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GUIDELINES

Routine quality control recommendations for nuclear medicine instrumentation

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Introduction

These recommendations cover routine quality control (QC) of instrumentation used within a nuclear medicine department. Routine QC testing starts after installation of the instrument, and after acceptance testing, and continues on a regular basis throughout its lifetime. Additional periodic tests may be carried out to provide more in-depth testing. Recommendations for acceptance testing are covered in a separate document. These recommendations must be considered in the light of any national guidelines and legislation, which must be followed. The recommendations cover the types of tests to be performed, and suggested frequencies, but they do not specify the protocols to be followed, which are available from other reference sources quoted.

Acceptance and reference tests

After installation, and before it is put into clinical use, a nuclear medicine instrument must undergo thorough and careful acceptance testing, the aim being to verify that the instrument performs according to its specifications and its clinical purpose. Each instrument is supplied with a set of basic specifications. These have been produced by the manufacturer according to standard test procedures, which should be traceable to standard protocols, such as the NEMA and IEC performance standards [1–4, 11, 17, 30, 37]. By following such standard protocols in the clinical setting, with support from the vendor for supplying phantoms and software where necessary, specifications can be verified and baseline performance data created. Additional tests are usually also needed in order to more

thoroughly test individual components of an instrument. These acceptance test results form the reference data for future QC tests, and some may be repeated periodically, such as at half-yearly or yearly intervals, or whenever a major service or component change has been carried out.

Routine tests

Once the instrument has been accepted for clinical use, its performance needs to be tested routinely with simple QC procedures that are sensitive to changes in performance. Tests must be performed by appropriately qualified and trained staff, and detailed local operating procedures should be written for this routine work. All test results must be recorded and monitored for variations, and appropriate actions taken when changes are observed. The QC tests are an important part of the routine work, and sufficient equipment time and staff time must be allocated for routine QC.

Action thresholds, follow-up, record keeping and review, and monitoring

Records of test results should be kept in a log-book or digital record. Immediate review of the QC results is essential, comparing them to the usual values obtained, and to the action thresholds for that test. Action thresholds should be set locally, taking into account the manufacturer's recommendations, and other professional guidance. Action thresholds should be set to maintain the system within the specification value of a parameter. When action thresholds are reached a decision needs to be made about whether the instrument is fit for use. The QC operating procedure should make clear the actions to be taken when an action threshold is reached or exceeded, and who is responsible for the decision to use the equipment.

The follow-up actions taken when test results are unsatisfactory and solutions to a problem must be recorded. Such a record may assist troubleshooting if a similar problem occurs.

Routine test recommendations and test frequency

Recommendations for basic routine QC tests that should be scheduled and carried out for the main instruments of the nuclear medicine department are presented in Tables 1, 2, 3, 4, 5, 6, 7, 8 and 9. The tables give briefly the purpose of the test, suggested frequency, and a comment. These are not intended to supersede national guidelines or national regulations, which should always be followed. The test frequencies given should be followed and adjusted according to observations of instrument stability and environmental stability (power supply, temperature and humidity). Where the frequency is indicated as a dual time period, e.g. weekly/monthly, it is recommended that tests are carried out at the shorter time period, and that the test frequency is only reduced if regular testing gives evidence that the system is stable. There is also a note in the legend to each table giving the general type of technology that the recommendations apply to. Specific systems may employ technologies that need other checks, as specified by the manufacturer.

It is a principle of radiation safety and patient protection to ensure that before the administration of a radiopharmaceutical there is suitable equipment to complete the procedure, and that the equipment is functioning correctly. The correct basic function of the device must always be checked after any engineering intervention for repair or calibration, and appropriate engineer's checks may satisfy this need.

Note: The clocks within the department, within all instruments and all computers must be synchronized and checked daily/at least weekly. This is an essential requirement for accurate activity administration and quantitative data analysis.

Procedures and references

Test procedures are not included in this document, but can be found by reference to standard descriptions (e.g. [1–4]) and national and international protocols. Any manufacturer-supplied test procedures, test phantoms and software should also be taken into account when writing local operating procedures. Some essential literature references are given. They should be consulted for detailed generic test procedures and advice regarding test evaluation, action thresholds and follow-up. It is recommended that each department create detailed written routine QC test procedures specific for each instrument in use. By following standard QC procedures, consistency in test results can be assured and trends monitored.

Table 1 Routine QC tests for a gamma camera: planar, whole-body, SPECT and SPECT/CT. *Equipment type*: scintillation Anger gamma camera

Test	Purpose	Frequency	Comments
GC1. Physical inspection	To check collimator and detector head mountings, and to check for any damage to the collimator	Daily	Inspect for mechanical and other defects that may compromise safety of patient or staff; if collimator damage is detected or suspected, immediately perform a high-count extrinsic uniformity test
GC2. Collimator touch pad and gantry emergency stop	To test that the touch pads and emergency stops are functioning	Daily	Both the collimator touch pads and gantry emergency stop must function if there is an unexpected collision with the patient or an obstacle during motion; the touch pads must be checked each time the collimators are changed
GC3. Energy window setting for ^{99m}Tc	To check and centre the preset energy window on the ^{99m}Tc photopeak	Daily	The test is intended to check the correct ^{99m}Tc energy window
GC4. Energy window setting – other radionuclides to be used	To test that preset energy windows are properly centred for the energies of other clinically used radionuclides	Daily when used	Frequency of the test should be adapted to the particular camera and frequency of use of the radionuclides
GC5. Background count rate	To detect radioactive contamination/excess electronic noise	Daily	The background count rate should be stable under constant measuring conditions
GC6. Intrinsic/extrinsic uniformity and sensitivity for ^{99m}Tc (or ^{57}Co) – visual	To test the response to a spatially uniform flux of ^{99m}Tc (or ^{57}Co) photons, for uniformity and overall sensitivity	Daily	Visually inspect either an intrinsic or extrinsic (whichever is most convenient) low count uniformity acquisition; if intrinsic method is selected, each collimator must be checked periodically by an extrinsic uniformity test (preferably with high-count acquisition – see next test); record the cps/MBq to check and monitor sensitivity
GC7. Intrinsic/extrinsic uniformity and sensitivity for ^{99m}Tc (or ^{57}Co) – quantitative	To monitor the trend in uniformity with quantitative uniformity indices, and to check the sensitivity	Weekly/monthly	The most convenient method should be selected; monitor uniformity indices: integral and differential uniformity in central and useful field of view from a high-count image; if the intrinsic method is selected, a high-count extrinsic measurement is also required routinely, and especially when collimator damage is suspected; record cps/MBq to check sensitivity
GC8. Intrinsic uniformity for other radionuclides	To test the response of a spatially uniform flux of photons emitted by other clinically used radionuclides	Three-monthly	Uniformity of detector response for every radionuclide in use should be tested periodically; frequency of the test should be adjusted to the frequency of use of the radionuclide in question
GC9. Spatial resolution and linearity – visual	To detect distortion of spatial resolution and linearity	Six-monthly	Visual-quadrant bar or orthogonal hole pattern; intrinsic or extrinsic, depending on convenience; if an orthogonal hole pattern is used, the results can be quantified if special software is available
GC10. Multiple window spatial registration (MWSR)	To test that the images acquired at different photon energies superimpose when imaged simultaneously, in an additive or subtractive mode	Six-monthly/yearly	Relevant for dual radionuclide studies or imaging of radionuclides with multiple energy windows (e.g. ^{67}Ga or ^{111}In)
GC11. Pixel size	To determine absolute pixel size	Six-monthly	Pixel size is especially important for quantitative imaging and multimodality matching and attenuation correction

Table 1 (continued)

Test	Purpose	Frequency	Comments
Whole-body			
GC12. Whole-body scan spatial resolution in air	To test spatial resolution both parallel and perpendicular to the direction of motion	Yearly	Line sources or point sources may be used, positioned at different positions along the length of the whole-body scan; attention should be paid to the spatial resolution at the start and end of the whole-body scan
SPECT			
GC13. Detector head tilt	To adjust the alignment of detector head tilt in the Y-axis	Before use	For cameras with variable detector head tilt that rely on manual adjustment of tilt using a spirit level or angle gauge for adjusting the detector tilt
GC14. Uniformity calibration	To update a uniformity map for software uniformity correction	As required	To be performed each time the detector uniformity is beyond the limits of acceptability for a SPECT camera
GC15. COR alignment	To check that the mechanical and electronic CORs are aligned, i.e. COR offsets are within limits of acceptability, in X and Y directions	Weekly/monthly	The frequency of the test depends on detector COR stability and should be adjusted accordingly; the test should be done for all collimators used for SPECT studies, and for each multiple detector configuration used; ensure that procedure checks both X and Y directions
GC16. COR calibration	To update COR offsets	As required	COR calibration should be performed when COR offsets are beyond the limits of acceptability
GC17. Tomographic spatial resolution in air	To check tomographic spatial resolution of the system in air, with no scatter	Six-monthly	To check that the tomographic spatial resolution is not degraded by data acquisition or the reconstruction process
GC18. Overall system performance	To test tomographic uniformity and contrast resolution, and attenuation correction if available	Six-monthly	A total performance phantom (e.g. Jaszczak) should be used; uniformity of reconstructed slices with a uniform activity (no sphere/rod inserts) and contrast resolution of slices with cold spheres or rods should be monitored; if software attenuation correction is available, it should be applied to the images
GC19. Attenuation correction: radionuclide transmission source	To check uniformity and count rate responses of the transmission radionuclide source	Daily when used	Good uniformity and adequate counts in the transmission image is required to create the attenuation correction map; these two parameters should to be checked whenever this method of correction is used

COR centre of rotation.

Detector uniformity can be tested intrinsically (without collimator) or extrinsically (with collimator in place). Intrinsic uniformity is tested with a point source of activity, whereas extrinsic uniformity is tested with a with flood or sheet source (e.g. ^{57}Co). The detector uniformity test can be coupled with monitoring of detector sensitivity, provided the same activity is used each time. Changes in detector sensitivity signal a problem, and also affect total time of the collection of predefined counts.

Quantitative assessment of uniformity is based on NEMA standards: integral and differential measures of uniformity in the useful and central field of view.

Count acquisition: *low* 3–4 million counts; *high* to give about 10^4 counts per pixel (e.g. 30–40 million counts for matrix type 64x64)

Multiple detector cameras require that assessment of uniformity be performed for every detector.

Test of COR alignment and calibration of multiple detector camera should be performed for all clinically used detector configurations, e.g. H-mode (180° opposed configuration), and L-mode (90° angled configuration) for dual detector cameras.

Table 2 Routine QC tests for PET and PET/CT. *Equipment type*: coincidence, scintillator system (fixed and mobile systems)

Test	Purpose	Frequency	Comments
PET1. Physical inspection	To check gantry covers in tunnel and patient handling system	Daily	Inspect for mechanical and other defects that may compromise safety of patient or staff
PET2. Daily QC	To test and visualize proper functioning of detector modules; visual inspection of 2-D sinograms (automated)	Daily	To be performed with point or rod sources without attenuating object inside scanner field of view
PET3. Uniformity	To estimate axial uniformity across image planes 1−[max] by imaging a uniformly filled object	After maintenance/new setups/normalization	To be also performed after software upgrade or changes; the object could be a 20-cm diameter ^{68}Ge cylinder, or a refillable cylinder with ^{18}F
PET4. Normalization	To determine system response to activity inside the field of view	Variable (at least six-monthly)	Frequency of test depends on system reliability and service; must be performed after firmware upgrade and hardware service; use phantoms and instructions as recommended by manufacturer
PET5. Calibration	To determine calibration factor from image voxel intensity to true activity concentration	Variable (at least six-monthly)	Must follow a new normalization; follow the manufacturer's procedures
PET6. Spatial resolution	To measure spatial resolution of point source in sinogram and image space	Yearly	Use a ^{18}F point source (nonstandard) or linear source
PET7. Count rate performance	To measure count rate as a function of (decaying) activity over a wide range of activities	After new setups/ normalization/ recalibrations	To include count loss correction; and specific measurements of: (a) total/random/ scatter/net true coincidences, and (b) noise equivalent count rate
PET8. Sensitivity	To measure the volume response of the system to a source of given activity concentration	Monthly	Perform according to NEMA NU2 standards with a set of sleeved rod sources [11]; an alternative method is given in NEMA-NU2 1994
PET9. Image quality	To check hot and cold spot image quality of standardized image quality phantom	Yearly	According to NEMA NU2 image quality test [11]; required after system installation, not mandatory during clinical operation

Table 3 X-ray CT – as part of PET/CT and SPECT/CT (for diagnostic purposes)

Test	Purpose	Frequency	Comments
CT1. X-ray CT – daily	Daily procedures	Daily	Follow manufacturer's procedures for daily use, and guidance from the medical physics expert for diagnostic radiology
CT2. X-ray CT – numbers	To determine CT number accuracy	Monthly	CT number accuracy: water and air
CT3. X-ray CT – alignment	To determine 3-D alignment vector of PET or SPECT and CT field of view	At least monthly	Manufacturer provides alignment phantom; to be also performed after major service
CT4. X-ray CT – performance	To check CT performance and radiation exposure	As advised by the radiation protection adviser and medical physics expert for diagnostic radiology	The CT scanner is an X-ray device that must be checked according to national radiation safety legislation under the direction of the appropriate radiation protection adviser and medical physics expert for diagnostic radiology

Table 4 Routine QC tests for a radionuclide calibrator. *Equipment type*: gas ionization chamber; the checks also apply to scintillation based calibrators, but additional checks may apply (see manufacturer's documentation)

Routine test	Purpose	Frequency[a]	Comments
RC1. Physical inspection	To check system and any source holders and other accessories for damage	Daily	The chamber may be concealed, and not accessible for physical inspection, but the loose accessories should be checked
RC2. High voltage	To check the constancy and correct operating voltage	Daily/as recommended by manufacturer	Essential for an accurate activity measurement
RC3. Clock accuracy	To check that the calibrator clock is the same as the time of day	Daily	Essential for calibrating radioactivity to a specific time of day; clock time throughout the department must be the same (i.e. all wall clocks and internal computer clocks)
RC4. Zero adjustment	To check that the display is at zero when no radioactivity is present	Daily	Record the zero setting (before any adjustment); a drift in "zero" reading may indicate that the instrument needs repair
RC5. Background counts	To check background response under operational conditions appropriate for a particular radionuclide; to detect contamination	Daily	Perform the test with the source holder/liner in place in the chamber; remove nearby radioactive sources that might cause an incorrect background reading; check on each radionuclide setting to be used that day
RC6. Constancy	To check the stability and reproducibility of the ionization chamber, electrometer, and calibrator nuclide settings	Daily	Measure a long half-life radionuclide, e.g. ^{137}Cs with its own calibration factor; also, obtain relative measurements for each nuclide setting to be used that day
RC7. Stability	To check the short-term counting precision	Yearly	Counting precision is a measure of the stability of the whole system, and is measured by repeated measurements and application of the chi-squared test
RC8. Accuracy	To check the accuracy of the activity reading	Yearly	This requires readings of sources of known activity; refer to the supplier and national measurement standards for guidance
RC9. Linearity	To confirm that the calibration setting for a particular radionuclide indicates the correct activity over the entire range of use	Six-monthly/yearly	The change in response when the measurement range is changed should be minimal; the range of use should be chosen between the maximum activity to be measured (e.g. in the GBq range for a ^{99m}Tc eluate) to the lowest activity to be measured (e.g. 1 MBq) for a particular radionuclide

[a] *Daily*: at the beginning of the day.

Table 5 Routine QC tests for a thyroid uptake probe. *Equipment type*: nonimaging scintillation detector

Test	Purpose	Frequency	Comments
TP1. Physical inspection	To check collimator and probe mounting, and cable connections	Before use	These should be checked for mechanical defects, with particular regard to patient and staff safety
TP2. Background count rate	To assess the count rate level without surrounding radioactivity; to detect contamination	Before use	This measurement should be stable over time; the background level determines the minimal detected level of activity
TP3. High voltage	To check constancy and correct operating voltage	Before use	Test for instruments where appropriate, if the capability is available; essential for stable and sensitive measurements
TP4. Energy spectrum/ energy window calibration	To ensure that the operating energy window is centred on the photopeak	Before use	Test for instruments where appropriate, if the capability is available; the sensitivity of the uptake measurement depends on the correct energy window width setting

Table 5 (continued)

Test	Purpose	Frequency	Comments
TP5. Sensitivity	To test the constancy of the instrument and settings; this will test that the high voltage and energy window setting are correctly set	Before use	For QC purposes, a long half-life radionuclide ^{133}Ba source can be used for ^{131}I thyroid uptake measurements; the source must be measured in a constant geometry with respect to the probe
TP6. Stability	To check the short-term counting precision	Six-monthly	Counting precision is a measure of the stability of the whole system, and is measured by repeated measurements and application of the chi-squared test

Table 6 Routine QC tests for a nonimaging intraoperative probe. *Equipment type*: nonimaging gamma ray detecting probe; any type of detector

Routine test	Purpose	Frequency	Comments
PR1. Power source – for battery-operated systems	To check for full operating voltage and sufficient charge	Daily, or before use	A full battery charge is needed when the instrument is used at surgery; the capacity of the battery must be sufficient to supply the total power requirements for the duration of clinical surgical procedure(s); follow manufacturer's instructions and frequency recommendations for checking available battery capacity
PR2. Physical inspection	To check for any damage to the probe, measuring unit, and cables	Daily, or before use	To prevent use of a damaged or unsafe instrument; cables are particularly prone to damage
PR3. Background count rate	To check background level when no activity is present; to check for contamination	Daily, or before use	Check under standard conditions and for each collimator used; the background level determines the minimal activity that can be measured
PR4. Sensitivity/ constancy	To test constancy and reproducibility	Daily, or before use	Use an appropriate long half-life source, measured in a constant geometry with respect to the probe; measure with all energy window settings and for each probe and collimator to be used clinically
PR5. Stability	To check the short-term counting precision	Six-monthly	Counting precision is a measure of the stability of the whole system, and is measured by repeated measurements and application of the chi-squared test
PR6. Energy spectrum	To check response over the energy range of the detector	Six-monthly	If the instrument offers the capability; follow manufacturer's recommendations

Table 7 Routine QC for an in vitro manual or automatic gamma counting system. *Equipment type*: single-sample or multi-sample gamma counter, with scintillation detector

Routine test	Purpose	Frequency	Comments
AGC1. Energy window calibration	To ensure that the window settings of the pulse height analyser are set appropriately	Three-monthly	This should be checked for the radionuclide(s) to be measured
AGC2. Background count rate	To measure the count rate without radioactivity; to detect contamination	Before use	Background should be stable under constant operating conditions; the background measurement also forms an integral part of a clinical measurement
AGC3. Sensitivity	To test the constancy of the instrument and settings	Before use	Use a long half-life radioactive source; be aware of high count rate (pile-up) effects
AGC4. Stability	To check the short term counting precision	Six-monthly	Counting precision is a measure of the stability of the whole system, and is measured by repeated measurements and application of the chi-squared test

Table 8 Routine QC for radiation monitoring instruments: exposure meter, contamination monitor, personnel monitor. *Equipment type*: any type of ionizing radiation detection monitor. The radiation protection adviser should be consulted to ensure compliance with national legislation and guidance on radiation dose measuring instruments

Routine test	Purpose	Frequency	Comments
RM1. Physical inspection	To check for any damage to the detector, measuring unit and cables	Before use	To prevent use of a damaged or unsafe instrument
RM2. Battery voltage	To check that battery level is sufficient	Before use	Low battery voltage will result in inaccurate and unreliable measurements
RM3. Background count rate	To measure the count rate level in an ambient environment without nearby radioactivity	Before use	Background level forms the baseline level and should be stable
RM4. Sensitivity	To test constancy	Yearly	Measure, in a constant geometry, a long half-life radioactive source suited to the instrument's use and efficiency rating
RM5. Accuracy, precision and linearity of response	To measure the accuracy, precision, and linearity of response	Yearly in therapy environment; two-yearly in diagnostic environment	Source size and activities to be selected to suit the particular instrument; this is particularly relevant for instruments used in patient therapy locations; the radiation protection adviser should be consulted to ensure compliance with national legislation and for guidance on radiation dose measuring instruments

Table 9 Routine QC tests for a preclinical PET. *Equipment type*: small-animal positron emission tomograph

Test	Purpose	Frequency	Comments
PCP1. Physical inspection	To check gantry and handling system	Daily	Inspect for mechanical and other defects that may cause system failure
PCP2. Background count rate	To detect excess electronic noise	Daily	Compare the value with the reference value
PCP3. Detector check	To check that all detectors/block are actually working	Daily	
PCP4. Energy resolution	To check the energy resolution of the whole system by summing the energy spectra of each detector/block	Weekly	Repeat the energy calibration if the value is larger than that measured during acceptance testing; then check that the photopeak in the spectra of each detector/block is correctly aligned with the expected 511 keV value
PCP5. Pixel identification (if applicable)	To check that the image of the pixel is correctly assigned to the corresponding scintillating matrix element	Weekly	Repeat the pixel identification procedure if not satisfactory
PCP6. Spatial resolution	To evaluate the spatial resolution of the system	Three-monthly	This can be done with a Derenzo phantom or similar with a user-defined procedure
PCP7. Sensitivity-quantitative (NEMA method)	To check the absolute sensitivity	Three-monthly	This test should be performed in accordance with the standard method described in the NU 4-2008 document
PCP8. Image quality	To determine recovery coefficients and signal to noise ratio performance of the imaging system	Three-monthly	Use the hot and cold spot image quality of standardized image quality phantom described in the NU 4-2008 document
PCP9. Uniformity	To estimate axial uniformity across image planes by imaging a uniformly filled object	Yearly	Compare with the value measured during acceptance testing
PCP10. Calibration	To determine calibration factor from image voxel intensity to true activity concentration	Monthly	Requires source of known activity concentration (well-counter or prefilled, long-lived isotope); requires an appropriately quality controlled well-counter on site

Table 9 (continued)

Test	Purpose	Frequency	Comments
PCP11. Linearity check	To measure the response of the imaging system as a function of (decaying) activity over a wide range of activities	Yearly	This test could be performed with a user phantom or with the image quality phantom described in the NU 4-2008 document; check after software and hardware updates and after major setups (when possible)
PCP12. Attenuation and scatter correction (if applicable)	To measure the effectiveness of the attenuation and scatter correction, if these are implemented	Three-monthly	This test could be performed with the standard method described in the NU 4-2008 document

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References

1. National Electrical Manufacturers Association. NEMA NU 1. Performance measurement of scintillation cameras. Rosslyn, VA: National Electrical Manufacturers Association; 2001, 2007.
2. International Electrotechnical Commission. IEC 60789. Medical electrical equipment – Characteristics and test conditions of radionuclide imaging devices – Anger type gamma cameras. Geneva: International Electrotechnical Commission; 2005.
3. International Electrotechnical Commission. IEC 61675-2. Radionuclide imaging devices – Characteristics and test conditions – Part 2: Single photon emission computed tomographs. Consolidated Edition 1.1. Geneva: International Electrotechnical Commission; 2005.
4. International Electrotechnical Commission. IEC 61675-3. Radionuclide imaging devices – Characteristics and test conditions – Part 3: Gamma camera based whole body imaging systems. Ed 1. Geneva: International Electrotechnical Commission; 1998.
5. Deutsches Institut für Normung. DIN 6855-2:2005-01. Quality control of nuclear medicine instruments. Part 2: Constancy testing of single crystal gamma-cameras used in planar scintigraphy and in Anger type gamma cameras with rotating detector heads used in single photon emission tomography. Berlin: Deutsches Institut für Normung.
6. International Atomic Energy Agency. Quality assurance for SPECT systems. Human Health Series No. 6. Vienna: International Atomic Energy Agency; 2009. http://www-pub.iaea.org/MTCD/publications/PDF/Pub1394_web.pdf. Accessed 15 Dec 2009.
7. International Atomic Energy Agency. Quality control atlas for scintillation camera systems. ISBN 92-0-101303-5. Vienna: International Atomic Energy Agency; 2003. http://www-pub.iaea.org/MTCD/publications/PDF/Pub1141_web.pdf (low resolution images). Accessed 15 Dec 2009.
8. Hines H, Kayayan R, Colsher J, Hashimoto D, Schubert R, Fernando J, et al. Recommendations for implementing SPECT instrumentation quality control. Nuclear Medicine Section – National Electrical Manufacturers Association (NEMA). Eur Nucl Med 1999;26(5):527–32.
9. Busemann-Sokole E. Measurement of collimator hole angulation and camera head tilt for slant and parallel hole collimators used in SPECT. J Nucl Med 1987;28:1592–8.
10. Blokland JA, Camps JA, Pauwels EK. Aspects of performance assessment of whole body imaging systems. Eur J Nucl Med 1997;24(10):1273–83.
11. National Electrical Manufacturers Association. NEMA NU 2. Performance measurements of positron emission tomographs. Rosslyn, VA: National Electrical Manufacturers Association; 1994, 2001, 2007.
12. Turkington TG. Introduction to PET instrumentation. J Nucl Med Technol 2001;29:4–11.
13. Fahey FH. Data acquisition in PET imaging. J Nucl Med Technol 2002;30:39–49.
14. Daube-Witherspoon ME, Karp JS, Casey ME, DiFilippo FP, Hines H, Muehllehner G, et al. PET performance measurements using the NEMA NU 2-2001 standard. J Nucl Med 2002;43(10):1398–409.
15. von Schulthess GK. Positron emission tomography versus positron emission tomography/computed tomography: from "unclear" to "new-clear" medicine. Mol Imaging Biol 2004;6(4):183–7.
16. International Electrotechnical Commission. IEC/TR 61948. Nuclear medicine instrumentation – Routine tests – Part 3: Positron emission tomographs. Geneva: International Electrotechnical Commission; 2005.
17. Bergmann H, Dobrozemsky G, Minear G, Nicoletti R, Samal M. An inter-laboratory comparison study of image quality of PET scanners using the NEMA NU-2 2001 procedure for assessment of image quality. Phys Med Biol 2005;50:2193–207.
18. Zanzonico P. Routine quality control of clinical nuclear medicine instrumentation: a brief review. J Nucl Med 2008;49(7):1114–31.
19. International Atomic Energy Agency. Quality assurance for PET and PET/CT systems. Human Health Series, No. 1. Vienna: International Atomic Energy Agency; 2009. http://www-pub.iaea.org/MTCD/publications/PDF/Pub1393_web.pdf. Accessed 15 Dec 2009.
20. Lin PJP, Beck TJ, Borras C, et al. Specification and acceptance testing of computed tomography scanners. New York: American Association of Physicists in Medicine; 1993.

21. Shepard SJ, Lin PJP, Boone JM, et al. Quality control in diagnostic radiology. College Park: American Association of Physicists in Medicine; 2002. p. 1–74.
22. American College of Radiology. Technical standard for medical nuclear physics performance monitoring of PET-CT imaging equipment. Reston, VA: American College of Radiology. http://www.acr.org/SecondaryMainMenuCategories/quality_safety/guidelines/med_phys/pet_ct_equipment.aspx. Accessed 15 Dec 2009.
23. International Atomic Energy Agency. Quality assurance for radioactivity measurement in nuclear medicine (appendix VII), Technical Report Series No. 454. Vienna: International Atomic Energy Agency; 2006. http://www-pub.iaea.org/MTCD/publications/PDF/TRS454_web.pdf. Accessed 15 Dec 2009.
24. International Electrotechnical Commission. IEC/TR 61948 series. Nuclear medicine instrumentation – Routine tests – Part 4: Radionuclide calibrators (IEC 2006-11). Geneva: International Electrotechnical Commission.
25. Deutsches Institut für Normung. DIN 6855-11:2009-05. Constancy testing of nuclear medicine measuring systems – part 11: Radionuclide calibrators (IEC/TR 61948-4:2006, modified). Berlin: Deutsches Institut für Normung.
26. Gadd R, Baker M, Nijran KS, Owens S, Thomas W, Woods MJ, et al. Protocol for establishing and maintaining the calibration of medical radionuclide calibrators and their quality control. Measurement Good Practice Guide No. 93. Teddington, UK: National Physical Laboratory; 2006. http://resource.npl.co.uk/cgi-bin/download.pl?area=npl_publications&path_name=/npl_web/pdf/mgpg93.pdf. Accessed 15 Dec 2009
27. International Atomic Energy Agency. Quality control of nuclear medicine instruments 1991. Technical document 602. Vienna: International Atomic Energy Agency; 1991. http://www-pub.iaea.org/MTCD/publications/PDF/te_602_web.pdf). Accessed 15 Dec 2009.
28. International Atomic Energy Agency. Quality control of nuclear medicine instruments. Technical document 317. Vienna: International Atomic Energy Agency; 1984. http://www-pub.iaea.org/MTCD/publications/PDF/te_317_prn.pdf. Accessed 15 Dec 2009.
29. Deutsches Institut für Normung. DIN 6855-1: 2009-07. Constancy testing of nuclear medicine measuring systems – Part 1: Radiation counting systems for measurements in vivo and in vitro (IEC/TR 61948–1:2001, modified). Berlin: Deutsches Institut für Normung.
30. National Electrical Manufacturers Association. NEMA NU 3. Performance measurements and quality control guidelines for non-imaging intraoperative gamma probes, Rosslyn, VA: National Electrical Manufacturers Association; 2004.
31. Zanzonico P, Heller S. The intraoperative gamma probe: basic principles and choices available. Semin Nucl Med 2000;30(1):33–48.
32. Halkar RK, Aarsvold JN. Intraoperative probes. J Nucl Med Technol 1999;27(3):188–93.
33. Britten AJ. A method to evaluate intra-operative gamma probes for sentinel lymph node localisation. Eur J Nucl Med 1999;26(2):76–83.
34. Perkins AC, Britten AJ. Specification and performance of intraoperative gamma probes for sentinel node detection. Nucl Med Commun 1999;20(4):309–15.
35. Tiourina T, Arends B, Huysmans D, Rutten H, Lemaire B, Muller S. Evaluation of surgical gamma probes for radioguided sentinel node localization. Eur J Nucl Med 1998;25(9):1224–31.
36. Cherry SR, Sorensen JA, Phelps ME. Physics in nuclear medicine. 3rd ed. Philadelphia: Saunders/Elsevier Science; 2003. ISBN 0-7216-8341-X.
37. National Electrical Manufacturers Association. NEMA NU 4. Performance measurement of small animal positron emission tomographs. Rosslyn, VA: National Electrical Manufacturers Association; 2008.
38. International Electrotechnical Commission. IEC 61223-1. Evaluation and routine testing in medical imaging departments – Part 1: General aspects. Geneva: International Electrotechnical Commission; 1993.
39. Bergmann H, Minear G, Raith M, Schaffarich PM. Multiple window spatial registration error of a gamma camera: ^{133}Ba point source as a replacement of the NEMA procedure. BMC Med Phys 2008;8:6.
40. Kwang K, Lee B, Choe J. SU-FF-I-79: development of the practical guidelines of PET-CT quality control. Med Phys 2009;36:2452.
41. ImPACT Information Leaflet No. 1: CT Scanner Acceptance Testing, Version 1.02, 18/05/01, http://www.impactscan.org/reports.htm.