

ORIGINAL ARTICLE

Efficacy of optimization of intraoperative gamma probe in detection of sentinel lymph nodes in breast cancer and melanoma patients

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Abstract

Aims Breast cancer patients often have associated metastases, caused by cancerous cells spreading through the lymphatic system to other areas of the body. As a result, it is common to remove and assess the sentinel lymph node (SLN) during the surgical removal of the tumour. To localise the SLN, an injection of 99mTc-Nanocoll is administered interstitially or intradermally which is transported to SLNs via the lymphatic system. A nuclear medicine scan is then acquired. A gamma probe is used to locate the SLN during the surgical procedure with the aid of the nuclear medicine scan images. The aim of this study was to optimise the performance of an intraoperative gamma probe system (Europrobe) having both scintillation and semiconductor probes for more accurate detection of SLN in melanoma and breast cancer patients.

Methods The surgical Europrobe system is equipped with one scintillation CsI(Tl) detector and one semiconductor CdTe detector. Tests were performed against The National Electrical Manufacturers Association (NEMA) guidelines using an in-house developed phantom.

Results The CsI(Tl) detector has superior sensitivity and better side shielding effectiveness. The CdTe probe has better spatial and energy resolutions.

Conclusion : It is not possible for a probe to have optimum performance for all parameters, so a compromise must be reached depends on clinical and surgical preference. The Europrobe has scintillation and semiconductor probes, which allows the user to choose the most suitable probe for the intended application. The scintillation probe has high sensitivity, which is important for detection of low nodal activity, or deep-seated nodes. The semiconductor probe has superior spatial and energy resolutions, which are important for accurate localisation and scatter rejection.

Key words: *ALARA, exposure rate, isolation room, radioiodine, I-131*

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Introduction

Sentinel Lymph Node (SLN) biopsy is a minimally invasive technique for the identification and removal of the first lymph node draining a tumour. Precise prediction of the site of a SLN is not infallible due to the nature of SLN excision, variations in pattern of lymph node distribution and also due to the presence of nodes in unexpected places. A further difficulty may arise if there is more than one sentinel node. Knowledge of node location relative to the skin and its depth aids biopsy and excision. The status of metastasis in regional lymph nodes in patients with early solid cancer has clear predictive value for survival. If a metastasis is found in regional lymph nodes, it decreases the 5-year survival of patients by approximately 30-40% in melanomas [1] and breast cancers [2].

SLN mapping for melanoma has put to rest the controversy of elective LN dissection by saving unnecessary dissection in 80% patients and directing the surgeon to those patients most likely to benefit from LN dissection [3]. Intraoperative gamma probes are increasingly used to localize the first draining node from a tumour in melanoma and breast cancer. After the incision, the probe is introduced into the wound and the dissection is directed to the node.

Although the role of SLN dissection is to provide accurate staging at the initial diagnosis of primary melanoma or breast cancer and to enhance such accuracy, it requires (a): accurate identification and localisation of SLN by preoperative lympho scintigraphy and intraoperative mapping and dissection and (b): meticulous histologic evaluation [4]. For breast cancer patients, axillary node involvement is important for staging and management, but is difficult to establish using non-invasive techniques [5]. Axillary lymph node dissection leads to considerable morbidity and results in over-treatment of patients who do not have lymph node metastases [6]. SLN biopsy avoids unnecessary axillary clearance in the majority of patients who do not have lymph node involvement. In the period of 2006-2007, of 11,993 invasive cancers with known nodal status, 24% were found to be positive [7]. Intraoperative gamma probes are becoming more commonly used in sentinel lymph node biopsy for patients with invasive breast cancer to detect Tc-99m nanocolloid in the sentinel node. The Audit of Screen Detected Breast Cancers for the Year of Screening April 2006 - March 2007 [7] showed that 42% of surgeons who performed SLN biopsy used nanocolloid isotope and blue dye together. This has increased from 27% in the period of the previous audit 2005/6 [8].

The discrimination of sentinel lymph nodes depends on the depth of the node below the skin surface, the level of uptake, the distance from the high activity injection sites, and the amount of scatter background. In determining the most appropriate probe, consideration is usually given to the high sensitivity, good spatial and energy resolutions, highly absorptive side shielding, collimation, good count rate linearity and other features such as the overall ergonomics and design of the probe, the ease of peri-operative use, etc [9-10]. Various authors have performed tests to characterise the performance of different probe systems. Yu et al. [11] tested the Navigator GPS system (United States Surgical Corporation, Norwalk, Connecticut, United States) to investigate the sensitivity, dead time, spectral resolution and ergonomic characteristics using their own protocols. Tiourina et al. assessed four different probe systems, measuring transmission through side shielding, angular sensitivity, absolute sensitivity in air, sensitivity in water, and off-axis sensitivity [9]. Britten assessed three different probe systems - a Europrobe, a Navigator GPS and a Neoprobe 1500 (Neoprobe Corporation, Dublin, Ohio, United States). He measured sensitivity profiles for each of these to determine the spatial resolution and on-axis sensitivity. The work then compared the different probe systems based on the measurements, as well as on simulated data. This simulation method allowed probe systems to be compared for the task of sentinel node detection and localisation, whereas using performance parameters alone cannot give an overall performance ranking [10].

The NEMA guidelines include all of the performance parameters investigated independently by these authors. However, limitations in the probe systems can cause difficulties in following the NEMA guidelines. For example, Yu *et al.* [11] found that their Navigator GPS probe system could not achieve the high counting statistics required by the NEMA guidelines. The Europrobe system used in this study caused the same difficulty, since for some tests the system's maximum counting time of 50 seconds did not allow sufficient counts to be recorded to comply with the guidelines. In these instances, the measurement was repeated several times to gain sufficient total counts, and the mean value was taken. Yu et al. Also found that the test for the energy resolution required counts to be collected for each energy channel, which is not possible using the Navigator system. The Europrobe system also cannot discriminate the recorded counts into such narrow energy channels. This difficulty is resolved by connecting a multichannel analyser to the system.

We performed various testing of an intraoperative probe system (Eurorad, Strasbourg, France) in accordance with the NEMA guidelines NEMA NU-3 [12]. This article describes the tests performed and summarises the performance characteristics of the Europrobe system for optimum use of the system during lymph node biopsies of breast cancer patients.

Methods

System Description

A Europrobe System consisting of one read-out module and two detection probes was selected. The probes are a high sensitivity Thallium-doped Caesium Iodide CsI(Tl) scintillation probe and a Cadmium Telluride CdTe semiconductor probe, both of which include internal collimation. The CsI(Tl) crystal has 7mm diameter and 10 mm length and the probe head diameter is 16 mm. The 99mTc energy window is 110 - 200 keV and the open energy window is > 100 keV. The CdTe crystal is 5 x 5 x 3 mm and the probe head diameter is 11 mm. The 99mTc energy window is 110 - 170 keV and the open energy window is >20 keV. The NEMA measurements were performed with the system configured as per clinical use for breast SLN biopsy with ^{99m}Tc. The ^{99m}Tc energy window was selected wherever NEMA NU- 3 specified use of an isotope energy window, and the integration time in the count rate mode was 1.0 second. Background measurements were made prior to each test and subtracted if non-zero.

Performance Measurement Tests

The performance measurement tests in Section 3 of NEMA NU-3 were performed for both probes. Six of the performance tests must be performed in a scatter medium. The NEMA guidelines specify that adequate water scatter volume will be provided by a water bath 20 cm wide x 20 cm long x 15 cm water depth and state that the point source must be positioned accurately and reproducibly within the water bath. This was achieved through the design of a suitably sized water tank (Figure 1) based on the NEMA specifications and suggestions [12].

A point source consistent with NEMA NU 3 was created using drops of 99mTc contained in a 2 mm diameter 3 mm deep hole in a strip of Perspex. Two systems were designed to position this point source relative to the probe. Both positioning systems allow source-to-probe distances of 10, 30, 50, 70 and 100 mm. The first system allows the source to be moved horizontally relative to the probe at constant depth below the water surface (Figure 1-a), and the second allows the point source to be pivoted through an arc about the centre of the probe face (Figure 1-b). Each probe was placed inside a latex

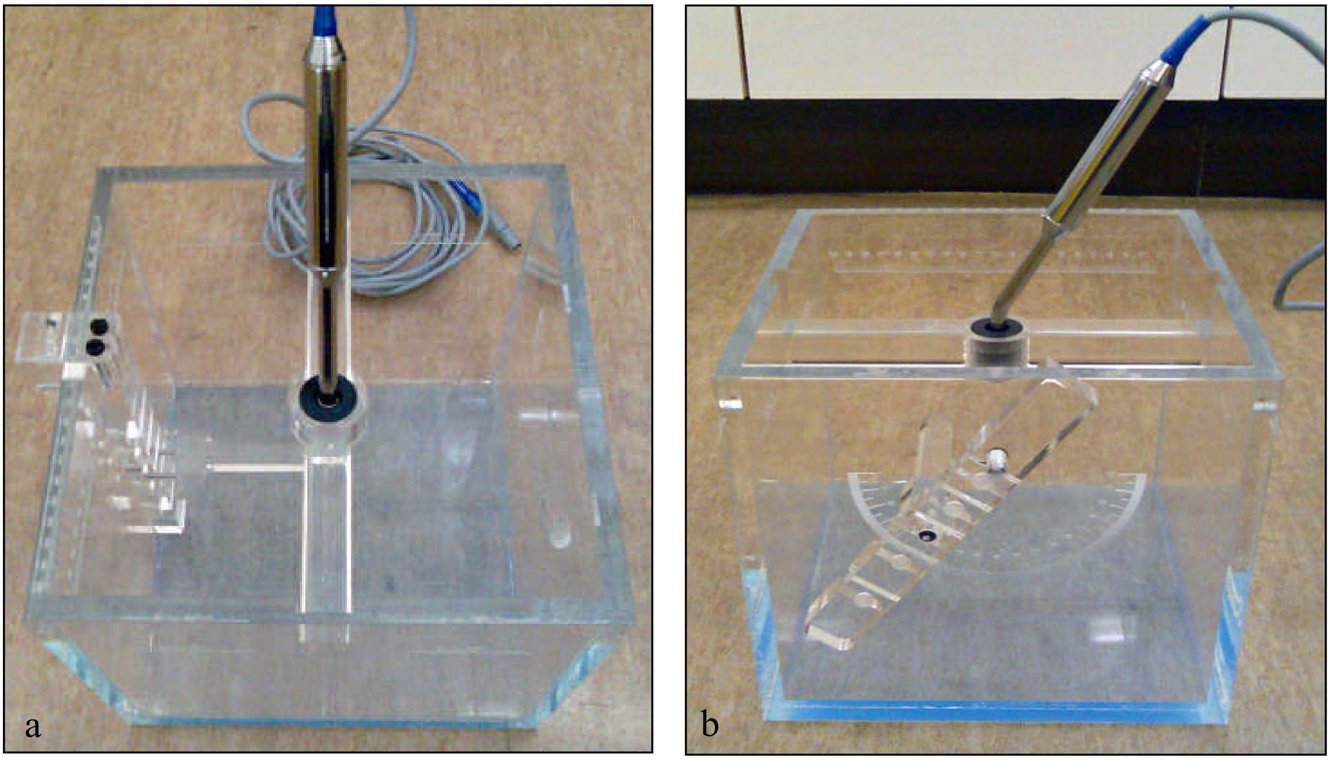


Figure 1 *Water tank, probe holder and source holder used to perform the measurements in a scatter medium. (a) Positioning system used to move the source horizontally relative to the probe face; (b) positioning system used to pivot the source through an arc about the centre of the probe face*

glove to prevent water damage. A multichannel analyser (MCA) was required to perform the energy resolution measurements. The Europrobe manufacturer, Eurorad, recommended use of an Amptek MCA 8000A (Amptek Inc., Bedford, MA, USA).

Each point source was assayed three times in a Capintec CRC-35R radioisotope calibrator to obtain a mean value, which was then decay corrected for each probe measurement. The accuracy of the calibrator is better than 5% based on daily tests with a ^{137}Cs reference source. The most recent annual ^{99m}Tc accuracy calibration gave a deviation of less than 1%. Each probe counting measurement was repeated three times and the mean result was used.

Count rate capability in a scatter medium

The count rate capability measurements described in NEMA NU-3 were performed first to determine the linear response region for each probe [12] . A ^{99m}Tc point source was placed at a depth of 30 mm in the water tank, directly under the probe tip. The probe and tank were left in position throughout the test to avoid positional variations.

NEMA NU-3 states that the probe sensitivity should be measured for various source activities in a scatter medium, and since 99mTc is short-lived, they recommend a decaying source method. The decay corrected activities were plotted against the measured counts for each probe. A straight line constrained to pass through the origin was fitted to the points at low count rate. This straight line was used to determine the 20% loss count-rate capability.

Results

The results are summarised in the format suggested in NEMA NU-3 (Tables 1 & 2) and are further detailed in the text.

Table 1 *CsI(Tl) scintillation probe performance measurement data sheet in NEMA format [12]*

Section in NEMA	Test	Source	Energy* window	Results			
3.1	Sensitivity in air	Tc-99m	Open	48415 cps/MBq at contact	8102 cps/MBq at 10mm	2014 cps/MBq at 30mm	875 cps/MBq at 50mm
			Tc-99m	46127 cps/MBq at contact	7678 cps/MBq at 10mm	1889 cps/MBq at 30mm	827 cps/MBq at 50mm
3.2	Sensitivity in a scatter medium	Tc-99m	Tc-99m	n/a	8484 cps/MBq at 10mm	1560 cps/MBq at 30mm	610 cps/MBq at 50mm
3.3	Sensitivity through side shielding in air	Tc-99m	Open	n/a	n/a	n/a	0.69 cps/MBq at 50mm
			Tc-99m	n/a	n/a	n/a	0.49 cps/MBq at 50mm
3.4	Sensitivity to scatter	Tc-99m	Tc-99m	Corrected for sensitivity through side shielding? No			31.02 cps/MBq at 50mm lateral
3.5	Spatial resolution in scatter medium	Tc-99m	Tc-99m	45 mm FWHM at 30mm			90 mm FWTM at 30mm
3.6	Volume sensitivity in distributed activity in a scatter medium	Tc-99m	Tc-99m	Activity 15.31 MBq			65 cps/MBq
3.7	Short term sensitivity stability	Co-57 at 6 cm in air	Open	Mean count 16547	Calculated Chi squared: 20.18	Chi squared limits: 6.84 - 30.14	
			Tc-99m	Mean count 14573	Calculated Chi squared: 13.07	Chi squared limits: 6.84 - 30.14	
3.8	Count rate capability in a scatter medium	Tc-99m	Tc-99m	20% loss count rate capability: 3590		20% loss Tc-99m point source activity : 2.8 MBq	
3.9	Angular resolution	Tc-99m	Tc-99m	FWHM at 30mm 102 degrees		-	
3.10	Energy resolution	Tc-99m	n/a	FWHM energy resolution: 37 keV		Energy resolution: 26.5%	
3.11	Side and back shielding	Tc-99m	Tc-99m	Shielding effectiveness: 99.8%		Leak sensitivity: 0.22%	

Open energy window:100 keV – infinity; Tc-99m energy window:110 - 200 keV

Table 2 *Cd(Te) semiconductor probe performance measurement data sheet in NEMA format [12]*

Section in NEMA	Test	Source	Energy window*	Results			
3.1	Sensitivity in air	Tc-99m	Open	48166 cps/MBq at contact	4675 cps/MBq at 10mm	894 cps/MBq at 30mm	353 cps/MBq at 50mm
			Tc-99m	28557 cps/MBq at contact	2681 cps/MBq at 10mm	500 cps/MBq at 30mm	196 cps/MBq at 50mm
3.2	Sensitivity in a scatter medium	Tc-99m	Tc-99m	n/a	2861 cps/MBq at 10mm	498 cps/MBq at 30mm	139 cps/MBq at 50mm
3.3	Sensitivity through side shielding in air	Tc-99m	Open	n/a	n/a	n/a	3.02 cps/MBq at 50mm
			Tc-99m	n/a	n/a	n/a	1.0 cps/MBq at 50mm lateral
3.4	Sensitivity to scatter	Tc-99m	Tc-99m	Corrected for sensitivity through side shielding? Yes			6.83 cps/MBq at 50mm lateral
3.5	Spatial resolution in scatter medium	Tc-99m	Tc-99m	39 mm FWHM at 30mm			84 mm FWTM at 30mm
3.6	Volume sensitivity to distributed activity in a scatter medium	Tc-99m	Tc-99m	Activity 15.31 MBq			15 cps/MBq
3.7	Short term sensitivity stability	Co-57 at 5 cm in air	Open	Mean count: 11803	Calculated Chi squared: 13.89	Chi squared limits: 6.84 – 30.14	
			Tc-99m	Mean count 6155	Calculated Chi squared: 15.73	Chi squared limits: 6.84 - 30.14	
3.8	Count rate capability in a scatter medium	Tc-99m	Tc-99m	20% loss count rate capability: 5099		20% loss Tc-99m point source activity: 15.0 MBq	
3.9	Angular resolution	Tc-99m	Tc-99m	FWHM at 30mm 99 degrees		-	
3.10	Energy resolution	Tc-99m	n/a	FWHM energy resolution 12.5 Kev		Energy resolution 8.9%	
3.11	Side and back shielding	Tc-99m	Tc-99m	Shielding effectiveness 99.7%		Leak sensitivity 0.27%	

* Tc-99m energy window:110 - 170 keV; open energy window: 20 keV - infinity

Count rate capability in a scatter medium

Figure 2 shows the recorded count rates for the CsI (Tl) and CdTe probes for varying point source activities. The vertical line indicates the 20% count rate loss, i.e. negative 20% deviation from the fitted linear count rate. The 20% count rate loss occurs at 3590 cs-1 for CsI (Tl) and at the higher count rates for the CdTe probe (5099 cs-1), indicating that the relationship between source activity and count rate is linear over a wider range of activities for CdTe than for the CsI

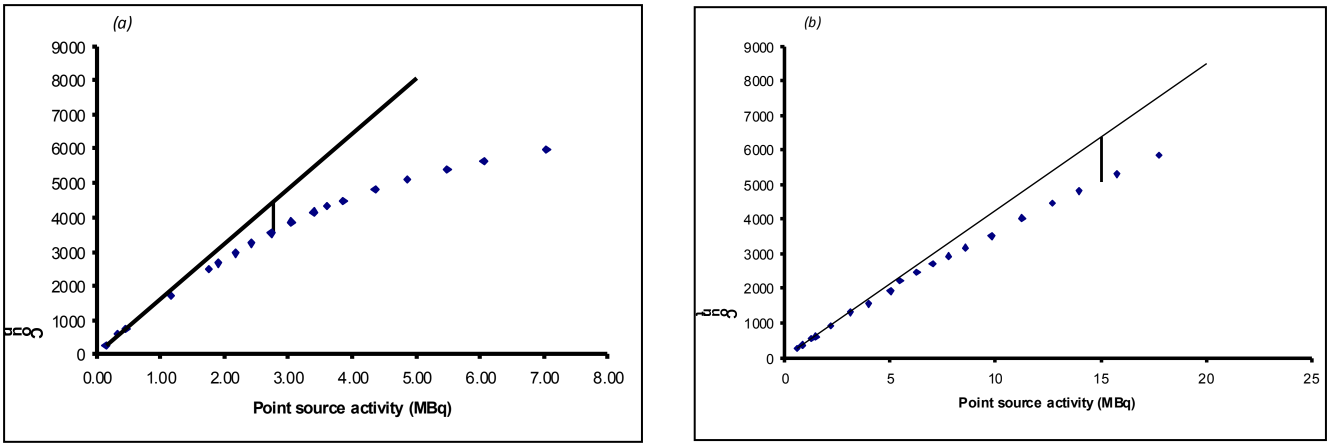


***Figure 2** The count rate capability measurements for Tc-99m point sources at 30mm depth in water, and the Tc-99m energy window. The vertical line indicates 20% count rate loss. (a) CsI(Tl) probe; (b) CdTe probe*

(Tl) probe. The observed 20% count rate losses were within the manufacturer acceptable range (3000 - 5500 cs-1). The Figure 2 allows the true count rate (Rt) to be estimated for a given activity from the fitted straight line. For each probe, four points on the graph were used to calculate the dead time using equation 1 for a paralysable system, where R0 and are the observed count rate and the dead time of the system. The dead times were (5.2 0.3) x 10-5 and (3.4 0.2) x 10-5 seconds for CsI (Tl) and CdTe probes.

Equation 1

$$R_o = R_t e^{-R_t \tau}$$

Sensitivity in Air

Sensitivity in the air for a ^{99m}Tc source in contact with the probe tip and at distances of 10, 30 and 50 mm are shown in Table 3. The results indicate that the CsI (Tl) probe has better sensitivity in air than the CdTe probe. Figure 3 shows the percentage difference between the sensitivities of the two probes, relative to the mean sensitivity of the probes, at each measurement point. The CsI(Tl) probe is more sensitive at all distances, but the difference increases as the source-to-probe distance increases. The difference in sensitivity between the probes is more apparent when the ^{99m}Tc window is used. This

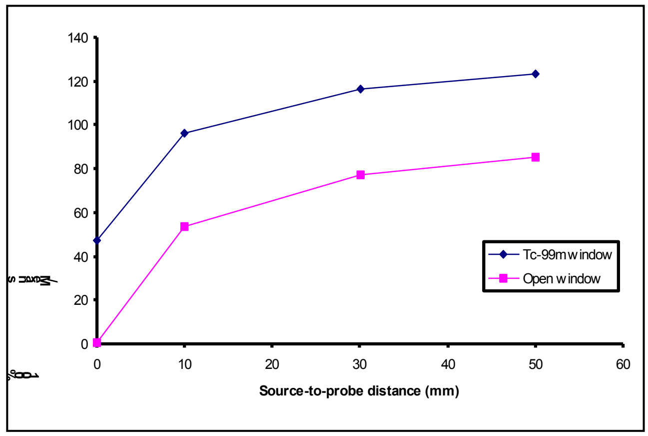


***Figure 3** Comparison of probe sensitivities for open and ^{99m}Tc windows*

may be explained by the narrower ^{99m}Tc energy window and better energy resolution of the CdTe probe both of which result in a higher proportion of detecting events being rejected. For both the probes, the manufacturer tests the sensitivity in air with a ^{57}Co source at 10 mm distance using the ^{99m}Tc window. The acceptable limits are 300 $cs^{-1}\mu Ci^{-1}$ for the CsI(Tl) and 80 $cs^{-1}\mu Ci^{-1}$ for the CdTe probes. The manufacturers had measured 343 $cs^{-1}\mu Ci^{-1}$ for the CsI(Tl) and 110 $cs^{-1}\mu Ci^{-1}$ for the CdTe probes on the unit tested by the authors. We were unable to repeat the measurement using ^{57}Co due to unavailability of the source with appropriate activity, though, the results

Table 3 *Results for sensitivity in air with ^{99m}Tc source*

		Sensitivity (cps/MBq)			
Source-to-probe distance		**Contact**	**10mm**	**30mm**	**50mm**
CsI(Tl)	Open window	48415	8102	2014	875
	Tc-99m window	46127	7678	1889	827
CdTe	Open window	48166	4675	894	353
	Tc-99m window	28557	2681	500	196

from a ^{99m}Tc source with the ^{99m}Tc window were measured to be 284 cs^{-1} Ci^{-1} and 99 cs^{-1} Ci^{-1} for the CsI(Tl) and CdTe probes respectively.

Our results indicate the measured sensitivity of CdTe probe is above the specified limit, whereas the measured sensitivity for CsI (Tl) is 5.3% below the manufacturer's acceptable limit. This discrepancy may be due to the different isotope energies. The probe sensitivity will be slightly lower for ^{99m}Tc than for ^{57}Co due to fewer of the higher energy photons being absorbed in the detector [12]. The ^{99m}Tc energy window includes the peaks of both ^{99m}Tc and ^{57}Co. After discussing the results with the manufacturer, it was agreed to be acceptable.

Sensitivity in a scatter medium

The results for sensitivity in a scatter medium (Table 3) show the CsI(Tl) probe has better sensitivity than the CdTe probe in a scatter medium and consequently is more suitable for detecting targets with low activity or at greater depths. The difference in sensitivity between the two probes increases as the distance increases, suggesting better detection and localisation will be achieved using the case (Tl) probe for sentinel lymph nodes at greater depths. The manufacturer could not provide acceptable limits for sensitivity in a scatter medium as the test is not performed for every probe system manufacturer. However, a test data was provided for one particular system using a ^{57}Co source [Table 4]. In a scatter medium, the difference in sensitivity using ^{57}Co and ^{99m}Tc depends on the source depth and detector characteristics [12].

Sensitivity through side shielding in air

The sensitivity of the CsI(Tl) probe was 0.69 cs^{-1}MBq^{-1} for the open window and 0.49 cs^{-1}MBq^{-1} for the ^{99m}Tc window. For the CdTe probe the sensitivity was 3.02 cs^{-1}MBq^{-1} for the open window and 1.00 cs^{-1}MBq^{-1} for the ^{99m}Tc window. The CsI(Tl) probe has lower sensitivity through side shielding than the CdTe probe and is therefore better at excluding photons from adjacent hot areas such as the injection sites.

The manufacturers test results with the ^{99m}Tc window were 0.96 cs^{-1}MBq^{-1} for the CsI(Tl) probe and 0.9 cs^{-1}MBq^{-1} for the CdTe probe. The sensitivity through side shielding was lower for our CsI(Tl) detector than for the test probe but slightly higher for the CdTe probe. In addition to the test described in NEMA NU 3, the side shielding was also assessed along the full length of each probe head by moving the source in 5mm steps from the probe tip towards the handle, maintaining the 50 mm lateral distance. Measurements were also made with the collimator in place to assess the level of extra shielding provided by the collimator (Figure 4). The measurements indicated that there is a large reduction in sensitivity through side shielding when the additional collimators are used for the both probes and very few counts are detected. The side shielding for the CsI(Tl) is less efficient towards the back of the probe head, whereas the CdTe probe has better side shielding towards the back of the probe head.

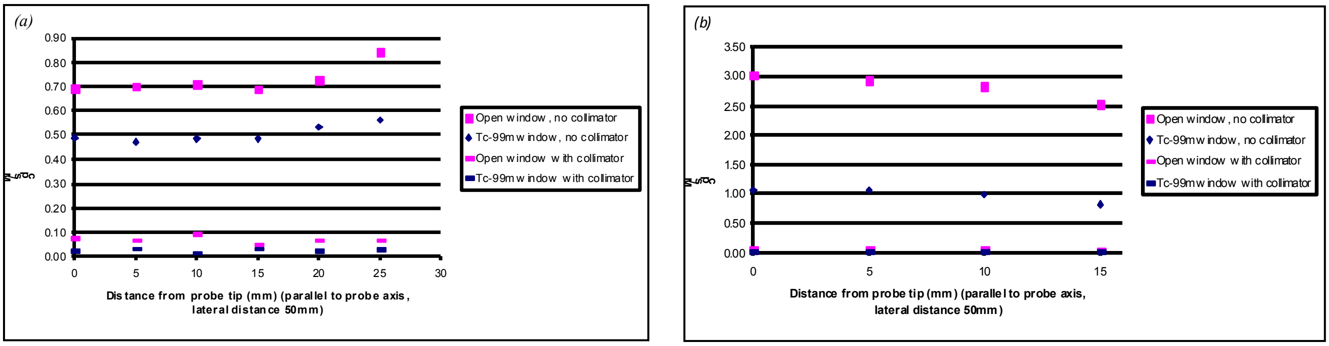


Figure 4 *Results for sensitivity through side shielding along the length of the probe heads at a 50 mm lateral distance. (a) CsI(Tl) probe; (b) CdTe probe*

Table 4 *Results for sensitivity in a scatter medium with a ^{99m}Tc source and the 99mTc energy window. Manufacturer's results for a different system using a ^{57}Co source are given for comparison with the percentage difference in brackets*

	Sensitivity (cps/MBq)		
	10mm	**30mm**	**50mm**
CsI(Tl)	8484	1560	610
CdTe	2861	498	139
Manufacturer's CsI(Tl)	8891	1720	621
	(-4.6%)	(-9.3%)	(-1.8%)
Manufacturer's CdTe	1781	357	80
	(60.6%)	(39.5%)	(73.8%)

probes and very few counts are detected. The side shielding for the CsI(Tl) is less efficient towards the back of the probe head, whereas the CdTe probe has better side shielding towards the back of the probe head.

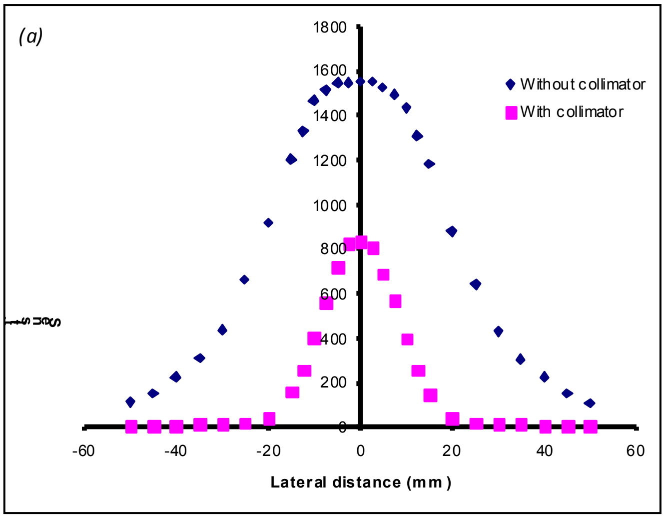
Sensitivity to scatter

The scatter sensitivity ($cs^{-1}MBq^{-1}$) for each probe was compared with the sensitivity through side shielding value from the previous test. NEMA NU 3 states that if the sensitivity through side shielding is greater than 10% of the measured sensitivity to scatter, then a correction should be made to the sensitivity to scatter measurement by subtracting the sensitivity through side shielding value. Without collimators, this correction was necessary for the CdTe probe, but not for the CsI (Tl) probe. Neither of the measurements with the collimators needed to be corrected.

For the CsI(Tl) probe, the sensitivity to scatter using the ^{99m}Tc window was 3.01 $cs^{-1}MBq^{-1}$ and 31.02 $cs^{-1}MBq^{-1}$ with and without the external collimator. For the CdTe probe with ^{99m}Tc window the results were 1.05 $cs^{-1}MBq^{-1}$ and 6.83 $cs^{-1}MBq^{-1}$ with and without the collimator. The CdTe probe is less sensitive to scattered photons than the CsI(Tl) probe. This is due to lower sensitivity, better energy resolution, and the narrower energy window for the CdTe probe. Having a lower sensitivity to scatter means that the CdTe probe is better able to reject photons emitted from adjacent sites of activity. However, the previous test showed that the scintillation probe had better side shielding in the air, which is also advantageous for excluding photons emitted from adjacent sites of activity.

Spatial resolution in a scatter medium

Figure 5 shows the sensitivity profiles for the spatial resolution measurements with a ^{99m}Tc point source. The full width half maximum (FWHM) and full width tenth maximum (FWTM) values calculated from the profiles (Table 5) show that without collimators the CdTe probe has better spatial resolution than the CsI(Tl) probe. This is due to the smaller size of the CdTe probe and its superior energy resolution allowing better rejection of scattered photons. As expected, the collimators



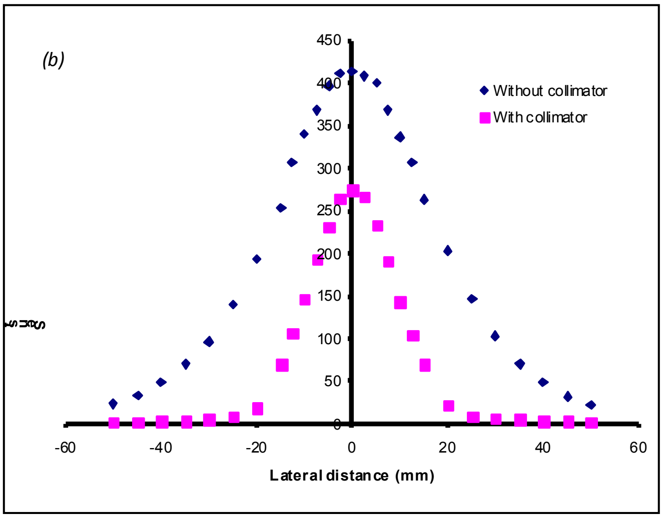


Figure 5 *The spatial resolution curves for the probes with a ^{99m}Tc point source at 30 mm depth and ^{99m}Tc energy window. (a) Cs(Tl) probe; (b) CdTe probe*

Table 5 *The full width half maximum (FWHM) and full width tenth maximum (FWTM) values for the sensitivity profiles. Manufacturer's results are shown without collimator and the percentage differences are given in brackets*

	FWHM (mm)			FWTM (mm)		
	Without collimator	**With collimator**	**Manufacturer's result without collimator**	**Without collimator**	**With collimator**	**Manufacturer's result without collimator**
CsI(Tl)	45	19	50 (-10%)	90	36	100 (-10%)
CdTe	39	21	40 (-2.5%)	84	39	74 (13.5%)

Table 6 *Dimensions of the internal and external collimators, and effective length calculated*

Collimator	**Diameter d**	**Distance b**	**Length *l***	**Effective length l_{eff}**	**Collimator resolution R_{coll}**
CsI(Tl) external	0.6	3	0.6	0.55	39
CdTe external	0.5	3	0.4	0.35	48

collimators improve the spatial resolution for both probes. When the collimators are in place, the two probes have similar spatial resolution with slightly better resolution for the CsI(Tl) probe. The peaks of the curves in Figure 5 show that the CsI(Tl) probe maintains better sensitivity with the collimators in place.

The collimator resolution [13] is given by equation 2, where "d" is the diameter of collimator hole, "b" is the distance from the source to the collimator face, "$l_{eff} = l - 2\mu^{-1}$" is effective length, "*l*" *is* the length of collimator hole and "μ" is the linear attenuation coefficient of collimator material. Both the internal and additional collimators are made from tungsten. The mass attenuation coefficient (μ/ρ) of tungsten at 140 keV is 2.15 cm^2g^{-1} based on interpolation of data for tungsten from National Institute of Standards and Technology Physical Reference Data [14]. Using ρ = 19.25 g/cm^3 [15], "μ" is calculated to be 41.4 cm^{-1}.

Equation 2

$$R_{coll} = \frac{d(l_{eff} + b)}{l_{eff}}$$

Table 6 gives the measured collimator dimensions for the external collimators of the two probes and the calculated collimator resolution. The calculations show that the collimator resolution of the external collimator for the larger CsI(Tl) probe is expected to be superior to that of the CdTe probe. This explains the superior measured spatial resolution of the CsI(Tl) probe with the external collimators in place. The measured FWHM with the external collimators was 19 mm for the CsI(Tl) probe and 21 mm for the CdTe probe. These values are better than the calculated external collimator resolutions due to the additional internal collimation, the size of the detectors and the geometry of the detector behind the collimator. The measured FWHM for the both probes were narrower than the manufacturer's test probe. The FWTM was wider for CdTl detector, but narrower for the CsI (Tl) in comparison with the manufacturer's test probe (Table 5).

Volume sensitivity to distributed activity in a scatter medium

The first column of Table 7 shows the volume sensitivity of the two probes to activity distributed in water. The test measures probe sensitivity over the full volume of the solid angle field of view, combined with scatter sensitivity [12]. The CsI(Tl) detector is significantly more sensitive to activity distributed within the volume. The CsI(Tl) probe tested in this study has a lower volume sensitivity and The CdTe probe has higher volume than the manufacturer's test probe. The differences in sensitivity are in agreement with the differences observed in the other sensitivity tests. The ratios of sensitivity in a scatter medium to volume sensitivity, represent how well a probe could identify an isolated "hot" target surrounded by background activity [12]. The ratios in Table 7 were calculated using the results from the "sensitivity in a scatter medium" measurements. The higher the ratio, the better the scatter rejection and the more likely it is that the probe could identify the hot target. Figure 6 shows a comparison between the two probes. For both probes, the ratio decreases as the source depth increases. The probes are therefore less able to identify a "hot" node surrounded by background activity if the node is deep. The CdTe probe has a higher ratio than the CsI(Tl) probe at all depths, but this difference becomes less significant with depth and at the depth of 50 mm the difference is negligible. In general the CdTe probe is better able to identify a "hot" node surrounded by background activity.

Short-term sensitivity stability

For each probe and energy window, Table 8 gives the mean count, the observed standard deviation, the expected standard deviation based on a Poisson distribution, and the Chi-squared value for the observations. For both probes the Chi-squared values fall within the 95% confidence interval so the observed variability agrees with the expected variability from photon counting statistics.

Table 7 *Volume sensitivity measurements for 99mTc distributed in water and the ratios of sensitivity in a scatter medium to the volume sensitivity. Manufacturer's results for volume sensitivity are given with the percentage differences in brackets*

	Volume sensitivity (cps/MBq)	Manufacturer's result		Ratio of sensitivity in a scatter medium to volume sensitivity at different depths		
				10mm	30mm	50mm
CsI(Tl)	65	95	(-31%)	129.9	23.9	9.3
CdTe	15	10.5	(+42.9%)	193.2	33.6	9.4

Table 8 *Chi-squared test results for sensitivity stability measurements with a ^{57}Co point source in air at 5 cm for the CdTe probe and at 6 cm for the CsI(Tl) probe. The 95% confidence levels are for a sample size of 20 with 19 degrees of freedom*

(a) Intrinsic sensitivity stability (open energy window)

	Mean count	Observed SD	Expected SD	Chi-squared value	Chi-squared limits (95% CI)
CsI(Tl)	16546.85	132.57	108.64	20.18	6.84 – 30.14
CdTe	11803.35	92.89	128.63	13.89	

(b) Sensitivity stability (^{99m}Tc energy window)

	Mean count	Observed SD	Expected SD	Chi-squared value	Chi-squared limits (95% CI)
CsI(Tl)	14573.20	100.11	78.45	13.07	6.84 – 30.14
CdTe	6154.70	71.38	120.72	15.73	

Angular resolution in a scatter medium

The Figure 7 shows the sensitivity profiles for the angular resolution measurements with a ^{99m}Tc point source. The FWHM were 102° for the CsI(Tl) probe and 99° for the CdTe probe. The CdTe probe has better angular resolution than the CsI(Tl) probe due to its smaller size. It was not possible to calculate the FWTM as the measurements could not be extended to angles greater than 68 degrees.

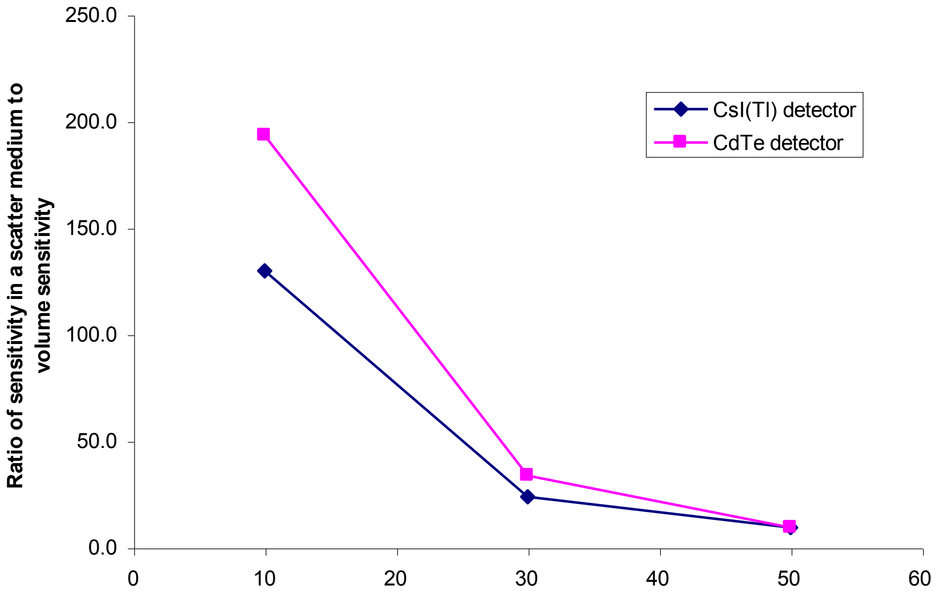


***Figure 6** The ratio of sensitivity in a scatter medium to volume sensitivity for a 99mTc source at various depths in water*

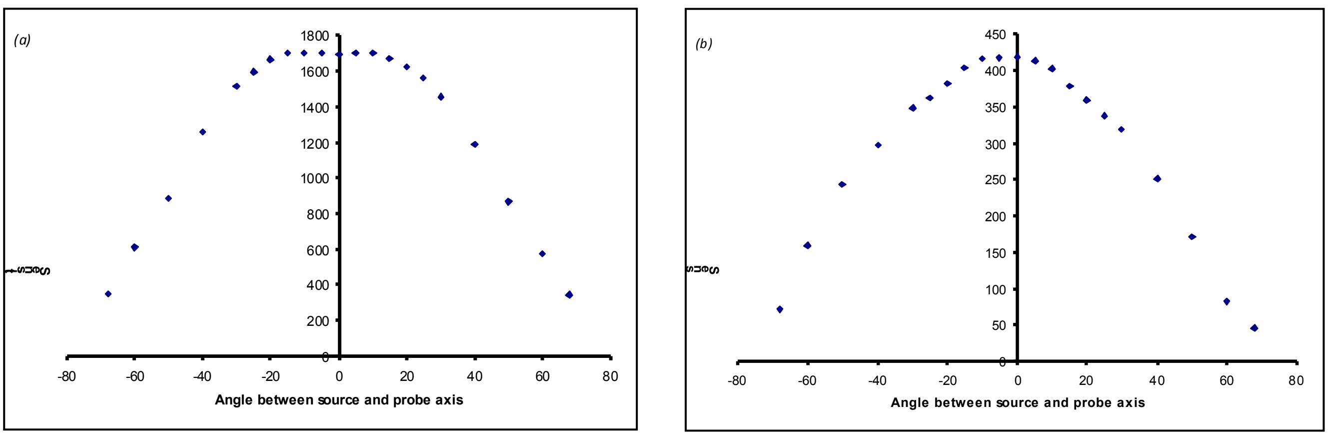


***Figure 7** The angular resolution curves for the probes with a ^{99m}Tc point source at 30 mm depth and ^{99m}Tc energy window. (a) Cs(Tl) probe; (b) CdTe probe*

The measurements were repeated several times, but in every case the results were the same for the CsI(Tl) probe where the sensitivity of the probe is slightly greater for a source angled at 5 or 10 degrees from the probe axis than directly in line with the probe axis. For this probe the peak was taken to be the sensitivity at 0 degrees. The angular resolutions measured for in this study were significantly worse than the manufacturer FWHM results (67° for the CsI(Tl) probe and 46° for the CdTe probe).

Energy resolution

The in-built capability of the Europrobe was not sufficient to allow narrow enough energy channels to assess the energy resolution. For the CsI(Tl) probe the narrowest channel width was 20 keV and for the CdTe probe 10 keV.

Table 9 *Energy resolution measured from spectra acquired with a multi-channel analyser using technetium-99m*

	Result from spectra (Tc-99m)		Manufacturer's result (Co-57)	
	Energy resolution (keV)	Energy resolution (%)	Energy resolution (keV)	Energy resolution (%)
CsI(Tl)	37 keV	26.5%	37 keV	30.2%
CdTe	12.5 keV	8.9%	7.8 keV	6.5%

Table 10 *The shielding effectiveness and leak sensitivity of both probes. Manufacturer's results are given with the percentage differences in brackets*

	Shielding effectiveness	Manufacturer's result	Leak sensitivity	Manufacturer's result
CsI(Tl) probe	99.78%	99.7% (+0.1%)	0.22%	0.24% (-8.3%)
CdTe probe	99.73%	99.6% (+0.1%)	0.27%	0.4% (-32.5%)

The Amptek MCA 8000A multichannel analyser allowed energy spectra to be acquired for both probes and these are shown in Figure 8 for a Tc-99m source. The MCA software calculates the centroid position and the full width at half maximum in terms of channel number. The calibration of energy (keV) was performed manually by acquiring spectra for Co-57 and I-131 in addition to Tc-99m, and plotting the channel number against peak energy. This allowed the energy resolution to be calculated for each probe for Tc-99m. These results are given for both probes in Table 9 with values from the manufacturer's test unit. As expected the CdTe probe has considerably better energy resolution than the CsI(Tl) detector. This is advantageous for nodes located close to the injection site, since the probe is better able to reject scattered photons.

In comparison with the manufacturer's results, the CsI(Tl) probe has the same energy resolution in keV but this corresponds to a lower percentage energy resolution for our measurement, performed with Tc-99m. The CdTe probe has less good energy resolution than the values specified for the manufacturer's test probe.

Side and back shielding

The highest count rates detected through the shielding gave maximum sensitivities of 76 $cs^{-1}MBq^{-1}$ for the CdTe probe and 102 $cs^{-1}MBq^{-1}$ for the CsI(Tl) probe. These values are greater than 0.1% of the sensitivity to a source at 10mm in the air, indicating that the source activity was large enough that 0.1% breakthrough could be detected, as specified in NEMA NU 3. Table 10 gives the shielding effectiveness and a leak sensitivity of each probe, and a comparison with the manufacturer's results for their test system. According to NEMA NU 3, the shielding should ideally allow penetration of less than 0.1% of photons. This is because the sentinel node activity may be 0.1% or less of the injected dose. The leak sensitivity for both probes is higher than 0.1% with slightly better shielding for the CsI(Tl) probe.

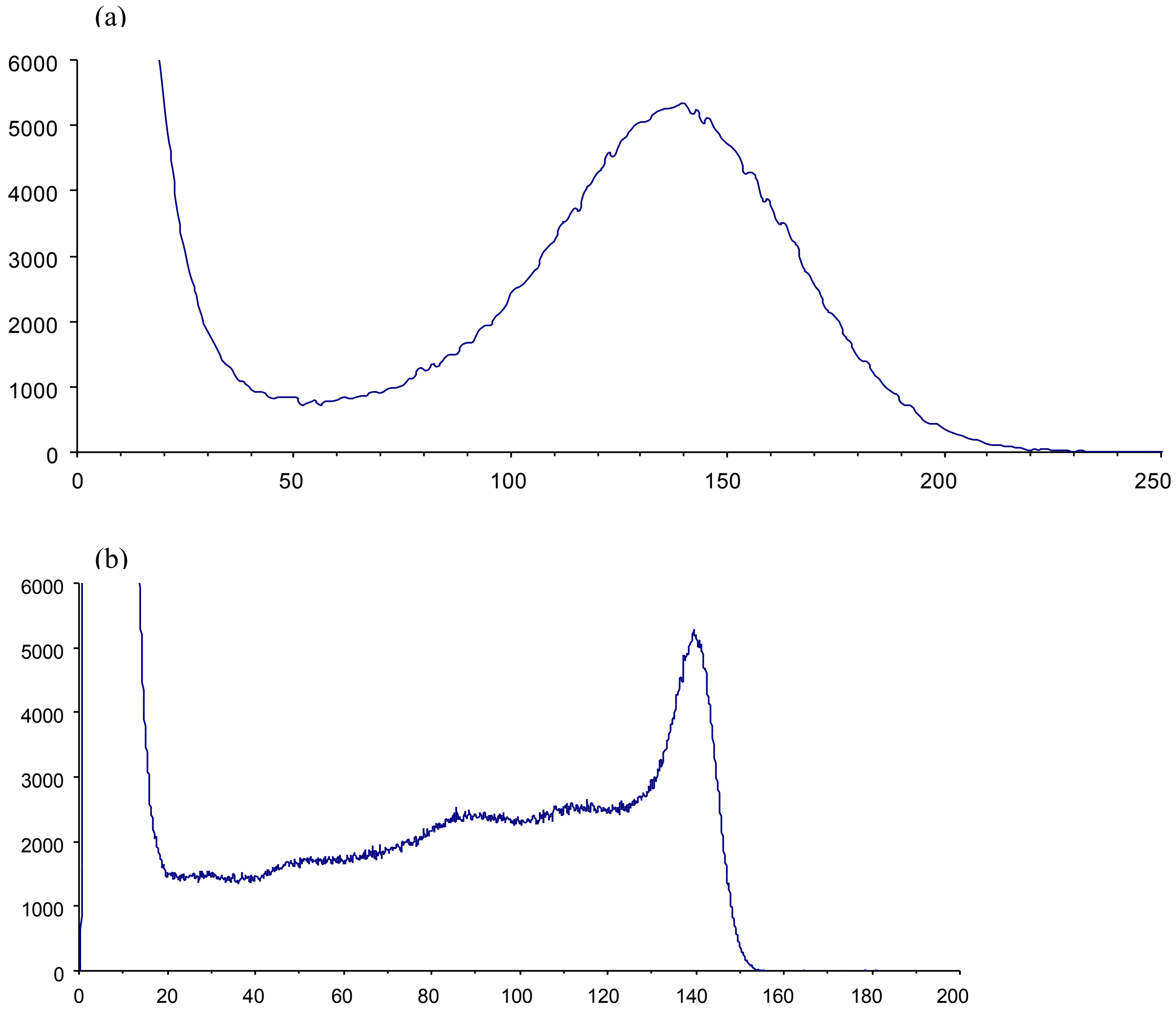


Figure 8 *Energy spectra for Tc-99m. (a) CsI(Tl) probe; (b) CdTe probe*

Discussion

When comparing the CsI(Tl) and CdTe probes, all of the performance parameters need to be considered. There is not one probe with superior performance for all parameters, so the most suitable probe depends on the intended use. The most significant parameters are the sensitivity, spatial resolution, energy resolution, side shielding effectiveness and count rate linearity.

The CsI(Tl) probe has better sensitivity in air and water than the CdTe probe, at all distances between 0-50 mm. This is to be expected due to the larger diameter and thickness of the crystal, as well as the better photon stopping efficiency of CsI(Tl). The ^{99m}Tc window settings also contribute to the difference in sensitivity, as the CdTe probe has a narrower window and better energy resolution resulting in better rejection of scattered photons. The CsI(Tl) probe is therefore more suitable for detecting targets with low activity or at greater depths. This is also emphasised in Figure 3 which shows that the difference in sensitivity between the probes becomes more significant at greater depths.

The spatial resolution of the small diameter CdTe probe is superior to that of the large diameter CsI(Tl) probe without the external collimators. When the collimators are in place, the two probes have similar spatial resolution with slightly better resolution for the CsI(Tl) probe. The CsI(Tl) maintains its superior sensitivity both with and without external collimators. This suggests that when accurate localisation is required for low counts, e.g. for a deep node, it may be advantageous to use the CsI(Tl) probe with the external collimator in place. However, the diameter of the external collimator is 19 mm, requiring a large surgical opening. The smaller size of the CdTe probe also contributes to the better angular resolution than the CsI(Tl) probe. The CdTe probe had significantly better energy resolution than the CsI(Tl) probe. This means that it is better able to reject photons scattered from adjacent "hot" sites. This is advantageous when searching for nodes close to the injection site.

The CsI(Tl) probe has lower sensitivity through side shielding than the CdTe probe, and is therefore, better at excluding photons from adjacent "hot" areas such as the injection sites. However, the CdTe probe was found to be less sensitive to scattered photons than the CsI(Tl) probe. This is to be expected given the superior energy resolution of semi-conductor detectors. The CdTe probe is therefore better at rejecting the photons detected from adjacent hot sites. These two aspects are both important in terms of localising a node close to the injection site. The CsI(Tl) probe is superior in terms of excluding photons from adjacent sites using shielding, and the CdTe probe is better at rejecting scattered photons that reach the detector. The leak sensitivity and shielding effectiveness are similar for both probes based on the detection of photons through the point of maximum sensitivity through the shielding. When considering the ratio of 'on-axis sensitivity' to 'sensitivity to distributed activity', the CdTe probe is better at identifying a "hot" node surrounded by background activity, and so, may be more suitable for nodes located close to the injection site.

The count rate is linear over a wider range of activities for the CdTe probe than for the CsI(Tl) probe, implying that it gives a more accurate representation of the activity of a source at higher activities. According to the BNMS procedure guidelines, if sentinel lymph node imaging is performed on the same day as surgery, the patient will be injected with a maximum of 20 MBq ^{99m}Tc-nanocoll [16]. Assuming that uptake in the sentinel lymph node is 1% of the injected activity [11] then this corresponds to an activity of 0.2 MBq in the sentinel node. According to the graphs in Figure 2, if the node is at a depth of 30 mm, there will not be a noticeable "dead time" effect for either of the probes. If the node is closer to the surface, and hence more photons are reaching the detector, the CsI(Tl) probe will lose more counts than the CdTe probe. However, there is usually a delay of several hours between injection and surgery, so the sentinel node activity will be less than 0.2 MBq.

In general, clinical studies have not stated a preference for scintillation or solid state probes since it is not possible for a probe to have optimum performance for all parameters [17]. Zanzonico *et al.* considered the spatial resolution to be the most important factor when considering sentinel node excision, since the target is small and needs to be accurately localised [17]. They suggest that the counting interval can be increased to compensate for lower sensitivity because the region to be sampled is limited, particularly if gamma camera imaging has been performed prior to surgery. Good energy resolution is also less important than good spatial resolution since nodes tend to be relatively superficial without substantial intervening scatter material.

Mariani *et al.* [18] feel that the most important performance parameter depends on the type of surgery, and consider sensitivity to be the most important parameter for breast sentinel node surgery. This is because it is essential to detect lymph nodes with a low count rate. Spatial resolution is less important if the aim is to remove all of the hot nodes, as is the case in breast SLN surgery. Side shielding or collimation becomes more important in cases where the injection site is close to the lymphatic drainage basin, because radioactivity from the injection site may be detected through the side shielding, or scattered to reach the detector face.

For the Europrobe system, the CsI(Tl) probe has superior sensitivity and side shielding and therefore, may be the optimal probe to use in many cases. However, if the node is close to the injection site, then it might be advisable to use the CsI(Tl) probe with the additional collimation to improve the side shielding and spatial resolution, or to use the CdTe probe to more accurately localise the node.

Conclusion

The intraoperative Europrobe system comprises of both scintillation and semi-conductor probes, which facilitates choice of the most suitable probe for the intended application. Since it is not possible for a probe to have optimum performance for all parameters, a compromise must be reached depending on clinical needs and preferences. The results, based on NEMA performance measurements and optimisation process underscores the importance of characterising gamma probe performance for each individual system. Our results suggest that the performance can vary significantly for different units of the same model. Other authors who have carried out performance measurements for systems other than the Europrobe, have also found considerable differences in performance between probe makes and models and hence their efficacy in accurate detection of SLN during lymph node biopsies of breast cancer patients.

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