AAPM REPORT NO. 9

# COMPUTER-AIDED SCINTILLATION CAMERA ACCEPTANCE TESTING

Published for the
American Association of Physics in Medicine
by the American Institute of Physics

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A Task Group of the
Nuclear Medicine Committee
American Association of Physicists in Medicine



Published for the
American Association of Physicists in Medicine
by the American Institute of Physics,

Further copies of this report may be obtained from

Executive Secretary
American Association of Physicists in Medicine
335 E. 45 Street
New York, NY 10017

Library of Congress Catalog Card Number: 82-73382
International Standard Book Number: 0-883 18-407-g
International Standard Serial Number: 027l-7344

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Published by the American Institute of Physics, Inc.
335 East 45 Street, New York, New York 10017

Printed in the United States of America

Computer-Aided Scintillation Camera Acceptance Testing

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# Computer-Aided Scintillation Camera Acceptance Testing

## Introduction:

The purpose of this protocol is to present a uniform set of procedures that a physicist may use for acceptance testing of a single crystal scintillation camera that is interfaced to a computer system. The measurements described are suitable for either a new camera/computer system mounted on a single chassis or a new camera that is interfaced to an existing computer system. It is expected that there will be variations in the measured parameters as the camera ages or is serviced. The present measurements will serve as baseline values to document these changes and as an aid in a quality assurance program.

The measurements described in this protocol are patterned after the protocol previously written by the AAPM Nuclear Medicine Committee, "Scintillation Camera Acceptance Testing and Performance Evaluation", (AAPM Report No. 6, 1980) and the NEMA Publication Standards No. NUI-1980 "Performance Measurements of Scintillation Cameras".*

In order to minimize the need for specialized equipment, this document describes only those measurements which test overall camera/computer system performance; these include tests of the properties of the analog-to-digital converters (ADC) transmission lines and line drivers, as well as the camera itself. If it is found that a parameter deviates considerably from the expected value, further tests not described in this document may be required to isolate the defective subsystem.

The National Electrical Manufacturers Association (NEMA) document mentioned above was drawn up by a broadly based committee of representatives from most of the American manufacturers of scintillation cameras. This document defines terms and gives specific protocols for measuring performance parameters of scintillation cameras. Not all manufacturers will choose to measure and report all NEMA specifications. At the very least one should expect to receive on request performance data in the form of tables and images resulting from the manufacturer's final test procedures measured on the camera in question. If their test methods differ from the NEMA standards they should be specified. Using these results, the physicist can then compare them to the results of his/her own measurements using this AAPM protocol and, by using his/her professional judgement, decide whether the camera is satisfactory. In the NEMA protocol reference is made to class standards. A class standard is a value which characterizes a specific performance parameter typical of the given model number,

*The NEMA Standards Publication No. NUI-1980 can be purchased for $7.65 from NEMA, Orders Department, 1201 L Street, NW Washington, DC 20037.

but not necessarily measured on every camera. Most of the NEMA protocols describe tests performed on each camera manufactured. In this protocol, when tests are presented that relate to NEMA class standards, a specific note to that effect precedes the protocol for the test.

The physicist should obtain the operator's manual and service manual for all components in the system and become thoroughly familiar with the system before proceeding with these tests.

Certain sections of this protocol are marked optional. These sections require specialized equipment or are not directly relevant to clinical operating conditions. Individual judgement should be exercised in utilizing these sections.

## Pre-Test Conditions:

When performing the acceptance tests, sources of radio-activity should be handled in accordance with proper techniques. All containers of unsealed sources should be kept on absorbent pads and handled by gloved personnel wearing appropriate dosi-meters. In all cases the measurements should be performed with the room background as low as achievable and other sources (such as injected patients) carefully excluded from the area. During the period of time the crystal is not protected by the collimator, for example, when performing intrinsic studies, extreme care must be taken not to damage the crystal by mechanical or thermal insult.

If x-ray film is used, the processor should be checked to assure that it is properly developing films (3).

## Log Book:

At the time of acceptance testing of a new system, a permanent record book should be initiated for that system. The results of the performance testing should be recorded, including the labeled images and all information necessary to duplicate the results at some later date. Parameters recorded should include the date and time, radionuclide, source activity, background rates, configuration of source, console and system parameters, source-detector distance, collimator, counting time, number of counts, and scatter material. Some console parameters may change if adjustments are made on the camera.

Subsequent quality control, component failure and maintenance records should be recorded in the same book. As previously mentioned, the user should request of the manufacturer all performance data available and include this in the log book.

# Glossary

## Central Field of View (CFOV)

The central field of view (CFOV) is a circular area with a diameter that is 75 percent of the diameter of the useful field of view (UFOV). The CFOV is centered on the center of the UFOV. See Fig. G.l. This definition may not apply to rectangular field of view cameras.

## Class Standard

A class standard is a value(s) which characterizes a specific performance parameter typical of the given model number of series of scintillation cameras for which it applies. Usually the parameter is of auxiliary interest and is a subset of a measured standard.

## Differential Linearity

Differential linearity or a scintillation camera is the positional distortion or displacement per defined unit distance, with respect to incident gamma events on the crystal.

## Differential Uniformity

Differential uniformity of a scintillation camera is the amount of count density change per defined unit distance when the detector's incident gamma radiation is a homogeneous flux over the field of measurement.

## Digitization Resolution

Digitization resolution is the size in centimeters, of the channels utilized in the conversion of analog scintillation camera signals into discrete bits of data for quantitative measurement.

## Full Width at Half Maximum (FWHM)

Full width at half maximum (FWHM) is the spread of a point or line response curve at 50 percent of the peak amplitude on each side of the peak.

## Full Width at Tenth Maximum (FWTM)

Full width at tenth maximum (FWTM) is the spread of a point or line response curve at 10 percent of the peak ampltiude on each side of the peak.

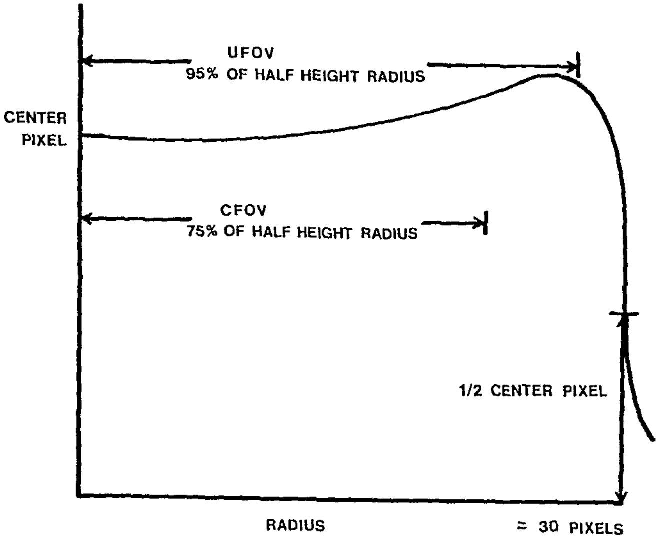



Figure G.l The relationship of the UFOV and CFOV to the digitized image.

Integral Linearity

Integral linearity of a scintillation camera is the maximum amount of positional distortion or displacement within the useful field of view.

Integral Uniformity

Integral uniformity of a scintillation cameras it the maximum deviation in count density from the average count density over the field of view of the camera.

Intrinsic

Intrinsic means the basic scintillation camera without variables which may change its observed characteristics, e.g. collimator or display device.

NEMA

National Electrical Manufacturers Association.

Temporal Resolution

A term used to describe the ability of a counter to resolve events closely spaced in time.

Useful field of view (UFOV)

The useful field of view (UFOV) is a circular area with a diameter that is the largest inscribed circle within the collimated field of view. See Figure G.1. This definition may not apply to rectangular field of view cameras.

Test Equipment Required

1) Lead mask 3-mm thick identical in size and shape to the useful field of view (for various measurements).

2) Tc-99m point sources, various activities required (for various measurements).

3) Two lead source holders for two of the Tc-99m point sources. Six mm shielding required on all sides but one (for temporal resolution measurements); see figure 2.1.

4) A number of copper filters, 1 to 2 mm in thickness, to provide filtration for the lead source holders described in item 3. (see Figure 2.1)

5) Scatter phantom for temporal resolution measurements. (see Figure 2.2)

6) Orthogonal hole pattern: 6-mm thick lead sheet with square array of 1.8-mm diameter holes spaced on 19 mm centers. This pattern must be made to very close tolerances to achieve desired goals. Linear dimensions must be held to 1% variations of nominal dimensions (used in linearity and sensitivity tests).

7) Volumetric flood source, 2.5-cm active thickness, at least as large as the UFOV (with thickness variation of less than 1%). This may require special construction and filling procedures to achieve.

8) Lead source holder with 3-mm diameter hole (for optional point source sensitivity test).

9) Slit mask consisting of a plate with parallel 1 mm slits. The length of the slits should be at least equal to the UFOV. These slits should be spaced at least 3 cm apart. The number of slits will depend on the digitized field size in the axis of interest. The plate should be at least 3-mm thick (used in measurement of intrinsic resolution).

10) Capillary tubes (used in measurement of extrinsic resolution).

11) Multichannel analyzer and associated equipment (used for optional test to measure energy resolution).

12) Bar pattern or orthogonal hole pattern (for measurement of intrinsic resolution and display system resolution).

# 1.0 Physical Inspection for Shipping Damages and Production Flaws.

1.1 Detector Housing and Support Assembly:

Inspect the aluminum can surrounding the NaI(T1) detector, shielding and support stand.

1.2 Electronics Console and Computer Console:

Inspect the dials, switches and other controls.

1.3 Image Display Modules (Analog, and Digital):

Inspect the dials, switches and other controls.

1.4 Image Recording Module:

Inspect the mechanical operation of rollers or film transfer mechanism. Clean the rollers and check camera lenses for scratches, dust or other debris.

1.5 Hand Switches:

Inspect the hand switches for proper mechanical operation and confirm that the cabling has acceptable strain relief at maximum extension.

1.6 Collimators:

Inspect the collimators and if possible check that collimator aperture correctly centers over NaI(T1) crystal.

1.7 Electrical Connections, Fuses, Cables:

Inspect for any loose or broken cable connectors, and pinched or damaged cables. Obtain from the manufacturer the locations of all fuses or circuit breakers necessary to check equipment failure.

1.8 Optional Accessories, e.g. Scan Table, Stress Equipment, Physiological Gates or Triggers.

Scan Table and Stress Equipment - Inspect the bed alignment, vertically and horizontally, and all cables, switches or other controls.
Physiological Gates or Triggers - Follow procedures in sections 1.2, 1.3 and 1.4.

1.9 Camera Head Shielding Leakage:

1.9.1 Prepare a syringe to contain 5 to 10 mCi (200 - 400 MBq) of Tc-99m.

1.9.2 Position the syringe about the detector head, with the collimator in place, at a distance of approximately 0.5 meters. Move syringe in a plane parallel to the crystal and record count rate every 45" while observing the persistence oscilloscope for effects of defective shielding.

1.9.3 Note integrity and uniformity of shielding in the log book.

1.9.4 Repeat 1.9.2 and 1.9.3 with approximately 200 uCi (7.5 MBq) of I-131 or Ga-67 if camera is designed to be used at energies higher than 140 keV. Choose a source compatible with the maximum energy limit of the camera.

## 2.0 Temporal Resolution

The measurement of temporal resolution is sensitive to many factors, such as:

1) thickness of scattering material about the source
2) pulse height analyzer window width
3) photopeak centering
4) count rate
5) presence of correction circuitry for uniformity, energy, or spatial linearity
6) presence of peripheral electronic equipment
7) location of sources with respect to detector face.

Therefore it is important to standardize carefully all these factors so that measurements are reproducible. If correction devices are employed for field uniformity, energy, or linearity, all measurements shall be consistenttly performed with these devices on or off and the results so indicated. Data should be acquired separately by the computer in order to evaluate the overall performance of the total system as well as the camera itself.

NEMA specifies five parameters to be measured: input count rate for a 20 percent count loss, maximum count rate, and as class standards, typical incident versus observed count rate curve, system spatial resolution and intrinsic flood field uniformity at 75,000 cps (observed count rate).

This protocol specifies the measurement of input count rate for a 20% count loss (2.11, maximum count rate (2.2), extrinsic spatial resolution at 75,000 cps (6.3.9) intrinsic flood field uniformity at 75,000 cps (3.3.1) and extrinsic temporal resolution (2.3). All but the last measurement are comparable to NEMA measurements.

### 2.1 Measurement of Intrinsic Temporal Resolution (without scatter)

2.1.1 Remove the collimator and mask the camera to the useful field-of-view.

2.1.2 Center a 20% analyzer window about the Tc-99m photopeak in the absence of significant cps or less.

2.1.3 Measure background count rate (should be <500 cps).

2.1.4 Prepare two Tc-99m sources:

The sources are to be placed in lead source holders providing at least 6 mm lead on the back and sides to prevent excessive background radiation. The radiation from the sources shall be filtered by at least 6 mm copper placed over the source to reduce scatter from the source holder. The dimensions of the source and holder must be chosen so that the camera field-of-view is not restricted at the specified working distance of at least 1.5 meters from the crystal (Fig. 2.1). If the value of the paralyzing deadtime $\tau$ is known approximately, the activity of each source should be sufficient to produce an observed count rate of $(0.10/\tau) + 20\%$. Otherwise, the source activity should be sufficient to produce about 30,000 cps. If a preliminary measurement of $\tau$ is outside the range 2.7-4.0 μsec the count rate should be adjusted by changing the sources or increasing the distance or filtration before repeating the measurement of $\tau$ as described in 2.1.5.

2.1.5 Use the following counting procedure at a preset time of 100 sec for each step. Maintain the same elapsed time between source measurements in order to cancel the effect of radioactive decay. Record data from the camera scaler and also from the computer. Use the same source positions at each step.

1. Place source #1 under the camera and record the count.

2. Place source #2 beside #l and record the count from the combined sources.

3. Remove source #l and measure source #2 only.

4. Repeat the above set of measurements in reverse order as a control procedure.

2.1.6 Calculate the paralyzing deadtime for the camera alone and the camera-computer system.

$$\tau = \left[\frac{2\ R_{12}}{(R_1 + R_2)^2}\right] \ln\left[\frac{R_1 + R_2}{R_{12}}\right]$$

where $R_1$, $R_2$, and $R_{12}$ are the average of the two measured net counting rates from #1 source, #2 source, and sources #l and #2 combined. The two values of $\tau$ should agree within 1% if the camera is stable. Greater values of $\tau$ from computer data than from the scaler demonstrate computer data losses.

2.1.7 Calculate the input count rate for 20% data loss ($R_{-20\%}$):

$$R_{-20\%} = \frac{1}{\tau} \ln \frac{10}{8} = \frac{0.2231}{\tau}$$

Compare with manufacturer's specification.

(The present NEMA standard protocol is to measure sources "suspended" unshielded in front of the camera at about 1.5 meters. With such sources it is impossible to avoid scatter from floor and walls. Paralyzing deadtime, $\tau$, is greater, typically by a factor of about 1.3, than with the reduced-scatter sources described above.)

2.2 Measurement of the Maximum Intrinsic Count Rate of Camera (optional).

2.2.1 Remove collimator and position mask as in 2.1.1.

2.2.2 Adjust analyzer window as in 2.1.2.

2.2.3 Prepare a Tc-99m source of approximately 4 mCi (150 MBq) for use in the lead source holder described in 2.1.4. Place at least 6 mm thickness of copper filtration over the source holder. Place the source holder on the floor centered at the detector axis at about 1.5 meters from the crystal. Move the camera detector up and down and increase the copper filtration-if necessary to find the maximum count rate. At this point any change in the distance will decrease the observed count rate.

2.2.4 Compare with manufacturer's specification

2.3 Measurement of Extrinsic Temporal Resolution (optional).

2.3.1 Attach all purpose or high sensitivity collimator to camera.

2.3.2 Adjust analyzer window as in 2.1.2

2.3.3 Prepare two sources of Tc-99m:

If the value of the extrinsic paralyzing deadtime ($\tau_s$) is known approximately, the activity of each source should be sufficient to produce an observed count rate of (100,000/ $\tau_s$) ±20% when placed in the scatter phantom of Fig. 2. For a typical value of $\tau_s$ of 5 μsec, the observed count rate should be adjusted to about 20,000 cps. The activities will usually be in the range l-7 mCi (SO-250 MBq), depending on the deadtime and collimation. The source volumes should be about 5 ml. With the scintillation camera directed horizontally, place the phantom so that the surface nearest the tubes is on the face of the collimator with the tubes ertical at the center of the field-of-view.

2.3.4 Follow the counting procedure of 2.1.5.

2.3.5 Calculate the paralyzing deadtime in the presence of scatter ( $\tau_s$):

$$\tau_S = \left[\frac{2\ R_{12}}{R_1+R_2)^2}\right] \ln\left[\frac{R_1+R_2}{R_{12}}\right]$$

2.3.6 Calculate the observed counting rate incurring 25% data losses ($R_{S-25\%}$):

$$R_{S-25\%} = \frac{1}{\tau_S}\left(\frac{3}{4}\ \ell n\ \frac{4}{3}\right) = \frac{0.216}{\tau_S}$$

A 25% data loss is suggested as an upper limit for clinical operation. It should be noted that at counting rates incurring 25% data losses, a 2% increase in patient activity is required to produce a 1% increase in the observed counting rate and that attempts to produce higher counting rates would result in increased patient exposure without commensurate improvement in information quality. The foregoing protocol enables one to adjust the patient dose and camera parameters for whatever trade-off the operator considers optimum.

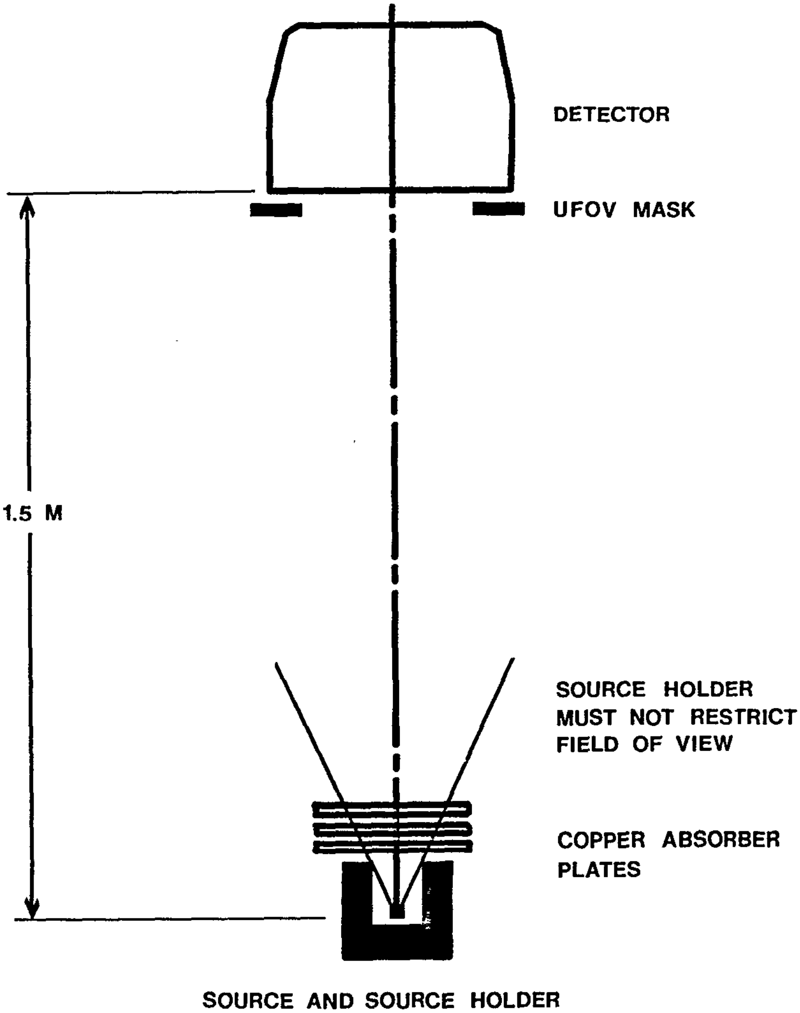



Figure 2.1. Source and detector arrangement for the temporal resolution measurements.

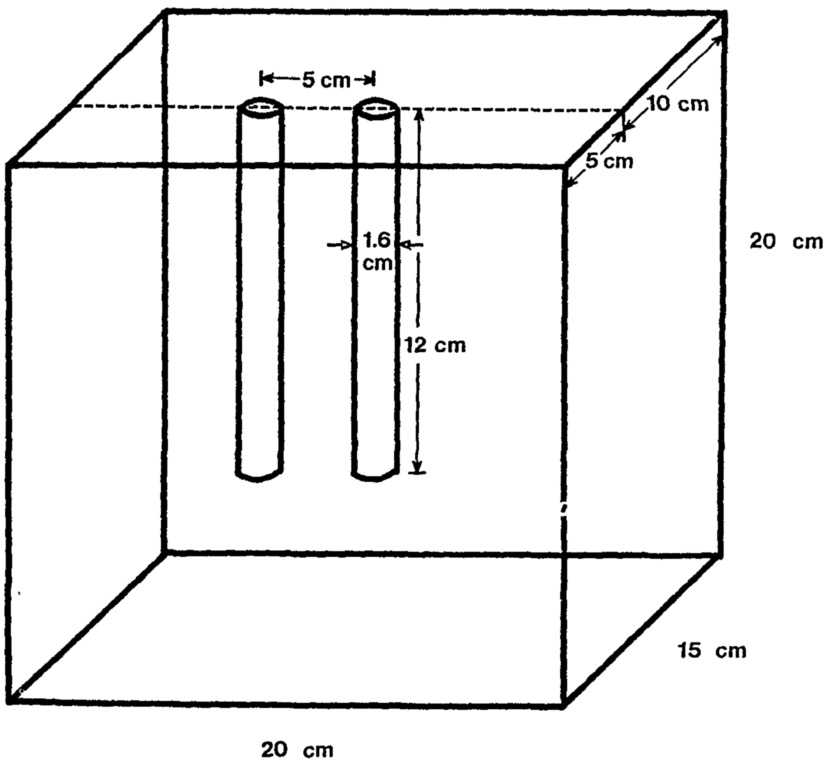



Figure 2.2. Phantom used in measurements of extrinsic temporal resolution.

## 3.0 Intrinsic Uniformity Testing

The uniformity, or counts per unit area of the detector will be measured in this section. Three basic measures are used to express the degree of non-uniformity. Two measures are identical to the NEMA measure: smoothing of the flood image followed by a calculation of integral uniformity and differential uniformity. See glossary for exact definitions of these terms. The third measure of uniformity is the statistical uniformity index (4,5,6). This index is valuable in a quality assurance program. After a test of ADC performance the basic camera uniformity is measured without collimator and without correction circuitry, if possible (3.1 and 3.2), the camera uniformity is measured with correction circuitry and as a function of count rate, PHA (3.3) calibration, collimation and isotopte energy. Point source sensitivity, while related to camera flood field uniformity, is defined and measured using distinctly separate techniques outlined in Section 5.0. System sensitivity and collimator efficiency are measured in the last part of this section (3.4).

### 3.1 Intrinsic Uniformity (Collimator removed):

3.1.1 Mask the crystal area to the useful field of view (UFOV), as defined by the collimators, with a lead mask at least 3-mm thick and carefully centered to ensure the same UFOV as that described by the collimators.

3.1.2 Obtain a quantity of Tc-99m in a point source configuration (activity in a volume of 1 cc or less is acceptable) to yield a counting rate not exceeding 30 kcps for the pulse height analyzer (PHA) window and geometric conditions used below. If the results in section 2 on Temporal Resolution indicate the count rate loss exceeds 10% (just due to the camera), decrease this count rate limit so as not to exceed 10% loss.

3.1.3 Assay the source and record the activity and time of assay.

3.1.4 Suspend the source a distance of at least five mask diameters from face of the crystal and aligned with the center of the detector. Measure and record the distance.

3.1.5 Properly adjust the PHA. Record the calibration factors and the PHA window (15% or 20%, the same as that used clinically.) The NEMA standard specifies a 20% window.

3.1.6 Analog Image Acquisition and Analysis

3.1.6.1 Disable any uniformity correction circuitry in either the camera or the computer, if possible.

3.1.6.2 Use the camera display device that is employed clinically.

3.1.6.3 Acquire the analog picture simultaneously with the digital picture. The intensity should be set for approximately 20-30 million count image or until overflow, whichever comes first.

3.1.6.4 Record the orientation, date, time of day, acquisition time, camera scaler reading, and room temperature. Calculate the average counting rate and compare to 3.1.2 and record.

3.1.6.5 Inspect the image for non-uniformities. It is emphasized that this picture must be <u>critically</u> examined since it is the basis for subsequent analysis. If unacceptable uniformities are found, correct them before analyzing the digital image. After camera repair is performed, repeat 3.1 through 3.1.6.5.

3.1.7 Digital Image Acquisition

3.1.7.1 Acquire the digital image in a 64 x 64 x 16 bit matrix.

3.1.7.2 Amplifier gains and ADC conversion gains are adjusted such that the diameters in the X and Y direction of the field image (masked) are converted into at least 60 of the 64 pixels of the ADC range. For a non-circular FOV use the diameter of a circle circumscribing the UFOV.

3.1.7.3 Collect a minimum of 10,000 counts in the center pixel of the image to achieve a -1% standard deviation in pixel count.

3.1.7.4 View the image with a 200 count window (this represents 2% of the average) while adjusting the "background subtraction" about the average. Carefully inspect these images for lines of pixels systematically extending across the image either in the X or Y directions. If there are no "X or Y lines" extending across the image proceed with the analysis of the digital image. If "X or Y lines" are present check the differential nonlinearity of the ADC's with the manufacturer before proceeding with the analysis of the digital image.

## 3.2 Digital Image Analysis

### 3.2.1 Field Mask

3.2.1.1 Ascertain the counting rate from the digital image and compare to that recorded from Sec. 3.1.6.4. If they differ by more than 1%, investigate the cause for this discrepancy before proceeding with the analysis of the digital image. Define a region of interest in the following way:

3.2.1.2 Average the 100 pixels that are closest to the center of the image.

3.2.1.3 The central portion of the image is identified as all the pixels containing more counts than half this average.

3.2.1.4 Further restrict this field of view for calculation by moving in from the perimeter of the central portion three pixels in all directions. This region of interest (ROI) will be used in subsequent calculations. This region of interest is smaller than the UFOV (useful field of view) of the NEMA standards.

### 3.2.2 Evaluation of NEMA parameters

3.2.2.1 By using one pixel outside of the ROI, smooth the data once by convolution with the following weighted 9 point filter function.

| | | |
|---|---|---|
| 1 | 2 | 1 |
| 2 | 4 | 2 |
| 1 | 2 | 1 |

3.2.2.2 "Integral uniformity" is the maximum deviation of the counts in the pixels, expressed as a percent.

$$\text{Integral Uniformity} = \pm 100 \left[\frac{\text{Max} - \text{Min}}{\text{Max} + \text{Min}}\right]$$

Where $\begin{matrix}\text{(Min)} \\ \text{(Max)}\end{matrix} = \begin{matrix}\text{(Minimum)} \\ \text{(Maximum)}\end{matrix}$ counts in a pixel.

3.2.2.3 "Differential Uniformity" is the maximum rate of change over a specified distance of the counts in the pixels, roughly the slope. The flood is treated as a number of rows and columns (slices).

Each slice is processed by starting at one end, examining for 5 pixels from the starting pixel and recording the maximum difference by determining the highest (Hi) and lowest (Low) pixels in the group of 5. The start pixel is moved forward one pixel and the next 5 pixels are examined, etc. For all the slices the largest deviation is found. Differential uniformity is expressed as a percent from this largest deviation as:

$$\text{Differential Uniformity} = \pm 100 \left[\frac{\text{Hi} - \text{Low}}{\text{Hi} + \text{Low}}\right]$$

3.2.2.4 The CFOV (central field of view) of the NEMA standard is approximated by restricting the field of view by moving in 4 pixels from the previously defined ROI in all directions. The "Integral Uniformity" of 3.2.2.2 and the "Differential Uniformity" of 3.2.2.3 should be compared to the manufacturer's data for the CFOV for this region of interest.

3.2.3 Flood field uniformity with statistical uniformity Index (optional)

The Statistical Uniformity Index together with High and Low Pixel Images result in sensitive uniformity measures which are very useful in a quality assurance program.

3.2.3.1 Calculate the mean (AVG) and the standard deviation SIG of the unsmoothed counts/pixel for the ROI as defined in 3.2.1.3 and 3.2.2.4.

3.2.3.2 The Uniformity Index* is calculated as a percent as:

$$\text{Uniformity Index} = \underline{+}\,100\,\frac{(SIG^2 - AVG)^{1/2}}{AVG}$$

3.2.3.3 Construct two images of all those pixels having counts outside the range:

$$AVG \pm 2\,(SIG^2 - AVG)^{1/2}$$

Low Pixel Image having counts lower than:

$$AVG - 2\,(SIG^2 - AVG)^{1/2}$$

and High Pixel Image having counts higher than:

$$AVG + 2\,(SIG^2 - AVG)^{1/2}$$

If the pictures are random patterns of pixels, then no further action is required. For clusters of pixels investigate the cause of the non-uniformity.

3.2.3.4 Store for future reference the entire digital image and the High and Low Pixel Pictures.

3.3 Effects on Uniformity

3.3.1 Count Rate

3.3.1.1 Perform the measurements of Sections 3.1 and 3.2 at 75 kcps. This corresponds to NEMA class standard test.

3.3.1.2 Compare the Uniformity Index and the Low and High Pixel Pictures with those acquired for the low count rate. Major discrepancies should be investigated with the manufacturer.

3.3.2 PHA Misadjustment (optional)

3.3.2.1 Perform the measurements of Sections 3.1 and 3.2 for a "reasonable" pulse height analyzer maladjustment. The acceptable

*See references 4 and 5 for further information.

uniformity of the image acquired in Section 3.1.6.5 must be used to determine acceptability of the floods for the high and low adjustments of the window. The calibration should not be changed by an amount that makes the flood unacceptable. Record the parameters such as peak shift and count rate change. A "reasonable" mal-adjustment would give a drop in count rate of 10%.

3.3.2.2 Record the changes in Uniformity Index and Low and High Pixel Pictures as a beginning basis for quality control limits.

3.3.3 Collimation

3.3.3.1 Install a collimator.

3.3.3.2 Using the volumetric flood source, perform the measurements in Sections 3.1 and 3.2, adjusting the activity in the flood source to not exceed the 30 kcps.

3.3.3.3 Compare the Uniformity Index and the Low and High Pixel Pictures with those acquired for the intrinsic uniformity. Major discrepancies should be investigated with the manufacturer. It is useful to subtract the images from Section 3.1.7 from the image from Section 3.3.3. The difference image should be scrutinized closely for organized patterns associated with collimator defects or with rotation of the collimator.

3.3.3.4 Repeat for all collimators.

3.3.4 Energy

3.3.4.1 If other radionuclides are imaged, perform the measurements of Sections 3.1 and 3.2 with these radionuclides. It is especially useful to study a low energy emitter (70-80 keV) and a high energy emitter (300-400 keV). For high energy collimators, the lead septa may be visible with high resolution cameras.

3.3.4.2 Compare the Uniformity Index and the Low and High Pixel Picture with those obtained for **Tc-99m.** Major discrepancies should be investigated with the manufacturer.

3.3.5 Uniformity Correction

3.3.5.1 It has been noted that uniformity testing is to be carried out without uniformity correction applied, if possible. Repeat 3.1 and 3.2 with uniformity correction ON if it has been disabled. Record the fractional count change which results from uniformity correction.

3.3.5.2 For a quality assurance program it may suffice to measure the count rate loss with the uniformity correction activated as a measure of the acceptability of the uncorrected flood. This measurement can be carried out in connection with Section 3.3.2.1.

3.4 System sensitivity and relative collimator efficiency

3.4.1 System Sensitivity

3.4.1.1 Place a parallel hole collimator on the camera.

3.4.1.2 Prepare a calibrated flat disc source of Tc-99m with a surface area of approximately 25-100 cm2 (a flat tissue culture flask provides a convenient fluid holder). Adjust the activity to yield 8-10 kcps with a 20% window centered over the photopeak. Record activity of the source.

3.4.1.3 With the source resting directly on the center of the protected collimator, measure the counting rate with at least 100 kcps. Record the count rate.

3.4.1.4 Remove the source and record the background count rate.

3.4.1.5 The sensitivity is calculated as:

net counts $sec^{-1}$ $\mu Ci^{-1}$ or net counts $sec^{-1}$ $Bq^{-1}$ in SI units.

3.4.2 Relative Collimator Efficiency

3.4.2.1 Having established the absolute sensitivity for one collimator, the relative sensitivity measurements may be made with an uncalibrated source and the absolute sensitivites obtained by referring to the absolute measurement.

3.4.2.2 Obtain the net counts/sec for the same activity in source as described in 3.4.1.2. Properly correct for the decay of Tc-99m.

3.4.2.3 Calculate the relative collimator sensitivities and compare with manufacturer's specifications.

3.4.2.4 Record the background counting rate for each collimator. Acceptable rates with a collimator are 20-50 cps.

4.0 Spatial Linearity (optional)

This test measures the spatial distortions in the intrinsic image. See references 10, 11, and 12 for background information.

4.1 Position the orthogonal hole pattern (OHP) on the detector, taking care not to damage the crystal. The x and y axes of the OHP must coincide with the x and y axes of the computer matrix.

4.2 The pattern is used in combination with the volumetric flood source and the orthogonal hole pattern image acquired as a 128 x 128 x 16 bit digital matrix. Between 7 and 10 million counts should be accumulated in the image.

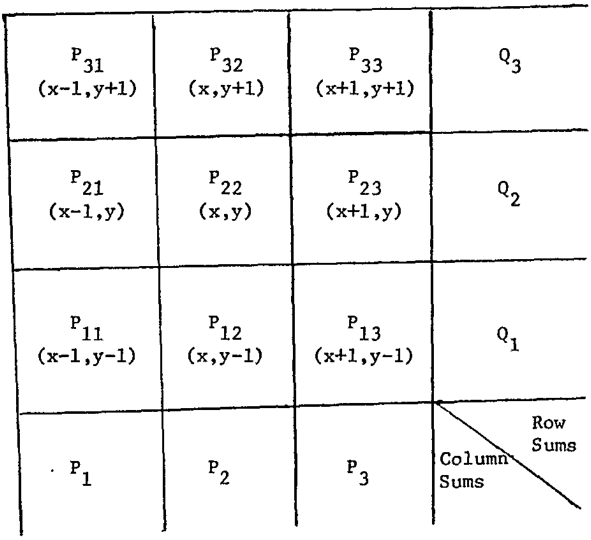
4.3 A computer program (described below) locates each peak in the OHP image then computes x and y coordinates for that peak. An ideal rectangular grid of ideal peak locations is determined, and nonlinearity of the camera-computer system is measured by determining the displacement between the ideal and measured peak locations.

4.3.1 The image consists of 128 rows of pixels. The count contents of the pixels in each row are summed to give an array of 128 sums. Searching this array for maxima identifies the approximate row locations of local peaks in the image.

4.3.2 Once a row containing local peaks is located, a search across that row is performed to determine the column locations of the local maxima. (A local maximum is defined as a pixel with a count greater than or equal to each of its eight nearest neighboring pixels.)

4.3.3 For each local maximum, isolate a 3 by 3 pixel region of interest centered on that local maximum (see Figure 4.1).

4.3.4 Sum the three pixels in each of the columns in the region of interest to yield three sums, $P_1$, $P_2$, $P_3$.




$P_1 = P_{11} + P_{21} + p_{31}$ $\quad$ $Q_1 = P_{11} + P_{12} + P_{13}$

$P_2 = P_{12} + P_{22} + P_{32}$ $\quad$ $Q_2 = P_{21} + P_{22} + P_{23}$

$P_3 = P_{12} + P_{23} + P_{33}$ $\quad$ $Q_3 = P_{31} + P_{32} + P_{33}$

Figure 4.1: A schematic representation of determining the sums in step 4.3.4 and 4.3.5. The squares represent individual pixels in a digital image matrix. The pixel coordinates are represented within parentheses. The count content of the pixel is represented by the $P_{ij}$'s. The column and row sums of pixel counts are represented by the $P_i$'s and $Q_i$'s. The pixel with coordinates (x,y) at the center of the 3 by 3 region of interest is a "local maximum" which has a count content greater than or equal to the count contents of each of its eight nearest neighboring pixels.

4.3.5 If the values $P_1$, $P_2$, and $P_3$ are the three sums from left to right with $P_2$ including the content of the local maximum, and if the local maximum has pixel coordinates (x,y), the interpolated x coordinate of the peak (xi) is

$$x_i = x + \frac{P_3 - P_1}{2(2P_2 - P_1 - P_3)}$$

Similarly, sum the three pixels in each row. This will yield three sums, $Q_1$, $Q_2$, and $Q_3$ from bottom to top. If the local maximum has pixel coordinates (x,y) and is included in the sum $Q_2$, the interpolated y coordinate of the peak, $y_i$ is

$$y_i = y + \frac{Q_3 - Q_1}{2(2Q_2 - Q_1 - Q_3)}$$

(Both equations may be derived by fitting a parabola to the values and using the vertex of the parabola as the interpolated coordinate of the peak.)

4.3.6 The interpolated coordinates of the peak ($x_i$,$y_i$) will be termed the "measured" coordinates of the peak in the following discussion. After the coordinates of each peak are measured, the coordinates of adjacent peaks are used to compute the average spacing in the x, then the y directions of the measured peak locations. The average peak spacings are computed for two reasons: (1) to determine the "dilation" of the system and (2) to construct an "ideal" grid of peak locations.

4.3.7 A rectangular grid of ideal peak locations is constructed with the center peak in the ideal grid superimposed on the center peak in the grid of measured peak locations. The x (or y) spacing between the peaks in the ideal grid is equal to the average x (or y) spacing of the peaks in the measured grid.

4.3.8 The nonlinearity of the system at a given location is obtained by finding the difference between the ideal and the measured peak locations. A nonlinearity vector is constructed with its tail at the ideal peak location and its head at the measured peak location. The x and y components of the nonlinearity vector give the direction and magnitude of the x and y nonlinearity of the system at that location.

4.3.9 Unfortunately, the ideal grid described in section

4.3.7 is not the "best" ideal grid, since its position relative to the measured peak locations was chosen arbitrarily. Therefore, compute the average x and y nonlinearity vector components and subtract these average values from the x and y components of each of the nonlinearity vectors derived in section 4.3.8. These final values give a description of the spatial linearity performance of the camera-computer system.

4.3.10 Evaluation:

4.3.10.1 The dilation of the system is obtained by dividing the average peak spacing in the x direction by the average peak spacing in the y direction.

4.3.10.2 The differential linearity of the system is given by the standard deviations of the x and y nonlinearity vector components.

4.3.10.3 The absolute linearity of the system is given by the maximum absolute values of the x and y nonlinearity vector components.

4.3.10.4 The differential and absolute linearity of the system should be reported in millimeters. The conversion between pixels and millimeters in the x and y directions can be obtained from the average x and y peak spacings since the corresponding spacings between the holes in the orthogonal hole phantom are known. NEMA reports the average value of the x and y directions for differential linearity and the maximum value for the absolute linearity.

## 5.0 Point Source Sensitivity

Two protocols are included in sections 5.1 and 5.2. Only one protocol needs to be performed. The first relies on having the orthogonal hole pattern as described in equipment section and the appropriate program described in 5.1.4.

The second method of measuring the point source sensitivity uses a simple collimated source and simple computer program together with many repeated measurements at various positions on the crystal to determine the overall point source sensitivity.

There is an NEMA class standard similar to the second test. The point source sensitivity is considered a very valuable parameter of a camera to measure, especially when quantitative regional counting is being performed. See references 10, 11, and 12 for further background information.

## 5.1 Point Source Sensitivity (Method 1)

5.1.1 Software: An OHP image is acquired as a 128 by 128 x 16 bit digital matrix. A computer program locates each "hot spot" in the OHP image, then centers a 5 by 5 pixel region-of-interest over each hot spot. A method of search is described in sections 4.3.1 and 4.3.2. The integral count in each region of interest is determined. The mean and standard deviation of the integral counts are calculated.

5.1.2 Carefully place the orthogonal hole test pattern on the detector surface. Do not use a collimator with the OHP.

5.1.3 Fill the flood source with a 5-10 mCi (200-400 MBq) Tc-99m pertechnate solution. Agitate the flood source to mix the contents thoroughly.

5.1.4 Place the flood source on the OHP covering all holes of the OHP. Tilt the detector slightly to remove bubbles in the flood source from the detector field of view if necessary.

5.1.5 Disable the system uniformity corrector, if possible.

5.1.6 Center a 20% energy window about the 140 keV photopeak. The count rate should be less than 30 kcps.

5.2.6 Acquire an image of the source using both the camera and the computer. The image should be acquired as a 128 x 128, 16 bit digital image. Acquire the images for approximately 5 seconds. All subsequent image acquisitions must be taken for the same length of time as this initial image for comparisons to be valid.

5.2.7 Examine the computer image for pixel overflow. If the pixel overflow has occured, decrease the imaging time until it is no longer occuring. There should be a minimum of 30-50 thousand counts per image.

5.2.8 Record the integral counts in both the analog (i.e. camera) and digital (i.e. computer) image.

5.2.9 Repeat 5.2.6 through 5.2.8 at 25%, 50%, and 75% of the distance from the center of field of view along the +X and -X axes.

5.2.10 Repeat 5.2.9 for the Y axis.

5.2.11 Repeat 5.2.9 for lines at 45° to the x axis.

5.2.12 Decay corrections may be necessary.

Evaluation

5.2.13 Average the integral counts and determine the standard deviation and maximum deviation from the mean for both the analog and digital acquisitions.

5.2.14 The measured coefficient at variation should be a few (1-2%) percentage points of the average integral counts.

5.2.15 Individual integral count values should be examined to determine localized regions on the detector of increased or decreased point source sensitivity.

5.1.7 Acquire a 128 x 128 x 16 bit digital image of the OHP. The image should contain a minimum of 7 million total counts.

5.1.8 After the image acquisition is complete, use the computer to determine integral counts in each hot spot of the OHP image. Record the mean and standard deviation of the integral counts in each hot spot. Calculate the coefficient of variation:

$$\text{Coefficient of Variation} = \frac{\text{standard deviation}}{\text{mean}} \times 100\%$$

5.1.9 Since this method is prone to systematic errors introduced by variations in OHP and flood source constructions, as well as limitations in the algorithm to integrate the counts in the hot spots, absolute comparisons are not reliable. Therfore, the performance of the system should be compared with another well-tuned system. Secondly, integral counts from individual hot spots can be compared with one another to detect regional variation in point source sensitivity. Systematic variations can be quantified by repeating and rotating the pattern and flood source with respect to the crystal and each other. Typical numbers for this test result in a coefficient of variation <3%.

5.1.10 Repeat with system uniformity corrector ON if quanitative counting is performed with the instrument in this state.

5.2 Point Source Sensitivity (Method 2)

5.2.1 Disable the system uniformity corrector, if possible.

5.2.2 Collimate a Tc-99m source with a single hole 3 mm in diameter in a lead container 6-mm thick.

5.2.3 Center a 20% energy window about the 140 KeV photo-peak.

5.2.4 Direct the camera so the uncollimated detector surface is facing upward. Carefully place the source on the center of the detector.

5.2.5 Adjust the source strength so that no more than 10,000 counts per second are detected at the surface of the uncollimated detector.

## 6.0 Intrinsic and extrinsic spatial resolution

### 6.1 Intrinsic resolution

The measurement of intrinsic spatial resolution, in order to be most useful to the user, must be made at various points on the face of the crystal. The most common measure of spatial resolution is the FWHM. This parameter and the associated FWTM are difficult to measure accurately at multiple places on the crystal, using conventional computer interfaces.

Studies (7) have shown that the pixel size must be at least 2.5 pixels/FWHM to achieve a systemic error of less than 5% when the FWHM is calculated by fitting the LSF to a Gaussian on a background pedestal by means of a $CHI^2$ minimization technique. This implies that if the FWHM is 4 mm then a 256 x 256 matrix is required for all cameras. NEMA procedures require that the pixel size be ≤ 0.1 FWHM. The systematic error in this case can be totally neglected. In writing this protocol, several alternative procedures were considered, such as: 1) since the digitization leads to a systematic error this could be corrected for by look-up table methods 2) assume the user would have necessary digitization capability available, and 3) measure the LSF by differentiation of the edge response function (8). Since alternatives 1 and 3 have not been well documented at this time, alternative 2 was chosen as the most reliable for the user to measure intrinsic FWHM and FTWM.

NEMA measurements use a slit mask consisting of parallel slits of l-mm width over the length of the UFOV and spared 3 cm apart across the UFOV. The central slit lies on the axis and measurements in both x and y directions are made. FWHM and FWTM are reported.

Note: As mentioned above, the digitization must provide for a minimum of 2.5 pixels/FWHM in order for the FWHM to be calculated accurately. A coarser digitization will lead to significant error. On the other hand if computer interface to the gamma camera allows finer digitization, then accuracy is improved and calculation of the FWHM and FTWM may be made easier. A zoom feature of the interface will be useful.

6.1.1 The resolution mask consists of a plate with parallel 1 mm slits. The length of the slits should be at least the UFOV. These slits should be spaced at least 3 cm apart. The number of slits will depend on the digitized field size in the axis of interest. The plate should be at least 3-mm thick.

6.1.2 The data in the direction perpendicular to the axis being measured (parallel to the slits) should be grouped in 3-cm wide bins. This improves statistics and is similar to NEMA technique.

6.1.3 A Tc-99m point source spaced at greater than 5 UFOV diameters giving a count rate of <10 kcps through a 20% window shall be used.

6.1.4 Accumulate a computer image which results in at least 10,000 counts in the peak pixels associated with each LSF.

6.1.5 The distance between peaks in the profile curve (in pixels) should be divided into the center-to-center distance between slits (in mm) to determine the distance represented by each pixel (in mm/pixel).

6.1.6 The FWHM in mm should be determined by 1) direct measurement using linear interpolation if the digitization is <0.1 FWHM or 2) fitting the curve to a Gaussian-plus pedestal by means of a $CHI^2$ minimization as represented by

$$Y = A + Be^{-C(X-M)^2}$$

where A = Background level
B = Peak height
M = Peak mean location

and Std deviation, $\sigma = \sqrt{1/2C}$

See reference 13 for further information on the curve fitting procedure.

6.1.7 If digitization is <0.1 FWHM, then the FWTM can be calculated by linear interpolation for raw data as well. If fitting was necessary, then an independent measure of FWTM can not be made.

6.1.8 Determine the average FWHM of the values obtained for both the UFOV and CFOV.

6.1.9 Determine the average FWTM of the values obtained, if possible, for both the UFOV and CFOV.

6.1.10 Repeat 6.1.1-6.1.9 for a Xe-133 or Tl-201 source (optional).

6.2 Intrinsic resolution and display system test.

6.2.1 Resolution at 140 keV:

6.2.1.1 Mask the outer edge of the crystal with the 3-mm thick lead mask. If available, an electronic field limiting device can be used.

6.2.1.2 Poistion a point source of Tc-99m at least 5 UFOV diameters from the crystal.

6.2.1.3 Center the 20% window about the photopeak, and enable the uniformity correction circuit.

6.2.1.4 Place a transmission pattern of equally spaced lead (thickness at least 3 mm) and Lucite strips on a quadrant or parallel bar design carefully aligned with the x and y axes of the crystal on the surface of the crystal.

The transmission pattern should be matched to the resolution of the camera so that at least one set of bars is not resolved. The increment of bar width from one bar size to the next should be small so that the intrinsic resolution can be measured with reasonable accuracy. An orthogonal hole pattern could also be used in this test.

6.2.1.5 Obtain an image of the transmission pattern with the count rate less than 10,000 cps. the image size less than 5.7 cm, and a total of 1.5 million counts collected for a small field-of-view crystal and 3.0 million for a large field-of-view crystal.

6.2.1.6 Determine the bar width just resolved by visual inspection. This distance times 1.75 approximates the full-width at half-maximum intrinsic resolution, and can be compared to the appropriate manufacturer's specifications, and the results of Sec. 6.1.

6.2.1.7 Repeat above 3 steps with the bars turned at an angle 90° to the original direction. If a four quadrant transmission pattern is used, continue to rotate the transmission pattern until the smallest bar width resolved has been imaged in all quadrants in both X and Y directions. It will be necessary to invert the quadrant bar phantom to achieve this. It is important that the amount of scatter and distance to crystal not change after inversion.

6.2.1.8 Observe any spatial distortion of the bar images in both directions. Determine if the resolution is maintained across the camera face and if it is equal in the X and Y directions.

6.2.1.9 Calculate magnification factor, $M_f$, in the X and Y directions:

$$\frac{\text{image bar width}}{\text{actual bar width}} = M_f$$

A different magnification factor can be calculated for each clinically used image size.

6.2.2 Resolution at lower energies (optional):

Repeat steps 6.2.1.2 through 6.2.1.6 using a point source of Xe-133 or Tl-201. Determine the bar width just resolved by visual inspection.

6.3 Extrinsic or system spatial resolution (with and without scatter).

6.3.1-6.3.9 describes a measurement similar to the NEMA test. The NEMA tests are reported as a class standard. The same qualifications on digitization holds in this section as in 6.1, but the requirements are much more easily met.

6.3.1 Fill two capillary tubes with high specific activity Tc-99m. The length of the tubes should be up to the UFOV if possible and at least 5 cm long and the internal diameter should be <l.0 mm.

6.3.2 The count rate should not exceed 10 Kcps through 20% centered window. If desired, higher count rates can be separately measured and reported.

6.3.3 Place the sources 10 cm from the face of the collimator on the x axis and parallel to the y axis (other depths can be measured at 5-cm intervals if desired).

6.3.4 Acquire an image in the computer. There should be at least 10,000 counts in the peak pixel of the LSF. Digitization in the perpendicular direction should be 3 cm or less.

6.3.5 Place the second capillary tube 5-cm away from and parallel to the first tube and acquire another image on the computer. Keep both tubes in a plane parallel to the collimator. Calculate the number of pixels per mm for calibration purposes.

6.3.6 Introduce 10 cm of lucite, or an equivalent plastic or water between the collimator and the single capillary tube and 5 cm of similar material behind the capillary tube. Acquire a computer image and obtain at least 10,000 counts in the peak pixel of the LSF. The capillary tube should be on the X axis of the image and parallel to the y axis.

6.3.7 Repeat 6.3.4-6.3.6 with the capillary on the Y axis and parallel to the Y axis.

6.3.8 Calculate FWHM and FWTM in mm, averaging all values obtained for both X and Y axes. Report separate values with and without scatter separately.

6.3.9 Repeat 6.3.4-6.3.7 with a total count rate of 75 kcps. It may be necessary to do this with both line sources in position at the same time.

7.0 Multiple window spatial regristration

The spatial registration of the images from each of the camera's windows shall be measured and the deviation between the images for a collimated point source reported as the larger of the X and Y measurements, in millimeters.

7.1 The radioisotope to be employed is Ga-67. If the camera has two windows, the peaks at 93 KeV and 296 KeV shall be employed. For three windows the peak at 184 KeV shall be additionally employed.

7.2 The total count rate shall not exceed 10 kcps through all three windows. Each window shall be centered on the photopeak and have a width of 20%.

7.3 A Ga-67 source, collimated through a hole 3 mm in diameter by a minimum of 6 mm in length, shall be placed at two points on each (X & Y) axis, acquired through the 2(3) windows, and the displacement in millimeters computed.

7.3.1 For the X-axis displacement measurement, the digitization resolution shall be <0.1 FWHM of the X-axis if possible. Y-axis resolution is irrelevant.

7.3.2 The collimated source shall be placed on the X-axis, 75% of the UFOV radius from the center of the UFOV (on the CFOV circumference). At least 1000 counts shall be acquired in the peak channel through each window.

7.3.3 If a digitization resolution is <0.1 FWHM, the center of the peak for each window shall be determined as the average of the half-maximum channels as described in 6.1.6. If digitization resolution is <0.5 FWHM, a centroid calculation should be performed to determine the center of the peak. The displacement(s) (1 or 2) shall be the difference in the 296 KeV peak (and 184 KeV peak) center(s) from the center of the 93 KeV peak.

7.3.4 The source is moved to a point on the -X axis, 75% of the UFOV radius from the center to the UFOV. The measurement and calculation of displacement (7.3.3) repeated. Since the distance between the two source locations is known, the 2 (or 4) X displacement values can be converted into millimeters.

7.3.5 The largest of these 2 (or 4) X displacement values in mm is recorded as the maximum X registration error, in millimeters.

7.4 The Y axis displacement values are measured via the procedure in 7.3 substituting Y axis and X axis, and the maximum Y registration error in millimeters is recorded.

7.5 The larger of the X or Y displacements is reported.

Note on multiple window registration

To obtain 10 pixels per FWHM (7.3.1) it may be necessary to use the Zoom (Variable ADC Gain). This will make the calibration of distance in Section 7.3.4 impossible. Instead, place the source at 2 positions more than 100 pixels apart, and measure the physical displacement. Use this to calculate mm per pixel and thereby calibrate mm per pixel and thereby calibration X and Y.

## 8.0 Energy Resolution (optional)

This measurement, in general, requires the use of a separate pulse height analyzer. This is described below in section 8.1. It should be possible, but has yet to be investigated, that the computer could be used for this measurement. Some computers have energy channels; on others the X channel could be used as the energy channel, while Y receives a fixed voltage. The result should be equivalent to a 128 or 256 channel multichannel analyzer. However, biased amplifiers and variable delay circuits may be needed to adequately perform this measurement with the computer.

The measurements below require interfacing the camera Z pulse, before it is processed by the camera analyzer system, to an external multichannel analyzer or single channel analyzer. The manufacturer's assistance should be obtained so the camera's warranty is not compromised.

### 8.1 Full width at half maximum of the photopeak:

8.1.1 These measurements should be made with an uncollimated detector, and a count rate of 10 kcps from a small source (less than 2 cm in diameter) placed at a distance of at least 2-UFOV diameters from the detector face on the central axis.

Mask the outer edge of the crystal with the 3-mm thick lead mask. If available, an electronic field limiting device can be used.

8.1.2 Using a Tc-99m source, adjust the gain on the pulse height analyzer so that there are 10 or more sampling channels in the energy range corresponding to the full width at half maximum (FWHM) of the photopeak (140 KeV). Determine the channel position of the center of the photopeak (140 KeV).

8.1.3 Replace Tc-99m with a source of Co-57 and then In-111. Determine the center of the 172 KeV photopeak of In-111 and the center of the Co-57 photopeak. Note: other sources may be used to calibrate the pulse height analyzer at 2 energies other than the energy of interest. Their energies should be on each side of the photopeak and not differ from the photopeak energy by more than 50%.

8.1.4 Acquire the energy spectrum of Tc-99m, obtaining a minimum of 50,000 counts in the center channel, 8.1.5 Acquire a background spectrum over the same channels as in 8.1.4 with all sources of radioactivity removed.

8.1.6 Subtract the background spectrum from the Tc-99m spectrum normalized for equal counting times.

8.1.7 Determine the channel numbers for the upper and lower FWHM points, using linear interpolation between points. Subtract the lower from the upper channel number. Multiply this difference by the KeV/channel (calculated in 8.1.3) to determine the FWHM ( $\Delta E$) in energy units.

Calculate: $\frac{\Delta E \times 100}{140} = \%\ \text{FWHM}$

8.1.8 Calculate the photopeak efficiency by determining the ratio:

$$\frac{\text{net counts in the photopeak}}{\text{net counts in the entire spectrum}}$$

Note: the true photopeak counts may be obtained by fitting the photopeak curve to a Gaussian distribution and determining the area under the curve. This will correct for scattered events near the photopeak.

The photopeak efficiency is sensitive to count rate and gamma ray energy.

8.2 Window width calibration (can be performed only if a multichannel analyzer with a coincidence mode is available).

The sensitivity of a given camera measurement is particularly dependent upon the accuracy of the window width calibration. For example, in the comparison of the sensitivity of two cameras, each with a nominal 20% window, when the cameras actually have windows of 19% and 21% will result in significant systematic differences. The window width may be measured with a multichannel analyzer calibrated and operated as discussed above for energy resolution and measurement. In addition, the camera unblanking pulse, i.e. the output of the camera single channel analyzer shall be input to the coincidence circuitry of the multichannel analyzer. Operating the multichannel analyzer in the coincidence mode will thus yield the energy spectrum which is accepted by the gamma camera single channel analyzer.

8.2.1 Use a Tc-99m source as described in 8.1.2 and a 20% window to acquire a spectrum through the multi-channel analyzer operating in the coincidence mode.

8.2.2 The width of the window shall be measured at the width where the counts are reduced to one-half of the peak value, linearly interpolated between those points in the spectrum. This width shall be expressed as the percent of the gamma ray energy.

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