Guidelines for Quality Control Testing of Molecular Breast Imaging Systems

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ABSTRACT

Molecular breast imaging (MBI) is a nuclear medicine test that uses dedicated gamma cameras designed for imaging of the breast. Despite growing adoption of MBI, there is currently a lack of guidance on appropriate quality control procedures for MBI systems. Tests designed for conventional gamma cameras either do not apply or must be modified for dedicated detectors. Our objective was to provide practical guidance for physics testing of MBI systems by adapting existing quality control procedures for conventional systems.

Methods: Physics tests designed for conventional gamma cameras were attempted on a dedicated MBI system and modifications were made as necessary to accommodate the MBI system’s pixelated detector, limited space between dual detector heads, and inability to fully rotate the detector gantry.

Results: Quality control testing of uniformity, spatial resolution, count sensitivity, energy resolution, and lesion contrast are recommended and warrant special considerations for MBI systems as detailed herein. Physics tests of intrinsic uniformity, count rate parameters, and overall system performance for SPECT, do not apply to dedicated MBI systems.

Conclusions: Routine physics testing of dedicated MBI equipment is important for verifying system specifications and monitoring changes in performance. As MBI grows in adoption, routine testing may be required for obtaining and maintaining accreditation from regulatory bodies.

Keywords: molecular breast imaging, quality control, dedicated gamma camera
INTRODUCTION

The goal of physics testing of clinical imaging equipment is to ensure optimal performance and accurate imaging. Routine testing is important for monitoring changes in system performance and may be needed for obtaining and maintaining accreditation from regulatory bodies. However, there is currently a lack of resources available to guide quality control procedures specific to dedicated gamma cameras used for molecular breast imaging procedures.

Several types of dedicated molecular breast imaging (MBI) cameras are currently available (1). Here, we refer to MBI as imaging systems comprising detectors designed for single-photon-emitting radionuclides and do not include information regarding dedicated breast PET imaging systems. Some dedicated MBI detectors comprise pixelated arrays of sodium iodide coupled to position-sensitive photomultiplier tubes (also known as breast specific gamma imaging (2)). Other detector configurations include a multi-crystal array of cesium iodide coupled to solid-state silicon photodiodes (3) and a completely solid-state detector that utilizes cadmium zinc telluride (CZT) (2). Collimators for MBI systems can vary in design. Some have a standard hexagonal-hole collimator while other systems have a square-hole collimator matched to the individual square detector elements (4). MBI units can also have single or dual detector heads. In all of these systems, the size of the detector is reduced relative to that of a conventional gamma camera, to accommodate positioning of the breast directly on or close to the detector. Differences between dedicated MBI and conventional gamma cameras, such as the smaller detector size, pixelated detectors, and the inability to accommodate standard-sized phantoms, must be considered when performing physics testing as many of the conventional tests either do not apply or must be modified for dedicated systems.
Here, we provide practical guidance for physics testing of MBI systems by adapting existing quality control procedures for conventional systems.

**QUALITY CONTROL TESTS**

TABLE 1 summarizes the recommended quality control procedures and testing frequencies for MBI systems.

**Uniformity**

Uniformity testing of the MBI detector(s) needs to be performed each day of operation, similarly to conventional nuclear medicine gamma cameras. Integral uniformity should be evaluated. Other uniformity metrics used by some manufacturer software programs, such as standard deviation divided by the mean, are not sufficient for measuring uniformity of the detectors as they are not consistent with National Electrical Manufacturers Association standards (5). Some MBI units have a fixed collimator that is not designed to be removed. For these systems, only extrinsic uniformity should be evaluated as removing the collimator may compromise the system.

To acquire the uniformity flood, either a sheet source or refillable flood source can be used. A refillable flood source with technetium-99m pertechnetate (TcO₄⁻) is fast, easy, and less expensive than purchasing ⁵⁷Co sheet sources. If using a refillable source, select one that is slightly larger than the detector field of view to ensure the entire detector is covered by the source. This smaller size flood source greatly facilitates handling and adequate mixing of the TcO₄⁻. While ⁹⁹mTc sestamibi is typically the radiopharmaceutical of choice for clinical MBI studies, do not use ⁹⁹mTc sestamibi in any acrylic or plastic sources, as it can adhere to the plastic (FIGURES 1A and 1B), and if used in a flood source, may result in a non-uniform flood.
To acquire uniformity flood images, sandwich the source between the two detectors, or detector and compression paddle for single-head systems, and rotate the camera to an angle to move any air bubbles out of the field of view (FIGURE 2). Keeping an air bubble in the phantom is helpful for mixing. The same energy window used for clinical imaging should be used for performing physics testing. On CZT-based systems, some imaging centers employ a wider energy window such as 110 keV – 154 keV instead of the standard 140 ± 10% keV energy window (6,7). Acquiring at least 7.5 million counts (Mcts) per detector is sufficient for flood images.

If using a $^{57}$Co sheet source, some additional points should be considered. New $^{57}$Co sheet sources often contain high-energy contaminants ($^{56}$Co and $^{58}$Co) (8). If these contaminants are present, using a $^{57}$Co sheet source for a uniformity correction map can produce artifacts in the $^{99m}$Tc imaging studies (FIGURES 3A and 3B). These contaminants have shorter half-lives than $^{57}$Co and are typically decayed away within 6-8 months. On a conventional gamma camera, increasing the distance between the source and the detector by placing the source on cups or other smaller objects can help minimize the effects of these high energy contaminants. However, this approach is not feasible with dedicated systems as there may be insufficient space to place cups outside the detector field of view. Also, the collimators on MBI units are much more susceptible to the high energy contaminants, since they are designed for higher sensitivity. Thus, it is important to check for contaminants in new $^{57}$Co sheet sources by examining the camera’s energy spectra and allow decay of any contaminants before routinely using $^{57}$Co sources as a surrogate for $\text{TcO}_4^-$.

Upon completion of the uniformity flood acquisition, the images should be transferred to an analysis workstation that can perform a uniformity calculation using the National Electrical
Manufacturers Association standard (5). Results should show less than 5% integral uniformity across the field of view.

If individual detector modules are evident or if hot or cold pixels are observed on the daily uniformity flood(s), a new uniformity calibration map will need to be performed, according to manufacturer’s directions. A uniformity flood image should be acquired again following the calibration map to confirm that the system uniformity is acceptable.

**Spatial Resolution**

Unlike a conventional gamma camera system, the pixelated MBI system has a fixed imaging matrix with each pixel in the matrix matched to an individual detector element. Because of this, the resolution of these types of systems does not change over time. Nevertheless, system spatial resolution can be evaluated by acquiring a planar image of either a single-photon emission computed tomography (SPECT) phantom or a four-quadrant bar phantom. According to the American College of Radiology, it is recommended to perform this test at least semi-annually on pixelated detectors (9).

Because a standard SPECT imaging phantom does not fit between the detectors of most MBI systems, this test will usually be performed with a bar phantom. Bar phantoms for conventional gamma cameras may be cumbersome to use as they are quite large (typically ~ 56 cm x 43 cm). A bar phantom designed for a cardiac system may be a better option to use for the smaller detectors of an MBI unit. These phantoms are typically 39 cm x 23 cm (10). While this phantom is still larger than the detectors at 20 cm x 16 cm, it will be easier to work with and better fits the MBI detectors.
To acquire an image for system resolution, place the bar phantom directly on the lower detector and then place either a $^{57}$Co sheet source or a fillable phantom with TcO$_4^-$ above the phantom. Move the detectors as close together as possible, tightly sandwiching the source and phantom between the two detectors or detector and compression paddle. Rotating the gantry when using a fillable phantom will be useful in moving the air bubble out of the field of view. An acquisition of 7.5 million counts should be sufficient. If using $^{99m}$Tc, apply the same energy window used for clinical imaging. If the system has an upper detector, acquire a second image with the radioactive source placed directly on the lower detector and the resolution phantom above the source. Again move the detectors as close together as possible, tightly sandwiching the source and phantom between the two detectors so that the phantoms will not move with rotation of the gantry. Acquire 7.5 Mcts on the upper detector. It’s possible that aliasing artifacts may appear with a small bar phantom (FIGURE 4A). If this occurs, angling the phantom across the field of view may help reduce this effect.

Quantitative analysis of the images can be performed if software is available or a simple visual analysis can be done by making a notation of which quadrant with the smallest bar width is resolvable.

Alternatively, resolution of the MBI systems could be tested with a point or line source method (FIGURE 4B). However, these methods are difficult to perform correctly and can produce inconsistent results [11]. Resolution can change with the angle of the line or the position of the point source on the collimator. Because of these reasons, line and point source methods are not recommended for routine spatial resolution testing.
Sensitivity

The standard criteria for evaluating the relative sensitivity of nuclear medicine gamma detectors is a difference of less than 5% between the two detectors of a dual headed camera (9). Sensitivity is reported as the number of counts per minute per unit of radioactivity. The standard criteria of less than 5% may be difficult to achieve with some commercial MBI systems, particularly those with tungsten collimators where the manufacturing tolerances are not as tight as those with lead collimators.

With a conventional gamma camera, a flask would be filled with a small volume of water – just enough to cover the surface area of the flask when lying on its side (FIGURE 5A). Approximately 7.4 MBq (200 uCi) of TcO₄⁻ is added to the background volume and mixed thoroughly. The flask is then placed directly on the surface of the collimator and an image is acquired for two minutes. This is repeated for the second detector where applicable. To calculate the sensitivity, the exact activity of the syringe before and after filling the flask should be documented, as well as the image start time. A sensitivity difference between detector heads of less than or equal to 5% is considered acceptable. The sensitivity should be within ± 10% of the manufacturer’s stated specification, at a defined energy acceptance window.

For MBI systems with one detector, the above procedure may be used. Instead of comparing the sensitivity of one detector to the other, the number of counts per minute should be compared with the manufacturer’s specifications to determine if the sensitivity is within acceptable limits.

For MBI systems with dual detectors, there are special considerations. If the MBI detectors are able to rotate through 180 degrees, follow the conventional method listed above. However, if the MBI detectors are not able to rotate 180 degrees, the flask will not be able to be
placed directly on each detector. Instead, sensitivity images can be acquired simultaneously with the flask sandwiched between the two detectors. The flask should be filled completely with water to minimize differences between detector geometry. Rotate the detectors slightly to move air bubble (if any) away from the center of the flask image (FIGURE 5B). Acquire a two minute image on both detectors simultaneously. A relative sensitivity difference of less than 10% is more reasonable to achieve with these systems.

**Energy Resolution**

The energy resolution of an MBI system should be analyzed annually to “verify that the scatter rejection is sufficient to provide optimal contrast in clinical studies” (9). For MBI systems with collimators that cannot be removed, this test can be performed extrinsically. For most MBI systems, the energy spectrum shown on the acquisition screen does not have adequate detail to allow a measurement of energy resolution. There are two other methods that can be used to calculate the energy resolution: analysis of count data from images acquired at multiple windows distributed across the photopeak and the count rate analysis method.

To calculate the energy resolution using multiple windows across the photopeak, two keV energy windows may need to be manually created, depending on the MBI system in use. If using a $^{57}$Co sheet source, a total of nine energy windows should be created, each two keV wide and ranging from 112 – 130 keV. A point source with approximately 5.55 MBq (150 uCi) of $^{99m}$Tc may also be used. This source should ideally be centered between the two detectors or placed a few centimeters above the lower detector in a single head system. When using $^{99m}$Tc, energy windows should be two keV wide and range from 130-146 keV.
An image for each energy window should be acquired for 60 seconds. The counts acquired in each image can be plotted or the counts can be analyzed to determine the full-width at half maximum and energy resolution. Compare results with manufacturer’s specifications to determine if results are acceptable. Note this latter method only assesses part of each detector field of view and may not accurately represent overall energy resolution.

To estimate the energy resolution using the count rate analysis method, place a $^{57}$Co sheet source or $^{99m}$Tc flood source between the detectors as described above. Determine the peak energy location and reduce the energy window to two percent or two keV, depending on available settings for the MBI system. Note the peak count rate at this energy window. Next, determine half of the count rate and locate the energy at which this occurs, both below and above the peak location. The energy locations can be used to estimate the full width at half maximum and energy resolution of the system.

**Contrast Detail Phantom**

When evaluating the performance of MBI units, it would be beneficial to measure the contrast of lesions detected by the system, as the primary function of these systems is hot-spot detection. There are currently no ideal phantoms that are commercially available. For most MBI systems, a standard Jaszczak phantom (Data Spectrum Corporation, Durham, North Carolina) cannot be used because it is too large. Alternatively, a mini-Jaszczak phantom could be used. While there is currently no recommended phantom for MBI testing, our practice is currently using an acrylic contrast detail phantom (Merrimac Tool Company, Amesbury, MA) to evaluate the contrast-to-noise ratio. The phantom contains 48 holes (lesions) ranging from 3 to 10 mm in diameter and has an overall thickness of 6 cm (FIGURE 6A). It comprises a 3 cm thick central
section containing the lesions that can be filled with a $^{99m}$Tc solution, and two 1.5 cm thick plates that can be placed in front of or behind the central section which allows imaging of the holes at various distances from the collimator surface. The holes are centered at the mid-plane of the central section. Each hole size is represented six times with hole depths of 6.0, 8.0, 9.9, 11.9, 13.8, and 15.8 mm. The background region has a depth of 3.0 mm. Hence the phantom represents lesion/background ratios of 2.0:1, 2.7:1, 3.3:1, 4.0:1, 4.6:1, and 5.3:1. The overall 6-cm thickness is designed to match the typical thickness of the compressed breast observed in clinical MBI studies (2).

The central section of the phantom should be used in combination with the two acrylic plates to vary the distance from the detector to the lesions from 1.5 cm to 3.0 cm to 4.5 cm. For this test, fill the background of the phantom with water and add approximately 185 MBq (5 mCi) TcO$_4^-$. Shake the phantom well and then tap the sides to ensure that all air bubbles are dislodged from the holes. For the first acquisition, place the phantom directly on the face of the lower detector and place the two spacer plates directly above it. If there is an upper detector, move it in as close as possible to the spacer plates. Rotate the detectors slightly to move any air bubble within the phantom out of the field of view (FIGURE 6B). For this acquisition, the lower detector will have a distance of 1.5 cm to the lesions in the phantom; the upper detector will have a distance of 4.5 cm. Acquire 1 Mcts. For the next acquisition, move one of the spacer plates below the phantom. Now the lower and upper detectors will have a distance of 3.0 cm. Again, acquire 1 Mcts. For the final image acquisition, move the second spacer plate below the phantom. The lower detector will have a distance of 4.5 cm to the lesions in the phantom; the upper detector will have a distance of 1.5 cm. One million counts will also be acquired for these subsequent images.
Upon completion of the three image acquisitions (FIGURES 7A, 7B, and 7C) for each detector (six images total), transfer the images to a viewing workstation. Count the number of lesions visualized in each of the images and compare results to the criteria table below (TABLE 2). It is recommended to perform this test quarterly and to track and compare results each quarter in order to monitor system performance.
SUMMARY

Modern MBI units differ from conventional gamma cameras in many ways. When performing physics testing, one needs to be aware of these differences. Based on our experience, we propose the following quality control tests for MBI systems: uniformity, spatial resolution, sensitivity, energy resolution, and lesion contrast. Frequency of testing should be performed as indicated by your accreditation body with special consideration for any additional state regulations. As technology evolves, these quality control procedures may need to be redefined to accommodate improvements in MBI systems.
FINANCIAL DISCLOSURE

Two authors (MKO and CBH) have received royalties for licensed MBI technology per agreement between Mayo Clinic and Gamma Medica. None of the other authors have any relevant financial disclosures.
REFERENCES


FIGURES

**FIGURE 1.** Examples of $^{99m}$Tc pertechnetate and $^{99m}$Tc sestamibi in a plastic flask. A) A flask filled with $^{99m}$Tc pertechnetate provides a homogenous mixture within the flask. B) A flask filled with $^{99m}$Tc sestamibi demonstrates a non-uniform distribution. Also notice the increase in counts along the surface of the flask.

**FIGURE 2.** Proper positioning for a uniformity flood acquisition using a refillable flood source. Refillable $^{99m}$Tc flood source is positioned between the upper and lower detectors of a dual-head CZT system. Note that the gantry is angled to ensure any air bubble in the phantom is outside the field of view.
FIGURE 3. New $^{57}$Co sheet sources have the potential to create artifacts. A) A uniformity flood obtained using a $^{57}$Co sheet source and utilizing a $^{57}$Co correction map. B) A uniformity flood acquired using a $^{99m}$Tc flood source and utilizing the $^{57}$Co correction map. This image was acquired immediately following the acquisition of image A. Notice the artifact over one module in the middle of the detector.

FIGURE 4. Examples of aliasing artifacts on a pixelated imaging system. A) Aliasing artifact from imaging a bar phantom. B) Artifact from a line source for evaluating spatial resolution. Image of line source has been zoomed to show detail.
FIGURE 5. Recommended setup for measurement of system sensitivity. A) For a single-head system, fill the flask with a small volume of water – just enough to cover the surface area of the flask when lying on its side. B) For a dual-head system, the flask should be filled completely with water to minimize differences between detector geometry. Both images can be acquired simultaneously.
FIGURE 6. Contrast detail phantom. A) This phantom contains a 3 cm thick central section with multiple hole sizes and depths. B) Display of image setup using two 1.5 cm thick acrylic plates on either side of the contrast detail phantom. Note camera is angled to move air bubble out of field of view.
FIGURE 7. Sample contrast detail phantom images. These images were acquired at distances of (A) 1.5 cm, (B) 3.0 cm and (C) 4.5 cm from collimator face.
**TABLE 1. Recommended quality control testing program for MBI systems.**

<table>
<thead>
<tr>
<th>Test</th>
<th>Equipment</th>
<th>Frequency</th>
<th>Acquisition Details</th>
<th>Passing Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniformity</td>
<td>$^{57}$Co sheet source or fillable phantom</td>
<td>Daily</td>
<td>7.5 Mcts</td>
<td>$\leq$5% integral uniformity</td>
</tr>
<tr>
<td>Spatial Resolution</td>
<td>4-quadrant bar phantom</td>
<td>Semi-annually</td>
<td>7.5 Mcts; phantom angled across field of view</td>
<td>Meets manufacturer’s specifications</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>Flask</td>
<td>Annually</td>
<td>120 second images</td>
<td>$\leq$10% difference between 2 detectors</td>
</tr>
<tr>
<td>Energy Resolution</td>
<td>Point source</td>
<td>Annually</td>
<td>2 keV energy windows; 1 minute images</td>
<td>FWHM $\leq$ 10%</td>
</tr>
<tr>
<td>Lesion Contrast Test</td>
<td>Contrast detail phantom</td>
<td>Quarterly</td>
<td>1 Mcts; Images at 3 depths</td>
<td>CNR $&gt;3$; Count number of visible lesions at each depth</td>
</tr>
</tbody>
</table>

* All tests should be performed at acceptance testing and following major service work.
TABLE 2. Suggested number of lesions visualized in the contrast detail phantom for satisfactory, marginal, and fail criteria.

<table>
<thead>
<tr>
<th>Distance</th>
<th>Satisfactory</th>
<th>Marginal</th>
<th>Fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 cm</td>
<td>42</td>
<td>40</td>
<td>&lt;40</td>
</tr>
<tr>
<td>3.0 cm</td>
<td>37</td>
<td>35</td>
<td>&lt;35</td>
</tr>
<tr>
<td>4.5 cm</td>
<td>32</td>
<td>30</td>
<td>&lt;30</td>
</tr>
</tbody>
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