Direct, In Vivo Calibration Measurement of $^{241}$Am in the Axillary Lymph Nodes Using the Livermore Thoracic Phantom

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1.0 ABSTRACT

The Livermore Torso Phantom, the consensus calibration phantom for measuring internally deposited radioactive materials in the lungs, liver and tracheo-bronchial lymph nodes, has been modified for calibrating direct, in vivo measurements of $^{241}$Am in the axillary lymph nodes. The axillary lymph nodes may contain radioactive material mobilized from a wound in a finger or hand which may confound results of a direct, in vivo measurement of the lungs or liver. Modifications to the Livermore Torso Phantom involved milling a pair of parallel, flat bottom cylindrical holes into the left and right shoulders (below the humeral head) for inserting a pair of solid 1.40 cm diameter cylindrical rods made of a 100% muscle tissue substitute. A precisely known quantity of radioactive material was sealed in a 1 cm diameter, 2.54 cm deep well located at the end of each rod. The location adopted for the simulated lymph nodes was determined according to the position of the Level I and the combined Level II +III axillary lymph nodes reported in the literature. Discrete calibration measurements were performed for axillary lymph nodes located in the right and left side of the thorax using a pair of 3000 mm$^2$ high resolution germanium detectors. The efficiency for measuring $^{241}$Am in the right and left lymph nodes is 2.603% ± 0.0342% and 5.453% ± 0.0716%, respectively. Activity deposited in the right and left axillary lymph nodes was found to contribute 0.183% and 0.289%, respectively, to a lung measurement and 0.013% and 0.002%, respectively, to a liver measurement. Thus, results of this research demonstrate that $^{241}$Am deposited in the axillary lymph nodes has the potential to confound direct, in vivo measurements of activity in the lung or liver.

2.0 INTRODUCTION

Radiation workers who have a potential for inhaling radioactive materials may be monitored using direct, in vivo measurements for radioactive materials deposited in the lungs. Results of such measurements may potentially be confounded by the presence of radioactive materials deposited in any of the lymph nodes located in the chest. Reports in the literature demonstrate that, in time, a fraction of the radioactive contamination deposited in a wound located on a finger, hand, or arm is likely to migrate to the axillary lymph nodes where it has the potential to interfere with a direct, in vivo measurement of activity in the lungs or liver. [1] [2] [3] [4] [5]

The Livermore Torso Phantom is the consensus standard for calibrating detector systems used for in vivo measurement of radioactive materials deposited in the lungs, liver, or tracheo-bronchial lymph nodes. The phantom is a surrogate for the adult male thorax and contains removable internal structures to simulate the lungs, liver, heart, skeleton, GI track, and tracheo-bronchial lymph nodes. The liver, lungs, and tracheo-bronchial lymph nodes can be fabricated with a known quantity of radioactive material for performing calibration measurements. [6] This paper describes the design and fabrication of a surrogate for the axillary lymph nodes and their use in the Livermore Torso Phantom that has been modified to accommodate these new structures.

2.1 AXILLARY LYMPHATIC SYSTEM

The human axillary lymphatic system includes a complex arrangement of 20 to 40 lymph nodes arranged into 5 main groups. These individual groups have unique names, locations, and functions. All the axillary lymph nodes are generally categorized into three levels centered around and under the pectoralis minor muscles of the upper torso. Level I axillary lymph nodes are located below the pectoralis minor muscle and run along the outer edge of the upper thorax and under the arm and shoulder. Level II nodes are primarily situated behind the pectoralis minor muscle. Level III lymph
nodes are located next to the Level II nodes and are the innermost axillary lymph nodes located closer to the neck on the upper border of the pectoralis minor muscle. The Level II and Level III axillary lymph nodes are situated close together and extend along the bottom edge of the clavicle. In most cases, all three levels of lymph nodes are located in front of the anterior posterior (AP) separation midline. [7][8] The Level II and Level III axillary lymph nodes are deeper below the anterior surface of the thorax than the Level I lymph nodes. Fig. 1 shows the generalized location of the lymph nodes in the axilla region in relation to the humeral head of the shoulder. [9] The location of the Level I, II, and III axillary lymph nodes vary greatly from person to person.

Figure 1: Diagram of Axillary Lymph Nodes Measurement Technique [9]

The primary function of the axillary lymphatic system is to re-circulate proteins and other interstitial fluids removed from tissue back into the blood stream. [10] Proteins and other massive particles easily permeate lymphatic capillaries which are significantly porous and allow for easy transfer of fluids and proteins. Each group and level of lymph nodes associated with the axillary lymphatic system draws lymphatic fluid from specific areas of the body. Fixed white blood cells, known as macrophages, are produced in the axillary lymph nodes and can engulf or capture unknown particles and materials (such as bacteria and foreign bodies) that pass through the nodes as part of the body’s immune system in a process known as phagocytosis. Particles entering the lymphatic system via a wound on the hand, wrist, or arm can be phagocytized to the axillary lymph nodes in a manner similar to the fate of insoluble particles deposited in the respiratory tract that may be transferred and permanently retained in tracheobronchial lymph nodes. [11]

The transport and retention of insoluble particles in the lymph nodes of the axilla introduced through wounds or cuts of the hand, finger, wrist, or arm is not clearly defined. However, sentinel lymph node mapping, a procedure which involves tracking the uptake and retention of a dye into the lymphatic system explicitly for linking a specific group of lymph nodes to a cancerous malignancy, demonstrates that the rate at which colloidal particles move through the body and are retained in the axillary lymphatic system is inversely dependent on the size of the particle. [12]

3.0 METHOD AND MATERIALS

3.1 ADDITION OF AXILLARY LYMPH NODES

The Livermore thoracic phantom is the de facto consensus standard for calibrating direct, in vivo measurements of low photon energy emitting radioactive materials deposited in the lungs, liver and tracheo-bronchial lymph nodes. [13] Although not considered in the original design criteria for the Livermore phantom, calibration factors are needed to determine the quantity of activity deposited in
the axillary lymph nodes since it is intuitive that lung measurements may be confounded by the presence of activity in these organs.

Computed tomographic (CT) images of the Livermore phantom were obtained to determine the positions of the imbedded rib, vertebrae and the conventional removable organs relative to the proposed locations for the new right and left axillary lymph nodes. The Livermore phantom, like the human, is not entirely symmetric so that the efficiency for detecting activity is not identical using a pair of detectors over the right and left axillary lymph nodes. Likewise, confounding contributions from activity in the lymph nodes to lung and liver measurements will be different depending upon whether the right or left axillary lymph nodes are involved. The optimum location for these axillary lymph nodes was determined following a comprehensive review of the literature. Bentel et al. [7] developed the following relationship to predict the depth of the axillary lymph nodes below the anterior surface of the thorax: \( AX = \frac{1}{2} AP - 3 \) cm, where AP is the anterior to posterior thickness of the torso about 2-3 cm caudal to the humeral head and AX is the depth of the lymph node measured from the anterior surface of the thorax. The calculated depths for the right Level I and Level II + III lymph nodes using Bentel’s relationship for the Livermore phantom are 3.24 cm and 4.55 cm, respectively. The left side Level I and Level II + III lymph nodes are 2.86 cm and 3.7 cm below the anterior surface of the thorax, respectively. A decision was made to combine the Level II and Level III lymph nodes into a single structure given the close proximity of these nodes cited in the literature. Thus, for calibration measurements, the axillary lymph nodes can be simulated by inserting two point sources within either the right or left shoulder of the Livermore Torso Phantom.

A modification was made to the Livermore Thoracic Phantom that involved using a milling machine to create two pairs of identical, parallel, flat bottom holes in the right and left pectoral minor muscle, respectively, to accommodate removable cylindrical structures that simulate axillary lymph nodes. The holes are 1.43 cm in diameter and were drilled into pectoral minor muscles beginning at the extreme right and left shoulders of the Livermore phantom. (Fig 2) The depth of the holes for the Level I and Level II + III axillary lymph nodes are 3.0 cm and 6.4 cm, respectively. The position of the holes was selected to minimize loss of material and to avoid any change that would negatively impact the original design criteria for the phantom. Blank (no radioactivity) lymph nodes are provided to fill the holes when radioactive lymph nodes are not desired.

Figure 2: Milling of channels in the Livermore Torso Phantoms for the Level I and Level II + III Lymph Nodes. The phantom is positioned on its side under the milling machine.

The cylindrical lymph node plugs have a diameter of 1.40 cm and are fabricated using a 100% muscle tissue formulation to fit snugly into the holes. The end of each cylinder has a 1.00 cm diameter 2.54 cm long well in which the desired quantity of radioactive material can be permanently sealed. A small plug made of 100% muscle tissue substitute is used to seal radioactive material in the channel (Fig. 3). A set of four cylindrical lymph node plugs containing precisely known quantities of \(^{241}\)Am were fabricated. A duplicate set of lymph nodes without radioactive material was fabricated to fill the
channels as blanks. A third set of lymph nodes containing small metal tubes instead of radioactive material were fabricated for CT scanning to reveal the actual position of the nodes when installed in the Livermore Torso Phantom.

Figure 3: Axillary Lymph Node Plugs in holder prior to sealing radioactive solution in the ends.

The desired dimensions, locations, placement, and depths of the Level I and combined Level II + III lymph node plugs adopted for the Livermore phantom are shown in Fig. 5 based on an extensive literature review and measurements taken from the phantom’s CT images. It was necessary to estimate the position of the humeral head on the right and left side of the thorax since the Livermore phantom does not include this structure in the imbedded skeleton. The desired and actual locations for the lymph nodes are listed on Table 1.

Table 1: Desired and actual positions of the right and left axillary lymph nodes in the Livermore Torso Phantom determined by CT image analysis.

<table>
<thead>
<tr>
<th>Channel</th>
<th>X₁</th>
<th>X₂</th>
<th>X₃</th>
<th>X₄</th>
<th>Y₁</th>
<th>Y₂</th>
<th>Z₁</th>
<th>Z₂</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Desired Positions (cm)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Right</strong></td>
<td>5.5</td>
<td>8.9</td>
<td>6.2</td>
<td>8.0</td>
<td>3.2</td>
<td>4.5</td>
<td>8.6</td>
<td>7.0</td>
</tr>
<tr>
<td><strong>Left</strong></td>
<td>5.5</td>
<td>8.9</td>
<td>6.3</td>
<td>7.9</td>
<td>2.9</td>
<td>3.7</td>
<td>8.5</td>
<td>6.6</td>
</tr>
<tr>
<td><strong>Actual Position (cm)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Right</strong></td>
<td>5.0</td>
<td>8.0</td>
<td>5.9</td>
<td>7.6</td>
<td>3.3</td>
<td>4.5</td>
<td>8.0</td>
<td>6.5</td>
</tr>
<tr>
<td><strong>Left</strong></td>
<td>5.3</td>
<td>8.7</td>
<td>6.2</td>
<td>8.0</td>
<td>2.5</td>
<td>3.5</td>
<td>8.0</td>
<td>5.6</td>
</tr>
<tr>
<td><strong>Percent Difference</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Right</strong></td>
<td>10.0</td>
<td>11.3</td>
<td>5.1</td>
<td>5.3</td>
<td>3.0</td>
<td>0.0</td>
<td>7.5</td>
<td>7.7</td>
</tr>
<tr>
<td><strong>Left</strong></td>
<td>3.8</td>
<td>2.3</td>
<td>1.6</td>
<td>1.3</td>
<td>16.0</td>
<td>5.7</td>
<td>6.3</td>
<td>17.9</td>
</tr>
</tbody>
</table>
The actual physical locations of the axillary lymph nodes inserted into the phantom after milling were determined from a CT image using lymph node plugs with opaque metal tubes replacing the radioactive material (Fig. 5). An additional 2.54 cm was added to the desired values for X₁ and X₂ to accommodate the shallow well containing radioactive material. The Level I and Level II + III lymph node plugs on the left side were milled at a slight angle causing the actual measurements of Y₁ (16.0%) and Z₂ (17.9%) to differ by more than 10% from their desired values.
Figure 5: CT image showing internal structures of the Livermore Torso Phantom and the actual positions of the right and left Level I (lower) and Level II + III (upper) simulated axillary lymph nodes. White blocks designate the positions of the simulated lymph nodes and were formed by inserting metal pins into the lymph node plugs where radioactive material would normally be inserted.

4.0 RESULTS

4.1 MEASUREMENTS OF THE AXILLARY LYMPH NODES, LUNGS, AND LIVER

A series of measurements using an array of 3000 mm$^2$ high resolution germanium detectors were performed with the modified Lawrence Livermore Thoracic Phantom at the University of Cincinnati In-Vivo Radiation Measurements Laboratory to determine the efficiency for detecting $^{241}$Am in the lung, liver, and axillary lymph nodes. An array of two detectors was used to measure activity in the axillary lymph nodes with the edge of one detector positioned directly under the clavicle and the edge of the other detector along the junction between the shoulder and thorax. Three and four detectors were used to measure activity in the liver and lungs, respectively. Table 2 lists the measured detection efficiency for $^{241}$Am for each organ.

Table 2: Detection efficiency for $^{241}$Am deposited in the axillary lymph nodes, liver and lungs using arrays of high resolution germanium detectors.

<table>
<thead>
<tr>
<th>Measurement Position</th>
<th>% Efficiency (cps Bq$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left Axillary Lymph Node</td>
<td>$5.453 \pm 0.072$</td>
</tr>
<tr>
<td>Right Axillary Lymph Node</td>
<td>$2.603 \pm 0.034$</td>
</tr>
<tr>
<td>Liver</td>
<td>$1.056 \pm 0.017$</td>
</tr>
<tr>
<td>Lungs</td>
<td>$1.466 \pm 0.020$</td>
</tr>
</tbody>
</table>
The change in detection efficiency with energy of the activity deposited in the axillary lymph nodes was determined for the photons and x-rays emitted by $^{241}\text{Am}$ (Fig. 6). Since the axillary lymph nodes are closer to the anterior surface on the right than on the left, the detection efficiency is likewise higher on the right than on the left.

4.2 INTERFERENCE FROM AXILLARY LYMPH NODES ON LUNG AND LIVER MEASUREMENTS

Measurements were performed to investigate whether activity deposited in the axillary lymph nodes would interfere with direct, \textit{in vivo} measurements of activity in the lung and liver. The axillary lymph nodes containing a known quantity of $^{241}\text{Am}$ were installed first in the right and then in the left shoulder of the Livermore Torso Phantom. An array of three and four detectors were positioned over the liver or lung region, respectively, with a blank (i.e., no activity) liver or lung set installed in the Livermore Torso Phantom. Table 3 lists the confounding contribution that $^{241}\text{Am}$ activity at 59.5 keV in the right or left axillary lymph nodes makes to a liver or lung measurement.

<table>
<thead>
<tr>
<th>Right Axillary Lymph Nodes</th>
<th>Left Axillary Lymph Nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0130 ± 0.0002</td>
<td>0.0020 ± 0.0001</td>
</tr>
<tr>
<td>0.1830 ± 0.0024</td>
<td>0.2890 ± 0.0038</td>
</tr>
</tbody>
</table>

Table 3: Contribution to Direct, \textit{In Vivo} Measurement of Liver or Lung from $^{241}\text{Am}$ activity in the right or left axillary lymph nodes.
5.0 DISCUSSION

Prior to modifying the Lawrence Livermore Torso Phantom to accommodate the right and left axillary lymph nodes, computerized tomographic (CT) images showed that the internal structure of the left and right shoulders were significantly physically different in AP thickness, size and shape. Therefore, the actual location and depth of the left lymph node plugs are more superficial than the right plugs, differing about 17.0 % from the desired location and depth.

The efficiency for measuring 73.1 kBq of $^{241}$Am in the right and left lymph nodes is $2.60 \pm 0.03 \%$ and $5.45 \pm 0.07 \%$, respectively, using the 59.5 keV photon. The actual depth of the Level I axillary lymph nodes from the anterior surface of the thorax on the left side is 2.5 cm vs. 3.3 cm for the right side. Although it was desired to determine the variation in detection efficiency with thickness of the chest wall, the overlay plates used with the Livermore Torso Phantom do not completely cover the axilla region of the shoulder. Future research will include fabricating new chest plates for the phantom so that the change in efficiency with chest wall thickness can be determined. This research is necessary since a correction should be made to the estimated activity to account for the attenuation of the low energy photons due to the thickness of the chest wall.

Activity deposited in the right or left axillary lymph nodes has been shown to confound direct, in-vivo measurements of liver and lungs. The axillary lymph nodes closest to the contaminated extremity wound are the eventual target for activity transported from the wound. Because the axillary lymph nodes are close in proximity to the lungs, interference is most likely to occur during a direct, in vivo measurement of the lungs rather than the liver. However, Table 3 shows that some contribution to a direct, in vivo measurement of the liver is possible from activity deposited in the axillary lymph nodes.

6.0 CONCLUSION

Experience has demonstrated that radioactive contamination in a wound on the finger or hand may be transported in time to the axillary lymph nodes and interfere with other routine in vivo measurements. Thus, the Livermore Torso Phantom was modified for calibrating direct, in vivo measurements of $^{241}$Am in the axillary lymph nodes and determining the interference produced on a measurement for activity deposited in the lungs or liver. The modifications include the addition of two cylindrical plugs made using a formulation of polyurethanes that simulate human muscle having a known quantity of radioactive material permanently sealed in the end of the plug. The plugs are inserted into either the right or left shoulder and simulate a grouping of Level I and Level II + III axillary lymph nodes that are actually distributed throughout the tissue. The modifications made to the Livermore Torso Phantom to accommodate the axillary lymph nodes make no change in the original design performance specifications for the phantom. The counting efficiency at 59.5 keV for $^{241}$Am in the right and left axillary lymph nodes is $2.60 \pm 0.03$ count sec$^{-1}$ Bq$^{-1}$ and $5.45 \pm 0.07$ count sec$^{-1}$ Bq$^{-1}$, respectively. The interference to a direct, in vivo measurement of the lung from activity deposited in the right and left axillary lymph nodes is $0.183\% \pm 0.002\%$ and $0.289 \pm 0.004$, respectively. Therefore workers having a wound on a hand or finger potentially contaminated with a radioactive material should be monitored for activity in the axillary lymph nodes to avoid a potential for incorrectly assigning to the lungs a deposition that is actually located in the axillary lymph nodes.

7.0 REFERENCES


