MEASUREMENT OF THE ATTENUATION COEFFICIENT FOR LIVERMORE THORACIC PHANTOM LUNGS FABRICATED USING CONTEMPORARY MATERIALS

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Abstract—The University of Cincinnati has reproduced the original formulation for the Livermore Thoracic Phantom lungs using contemporary materials and has adopted the linear attenuation coefficient as the primary quality assurance parameter for evaluating the performance capabilities of these new lung phantoms. The Livermore Thoracic Phantom was originally fabricated in 1978 to intercalibrate detector systems used to measure plutonium and other low-energy, photon emitting radionuclides deposited in the respiratory tract. The linear attenuation coefficient is a critical performance indicator for these phantom lungs since the presence of any material with a high effective atomic number (where $Z \geq 20$) will make a significant change in the photoelectric cross section, the predominant mode of interaction for plutonium x rays. A set of test lungs was fabricated with KCl to introduce a known quantity of ^{40}K in the phantom and to determine, by measurement and calculations, what change would be made to the attenuation coefficient at photon energies below 100 keV as a result of the modified formulation. The KCl increased the linear attenuation coefficient below 60 keV by more than a factor of two, which would produce a substantial systematic error in any subsequent calibration measurements performed with these modified phantom lungs. These results support use of the attenuation coefficient as an important performance indicator for the Livermore Thoracic Phantom lungs and also suggest that KCl not be added to the lung tissue substitute formulation as a means to incorporate ^{40}K in the phantom for low energy calibrations.
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INTRODUCTION

THE LIVERMORE Thoracic Phantom provides a somewhat realistic consensus calibration standard for mea-

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suring plutonium and other low energy photon-emitting radionuclides deposited in the respiratory tract (Dean 1976; Griffith 1978). The need for such a phantom was originally based upon the desire to more accurately evaluate the results of *in vivo* measurements for plutonium deposited in the lungs of workers. Routine *in vivo* measurements are an integral part of a comprehensive, internal radiation dosimetry monitoring program at DOE facilities where transuranic radioactive materials are processed.

In vivo measurement of plutonium in the lungs has always been a technical challenge, even with the high resolution germanium detector systems available today (Toohey 1991). These measurements typically involve placing an array of detectors on the anterior thorax of a person and detecting low energy x rays and photons which penetrate the thoracic tissue. Accurate calibrations are particularly difficult to perform because low energy photons are easily attenuated by muscle, bone, and other adipose tissue (Swinth 1973, 1979). The Livermore Thoracic Phantom was developed to address some of these physical concerns while providing a device which is anatomically suitable for calibrating *in vivo* measurement systems. The selection of tissue substitute materials for use in the phantom involved developing chemical formulations for substitute organs and tissues that would exhibit the same attenuation coefficients at low energies as the original tissue.

Special emphasis in the design of the Livermore Thoracic Phantom was directed towards selection of a tissue substitute material for the lungs. In particular, these mock lungs had to have a density of 0.26 gm cm^{-3} and exhibit a linear attenuation coefficient similar to human lungs below 20 keV, the predominant emission from plutonium. Attenuation at this energy is almost entirely produced by photoelectric interactions. Newton and White (1978) calculated the Compton and photoelectric attenuation coefficients for 26 types of lung tissue substitute materials and found a considerable range of values for photon energies of 13.6 keV, 17.2 keV, and 20.2 keV. Weber and van den Berge (1969) described the importance of coherent Rayleigh scattering as well as Compton scattering for phantom materials.

Griffith (1978) adopted a formulation for Livermore Thoracic Phantom lungs which consisted of a foamed polyurethane and $CaCO_3$. This formulation is identified as Griffith Lung in ICRU Report No. 44 (1989). The desired density and attenuation coefficient of the phantom lungs is achieved by carefully adjusting the quantity of polyurethane and $CaCO_3$ in the formulation. Mock lungs for plutonium calibrations should have a density range between 0.26 gm cm^{-3} and 0.30 gm cm^{-3} and a linear attenuation coefficient of 0.28 cm^{-1} at approximately 16 keV (ICRU 1989).

An extensive series of interlaboratory comparisons was conducted in the United States and Europe to verify the performance of the original Livermore Thoracic Phantom. Each participating laboratory measured the phantom and compared its results to *in vivo* measurements of human volunteer subjects who inhaled short-lived radioactive materials which emit low energy photons or x rays similar in energy to plutonium. Results of these intercomparison measurements confirmed the validity of the Livermore Thoracic Phantom for low energy photons (Griffith 1978; Newton 1978a, 1978b; Newton 1984; Toohey 1991). Newton claimed that use of the Livermore Thoracic Phantom would produce calibration factors correct to within 20% or better (Newton 1984).

There have been a few modifications made to the original Livermore Thoracic Phantom since it was first produced in 1978. The contemporary commercial version of the Livermore Thoracic Phantom has a physical appearance similar to the original version, but some of the original tissue substitute materials have been modified or replaced as the formulations supplied by manufacturers have been eliminated or changed. This is especially true for the foaming polyurethane used to produce the lungs. Changes in formulation were made to increase the working time of the material. (The original formulation of the two-part polyurethane foam produced a very rapid reaction after the components were mixed, typically allowing only 10 s to fill and seal the lung mold!) Another change in formulation was required when the original manufacturer of polyisocyanate, the basic raw material in the polyurethane, discontinued making the component formulation specified in the original Livermore procedure. Other, apparently benign physical changes in the phantom have been incorporated into the design, such as adding a neck and pelvic segment, which extends application of the phantom to more than just thoracic measurements.

Although several changes in design and materials for the phantom have been incorporated since its inception in 1978, no tests have been made to document that the technical performance of the contemporary calibration phantom meets the original design criteria for plutonium. Since it is unlikely that the original international phantom validation will be repeated in the near future, and recognizing that substantial changes have been made in the lung phantom formulations, concern was raised about the contemporary version of the Livermore Thoracic Phantom, and whether it can achieve the same stringent performance criteria for low energy photons as established for the original phantom.

An informal, qualitative intercomparison was performed using one of the three original Livermore Thoracic Phantoms and a contemporary version of the thoracic phantom. The discrepancy in performance was thought to be associated with a change in the lung formulation materials. Resolution of this question led to a thorough investigation into the original formulations used to manufacture lungs for the Livermore Thoracic Phantom with the aim of reproducing the formulation using contemporary materials (Glover 1992).

Recently, as part of the U.S. Department of Energy Laboratory Accreditation Program, KCl was added to the lung formulation so that ^{40}K could be introduced as an interfering radionuclide similar to that encountered when a human subject is measured *in vivo*. Approximately 89.6 g of KCl (2.8 KBq) was required in the right lung and 70.4 g (2.2 KBq) in the left lung (MacLellan 1988). Rather than making a permanent change in formulation for the Livermore Thoracic Phantom lungs, it was suggested that an alternative phantom be constructed especially for accreditation testing. This phantom would include KCl in the phantom shell thus avoiding the need to modify the original design criteria for the lungs (Kramer 1990). Distributing KCl throughout the phantom shell, rather than concentrating all the material in the lungs, should produce a smaller, albeit non-negligible, impact when performing calibrations for low energy photons. Any change in the original formulations for the Livermore Thoracic Phantom organs would likely introduce a change in their performance, especially when using radioactive standards which emit low energy photons. This is certainly true for the lungs which exhibit a very large change in attenuation coefficient whenever the formulation is modified even slightly.

OBJECTIVE

This paper will discuss the importance of the attenuation coefficient as a performance indicator for the phantom lungs and describe a destructive method for testing the attenuation coefficient of lungs fabricated at the University of Cincinnati (UC). The UC lungs use the original procedures developed by Livermore but substitute contemporary materials having chemical formulations comparable to the original components. The UC lungs are fully compatible with the original chemical formulations for the Livermore Thoracic Phantom lungs and exhibit radiological characteristics which are fully consistent with the original Livermore specifications. Even the formulation for the original epoxy sealant has been reproduced. The only change which was incorporated into the UC procedure follows that adopted by Livermore when they found that it was unnecessary to use acetone with a lan-

thanide nitrate carrier to distribute the radioactive standard solution in the original sets of lungs. It will be shown what change is made to the attenuation coefficient when KCl is added to the formulation.

METHODS

The chemical formulation equivalent to the Livermore lung tissue substitute adopted by the University of Cincinnati (UC) was developed from the elemental composition of hydrogen, carbon, nitrogen, oxygen, magnesium, calcium, and tin listed for Griffith Lung in ICRU Publication No. 44 (1989). Raw materials, including polyurethane, calcium carbonate ($CaCO_3$), and catalyst, were selected for the UC formulation to produce a final reacted polyurethane having an elemental composition consistent with the Griffith Lung (Glover 1992). Table 1 lists the elemental composition of the constituents of the UC lung tissue substitute. An extensive review of historical references, laboratory notebooks at Livermore National Laboratory, and discussions with suppliers of organic chemicals led to the identification of manufacturers willing to produce a series of contemporary products which duplicate the original specifications for the Livermore lungs and the epoxy sealant applied to the exterior surface of the lungs (Glover 1992).

The mass attenuation coefficients for the lung formulations adopted by the University of Cincinnati were calculated using XCOM, a personal computer program for calculating photon cross-sections based upon the elemental composition of the materials used in the tissue substitute (Berger and Hubbell 1987). The uncertainty in the mass attenuation coefficient calculated by XCOM for low-Z elements at low photon energies may range from 5% to 10% (ICRU 1989). Using XCOM, it can be shown that lung tissue substitutes, which incorporate elements having radiological characteristics dissimilar to those of the original Livermore specifications, are very likely to exhibit an attenuation coefficient substantially different than that of the original formulation.

Verification of the attenuation coefficient for the phantom lungs fabricated at the University of Cincinnati was accomplished by performing destructive measurements on several different samples of lungs. Measurements of the attenuation coefficient at 16.6 keV, using a [93m]Nb source and uniformly thick samples cut from lungs, demonstrate that the new materials are in excellent agreement with the original Livermore specifications as listed in ICRU Report No. 44 and calcu-

lated by XCOM. Measurement of the attenuation coefficient is a very sensitive test which can be used to predict the performance capabilities of a new lung tissue substitute material. Measurement of the attenuation coefficient will be shown to be an adequate predictor of the performance of the lungs and also represents the best parameter for describing the quality of the lung phantom, especially when radionuclides involving low photon energy or x rays are measured. Even the introduction of a small amount of an element with a high effective Z (i.e., Z>20) will make a significant change in the attenuation coefficient. This is because the photoelectric effect, which is the predominant mode of interaction at low energy, is highly dependent upon the effective Z (actually, Z^4).

PROCEDURE

Several sets of lungs were fabricated at the University of Cincinnati for destructive analysis and measurement of the attenuation coefficient. Individual core samples, having a diameter of 6.25 cm each, were cut from three different lungs. Lung phantoms selected for this analysis were fabricated using identical procedures but at different times during the month to test whether there may be some unknown systematic bias in the procedure. In two of the lungs, replicate samples were obtained by withdrawing cores from different positions within the same lung. Measurement of the attenuation coefficient in samples from replicate cores of the same lung will determine whether there is any significant dependence of the attenuation coefficient with position inside the lung. Whenever possible, cores were cut in both parallel and perpendicular directions to the major axis of the lung.

Cores from each lung were cut into uniform slices nearly equal in thickness. The thickness of each slice was measured at four different locations using a micrometer. These measurements were repeated by the same individual but on different days to confirm the original thickness results. The mean thickness and variance for each slice of the core was determined using a total of 8 individual measurements.

Transmission measurements were performed using a [93m]Nb point source in a low radiation background shielded enclosure with 15.24-cm-thick steel walls to minimize the contribution from background due to the natural radiation environment. A 3-mm-thick, 5.08-cm-diameter NaI(Tl) detector having a 0.127-mm-thick beryllium entrance window was used to measure the transmission of the 16.6 keV (average) [93m]Nb x rays through different layered slices of the lung core material. This energy closely resembles the x ray energy emitted by plutonium and duplicates that used by Griffith during testing of the components used in fabrication of the original Livermore Thoracic Phantom (Griffith 1978). Although Griffith measured the transmission of the [93m]Nb x rays in muscle and adipose tissue substitute materials, we found no reports in the literature or Livermore research notebooks

Table 1. Elemental composition of lung phantom materials (weight percent).

	H	C	N	O	Ca	Mg	Sn
Polyurethane	8.443	63.50	4.436	23.52	0	0.11	0
Calcium carbonate	0	12.00	0	47.96	40.04	0	0
Catalyst	7.9	48.6	0.39	16.9	0	0	26.20

which give results of attenuation measurements in the foaming polyurethane lung substitute material.

Attenuation measurements performed with the UC lung substitute material used a detector configuration similar to that described by Griffith in which the source-to-detector distance was 14 cm (Griffith 1978). Fig. 1 illustrates this geometrical arrangement. For the purposes of error analysis, the measurement results were assumed to follow a Poisson distribution. Each measurement was corrected for background.

RESULTS

The results of the attenuation measurements for lung number 49, lung 46, and lung 44 are shown in Tables 2 and 3. The chemical formulation for lung number 44 was modified by the addition of 89.6 g of KCl, i.e., 2.8 KBq ^{40}K. Although 89.6 g KCl is added to the formulation, only 81 g KCl will be in the lung since some KCl will remain with the residual materials after the lung mold is filled.
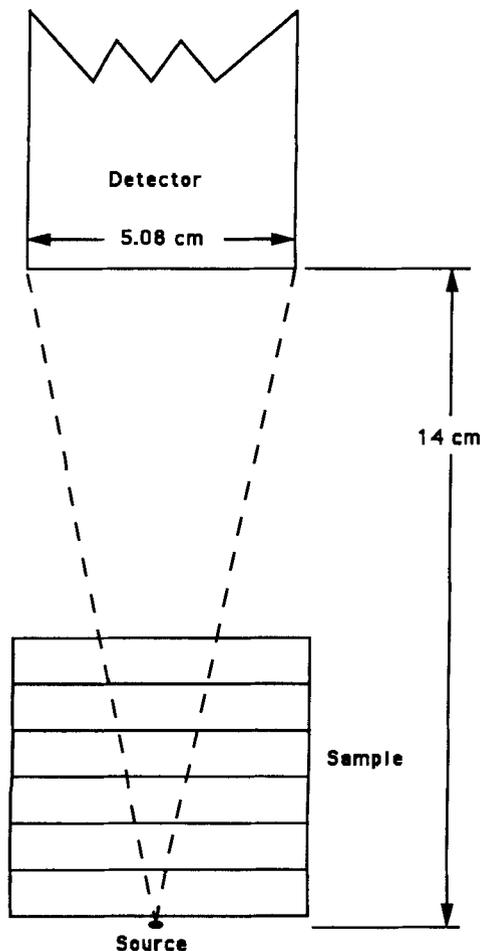

Fig. 1. Geometrical arrangement of detector and standard source when measuring transmission of ^{93m}Nb x rays through samples of lung tissue substitute material.

Table 2. Measurement of transmission of ^{93m}Nb x rays through lung tissue substitute formulation.

Sample I.D.	Sample thickness (cm)	Net count rate (cpm)	Relative count rate
44a	0	3473 ± 19	1 ± 0.007
	0.588 ± 0.017	2433 ± 16	0.701 ± 0.007
	1.207 ± 0.026	1638 ± 13	0.472 ± 0.006
	1.815 ± 0.026	1090 ± 11	0.314 ± 0.006
	2.418 ± 0.033	713 ± 9	0.205 ± 0.006
	2.974 ± 0.039	485 ± 7	0.140 ± 0.006
44b	0	3476 ± 19	1 ± 0.007
	0.590 ± 0.023	2306 ± 16	0.644 ± 0.007
	1.210 ± 0.026	1544 ± 13	0.444 ± 0.006
	1.833 ± 0.028	1037 ± 11	0.298 ± 0.006
	2.447 ± 0.040	727 ± 9	0.209 ± 0.006
	2.991 ± 0.043	455 ± 7	0.130 ± 0.006

The source used in all measurements was a ^{93m}Nb point source[‖] having an activity of approximately 7.9 × 10⁴ Bq. Results of replicate samples are given for lung number 44 and lung 46 since both were the equivalent size of the right lung of Reference Man (ICRP 1981) which made it possible to cut more than one core sample from each lung. It was not physically possible to obtain more than one core sample from lung No. 49 since it was equivalent in size to the left human lung which is smaller than the right lung. The errors reported with each measurement reflect the total propagated uncertainty in thickness and count rate.

The linear attenuation coefficient for each lung core sample was determined by performing a weighted least square regression of the count rate and sample thickness for several different values of sample thicknesses. Fig. 2 illustrates the results of the linear

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[‖] Standard Reference Material SRM 4267-30, National Institute for Standards and Technology, Gaithersburg, MD 20899.

Table 3. Measurement of transmission of ^{93m}Nb x rays through lung tissue substitute formulation.

| Sample I.D.	Sample thickness (cm)	Net count rate (cpm)	Relative count rate
46a	0	3487 ± 19	1 ± 0.007
	0.380 ± 0.010	3040 ± 18	0.889 ± 0.007
	0.806 ± 0.015	2688 ± 17	0.771 ± 0.007
	1.206 ± 0.017	2407 ± 16	0.690 ± 0.007
	1.851 ± 0.029	1996 ± 15	0.573 ± 0.006
	2.575 ± 0.037	1602 ± 13	0.460 ± 0.006
46b	0	3519 ± 19	1 ± 0.007
	0.506 ± 0.020	2968 ± 18	0.843 ± 0.007
	1.040 ± 0.042	2589 ± 17	0.736 ± 0.007
	1.628 ± 0.053	2130 ± 15	0.605 ± 0.006
	2.318 ± 0.077	1706 ± 13	0.485 ± 0.006
49	0	3488 ± 19	1 ± 0.007
	0.587 ± 0.019	2928 ± 18	0.840 ± 0.007
	1.085 ± 0.024	2514 ± 16	0.721 ± 0.006
	1.654 ± 0.027	2196 ± 15	0.630 ± 0.006
	2.233 ± 0.029	1859 ± 14	0.533 ± 0.006
	2.808 ± 0.032	1560 ± 13	0.447 ± 0.006
	3.380 ± 0.037	1314 ± 12	0.377 ± 0.006
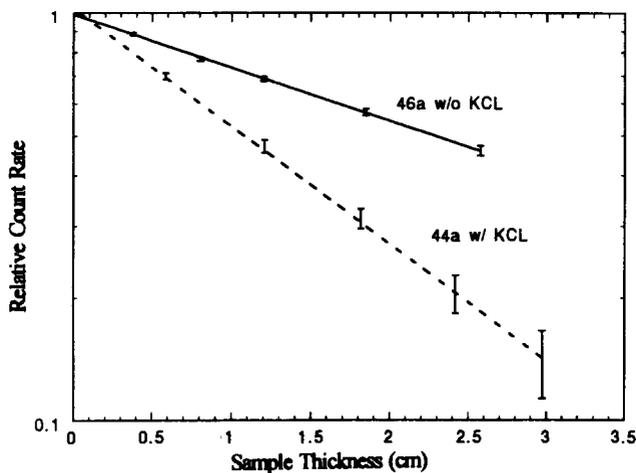
Fig. 2. Transmission of ^{93m}Nb x rays through samples of lung tissue substitute material. Sample No. 46a represents standard formulation described in text. Sample No. 44a contains KCl and represents a non-standard lung tissue substitute formulation.

regression obtained with lung number 46 (Core A) and 44 (Core A). It is obvious from the slope of these curves that lung number 44, which contains 81 g KCl, has a significantly greater linear attenuation coefficient than lung number 46. Table 4 lists a summary of the linear attenuation coefficient for all five samples reported in this paper. The data in Table 4 indicate that the linear attenuation coefficient for lung number 46 and 49 are within the recommended specifications for the original Livermore Thoracic Phantom. However, the addition of 89.6 g of KCl increased the linear attenuation coefficient at approximately 16 keV by nearly a factor of two compared to values for Griffith lung and human lung given in ICRU Report No. 44 (1989). The density for human lung, 0.26 gm cm^{-3}, is used to convert the mass attenuation coefficient (μ/ρ) reported in ICRU Report No. 44 to values of linear attenuation coefficient measured in this work. The actual density of each lung phantom is a measured value.

DISCUSSION

The original design criteria established for the Livermore Thoracic Phantom was validated by an elab-

Table 4. Linear attenuation coefficient measured in samples of phantom lungs.

Sample I.D.	Linear attenuation coefficient[a] (cm^{-1})
44a	0.652 ± 0.006
44b	0.662 ± 0.007
46a	0.301 ± 0.005
46b	0.308 ± 0.008
49	0.285 ± 0.003
Human lung[b]	0.312

[a] 16.6 keV average x ray energy from ^{93m}Nb.
[b] Calculated assuming a density of 0.26 g cm^{-3}.

orate international intercomparison of measurement results performed with human volunteers who inhaled labeled ^{103}Pd and whose lungs contained a known quantity of the radionuclide. ^{103}Pd emits x rays at 20.2 and 22.8 keV, somewhat higher in energy than plutonium. A second validation exercise was conducted using ^{92m}Nb, which emits Zr K x rays at 15.8 and 17.7 keV as well as a 934 keV photon. Each of the participating laboratories also calibrated their detector systems using a set of Livermore lungs containing the radioactive material. The results of both these intercomparisons have demonstrated the suitability of the Livermore Thoracic Phantom as an adequate calibration device for low energy emitting radioactive materials deposited in the lungs (Newton 1984). Recent interests in extending the application of the Livermore Thoracic Phantom to calibrations at higher photon energies have led to the adoption of the Livermore Thoracic Phantom as a pseudo-standard for any radioactive material deposited in the lungs, liver, kidney, and GI tract. The commercial version of the phantom has removable internal organs to which most any radionuclide can be added.

Table 5 lists calculated values for the mass attenuation coefficient at photon energies between 1 keV and 100 keV for human lung tissue and the lung tissue substitute formulation developed at the University of Cincinnati. The mass attenuation coefficients listed in Table 5 were calculated using XCOM and the known elemental composition for the contemporary materials used to fabricate Livermore-equivalent lungs at UC. The measured linear attenuation coefficient is easily converted to a mass attenuation coefficient by dividing by the density of the phantom lung. Fig. 3 shows how the calculated mass attenuation coefficient for human lung and the UC lungs vary with energy. The deviation of the lung containing KCl from the results for human lung is very apparent. Fig. 4 shows the percent deviation of the calculated mass attenuation coefficient for each of the three lungs from that for human lung as reported in ICRU publication No. 44. Again, it is very apparent from the results shown in Fig. 4 that KCl introduces a significant bias in the mass attenuation coefficient for the phantom lung and would likely produce a concomitant error in calibration measurements performed at low photon energies, especially for plutonium and ^{241}Am.

An evaluation of the change in the attenuation coefficient of the phantom lungs with the addition of KCl was conducted to determine whether it was theoretically possible to introduce approximately 2–5 KBq of ^{40}K activity by altering any of the required components, especially the CaCO$_3$, to account for the KCl. XCOM was used to calculate the mass attenuation coefficient for the modified lung formulation. Fig. 5 illustrates the percent deviation in the mass attenuation coefficient at different energies with increasing amounts of ^{40}K in the phantom lung. Even when the CaCO$_3$ is completely eliminated from the formulation, it is not possible to achieve the appropriate mass attenuation coefficient with the desired ^{40}K activity.

Table 5. Comparison of calculated mass attenuation coefficients for human lung and lung tissue substitute material.

	Calculated mass attenuation coefficient without coherent scatter (XCOM) (cm²g⁻¹)				Percent deviation of mass attenuation coefficient without coherent scatter (XCOM) from human lung (ICRU 44) (cm²g⁻¹)			
Energy (keV)	Human lung (ICRU 44)	TEST 44	TEST 46	TEST 49	Energy (keV)	TEST 44	TEST 46	TEST 49
1.00	3800.00	2840.00	2740.00	2740.00	1.00	−25.26	−27.89	−27.89
2.00	574.00	420.00	398.00	398.00	2.00	−26.83	−30.66	−30.66
3.00	188.00	217.00	122.00	122.00	3.00	15.43	−35.11	−35.11
4.00	82.40	158.00	51.80	51.70	4.00	91.75	−37.14	−37.26
5.00	42.40	97.50	39.90	39.80	5.00	129.95	−5.90	−6.13
6.00	24.50	59.10	23.50	23.50	6.00	141.22	−4.08	−4.08
7.00	15.40	38.40	15.00	15.00	7.00	149.35	−2.60	−2.60
8.00	10.30	26.40	10.20	10.20	8.00	156.31	−0.97	−0.97
9.00	7.19	18.90	7.23	7.21	9.00	162.87	0.56	0.28
10.00	5.23	14.00	5.31	5.30	10.00	167.69	1.53	1.34
11.00	3.93	10.60	4.03	4.02	11.00	169.72	2.54	2.29
12.00	3.03	8.28	3.14	3.13	12.00	173.27	3.63	3.30
13.00	2.40	6.58	2.50	2.49	13.00	174.17	4.17	3.75
13.60	2.10	5.78	2.20	2.19	13.60	175.24	4.76	4.29
14.00	1.93	5.32	2.03	2.02	14.00	175.65	5.18	4.66
14.50	1.75	4.81	1.84	1.84	14.50	174.86	5.14	5.14
15.00	1.59	4.37	1.68	1.67	15.00	174.84	5.66	5.03
15.50	1.45	3.98	1.53	1.53	15.50	174.48	5.52	5.52
16.00	1.33	3.63	1.41	1.40	16.00	172.93	6.02	5.26
16.50	1.22	3.33	1.30	1.29	16.50	172.95	6.56	5.74
16.60	1.20	3.27	1.28	1.27	16.60	172.50	6.67	5.83
17.00	1.13	3.06	1.20	1.20	17.00	170.80	6.19	6.19
17.06	1.12	3.03	1.19	1.18	17.06	170.54	6.25	5.36
17.50	1.04	2.82	1.11	1.11	17.50	171.15	6.73	6.73
18.00	0.97	2.61	1.03	1.03	18.00	169.07	6.19	6.19
19.00	0.85	2.24	0.90	0.90	19.00	165.09	6.75	6.51
20.00	0.74	1.94	0.80	0.80	20.00	160.75	6.99	6.85
20.29	0.72	1.87	0.77	0.77	20.29	160.08	6.95	6.82
25.00	0.46	1.07	0.49	0.49	25.00	134.14	6.78	6.56
30.00	0.34	0.70	0.36	0.36	30.00	108.66	8.66	8.66
40.00	0.24	0.39	0.25	0.25	40.00	61.16	4.96	4.96
50.00	0.21	0.28	0.21	0.21	50.00	34.13	2.40	2.40
59.54	0.19	0.23	0.19	0.19	59.54	20.31	1.04	1.04
60.00	0.19	0.23	0.19	0.19	60.00	19.27	0.52	0.52
70.00	0.18	0.20	0.18	0.18	70.00	11.54	0.00	0.00
80.00	0.18	0.19	0.17	0.17	80.00	6.29	−1.14	−1.14
90.00	0.17	0.18	0.17	0.17	90.00	3.55	−1.18	−1.18
100.00	0.16	0.17	0.16	0.16	100.00	1.83	−1.22	−1.22
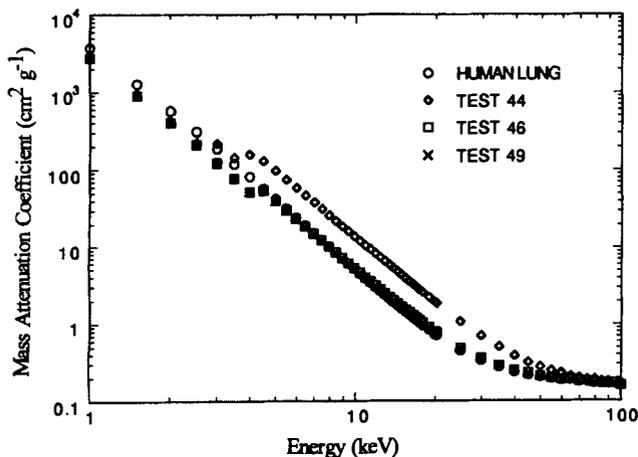
Fig. 3. Comparison of the calculated mass attenuation coefficient for three phantom lungs and human lung. Sample No. Test44, which includes 81 g of KCl, has a mass attenuation coefficient significantly greater than that for the other samples and human lung.

The KCl introduces a very large percentage deviation in the mass attenuation coefficient from that obtained when phantom lungs are produced using the standard formulation and would introduce a significant performance bias if such lungs were used to calibrate for low energy photons.

CONCLUSION

It is obvious from the data reported in this paper that lungs used in the Livermore Thoracic Phantom to calibrate *in vivo* measurement systems that monitor plutonium, americium, and uranium should be fabricated according to the original specifications adopted by Griffith (1978). Since the linear attenuation coefficient measured with the UC Livermore equivalent lungs has been shown to be remarkably sensitive to even minor changes in the materials of fabrication, it is important not to alter these components. Commercial
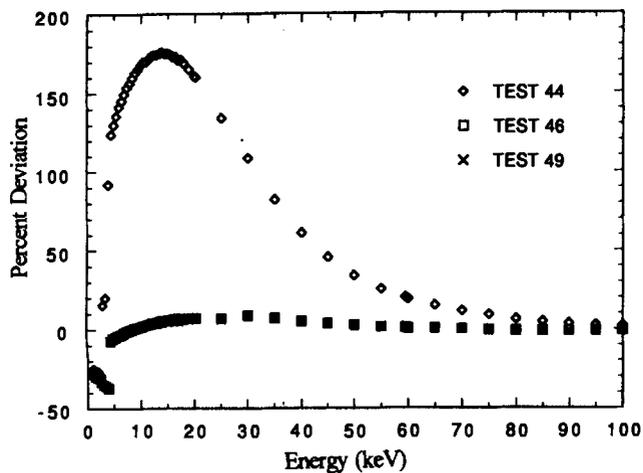
Fig. 4. Percent deviation of the calculated mass attenuation coefficient relative to human lung. Sample No. Test44, which was fabricated with 89.6 g KCl added to the standard formulation, has a mass attenuation coefficient nearly a factor of two greater than human lung between 10 keV and 20 keV, the energy region for plutonium x rays. The standard formulation deviates little from human lung above 10 keV.

suppliers of calibration lungs which contain low energy, photon emitting radioactive materials should certify and document that the attenuation coefficient of their product meets the criteria specified for the original Livermore Thoracic Phantom. Use of lungs which have an attenuation coefficient which differs from the
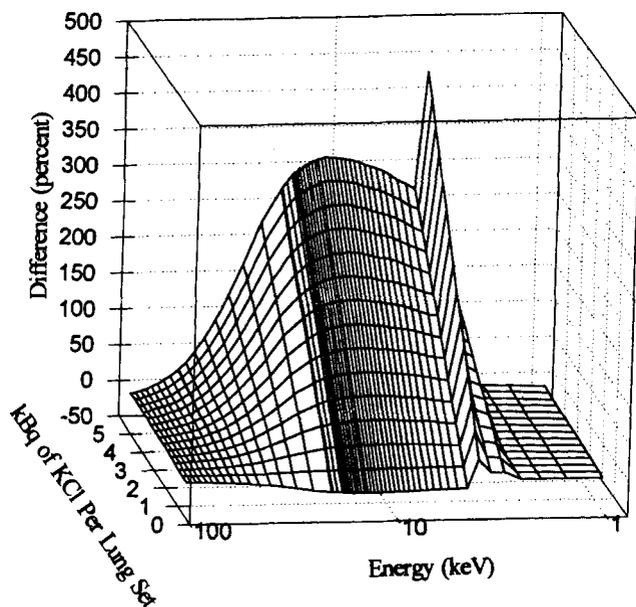

Fig. 5. Calculated percent deviation in the mass attenuation coefficient from the original Livermore formulation due to the addition of KCl. Even with all $CaCO_3$ eliminated, it was not possible to achieve the mass attenuation coefficient equal to human lung in the plutonium x-ray region when KCl was added to the standard formulation.

original specification will introduce a systematic error into the measurement results for low energy emitting radionuclides.

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