Chapter-4

Comparison of the simulated results with measurements - Validation

4.0 Introduction

This chapter discusses the validation of theoretical modeling of various in-vivo monitoring systems with experimental results. This chapter also deals with the estimation of uncertainties in calibration factors due to the distribution of sources at different depths in the Masonite cut sheet phantom. A comparison of the calibration factors as well as CSFs of shielded chair using Masonite cut sheet phantom and Indian adult BOMAB phantom are presented. Quantification of the error in the estimation of the partial body activity using the calibration factors of wholebody distribution is described. The uncertainty associated with the estimation of $^{133m\text{Xe}}$ present in the thorax region using the calibration factors of wholebody and thorax region is discussed. This chapter also presents a study on the optimum number of static detector locations required to simulate the scanning mode of shadow shield counting system. The efficiencies of Phoswich for $^{241\text{Am}}$ present in lungs and the liver obtained with LLNL phantom measurements are compared with that of ICRP male voxel phantom. The quantification of the sources of uncertainties like detector positioning and body size in the estimation of actinides using Phoswich detector are also discussed.

All the deviations calculated in this chapter are with respect to the measured value.

\[ \text{Deviation \%} = \frac{\text{simulated value} - \text{measured value}}{\text{measured value}} \]  

4.1
4.1 Shielded chair

4.1.1 Validation of shielded chair model using Masonite cut sheet phantom

Validation of the shielded chair modeling was done by comparing the simulated spectrum and calibration factors with the measured ones. Generally validation is done by comparing the photopeak calibration factors but since CSFs are also studied the entire simulated spectrum is compared with the measured one. The measured $^{137}$Cs spectrum and the simulated spectrum with and without all shielding components of the counting system are shown in Fig. 4.1. It is observed that though the deviation in the photopeak region is less, there is a large mismatch in the scattering region (40 - 400 keV) when the modeling was done without considering the shielding components of the system. This will result in large error in the estimation of CSFs which will lead to inaccurate estimation of activities of the low energy gamma emitters in the presence of high energy gamma emitting radionuclides. This deviation in the CSFs can be reduced by simulating all the surrounding shielding components. This can

Fig.4.1 Spectrum of $^{137}$Cs loaded in Masonite cut sheet using SC (a)Measured spectrum (b) Simulated spectrum without SS shell, support plate and detector shielding (c) Simulated spectrum with all the shielding components
be inferred from spectrum (a) and (c) of Fig.4.1. A good agreement with respect to the spectral shape, FWHM of photopeak, counts in the full energy peak and counts/keV in all the energy regions including the scattering region was observed. From this study it is clear that the scattering due to surrounding/shielding components greatly influence the counts in the 40 -400 keV region (Table 4.1). However, when all the components of exact dimension were modeled the measured and the simulated spectra matched within 10% in all regions validating the modeling of SC counting system. This was found to be consistent for other radionuclides also.

### Table 4.1 Influence of scattering from shielding components in the lower energy region for 662keV gamma photons

<table>
<thead>
<tr>
<th>Component added</th>
<th>counts/photon in 40-400 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>without SS shell</td>
<td>0.003227</td>
</tr>
<tr>
<td>3 mm SS in front and 6 mm SS in back</td>
<td>0.003602</td>
</tr>
<tr>
<td>shielding around the detector</td>
<td>0.003707</td>
</tr>
<tr>
<td>6 mm SS in front</td>
<td>0.003902</td>
</tr>
<tr>
<td>Measurement</td>
<td>0.004317</td>
</tr>
</tbody>
</table>

#### 4.1.2 Comparison of simulated and measured calibration factors - SC

The efficiency curve plotted using simulated values is shown in Fig.4.2. The calibration factors obtained from simulation are fitted using exponential function given by

\[
\varepsilon = a \times \exp(-b \times E)
\]

4.2

Where, \( \varepsilon \) is the calibration factor (Counts/photon), \( E \) is the photon energy in keV, \( a \) and \( b \) are fitting constants. Using the fitted equation, the calibration factors for radionuclides which are not readily available for calibration purpose can be estimated. Table 4.2 gives the predicted calibration factor (using equation 4.2) along with the measured values for typical energies.
Fig. 4.2 Simulated efficiency curve of shielded chair using Masonite phantom

Table 4.2. Measured and the calculated calibration factors of SC using Masonite phantom

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>Calibration factor (Counts/photon)</th>
<th>Ratio C/E</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured (E)</td>
<td>Simulated (C)</td>
</tr>
<tr>
<td>279</td>
<td>3.60E-03</td>
<td>3.35E-03</td>
</tr>
<tr>
<td>662</td>
<td>3.01E-03</td>
<td>2.81E-03</td>
</tr>
<tr>
<td>834</td>
<td>2.70E-03</td>
<td>2.60E-03</td>
</tr>
<tr>
<td>1274</td>
<td>2.38E-03</td>
<td>2.19E-03</td>
</tr>
<tr>
<td>1332</td>
<td>2.32E-03</td>
<td>2.15E-03</td>
</tr>
</tbody>
</table>

The ratio of the predicted calibration factor to the measured calibration factor varies from 0.92 to 0.96 for the energy range 250 keV to 1500 keV. The agreement of the measured and the predicted calibration factors is within -8%. These predicted values are well within the performance criteria of 50% to -25% (ANSI 1996) [133] thereby validating the use of equation 4.2 to estimate the efficiency. The difference in the simulated and experimental
(efficiency) values could be due to the error in the source activity and the position of the sources in the phantom [134]. Simulation provided additional calibration factor data in the energy range 1500 - 3000 keV.

### 4.1.3 Comparison of measured and simulated CSFs in different energy region

Apart from calibration factors, CSFs in different reference energy regions due to different radionuclides were also estimated in terms of CPS/Bq from the respective simulated spectrum by correcting simulated value with the yield of the high energy photon are summarized in Table 4.3. The deviations between the measured and the simulated values are within ±20% in all the reference regions, which is within ANSI criteria. Literature on the numerical estimation of CSFs is scanty and their comparison with the measurement is not reported in literature.

<table>
<thead>
<tr>
<th>Filled Radionuclide (Energy-keV)</th>
<th>CSFs in other ROI(CPS/kBq)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$^{57}$Co (110-140 keV)</td>
<td>$^{203}$Hg (230-330 keV)</td>
<td>$^{133}$Ba (330-415 keV)</td>
<td>$^{137}$Cs(590-720 keV)</td>
</tr>
<tr>
<td></td>
<td>Measured</td>
<td>Simulated</td>
<td>Measured</td>
<td>Simulated</td>
</tr>
<tr>
<td>$^{203}$Hg(279)</td>
<td>1.06</td>
<td>0.95</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>$^{137}$Cs(626)</td>
<td>0.70</td>
<td>0.61</td>
<td>1.24</td>
<td>1.19</td>
</tr>
<tr>
<td>$^{60}$Co(1173&amp;1332)</td>
<td>1.23</td>
<td>1.25</td>
<td>2.30</td>
<td>2.00</td>
</tr>
</tbody>
</table>

### 4.1.4 Influence of source depth on the calibration factors

In Masonite cut sheet phantom, sealed point sources can be loaded at different depths during calibration. The variation in the sources depth will affect the calibration factors derived for the system. The calibration factor of the SC system with Masonite phantom having uniform distribution of $^{137}$Cs was theoretically simulated. This uniform distribution can be represented experimentally by the use of multiple point sources. Hence, for the case of
Masonite cut sheet phantom, the source depth which will closely simulate the uniform distribution was estimated. In order to accomplish this, simulations were carried out by loading point sources at different depths of the phantom. Calibration factors were estimated in all the cases and compared with the uniform distribution. The simulated calibration factors with sources distributed at different depths are shown in Table 4.4 along with the calibration factor for uniform distribution. From the table it is clear that the source distributed at mid-thickness gives almost same (>2 %) calibration factor as that of uniform distribution. For the distribution of sources at the bottom and top surface the variation in calibration factor with respect to mid-thickness distribution for 662 keV gamma photons is -40% and +60% respectively. As the energy increases the deviation decreases (-33% to 51% for 1332 keV) and vice versa (-52% and 75% for 122 keV). The observed trend is due to self attenuation and geometrical factor. This study showed that 5 sources distributed at mid-thickness gives calibration factors close to uniform distribution.

<table>
<thead>
<tr>
<th>Source distributed at</th>
<th>Bottom</th>
<th>Top</th>
<th>Uniform</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middle</td>
<td>CF*</td>
<td>% Dev</td>
<td>CF*</td>
</tr>
<tr>
<td>2.81E-03</td>
<td>1.67E-03</td>
<td>-40</td>
<td>4.43E-03</td>
</tr>
</tbody>
</table>

*Note: CF = calibration factor

### 4.1.5 Comparison of calibration factors and CSFs - BOMAB phantom and Masonite cut sheet phantom

Shielded chair is calibrated using in-house built Masonite cut sheet phantom. Indian adult BOMAB phantom is the Indian representative of the standard international phantoms with uniform distribution of sources. In order to validate the use of Masonite phantom as a calibration tool for Indian reference adult a comparison of the calibration factors and CSFs of both the phantoms were made using shielded chair system. For this, Indian BOMAB phantom
was modeled along with SC. The calibration factors and CSFs were estimated for different energies. Table 4.5 gives the simulated calibration factors for the BOMAB phantom and Masonite cut sheet for different photon energies.

<table>
<thead>
<tr>
<th>Energy(keV)</th>
<th>Calibration factor (Counts/photon)</th>
<th>% Deviation (BOMAB –Masonite)/Masonite</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BOMAB</td>
<td>Masonite</td>
</tr>
<tr>
<td>279</td>
<td>3.33E-03</td>
<td>3.35E-03</td>
</tr>
<tr>
<td>662</td>
<td>3.14E-03</td>
<td>2.81E-03</td>
</tr>
<tr>
<td>834</td>
<td>2.84E-03</td>
<td>2.60E-03</td>
</tr>
<tr>
<td>1332</td>
<td>2.42E-03</td>
<td>2.19E-03</td>
</tr>
</tbody>
</table>

From the table, it can be observed that the calibration factors of Masonite phantom and of BOMAB phantom varies between -1% and 12%. Similarly the Compton scattering factors (CSFs) obtained using measurement with Masonite phantom and simulated with BOMAB phantom for various energies are listed in Table 4.6.

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Contribution in other ROI(CPS/kBq)</th>
<th>203Hg (230-330 keV)</th>
<th>133Ba(330-415 keV)</th>
<th>137Cs(590-720 keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured</td>
<td>Simulated</td>
<td>Measured</td>
<td>Simulated</td>
</tr>
<tr>
<td>133Ba</td>
<td>1.45</td>
<td>1.61</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>137Cs</td>
<td>1.24</td>
<td>1.13</td>
<td>0.69</td>
<td>0.62</td>
</tr>
<tr>
<td>60Co</td>
<td>2.3</td>
<td>2.23</td>
<td>1.23</td>
<td>1.15</td>
</tr>
</tbody>
</table>

The agreement between the measured and the simulated CSFs are found to be within 10%.

The agreement between the calibration factors and the CSFs of both the phantoms in the energy range 250 keV to 3000keV is within the acceptable ANSI Criteria, confirming that the Masonite phantom is equivalent to BOMAB phantom in this energy range. So the use of Masonite phantom as an alternate tool for calibration of wholebody counters is justified.
4.1.6 Simulation of partial body efficiencies

Radionuclides normally get deposited in different parts of the body like thorax, abdomen, neck etc., depending on the type of radionuclide and the mode of intake.

In order to estimate the calibration factors of various radionuclides for partial body distribution, one require phantom parts in multiple sets, each loaded with different radionuclides which is practically difficult. Estimation of partial body activity using calibration factors corresponding to whole body will result in large error [21]. Hence partial body efficiencies were simulated for a few radionuclides present in different parts of the body. Table 4.7 summarizes the theoretical calibration factors for sources distributed in different parts of the body along with the simulated calibration factors for uniform distribution. From the table it is clear that the activity of $^{131}$I present in the thyroid region is overestimated by a factor of 1.35 when the calibration factor of wholebody distribution is used for the activity estimation. The overestimation in the activity of the thorax region varies from 1.48 to 1.72 for the energy range 600 to 1332 keV. The underestimation in the activity of pelvis region varies from 0.47 to 0.6 for the same energy range.

Hence, organ specific calibration factors are required to improve the accuracy in the estimated activity in partial body and these values can be numerically simulated easily without physical phantoms.

<table>
<thead>
<tr>
<th>Organ</th>
<th>Calibration factor (CPS/Photon) for different energies</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>354(keV)</td>
</tr>
<tr>
<td>Neck</td>
<td>4.37E-03</td>
</tr>
<tr>
<td>Thorax</td>
<td>----</td>
</tr>
<tr>
<td>Pelvis</td>
<td>----</td>
</tr>
<tr>
<td>Wholebody</td>
<td>3.25E-03</td>
</tr>
</tbody>
</table>
As a practical application, the calibration factor for $^{133m}$Xe for thorax region was obtained through simulation. This value was used for the estimation of $^{133m}$Xe activity in an exposure event. Had the activity estimation done through the use of whole body calibration factor, it would have resulted in an overestimation of the activity by a factor of 1.5.

4.2 Shadow shield counter

4.2.1 Validation of Shadow shield counter modeling with Masonite cut sheet phantom

The SSC has scanning mode geometry and the calibration factor for the scanning mode was obtained by averaging the calibration factors of 10 static detector positions separated by a distance of 16 cm along the height of the phantom. The simulated calibration factor for $^{137}$Cs was lesser by 16%, compared to the calibration factor obtained through scanning mode measurement. In order to reduce this error, distance between two adjacent positions was adjusted to 10 cm, which is equal to the diameter of the detector. This makes the number of positions to 16. The deviation in the simulated and the measured calibration factor is less than 5%, which is of the order of the error in the calibration measurement, thereby validating the method adopted for the simulation of scanning mode of the SSC. This study revealed that the optimum displacement of detector should be equal to its diameter to obtain calibration factors within 5% to 10% deviation in the energy range of 250 keV to 1.5 MeV.

4.2.2 Comparison of simulated and measured calibration factors–Shadow shield counter

Using the validated model, the calibration factor of SSC with Masonite cut sheet phantom was estimated for various energies. Fig.4.3 gives the simulated and the measured efficiency values for various energies. The simulated values were fitted to the exponential equation given in 4.2 and the empirical constants ‘$a$’ and ‘$b$’ were obtained as 0.00105 and 0.0013 respectively.
Table 4.8 gives the calibration factors determined using the fitted equation and the measured values obtained for scanning mode are found to be matching within ±12% with the values obtained through measurements in scanning mode. This deviation is within the acceptable ANSI criteria.

![Graph showing efficiency vs energy with equation: EFF=3.406E-04+1.05E-03*exp(-1.302839E-03*Energy) and R²=0.9938](image)

**Fig.4.3** Measured and the simulated efficiency values of SSC with Masonite cut sheet phantom

Table 4.8 Simulated and measured calibration factors (CPS/photon) of SSC with Masonite phantom

<table>
<thead>
<tr>
<th>Energy(keV)</th>
<th>Measurement (E)</th>
<th>Simulation(C)</th>
<th>C/E</th>
</tr>
</thead>
<tbody>
<tr>
<td>354</td>
<td>1.07E-03</td>
<td>1.003E-03</td>
<td>0.93</td>
</tr>
<tr>
<td>662</td>
<td>7.80E-04</td>
<td>7.84E-04</td>
<td>1.01</td>
</tr>
<tr>
<td>834</td>
<td>6.23E-04</td>
<td>6.95E-04</td>
<td>1.12</td>
</tr>
<tr>
<td>1332</td>
<td>4.84E-04</td>
<td>5.26E-04</td>
<td>1.09</td>
</tr>
</tbody>
</table>
4.3 Phoswich detector

4.3.1 Validation for Low Energy gamma Photon measurements

The modeling of the Phoswich detector was verified by comparing the simulated and measured calibration factors for $^{241}$Am point source. The simulated efficiencies for 17 keV and 59.54 keV gamma photons are estimated as 0.0287 CPS/Bq and 0.0263 CPS/Bq respectively. These simulated efficiencies are observed to be lower by 4.5 % and 3.3% compared to the measured values for the same energies, thereby validating the detector modeling.

4.3.2 Validation of voxel phantom modeling

The validation of the voxel phantom modeling was done using LLNL voxel phantom having TP alone. The efficiencies for $^{241}$Am and Natural Uranium present in the lungs were numerically estimated. Table 4.9 shows the simulated and the measured efficiencies of LLNL phantom with TP for various radionuclides. The deviation between the simulated and the measured calibration factor for LLNL phantom with TP is 2% for $^{241}$Am thus validating the voxel phantom modeling. The simulated and the measured efficiencies of Natural Uranium show a deviation of <2% illustrating the fact that the distribution of 6 source plugs in each lung could simulate nearly a uniform distribution. Similar studies by Hunt et al. [135] have also shown that the geometrical mean of efficiencies obtained from point source distributed at the front, middle and back of the lungs is close to the calibration factor for homogenous distribution.

Table 4.9 Measured and simulated efficiencies of $^{241}$Am and Natural U using LLNL phantom with TP

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Energy used</th>
<th>Efficiency (CPS/kBq)</th>
<th>Deviation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Measured</td>
<td>Simulated</td>
</tr>
<tr>
<td>$^{241}$Am</td>
<td>59.54 keV</td>
<td>1.30</td>
<td>1.32</td>
</tr>
<tr>
<td>Natural Uranium</td>
<td>63 and 93 keV</td>
<td>7.05</td>
<td>7.2</td>
</tr>
</tbody>
</table>
4.3.3 Validation for High Energy gamma Photon measurements

Phoswich detector with a few selected high energy photon emitters like $^{137}$Cs, $^{133}$Ba and $^{60}$Co were modeled. The measured point source calibration factors for different high energies and the corresponding simulated calibration factor are listed in Table 4.10.

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>Calibration factor (CPS/Photon)</th>
<th>% deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured</td>
<td>Simulated</td>
</tr>
<tr>
<td>356</td>
<td>0.0733</td>
<td>0.0753</td>
</tr>
<tr>
<td>662</td>
<td>0.0483</td>
<td>0.0500</td>
</tr>
<tr>
<td>1332</td>
<td>0.0291</td>
<td>0.0298</td>
</tr>
</tbody>
</table>

From the table it is clear that the maximum deviation between the measured and simulated values is <5%. This validates the Phoswich detector model for high energy photon measurement.

4.3.4 Calibration factor of Phoswich detector for $^{239}$Pu present in the lungs of LLNL phantom

Having validated the Phoswich detector modeling for LEP measurement and the voxel phantom modeling technique, simulation was carried out to derive the calibration factor of $^{239}$Pu present in the lungs sets of LLNL phantom with TP. The estimated calibration factor is 75 CPS/MBq. This could not be verified experimentally due to the non-availability of $^{239}$Pu loaded lung sets in the LLNL phantom at IGCAR, presently.

4.3.5 Efficiency for ICRP voxel phantoms

**Efficiency of $^{241}$Am present in the lungs:** The validated Phoswich model was used to estimate the calibration factors of different actinides present in the lungs and liver of ICRP-AM voxel phantom. The measured efficiency curve for $^{241}$Am obtained using LLNL phantom.
having different MEQ-CWT is shown in Fig. 4.4 along with the simulated efficiency value of ICRP-AM.

Using the fitted equation established from the measurements with LLNL phantom, the efficiency value corresponding to the MEQ-CWT of ICRP male phantom was estimated. Table 4.11 compares the results obtained from the measurement of LLNL phantom and simulation using voxel phantoms. The simulated efficiency value of ICRP male voxel phantom (Table 4.11, S.No. 2) is less by 13%. This deviation is due the difference in the lung size of the phantoms. The ICRP male lungs are narrower and deeper compared to the LLNL lungs. Because of the larger size of the detector, the efficiency increase due the reduction in width is not greater than the reduction in efficiency due to the increase in the depth. So, overall the efficiency has got reduced. The same difference in the lung shapes is quoted for the difference in the calibration factor at 60 keV for JAERI and LLNL phantom by Kramer [117].
Table 4.11 LLNL measured and voxel phantom simulated calibration factors (CPS/kBq) for Phoswich detector

<table>
<thead>
<tr>
<th>S.No</th>
<th>Radionuclide</th>
<th>Experiment</th>
<th>Simulation</th>
<th>% Deviation #</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Phantom CF*</td>
<td>Phantom CF*</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Pu-239</td>
<td>JAERI 0.00676</td>
<td></td>
<td>0.005</td>
</tr>
<tr>
<td>2</td>
<td>Am-241</td>
<td></td>
<td>9.9</td>
<td>8.7</td>
</tr>
<tr>
<td>3</td>
<td>Am-241 liver</td>
<td></td>
<td>20.78</td>
<td>23.54</td>
</tr>
<tr>
<td>4</td>
<td>Contribution to lung counts from liver</td>
<td>LLNL 5.9</td>
<td>ICRP male voxel phantom 5.4</td>
<td>-9.7</td>
</tr>
<tr>
<td>5</td>
<td>Contribution to liver counts from lungs</td>
<td></td>
<td>2.9</td>
<td>2.5</td>
</tr>
<tr>
<td>6</td>
<td>Natural Uranium</td>
<td></td>
<td>5.92</td>
<td>5.28</td>
</tr>
<tr>
<td>7</td>
<td>Am-241</td>
<td></td>
<td>9.04</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Pu-239</td>
<td></td>
<td>0.0152</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Pu-239</td>
<td></td>
<td>0.0146</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Am-241</td>
<td>LLNL 27</td>
<td></td>
<td>12</td>
</tr>
</tbody>
</table>

Note *: CF = calibration factor, # with respect to the measured values.
Calibration factor of $^{239}$Pu present in the lungs of ICRP-AM: The simulated calibration factor for $^{239}$Pu present in the lungs of ICRP-AM for Uranium Lx-rays is given in Table 4.11. The simulated calibration factor was compared with the measured value obtained using the JAERI phantom as there is no $^{239}$Pu loaded lung set in LLNL phantom. The simulated value (Table 4.11, row 1) is 26% lesser than the measured value. The deviation is due to the difference in the physical and the simulated phantom with respect to the MEQ-CWT, shape of the lungs or other organs etc. The variation of calibration factors with respect to the MEQ-CWT could not be estimated as the JAERI phantom did not have overlay plates with different MEQ-CWT. Variation in the lung size and the heart size of the phantoms could have also contributed to the difference.

CSF in 17 keV region due to 59.54 keV gamma photons: The simulated CSF in 17 keV region due to the 59.54 keV gamma photons of $^{241}$Am was estimated to be 0.748 CPS per kBq of $^{241}$Am activity in lungs. This factor is necessary for correction of 17 keV counts due to the scattering of 59.54 gamma photons when $^{239}$Pu is measured in the presence of $^{241}$Am. This factor depends on the CWT and composition. When this contribution is not subtracted it will result in the overestimation of the activity of the $^{239}$Pu.

Calibration factor for Natural Uranium present in the lungs of ICRP-AM: The simulated spectrum of Natural Uranium present in the lungs of ICRP-AM is shown in Fig.4.5 along with the spectrum measured using LLNL phantom. From the figure it is clear that the simulated spectrum showed a decrease in counts in the energy region from 70keV to 90keV and also above 100 keV compared to the measured spectrum. The reason for the difference in counts is because the simulation did not include the HEP emitted from the immediate daughters of $^{238}$U ($^{234m}$Pa) and the 185 keV photons from $^{235}$U. When these high energies were also added in the simulation, the counts in the 70 to 90 keV region and above 100 keV
were closer to the measured values as shown in fig. 4.6. Exact matching could not be obtained since the PSD used in the Phoswich detector is not 100% efficient in discriminating the interference from HEPs, resulting in slightly higher counts in the measured spectrum. In
addition, the Bremsstrahlung due to betas (500 and 2310keV) of $^{234}\text{mPa}$ also contributes to the increased counts in the measured spectrum [124]. Calibration factor of Natural Uranium was estimated from the simulated spectrum and is given in Table 4.11. An underestimation of 12% in the calibration factor was found (Table 4.11, row 6) in the simulation compared to the measured one with same MEQ-CWT. This is equivalent to the deviation obtained for uniform distribution of 60 keV indicating that the six vial distribution at the centre of each lungs is equal to uniform distribution.

_Establishing an efficiency curve for low energy photons:_ Efficiencies were estimated for other low energies like 32, 81, 93 keV photons present in the lungs and are shown in Fig.4.7. The efficiency value is lower for 17 keV, due to the attenuation in the human chest wall and found to increase with the increase in energy because the smaller thickness of the NaI(Tl) detector results in lesser counts in the photopeak region.

![Efficiency plot of Phoswich detector for low energy photons](image-url)
Calibration factor of $^{241}\text{Am}$ present in the liver of ICRP-AM: The calibration factor for $^{241}\text{Am}$ in the liver was estimated theoretically as well as experimentally and are given in Table 4.11. It was observed that the simulated calibration factor (Table 4.11, Row 3) is 13% higher than measured calibration factor for the same MEQ-CWT. This variation can be attributed to the uncertainties in the certified activity of the source and minor variations in the physical dimensions of both the phantoms. The measured spectral response of $^{241}\text{Am}$ in the liver of

LLNL phantom with 3B overlay which had a closer MEQ-CWT (3.04 cm) and the simulated one is shown in Fig. 4.8. It can be observed from the Fig.4.9 that both the spectra are matching with respect to peak position, peak area counts and the spectral shape.

Cross talk in lungs and liver: Significant portions of the inhaled Pu/Am can be found in liver, after a certain period of time. According to the biokinetic behavior of $^{241}\text{Am}$, the activity in liver is maximum on 300$^{th}$ day after intake for M class and on 1000$^{th}$ days post intake for S class. This would be interfering with the lung measurements in follow-up in-vivo monitoring.
Similarly, while monitoring old intake through liver measurements, the lung activity due to new intake will interfere with the measurements. Hence, experiment as well as simulation was conducted to quantify these interferences for $^{241}$Am. The cross talk to the detector placed at the lungs due to presence of activity in the liver was simulated as 5.4 CPS/kBq of $^{241}$Am activity. It is 10% lesser (Table 4.11, row 4) compared to the measured value for the same MEQ-CWT.

The cross talk to the detector placed at the liver due to presence of activity in the lungs was numerically estimated as 2.5 CPS/kBq which is 12% (Table 4.11, row 5) lesser than the measured value for the same MEQ-CWT. Fig 4.9 gives the simulated $^{241}$Am spectra obtained in both the cases. From the figure it is observed that the contribution from the activity in the liver to the lung measurement is more than the contribution from the activity in the lungs to the liver.

Fig 4.9. Simulated cross talk in lungs due to liver activity and vice versa
Calibration factor of $^{241}$Am and $^{239}$Pu present in the lungs of ICRP-AF (Anterior positioning of the detector): The validated Phoswich model was positioned over the anterior chest region of the ICRP-AF voxel phantom. Calibration factors of $^{241}$Am and $^{239}$Pu present in the lungs were estimated and is listed in Table 4.11. The simulated calibration factors for $^{241}$Am and $^{239}$Pu are 1.5 and 3 times higher than that of the male phantom respectively. This is due to the presence of breast tissues which is mostly adipose in nature. Adipose tissue has lower attenuation coefficients compared to muscle owing to its lower density. Neither measurement nor the simulated value is available in literature for female phantoms for single Phoswich detector.

Posterior positioning of the detector: For the anterior positioning of the detector, the calibration factor is a function of breast size and one has to establish an empirical formula for estimating the breast size of females which has significant variation even amongst the same ethnic group [136]. In order to overcome the influence of the breast size on the calibration factors, an alternate placement of the detector was attempted by placing the detector at the back of the subject. The calibration factor of $^{241}$Am present in the lungs for the detector placed on the back of the ICRP-AF phantom was simulated and found to be 7.9 CPS/kBq, which is 12% less than the calibration factor obtained in the supine geometry. This reduction in calibration factor compared to supine geometry is due to attenuation of the gamma photons in the scapulae and spine. But still this can be used when the empirical relation for the breast size estimation is not available. The prone geometry for the female has 37% higher calibration factor compared to the supine geometry of ICRP-AM

4.3.6 Indian Thorax voxel phantom calibration factor

The validated Phoswich detector model was placed over the chest region of the Indian thorax voxel phantom in the same way as in ICRP-AM and the calibration factors of $^{239}$Pu and $^{241}$Am in the lungs were estimated. The calibration factors are listed in Table 4.11.
calibration factor of $^{241}\text{Am}$ and $^{239}\text{Pu}$ for Phoswich detector using Indian voxel phantom were almost higher by 2 times and 3 times respectively than that of ICRP-AM. The higher calibration factor is due to the less thickness of the chest wall and decreased lung volume in Indian thorax phantom. Kramer et al. [137] discusses the variation in calibration factor with the volume of the lung and concludes that the counting efficiency increases with the reduction in the lung volume. The calibration factor of actinides for Phoswich detector using the Indian thorax voxel phantom was estimated out for the first time. This brings out the need for estimating the calibration factors based on Indian reference phantom which has to be developed.

4.3.7 Uncertainty in calibration factor due to positioning of the detector

Numerical simulation has been applied to investigate the best counting geometry and to quantify the uncertainty due to improper positioning of the detectors. The efficiencies of $^{241}\text{Am}$ present in the lungs for different detector positions over the chest of ICRP-AM were estimated. These values were used to estimate the overall uncertainties in the calibration factor for the detector placement. Simulations were carried out by displacing the detector independently along X (lateral displacement), Y (vertical displacement) and Z (displacement along the height) directions. The results normalized to the value at the standard position of measurement $(x_0, y_0, z_0)$ are shown in Fig.4.10.

The variations in efficiencies along the three directions were fitted to polynomial functions given by,

$$\varepsilon(x) = \varepsilon(x, y_0, z_0) = 0.003x^2 + 0.002x + 0.99 \quad \text{(Lateral displacement)}$$ 4.2

$$\varepsilon(y) = \varepsilon(x_0, y, z_0) = -0.054y + 0.956 \quad \text{(Displacement from the chest surface)}$$ 4.3

$$\varepsilon(z) = \varepsilon(x_0, y, z_0) = -0.004z^2 - 0.009z + 0.994 \quad \text{(Displacement along height)}$$ 4.4
The simulated results of $^{241}\text{Am}$ calibration factor of the Phoswich detector positioned at various point over the chest of the ICRP-AM is used to estimate the overall uncertainty in the calibration factor for the detector displacement.

From the figure it is clear that the calibration factor is highest at $(x_0,y_0,z_0)$ and this is the optimum position of the detector for the measurement of actinides. As the distance increases between the chest plate and the detector, the calibration factor follows inverse square law. For the movement along the height of the subject, when the detector is moved towards the head, the area of the lung viewed by the detector remains almost constant and therefore there is not much change in calibration factors, whereas when it is moved towards the legs (positive), the area of the lung viewed is reduced so the calibration factor gets decreased to a little greater extent compared to the opposite direction movement. As the detector is moved towards right,
the area of lungs viewed by the detector becomes reduced due to the obstacle from the heart, leading to the reduction in the calibration factors. Considering the present positioning system of lung monitor, the maximum expected variation along any of the axes could be in the range of ± 2 cm. This variation has been considered in the estimation of uncertainties. Table 4.11 gives the uncertainties in the calculated efficiency, in terms of Coefficients of variation.

This study clearly indicates that the displacement of detector by ± 2 cm laterally and along the height will vary the calibration factor only by 2%. The individual contribution to the calibration factor uncertainty due to positional inaccuracy along all the axes was calculated. Assuming statistical independence, the propagation of the uncertainty is estimated using the following equation [32].

\[
\sigma^2(Eff(x,y,z)) = \sigma^2(Eff(x)) + \sigma^2(Eff(y)) + \sigma^2(Eff(z))
\]  

Then the total uncertainty calculated from the values listed in Table 4.12 is about 9.5%. As it can be seen, the movement of detector along Y axis results in a maximum error of 9% for 2 cm displacement. Study using two HPGe detectors placed over the right lung has also showed deviation in the same range [138]. Movement in the other axis results in errors less than 2%. Since, the present lung monitor (203 mm diameter) has a large area covering both the lungs completely, the variation of calibration factor resulting from the displacement is smaller in magnitude. For detectors with smaller areas these uncertainty values would be much higher and it is important to quantify it. In general, uncertainties upto 10% are
acceptable when compared to other uncertainties like CWT, organ shape and size etc., resulting in a measurement error (around 40%) [33], especially for low energy gamma photons.

4.3.8 Calibration factor of High Energy gamma photon emitters present in the lungs

Using the ICRP male voxel phantom the calibration factor of Phoswich (CsI crystal) for high energy photon emitters above 250 keV present in the lung was estimated by numerical simulation and is shown in Fig.4.11. These calibration factors are used for estimating HEP emitters, if any present, simultaneously during a lung monitoring.

4.4 Validation of the thyroid detector model

The thyroid detector was modeled with the neck region of the ICRP-AM. The distance between the detector and the neck is 21 cm. Calibration factor was simulated for $^{131}$I using 364 keV photons. The simulated calibration factor of thyroid monitor for $^{131}$I has a good agreement (<1% deviation) with the measured value. This proved the simulation expertise in modeling the flat field collimator apart from the scintillator detector and the modeling of Mathematical phantom (thyroid phantom).
4.5 Conclusion

The results of the simulation are broadly consistent with the results of the calibration measurements for all the in-vivo monitors indicating that mathematical phantoms could eventually complement physical phantoms in the calibration of in-vivo measurements for radionuclides. This instilled confidence in us for using the numerical calibration methods developed for the in-vivo monitors through this thesis work. Numerical calibration of wholebody counters (Shielded Chair and Shadow Shield Counter) using Masonite cut sheet phantom has not been reported in literature. The simulation study showed that the current distribution of 5 sources at mid thickness is equal to uniform distribution for wholebody counting systems. Comparison of the Masonite phantom and Indian adult BOMAB as a calibration tool for shielded chair counting system is unique. It was evident from the research work that the in-house built Masonite cut sheet phantom is equivalent to Indian BOMAB phantom as a calibration tool for shielded chair counting system for energies above 250 keV. The study to simulate the scanning geometry with multiple static detector positioning has shown that the optimum number of static detector location is equal to the quotient of the length scanned and the diameter of the detector. Numerical estimation of the Compton Scattering factors is very limited and their comparison with the experimental one is almost not reported in literature. Theoretical study of the calibration factors of LEPs and HEPs present in the lungs, liver, for male and female workers using single Phoswich detector is not reported. Estimation of calibration factors of Phoswich detector for LEPs using Indian voxel phantom is not reported in the literature. The simulation study carried out in the thesis work has helped in the estimation of the Indian reference specific calibration factor of $^{241}$Am and $^{239}$Pu and thus the uncertainty in the activity estimation. The close matching between the simulation results of uniform distribution of Natural Uranium lung set and the hole matrix lung set has shown that the distribution of 12 plugs in the lung set at middle of the lungs is
equal to the uniform distribution for single Phoswich counting geometry. The simulation study carried out for the Phoswich system at IGCAR to estimate the variation of calibration factor due to change in the detector positioning has showed a maximum variation of <10% when the displacement of the detector is within 1 cm. The large variation in the efficiencies obtained using various phantoms proves the importance of quantifying the uncertainties in lung counting and confirms the requirement of personalized computational phantoms for lung monitor calibration.

The next chapter discusses the application of the numerical simulations to estimate the size correction factors for calibration factors and to reduce the bias in the estimated activity in the phantoms received as part of intercomparison exercise and also the development of voxel phantom from CT images and modeling of HPGe detectors.