Practicality of NEMA Performance Specification Measurements for User-Based Acceptance Testing and Routine Quality Assurance

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National Electrical Manufacturers Association (NEMA) performance specifications provide the only standardized and traceable measurements of scintillation-camera performance that are widely accepted by manufacturers. The NEMA publication describing the performance specifications suggests that elaborate equipment beyond a standard imaging computer is required for the measurements. For this reason the tests are currently unsuitable for both user-based acceptance testing and daily quality assurance. We have implemented five of the eight NEMA performance measurements as routine quality-assurance procedures on our computerized scintillation cameras. In addition, we have shown that seven of the eight NEMA measurements can be performed in a manner traceable to NEMA, with energy resolution as the single exception. With a standard imaging computer, NEMA phantom, and minor modification to NEMA collection and analysis constraints, we have analyzed images for intrinsic uniformity, resolution, linearity, and multiple-window spatial registration as well as for system spatial resolution both with and without scatter.


Methods and phantoms for scintillation-camera performance testing and quality assurance have proliferated during the first quarter century of the camera's history. Measurement techniques have changed in response to improved imaging characteristics, reductions in measuring times, and the clinical availability of computer-assisted analysis (1-9). One comprehensive set of scintillation-camera performance measurements, developed by the National Electrical Manufacturers Association (NEMA) in conjunction with user organizations, has received wide publicity but limited utilization by users (10). NEMA performance measurements have been well accepted by the manufacturers, and most major companies now specify their product performance in terms of these standardized and traceable specifications. This approach to performance documentation facilitates quantitative comparison of cameras by the user with the assurance that all reported values are measured in the same way and therefore are directly comparable (11). Since the values are readily available from manufacturers, it would be advantageous to incorporate them into performance specifications for camera purchase and into acceptance-testing measurements to be performed in the field. The ideal performance-testing procedures could also be utilized for routine quality-assurance measurements. The major drawback to the NEMA measurements is the suggestion that complex equipment and extensive data reduction are needed for the tests (12-15). NEMA's position regarding end-user usage is stated as:

"Elaborate measurement equipment is required in order to accomplish the purpose of these standards: ... Because of the use of this equipment, these standards are not intended for acceptance testing at installation, user
quality assurance, or for use as a user quality control procedure."

Some of the NEMA measurements require a 10-bit analog-to-digital converter and, from a practical point of view, need computer analysis of the digitized data. We believe that a conventional nuclear medicine image-processing computer with 8-bit ADC resolution can be used effectively for data acquisition and analysis in the NEMA tests.

MATERIALS AND METHODS

All NEMA measurements (and approximations to them) were made on four cameras: (a) a General Electric 61-tube 400T, (b) a Picker Dynamo small-field-of-view mobile camera, (c) an Ohio Nuclear Sigma 410 large-field-of-view camera, and (d) a General Electric 61 tube 400AT. All data collection was implemented on a standard-configuration Digital Equipment Corporation Gamma-11 (PDP-11/34A) computer.

Intrinsic flood-field uniformity. The flood-field uniformity of a scintillation camera has been the most widely used indicator of camera stability. For any scintillation camera interfaced to a programmable imaging computer, the implementation of exact NEMA traceable uniformity measurements is both possible and practical. According to the NEMA protocol, a Tc-99m point (= small) source is placed at a distance of 5 useful

![Image](https://via.placeholder.com/150)

FIG. 1. NEMA analysis of flood-field uniformity for UFOV and CFOV. Left-hand side (A) shows UFOV and CFOV, where pixels labeled with maximum and minimum count number have been set equal to zero for visualization. Right-hand side (B) shows five consecutive pixels (set equal to zero) that determine differential linearity for UFOV and CFOV, respectively. Largest deviations over 5 pixels are indicated. Integral and differential uniformity values for flood image are shown for UFOV and CFOV of GE 61-tube 400T camera (uniformity corrector disabled).
field of view diameters (UFOV) and the flood-field image is acquired in a $64 \times 64$ matrix to a count depth of 4000 counts per pixel. The NEMA requirement of 4000 counts per pixel implies a flood image of 12 million counts for a circular field of view. This requirement is a major departure from the images containing 1 to 3 million counts routinely collected for visual interpretation of field uniformity. For low-count-rate imaging ($<30,000$ cps) the 12-million-count image requires 8–10 min of collection time. For acceptance testing, a point source should be used to assure uniformity of the source field. The 4000-c/pixel requirement may demand some additional complexity in the programming for uniformity analysis of computer systems limited to less than 12 bits of depth in the image matrix.

Data analysis of the flood image is initiated with application of a standard nine-point smoothing kernel to reduce the effects of random fluctuations in the data. Smoothing is followed by a radial search for the digital UFOV (defined by 95% of the average half-height radius). All points outside the UFOV are set to 0 (i.e., are masked). To determine the integral uniformity $[I.U. = (\text{MAX-MIN})/(\text{MAX + MIN})]$, a search for the pixels with maximum (MAX) and minimum (MIN) counts in the smoothed and masked UFOV image is quickly accomplished in Cartesian coordinates. A search for the maximum difference in counts over any five (or six) consecutive pixels in every row and column (Hi-Low) is also performed to determine the differential uniformity $[D.U. = \pm 100.(\text{Hi-Low})/(\text{Hi + Low})]$ (19).

The searching routine is repeated after applying a central field of view (CFOV) mask defined by 75% of the UFOV radius. As a daily quality-assurance procedure, uniformity analysis should be applied to flood-field images both with and without uniformity correction if a user-defeatable corrector is available.

A complete uniformity analysis is shown in Fig. 1, and a generalized FORTRAN program can be obtained from the authors. The total data-reduction time is 20 sec for both uniformity-corrected and uncorrected images. The data are analyzed without operator intervention. In our institution the integral uniformity index and differential uniformity are computed daily. The results are plotted on a 4-mo graph with limits of acceptability established from the original performance specifications for the camera (Fig. 2).

**Intrinsic spatial resolution.** Changes in the intrinsic spatial resolution of a scintillation camera are expected much less frequently than uniformity changes caused by drifting photomultiplier tubes. Gross, localized changes in resolution are often coupled to degradation in camera uniformity and would be detectable during daily uniformity analysis. In most institutions spatial resolution is evaluated weekly or even less frequently by visual inspection of images of four-quadrant bar, PLES, BRH, orthogonal-hole, or other phantoms. NEMA resolution measurements require quantification of the full width at half maximum (FWHM) and full width at tenth
maximum (FWTM) of the line spread functions obtained from the multiple, isolated 1-mm slits in the lead sheet comprising the NEMA resolution/linearity phantom (NP). For these measurements the NEMA phantom is placed directly on the crystal face and a Tc-99m point source is centered at least 5 UFOV diameters above the phantom as described by the NEMA protocol. No collimator is used and the phantom is aligned with either the x or y camera axis. A full-field-of-view image is acquired in a 256 × 256 byte mode matrix to a density greater than 200 counts per pixel. Precise alignment with the x- or y-axis can be assured with slice-profile routines available on commercial computer systems. Exact alignment is essential because the intrinsic resolution is computed from the line spread function averaged over 3 cm. Once proper alignment is achieved, the phantom and camera head should be marked to facilitate repositioning. This image is followed by an NP image in magnification mode sufficient to produce line spread functions in the NP image with at least 10 pixels above the FWHM. The required counts per pixel for the image may also be decreased by the reciprocal of the magnification factor. Either the camera magnification (preferably) or computer zoom modes (or combinations of both) can be used to produce the magnification image; two images collected by this protocol are displayed in Fig. 3. For an information density greater than 200 counts per pixel at the low count rate (≤10,000 cps) called for in the protocol, approximately 12 min are required for data collection. Several frames are then acquired by changing the location of the magnified portion of the image in order to cover the entire UFOV. NP line sources presented horizontally are rotated for convenience so that all analyses of line spread functions (LSF) can be performed on horizontal profiles.

The resolution analysis of the NP image is initiated by establishing the pixel size in a direction perpendicular to the line-source images. This function is an internal calibration using the line-image separation defined by NEMA and machined into the phantom as exactly 3 cm. From an 80-pixel horizontal profile through the image center, the pixel spacing between each line pair is computed and averaged. Spacing values greater than 2 s.d. from the average are deleted and the remaining values are used for the pixel calibration. Pixel size in the orthogonal direction is assumed to be identical in order to add matrix rows to form 3-cm slice profiles from the bottom to the top of the magnified NP image (this assumption will be verified from the analysis of the rotated NP image). Each line spread function in the horizontal slice profile is fitted to a Gaussian function by a least squares technique and the FWHM and FWTM for the Gaussian function are reported. These values are also determined using the NEMA slope technique. In Fig. 4, values from both methods, as a function of the magnification factors, are displayed for comparison. The NP images for the system’s spatial resolution, with and without scatter, are treated exactly like the intrinsic resolution images; however, a magnification mode of 1.6 for a camera with 15 in. field of view is sufficient for the NEMA requirement of ten channels above FWHM, since system spatial resolutions are in the range of 6–10 mm for readily available collimators. For the magnification factor (1.6) most of the CFOV (85%) is covered, so no displacement of the magnified field of view is suggested. The system’s FWHM is averaged for the x and y directions (and the same for the FWTM), and the results reported (in mm) for the CFOV.

**Intrinsic spatial linearity.** Changes in intrinsic spatial linearity of a scintillation camera are expected to occur more often than changes in intrinsic resolution. Poor
intrinsic linearity is generally coupled to a degradation of intrinsic uniformity (16). Orthogonal-hole and PLES phantoms are generally used for a visual inspection of linearity. NEMA phantom images are acquired as 256 × 256 byte mode matrices in both x and y directions with no magnification. The absolute spatial linearity and intrinsic spatial differential linearity are calculated in both the x and y directions for the CFOV and UFOV. Real variable arithmetic is used for all computations. NEMA absolute linearity is reported as the maximum displacement of an imaged line source from an “ideal grid.” The differential linearity is the standard deviation of all the peak separations. Computer analysis of the full field of view begins with application of a UFOV (and CFOV) mask to the acquisition files similar to the procedure used during uniformity analysis. This UFOV and CFOV mask is now based on a 256 × 256 byte mode matrix. Consequently the NP images must be acquired in the same orientation as the flood-field image used to determine the masks.

The second and most difficult step in the analysis of intrinsic spatial linearity is the establishment of the “ideal grid.” No rigorous definition of this unique grid is included in the NEMA guidelines. An interesting approach to define a best set of parallel and equally spaced lines has been described by Koral et al. (9), but their line bar phantom is different from the one called for by the NEMA standards. We have established the following procedure for defining an “ideal grid.” A first estimate of the ideal spacing is obtained in a fashion identical to the pixel-size calibration for spatial-resolution analysis. The average NP line spacing (in pixels) is obtained and set equal to 3 cm as defined by the NEMA phantom construction. This grid spacing will later be adjusted to the minimum least squares fit of the data for the line spread function.

Matrix rows are summed into a single horizontal image profile over the UFOV and CFOV. In these summed rows of the NP image, each peak location is determined by a least squares fit to a Gaussian function with the same method as that used in the analysis of spatial resolution. The mean peak separation is then used to define a temporary grid. The central line of this ideal grid is aligned with the central line in the NP image profile and slid in discrete horizontal steps over the NP profile. The range of this sliding, relative to the central line, is ±5% (±1 pixel for a 15-in. FOV) of the estimated line bar spacing. The sum of the squared deviations from the line source images is calculated at each of these steps. A least squares fit to this function determines an optimal alignment value. The ideal grid’s line bar spacing is then varied by discrete values within a range of ±5% of the estimated line bar spacing, and the sliding fit is repeated for each discrete step. This process defines a curve of optimal alignment values, which provides a minimum for the best-fitting “ideal grid” spacing and alignment.

Results of this procedure are summarized in Fig. 5, where the “ideal” grids are overlaid on the line bar patterns. Following the definition of the grid, 3.0-cm horizontal rows are summed and the peaks determined by least squares fit to a Gaussian function. The final step includes calculation of the maximum displacement of any peak location in the NP image from the ideal grid. The differential spatial linearity is also determined from the standard deviation of all the peak separations from each other. All results are given in millimeters.

Count-rate performance and sensitivity. Although eight scintillation-camera parameters are addressed by NEMA, only six have been considered in this paper. The remaining two, intrinsic count-rate performance and system sensitivity, as well as point-source sensitivity (which is a class standard subsection of the intrinsic flood-field uniformity) can be measured exactly as prescribed by NEMA without use of 10-bit digitization. Data reduction for these tests can be accomplished with a hand-held calculator and manual data entry. Measurements of intrinsic spatial resolution and intrinsic flood-field uniformity, with an observed count rate of 75,000 cps, are also repeated and analyzed according to the previously described method.

Multiple-window spatial registration. To quantify any shift in spatial registration due to differences in energy-window amplification, the NP* can be used instead of the procedure for point source data collection defined by NEMA. The previously described linearity images are collected using each available window centered on the three principal gamma energies obtained with a Ga-67 source: 93.26, 184.5, and 296 keV. For our NP, penetration of the higher-energy gammas through the lead mask is not particularly severe: ~15% for the 296-keV photon, which contributes about 20% to the total photon yield. The 388-keV photons (relative yield 5%) show a 32% penetration and contribute to a uniform Compton background, which does not influence the results of the analysis. The collection of these three images should be repeated in the orthogonal direction. Analysis of the data proceeds as for the linearity analysis. Two NP line segments, spaced apart by ~75% of the UFOV diameter, are summed over the center of the line lengths to obtain the required 10,000 counts for the peaks. The two peak locations are then determined by a least squares fit, and the maximum x and y displacements of each LSF for all available windows are calculated and reported in millimeters.

RESULTS AND DISCUSSION

Data collection and analysis according to the NEMA protocol for intrinsic uniformity has been performed daily in our laboratory for the past 9 mo as a routine quality-assurance procedure. The technique is useful for quantitatively following detector dynamics; more im-
importantly, it provides a criterion for requesting service on a camera guaranteed by purchase specifications to meet a given NEMA-specified, uncorrected integral uniformity over the UFOV.

A major weakness in the single-valued NEMA measurement of uniformity is the lack of localization of the area of greatest nonuniformity, although it may be localized in either the CFOV or (UFOV-CFOV) ring in some cases. To address these deficiencies, a functional image of the uniformity flood field is also generated to visualize any area of correlated nonuniformities in the UFOV and CFOV (see Fig. 6). In the event that vendor-guaranteed uniformity is not met, the location may be irrelevant since service is required. However, another major application of these uniformity measurements involves the analysis of camera uniformity during camera rotation for SPECT imaging. In this application, if the NEMA uniformity value is constant but the location of nonuniformities changes, then the transaxial reconstruction may produce artifacts that reflect a changing detector response with angle. We use a Co-57 flood source attached to the detector head for this rotational testing of uniformity. Uniformity changes are monitored with the NEMA uniformity index. About 12 sec of data-processing time are required for computation of NEMA integral and differential uniformity and the functional image for both the CFOV and UFOV.

Intrinsic spatial resolution can be analyzed exactly as outlined by NEMA over a limited area of the camera’s field of view. The difficulty in strict compliance with NEMA data-collection requirements is the constraint that LSF data include ten channels (pixels) above the FWHM of the LSF. With the full 8-bit ADC of the computer (256 × 256 digitization) the number of pixels above FWHM is shown in Fig. 4 for our large-field-of-view tomographic system. To produce NEMA-specified LSFs, a zoom mode of approximately 4 would be required for a standard LFOV 400-mm camera with 3-mm FWHM resolution. Without magnification mode, digital undersampling (17) would overestimate by 2% the FWHM values when using a 256 × 256 matrix. If all magnification can be done in the camera, then there is the advantage of measuring an additional component of the camera that is not addressed by NEMA. If the
computer’s zoom mode is used, then this magnification circuitry of the computer interface may contribute to an overall degradation of resolution. This situation is still acceptable if both camera and computer are manufactured by the same firm. When this is not the case, however, the performance of the interface should be independently verified. If the magnification circuits degrade resolution below performance specifications, then field service or nonacceptance of the system is indicated regardless of whether the magnification circuitry or the basic camera circuitry is at fault.

To determine the FWHM and FWTM by the NEMA slope technique, it is apparent that a magnification factor of 2.5 is adequate, since the result is only 2% greater than that obtained with more than ten channels above FWHM (Fig. 4). The superiority of the NEMA definition and quantification of FWHM and FWTM over a least squares fit to a Gaussian-shaped LSF is also apparent in Fig. 4. The NEMA definition requires only a certain number of channels above FWHM, hence the results are independent of the exact shape of the LSF. The least squares method is sensitive to the number of points included in the fit and to the curve’s shape. Data processing requires ~10 sec per frame.

No correction for line source width (1 mm) has been incorporated into the computation of spatial resolution. This omission is irrelevant for NEMA acceptance testing and comparison with manufacturer’s specifications. For absolute measurement of intrinsic resolution, however, adjustments should be made for source width. Line-width corrections have been described (18). These corrections become more important as the resolution improves and approaches the 1-mm slit width of the phantom.

In the interest of using a single phantom for our three cameras, the effect of placing the phantom 5 cm above the crystal was investigated. This offset is necessary for resolution measurements on cameras with recessed crystals if one does not want to reduce the phantom to the recess diameter. For a 400-mm camera with the point source at 5 UFOV from the phantom, the geometrical spread produces an effective slit width of 1.025 mm instead of the specified 1 mm. This 2.5% increase in slit width becomes more important as camera resolution approaches the slit width, although measured values with phantom placement on and 5 cm away from the crystal face reveal no detectable variations in resolution.

Intrinsic spatial linearity is analyzed according to NEMA specifications with one minor modification: since our approach provides only four rather than the ten channels above FWHM, the peak definition was compromised somewhat by using a least squares method to an assumed Gaussian LSF profile of the NP image. Since only the peak positions of the LSF need be considered, the reduced number of channels above FWHM does not constitute an important departure from NEMA specifications. To obtain the best possible LSF definition, considerably more counts are accumulated than are specified by NEMA. The sliding “ideal grid” has been designed only to quantify minimal nonlinearities (below 2%). Gross nonlinearities of 2% and above have not been analyzed by this method, since such major problems would be detected easily by visual inspection. Computer analysis for the entire procedure requires about 5 min.

Multiple-window spatial registration can basically be analyzed according to NEMA specifications by compromising the peak location, as is done for the intrinsic spatial linearity analysis, i.e., four channels above FWHM instead of the required ten. Rather than using a Ga-67 source collimated through a hole 3 mm in diameter and collecting sequentially four point-source images on the –x, +x, –y, and +y axes (every pair at a distance equivalent to twice 75% of the UFOV radius), NP images for the x and y directions are acquired for all windows and the three principal gamma energies obtained from the Ga-67 source. Approximately 40 rows of the 256 × 256 byte mode matrix are summed over the central part of each NP image to achieve the required
number of counts (>10000) for the two peak values taken at a distance equivalent to the CFOV diameter. Besides being equivalent to the NEMA definition, the present suggested method provides an efficient way of measuring positional deviations in an image at different energies by using the same setup as for the measurement of the intrinsic spatial linearity.

**CONCLUSION**

Computer-based analysis of quality-assurance and user-based acceptance testing for scintillation cameras according to NEMA specifications is presented. Seven of the eight NEMA protocols can be performed with a conventional camera system and imaging computer. With the advent of 12-bit ADCs in the latest design of digitized scintillation cameras, even the energy resolution may become a user-measurable parameter traceable to manufacturers’ specifications, as well as rigorous NEMA measurement of intrinsic spatial linearity. Intrinsic flood-field uniformity, intrinsic spatial resolution,
and system spatial resolution, with and without scatter, can be analyzed exactly according to NEMA specifications. To assess intrinsic spatial linearity in a quantifiable fashion, we have defined an "ideal" grid. For the peak definition using a least-squares method to fit the Gaussian-shaped LSF, a minor modification had to be introduced. Data acquisition to test multiple-window spatial registration, as defined by NEMA, can be effectively substituted with an expansion of the NP data collected during linearity testing. Intrinsic Count-Rate performance, System Sensitivity, and Point Source Sensitivity require no special equipment or computer analysis, and can easily be performed according to NEMA specifications, without restrictions.

NEMA traceable measurements can be practically utilized for end-user scintillation-camera acceptance testing and even for routine quality assurance. Times, equipment, and suggested frequencies for each of these measurements are summarized in Table 1. All measurements (i.e., acceptance testing) can be done in 2 days. Quality-assurance procedures can be accomplished in about 30 min per day plus an additional 5 hr each month.

FOOTNOTE

* The NP (Nuclear Associates, 100 Voice Road, Carle Place, NY 11514) has been manufactured as a lead mask 4 mm thick; NEMA specifications suggest 3mm.

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REFERENCES


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