CHAPTER 15

DEVICES FOR EVALUATING IMAGING SYSTEMS

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15.1. DEVELOPING A QUALITY MANAGEMENT SYSTEM APPROACH TO INSTRUMENT QUALITY ASSURANCE

A quality management system (QMS) has three main components:

(a) Quality assurance (QA);
(b) Quality improvement;
(c) Quality control (QC).

The aim of a QMS is to ensure that the deliverables meet the requirements set forth by the users. The deliverables can be, in general, all the services provided in a nuclear medicine department, and the diagnostic imaging services in particular. In this section, the primary focus is the diagnostic imaging equipment and images produced by them.

15.1.1. Methods for routine quality assurance procedures

QA is a systematic programme for monitoring and evaluation of the process of production. It is an all-encompassing management plan to ensure the reliability of the production system. QA in diagnostic imaging, however, can help minimize the uncertainties and errors in equipment performance by supervising the entire image production process. This, in turn, will guarantee that the images generated are of diagnostic quality. QA can also help identify and rectify the problems, errors and malfunctioning and drifting of the performance earlier. Moreover, a QA programme can help the standardization of the image production process across centres and, thus, allows comparison of clinical results with other centres. This is especially imperative in multicentre clinical trials. A QA programme in nuclear medicine involves all aspects of nuclear medicine, including minimizing the exposure to personnel, patients and the public; preparation, safety, sterility

and administration of radiopharmaceuticals; patient handling; and ensuring the diagnostic quality of images produced.

QC is the process by which the performance level of a product is measured and then compared against the existing standards or tolerance values. QC activities are a subset of QA activities. QA focuses on the processes while QC focuses on the product.

QC with regard to imaging systems may entail:

— A series of performance measurements to assess the quality of the imaging system;
— Keeping the record of measurements;
— Monitoring the accuracy and precision of the results;
— Taking corrective actions in case the performance measurements are outside the tolerance levels or above the predetermined action levels.

The items above require:

— Defining the performance parameters to be measured;
— Preparing written procedures as to how and by whom the measurements should be carried out;
— Establishment of the frequency of performance tests and expected results in the form of tolerance and action levels;
— Training the persons who perform these measurements;
— Designing record forms (preferably electronic) to keep the measurement values;
— Logging and reporting all of the problems and actions taken.

Tolerance levels define the range within which the results are acceptable while action levels define the range beyond which a corrective action is required. The upper level of the tolerance range may concur with the lower level of the action range. If the performance of the system is just outside the tolerance range, an immediate corrective action may not always be needed and the imaging system can still be used for patient scanning, but a close monitoring of the system performance is critical in the following tests. Record keeping is critical and essential for trending the performance parameters to monitor the system and to intervene, when necessary, in an effective and timely manner.

Phantoms are indispensable tools for QC measurements. They are utilized to evaluate diagnostic imaging systems, as well as for other reasons in radiation protection, radiobiology and radiotherapy. The phantoms can be hot (containing a known amount of radioactivity) or cold (containing no radioactivity) for primarily measuring radiation interaction. Phantoms used in nuclear medicine

are usually injected with a radioisotope simulating a particular organ or tissue structure containing a particular radiopharmaceutical, while X ray computed tomography (CT) QC phantoms are employed to measure CT values of water and/or other materials by simulating different tissue types. IAEA Human Health Series Nos 1 and 6 [15.1, 15.2] include an extensive discussion of the QA for positron emission tomography (PET) and PET/CT systems, and single photon emission computed tomography (SPECT) systems, respectively.

The International Commission on Radiation Units and Measurements (ICRU) in ICRU Report 48 [15.3] defines the phantom as a material object that includes one or more tissue substitutes and is used to simulate radiation interaction in the body. Furthermore, "any material that simulates a body tissue in its interaction with ionizing radiation is termed a tissue substitute" [15.4].

The ICRU distinguishes the 'physical phantoms' from what are usually called 'software phantoms' by defining them as 'phantoms' and 'computational models', respectively. In this chapter, the convention of the ICRU is followed for consistency in the terminology and to avoid any potential misunderstanding that the other naming conventions may lead to.

According to Ref. [15.3], phantoms can be grouped under three categories with respect to their primary usage: dosimetric, calibration and imaging phantoms. The dosimetric phantoms are used to measure absorbed dose while calibration phantoms are employed to calibrate a particular photon detection system such as a PET scanner to convert the number of detected photons to actual activity per tissue volume. An imaging phantom is used for assessing image quality or characterizing imaging systems. The ICRU further defines three subcategories under the above three functional categories. These are body, standard and reference phantoms. Body phantoms are built in the shape of a body and consist of multiple tissue substitutes or organs. These phantoms are more often referred to as anthropomorphic phantoms as they simulate the human body. The anthropomorphic torso phantom, which is discussed later in the chapter, consisting of liver, heart, spine and lung inserts, is used in nuclear medicine for testing image quality and is an example of this category.

In this chapter, physical phantoms or simply phantoms and computational models that have applications in nuclear medicine are discussed. Throughout this chapter, many commercial phantoms are mentioned and are pictured in figures for ease of understanding. This does not, however, constitute an endorsement of these commercial products.

15.2. HARDWARE (PHYSICAL) PHANTOMS

The use of phantoms dates back to the beginning of the 20th century. In the 1920s, water tanks and wax blocks were often used for X ray experiments and, to this day, these materials are still in use in certain applications. In the 1960s, more reliable tissue substitutes and sophisticated phantoms began to appear.

Today, phantoms are used in performing numerous tasks within the field of diagnostic imaging and radiation therapy. This includes testing the performance of imaging equipment, measuring radiation dosage during therapy, teaching interventional image guided procedures and servicing equipment in the field.

Hardware phantoms are the indispensable tools for medical physicists to enquire about or characterize medical imaging systems. These phantoms provide the means to determine, not only qualitatively but also quantitatively, the performance characteristics of medical imaging systems.

As compared to computational models, physical phantoms may be advantageous in that data are acquired with an actual scanner and contain the effect of the parameters that impact on the entire photon detection process. One major disadvantage of physical phantoms, however, is the difficulty of simulating the change of the activity in an organ in time. Although phantoms that simulate cardiac motion, for instance, are available commercially or are being developed by researchers in various institutions, in general, phantoms simulating physiological processes such as breathing are difficult to build and are not widely available.

In this section, the hardware phantoms that are used to measure the performance characteristics of gamma cameras and PET scanners are discussed. Some of these phantoms are also known as test phantoms. Their physical characteristics are reviewed along with a brief description of their purpose of use. Some practical suggestions are also provided about the preparation of the phantoms that require injection of radioactivity. Although the focus of this section is primarily on discussing the phantoms themselves, the positioning and data acquisition requirements are also addressed. The analysis of the acquired phantom data is not the subject of this chapter. For the analysis of gamma camera and SPECT performance test data, please see Ref. [15.5] in which the test methods suggested by the National Electrical Manufacturers Association (NEMA) are discussed. The authors have also developed a software application and made it publicly available free of charge [15.5].

15.2.1. Gamma camera phantoms

The gamma camera is the most widely used diagnostic imaging system available in nuclear medicine departments. Owing to their physical characteristics,

gamma cameras require very close attention and, therefore, more frequent and a larger number of tests than any other diagnostic imaging modality in radiology. One of the important QC tests that has to be carried out daily on every gamma camera is the uniformity test. This test shows the current status of the gamma camera and allows monitoring of any possible deterioration in the performance of the camera. It can also signal whether there has been any malfunctioning in the detector elements, such as the photomultiplier tubes or the crystal, since the last QC test was conducted. These assessments can be performed qualitatively or quantitatively by a computer program.

15.2.1.1. Point source holders

This phantom is used to hold point sources that are employed in intrinsic uniformity, resolution and linearity measurements. It is made up of lead and its main purpose is to shield the walls, ceiling and personnel, and collimate the γ radiation to the detector. Figure 15.1 shows a picture of a source holder. Copper plates (1–2 mm thick) should be placed in front of the source holder to act as absorbers and stop the low energy photons. When placed on the floor, source holder height can be adjusted such that the point source is directed to the centre of the detector under investigation.

FIG. 15.1. Point source holders in a slanted position so that they can point to the detectors from the floor.

15.2.1.2. ^{57}Co flood sheets

Gamma cameras should also be tested extrinsically (collimator in place) using a ^{57}Co sheet source. The cost of ^{57}Co sheet sources is relatively high and they should be replaced every 2 years. It should be noted that new sheet sources

may contain ^{56}Co and ^{58}Co impurities. These radionuclides have a shorter half-life (77.234 and 70.86 d, respectively) than that of ^{57}Co (271.74 d) and emit high energy γ rays (>500 keV). If the impurities result in non-uniformities, the sources can also be left to decay for a while before being used. It is advisable to place the sheet source at a distance of 5–10 cm from the collimator during the scan. Figure 15.2 shows a commercial ^{57}Co flood source.

FIG. 15.2. Picture of a ^{57}Co flood source.

15.2.1.3. Fillable flood phantoms

Although ^{57}Co flood sources are more convenient and easy to use, their higher cost may be a factor affecting accessibility. If one cannot have access to ^{57}Co flood sources, then a fillable water phantom source is a good alternative. These phantoms are available commercially but they can also be manufactured in a machine shop from Perspex. The commercial ones are available in different dimensions for different detector sizes. It is necessary to be careful in filling these phantoms to prevent bubble formation, contamination of the outside surface of the phantom or the workplace, and/or bulging of the phantom in the centre. Bulging of the phantom and air bubbles formed in the phantoms can affect the uniformity of the captured image. Depending on the size and volume of the phantom, around 370 MBq (10 mCi) of ^{99m}Tc activity will be sufficient to give a count rate of 20 kcounts/s in the image. The acquisition of the image is performed in the same way as the ^{57}Co flood sources.

15.2.1.4. Slit phantom

Slit phantoms are used to measure the intrinsic resolution of a gamma camera detector. The phantom is made of a 3 mm thick lead mask consisting of 1 mm wide parallel slits that are 30 mm apart. Slit phantoms, which are usually manufactured by the gamma camera vendors, vary in size to fit perfectly to particular detectors. They are made in pairs to measure the intrinsic resolution in the X and Y directions (see Figure 15.3). These masks are placed in the closest possible proximity to the crystal covering its entire area. Measurement is performed using a ^{99m}Tc point source centred at a distance more than five times the largest dimension of the useful field of view (UFOV) of the crystal. The activity of the point source is adjusted, so that the count rate is less than 20 kcounts/s.

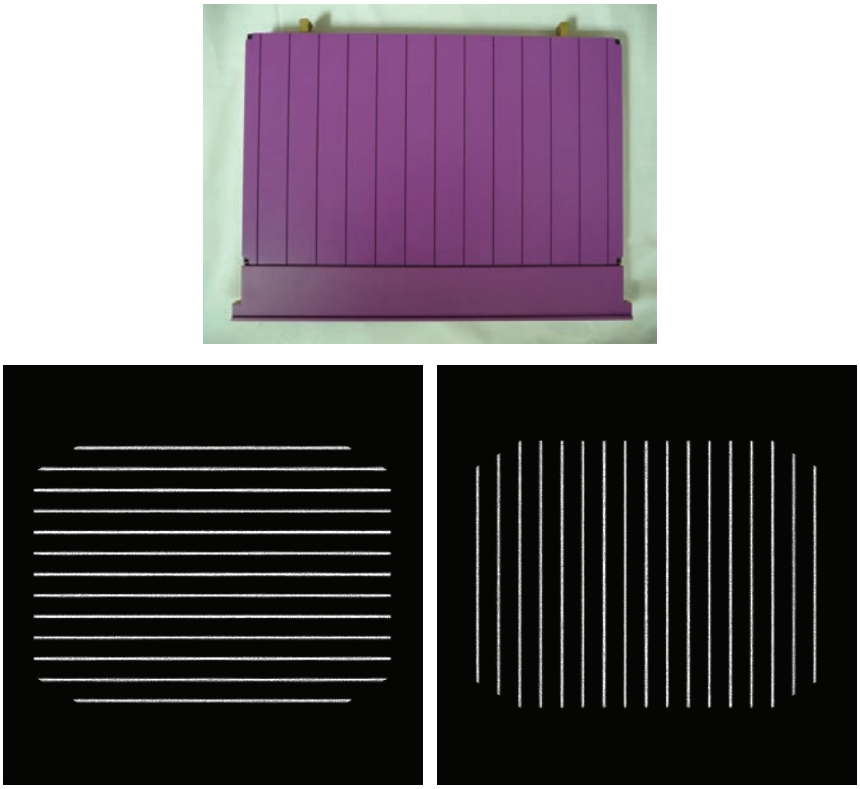


FIG. 15.3. Top: picture of the slit phantom designed for a cardiac camera whose field of view is smaller than that of a typical gamma camera. Bottom: acquired images of the slit phantoms for a typical gamma camera to measure the resolution in the Y (left image) and X (right image) directions. The white vertical and horizontal lines denote the image of 1 mm slits.

15.2.1.5. Dual-line source phantom and scattering medium

This phantom, suggested by NEMA NU 1-2007 [15.6], is used to measure the extrinsic resolution of the system with and without a scattering medium. It consists of two parallel line sources 1 mm in internal diameter and with a centre to centre distance of 5 cm. The line sources are built so that they are positioned 10 cm above the collimator. Figure 15.4 shows a simple custom built, dual-line source phantom. The capillary tube shown as dark lines in the figure is commercially available but a butterfly IV line can also be utilized.

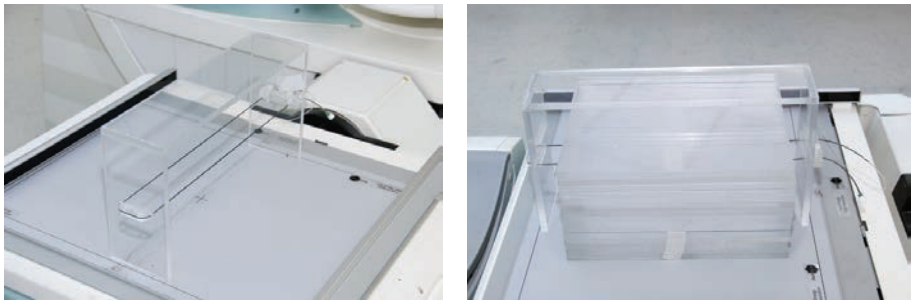


FIG. 15.4. A custom built, dual-line source phantom. On the left is the phantom positioned on the detector, and on the right the same line sources are immersed in a scattering medium consisting of sheets of Perspex.

The line is filled with ^{99m}Tc activity solution with a concentration of about 550 MBq/mL (15 mCi/mL) to achieve an adequate count rate when used with the scattering medium. When measuring X and Y resolutions, the lines are placed parallel to the Y and X directions, respectively. In both cases, one of the lines should be positioned in the centre of the field of view (FOV). The acquired image should have at least 1000 counts in the peak channel of the line spread function.

To measure the extrinsic resolution with scatter, the dual-line source is embedded into Perspex sheets, 10 cm of which are placed between the collimator and the line sources and 5 cm placed above the lines as seen in Fig. 15.4. The Perspex sheets under the sources create a scattering medium and the ones above a backscattering medium. For a perfect contact between the sheet and the line sources, it is recommended to make two grooves, through which the lines run, in one of the sheets to insert the two lines.

15.2.1.6. Bar phantom

The second most frequent QC test in nuclear medicine is the resolution test performed with bar phantoms. Bar phantoms can be used to measure,

semi-quantitatively (i.e. visually), the extrinsic and the intrinsic resolution of a gamma camera. Images of bar phantoms can also be useful for the qualitative evaluation of the gamma camera linearity which is normally measured by the slit phantom.

Bar phantoms are made of lead strips embedded into plastic and typically arranged in four quadrants. The lead strips are radio-opaque, while plastic strips are radio-lucent. Each quadrant has strips of different thickness. The rectangular bar phantom image shown in Fig. 15.5 (middle) has four quadrants with strip sizes of 2.0, 2.5, 3.0 and 3.5 mm, while the image on the right has four quadrants with strips of sizes 3.2, 4.6, 6.3 and 10 mm. In the images of the bar phantoms, displayed in grey colour maps, white lines correspond to the plastic strips while black lines correspond to lead strips. In a bar phantom, the strips are separated with the same distance as the strip width.

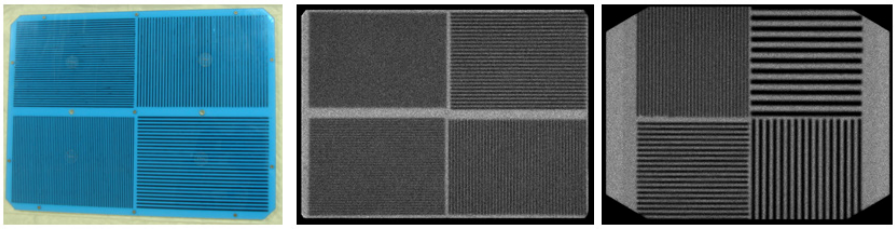


FIG. 15.5. Left: picture of a typical four-quadrant rectangular bar phantom. Middle: image of the left bar phantom acquired by an ECAM gamma camera. Right: image of a bar phantom acquired with an ADAC FORTE gamma camera. Both images were acquired at a matrix size of 512 × 512 and with a total count of 10 Mcounts.

In routine QC tests, normally performed weekly or biweekly, bar phantoms are used for the visual assessment of the extrinsic resolution (collimator mounted), together with a flood source discussed in the previous section. Normally, a low energy high resolution, parallel-hole collimator is used during this test. The bar phantom is first placed directly on the collimator and the flood source is placed on top of the bar phantom. Since the gamma camera resolution is dependent on the distance from the detector, operators should make sure that the bar phantom and the collimator are in direct contact with each other. A 10 Mcount image of the bar phantom is normally acquired and evaluated visually to check the detector resolution and linearity.

When used for determining the intrinsic resolution, the bar phantom is again placed on the detector without the collimator in place, and a ^{99m}Tc point source is placed at a distance five times the largest dimension of the crystal away from the bar phantom. As a rule of thumb, the intrinsic resolution of a detector

in terms of the full width at half maximum (FWHM) of the line spread function can be approximately determined as FWHM ≈ $1.7S_b$, where S_b is the size of the smallest resolvable bars.

15.2.1.7. Dual-line phantom for whole body imaging

This phantom is used to test the whole body resolution of a gamma camera system. It consists of two parallel line sources which are 1 mm in internal diameter and 10 cm centre to centre. Figure 15.6 shows a custom built, dual-line phantom. The line is usually filled with ^{99m}Tc activity with a concentration of about 370 MBq/mL (10 mCi/mL) to achieve an adequate count rate. During the testing, the line sources are placed at a distance of 10 cm from both collimators. When measuring the perpendicular resolution, the lines should be placed parallel to the bed direction with one of them being in the centre of the bed. When measuring the parallel resolution, the lines should be positioned perpendicular to the direction of the bed movement. The whole body resolution is calculated from the FWHMs of the line profiles extracted from the image of the dual-line sources.

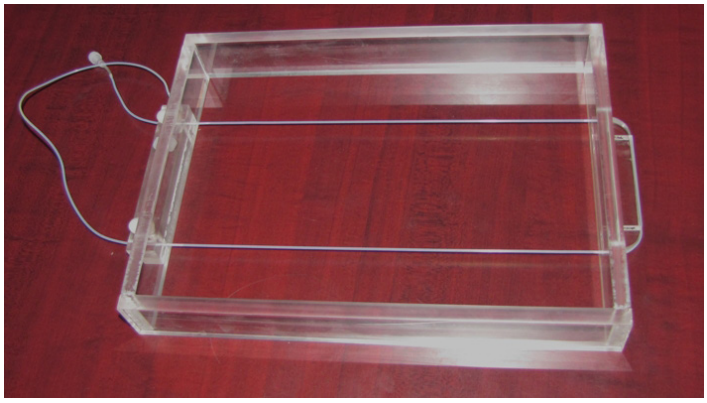


FIG. 15.6. Dual-line phantom for whole body resolution tests.

15.2.1.8. Planar sensitivity phantom

In a planar sensitivity test, the accuracy of the response of the detector to a radioactive source of known activity is measured for the particular collimator. It is suggested to use a Petri dish containing around 3 mm of water homogeneously mixed with a suitable activity (around 40 MBq) of ^{99m}Tc. The activity should be drawn into a syringe and then measured accurately in the dose calibrator. After injecting the activity in the Petri dish, the residual activity in the syringe

should be measured. The residual activity is subtracted from the initial activity to determine the net activity injected into the dish. This dish should be placed at a distance of 10 cm from the face of the collimator. It is recommended to acquire two images. The average count, in units of counts per megabecquerel per second or counts per minute per microcurie, is determined to measure the planar sensitivity of the system.

15.2.1.9. Multiple window spatial registration phantom: lead-lined point source holders

A multiple window spatial registration test measures the camera's ability to position photons of different energies. In this section, the phantom is discussed, as described in Ref. [15.6], together with its preparation and the measurement procedures. The details of the test conditions and test phantoms can be found in Ref. [15.6]. A schematic drawing of the lead phantom is given in Fig. 15.7. As suggested by NEMA, nine of these lead-lined source holders are placed on the surface of the detector. The relative position of each holder is shown in the drawing. Plastic vials, as seen in Fig. 15.7, can be used to hold the actual activity of ^{67}Ga (~7–11 MBq (200–300 μCi) in each). Other acquisition parameters and camera settings are given in Table 15.1.

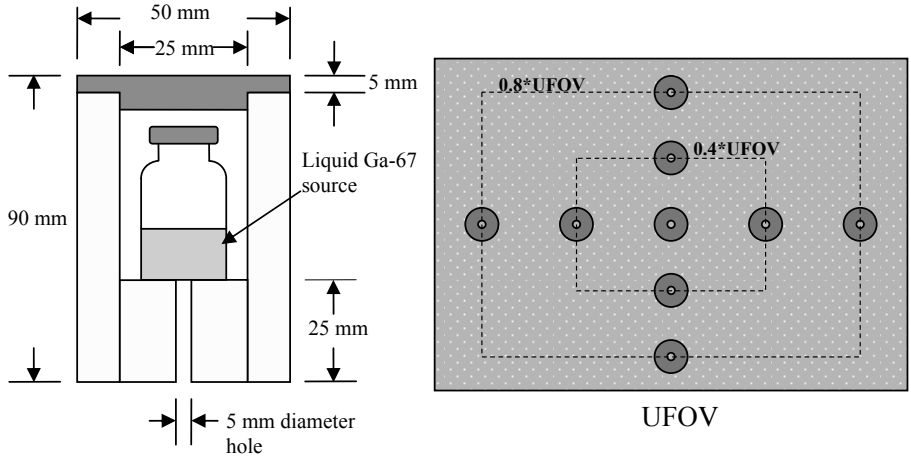


FIG. 15.7. Multiple window spatial registration phantom lead-lined point source holders. On the right is the top view of the point sources or source holders placed on the detector crystal. The locations of the point sources are determined by multiplying the dimensions of the useful field of view (UFOV) by 0.4 and 0.8. On the left is the cross-sectional view of the source holder together with the source vial.

Images of nine (or four) point sources of ^{67}Ga are acquired normally at three different photopeak energy windows (the three photopeaks for ^{67}Ga are 93, 185 and 296 keV).

The aim of the subsequent calculation is to find the centroids of these points in the image acquired at different energy windows and to compare the displacement between the point source images acquired at different energy windows. The maximum displacement between the centroids of point sources is the performance parameter indicating the error in multiple window spatial registration. The details of the calculation of this performance parameter can be found in Ref. [15.6].

TABLE 15.1. IMAGE ACQUISITION AND CAMERA SETTINGS

Radionuclide	^{67}Ga
Activity	~7–10 MBq in each source
Total counts	1000 counts in the peak pixel of each point source
Energy window	15%
Count rate	<10 kcounts/s
Pixel size	<2.5 mm
Matrix size	~1024 × 1024

15.2.2. SPECT phantoms

15.2.2.1. Triple-point source for SPECT resolution

Triple-point source phantoms are used for measuring the SPECT resolution in air (i.e. under no scatter conditions) or measuring centre of rotation (COR) alignment. Further details on the test conditions and the phantom can be found in Ref. [15.6].

For this purpose, thin-walled glass capillary tubes with an internal diameter of less than 2 mm are used. These point sources can be prepared as follows. First, a ^{99m}Tc solution of high concentration (about 5.5 GBq/mL) is prepared in a small (1 mL) syringe. Then, drops of small sizes are created on the surface of a clean plastic. These small drops can be drawn up into the capillary tubes by the principle known as capillary action by simply touching them. It may take a few trials to get a small size drop. At the end, the capillary tubes should be sealed on both ends with a capillary tube sealer such as Critoseal®. The point sources should be made as spherical as possible, that is, their transaxial and

axial extents should be similar in length. Their maximum dimension (the axial extent of the activity) should not exceed 2 mm. The activity in the point sources should not vary more than 10%. The point sources should be suspended in air and positioned in accordance with the suggestions in Ref. [15.6] (Fig. 15.8). An alternative practical solution to suspend the point sources in air is to mark the positions of the point sources on a thin paper attached to a polystyrene (widely known as Styrofoam) sheet, and use this as a source holder. The scatter caused by the holder should be negligible.

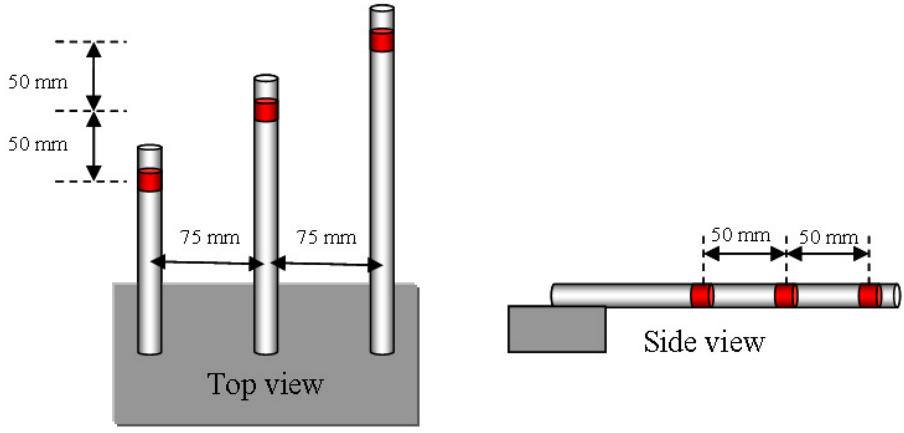


FIG. 15.8. Top and side views of the position of the point sources as suggested by the National Electrical Manufacturers Association.

15.2.2.2. Triple-line source phantom for SPECT resolution

The SPECT resolution with scatter is measured using the triple-line source phantom. This performance test is normally performed as part of the acceptance testing and annual testing. As described in Ref. [15.6], this phantom consists of a cylinder made of plastic (lucite or Perspex) with three line sources oriented along the axial direction (see Fig. 15.9). The cylinder is filled with water to create a scattering medium. The line sources are available either as inserts of ^{57}Co lines or hollow metal tubes to be filled with ^{99m}Tc solution. Here, the latter is discussed (Fig. 15.10). The inner diameter of the line sources is less than 2 mm. Both ends of the line sources are available for injecting the activity and are normally closed with small caps after the injection.

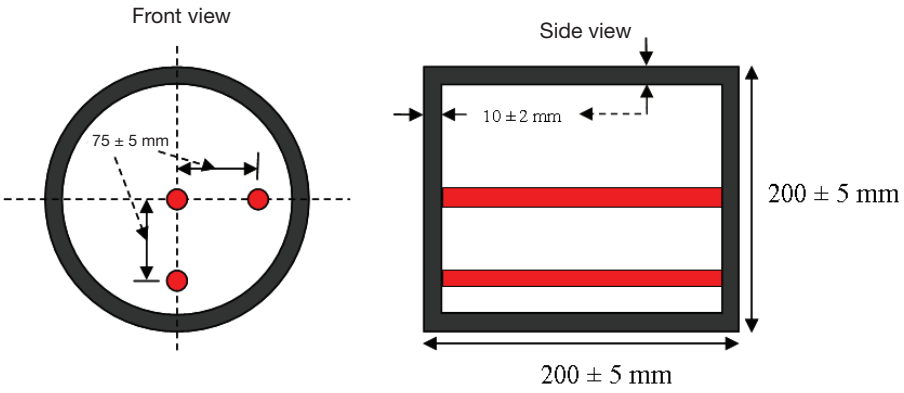


FIG. 15.9. Schematic drawing of the front and side views of a triple-line source phantom.

FIG. 15.10. A commercial triple-line source phantom with three line sources inside. The tank is filled with water to simulate a scattering medium.

The line sources should all be emptied of the decayed solution left from the previous test using two empty syringes attached at both ends of the line source. During the injection of each line source, two syringes are attached to both ends, one empty and one with activity of a concentration around 300–500 MBq/mL. While pushing the plunger of the syringe with the activity, that of the empty syringe should also be pulled very slowly until ^{99m}Tc solution appears from the other end. The filled line source should be securely sealed from both ends with the original caps, ensuring that there is no leak. It should also be ensured that the entire line source is uniformly filled.

During measurement, according to Ref. [15.6], the centre line source should be on the axis of rotation centred in the FOV within ±5 mm. The pixel size should be small enough (<FWHM/3) to prevent aliasing. Since this test has to be carried out with the collimator, a high resolution collimator is the best choice. During data acquisition, a 0–360° range should be evenly covered. Some of the acquisition parameters and camera settings are given in Table 15.2.

TABLE 15.2. ACQUISITION PARAMETERS AND CAMERA SETTINGS FOR THE SPECT RESOLUTION WITH SCATTER TEST

Radionuclide	^{99m}Tc
Count rate (kcounts/s)	<20
Total kilocounts per view	100
Scan time/view	~5 s at 20 kcounts/s
Energy window	15%
Collimator	Low energy high resolution
Radius of rotation	150 ± 5 mm
Total number of views	≥120
Pixel size	<2.5 mm

After the measurement, the resolution parameters should be calculated according to the method set forth in Ref. [15.6].

15.2.2.3. Volume sensitivity and detector to detector variation measurement phantom

Volume sensitivity is the total system sensitivity to a uniform concentration of activity in a specific cylindrical phantom. Factors such as detector configuration, collimator type, radionuclide, energy window setting and source configuration will impact the volume sensitivity in SPECT. Detector to detector sensitivity variation is the relative difference in sensitivity of the individual detector heads in a tomographic mode. The data acquired in a volume sensitivity test are directly used to calculate this performance parameter as well.

The volume sensitivity in SPECT is measured using a cylindrical phantom with an inner diameter and a length of 200 ± 5 mm (see Ref. [15.6]). The recommended wall thickness is 10 ± 2 mm. The volume of the phantom has to be accurately measured to accurately calculate the source concentration. The

phantom is filled with water uniformly mixed with a known amount of activity (approximately 350 MBq) of ^{99m}Tc. The activity amount should be such that the count rate at the photopeak energy window is 10 000 ± 2000 counts/s. The following parameters have to be accurately determined and recorded to calculate the volume sensitivity:

— Volume of the phantom;
— Pre- and post-injection syringe activity to determine net injected activity;
— Elapsed time half way through the SPECT acquisition;
— Total scan time.

Further details of the measurement and calculations can be found in Ref. [15.6].

15.2.2.4. Total performance test phantoms

Image quality measures or overall SPECT system performance, such as noise, tomographic uniformity, contrast and lesion detectability, are measured using total performance phantoms. These phantoms are commercially available and are not so easy to build in an institutional workshop. There are several commercial phantoms for this purpose. Some of the phantoms that are frequently used to assess the performance of a SPECT system are discussed. It should be noted that these phantoms can also be used to evaluate PET systems.

15.2.2.5. Carlson phantom

The Carlson phantom (designed and developed by R.A. Carlson, Hutzel Hospital, Detroit, MI, USA, and J.T. Colvin, Texas Oncology PA, Dallas, TX, USA) in this category is frequently used for evaluating the tomographic uniformity, image contrast, noise and linearity. The main source tank (see Fig. 15.11) is made of acrylic with dimensions: 20.32 cm inside diameter, 21.59 cm outside diameter and 30.48 cm length. The phantom comes with various inserts, which are demonstrated and described in Fig. 15.11, to evaluate the performance parameters noted above. The thick plastic screws on the top lid allow easy filling and draining of the tank with water. The ^{99m}Tc solution injected inside the tank serves as the background activity, which may vary between 300 and 550 MBq, depending on the collimator used [15.7].

There is an insert or section for each performance measure. The SPECT uniformity is assessed using the uniform section of the phantom. The non-uniformities in the gamma camera can result in severe ring or bull's-eye artefacts. These artefacts can be checked for by looking at the uniform transverse

slices. The amount of noise can be quantitatively calculated from the uniform section.

15.2.2.6. Jaszczak circular and elliptical phantoms

Similar to the Carlson phantom, Jaszczak elliptical and circular phantoms are used to evaluate the overall performance of SPECT systems after a repair or preventive maintenance, or during acceptance testing or quarterly testing. In addition to the purposes above, these phantoms can be used in evaluating the impact of reconstruction filters on resolution, as well as for other purposes in research studies.

Jaszczak phantoms consist of a main cylinder or tank made of acrylic with several inserts (see Fig. 15.12). They are manufactured and sold by Data Spectrum Corporation (NC, USA). Jaszczak phantoms, which may have circular or elliptical tanks, come in several different flavours. The cylinders of all models of the circular flanged phantoms have the same physical specifications: 21.6 cm inside diameter, 18.6 cm inside height and 3.2 cm wall thickness. The principal differences between the different models of the flanged cylindrical Jaszczak phantoms are the diameters of the rods and solid sphere inserts. The circular phantom has flanged and flangeless models. The latter is recommended by the American College of Radiology for accreditation of nuclear medicine departments. These different models are designed to test a range of systems, from low resolution to ultra-high resolution, which has rods and spheres smaller than the others.

All Jaszczak phantoms have six solid spheres and six sets of cold rods. In flanged models, the sizes of the spheres vary. The number of rods in each set depends on the size of the rod in that set as different models of the phantom have rods of different sizes. In flangeless models, the diameters of the spheres are 9.5, 12.7, 15.9, 19.1, 25.4 and 31.8 mm, while the rod diameters are 4.8, 6.4, 7.9, 9.5, 11.1 and 12.7 mm. Both solid spheres and rod inserts mimic cold lesions in a hot background. Spheres are used to measure the image contrast while the rods are used to investigate the image resolution in SPECT systems.

15.2.2.7. Anthropomorphic torso phantoms

Anthropomorphic torso phantoms are used in testing gamma cameras in SPECT mode to evaluate data acquisition, attenuation correction and image reconstruction methods. They normally simulate or model the upper torso of the body (from the heart down to the diaphragm) of an average male or female patient. These phantoms consist of a body-shaped (elliptical) cylinder with fillable inserts for organs such as the heart, lungs and liver (see Fig. 15.13).

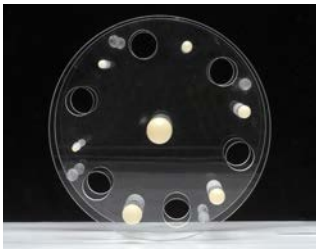
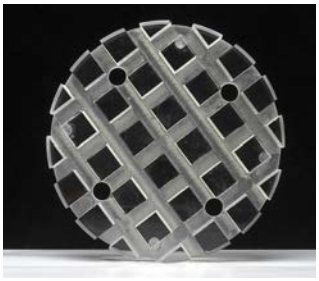
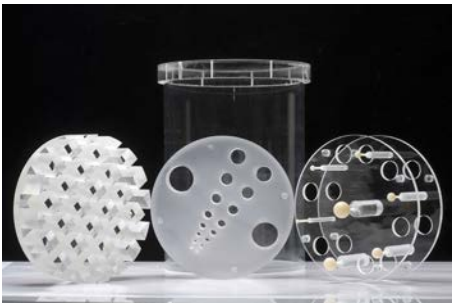
Phantom	Description
Hot lesions 	Eight pairs of holes drilled through a solid acrylic block, with diameters of 4.7, 5.9, 7.3, 9.2, 11.4, 14.3, 17.9 and 22.3 mm, model hot lesions with the background activity injected.
Cold rods and spheres 	Seven rods, with diameters of 5.9, 7.3, 9.2, 11.4, 14.3, 17.9 and 22.3 mm, simulate cold lesions. Each rod is 25% larger in diameter than the preceding one. Seven solid spheres of the same diameters as rods, the centre one being the largest, are attached to the rods.
Linearity/uniformity section 	Crossed grid of cut out channels, again in an acrylic block, can be used to assess the linearity. The region where only background activity is available is used to evaluate the tomographic or SPECT uniformity.
	Picture of the Carlson phantom tank together with all three inserts.

FIG. 15.11. Carlson phantom and its inserts.

FIG. 15.12. Jaszczak phantom used for verifying image quality (phantom by Data Spectrum Corporation, USA).

Defects can also be added to the heart insert. Lung inserts are filled with Styrofoam beads and water to emulate lung tissue density. The phantoms can be used to evaluate non-uniform attenuation correction methods including CT based attenuation correction in SPECT/CT systems and scatter compensation methods. When used with the optional cardiac insert, cardiac SPECT data acquisition and reconstruction methods may also be evaluated.

Filling the inserts with different distributions of radioactivity is not as easy as filling other phantoms because of the multiple organs and the organ to background ratios that need to be adjusted. To set the concentration ratios, the volumes of the organ inserts need to be measured accurately a priori. For a simulation of a 1110 MBq (30 mCi) sestamibi stress study, the injected activity concentrations, as suggested in Ref. [15.8], are given in Table 15.3.

Torso phantoms can be integrated with the fillable breast phantom, which is also commercially attainable. These breast phantoms allow the inclusion of inserts to simulate breast lesions that can be employed to evaluate lesion detectability.

The volumes in the second column in Table 15.3 are the measured volumes of the torso phantom inserts.

TABLE 15.3. SUGGESTED ACTIVITY CONCENTRATIONS AND MEASURED VOLUMES OF INSERTS FOR THE ANTHROPOMORPHIC TORSO PHANTOM

Section	Volume (mL)	Activity concentration (kBq/mL)	Total activity (MBq)
Heart	117	250	30
Tissue	8620	25	225
Liver	1177	150	175
Lungs		0	0

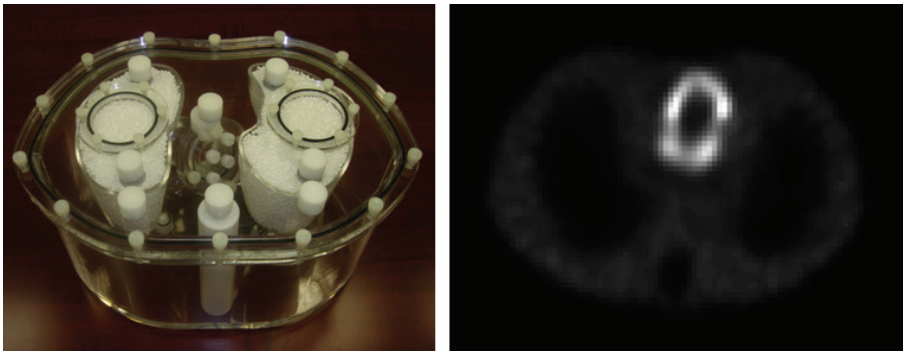


FIG. 15.13. A commercial anthropomorphic phantom and a transaxial slice cutting through the heart and lungs from its image acquired by a SPECT/CT system.

15.2.2.8. Hoffman brain phantom

This phantom, developed by Hoffman et al. [15.9], provides an anatomically accurate simulation of the radioactivity distribution in normal brain. Using this phantom, cerebral blood flow and metabolic activity in the brain can be simulated. It can be used in both PET and SPECT systems to optimize/investigate imaging acquisition protocols, to evaluate attenuation and scatter correction methods, and to measure the performance of imaging systems. It consists of a water fillable cylinder (i.e. a single-fillable chamber) containing 19 separate layers each 6.4 mm thick (see Fig. 15.14). The fillable water volume is about 1.2 L. Water freely permeates between layers to simulate concentration ratios of 4:1:0 between grey, white and ventricle, respectively, in normal brain. The 2-D version, consisting of a single slice, and a 3-D version of the phantom are available commercially.

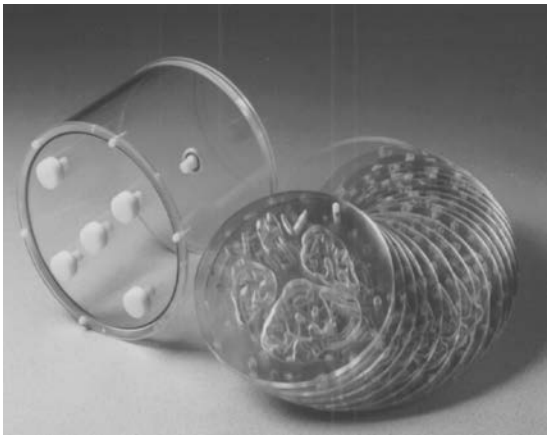


FIG. 15.14. Three dimensional Hoffman phantom with a water fillable cylinder and layers of inserts (phantom by Data Spectrum Corporation, USA).

15.2.2.9. Defrise phantoms

These phantoms are designed for measuring the performance of small animal imaging systems (both SPECT and PET). They can be used to investigate image quality or resolution. Figure 15.15 shows the hot spot phantom manufactured by Data Spectrum Corporation, USA. This phantom is a miniaturized version of the image quality phantoms mentioned in the previous sections. The phantoms are available in different sizes for imaging systems with different FOVs.

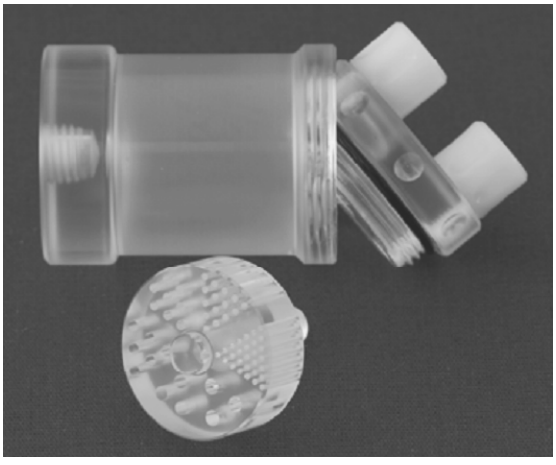


FIG. 15.15. Defrise hot spot phantom manufactured by Data Spectrum Corporation, USA.

15.2.3. PET phantoms

15.2.3.1. National Electrical Manufacturers Association image quality phantom

Measuring image quality in an objective manner has been one of the most difficult tasks in PET. Image quality in PET can be determined by calculating performance parameters, such as uniformity, noise, lesion contrast, spatial resolution, and the accuracy of the attenuation and scatter correction techniques. In this section, the NEMA image quality (IQ) phantom is described. This phantom (known as the NEMA IEC (International Electrotechnical Commission) body phantom) was originally recommended in IEC standards and was then adopted by NEMA. In addition to the above performance parameters, the image registration accuracy between the PET and CT gantries in a PET/CT scanner can be assessed. This phantom is commercially available from Data Spectrum Corporation, USA. The IQ phantom consists of four main parts:

(a) Fillable spheres: The six fillable spheres are used for measuring hot and cold lesion contrast. The inner diameters of the six spheres are 10, 13, 17, 22, 28 and 37 mm. The two largest spheres (28 and 37 mm) are filled with water to mimic cold lesions, while the rest are injected with ^{18}F activity with lesion to background ratios of 4:1 and 8:1 to mimic hot lesions. The spheres are attached to the cover or top lid through capillary stems. The

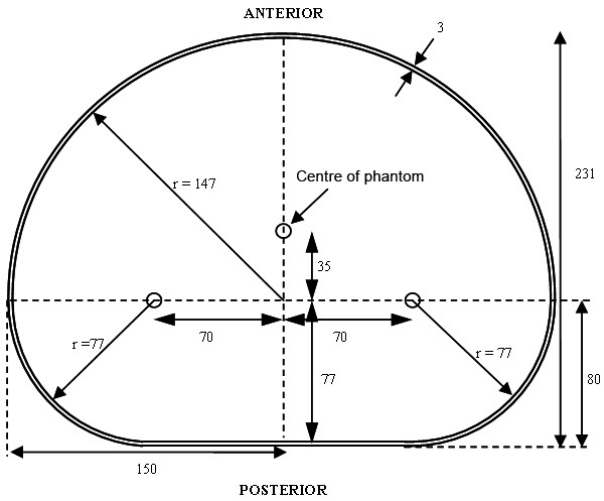


FIG. 15.16. Cross-section of the body part of the International Electrotechnical Commission image quality phantom made of acrylic. The dimensions are given in millimetres (reproduced with permission).

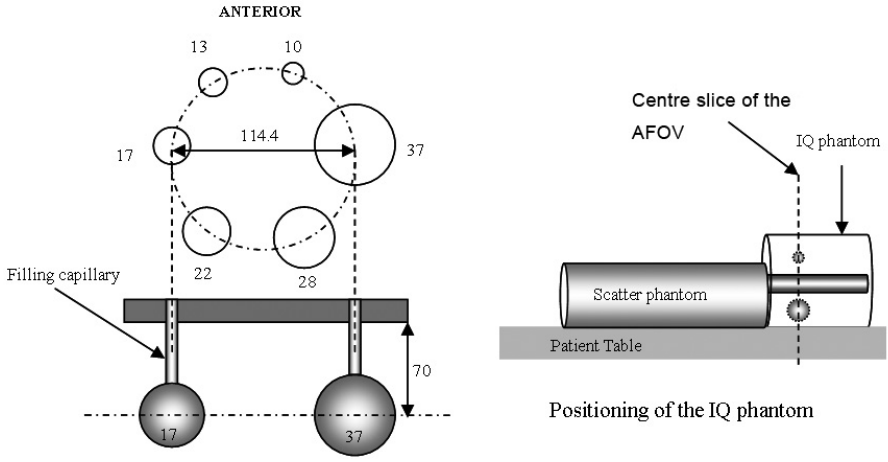


FIG. 15.17. Transaxial (top left) and coronal (bottom left) cross-sectional view of the image quality (IQ) phantom through the centres of fillable spheres. Sphere diameters and the other dimensions are given in millimetres (reproduced with permission). On the right is the schematic drawing demonstrating the positioning of the IQ phantom together with the scatter phantom.

filling is also done through the capillaries without removing the cover lid. Filler screws for each fillable part inside the body phantom allow easy access. A picture of the phantom is shown in Fig. 15.18.

(b) Cylindrical insert: A cylindrical section that is filled with a mixture of polystyrene beads and water to mimic lung (the density of which is around 0.3 ± 0.1 g/mL) attenuation is placed axially in the centre of the phantom with the same length as the body phantom. The outside diameter of the insert is about 5 cm.

(c) Phantom preparation: Table 15.4 shows the measured volumes of the various inserts and the torso cavity of the IQ phantom. It is suggested that all the volumes be measured upon acquiring a new IQ phantom. The activities used to fill the phantom should be measured using a calibration time that corresponds to the planned PET acquisition time, taking into account the time necessary for the preparation and positioning of the phantom for this test. Table 15.4 shows the typical activity concentrations that may be prepared and injected into the background and the hot spheres in order to have the proper activity concentration at the time of the scan (supposed to be performed 45 min after phantom preparation). It should be noted that the activity concentration ratio in the table is 8:1. A 4:1 activity concentration ratio can be easily obtained by doubling the amount of activity in the background.

FIG. 15.18. National Electrical Manufacturers Association/International Electrotechnical Commission image quality phantom.

TABLE 15.4. MEASURED VOLUMES OF THE NATIONAL ELECTRICAL MANUFACTURERS ASSOCIATION/INTERNATIONAL ELECTROTECHNICAL COMMISSION IMAGE QUALITY PHANTOM AND SUGGESTED ACTIVITIES FOR A CONCENTRATION RATIO OF 8:1

Phantom section	Volume (mL)	Typical activity (MBq)	Activity concentration at time of preparation (kBq/mL)	Activity concentration at time of scan (kBq/mL)
Torso cavity	9700	n.a.		
Four hot spheres	Different sizes	n.a.	56	42.4
Two cold spheres	Different sizes	n.a.		
Lung insert	353	n.a.		
Background (torso – all inserts)	9286	65	7	5.3

Note: n.a.: not applicable. The scan is supposed to be performed 45 min after phantom preparation. For a description of the phantom, please see: http://www.spect.com/pub/NEMA_IEC_Body_Phantom_Set.pdf

There are different suggestions as to how to prepare the IQ phantom. The following is a summary of one possible approach:

— The NEMA recommends an activity concentration for the background of 5.3 kBq/mL at the time of the scan, assuming that a normal 70 kg patient injected with 370 MBq of activity will have a similar background activity in the body (370 MBq/70 000 mL, ~5.3 kBq/mL).
— The amount of time to fill and position the phantom must be estimated to determine the amount of activity at the time of preparation of the phantom. A typical time frame for this process would be 45 min.
— Two separate activities of 65 MBq are prepared and one of them is injected into the background. This results in a background activity concentration of 65 MBq/9286 mL = 7 kBq/mL. The activity concentration will be reduced to ~5.3 kBq/mL after 45 min (time of scanning).
— Another solution for the hot spheres with an activity concentration of ~56 kBq/mL is prepared separately. ^{18}F activity of 5.6 MBq can be injected into 100 mL of cold (non-radioactive) water to obtain this concentration. If the measured activity is slightly more or slightly less, the volume of the cold water can be adjusted accordingly to achieve the intended concentration.
— The ^{18}F activity is injected into the torso cavity (i.e. background), which is already filled with cold water, and then the hot spheres are filled with the prepared ^{18}F solution.
— After having acquired the images of the phantom for the ratio of 8:1, the previously prepared activity of 65 MBq is added to the background in order to obtain an activity concentration ratio of 4:1.
— The phantom is acquired for the 4:1 ratio one half-life (~110 min) after the first scan, when the activity concentration in the background will be ~5.3 kBq/mL.

One of the disadvantages of the above filling method is the difficulty of mixing the background activity uniformly into the cold water; however, the method obviates the need for removal of the top lid with attached spheres and refilling of the background in each experiment.

15.2.3.2. National Electrical Manufacturers Association scatter phantom

The scatter phantom, whose specifications were set forth by NEMA guidelines (NEMA NU 2-2007 [15.10]), is used to measure the count rate performance of PET scanners in the presence of scatter. In other words, it is used to measure the amount of scatter in terms of the scatter fraction, the effect of dead time and the random events generated at different levels of source activity.

The phantom consists of a solid, 70 cm long, polyethylene cylinder with an outer diameter of 203 ± 3 mm and a line source insert. The line source insert is made of a clear polyethylene tube at least 80 cm in length, and with inner and outer diameters of 3.2 ± 0.2 and 4.8 ± 0.2 mm, respectively. The volume of the line source is approximately 6 mL. The solid cylinder comes in four segments for ease of fabrication and handling. During the assembly, these four segments should be tightly fitted to prevent the formation of scatter-free air gaps in between them. A hole (6.4 ± 0.2 mm in diameter) is drilled along the central axis of the cylinder at a radial distance of 45 ± 1 mm (see Fig. 15.19) to insert the aforementioned line source. The scatter phantoms are commercially available.

The line source insert should be uniformly filled with a ^{18}F solution. The amount of activity is usually recommended by the manufacturer and should be in the central 700 ± 5 mm part of the insert. The line source should be inserted such that the activity region remains completely within the 70 cm long phantom. Further detail about phantom preparation and data acquisition can be found in Ref. [15.10].

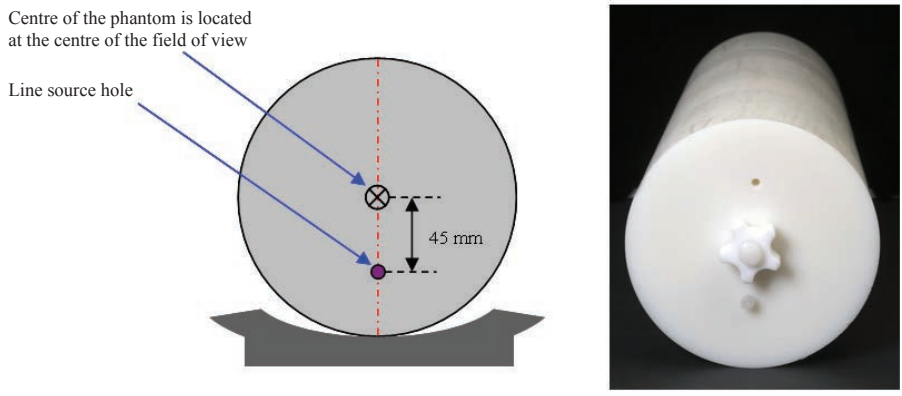


FIG. 15.19. Positioning of the scatter phantom on the patient bed: transaxial view (left); picture of the National Electrical Manufacturers Association scatter phantom (right).

15.2.3.3. National Electrical Manufacturers Association sensitivity phantom

Sensitivity is the number of counts per unit time per unit of radioactivity concentration within the FOV. To be able to compare different PET scanners, the sensitivity performance measure should be independent of factors such as scatter, attenuation, count losses and random events. Therefore, in PET, unlike SPECT, the sensitivity is measured using a special phantom developed by Bailey et al. [15.11] and later adapted by NEMA. The NEMA sensitivity phantom allows the determination of the attenuation-free sensitivity.

The sensitivity phantom consists of five concentric aluminium sleeves (70 mm in length), each with a wall thickness of 1.25 mm. The inner diameters of the five tubes are 3.9, 7, 10.2, 13.4 and 16.6 mm. The line source, made from clear polyethylene, is filled uniformly with ^{18}F in solution and inserted into the smallest sleeve and suspended in air within the FOV of the scanner. The line source is filled with activity, such that the dead time losses are less than 1% and the random events are less than 5% of the true rate. Figure 15.20 shows the sensitivity phantom: the five aluminium sleeves and the tube. The figure also shows the positioning of the phantom during the scan. In this case, a shower curtain rod and the point source holder from the scanner vendor are used to suspend the phantom within the FOV. A sling can be constructed from tape to hang the phantom in that position as well. It should be noted that the centre of the aluminium sleeves should coincide with the centre of the AFOV of the scanner.

FIG. 15.20. Pictures of the National Electrical Manufacturers Association sensitivity phantom: positioning of the phantom within the gantry (right). A spring tensioned shower curtain rod and the point source holder are used to suspend the phantom within the field of view. The aluminium sleeves (left and centre) should coincide with the centre of the axial field of view.

15.2.3.4. Triple-point source phantom for spatial resolution

Hematocrit or capillary tubes are commonly used to create point sources for measuring the spatial resolution of PET scanners. The inner and outer diameters of these tubes should be less than 1 and 2 mm, respectively. The axial extent of the activity in the tube should be no more than 1 mm. As for the NEMA NU 2-2007 guidelines [15.10], three point sources should be positioned as shown in Fig. 15.21. It should be noted that the central point source is positioned 1 cm above the centre of the FOV.

A high concentration of ^{18}F activity in a solution should be prepared such that neither the dead time losses nor random events exceed 5% of the total event rate. The actual activity concentration to be used, more than approximately 200 MBq/mL, is normally provided by the manufacturer. The preparation of the

point sources in hematocrit tubes is undertaken as discussed in Section 15.2.2.1. The point sources are positioned and the data are acquired at the centre of the FOV as well as at a distance a quarter of the FOV away from the centre (see Fig. 15.21). Figure 15.22 shows a point source holder with capillary tubes mounted on it.

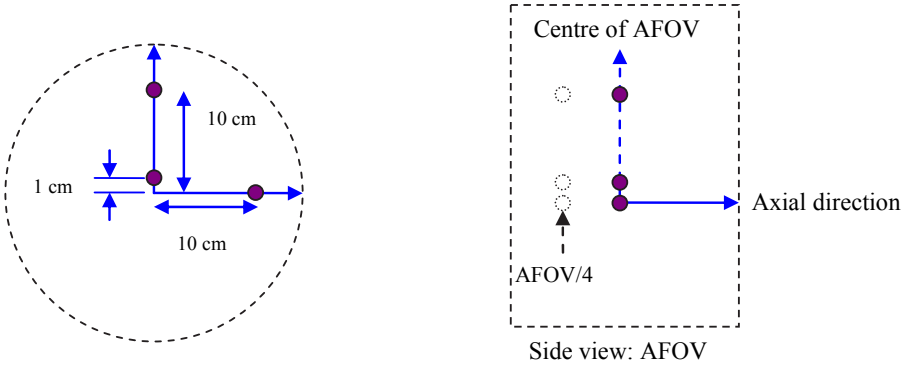


FIG. 15.21. Positioning of the three point sources in the centre of the axial field of view (AFOV). The view into the gantry bore (left) and the side view (right) in which the dashed circles denote the axial position of the sources in the second scan.

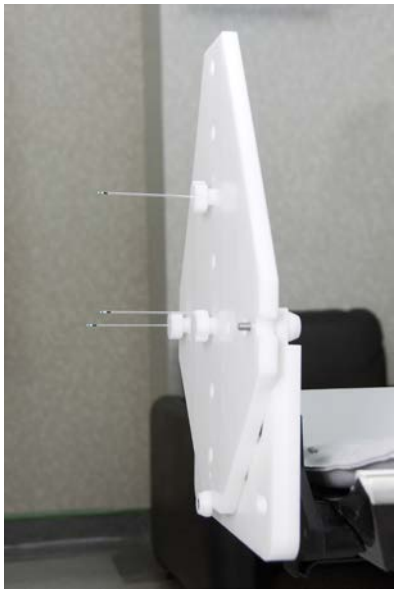


FIG. 15.22. Three capillary point sources mounted on a point source holder used in PET to measure spatial resolution.

15.3. COMPUTATIONAL MODELS

Computational models can be categorized in three groups:

(a) Mathematical models;
(b) Voxelized computational models;
(c) Hybrid computational models.

This enumeration also reflects the progress of the development as the listing is from simple to more realistic and sophisticated. This order of classification also reflects the chronological order of the development process of the computational models.

Mathematical models, also known as stylized models, simulate the organs with geometric primitives such as ellipsoids, cylinders, spheres and rectangular ellipsoids. These rather simple, geometrically well defined shapes representing the organs or structures in the body are defined using the surface equations of these primitives. The mathematical models were very early models and crude in their representation of organs. The well known models, which have been adopted by the Medical Internal Radiation Dose Committee of the Society of Nuclear Medicine and have been used for many years in dose calculations, are mathematical models. Although for a while these models served the purpose, the need for a more realistic definition of organs, and, therefore, a more realistic representation of the body, has always been there.

The advent of tomographic imaging technology, particularly X ray CT and magnetic resonance imaging (MRI) made it possible to obtain high resolution images of the body. In voxelized models, also known as tomographic models, the organs are defined by the structures segmented from high resolution tomographic images such as X ray CT and MRI. The segmented structures consist of volumetric image elements called voxels, each of which is assigned a value indicating the organ to which it belongs. The smaller the voxel dimensions, the more realistic the surface of organs can look. Depending on the dimension of the voxels, it may be challenging to define thin or small structures such as skin.

The Visible Human Project initiated and conducted by the United States National Library of Medicine has played a significant role in the development of voxelized models. As part of this project, CT and MRI images and cryosection photographs of a 38 year old male cadaver were made available in the public domain. To produce the colour photographic images of the cryosections, the cadaver was frozen and sliced into 1 mm thin sections and photographed at a resolution of 2048 pixels × 1216 pixels. This project has led to the development of many voxel based computational models [15.12–15.14]. The construction of voxel based models is a lengthy and tedious process and requires several steps.

First, high resolution images of the body need to be acquired. Then, the individual organs and structures are segmented from the high resolution images. The segmentation is the most challenging task as the boundaries between organs and tissues are often not well defined. Researchers, therefore, resort to tedious manual or semi-automated segmentation methods. Obtaining CT scans of desired pixel resolution or dimension and slice thickness may result in a significant amount of exposure to ionizing radiation; thus, it is difficult to recruit healthy subjects for this purpose. As a result, some of the voxel models have been constructed from medical images of patients. For example, the Zubal phantom [15.15] was created from CT scans of a patient by manual segmentation. These limitations on pixel dimensions and slice thickness have made cadavers an attractive choice for building voxel based models. In voxelized models, the surface of the organs are jagged, piece-wise continuous and, therefore, not smooth. Other issues, such as shifting of internal organs and non-rigid transformations in organ shape during the scan in the supine position, may limit the generality of these models.

Hybrid models combine the best of both worlds. Surfaces of the segmented structures in voxelized models are defined by mathematical formulations used to define irregularly shaped surfaces such as 3-D B-spline surfaces.

A group of researchers developed a series of 3-D and 4-D computational models. Their first model, the mathematical cardiac torso phantom, was a mathematical model based on simple geometric primitives but also used cut-planes and overlaps to create complex biological shapes to be used in nuclear medicine research. This model also included a beating heart based on gated MRI patient data and a respiratory model based on known respiratory mechanics. With this model, emission and transmission data could be simulated. The following models, 4-D NCAT and cardiac torso (XCAT) (see Fig. 15.23), were based on the visible human CT dataset. The organ shapes, i.e. surfaces, were reconstructed using the primitive non-uniform rational B-spline (NURBS) surfaces. The 4-D models use cardiac and respiratory motions developed using 4-D tagged MRI data and 4-D high resolution respiratory-gated CT data, respectively. These models, from the hybrid class, can successfully model not only the anatomy but also physiological functions such as respiratory and cardiac motion.

Such 4-D models can be used to accurately simulate SPECT and PET images of the torso and can be particularly helpful for optimizing image acquisition protocols and image reconstruction algorithms, and understanding the various effects of these complex motions on the acquired PET or SPECT images. These models are also accessible free of charge for academic research.

These models have been widely used in internal absorbed dose calculations in nuclear medicine or in calculation of dose distribution from external sources in radiation therapy and in studying issues pertinent to imaging systems and their

performance characteristics. They have also been quite helpful in the optimization of image acquisition protocols and reconstruction methods.

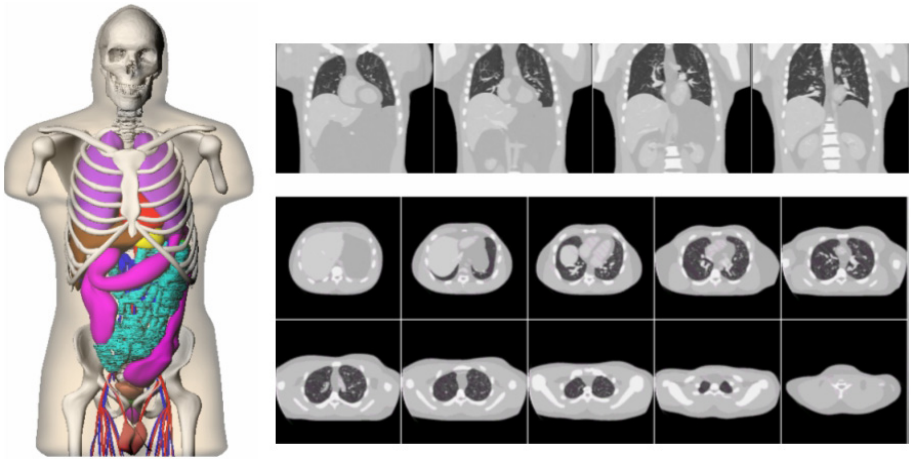


FIG. 15.23. Left: initial extension of the 4-D XCAT anatomy. Right: simulated chest X ray CT images from the extended 4-D XCAT. Coronal (top row) and transaxial (bottom two rows) reconstructed slices are shown (reproduced with permission from P. Segars).

Since anatomy and physiological functions are accurately known, they can serve as gold standards. Computational models may be preferred because the use of physical phantoms leads to unnecessary occupational exposure to radiation, and the preparation and repetition of the experiments using physical phantoms can be lengthy and time consuming.

An ideal model should be able to conform, reasonably well, to the size and shape of the object being represented. Currently, as personalized medicine is the strong driving impetus for most current research in many pertinent fields, personalized modelling should be the aim in computational model development research.

15.3.1. Emission tomography simulation toolkits

15.3.1.1. SimSET

SimSET, first released in 1993 and developed at the University of Washington, is a simulation package that can simulate PET and SPECT emission tomography systems using Monte Carlo simulations. It can model the photon interaction process as well as the imaging detector geometries. SimSET allows

the use of a different object description such as a Zubal phantom to simulate a whole body phantom. SimSET is freely available for use.

15.3.1.2. GATE

Owing to the limitations of SimSET regarding the modelling of complex detector geometries, the need for a more sophisticated emission tomography simulator arose. To meet this need, a group of physicists from different institutions around the world formed the OpenGate collaboration. Out of this collaboration, a simulation toolkit (GATE) for nuclear medicine applications was developed and has been available since 2001. GATE uses the existing libraries of Geant4, which is a comprehensive simulation toolkit that simulates the interaction of particles as they traverse through matter. GATE is unique and superior in that it can model time dependent phenomena such as source and detector movement and source decay kinetics. It includes validated geometry modelling tools that can model complex scanner geometries. It also includes the description and models of several commercially available PET and SPECT scanners. GATE can simulate CT scans and can perform dose calculations. GATE is also freely available for use.

15.4. ACCEPTANCE TESTING

15.4.1. Introduction

As discussed in Ref. [15.16], gamma cameras are evaluated at different levels of testing before being made ready for clinical use. The first set of tests is carried out in the factory before shipment. Manufacturers test gamma cameras to check whether the performance parameters meet the specifications quoted to customers. NEMA has published several guidelines that describe the methods to measure the performance parameters of gamma cameras and PET systems [15.6, 15.10]. These guidelines provide standardized criteria for manufacturers to measure and report the performance of their scanner. The IEC has also published several technical reports [15.17–15.19] describing the tests to be performed during acceptance testing which reflects as closely as possible the clinical settings in which gamma cameras and PET systems are operated. Most manufacturers quote the performance of their systems according to NEMA guidelines [15.6].

The second level of testing is the acceptance testing performed after the scanner arrives at the site. These tests should be performed by the user or a third party, usually a qualified medical physicist, to determine whether the

system performs according to the manufacturer's specifications and free of any deficiencies, flaws or defects.

The baseline performance of the equipment will also be established. These data provide guidance in the determination of the optimal operating parameters for routine use and ensure that the imaging equipment meets regulatory requirements for radiation safety [15.1].

These tests are usually very involved and require sophisticated phantoms and dedicated software to calculate the performance parameters. Several national and international agencies have set forth a range of tests, to be performed during acceptance testing, that are easier (than the NEMA tests) to conduct. The American Association of Physicists in Medicine (AAPM) is one of these agencies that has produced several publications for testing gamma cameras during acceptance and routine testing. The reports, AAPM 6, AAPM 9 and AAPM 22 [15.20–15.22], describe methods to perform acceptance testing on analogue, computer-aided and SPECT capable gamma cameras, respectively. These reports describe tests similar to those of NEMA. Moreover, the IAEA has published several books describing the methods to perform tests on gamma cameras during acceptance, reference and routine testing. Among them are TECDOC-317 and TECDOC-602 [15.16, 15.23]. The IAEA has recently published guidelines for QC and QA tests for PET and PET/CT scanners [15.1].

During acceptance testing, the user should also conduct reference tests which constitute the third level of testing. These tests reflect the performance of the system under clinical settings, are easy to perform and can be performed within an acceptable time frame. These tests, in addition to some other acceptance tests, will establish the baseline performance characteristics for routine QC tests. The results of routine tests are compared against the results of these tests.

Routine tests constitute the fourth level of testing. These are the tests performed on a regular basis by users. Depending on the variability (in time) of the performance parameter and its impact on image quality, test frequencies may range from daily to annual. Several guidelines have been published on routine tests, describing them and specifying their frequencies and the tolerance limits. The IEC published standards 61675-2 and 61948-2 [15.18, 15.24] for gamma camera routine testing including SPECT, and standard TR 61948-3 [15.25] for PET routine testing. The AAPM has also published Report No. 52 [15.7] which describes methods for measuring the quantification of SPECT performance.

Several issues regarding acceptance testing should be considered. Some phantoms are used during acceptance testing and after major repair only, and may be included in the purchasing contract. The manufacturer may also lend their customers these phantoms during the period of acceptance testing. The slit phantom used for testing linearity and intrinsic resolution of gamma cameras is a typical example. The calculation of performance parameters from the image data

in PET and the gamma cameras and SPECT systems may require sophisticated software applications; thus, in such a case, the manufacturer must provide the calculation software. The documentation for the acceptance test procedures may be made available by the vendor. If needed, the recommendation of the manufacturer should be followed, for instance, with regard to the amount of activity required for each test. In multimodality imaging systems, additional tests, which are not discussed in the existing guidelines, such as the accuracy of image registration and attenuation correction, must also be conducted.

Before starting acceptance testing, the following additional issues should be considered:

— An accurate dose calibrator is an essential part of acceptance testing and must, therefore, be available.
— The required amount of radioactivity has to be arranged before starting acceptance testing, so that the acceptance testing procedure does not experience any interruption.
— Proper calibration of the imaging system prior to acceptance testing is of paramount importance. Any major erroneous calibration or lack of calibration may result in an increase in commissioning cost and undue delays in acceptance testing.
— The order of the tests that will be conducted must be arranged so that any malfunctioning or improper calibration can be discovered early on. This will minimize the number of tests that must be repeated after recalibration of the system.
— If the medical physicist is not familiar with the system, a vendor representative who knows how to operate the scanner and how to run the calculation software should be present during acceptance testing.
— All the required phantoms discussed in earlier sections of this chapter should be made ready and prepared in advance.

15.4.2. Procurement and pre-purchase evaluations

When an institution decides to buy an imaging system, the administration should start the planning properly by defining the purpose(s) for acquiring the system and form a committee of a team of professionals to take on all of the responsibilities from purchasing to setting up the system.

The purchasing committee should include the following professionals, as defined in Ref. [15.1]:

— Nuclear medicine and radiology physicians;
— A medical physicist with experience in nuclear medicine;

— If buying SPECT/CT or PET/CT, a medical physicist experienced in diagnostic radiological physics should be included;
— A medical physicist experienced in radiation therapy if the system will be used in radiation therapy planning;
— An administrator from the radiology department;
— A radiation protection expert;
— A person qualified in radiochemistry or radiopharmacy, if in-house production of radiopharmaceuticals;
— A nuclear medicine technologist;
— A hospital management expert;
— A bioengineering expert in imaging systems.

The role of this committee is to:

— Choose the location;
— Set the specifications of the system;
— Prepare the tender documents;
— Choose the proper system;
— Supervise the installation process;
— Supervise the acceptance and commissioning procedure.

This committee should start by choosing the proper space to host the system. This location should be inside a radiation-controlled area, with the door of the room opening to a closed vicinity (not to a public corridor). The room should be wide enough to host the scanner, give accessibility to patient stretchers and provide free space to maintenance engineers. If possible, the room should be far away from MRI scanners to avoid any interference from their magnetic field. If buying SPECT/CT and the CT sub-component will be used as a stand alone system occasionally, it is advisable to have the scanner as close as possible to the radiology CT scanner to act as a backup system when needed. This is also true for the PET/CT systems if there is no on-site cyclotron. For scanners inside institutions having a cyclotron, it is advisable to have the scanner as close as possible to the cyclotron. This will allow the quick transfer of isotopes with very short half-lives using dedicated lines or manual means.

The process of setting the specifications starts by agreeing on the purpose for which the scanner will be used. Again, based on the applications that the system will be used for, the different add-on components to be ordered will be decided.

After defining all of the components, the specifications of the scanner and each component should be set. To define a suitable specification, the committee members should know what suitable systems are available that may meet their

needs. After studying these systems, the required specifications should be set with the aim of not excluding any available system initially. As a good practice, one or several Excel work-sheets should be developed. The work-sheet(s) should list all of the specifications, hardware, performance parameters, imaging table, standard software, optional software, etc. Under each category, a list of different specifications in that category should be listed with their limits. Examples of hardware specifications are crystal(s) dimension and shape, number of photomultiplier tubes, bore diameter and head movement ranges. Examples of performance specifications are resolution, uniformity, dead time, SPECT specifications, noise equivalent count rate and sensitivity. Examples of imaging table specifications are pallet thickness, attenuation factor, scan range and speed, minimum and maximum floor clearance, and weight limits. Knowing all of the software that comes with the system on the acquisition and processing stations and the optional ones available is necessary at this stage. The work-sheet(s) will be distributed to all vendors as a soft copy, so that the answers from each will be rearranged in one sheet to allow easy comparison of each specification between vendors.

The tender should be prepared by the committee members and should follow the institution's local regulations. It should include a summary of the terms and conditions of the new equipment purchase deal. The following items may be requested in a tender:

— Name and model of the equipment.
— Terms of pricing; way of payment, site preparation, accessories, etc.
— Application specialist training.
— System upgrade conditions.
— Equipment references; short list of current users of similar system, local or international.
— Training of staff.
— Equipment warranty.
— Scheduling installation process and way of coordination.
— Responsibility of site preparation, including removal of old equipment.
— User and engineering manuals and equipment specifications (NEMA and others).
— Acceptance testing to be performed by a medical physicist (the system should comply with NEMA or local specifications).
— Commitments of the vendor to provide maintenance, and spare parts readiness.
— Specifications of local civil work and materials used.

Other steps that may assist the committee in the evaluation stage are:

— Site visits: Manufacturers take the prospective customers to their reference sites to evaluate the systems and listen to the users.
— Evaluation of the clinical and phantom images provided by the manufacturers: It is recommended that this be carried out on a common imaging workstation for an objective comparison of different imaging systems because each imaging workstation may process images differently before displaying them on the screen. The medical physicist has to facilitate the unbiased and blind comparison of the clinical images by the nuclear medicine physicians.
— Surveying centres with similar systems through a written questionnaire can also be very effective and beneficial.
— Inviting the vendor representatives to present their product in detail.

After thorough evaluation of all systems, the committee decides on the most appropriate system upon considering the cost and other factors such as the availability of a good maintenance service in the region.

After the system is chosen, the committee should supervise the installation process. It should help the vendor representative to finalize all of the paper work and get the access permits to the location. The system should be installed completely with all the accessories and software ordered.

The local medical physicist or a private consultant should perform the acceptance testing on the system. The committee should facilitate and make available all of the necessary resources to the medical physicist to complete the task and get the system ready for clinical use.

15.4.3. Acceptance testing as a baseline for regular quality assurance

As mentioned in Section 15.4.1, the medical physicist should produce reference tests during acceptance testing. Tests should be acquired that are easy to perform with less sophisticated procedures and that can be conducted within an acceptable period by the user. These tests should reflect the performance of the system in the working environment. The results of the routine tests should be compared against the results of these reference tests.

For example, the medical physicist may acquire a five or ten million counts uniformity image as a reference image for the system uniformity test during the acceptance period. This is less sophisticated than the usual 30 million counts uniformity image acquired for the acceptance testing. Another example is acquiring a 10 million counts image for the bar phantom during the acceptance testing and considering it a reference image. Some of the results of acceptance

testing would be considered reference values to be used during routine testing. The multiple window spatial registration, maximum count rate and system spatial resolution values are examples of these tests.

15.4.4. What to do if the instrument fails acceptance testing

During acceptance testing, most of the performance parameters of the system should be tested and compared with the manufacturer's specifications. These specifications should be required during tendering and be provided with the system. If any of the test results do not meet the specifications, the analyses should be re-evaluated carefully. Following this, the test should be repeated again, paying close attention to any possible mistakes made during the acquisition and processing of the data. The analysis should also be carried out carefully, making sure that an accurate method has been followed.

If the problem persists, the engineer should be called to rectify the problem and then it becomes the responsibility of the vendor to resolve the issue. The engineer should look for any malfunction in the system, repair it and then recalibrate the scanner. All of the required calibrations after this repair should be performed and the system should be ready for testing. The medical physicist should not start acceptance testing if the system still needs more calibration, as some calibrations may readjust some parameters.

If two or three tests of the same parameter fail, the vendor should either replace the affected part (if it was not done before) or replace the system. The latter procedure should be the last option to be taken, as it will affect the routine work of the clinic. The vendor should compensate the clinic and the medical physicist (if a third party) for unnecessary delays.

15.4.5. Meeting the manufacturer's specifications

The verification of performance specifications is one of the key reasons for performing acceptance testing. Acceptance testing should follow the local recommendations (in the institute or country) or one of the international bodies' recommendations. As was discussed earlier, for both PET and gamma cameras, there are a number of guidelines set forth by various international bodies or agencies (NEMA, IEC, AAPM and IAEA reports) as to what kind of tests should be carried out.

Currently, there are task groups that have been formed by the AAPM working on a new set of guidelines because the existing guidelines need additional sets of performance tests to evaluate the hybrid systems as a whole, and some modifications for the recently emerged new technologies are necessary.

The results of these tests should meet the specifications set by the manufacturer, as they are usually one of the main reasons for selecting a particular system. If one or more test results do not meet the manufacturer's specifications, the test should be repeated carefully. In the case of similar results, the vendor engineer should rectify the problem at hand and then repeat the calibrations if necessary.

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