Comparison of the LLNL and JAERI Torso Phantoms using four 70 mm Ge Detectors and four Phoswich detectors.

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INTRODUCTION

The Human Monitoring Laboratory (HML) uses both the Lawrence Livermore National Laboratory (LLNL) realistic torso phantom (Griffith et al. 1978) and the Japanese Atomic Energy Research Institute (JAERI) realistic torso phantom (Shirotani 1988). The JAERI phantom is smaller than the LLNL phantom and it was acquired to provide both a "smaller-person" calibration for the HML's germanium lung counting system and a "smaller-person" for the Canadian Lung Intercomparison Program.

The LLNL phantom has, by consensus opinion, been acclaimed as the de facto standard phantom for lung counting (Kramer and Inn 1991). However, the design of the LLNL torso phantom is based on a cadaver which was representative of a population of radiation workers at the Lawrence Livermore National Laboratories and at Los Alamos National Laboratories. The phantom represents a 1.77 m tall male weighing 76 kg. The design of the JAERI phantom is based on Japanese Reference Man (Tanaka et al. 1979), and represents a 1.68 m tall male weighing 63.5 kg.

This presentation describes the results obtained by comparing the phantoms using a large area germanium detector array and a four detector phoswich lung counting system.

MATERIALS AND METHODS

Phantoms: 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 (22 cm x 22 cm), whereas the JAERI lungs are longer and more shallow in depth (28 cm x 15 cm). The width of the lungs are similar, approximately 10 cm. The LLNL phantom has a large heart that obscures most of the lower portion of the left lung. Considering these difference it was expected that the counting efficiencies obtained from the two phantoms would be significantly different; however, this did not prove to be the case as discussed below.

The phoswich lung counter is configured to measure a supine subject from both the front of the chest and from the back. It was, therefore, necessary to measure the thickness of the backs of the phantoms to compare their performance characteristics with this counting system. The thickness of the region where the phoswich detectors were placed on each phantom was measured by using a CT scanner at a local hospital. Fourteen slices approximately 1 cm apart were taken for each phantom and these were used for the thickness measurements.

Germanium lung counter: The lung counting system at the HML consists of four large area germanium detectors supplied by EG&G Ortec. Each detector, which is cooled by a 17 liter Dewar, is 70 mm in diameter and 30 mm thick. The beryllium window is 0.5 mm thick. The detectors are housed in a counting chamber that is constructed of 20 cm thick low background steel. The interior is covered with a lead liner that is approximately 0.6 cm thick.

The detectors are individually calibrated: detector #1 is placed above the lower portion of the left lung and is above the heart; detector #2 is placed above the upper portion of the left lung; detector #3 is placed above the lower portion of the right lung, and detector #4 is placed above the upper portion of the right lung. The data was also summed to simulate a lung counter detector array for the purpose of comparing the LLNL and JAERI phantoms.

The LLNL phantom was measured with a lung set made of tissue substitute material containing a mixture of ^{241}Am/^{152}Eu. The activity of the sources was 38.9 kBq ^{241}Am and 16.4 kBq of ^{152}Eu on 1-Jan-96. The energies of interest were 17.7 keV, 59.5 keV, 121.8 keV, 344 keV.

The JAERI phantom is not supplied with radioactive lung sets. A set was manufactured for the HML by Pacific Northwest National Laboratories that contained ^{241}Am/^{152}Eu homogeneously distributed throughout the tissue substitute material. The activities of ^{241}Am and ^{152}Eu on 12-Mar-96 were the same: 18.25 kBq.

The LLNL phantom was measured in the lung counter with and without the B-series overlay plates. These plates simulate 50% adipose and 50% muscle. Unfortunately, when they are added to the LLNL phantom's chest plate the adipose mass fraction does not remain constant. The adipose mass fraction with no overlay plate is 0%, 15% with B1, 22% with B2, 26% with B3 and 30% with B4. In contrast, the JAERI phantom's adipose mass fraction is either 10% (no overlay, overlay plate CZ10879, overlay plate CZ11577), 20% (overlay plate CZ20853, overlay plate CZ21559) or 30% (overlay plate CZ30826, overlay plate CZ31541). The two phantoms also differ in their chest wall thicknesses. To further complicate matters, each phantom has a different chest wall thickness at the upper left, upper right, lower left and lower right positions for any given configuration i.e., with an overlay plate installed. Counting times were from 18,000 to 60,000 seconds in order to get good counting statistics. For example, the counting error at 17.7 keV is no more than 2.5% (at 2σ) for either phantom.

Phoswich Lung Counter: Cameco's Mobile Health Physics Laboratory consists of a low background monitoring chamber, a phoswich detector assembly and multichannel analyzer, all enclosed in a 12.2 meter air conditioned transport trailer. The counting chamber is constructed of 10.2 cm thick selected low background steel with a 3 mm lead liner. The interior dimensions are: 213 cm long, 132 cm high and 76 cm deep. Subjects are counted in a supine position using detectors positioned both above and below the chest cavity.

The acquisition system consists of four phoswich detectors: 12.5 cm diameter; 1.25 cm NaI(Tl); 5.1 cm CsI(Na). The phoswich detectors are connected through a multiplexer to a microcomputer based multichannel analyzer. The multichannel analyzer functions are controlled by the microcomputer, which also performs the data analysis and storage.

The phoswich counting system was used to measure the LLNL phantom containing a natural uranium lung set (701 mg) with and without the B-series overlays. The JAERI phantom, containing a natural uranium lung set (812 mg), was measured with the 10% adipose mass fraction overlay series. Data was analyzed separately for the front and back detector arrays.

RESULTS

Germanium lung counter: The efficiency data for the two phantoms is a function of the chest wall thickness and the adipose mass fraction. A more useful method of comparing the two sets of data is to determine the Muscle Equivalent Chest Wall Thickness (MEQ-CWT) of each configuration counted. 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. The presentation will show the counting efficiencies (cps/photon) at the four energies of interest for the phantoms with and without their overlay plates for the four detector positions: lower left, upper left, lower right, and upper right. The counting efficiency data for a Ge detector array at each of the four photon energies will also be presented.

Phoswich Lung Counter: The counting efficiency derived by Cameco Corporation is in units of cps/mg-natural-uranium. The counting efficiencies for the LLNL and JAERI phantoms at 63 keV, 93 keV and 185 keV measured using the top two-detector array will be discussed. The counting efficiency for the lower two-detector array was determined for each of the corresponding phantom plus overlay counts. The thickness of the back of the phantom could not be changed and so these counts are replicates of each other. This data will be discussed.

The CT scanner slices were used to obtain thickness measurements of the backs of the phantoms in the region where the phoswich detectors were placed. Approximately 11 thicknesses were measured on each of the 14 CT slices. Each thickness was measured normal to the area of the phantom where the detector face was placed. The resulting thickness were averaged giving the following values: JAERI, 4.48 ± 0.86 cm; LLNL, 3.39 ± 1.39 cm.

DISCUSSION

Germanium lung counter: *Detector #1* - This detector is placed over the lower portion of the left lung and is above the heart. The over-large heart in the LLNL phantom obscures most of the lung from the detector resulting in counting efficiencies that are much lower than the counting efficiencies derived from the JAERI phantom. The biggest difference is at the lowest energy, 17.7 keV, where the counting efficiency between the two phantoms varies from approximately a factor of six at low values of MEQ-CWT to a factor of 2.5 at larger values of MEQ-CWT. As the photon energy rises the difference between the two phantoms decreases to approximately a factor of two at 344 keV.

Detector #2 - This detector is placed over the upper portion of the left lung and agreement between the two phantoms is much better. At 17.7 keV the counting efficiencies are essentially equal. The counting efficiency for the JAERI phantom at the highest MEQ-CWT value is unexpectedly high and could be due to a positioning error. It has been left uncorrected to illustrate typical difficulties one encounters performing lung counting. As the photon energy rises the counting efficiencies diverge. The JAERI counting efficiencies differ from the LLNL phantom as follows: approximately

13% higher at 59.5 keV, about 8% higher at 121.8 keV, and about 5% at 344 keV.

The close agreement for the counting efficiencies of the two phantoms at 17 keV implies that the detectors are only "seeing" activity very close to the surface of the lungs. The lung shape is, therefore, not important; the "realism" of the chest plates and the counting efficiencies are similar. As the photon energy increases the counting geometry plays a larger role causing the deviations noted above. As the photon energy continues to rise, the geometry becomes less important again and the counting efficiencies begin to converge.

Detector #3 - This detector is placed over the lower portion of the right lung. The detector overlaps the edge of the lung in the LLNL phantom, whereas this does not occur in the JAERI phantom as the lungs are longer. At 17.7 keV the counting efficiencies are very similar except for the counting efficiency of the JAERI phantom at the lowest MEQ-CWT value. This count was repeated later and the same result obtained. There is no apparent explanation to account for this large difference. At 59.5 keV the counting efficiencies of the two phantoms differ. The JAERI phantom gives counting efficiencies that are 10% to 50% higher than that of the LLNL phantom. The difference decreases as MEQ-CWT increases. At 121.8 keV the JAERI counting efficiencies are between 5% to 30% higher than the LLNL phantom, and at 344 keV they are between 1% to 23% higher.

Detector #4 - This detector is placed over the upper portion of the right lung which is a position where there are the least geometry differences between the phantoms. At 17.7 keV the counting efficiencies appear to fall on a single curve. The reason has been discussed above. As the photon energy rises the difference noted above for Detectors 1 - 3 do not materialize supporting the geometrical identity of this counting position for the two phantoms.

Four-detector array - The counting efficiencies were summed to derive an array counting efficiency. The large difference between the phantoms demonstrated by detector 1 at 17.7 keV has been greatly moderated. The counting efficiency curves are now within 30% of each other over the range of MEQ-CWT's measured. As the energy rises the efficiency curves converge so that the difference between the counting efficiencies of the two phantoms varies as follows: 25% at 59.5 keV, 23% at 121.8 keV, and 14% at 344 keV.

Phoswich Lung Counter: *Upper two-detector array* - The efficiency curves show that the JAERI phantom gives higher counting efficiencies at all energies, in agreement with the findings from the Ge detector study above. The agreement between the counting efficiency curves is better than 15% at 63 keV, and 20 % at 93 keV and 185 keV.

Lower two-detector array - The counting efficiencies at 63 keV, 93 keV and 185 keV for the two-detector phoswich array were determined. The counting efficiency for the JAERI phantom is now approximately 15% lower than the LLNL phantom at the three photon energies studied. The predicted transmission of 60 keV photons through a thickness of 4.48 cm is 39% (JAERI) and 44% (LLNL) through 3.92 cm of tissue. These values account for the 15% reduction in efficiency of the JAERI phantom relative to the LLNL phantom and demonstrate that the phantoms have the same performance characteristics for rear counting at 63 keV, 93 keV and 185 keV.

The LLNL phantom was never intended to be used to calibrate counting systems that have rear mounted detectors; however, the JAERI phantom having a spine, ribs and scapula, is realistic in the back. The close agreement between the two phantoms now provides validation for the LLNL phantom to be used in this manner at energies of 63 keV, 93 keV and 185 keV.

CONCLUSIONS

The counting efficiencies derived from a LLNL phantom and a JAERI phantom shows the phantoms are very similar when measured with a four Ge-detector array. The counting efficiencies at 17 keV are within 30% of each other, with the JAERI phantom having the higher counting efficiencies. However, the individual Ge detector measurements have shown that the phantoms differ considerably in the lower portion of the left lung, because of the overly large heart. Measurements in other positions have shown that the phantoms give very similar counting efficiencies in the range of 17.7 keV to 344 keV.

This joint study between HML and Cameco corporation has shown that the phantoms are very similar when lung counting is performed using a two detector phoswich array. The rear mounted detectors at Cameco Corporation have shown that the LLNL phantom can be used to calibrate rear mounted detectors as the phantoms differ by 15% or less in their counting efficiencies at 63 keV, 93 keV and 185 keV.

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