A New Anthropometric Calibration Phantom for *In Vivo* Measurement of Bone Seeking Radionuclides

H. B. Spitz and J. C. Lodwick
University of Cincinnati, Department of Mechanical, Industrial & Nuclear Engineering, 598 Rhodes Hall, Cincinnati, Ohio 45221-0072 U.S.A.

ABSTRACT

A new anthropometric phantom having the shape of the adult human knee and containing a removable femur, patella, tibia, and fibula, has been developed for use in calibrating *in vivo* measurements of bone-seeking radionuclides. The shell of the phantom is assembled in three interlocking sections so that the skeletal components can easily be exchanged. All the materials used in the phantom have the same density, attenuation coefficient, and effective Z as that of human muscle and trabecular bone. A precisely known quantity of one or more radioactive materials is added to the trabecular bone substitute when molding the skeletal components for the phantom. An array of germanium or Phoswich detectors can easily be positioned on the top or sides of the knee phantom for calibration measurements. Estimates of the total skeletal content can be determined by measuring activity in the knee and adjusting the result for the fraction of skeleton monitored. The bones contained in the knee phantom represent approximately 10.7% of the total skeletal mass or approximately 12.4% of the total skeletal surface area. The counting efficiency for $^{241}\text{Am}$ in the knee (per unit detector surface area) is approximately $6 \times 10^{-5}$ cpm/Bq/mm$^2$ using an array of germanium or Phoswich detectors. A single knee phantom exhibits approximately the same counting efficiency as the conventional skull phantom, suggesting that the knee is a desirable alternative to the head, especially if contamination is present on the hair or face or if the person is uncomfortable with detectors surrounding their head. Intercomparison measurements using skull and knee phantoms demonstrate that measurement efficiencies are equivocal. Measurement sensitivity can be substantially improved by placing detectors over both knees rather than around the head since a larger fraction of the total body activity would be monitored.

INTRODUCTION

Estimating the quantity of radioactive material deposited in the respiratory tract from *in vivo* measurement of the anterior thorax is confounded by the presence of even the smallest quantity of activity in the skeleton (1). This is especially true for low energy photon emitting radionuclides, such as $^{241}\text{Am}$, plutonium, and uranium, because activity in the rib will likely be detected with greater efficiency than activity in the lungs. Therefore, it is necessary to determine the skeletal content of bone-seeking radionuclides whenever activity in the lung is measured. Adjustments can be made to the measured lung deposition to account for interference from activity deposited in the thoracic skeleton (2). Making these adjustments requires use of a realistic calibration phantom to convert detector response into a quantity of activity deposited in the skeleton. Although one-of-a-kind phantoms of the human skull, leg, and arm have been used to perform calibrations for bone-seeking radionuclides, each of these phantoms is unique and limited to only one radionuclide (3-5).

*In vivo* measurements for bone seeking radionuclides have been performed to evaluate occupational exposure to plutonium, $^{241}\text{Am}$, and uranium. The transuranic radionuclides are primarily bone surface seeking elements and will deposit at sites in the skeleton that contain a large proportion of available surface area. Recently, a new anthropometric calibration phantom was developed at the University of Cincinnati for calibrating *in vivo* measurements of stable lead in bone using X-ray fluorescence (6,7). This phantom has the shape and appearance of the midshaft of the adult human leg, includes a polyurethane shell that simulates human muscle, and a removable tibia fabricated using a tissue substitute material for cortical bone.

Following the design criteria adopted for the leg, a surrogate of the adult human knee was developed to calibrate *in vivo* measurements for bone seeking radionuclides. The knee phantom has the external shape and appearance of the human adult knee and contains a realistic femur, patella, tibia, and fibula. Unique formulations of polyurethanes, CaCO$_3$, and other trace materials are used in construction of the phantom to produce substitutes for human tissue having the same density, attenuation coefficient, and effective Z as that of human muscle and trabecular bone (8,9). The formulation for trabecular bone includes provision for a precisely known quantity of radioactive material that is either uniformly distributed throughout the bone matrix or deposited on the exterior
surface. The knee phantom is assembled in three interlocking sections that simplify inserting the skeletal structures and prevent streaming. One or more detectors can easily be positioned for counting on the top or sides of the phantom. The bones contained in the knee phantom represent approximately 10.7% of the total skeletal mass and may represent a desirable alternative to a skull phantom. In fact, improved sensitivity is likely achieved if in vivo measurements were performed with detectors positioned on both knees, since approximately 22% of the mass of the skeleton (and approximately 70% of the total bone surface area) could be measured.

METHODS & MATERIALS

Fabrication of the Phantom

A solid plaster cast of an adult male knee, flexed at approximately 20°, was formed and then used as a model to fabricate a silastic rubber mold. The knee phantom was fabricated using this mold and a muscle tissue substitute. Silastic rubber molds for each of the proximal ends of the tibia and fibula, the distal end of the femur, and the patella were also constructed using sections of natural bone as models. The knee phantom is cast in three interlocking sections so that the bones can easily be inserted and removed. Figure 1 shows the completed phantom along with the skeletal components removed.

Fabrication of Skeletal Components

A fibula, tibia, femur, and patella were used as models to fabricate permanent silastic rubber molds from which individual surrogate bones were formed. The desired radioactive material is added by mass in solution along with the other components when forming the trabecular bone substitute. The radioactive material is then uniformly distributed throughout the bone substitute. All the materials are thoroughly mixed and placed in a vacuum chamber to remove entrained air. Immediately after degassing, the individual molds for the skeletal components are filled and clamped shut. Curing is completed within approximately 24 - 48 hr. The total activity in each of the skeletal components is determined by the mass of each structure after removal of mold flash, if any. The mass of the residual material after filling the molds plus the mold flash are combined and can be analyzed to determine the residual activity for quality assurance documentation. An alternative method for labeling the bones is to directly apply radioactive material to the surface of the trabecular bone substitute after it has cured.

Fabrication of Tissue Substitute for muscle

Selecting the most optimum chemical formulation to produce tissue substitutes is based upon how well the final product approximates the density (\(\rho\)), attenuation (\(\mu\)), and effective atomic number (\(Z_{eff}\)) of the desired human tissue, especially for low photon energies (9). Griffith’s (10) formulation for 100% muscle equivalent material was selected for the shell of the knee phantom since it exhibits the appropriate \(\rho\), \(\mu\), and \(Z_{eff}\) and it is well characterized in ICRU Report #44 (8). Likewise, this formulation was adopted for the Livermore Thoracic Phantom (11), the defacto calibration standard for lung counting. This formulation contains a urethane polymer (Adiprene L-167) and a polyol compound (LHT-240). The reaction is catalyzed by a small amount of stannous octoate catalyst and a silicone anti-foaming agent (SAG-471) is used to inhibit foaming during mixing. An
amount of CaCO₃ is added to the polyurethanes to increase the effective atomic number and density of the final material. Unique formulations for muscle and trabecular bone have been adopted that differ only in the quantity of CaCO₃. Kellar (5) and Lodwick (12) describe the development and testing of the optimum formulations using contemporary materials for muscle and bone substitutes, respectively.

**In Vivo Calibration Measurements**

The knee phantom was measured using arrays of high-resolution germanium detectors at whole body counters located at three different facilities operated for the U. S. Department of Energy. The phantom was also measured using an array of Phoswich detectors at the New York University Medical Center whole body counter. Figure 2 shows the knee phantom being positioned under a 4-detector array of germanium detectors.

**RESULTS**

Several batches of tissue substitute materials were fabricated with different percentages of CaCO₃ to measure the density and mass attenuation coefficient at 59.54 keV. The elemental composition of each batch of material was used as input for the computer code XCOM (13) to calculate the attenuation coefficient at 59.54 keV. Table 1 gives the measured and calculated results for each batch of tissue equivalent material. The attenuation reported by XCOM is the total mass attenuation without coherent scattering. The difference between the measured and calculated mass attenuation coefficient in material with low calcium content is significantly greater than with high calcium content. The reason for this outcome is not known.

<table>
<thead>
<tr>
<th>Batch ID</th>
<th>% CaCO₃</th>
<th>Density (g/cm³)</th>
<th>Mass Attenuation (cm²/g)</th>
<th>Mass Attenuation* (cm²/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM2</td>
<td>0.00</td>
<td>1.19 ± 0.025</td>
<td>0.147 ± 0.069</td>
<td>0.183</td>
</tr>
<tr>
<td>TM1 †</td>
<td>4.30</td>
<td>1.18 ± 0.020</td>
<td>0.166 ± 0.0054</td>
<td>0.190</td>
</tr>
<tr>
<td>X1</td>
<td>15.00</td>
<td>1.33 ± 0.020</td>
<td>0.168 ± 0.0034</td>
<td>0.208</td>
</tr>
<tr>
<td>RB2 †</td>
<td>32.94</td>
<td>1.44 ± 0.033</td>
<td>0.213 ± 0.0056</td>
<td>0.237</td>
</tr>
<tr>
<td>CB14</td>
<td>45.00</td>
<td>1.55 ± 0.034</td>
<td>0.236 ± 0.0057</td>
<td>0.256</td>
</tr>
<tr>
<td>CB9-12</td>
<td>58.00</td>
<td>1.67 ± 0.024</td>
<td>0.271 ± 0.0041</td>
<td>0.277</td>
</tr>
<tr>
<td>CB13</td>
<td>60.00</td>
<td>1.70 ± 0.027</td>
<td>0.273 ± 0.0051</td>
<td>0.281</td>
</tr>
</tbody>
</table>

*The mass attenuation coefficient at 59.5 keV was calculated using XCOM and the elemental composition of each material used in the formulation of the tissue substitute.
† This formulation was adopted for 100% muscle.
‡ This formulation was adopted for trabecular bone.

Table 2 gives the results of *in vivo* calibration measurement for $^{241}$Am using the knee phantom at whole body counters with arrays of germanium or Phoswich detectors. The same phantom was used for all the calibration measurement results, except that a separate set of bones containing only $^{241}$Am was used with the Phoswich detectors. The detection efficiency per unit surface area of detector is relatively constant regardless of the type of detector used for the measurement.

Intercomparison measurements were also performed using the UC anthropometric knee phantom and two individual skull phantoms. Comparison of the measurement results using the knee and skull phantoms indicates that the calibrations are essentially equivocal. On the other hand, a greater fraction of the total skeletal content would be measured if detectors were positioned over both knees rather than over one knee or the skull. Therefore, it is likely that the most optimum counting position to measure the skeletal content of a bone seeking radionuclide is to place detectors adjacent to both knees.

**DISCUSSION**

Inhalation of a soluble, bone seeking radioactive material may lead to a fraction of the inhaled material being translocated to bone that could interfere with routine monitoring of the lungs and confound estimates of lung dose. Therefore, *in vivo* measurement of the knees or skull is appropriate whenever a lung measurement is found to be positive following suspected intake of a soluble bone-seeker.

<table>
<thead>
<tr>
<th>Measurement Site (detector surface area)</th>
<th># Detectors in Array</th>
<th>Count Rate (cpm)</th>
<th>Efficiency (cpm/nCi)</th>
<th>Efficiency (cpm/nCi/kg skeleton)</th>
<th>Efficiency (cpm/nCi/mm² detector surface area)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lab 1 (2000 mm²)</td>
<td>4</td>
<td>25,580</td>
<td>15.4</td>
<td>32.8</td>
<td>0.0019</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>45,514</td>
<td>27.4</td>
<td>58.3</td>
<td>0.0023</td>
</tr>
<tr>
<td>Lab 2 (2000 mm²)</td>
<td>2</td>
<td>8,861</td>
<td>5.3</td>
<td>11.3</td>
<td>0.0013</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>25,261</td>
<td>15.2</td>
<td>32.3</td>
<td>0.0019</td>
</tr>
<tr>
<td>Lab 3 (3500 mm²)</td>
<td>1</td>
<td>14,790</td>
<td>8.9</td>
<td>18.9</td>
<td>0.0025</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>26,973</td>
<td>16.3</td>
<td>34.5</td>
<td>0.0023</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>41,140</td>
<td>24.8</td>
<td>52.7</td>
<td>0.0024</td>
</tr>
<tr>
<td>NYU (18,241 mm²)</td>
<td>1</td>
<td>28,217</td>
<td>37.9</td>
<td>80.5</td>
<td>0.0021</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>62,602</td>
<td>84.1</td>
<td>178.5</td>
<td>0.0023</td>
</tr>
</tbody>
</table>

Use of the new anthropometric phantom of the human knee developed at the University of Cincinnati makes it possible to calibrate *in vivo* measurements for nearly any bone-seeking radionuclide. The phantom contains no natural human bone and uses tissue substitute materials for muscle and trabecular bone that have been especially formulated to exhibit radiological properties that are appropriate for a wide range of photon energies, including plutonium. The phantom has been designed with replaceable skeletal components, so that calibrations for more than one radionuclide can be performed using the same phantom. Likewise, background measurements can be performed with the phantom by inserting bones containing no radioactivity. Since the phantom is fabricated using a set of molds, multiple identical copies of the phantom can be easily produced. Contemporary, non-proprietary materials are used for all components of the phantom, so there are no restrictions on its distribution and use, other than regulations associated with the possession and transport of radioactive
Results of calibration measurements comparing the anthropometric knee phantom with the skull phantoms indicate that detection efficiencies for $^{241}$Am measured are essentially equivocal and independent of the type of detectors used for the measurement. Selection of the optimum location on the body to perform an \textit{in vivo} measurement for bone-seeking radionuclides is likely to depend upon the ability of the detector positioning system to accommodate placing detectors around the skull or on the knees. On the other hand, the likelihood of external radioactive contamination being found on the face or hair following accidental exposure may eliminate the skull as a suitable measurement site.

**CONCLUSION**

The new anthropometric phantom of the knee developed at the University of Cincinnati is suitable for performing calibrating in vivo measurements of bone seeking radionuclides. The phantom has the physical appearance of the adult male knee and is constructed of tissue substitute materials formulated from non-proprietary, contemporary polyurethanes and CaCO$_3$ that simulate human muscle and trabecular bone. Each of the bones of the knee can be fabricated with a precisely known quantity of radioactive material that is either uniformly distributed throughout the bone simulant material or applied to the surface. The measurement efficiency for $^{241}$Am in bone using the knee phantom has been determined using arrays of Phoswich and germanium detectors. Results of intercomparison calibration measurements at several whole body counters using skull phantoms and the knee phantom demonstrate that the efficiencies are equivocal. A greater fraction of the total skeletal deposition would be measured if detectors were positioned on both knees than by measuring the skull.

**ACKNOWLEDGEMENT**

This research was performed under the sponsorship of the U. S. Department of Energy Health Physics Faculty Research Award Program administered by Oak Ridge Associated Universities under management and operating contract DE-AC05-76OR00003. The authors gratefully acknowledge the technical collaboration provided by Dr. David Hickman, Dr. Norman Cohen, Lynn Ayers, Dr. James Watts, and Matt McFee, Dr. James Neton, and Mike Soldano.

**REFERENCES**


5. J. Kellar, Fabrication of an Anthropomorphic Calibration Phantom for \textit{In Vivo} Measurement of $^{152}$Eu in the Skull. MS Project, University of Cincinnati, Department of Mechanical, Industrial and Nuclear Engineering; Cincinnati, Ohio (1995).


12. Lodwick, J. Production of a Cortical Bone Substitute Material. MS Project, University of Cincinnati, Department of Mechanical, Industrial and Nuclear Engineering, Cincinnati, Ohio (1996).