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Historical Review of Lung Counting Efficiencies for Low Energy Photon Emitters

K. L. Jeffers, D. P. Hickman

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Abstract -This publication reviews the measured efficiency of a high purity planar germanium lung counting system and the variability observed in a historical set of calibrations. It compares the efficiency variation for multiple photon energies using efficiency measurements from multiple overlay thicknesses of a realistic torso phantom. The variations in efficiencies are compared with the current requirement for in vivo bioassay performance as defined by the American National Standards Institute.

Key words: detector, germanium; calibration; spectrometry, gamma; plutonium; whole body counting; bioassay

INTRODUCTION

Calibration of in vivo lung counting systems for low energy photon emitters is a multidimensional process that requires measurement of the efficiency as a function of photon energy and measurement of the efficiency as a function of attenuating tissue thickness between the radionuclide material in the lung and the detectors (Hickman 1988). The physics and statistical properties of the efficiency measurement process dictate that as the energy of the photon decreases, there is a corresponding increase in the uncertainty of the efficiency. The overlying tissue thickness and effective lung thickness do not affect the error associated with a person's calibration factor (Falk76). However, when evaluating the total propagated uncertainty for any particular measurement, the uncertainties associated with the measured efficiency need to be incorporated.

Lawrence Livermore National Laboratory (LLNL) has performed in vivo monitoring of radiation workers since the mid-1960s. In 1993, a high resolution low energy germanium lung measurement system was installed, replacing a phoswich style routine monitoring lung monitoring system. In 1998, an upgraded high resolution detector system was installed and has been used to monitor workers since. Lung calibrations for the new high resolution systems were performed annually when they were first installed; however as operational confidence increased and the new lung measurement system demonstrated stability, the calibration frequency requirement was relaxed. Eleven sets of calibrations were performed for the newer system from 1998 to the present.

METHODS AND RESULTS

Calibration of the LLNL germanium lung counting system has and continues to be performed using the LLNL Realistic Torso Phantom and a NIST traceable Am-241/Eu-152 (35.3 and 19.9 kBq respectively as of 30 April 1993) source distributed in the realistic lung material as described by Griffith et al. (Griffith et al. 1984). In August 2000 a new NIST traceable Am-241/Eu-152 lung set (78.9 and 18.6 kBq respectively as of 12 July 2000) was purchased and has been used for calibration since. Calibrations are performed for various muscle equivalent chest wall thicknesses using muscle equivalent (MEQ) overlay plates designed for use with the LLNL torso phantom. For each chest wall thickness (CWT), the efficiency is measured at several photon energies ranging from 17 to 245 keV. Since December of 2008, thicker overlays have been used to provide additional calibrations beyond 4 cm and up to 6.5 cm of MEQ overlay tissue. Efficiencies for energies above 245 keV also were not tallied until December 2008.

Efficiencies for these higher energy photons and thicker chest walls are not presented since there are a low number of efficiency measurements for CWTs greater than 4 cm and energies above 245 keV.

The phantom and detector orientation is positioned at the same angle and orientation as is used for the measurement of radiation workers. Detectors are positioned in direct contact with the torso or overlay material and the detector rotation is maintained constant for each overlay efficiency measurement. Using this calibration protocol LLNL has accumulated over 400 measurements of efficiency since 1998.

Efficiency results (counts per photon) are tallied by MEQ CWT and photon energy for the lung counting system. Efficiencies are evaluated for 17, 21, 26, 39.9, 45.4, 59.5, 98.4, 121.8, 244.7, and 295.9 keV photon groups. Efficiencies within each energy group are tallied for CWTs at 1.56, 2.1, 2.55, 2.68, 3.26, 3.28, and 4.00 cm. Count errors for the measured efficiencies are typically below 5% for all photon energies and CWTs. For CWTs with three or more efficiency measurements within a given photon energy the average efficiency and observed standard deviation is presented in Table 1.

Table 1. Average measured efficiency (x 10^{-4}) and observed standard deviation (in counts per photon) as a function of photon energy and chest wall thickness for the newer LLNL Lung counting system.

	Chest wall thickness (cm)						
Photon energy (keV)	1.56	2.1	2.55	2.68	3.26	3.28	4.0
17	11.3 ± 3.34	6.00 ± 1.4	5.31 ± 1.21	2.75 ± 0.91	1.92 ± 0.22	1.12 ± 0.53	0.32 ± 0.18
21	30.6 ± 10.8	18.3 ± 7.3	19.1 ± 6.86	11.3 ± 3.16	8.79 ± 3.16	6.13 ± 1.89	3.80 ± 1.17
26	96.6 ± 4.66	76.2 ± 1.36	58.4 ± 1.98	51.0 ± 22.3	29.0 ± 10.6	25.6 ± 3.77	15.8 ± 3.26
40	173 ± 4.24	145 ± 2.83	122 ± 7.78	117 ± 0.71	87.0 ± 6.93	64.6 ± 0.14	62.3 ± 2.69
60	189 ± 10.0	153 ± 9.36	137 ± 0.71	122 ± 8.28	[a]	97.2 ± 5.97	76.2 ± 3.73
122	213 ± 11.1	178 ± 10.5	160 ± 1.41	148 ± 7.80	[a]	121 ± 7.10	98.0 ± 4.68
245	137 ± 6.02	116 ± 6.01	105 ± 0.71	99.1 ± 4.09	84.1 ± 0.78	82.8 ± 4.03	69.2± 2.73

[a] Insufficient number of data points

A deviation score ($\mathbf{\Delta}$) for all of the efficiency measurements performed within a particular photon energy is computed using: $(x - \bar{x})$.

where:

x = the measured efficiency for a given calibration energy and CWT

$\bar{x}$ = the average efficiency for a given energy and CWT

The deviation score shows how each efficiency value differs from the average efficiency. The deviation score is sometimes called the error (of the measurement). The percent error for each measurement was then computed by dividing the deviation score by the average efficiency and

multiplied by 100. A summary of the measured efficiency errors for each calibration energy group (in percent) is provided in Fig. 1.

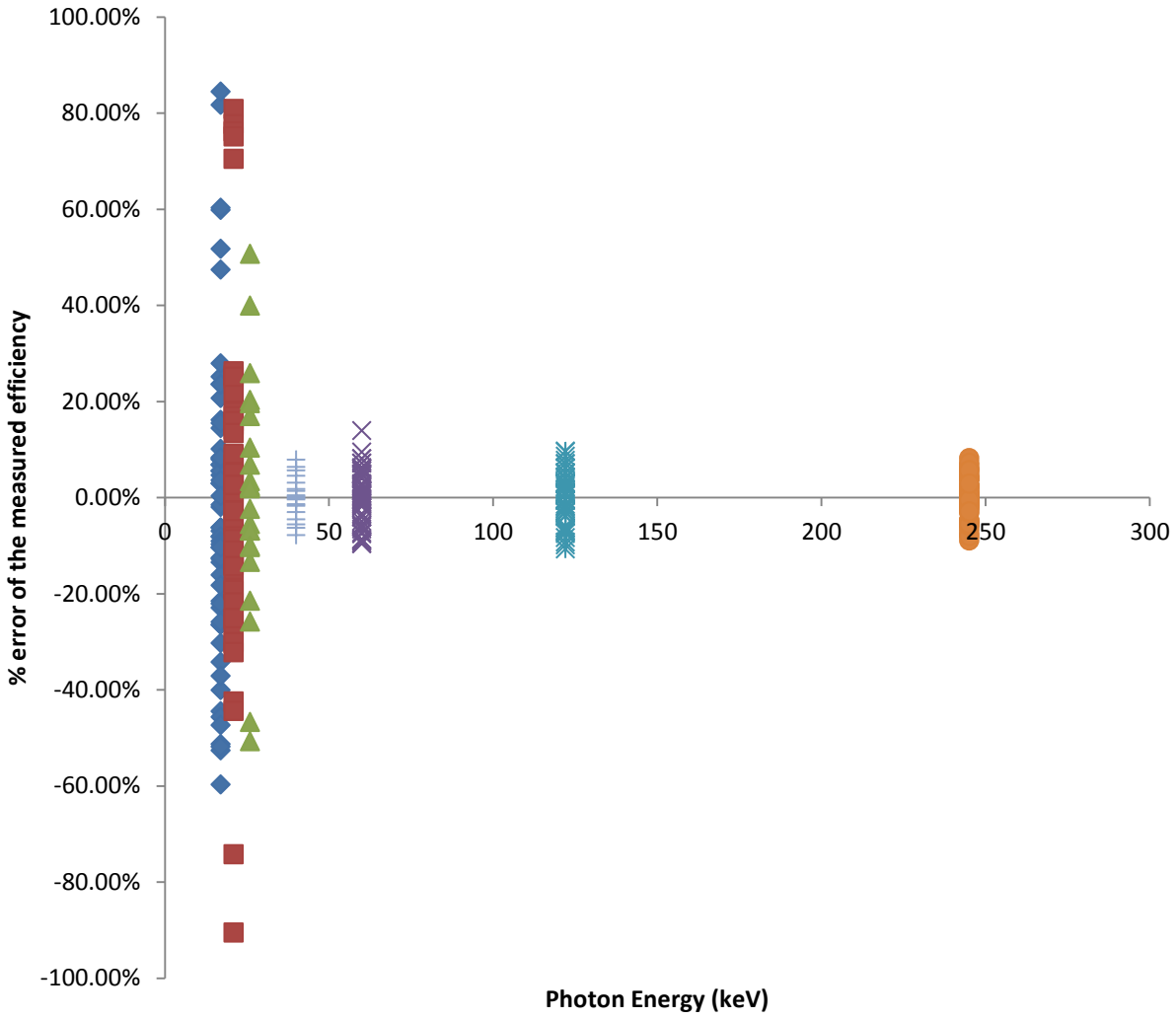

Fig. 1. The range of percent errors in the measured efficiency for the LLNL Lung counting system as a function of photon energy.

DISCUSSION

Factor of two errors in the lung measurement efficiency for plutonium (17 keV photons) will occur with every 0.6 cm of overlying tissue equivalent material unless corrections for the changes in efficiency are made (Ramsden69). Even if the count errors are controlled to an acceptable level (e.g., 5%), there are other systematic errors that broaden the error structure of the efficiency calibration for low energy photon measurements. These systematic errors appear to significantly decrease above approximately 40 KeV beyond which the calibration errors are in the range of 10 to 15%. Additional study is required for determining the source of the error expansion below 40 keV.

The latest American National Standard for the performance of radiobioassay (ANSI 13.30-2011 Performance Criteria for Radiobioassay) specifies that the combined effect of relative bias and relative precision as measured using the root mean square be less than 25% when making performance measurements (for lung) on a realistic phantom such as the LLNL Torso phantom. The results of the many years of data collected at the LLNL whole body counting facility presented in this publication indicate that the requirements of the new ANSI standard may be too restrictive for lower energy photons (i.e., below approximately 40 keV) when the total error of the calibration process is considered. Errors as high as 100% are more consistent with repeated efficiency measurements for photons below 40 keV and the ANSI standard error limitation of 25% could be overly restrictive.

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