Probes

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General

1. Introduction

Besides imaging equipment such as the gamma camera, in nuclear medicine, non-imaging detectors are used. The most important examples are the thyroid probe and the surgical probe.

Thyroid probes usually contain a NaI detector, a photomultiplier tube (PMT), a preamplifier and a counting unit. Thyroid probes can be used for determining the activity in the thyroid, but also for the localization of (increased) radioactivity elsewhere in the body. In general, thyroid probes have large detectors (approximately 5 cm) and are suitable for measuring high-energy radiation, such as that of ^{131}I.

Surgical probes are designed to localize foci with (increased) radioactivity during surgery. The crystal in these detectors is typically around 10 mm in size. Because in this case one is frequently working with the low-energy photons of ^{99m}Tc or even with the low-energy X-rays of ^{125}I, the detectors are often made of a semiconductor material (often CdZnTe) so that a PMT is not required.

Special attention is needed when ^{18}F is used as radionuclide. Due to the high photon energy (511 keV), a special collimator is applied, limiting the counting sensitivity of the probe and making tests more time consuming.

Overview of minimum test frequencies

Test	acceptance	yearly	quarterly	monthly	before use
Background	x			x	x
Sensitivity and linearity	x	x			
Sensitivity and variability	x		x		
Side shielding	x	x			
Field of view	x	x			
Energy spectrum	x				
Battery, cables, connectors	x				x

Overview of required equipment, phantoms and sources

Test	equipment	phantoms	sources
Background			
Sensitivity and linearity	not required, but convenient: tool to mount probe and source at various known distances		calibrated point source of clinical relevant radionuclides; not required, but convenient: calibrated sealed point source mimicking clinical relevant radionuclides
Sensitivity and variability	not required, but convenient: tool to mount probe and source at given known distance		idem
Side shielding			idem
Field of view	not required, but convenient: tool to mount probe and source at given known lateral distance or angle		idem
Energy spectrum			idem
Battery, cables, connectors			

2. Selection of tests and frequency

Primarily, the probes must comply with the (electrical) requirements as described in IEC-60601-1, part 1. In these recommendations, the specific requirements for nuclear medicine equipment are addressed. The tests and frequencies are basically selected using the principles described in the general introduction to Equipment. However, the principles are extended slightly, *i.e.* the tests are grouped into three main categories, namely tests for acceptance, constancy tests and tests before each use. In the given order, the tests become less in number and severity, but higher in frequency. Tests before use are simply meant to show that the probe has no defect and is giving an expected signal. With constancy tests, it is assumed that if the probe performs well, it still fulfills the acceptance criteria, in other words, probe functioning is stable. These principles imply that the three test categories are connected by one or more tests.

These recommendations are largely based on the NEMA NU 3 requirements, supplemented by substantiated requirements (such as are described e.g. in Brands *et al*).

From these requirements, optimal tests are distilled in terms of required sources (use of customary sources in nuclear medicine) and required measurements (determination of multiple quantities in one measurement).
Surgical probes, because of their mobile use, are particularly susceptible to breakage of cables, problems with contacts in the connecting plugs and damage to the crystal or semiconductor caused by falling or impact. In practice, in case of probes that are not directly mains-supplied, the most common problem would be an empty battery. Checking these items regularly is therefore very important and should be incorporated into the tests before each use. In addition, tests before use should contain indicative background and sensitivity measurements.
Constancy checks to be carried out (background signal, sensitivity and variability) are not very time-consuming. If the probe is used only irregularly, it is recommended that these checks are performed before each use. If the probe is used frequently, the frequency can be adapted (e.g. halving the frequency if no discrepancy has been found on four occasions: see the General Recommendations on Equipment Checks, Section 3: Frequency). If there is a suspicion of any irregularity, checks should be performed immediately.
On acceptance, it is recommended that the following parameters are determined: background signal, sensitivity, variability, linearity, side shielding and field of view, and if possible energy spectrum and resolution. All these parameters are important for the practical use of the probe. The measured values are compared with the specifications, if available. Sensitivity is measured both in a simple and more complex way, the first for constancy and the latter for acceptance purposes.

3. Required equipment, phantoms and sources

For the checking of a probe, the main requirements are point sources. It is convenient to use sealed sources, since they are easy to use and have a relatively long half-life. The gamma energies of the sealed source should represent the energies of the radiopharmaceuticals used in clinical practice. The clinically most relevant radionuclide, ^{99m}Tc, can be mimicked by ^{57}Co, except when measuring the energy spectrum and resolution. Other possible substitutes are ^{133}Ba for ^{131}I, ^{22}Na for ^{18}F and ^{129}I for ^{125}I. When using ^{129}I, pay careful attention to the distance between source and probe, given the very low energy. For ^{111}In and ^{67}Ga no such alternative is available. If the manufacturer has specified the transmission for a given photon energy, but the test has been performed with a radionuclide that also emits photons with a higher energy, abnormal readings may occur due to dead time problems. On acceptance, it is usually important that the clinically relevant gamma energy is used. Checking the constancy can usually be done with a different energy.
A tool in which a probe and a source can be mounted in well-defined positions relative to each other is convenient and timesaving. Surgical probes have sometimes a small field of view collimator built in. In that case, careful positioning is necessary to avoid (gross) measurement errors.
All measurements utilizing a radionuclide should be performed in air. If the measurements are performed flat on a table, make sure that at least 20 cm of air between the source and the table to prevent scatter effects.

4. Measuring conditions

According to NEMA NU 3-2004, some tests for surgical probes have to be carried out both with an open energy window and with a window that fits the radionuclide. Furthermore, it is sufficient to evaluate the energy windows used clinically (adapted to the radionuclide used in the test if, for example, ^{57}Co is used instead of ^{99m}Tc).

An excessively high count-rate should be avoided to prevent dead time effects (see Linearity). Most probes are able to count for a preset period of time, but some probes only report a count rate. NEMA NU 3-2004 does not apply to these latter probes and in this respect the following checks may sometimes be modified to some extent.

At very short counting times, the accuracy of the counting time may play a role. Make sure, therefore, that the counting has been sufficient. When making time-consuming measurements with fast decaying isotopes, correction for decay is necessary.

Due to loose connecters or bad cables, count changes may occur when the metal parts of the housing or the connectors are touched. It is therefore useful to start every test, besides with a battery check, with a check of cables and connectors.

5. Literature

- NEMA NU 3 Performance Measurements and Control guidelines for Non-Imaging Intraoperative Gammaprobes, NEMA-2004.
- IEC-60601-1, Medical electrical equipment – Part 1: General requirements for basic safety and essential performance, IEC 2005.
- Brands Peter J.M., Arends Bertjan, Muller Sara H. Sentinel node procedure bij mammacarcinoom, [Sentinel node procedure in breast carcinoma] Klinische Fysica 2001;2:27-31.
- Cherry SR, Sorensen JA, Phelps ME: Physics in Nuclear Medicine, 4rd ed. Philadelphia, Pa: Saunders/ Elsevier Science, 2012. ISBN 9781416051985.
- Povoski SP, Neff RL, Mojzisik CM, O'Malley DM, Hinkle GH, Hall NC, Murrey DA Jr, Knopp MV,
- Martin EW Jr A comprehensive overview of radioguided surgery using gamma detection probe
- technology. World J Surg Oncol. 2009;7:11.

Background Signal

1. Introduction and rationale

Even in the absence of a radioactive source, most probes still indicate a low signal due to the background radiation and internal noise in the probe. The background signal determines the minimum activity that can be measured. When affected, the zero level will be elevated. If possible, the specification of the manufacturer should be checked, but in any case, the normal value is set and checked.

2. Frequency

It is recommended that the background signal be checked on acceptance, with constancy tests and before use. To get a good statistical overview over time it is advised to perform this test monthly.

3. Method

Measure the background signal under controlled conditions.

4. Requirements

Usually none. Sometimes the manufacturer supplies a special shield for this purpose.

5. Procedure

Acceptance and constancy tests:

Remove all radioactivity from the immediate vicinity of the detector. Measure the background signal using all available collimators (also without collimator) and with all energy windows used clinically. If no specifications are available, perform 20 measurements of one minute, or, if the probe does not allow this long measurement time, as long as possible.

Before use:

As a test before each use it suffices to check whether the background is not any higher than the value established on acceptance.

6. Analysis and interpretation

Acceptance and constancy tests:

Calculate the average background signal in cps and its standard deviation, B_0 and sd_0, respectively at acceptance tests and B_1 and sd_1, respectively at constancy tests.
To test if B_1 is (statistically) equal to B_0, or if $B_1 - B_0 = 0$, calculate the Z-value according to $Z = (B_1 - B_0) / \sqrt{(sd_0^2/n + sd_1^2/n)}$. For 95% confidence limits, B_1 is considered equal to B_0 if the absolute value of Z is smaller than 1,96. Upon acceptance, calculate the minimum detectable activity due to background activity as the average background signal B_0 plus three times standard deviation sd_0 of the measured distribution [cps] divided by the sensitivity [cps/MBq].

Before use:

If there are problems with the background signal (that cannot be explained by the presence of radioactivity) this will mostly result in a (sometimes irregular) relatively high signal, or no signal at all. Both will be noticed clearly and are indications of hardware problems as described above.

7. Action thresholds and actions

Compare the measured background with the specifications, if possible. If these are not available (this is not a NEMA NU 3-2004 specification), make sure that the minimum detectable activity is adequate for the intended clinical use.
With 95% confidence limits, if Z is smaller than 1,96, the background signal is stable and the minimum detectable activity may be considered constant. If Z is larger than 1,96, the result must be considered abnormal.
Causes may include: contamination (of the probe itself or the environment), but also activity in the vicinity (patient, test source, active waste material). If the problem is persistent, the probe may be defective and the manufacturer must be contacted.

8. Pitfalls and marginal notes

a. Apart from the causes mentioned for a deviation in the background radiation, it may also be that too low a value for the lower limit of the energy window can give rise to an

increased background radiation level (system noise).

b. The background radiation may depend slightly on the location, so make sure this is also recorded.

Sensitivity and Linearity on Acceptance

1. Introduction and rationale

The sensitivity of a probe reflects the relationship between count rate (cps) and activity (kBq), provided the relationship is linear. The offset is determined by the background signal and/or detector noise, while the proportionality is related to the influence of the system dead time. Both sensitivity and linearity can thus be extracted from one set of measurements, i.e. the count rate as function of activity.
For constancy check purposes, sensitivity is measured in another, simpler way. This is described in the next section.

2. Frequency

In principle, for every radionuclide in demand, the sensitivity and linearity must be determined upon acceptance. The sensitivity is the most important parameter for the proper functioning of a probe. To get a good statistical overview over time it is advised to perform this test yearly.

3. Method

The sensitivity and linearity are measurements of count rate with a standard source. Accurate calibration of the source is important for this. The use of standard calibration sources with longer-lived radionuclides (see Probes, General, Measurement conditions) is therefore recommended. On acceptance it is important that the clinically relevant gamma energy is used. In this method the sensitivity is determined from the slope of the linear part of the graph resulting from measuring a point source at different distances from the probe.

4. Requirements

Since most probes are used with ^{99m}Tc, it suffices to use a ^{57}Co point source, preferably a pen marker type source. If the probe is used for other radionuclides, other appropriate test sources should be used.
A tool in which the probe and the source can be mounted in varying known positions from each other is convenient and timesaving.

5. Procedure

Carry out the check applicable for the energy windows in clinical use (adapted to the radionuclide used), all available collimators (also without collimator) and both with an open energy window and with the energy window pertaining to the radionuclide (surgical probe: NEMA NU 3 - 2004).
Take a relatively large reference distance from the source, *e.g.* 25 cm, straight in the field of view of the probe. The probe "sees" only a fraction of the (calibrated) activity. This fraction equals the (effective) detector (or collimator) surface area (in cm^2) divided by the surface area of the sphere with radius of the reference distance (7850 cm^2 in case of 25 cm).
Measurements are done over at least 20 distance points. Determine at least 10 distances

such that the count rates range from 10 cps up to 500 cps in more or less equal steps on a log scale, at least 5 distances in the count rate range from 500 cps up to 1000 cps and 5 distances in the count rate range from 1000 and higher. From the activity at the reference distance of 25 cm, calculate the activity at every distance using the inverse square law. Register this calculated activity and the measured count rate. If the electronics of the probe facilitate several measuring times, choose a time long enough to register e.g. 10.000 counts (i.e. 1% precision). If a measurement time to acquire 10.000 counts is not possible, repeat the measurements with a shorter time, until the sum of the measurements amounts to 10.000 counts. In this way, the measuring precision is always at least 1%. All counting data need to be corrected for the background data measured beforehand.

6. Analysis and interpretation

There are two methods to determine the sensitivity and the linearity of a probe.

1a Determination from graph

Make a graph of the measured count rates versus the calculated activities (kBq).
Draw the best straight line through the data points from 100 cps to 500 cps and extrapolate this line as far as needed. Calculate the slope of this line (cps/kBq) and the offset (cps).

1b Statistical determination

Use a computer program, *e.g.* a spreadsheet, to register measured count rates (cps) and calculated activities (kBq) and to generate a graph of the measured count rate versus calculated activity. Determine by linear regression on the count rates from 100 cps to 500 cps, the slope (cps/kBq), offset (cps) and their 95% confidence limits. (There are several textbooks on this subject)

2 Optimized determination

Like in 1b, apply linear regression initially on the first 3 lowest count rates vs activity and determine 95% confidence limits of both slope and offset. Repeat this for first 4 data points, 5 data points etc, until the smallest range for the 95% confidence limits is found.

The sensitivity of the probe is reflected by the slope (cps/kBq). The precision of this number can be described by the 95% confidence limits, if determined. The relevance of the offset is determined by whether the 95% confidence limits of the offset include zero. If so, then the offset is not statistically significant and reflects negligible (detector) noise. If the 95% confidence limits does not include zero, then the offset is relevant and affects the minimal detectable activity (see section on background signal).

Linearity is reported by the count rate (and activity) which deviates 20% from the regression line.

7. Action thresholds and actions

On acceptance, compare the result with the specifications, if available. In addition, verify that countrates encountered in the clinical setting are lower than the countrate at 20% deviation from the regression line. It is further recommended that on acceptance, a check needs to be made to verify that the probe is able to detect the minimum clinically detectable activity under realistic conditions of use (count time about 1 second) (see *e.g.* Brands *et al*: for a two-day sentinel node protocol for the breast: 10 cps/kBq at 10 mm).
Make sure the user is informed about the distance dependency of the probe.

8. Pitfalls and marginal notes
The activity must be calibrated. Preference is therefore given to a standard calibration source. In addition, the measurement is very sensitive to variations in the distance, especially at close distances. Fortunately, with the method above, the count rates at a larger distance are the most important for determining the sensitivity.

9. Additional checks
NEMA NU 3-2004 also provides checks of the sensitivity in the presence of scattered radiation and the volume-sensitivity so that these parameters can be checked upon acceptance if specifications are available.

Sensitivity and Variability on Constancy

1. Introduction and rationale
As stated in the former section, sensitivity is the most important parameter for proper functioning of the probe. Therefore, its constancy should be monitored over time.
Since periodically repeating the procedure, analyses and interpretation described in the former section would be too time consuming, a simpler test is done. This test concerns measurement of the count rate (where dead time effects can be neglected) at a fixed distance from a source with a known activity. In fact, this concerns measurement at one point of the linear part of the count rate versus activity relation described above. If the results of this measurement are constant, the sensitivity and linearity determined according to the former section are supposed to be constant. The constancy is tested by comparing the distributions of the sensitivities over time.

2. Frequency
According to the rationale, this check must be performed upon acceptance and constancy tests. It is further recommended that prior to every use, the readings of the probe be qualitatively checked, because this will facilitate early detection of loose contacts or broken wires. To get a good statistical overview over time it is advised to perform this test quarterly.

3. Method
Repeat the sensitivity measurement with a fixed source. Only one collimator configuration and one energy window need to be used for this.

4. Requirements
One source, for example, of a type also used for sensitivity on acceptance and linearity measurements. The count rate may be high (1000 cps) but must still be within the linear area (see linearity). Note that the setup and the source need *not* be the same as the combined sensitivity/linearity measurements, provided that the setup is the same for all constancy measurements. Even the source activities may (and mostly will) vary between status measurements, as long as geometric consistency is achieved. This gives room for the use of a practical setup and source.

5. Procedure

Mount the probe with collimator of choice and source in a fixed position with the source reasonably straight in the field of view of the probe. The position of the source is not critical, but must remain constant throughout the test. Carry out 20 measurements of about 10.000 counts.

If a measurement time to acquire 10.000 counts is not possible, repeat the measurements with a shorter time, until the sum of the measurements amounts to 10.000 counts. In this way, the measuring precision is always at least 1%.

Calculate the sensitivity (count rate divided by source activity, cps/kBq) for each measurement and the average and standard deviation of the set of 20 measurements.

6. Analysis and interpretation

It is assumed that there is an initial set S_0 of (n=20) measurements on acceptance with mean sensitivity C_0 and standard deviation sd_0. For the new set S_1 of (n=20) measurements, calculate the mean C_1 and standard deviation sd_1.

To test if C_1 is (statistically) equal to C_0, or if $C_1 - C_0 = 0$, calculate the Z-value according to $Z = (C_1 - C_0) / \sqrt{(sd_0^2/n + sd_1^2/n)}$. For 95% confidence limits, C_1 is considered equal to C_0 if the absolute value of Z is smaller than 1,96.

7. Action thresholds and actions

With 95% confidence limits, Z needs to be larger than 1,96 in order to call the probe performance instable.

8. Pitfalls and marginal notes

If the measurement is carried out with a probe in a fixed position, any instability due to loose contacts or broken wires may be overlooked.

Side Shielding

1.Introduction and rationale

The term 'side shielding' is often used to denote the shielding of the probe only from sources outside the visual field.

2. Frequency

It is recommended that this check be performed on acceptance and after – possible – damage to the probe housing. To get a good statistical overview over time it is advised to perform this test yearly.

3. Method

The direct side shielding is determined by measuring the count rate of a source in front of the crystal versus the count rate measured when the source is placed against the housing of the probe.

4. Requirements
A point source (approximately 1 MBq) of the clinically relevant radionuclide. The dimensions of the source should be small relative to the diameter of the collimator aperture.

5. Procedure
Carry out this test for all collimators (also without collimator) and with the energy windows applicable to the source. Place the source in front of the probe at 10 mm distance. Record the count rate (according to NEMA with a minimum of 1000 counts per counting period). Place the source against the housing of the probe and record the count rate. Move the source around the housing and determine the maximum count rate.

6. Analysis and interpretation
Determine the ratio between the maximum count rate all around and the count rate at a distance of 10 mm in front of the probe.

7. Action thresholds and actions
Compare the values found with the specifications, if available.

8. Pitfalls and marginal notes
Carrying out this test with a standard calibration source but with a different radionuclide is possible, but is not recommended. It is then necessary to correct for the transmission difference due to the energy difference. This is complex when the substitute radionuclide also emits photons of several energies.

Field of View

1. Introduction and rationale
The degree of collimation determines the field of view of a probe and the degree of suitability of a probe for the precise localization of activity.

2. Frequency
This check is recommended on acceptance. To get a good statistical overview over time it is advised to perform this test yearly.

3. Method
NEMA NU 3-2004 describes two methods for the surgical probe, both to be carried out in water. However, for the ease of use, the methods may be carried out in air.
Resolution
A source is moved at 30 mm in front of the probe on a line perpendicular to the probe axis along the front of the probe.
Angular dependence
A source is held at a fixed distance of 30 mm of the probe and the probe is rotated around the source.
For the thyroid probe, a comparable check can be carried out in air, but the distance chosen must be clinically relevant.

4. Requirements
A point source (approximately 1 MBq) of the clinically relevant radionuclide (ensure that the count rate is still in the linear range, see linearity) or as specified by the manufacturer.
A tool in which the probe and the source can be mounted in varying known positions (distance or angle) from each other is convenient and timesaving.

5. Procedure
Carry out the check for all collimators and with the energy windows being used clinically (adapted to the radionuclide being used). Collect at least 5000 counts right in front of the probe and at least 500 at all points within the FWTM.
Resolution
Measure translations for the surgical probe every 5 mm over a distance of 100 mm and at least 10 points within the FWHM, and proportionally scaled for the thyroid probe.
Angular dependence
Measure from -90° to +90° every 10° and between -25° and +25° every 5°.

6. Analysis and interpretation
Determine the FWHM and the FWTM for both the resolution and the angular dependence.

7. Action thresholds and actions
Compare with the specifications (both resolution and angular dependence are NEMA specifications). Ensure that the user is informed about the field of view of the probe.

Energy Spectrum and Resolution

Good energy resolution improves the ability of the probe to suppress scattered radiation and sometimes makes it possible to detect different radionuclides separately. The energy resolution should be checked on acceptance with a protocol comparable to that for the gamma camera (see there). For most surgical probes, however, it is not possible to determine the energy resolution. The energy spectrum cannot be made visible on the probe itself, the output for a multichannel analyzer is missing or there is no multichannel analyzer available or else the energy window cannot be adjusted freely enough to measure the energy spectrum step by step (in any case a very laborious method). If the energy resolution is of great importance for the clinical application, e.g. when carrying out dual-isotope measurements, it will have to be discussed with the manufacturer how to determine the energy resolution, for example according to NEMA NU 3-2004. Furthermore, if the constancy tests result in instable probe performance, comparison of the energy spectrum with the spectrum at acceptance can give important clues for the cause of the instability. If it is indeed possible to determine the energy resolution, the method as described in respect of the gamma camera may be followed. Note that, unlike in other measurements, for the energy spectrum and resolution measurements, clinically applied sources should be used.