameras with collimators, mounted on a gantry, which allows rotation around the organ to be depicted. During the rotation procedure, multiple two-dimensional projections of the three-dimensional radiopharmaceutical distribution is acquired and stored. A standard SPECT-

examination involves more than 100 images taken from different angles around the object. If a large number of angular data samples are taken, it is possible to reconstruct the cross-sectional images that represent the radiopharmaceutical distributions in the body. The images are processed and combined in a computer to produce a 3D image. The image reconstruction is normally performed with filtered back projection algorithms.

The GE Neurocam
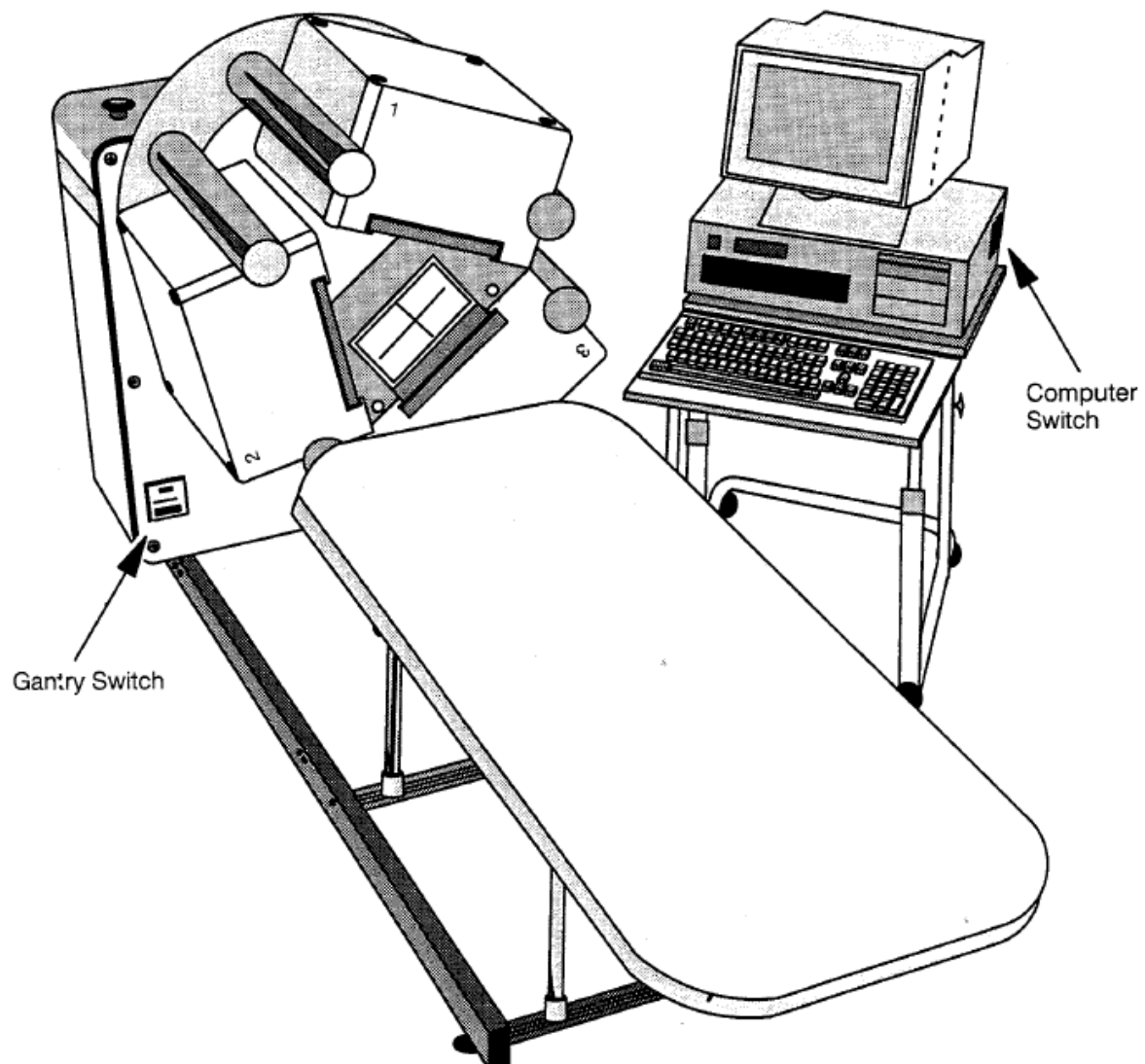
Figure 16. The GE Neurocam SPECT with three camera heads

The GE/CGR Neurocam is a triple-headed single photon emission tomography SPECT) system dedicated to multi-slice brain tomography. The system is donated to the School of Technology and Health at KTH by the Nuclear Medicine division of the Danderyd Hospital.

The Neurocam comprises three Anger-type gamma-cameras in a rotating gantry. The field of view (FOV) IS 20.0 * 17.6 cm. The front face of the cameras forms an almost equilateral triangular aperture within which the patient's head is positioned. The aperture is large enough to ensure to accommodate most adult heads but small enough to ensure close proximity imaging and hence better spatial resolution; the radius of rotation is 12.25 cm (centre of rotation to collimator face). The height of the headrest is fixed with respect to the gantry. The imaging table locks into place when pushed into the aperture. Each camera has 27 photomultiplier tubes (PMTs) coupled to a 6.5 mm-thick NaI (Tl) crystal with shielding for X- or gamma-rays of energy up to 170 keV. The collimators are light and easily handled. Thus, the Neurocam is suitable for the low-energy radionuclides technetium-99m, iodine-123, thallium-201 and xenon-133. Data acquisition is controlled by an IBM-compatible personal computer. Data are energy corrected on-line; linearity and uniformity corrections are made off-line for each planar image; centre of rotation (COR) corrections are made prior to tomographic reconstruction.

For more information go to: (Physical assessment of the GE/CGR Neurocam and comparison with a single rotating gamma-camera, 1992, European Journal of Nuclear Medicine and Molecular Imaging 19 (4): 236-242)

Collimator tests

To test the performance of the collimator a point source is placed in front of one of the camera heads and the resolution is measured as function of the distance to the source, *z*. For data acquisition the BTS is used and the image is analysed in a MatLab program. The Full Width Half Maximum, FWHM, resolution of the point-source image is determined for both x and y projections. To convert the measured channel numbers to centimetres the source is placed on a turn-table (gramophone) and the diameter of the recorded circle is measured, figure 16.
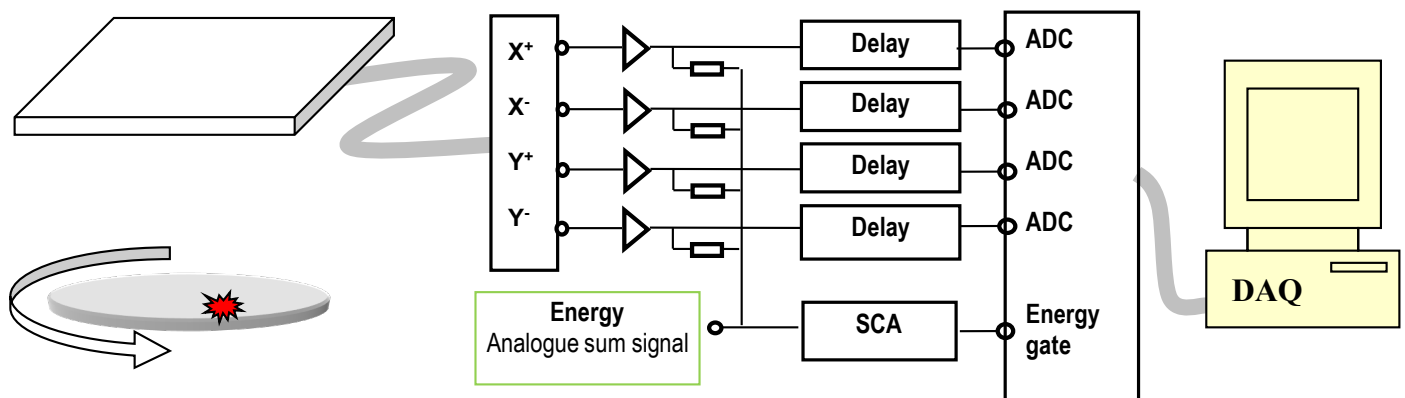

Camera Head 3
with Anger resistance matrix

Figure 17. Camera resolution FWHM is measured as function of z. The scale is converted from channel numbers to centimetres by measuring the image diameter of a circulating source.

The laboratory exercise

- Start the *Neurocam*,
- Start the computer
- Collect a gamma energy spectrum from a ^{57}Co source in *Camera Head 3*. Identify the photo-peak
- Adjust the energy window to accept only the photo-peak (122 keV) of the source
- Start the *Neurocam*, data acquisition program and collect images of the point source for distances between 0 and 35 cm. Note also the camera count-rate as function of distance.
- Calibrate the image for *x* and *y* directions in centimetres by collecting data from point sources positioned in defined places. Use an A4 sheet to mark positions.
- Measure the FWHM of the image as function of the collimator-source distance for a parallel hole collimator
- The beginning of a MatLab code (basically the reading in of the image) is available. It's called "load_gammacamera_measurement".

Preparatory exercises (to be completed BEFORE the lab!)

1. What is the basic difference between emission and transmission imaging in medicine?
2. Why is ^{99m}Tc so useful as radionuclide in gamma emission imaging?
3. How is ^{99m}Tc generated?
4. The major components of a gamma camera are …
5. What properties are necessary for a radiopharmaceutical to be successful in medical imaging?
6. What is the purpose of a collimator?
7. How does a camera image of a 10 cm diameter phantom filled with ^{99m}Tc look like, if the image is taken without a collimator?
8. How is the position of the photon impact on the scintillator determined in a gamma camera?
9. Calculate the number of full energy photons leaving a 30 cm diameter water-filled phantom if a small 37 mCi ^{99m}Tc source is placed in the centre of the sphere. Hint use NIST: html://physics.nist.gov/PhysRefData/XrayMassCoeff/cover.html
10. Calculate the absorbed dose rate in the phantom in Gy/s
11. This last exercise is designed as a way to help you learn the simple Matlab-programming steps needed for data treatment during the Gamma camera lab.
In this way you will be able to focus on the Physics and the technology behind Gamma-camera imaging during your lab without being distracted by Matlab-syntax problems.
Open a Matlab session and issue the following command:

    >> amatrix=rand(200,200);

This will generate a matrix (called amatrix) with dimensions 200 by 200 and with randomly generated elements. The elements will have numerical values in the interval [0,1].
Please note that each time you issue the above command the values stored in the matrix amatrix will be updated. If you want to generate a new matrix with new values or new

dimensions for testing purposes, it is advisable that you give the new matrix another name. (All names apart from mamoisanidiot are acceptable.)

Your task now is to write a "code" that will:
   a. Compute the sum of all columns and of all rows, respectively. (The result will be two vectors of 200 elements each with values in the interval [0,200]).
   b. Plot the sum of all columns and the sum of all rows in two separate graphs.

You should also perform simple tests to check that your "code" correctly does what it is supposed to do.

Write down your "code" and describe the tests you have performed and the corresponding results in a paper that has to be presented to the lab-assistant prior to or at the beginning of the Gamma camera lab.

Appendices:

A: Operating Neurocam
A.1 Switch on
1. Switch on the gantry power
2. Switch on the monitor and the Neurocam computer
3. The data acquisition program starts automatically. To start the program from DOS prompt type bts (for example after you have exited the acquisition program for transferring files to PC).

A.2 Switch off
1. Access the main menu by pressing ESC as many times as needed
2. Press F10 – Mainten.
3. Press F10 – Shutdown (it means only quit the program!)
4. Press F7 – Confirm
5. Now you should be at DOS prompt and you can switch off the computer, monitor and gantry.

A.3 Load and execute "0 static" protocol
1. Go to the main menu by pressing ESC as many times as needed

Steps 2 and 3 can usually be skipped since the protocol is already selected
2. Press F6 – Protocol
3. Select protocol static from the list and press Enter

4. Press F4 – P. Execute
5. Type the patient id (any characters, only use each id once!) and patient name
6. Choose yes in the correction mask option
7. Set the acquisition time to desired value (20-30 sec).
Changes have to be confirmed by F7 to come into effect.

8. Press F5 – Continue
9. Press F5 – Start
10. At the end of the acquisition, press F10 - Mainten and F10 - Shutdown. The image data will be stored on hard-disk.
11. If you want to transfer data to PC press F7 - Confirm and follow instructions in Appendix B

A.4 Energy window settings
The energy window size and offset can be changed by typing in actual numbers or by going into the spectrum display mode F2-Spc-Imgand window setting F3-Window. With the up/down arrow keys the window size can be changed. The CTRL+ left/right arrow keys set the offset of the window. F7 to save changes.

B: Transfer files between GE Neurocam SPECT computer and another PC via serial port

The Neurocam computer will be in the following called simply Neurocam, the computer (OSWindows) to transfer data to will be called just PC.

1. Connect the Neurocam computer and the PC with null modem cable (plug the cable into the RS232 connectors of the computers).

2. Start both the Neurocam computer and the PC. (PC:login: Lab, password: Student)

3. Start the hyperterminal program in the PC. You'll find it on the desktop.

4. When asked to type in a name type whatever you like. Choose "COM1" in "connect using" and "57600" in Bits per second".

5. Click on "Transfer", choose "Receive File" in the drop-down box of Transfer. In Place receive folder, select "C:\Users\Lab\Desktop\NeurocamData" and then press "Receive".

6. Start the term90.exe in the Neurocam computer (It is located in the C:\NC folder) by typing the following commands in the DOS command prompt:
c:
cd \NC
term90

7. Press the ALT+F buttons in the Neurocam computer. This opens the File menu of the term90 program.

8. Select the "Upload" menu item and the "ZMODE" protocol.

9. Select the file in the file selection window what you would like to transfer. The transfer starts automatically after the file selection. The program transfers only one file per time.

10. Press ALT+F to enter the menu and choose the "Exit" item to leave the data transfer program. The PC stores receives data files in a predefined folder (Desktop\Received). Note that the Neurocam stores the data files in the directory D:\. This is the current directory in the file selection window. The name of the data files starts with "DS00" followed by a four digit number. The highest number contains the last data of the last acquisition. The extension is .001 or .002 or a three digit number between 001 and 999.

11. If you need to go back to "1 static" protocol after transferring the data, press the ALT+X buttons in the Neurocam computer, choose yes to exit the program. Then enter the following commands in the DOS command prompt:
cd ..
bts