A *Virtual Torso* Phantom and its Comparison to the *LLNL* and *JAERI* Torso Phantoms

Gary H. Kramer, Suzanne Yiu, Barry M. Hauck and Linda C. Burns

National Calibration Reference Centre for *In Vivo* Monitoring, Human Monitoring Laboratory,
Postal Locator 6302D1, Radiation Protection Bureau, 775 Brookfield Road
Ottawa, Ontario K1A 1C1 CANADA.

INTRODUCTION

There will be an uncertainty on the estimate of activity in the lung if the lung counter is calibrated using a lung set that has the activity homogeneously distributed throughout the tissue substitute material and the deposition in the subject is heterogeneous. Preliminary data obtained in the HML suggested that individual detector calibration minimized this uncertainty; however, this study was performed with a limited number of source distributions and at only two energies: 63 and 93 keV. Other work from the HML extended that study using Monte Carlo code simulations to model the HML's detectors with a virtual phantom derived from the MIRD. The virtual phantom has also been used to investigate muscle equivalent chest wall thickness and other variations in the geometry of lung counting. This paper describes in detail the virtual phantom, procedures used to modify its dimensions, and compares the predicted counting efficiencies from the virtual phantom to measured efficiencies from the LLNL and JAERI phantoms.

METHODS AND MATERIALS

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 LLNL phantom was measured with a lung set made of tissue substitute material containing a mixture of ^{241}Am/^{152}Eu which was manufactured by the University of Cincinnati. 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 was 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. 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 2s) for either phantom.

LLNL and JAERI Phantoms: The LLNL phantom was obtained from Radiology Support Devices in 1981, and the JAERI phantom was obtained from Kyoto Kagaku Company in 1995. Both phantoms are realistic to better simulate the interaction of low energy photons (< 200 keV) with bone, cartilage, muscle and adipose tissues. 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 is similar, approximately 10 cm. The LLNL phantom has a large heart that obscures most of the lower portion of the left lung. The virtual phantom's lung shapes were modeled to resemble the LLNL phantom.

The Virtual Phantom and Detectors: The virtual germanium detectors were modeled based on specifications supplied by EG&G Ortec. They closely resemble the germanium detectors described above. Detector #1 was placed over the upper part of the left lung; detector #2 was placed over the lower part of the left lung and the heart; detector #3 was placed over the upper part of the right lung; detector #4 was placed over the lower part of the right lung.

The virtual torso was modeled on the torso section of the Medical Internal Radiation Dose, MIRD, phantom, but the lungs were modified to be more consistent with the size and shape of the lungs in the LLNL phantom. Each virtual lung was divided into eight sections, giving 16 sections in all, to approximately correspond to a lung set manufactured by Pacific Northwest National Laboratory for the HML. Each lung was described by a set of x, y, and z axes, the origin being set to the center of each lung, so that the effect of a heterogeneous distribution could be investigated and compared to experimental data. Lungs were filled with lung tissue, organs were filled with muscle tissue, ribs were filled with skeletal bone, and the torso cavity was filled with soft tissue. The elemental compositions of all tissues were taken from ICRP 44. The original design fixed the chest wall thickness at 1.63 cm, which corresponds to the chest plate cover of the HML's LLNL torso phantom.

Photons of any energy can be studied by setting the appropriate value in the MCNP data set. The origin and initial direction of the photons in each lung is randomly generated by the code. Only photons that interact with the germanium in the detectors will be tallied individually so that an individual detector efficiency can be obtained a given configuration. An array can be simulated by simply adding up the individual detector tallies for a given configuration. Each run should be performed on a single energy source. Error requirements can be met if 10^7 photon paths are simulated for photon energies of 20 keV or greater. The relative error should be less than 0.1 for all these simulations. The high tissue attenuation of the 17 keV photons requires that simulations be run using either 5×10^7 or 10^8 photons to meet the relative error requirement.

Construction of the Virtual Phantom: The virtual phantom is constructed by placing a series of geometrical solids in x, y, z space. The Z-axis is the vertical axis, the Y-axis is the transverse axis, and the X-axis is the anteroposterior axis.

The chest wall is defined by concentric elliptical cylinders parallel to the Z-axis. The inner and outer boundaries of the chest wall are defined by equation 1:

The parameters A, B, C, and D were chosen to give a chest wall thickness that was close to that of the LLNL phantom with no overlay plates (i.e., 1.6 cm). For example, they were 2.0408, 1, 1, and -289 for the inner surface, and 0.54627, 0.29134, 1, -100 for the outer surface.

For simplicity, the ribs were placed immediately underneath the chest wall. They are defined by the space between two concentric elliptical cylinders that are defined by equations similar to equation 1 (outer surface 2.0408, 1, 1, -289; inner surface 2.0849, 1, 1, -272.25). The distance between these elliptical cylinders varies from 0.47 cm to 0.50 cm. The ribs are formed by planes perpendicular to the Z-axis so that eight sections are created from the elliptical cylinder. The width of the ribs is the same as the distance separating them: 1.4 cm.

The lungs are comprised of ellipsoids that have had sections removed by intersection with other shapes so that they closely resemble the lungs in the LLNL torso phantom.. The ellipsoids are 19 cm (X-axis), 10 cm (Y-axis), and 20 cm (Z-axis); however, lungs are not ellipsoidal. The regular shapes must be modified by removing sections. The lungs are shaped on the inner side by excluding the volume common two ellipsoids The base of the lungs is truncated in a similar manner by excluding the volume common to two ellipsoids. The resulting volume of the left lung is 1589 ml and the right lung is 2061 ml. The lung volumes give a left-right ratio of 43.5 to 56.5. The LLNL phantom's lungs have a left right ratio of 43.4 to 56.6.

The lungs represent the source of photons. To allow the investigation of the effects of heterogeneous distributions, each lung is divided into eight sections by planes perpendicular to each of the x, y, z directions. The planes pass through the center of the modified ellipsoid. The y-z plane perpendicular to the x-axis passes through $x = 0$, the x-z plane perpendicular to the y-axis passes through $y = 6.5$ for the left lung and $y = -6.5$ for the right lungs, and the x-y plane perpendicular to the z-axis passes through $z = 0$.

Chest Wall Thickness: The original design set the chest wall thickness of the virtual phantom to 1.63 cm. Examination of the virtual phantom shows that this thickness is almost constant all around the phantom. This is not realistic. The chest wall of the HML's torso phantoms and real people tends to be thinner in the middle and thicken towards the outer edges.

The HML has also made chest wall thickness measurements on eight male and two volunteers using ultrasound. These values have a large uncertainty associated with them as the chest wall thickness in each counting area changes, as shown above. The virtual phantom can be altered to better reflect this by changing the parameter of the outer ellipse that described the virtual phantoms "skin"; however, simply increasing the semi-major and semi-minor axes proportionally will result in a uniform thickness change. This was done for the muscle-equivalent-chest-wall-thickness studies and it is a simple modification, but it does not reflect the variability in chest wall thickness as seen people. The alteration and estimation the chest wall thickness so that it better represents real people is more challenging. The methodology will be discussed during the presentation.

RESULTS AND DISCUSSION

The Monte Carlo code simulations predict how many photons will interact with the detector crystal. The detection efficiency is, therefore, measured in counts per photon; however, it must be converted to cps/photon to make the data comparable with the experimental data obtained from the two torso phantoms. The conversion was performed by dividing the counts per photon by an arbitrary time so that the derived cps/photon of the virtual phantom matched the counting efficiency of the 240 keV photons for the JAERI phantom. This photon energy was selected as it is relatively insensitive to minor changes in chest wall dimension, density, and rib construction. Indeed, the differences between the virtual phantom and the real phantoms do not manifest themselves until low photon energies are reached. The resulting counting efficiencies are shown in Table 1.

Table 1: Counting efficiencies (cps/photon) for the virtual phantom and the LLNL and JAERI phantoms.

Energy (keV)	Virtual Phantom	LLNL Phantom	JAERI Phantom
17	1.14×10^{-4}	3.43×10^{-4}	3.53×10^{-4}
20	8.15×10^{-4}	1.55×10^{-3}	1.67×10^{-3}
40	2.19×10^{-2}	1.87×10^{-2}	2.11×10^{-2}
60	2.77×10^{-2}	2.53×10^{-2}	2.80×10^{-2}
120	2.79×10^{-2}	2.89×10^{-2}	3.13×10^{-2}
240	2.01×10^{-2}	1.85×10^{-2}	2.01×10^{-2}

The counting efficiency data for the LLNL and JAERI phantoms was interpolated from measurements made on the phantoms to match the photon energies used in the Monte Carlo simulations. The virtual phantom agrees to within 15% of the torsos' counting efficiency at the higher photon energies (40 - 240 keV); however, at low photon energies the deviation is quite marked - factor two lower at 20 keV and factor three lower at 17 keV.

The under-prediction is almost certainly due to the construction of the virtual torso. The ribs extend all the way round the torso, whereas in reality the central part of the chest is covered with cartilage and not bone (except for the sternum which is not included in the virtual phantom). The lungs do not touch the inner surface of the chest wall along their length (Z-axis) due to the differences in curvature between the ellipsoidal lungs and the ellipsoidal cylinder that defines the torso. As a result there is intervening tissue between the lungs and the chest wall. This will have a noticeable affect on the simulation of low energy photons.

CONCLUSIONS

The comparison of measured and calculated counting efficiencies has shown that the virtual phantom is a good representation of both of the HML's torso phantoms (LLNL or JAERI) at photon energies above 40 keV. However, at low photon energies (17 and 20 keV) the virtual phantom grossly under predicts the counting efficiency of the torso phantoms. Nevertheless, it will be shown in another presentation that the data obtained from the Monte Carlo simulations accurately indicates the problems encountered in lung counting.