Lung counting: a function to fit counting efficiency of a lung counting germanium detector array to muscle-equivalent-chest-wall-thickness and photon energy using a realistic torso phantom.

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INTRODUCTION

Low energy photons are severely attenuated by passage through the tissues making up the human chest wall (muscle, adipose, cartilage, and bone). The counting efficiency of germanium detectors is, at low energies, a function of the chest wall thickness, the adipose content of the chest wall, and the photon energy. As the photon energy rises above 60 keV the influence of tissue composition (muscle adipose ratio) becomes unimportant and the counting efficiency will be a function of the chest wall thickness and the photon energy. Previously, there has been no attempt to generate a semi-empirical function that fits the counting efficiency to these parameters (chest wall thickness, adipose content, and photon energy). Instead, the detectors are calibrated at a given single energy and a function derived that relates the counting efficiency to the chest wall thickness.

Adipose content correction is performed either by using a series of calibration curves for various adipose content of the chest wall and interpolating the subjects adipose content of the chest wall, or by eliminating it as a variable. This is achieved by expressing the chest wall thickness, with its adipose content, as a muscle-equivalent chest wall thickness (MEQ-CWT). After the correction for tissue composition at low photon energies has been made by converting the chest wall thickness to a muscle equivalent chest wall thickness (MEQ-CWT), a series of empirical equations can be derived for each photon energy of interest. The relationship between the logarithm of the counting efficiency and MEQ-CWT is linear, meaning that the empirical equation is an exponential. This presentation takes that analysis one step further: a method of relating the counting efficiency to both MEQ-CWT and photon energy using a single function.

METHODS AND MATERIALS

Phantoms: The Human Monitoring Laboratory (HML) has both the obtained the LLNL torso phantom and the JAERI torso phantom. Both phantoms are realistic to better simulate the interaction of low energy photons (< 200 keV) with bone, cartilage, muscle and adipose tissues. The torso plates are constructed of muscle substitute material (LLNL) or adipose-muscle substitute mixture (JAERI) and contain synthetic bone, and cartilage. The overlay plates are constructed of different adipose-muscle substitute mixtures. The torso cavities contain lungs, heart, liver and other organs. All internal organs except the lungs are constructed of muscle substitute material; the lungs are constructed of lung substitute material. The JAERI phantom contains a full rib cage, spine and scapula in the rear of the torso. The LLNL phantom contains only a rib cage, and a spinal tissue block has been substituted for the spine.

The LLNL phantom has three sets of four overlay plates that when placed on the torso plate can simulate different total chest wall thickness from about 1.6 cm (no overlay) to 4.1 cm (thickest overlay plate added). Each overlay plate series simulates a different adipose-muscle ratio - 87:13 (series A), 50:50 (series B), and 0:100 (series C). The adipose-muscle ratios of the overlay plates must be combined with the torso plate cover (100% muscle) so that the combined muscle-adipose ratios vary from 15:85 to 52:48. The JAERI phantom is supplied with a torso plate cover and two series of overlay plates that simulate two different thicknesses, 2.3 cm and 3.0 cm, and three different adipose-muscle ratios - 10:90, 20:80, and 30:70. The shapes of the lungs of the two phantoms are different. The LLNL lungs are short and deep (sagittal diameter or length: 22 cm ; anteroposterior diameter: 22 cm), whereas the JAERI lungs are longer and more shallow in depth (sagittal diameter or length: 28 cm ; anteroposterior diameter: 15 cm). The transverse diameter (width) of the lungs are similar, approximately 10 cm. The dimensions of the JAERI lungs agree more closely with the lung dimensions of Reference Man than do the dimensions of the LLNL lungs. The LLNL phantom also has a large heart that obscures most of the lower portion of the left lung.

Muscle Equivalent Chest Wall Thickness (MEQ-CWT): The MEQ-CWT is the thickness of muscle-equivalent-absorber that reduces the photon flux from the lungs by the same amount as the actual combination of muscle and adipose tissue in the chest plate and overlay plates. It has been described in detail in another presentation at this meeting.

Counting Efficiency: Germanium detectors used for lung counting give a characteristic efficiency curve at a given chest wall thickness. When the energy is fixed and MEQ-CWT is the variable, the efficiency curve becomes exponential. The detectors in the HML have been calibrated in this manner and, at a given energy, the counting efficiency can be described as:

This equation is similar to the familiar equation that describes the amount of attenuation a photon beam will suffer in passing through a given material of thickness ‘x’. This equation is given by:

It follows that the parameter ‘q’ in equation 1 is a pseudo-linear attenuation coefficient. Unlike published values , ‘q’ is a linear attenuation coefficient for a specific geometry: a distributed source of uncollimated photons.

Construction of a single function: Preliminary data collected at KAERI had been expressed as a series of equations that describe the counting efficiency at each different chest wall thickness. The equation was of the type:

The parameters 'a - e' were found to change linearly with CWT so it was postulated that they also changed linearly with MEQ-CWT. The combined function would then be:

Where E = counting efficiency (cps/photon).
y = MEQ-CWT (cm).
x = Photon energy (keV).

Validation of the function: At a given photon energy the terms in Ln(x) can be thought of as constant so that the logarithm of counting efficiency, E, maybe expressed as:

Where

and

It follows that B is a pseudo linear attenuation coefficient as shown above and should be numerically equal to '-q'. However, equation 7 did not describe the change in the value of linear attenuation coefficient as a function of energy. Instead, the form shown in equation 2 was found to give a good fit. Therefore, equation 4 was modified to reflect this:

where: E = counting efficiency (cps/photon).
y = MEQ-CWT (cm).
x = photon energy (keV).

RESULTS AND DISCUSSION

Counting Efficiency: Efficiency data for the JAERI and LLNL phantoms collected with the HML's germanium lung counting system has been fitted to the function given above by equation 8. Chest wall thickness values were converted to MEQ-CWT values as described above and the data set of counting efficiency (cps/photon), MEQ-CWT and photon energy was fitted using TableCurve3D. Data from other facilities (Pacific Northwest National Laboratories - PNNL; Korea Atomic Energy Research Institute - KAERI; Oak Ridge National Laboratories - ORNL; Savannah River Site - SRS) has also been analysed with the same function. The results of these analyses are shown in Table 1. It is interesting to note how similar the coefficients are for the LLNL and JAERI phantoms at a given facility. Table 1 also shows the fit of the function of two data sets collected using the same phantom and two similar detector systems. The small change in parameters is probably due to positioning errors.

Table 1: Fit parameters for the function (equation 8) for various facilities and the LLNL and JAERI phantom.

	Facility - Phantom							
Parameter	HML-LLNL	HML-JAERI	ORNL-LLNL	PNNL-LLNL	KAERI-JAERI	KAERI-LLNL	SRS#1-LLNL	SRS#2-LLNL
a	-32.3209	-32.1249	-47.1498	-61.6890	-42.3967	-43.0890	-32.5610	-34.1099
b	-5.3001	-5.4588	2.7383	-0.3203	-4.8855	-4.8065	-6.7404	-5.7836
c	380.5824	377.9435	630.8592	792.1309	457.6919	464.7126	350.2526	381.0315
d	96.2882	98.2738	-47.0903	7.9681	92.6089	91.9086	118.5244	101.1092
e	-1783.2179	-1770.3989	-3408.5600	-4023.9600	-1870.3507	-1882.6121	-1555.7084	-1766.3743
f	-682.0458	-687.2429	261.6932	-110.4040	-678.4333	-677.9856	-802.8784	-688.8348
g	3714.1571	3757.2750	8195.8270	9108.2890	2975.2794	2903.3922	3124.5325	3745.9643
h	2119.5469	2095.4852	-592.5310	523.0079	2159.4029	2164.6024	2398.4434	2071.4445
i	-3106.5846	-3292.7693	-7469.7100	-7882.0800	-1446.4184	-1263.1086	-2575.8798	-3246.8134
j	-2476.8016	-2387.8713	390.3957	-838.6450	-2560.5866	-2569.6084	-2706.8749	-2362.6670
corr. coeff.	0.9998	0.9990	0.9997	0.9979	0.9998	0.9999	0.9976	0.9972
std error	0.0400	0.0758	0.0502	0.0638	0.0253	0.0237	0.0862	0.0949

CONCLUSION

A function has been found that will fit experimentally observed counting efficiency for an array of germanium detectors as a function of photon energy and MEQ-CWT. The function appears generally applicable over the range of existing phantoms and a wide range of equipment types. Subtle differences between the detector systems are shown by differences in the fit parameters. This analysis could be a useful addition to lung counting analysis software. The function shows that the LLNL and JAERI phantoms have very similar counting characteristics as evidenced by the similarity of the function parameters when measured using a single detector system.. One of the partial derivatives of the function predicts the *knee* of the function. It agreed well with observed interpolations except for historical data of a six-detector array. The disagreement supports the need for accurate CWT measurements of the torso phantom when doing lung counting with germanium detectors.

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