A Novel ^{141}Ce-Based Flood Field Phantom: Assessment of Suitability for Daily Uniformity Testing in a Clinical Nuclear Medicine Department

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Daily quality control testing of a γ-camera is of the utmost importance in assessing whether the camera is suitable for clinical use. The aim of our study was to assess the suitability of a fillable ^{141}Ce-based flood field phantom developed in-house for daily quality control testing of γ-cameras. **Methods:** Daily uniformity testing was performed for 113 d using the fillable ^{141}Ce phantom and a commercially available sheet-type ^{57}Co phantom, and the results were compared. **Results:** The average integral uniformity obtained by the ^{141}Ce and ^{57}Co phantoms was 3.24% and 2.72%, respectively, for detector 1 and 3.31% and 2.78%, respectively, for detector 2. **Conclusion:** The ^{141}Ce phantom we developed is a suitable alternative to the commercially available ^{57}Co phantom.

Key Words: ^{141}Ce flood field uniformity; ^{57}Co flood field uniformity; flood field phantom; gamma camera; surrogate radionuclide

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The γ-camera, one of the oldest and most widely used imaging devices in nuclear medicine, is a sensitive piece of equipment that can be affected by such factors as power fluctuations and changes in temperature or humidity. Routine quality control testing is critical for any type of nuclear medicine imaging device to ensure the quality of the clinical images it provides. In γ-cameras, such testing evaluates performance regarding uniformity, spatial resolution, spatial linearity, energy resolution, and peaking. Uniformity, or flood, quality control tests check the response of the detectors to uniform irradiation. The detectors pass the test if the obtained uniformity is within the defined reference limits (*1–3*).

Many possible problems with γ-cameras can lead to degradation of uniformity. Hence, uniformity testing is performed daily before the cameras can be used on patients. The method of testing can be either intrinsic or extrinsic. The intrinsic method, which requires that a ^{99m}Tc point source be prepared and the collimator removed every morning, is a tedious, time-consuming, and technically demanding process. In addition, this method does not evaluate the quality of a collimator. Hence, for daily testing in a nuclear medicine department, the extrinsic method is usually chosen. This method requires one of two types of flood field phantom: the fillable type or the sheet type. Fillable phantoms generally need to be refilled with ^{99m}Tc each day that the testing is performed. Sheet phantoms generally are ^{57}Co phantoms, which do not require refilling and can be used for up to 2 y (*4–6*). However, because the cost of ^{57}Co sheet phantoms is quite high, their use in small nuclear medicine departments of developing countries is limited, and many such departments are compelled to use ^{99m}Tc fillable phantoms. As an alternative to the ^{57}Co sheet phantom and the ^{99m}Tc fillable phantom, a new type of phantom—fillable with ^{141}Ce—has been developed in-house by the Isotope Production and Applications Division of the Bhabha Atomic Research Centre. This phantom requires refilling only every 50–60 d because of the long half-life of ^{141}Ce. ^{141}Ce emits monochromatic γ-photons with an energy of 145.4 keV, which is close to the 140-keV γ-energy of ^{99m}Tc, the radioisotope most commonly used for γ-camera imaging (*7,8*).

MATERIALS AND METHODS

This study took place over a 113-d span during which uniformity tests were performed every morning using both a commercially available ^{57}Co sheet phantom and the ^{141}Ce fillable phantom. The data were stored and analyzed.

Characteristics of Uniformity Phantoms

A uniformity phantom is a rectangular box or sheet that extrinsically irradiates the detectors of a γ-camera with a uniform flux of γ-rays across the field of view. The characteristics of the two radioisotopes (^{57}Co and ^{141}Ce) used in the uniformity phantoms of this study are listed in Table 1.

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TABLE 1
Parameters for the ^{57}Co and ^{141}Ce Phantoms

Parameter	^{141}Ce phantom	^{57}Co phantom
Isotope		
Atomic number	58	27
Half-life (d)	32.5	271.7
γ-energy (keV)	145.4	122
Scanning		
Collimator	LEHR	LEHR
Energy peak (keV)	145	122
Energy window (%)	10	10
Matrix	256 × 256	256 × 256
Kilocounts	4,000	4,000
Processing		
Workstation	Infinia Hawkeye 2	Xeleris 1.123
Field of view (mm)	550 × 350	550 × 350
Matrix	256 × 256	256 × 256

LEHR = low-energy, high-resolution.

Production of ^{141}Ce

^{141}Ce was produced by neutron irradiation of natural $Ce(SO_4)_2·4H_2O$ targets in the Dhruva nuclear reactor of Bhabha Atomic Research Centre at various neutron fluxes (ranging from 0.5×10^{13} to 0.5×10^{14} n/cm^2/s) for 1–4 mo. A ^{141}Ce solution was extracted from the irradiated targets by radiochemical processing and allowed to decay for a duration sufficient to eliminate the presence of relatively shorter-lived radionuclide impurities such as ^{137}Ce, ^{139}Ce, and ^{143}Ce (*9,10*).

Preparation of ^{141}Ce Phantom

The phantom, a fillable box made of 6-mm-thick acrylic glass, was designed and produced in-house (*7,8*). Its inner dimensions were 13.2 mm in depth, 655 mm in length, and 460 mm in width to cover the field of view of most commercially available γ-cameras (Fig. 1).

A trained radiation professional with more than 10 y of experience in preparing phantoms and handling open radioactive materials was tasked with filling the phantom. A double-layer plastic sheet with thick layers of absorbent sheeting was kept beneath the phantom. The filling aperture was surrounded by thick paper to absorb any radioactive solution that might spill.

First, the phantom was filled with distilled water. Then, 740 MBq of ^{141}Ce was added, the phantom was agitated to uniformly dissolve the isotope, and any air bubbles were removed. After preparation of the phantom was complete, the personnel, workplace, and all materials (e.g., gloves, absorbent paper, and plastic sheeting) were surveyed using a Ram Gene-1 radiation meter (Rotem Industries). Any material found to be contaminated was stored as radioactive waste for a duration sufficient for decay. The prepared phantom was not agitated again before being used for testing each morning, as it was assumed that the solution would remain uniform.

Uniformity Testing

The most commonly evaluated performance characteristic in the daily quality control testing of γ-cameras is uniformity. In intrinsic testing, the collimator is removed and a point source of ^{99m}Tc is centered over the detector at a distance 5 times the largest dimension of the crystal, providing a near-uniform photon flux impinging on the detector. In extrinsic testing, a fillable phantom source of ^{99m}Tc or ^{141}Ce, or a sheet source of ^{57}Co, is placed directly on the collimated detector. Four million counts are acquired, and the integral and differential uniformities of the flood image are quantitated to obtain the deviation from acceptable uniformity. Integral uniformity is calculated using the following equation (*5*):

$$\text{Integral uniformity} = \frac{(C_{\max} - C_{\min})}{(C_{\max} + C_{\min})} \times 100\%,$$

where $C_{\max}$ is the maximum count—and $C_{\min}$ the minimum count—in a pixel in the useful field of view.

Differential uniformity can be calculated for every 5-pixel segment in every row and column of the flood image using the following equation (*5*):

$$\text{Differential uniformity} = \frac{(C_{\max} - C_{\min})}{(C_{\max} + C_{\min})} \times 100\%,$$

where $C_{\max}$ is the maximum count in a pixel within 5 consecutive pixels in a row or column, and $C_{\min}$ is the minimum count in a pixel within the same 5 consecutive pixels in a row or column.

Uniformity testing of an Infinia Hawkeye 2 SPECT/CT scanner (GE Healthcare) was performed every morning before it was used on patients. Each day, testing was performed first using the ^{141}Ce fillable phantom and then using the ^{57}Co sheet phantom. The scanning parameters are summarized in Table 1. Uniformity and linearity corrections were applied for the ^{57}Co and ^{141}Ce acquisitions using ^{57}Co and ^{99m}Tc uniformity and linearity maps, respectively. Data from the ^{57}Co phantom were processed automatically by the software in the scanner, and data from the ^{141}Ce phantom

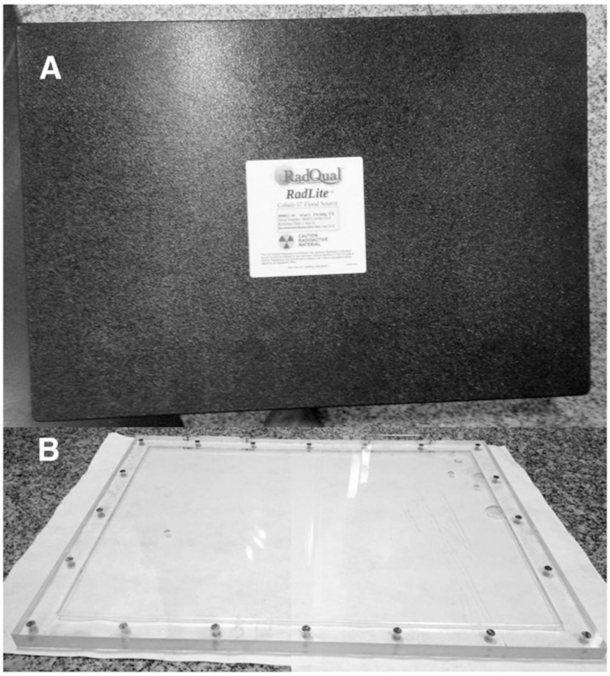

FIGURE 1. (A) Commercially available ^{57}Co sheet phantom (RadLite; RadQual, LLC). (B) ^{141}Ce fillable phantom developed in-house by Bhabha Atomic Research Centre.

TABLE 2
Average Integral Uniformity and Scanning Time for ^{57}Co and ^{141}Ce Phantoms

	Detector 1				Detector 2			
	^{57}Co phantom		^{141}Ce phantom		^{57}Co phantom		^{141}Ce phantom	
Index	Integral uniformity	Scanning time	Integral uniformity	Scanning time	Integral uniformity	Scanning time	Integral uniformity	Scanning time
Average	2.73 ± 0.34	208.6	3.24 ± 0.68	836.2	2.78 ± 0.30	208.6	3.32 ± 0.74	836.2
Minimum	2.12	187	1.90	224	2.03	187	1.87	224
Maximum	3.50	245	5.26	1,810	3.60	245	5.26	1,810

Uniformity data are percentages; scanning times are seconds.

were processed using uniformity software in the workstation (Xeleris 1.123; GE Healthcare). Table 1 summarizes the parameters applied to calculate integral uniformity for both phantoms, with the integral uniformity of the ^{57}Co phantom being considered the gold standard against which the ^{141}Ce phantom was to be compared. We divided our 113-day study period into halves (i.e., the first 41 tests and the last 48 tests; the remaining 24 d fell on weekends or holidays). We compared the average integral uniformity of the ^{141}Ce phantom with that of the ^{57}Co phantom for the entire study, the first half of the study, and the second half of the study.

Radiation Safety Testing

For both phantoms, a Ram Gene-1 radiation meter was used to determine the radiation exposure of any staff performing the testing. The initial radiation field was measured on all sides of the phantom, both at the surface and at a distance of 1 m, and the maximum and minimum radiation exposure was recorded. The radiation exposure of the professional who filled the phantom was measured using a pocket dosimeter (Aloka Medical, Ltd.).

Statistical Analysis

Two-tailed Mann–Whitney *U* testing was performed to determine the significance of differences in integral uniformity between the two phantoms at significance levels of 0.1 and 0.5 for the entire study, the first half of the study, and the second half of the study.

RESULTS

The phantoms underwent a background quality control test every morning before the uniformity test and always passed. For both phantoms, integral uniformity was within permissible limits (5%, as prescribed by the manufacturer of the ^{57}Co phantom) throughout the study. The average integral uniformity for the ^{141}Ce and ^{57}Co phantoms was 3.24% and 2.73%, respectively, for detector 1 and 3.32% and 2.78%, respectively, for detector 2 (Table 2), and the average scanning time for the entire study was 836.2 s and 208.6 s, respectively (Table 2). For both detector 1 and detector 2, the average integral uniformity for the ^{141}Ce phantom was comparable to that for the ^{57}Co phantom during the first half of the study (Table 3). The average integral uniformity for the ^{141}Ce and ^{57}Co phantoms during the first half of the study was 2.91% and 2.77%, respectively, for detector 1 and 2.88% and 2.81%, respectively, for detector 2. During the second half, the respective percentages were 3.61% and 2.65% for detector 1 and 3.79% and 2.75% for detector 2. The correlation of integral uniformity between the two phantoms was greater in the first half of the study than in the second half (Fig. 2). Table 4 shows the results of Mann–Whitney *U* tests; integral uniformity significantly differed between the ^{57}Co and ^{141}Ce phantoms during the entire study and during the second half of the study ($P < 0.00001$ [both detectors]) but not during the first half of the study ($P = 0.18024$ [detector 1] and 0.6818 [detector 2]).

Radiation exposure was also comparable between the two phantoms. With shielding, the average maximum radiation exposure at the surface and 1 m away was 0.2 and 0 μSv/h, respectively, for the ^{141}Ce phantom (containing 669.6 MBq at the beginning) and 2.0 and 0.2 μSv/h,

TABLE 3
Average Integral Uniformity and Scanning Time for ^{57}Co and ^{141}Ce Phantoms by Study Interval

	Detector 1				Detector 2			
	^{57}Co phantom		^{141}Ce phantom		^{57}Co phantom		^{141}Ce phantom	
Study interval	Integral uniformity	Scanning time	Integral uniformity	Scanning time	Integral uniformity	Scanning time	Integral uniformity	Scanning time
First half	2.77 ± 0.34	200.3	2.91 ± 0.54	440.89	2.81 ± 0.31	200.3	2.88 ± 0.55	440.89
Second half	2.65 ± 0.32	218.05	3.61 ± 0.65	1,313.4	2.75 ± 0.33	218.05	3.79 ± 0.67	1,313.4

Uniformity data are percentages; scanning times are seconds.

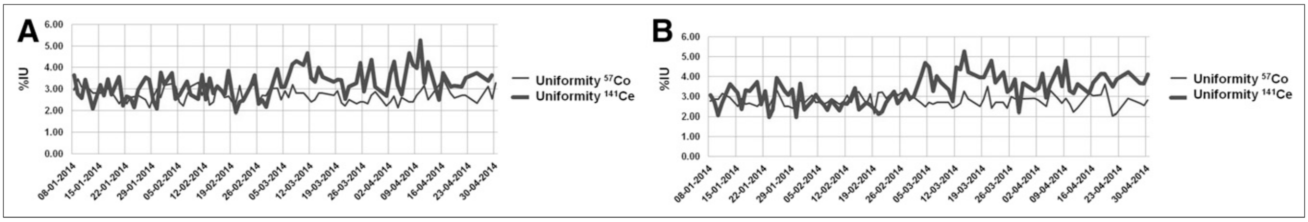

FIGURE 2. Graphs of uniformity obtained for ^{57}Co and ^{141}Ce phantoms with detectors 1 (A) and 2 (B).

respectively, for the ^{57}Co phantom (containing 285.4 MBq at the beginning). Without shielding, the respective values were 131 and 5 μSv/h for the ^{141}Ce phantom and 150 and 10.7 μSv/h for the ^{57}Co phantom. The radiation exposure of the professional who filled the phantom averaged 8.6 μSv.

DISCUSSION

Various authors (*1–6*) have suggested different protocols for testing the integral uniformity of a γ-camera, but these can be performed for only a single detector at a time. The test needs to be repeated after the second detector has been rotated in front of the flood. Hence, the testing is cumbersome and time-consuming and requires technical expertise. Extrinsic uniformity testing is performed without removing the collimator and ensures accurate performance of not only the system but also the collimator. Therefore, most nuclear medicine centers use this method for daily uniformity testing of modern γ-cameras. Our in-house–developed ^{141}Ce fillable phantom is an alternative to the ^{99m}Tc fillable phantom obviating daily filling with the radioisotope. The ^{141}Ce fillable phantom also eliminates dependency on imported ^{57}Co sheet phantoms. ^{99m}Tc is the workhorse isotope for diagnostic procedures on γ-cameras, and a ^{99m}Tc fillable phantom is the most suitable for quality control testing of γ-cameras. However, refilling such phantoms is cumbersome and tedious and can risk exposing the staff to an extra radiation burden. Our ^{141}Ce phantom requires refilling only once every 50 d, and in our study the professional who refilled it was exposed to an average of only 8.6 μSv. ^{141}Ce is a soft β-emitter, and the β-emission is attenuated by the acrylic glass of the phantom. ^{57}Co is widely used in phantoms because it has a photopeak (122 keV) close to that of ^{99m}Tc (140 keV), has a long half-life (271 d), and is available in the form of ready-to-use sheets. The photopeak of ^{141}Ce (145 keV) is even closer to that of ^{99m}Tc; hence, ^{141}Ce may be a suitable replacement for ^{57}Co (*6,11*).

In our study, a ^{57}Co sheet source with no more than 1% nonuniformity was considered the standard against which the ^{141}Ce filled phantom was to be compared. The comparative uniformity results between the two phantoms were consistent for the first half of the study (i.e., integral uniformity of 2.77% and 2.81% for detectors 1 and 2, respectively, for the ^{57}Co phantom and 2.91% and 2.88% for detectors 1 and 2, respectively, for the ^{141}Ce phantom). In the second half of the study, there were relatively more variations and significant differences in average integral uniformity for both phantoms. Mann–Whitney *U* tests also showed a significant difference in integral uniformity for both phantoms for the entire study and the second half of the study, whereas for the first half of the study there was no significant difference in integral uniformity. The difference in integral uniformity in the second half of the study can be attributed to the poor counting rate and gradual progression of nonuniformity in the distribution of the ^{141}Ce source. The average scanning time required for the ^{141}Ce phantom to complete the test was around 7 min in the first half of the study, or twice the average time required for the ^{57}Co phantom (3.5 min). In addition, the average scanning time required for the ^{141}Ce phantom to complete the test in the second half of the study was much higher (~21 min) than that required for the ^{57}Co phantom (3.5 min). The average radiation exposure at the surface of the ^{141}Ce phantom and 1 m away was also comparable to that of the ^{57}Co phantom.

Despite the encouraging results of our study, the suppliers of the ^{141}Ce isotope need to ensure its production and regular delivery to the nuclear medicine department. Production of ^{141}Ce in a reactor is a cumbersome, technically demanding process requiring much effort, expertise,

TABLE 4
Mann–Whitney *U* Test Results

	Detector 1				Detector 2			
	Significance level, 0.1		Significance level, 0.5		Significance level, 0.1		Significance level, 0.5	
Study interval	*z*	*P*	*z*	*P*	*z*	*P*	*z*	*P*
Entire study	−5.5624	<0.00001	−5.5624	<0.00001	−5.19875	<0.00001	−5.19875	<0.00001
First half	−1.34009	0.18024	−1.34009	0.18024	0.40806	0.6818	0.40806	0.6818
Second half	6.09634	<0.00001	6.09634	<0.00001	−7.28366	<0.00001	−7.28366	<0.00001

and professional commitment. However, the scientists at the Bhabha Atomic Research Centre have mastered the technique for easily producing this isotope on a regular basis, thus ensuring a regular supply to the clinical nuclear medicine department.

Although the supply of the ^{141}Ce isotope is not yet commercialized, the cost to produce it in our country (India) is not high (U.S. \$30–\$40/GBq), nor is the cost to supply it to the nuclear medicine department (U.S. \$50–\$60/GBq). Because the phantom will require refilling every 50 d, the total cost of a 2-y supply of the isotope will be approximately U.S. \$750, as compared with U.S. \$5,500 for one commercially available ^{57}Co phantom, which will also need replacement every 2 y. Extra radiation safety precautions need to be taken to avoid any major spillage of the ^{141}Ce isotope during phantom preparation. We follow and recommend stringent precautions and use the utmost care during handling of this isotope. The low cost and ease of handling of the ^{141}Ce phantom will facilitate its use for daily uniformity testing in the nuclear medicine department.

CONCLUSION

Our in-house–developed ^{141}Ce fillable phantom provided a reasonable result that was consistent with that of a standard ^{57}Co sheet phantom. The ^{141}Ce phantom may need to be refilled only once every 50 d, greatly reducing physical effort, time, and radiation exposure. Considering the easy availability and low cost of this ^{141}Ce fillable phantom, it may be considered a suitable alternative to ^{57}Co sheet phantoms and ^{99m}Tc fillable phantoms.

DISCLOSURE

No potential conflict of interest relevant to this article was reported.

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