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## 1. Aim and Motivation:

The goal of the QIBA Digital reference Object (DRO) project is to construct a common reference DICOM PET/CT test image that can be read by each vendor's PET/CT scanner (Figure 1). This test image, i.e. the DRO, will then be read on PET/CT display stations to check SUV computation fidelity, region of interest analysis performance and PET-CT image alignment. This is motivated by known variations in the standardized uptake value (SUV) calculations between display stations.
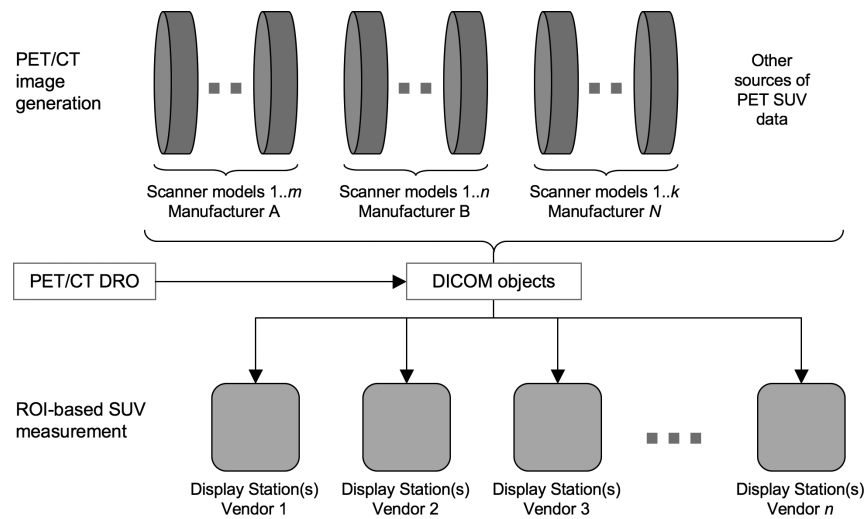


Figure 1. Data flow for DICOM PET/CT images, showing insertion of the QIBA Digital reference Object (DRO) as a testing device for PET/CT display stations.

## 2. Methods

We constructed a common reference test object as illustrated in Figure 2, based on the NEMA NU-2 Image Quality phantom and written out according to DICOM PET and CT standards. Properties of the DRO include
• Parametrically defined shapes
• Contrast, noise and smoothing are adjustable
• Paired anatomical (CT) and functional (PET) objects

There are five phases to the project. We are in phase 5.
1. Completion of extensions to DRO generation
2. DICOM validity testing
3. Testing DRO on multiple display stations with assistance of QIBA FDG-PET Technical Committee members
4. Communication of results to manufacturers. Release of white paper on recommended path for DRO extensions and adoption by manufacturers.

Specifically, we have
• Created and extensively tested a 'generic' DRO.
• Placed the generic DRO on a website for QIBA FDG-PET/CT TC members to download and test. (http://depts.washington.edu/petctdro/)
• Developed a user guide (appended)
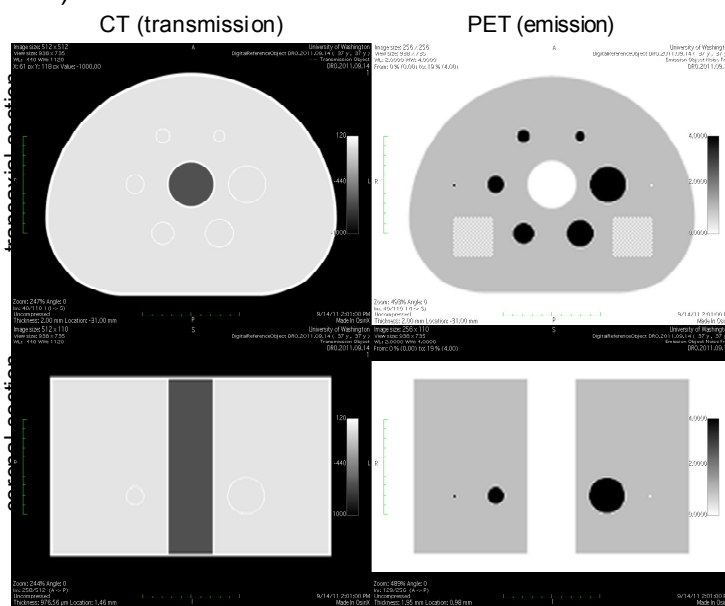• Requested QIBA FDG-PET Technical Committee member feedback using a testing survey (appended)



Figure 2: PET/CT Digital Reference Object for testing DICOM-based SUV measures Top: transaxial sections. Bottom: Coronal sections.

The analysis procedure is as follows:
1. Load DRO image sets into the display station either by DICOM transfer or from DVD or USB drive.
2. Placing 6 predetermined regions of interest (ROIs) as shown in Figure 3.

3. For each of the 6 ROIs, the following SUV values are recorded:
    a. maximum
    b. minimum
    c. mean
    d. standard deviation
    e. ROI diameter and/or area
4. Effect, if any, of image zoom is noted
5. Image alignment between PET and CT is checked for consistency
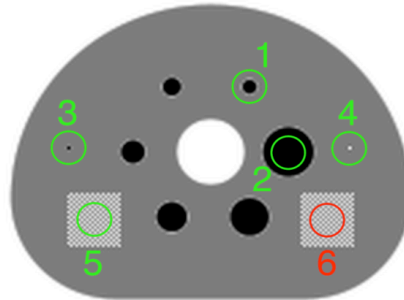6. Image fusion between PET and CT is checked for anomalies



Figure 3. Single transaxial slice of the PET component of the DRO showing ROI locations for measuring SUVs during testing.

Design considerations for the DRO are described in the appendix. Some of the specific design considerations for the test objects are as follows:

• The DRO is based on the NEMA / MITA Image Quality phantom. The SUV values in general are either 0, 1.0, or 4.0, except as noted below.

• The DRO has also been generated with smoothing and noise if more realistic looking images are desired.

• In ROIs 1 and 2 the fixed size of the ROI should provide identical results for SUVmax and different results for SUVmean and SUVmin.

• A single voxel in ROI 3 is set to 4.11, even if noise or smoothing are added to the DRO. This is to test both the SUVmax reporting capability and the number of significant digits provided by the display system

• Similarly, a single voxel in ROI 4 is set to -0.11. This also tests if negative images values are truncated.

• In ROIs 5 and 6 a checkerboard pattern is used to provide a deterministic test for calculation of the standard deviation. For ROI 5 the checkerboard is a single 2D plane to test for axial interpolation effects. For ROI 6 checkerboard is a 3D cube to facilitate testing on systems that do not provide 2D ROIs.


**4. Results**

A total of 13 sites participated, provide results from 18 different display systems. So far all have had a unique combination of (Vendor, Platform, Version) as shown in Table 1.

Table 1. Display systems tested.

|    | Vendor   | Platform                  | Version             |
|----|----------|---------------------------|---------------------|
| 1  | GE       | AW Volume Viewer          | 4.6                 |
| 2  | GE       | Dynamic VUE               | PDR_1.04-5c         |
| 3  | GE       | Volume Viewer             | 9.3.23              |
| 4  | GE       | Xeleris                   | 1.1452              |
| 5  | Hermes   | Hermes Hybrid Viewer      | PDR v 1.4C          |
| 6  | Keosys   | Keosys                    | N/A                 |
| 7  | MedImage | MedView                   | 11.6.3              |
| 8  | MedImage | MedView                   | 12.0.3              |
| 9  | MIM      | MIM Software              | 5.1 (Build AC-18-00) |
| 10 | MIM      | MIM Software              | 4.1.3 Patch D       |
| 11 | MIM      | MIM Software              | 5.3.0               |
| 13 | OsiriX   | OsiriX                    | v 4.0               |
| 14 | Philips  | EBW Fusion Viewer         | V4.5.2.6032         |
| 15 | PMOD     | PMOD                      | 3.208               |
| 16 | Segami   | Oasis                     | 1.9.2HF4            |
| 17 | Siemens  | Inveon Research Workplace | 1.1.0.1             |
| 18 | Siemens  | Inveon Research Workplace | 2.2                 |
| 19 | Siemens  | syngo.via MMonco          | VA11                |

4.1 Summary of Quantitative Performance of Viewers

Table 2 provides a general overview of the quantitative performance of viewers. Identifiers were removed. In general the core function of measuring mean and maximum SUV within a region was accurate. There were, however, differences in truncation of negatives values, and reporting of standard deviation values.

We note that for some of the errors shown in Table 2, it is not clear if they are due to the display and analysis platform or software, or due to mistakes in the DRO testing process.

In addition there were two anecdotal reports of new or newer versions of display software that 'failed' one or more critical tests. The quantitative performance of these reports was not provided to us. However, quantitative performance results after updated versions of these display platforms are included in the results of Table 2.

Table 2. Quantitative performance of viewers. Identifiers were removed. Blue identifies nominal results. Red identifies errors. Orange identifies potential concerns, and yellow identifies otherwise notable values, including missing results (blank cells) or unreported by the viewer ('n/a' in the cell).

| ROI Information | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **SUV Type (BW, LBM, BSA)** | BW | BW | BW | BW | BW | BW | LBM | BW | BW | BW | BW | BW | ? | BW | BW | BW |
| **Decimal places reported** | 1 | 1 | 3 | 2 | 1 | 1 | | maximum | 1 | 2 | 2 | 6 | 6 to 8 | 6 | 1 decimal Pla | 2 |
| **ROI type (2D, 3D)** | 3D | 2D | 2D | 2D | 2D | 2D (ROIs 1-5) | 3D | 2D Circle SUV | 2D | 2D | 2D | 2D & 3D | 2D | 2D | 2D | 3D |
| **ROI Area or Diameter?** | Diameter | area | Diameter | Area | Diameter | Area | 22 mm | Diameter for | Diameter | diameter | Area | Volume | 4.900146cm | DIAMETER | Area | AREA/VOLUM |
| **ROI Measurements** | | | | | | | | | | | | | | | | |
| **ROI 1 Max** | 4.0 | 4.0 | 4 | 4.00 | 4.0 | 4.0 | 4.0000095 | 4 | 4 | 4.00 | 4 | 4.000019 | 4 | 4 | 4.0 | 4.00 |
| **ROI 1 Min** | 0.5 | 0.5 | 0.52 | 0.52 | 0.5 | 0.5 | 0.5199092 | 0.52 | 0.5 | 0.52 | 0.52 | 0.519943 | 0.52 | 0.622 | 0.5 | 0.52 |
| **ROI 1 Mean** | 1.1 | 1.4 | 1.36 | 1.33 | 1.4 | 1.4 | 1.2212964 | 1.396 | 1.3 | 1.39 | 1.73 | 1.390698 | 1.341 | 1.296 | 1.4 | 1.36 |
| **ROI 1 STD** | | | 0.939 | 0.91 | 1.0 | 1.0 | 0.7435832 | 0.974 | 0.9 | 0.97 | 1.223 | 0.968925 | 0.917 | 0.847 | N/A | 0.93 |
| **ROI 1 Diam / Area** | 24mm diame | 492.1 mm2 a | 25 mm | 4.82 cm^2 | 25.0 | 443.7 mm^2 | 22 mm | R = 12.3 | 25.0 mm | 25 | 5.11cm | 0.984192 | 4.900146cm | 25mm | 490 mm2 | 484 |
| **ROI 2 Max** | 4.0 | 4.0 | 4 | 4.00 | 4.0 | 4.0 | 4.0000095 | 4 | 4 | 4.00 | 4 | 4.000019 | 4 | 4 | 4.0 | 4.00 |
| **ROI 2 Min** | 0.6 | 4.0 | 4 | 4.00 | 4.0 | 4.0 | 4.0000095 | 4 | 4 | 4.00 | 4 | 4.000019 | 4 | 4 | 4.0 | 4.00 |
| **ROI 2 Mean** | 3.9 | 4.0 | 4 | 4.00 | 4.0 | 4.0 | 4.0000095 | 4 | 4 | 4.00 | 4 | 4.000019 | 4 | 4 | 4.0 | 4.00 |
| **ROI 2 STD** | | | 0 | 0.00 | 0.0 | 0.0 | 2.61E-07 | 0 | 0 | nan | 0 | 0 | 0 | 0 | N/A | NaN |
| **ROI 2 Diam / Area** | 24mm diame | 492.1 mm2 a | 25 mm | 4.82 cm^2 | 25.0 | 443.7 mm^2 | 22 mm | R = 12.3 | 25.0 mm | 25 | 4.95.91cm | 0.991821 | 4.900146cm | " | 490 mm2 | 493 |
| **ROI 3 Max** | 4.1 | 4.1 | 4.11 | 4.11 | 4.1 | 4.1 | 4.1099997 | 4.11 | 4.1 | 4.11 | 4.11 | 4.110001 | 4.11 | 2.555 | 4.1 | 4.11 |
| **ROI 3 Min** | 1.0 | 1.0 | 1 | 1.00 | 1.0 | 1.0 | 0.99998724 | 1 | 1 | 1.00 | 1 | 0.999922 | 1 | 0.999 | 1 | 1.00 |
| **ROI 3 Mean** | 1.0 | 1.0 | 1.021 | 1.02 | 1.0 | 1.0 | 1.0042257 | 1.024 | 1 | 1.02 | 1.02 | 1.023846 | 1.022 | 1.01 | 1 | 1.02 |
| **ROI 3 STD** | | | 0.256 | 0.25 | 0.3 | 0.3 | 0.11473396 | 0.275 | 0.3 | 0.28 | 0.27 | 0.271721 | 0.26 | 0.126 | N/A | 0.25 |
| **ROI 3 Diam / Area** | 24mm diame | 492.1 mm2 a | 25 mm | 4.81 cm^2 | 25.0 | 443.7 mm^2 | 22 mm | R = 12.3 | 25.0 mm | 25 | 5.04cm | 0.991821 | 4.900146cm | " | 490 mm2 | 497 |
| **ROI 4 Max** | 1.0 | 1.0 | 1 | 999.94 mSUV | 1.0 | 1.0 | 0.99998724 | 1 | 1 | 1.00 | 1 | 0.999922 | 1 | 0.999 | 1 | 1.00 |
| **ROI 4 Min** | 0.0 | 0.0 | -0.1 | -109.88 mSU | 1.0 | 1.0 | -0.1098776 | -0.11 | -0.1 | 0.00 | -0.11 | -0.109877 | -0.11 | 0.445 | 0 | -0.11 |
| **ROI 4 Mean** | 1.0 | 1.0 | 0.992 | 992.44 mSU | 1.0 | 1.0 | 0.9984767 | 0.991 | 1 | 0.99 | 0.99 | 0.99145 | 0.992 | 0.996 | 1 | 0.99 |
| **ROI 4 STD** | | | 0.094 | 91.23 mSUV | 0.0 | 0.0 | 0.04091707 | 0.098 | 0.1 | 0.09 | 0.096 | 0.096593 | 0.092 | 0.044 | N/A | 0.09 |
| **ROI 4 Diam / Area** | 24mm diame | 492.1 mm2 a | 25 mm | 4.82 cm^2 | 25.0 | 439.9 mm^2 | 22 mm | R = 12.3 | 25.0 mm | 25 | 5.04cm | 0.999451 | 4.900146cm | " | 490 mm2 | 494 |
| **ROI 5 Max** | 1.0 | 0.9 | 0.9 | 899.97 mSU | 0.9 | 0.9 | 0.99998724 | 0.9 | 0.9 | 0.90 | 1 | 0.899985 | 0.9 | 0.95 | 0.9 | 0.90 |
| **ROI 5 Min** | 0.1 | 0.1 | 0.1 | 99.97 mSUV | 0.1 | 0.1 | 0.10000705 | 0.1 | 0.1 | 0.10 | 0.1 | 0.099977 | 0.1 | 0.549 | 0.1 | 0.10 |
| **ROI 5 Mean** | 1.0 | 0.5 | 0.5 | 492.02 mSU | 0.5 | 0.5 | 0.9307193 | 0.507 | 0.5 | 0.51 | 0.75 | 0.512289 | 0.492 | 0.75 | 0.5 | 0.50 |
| **ROI 5 STD** | | | 0.401 | 401.25 mSU | 0.4 | 0.4 | 0.22840944 | 0.4 | 0.4 | 0.40 | 0.378 | 0.399815 | 0.401 | 0.201 | N/A | 0.40 |
| **ROI 5 Diam / Area** | 24mm diame | 492.1 mm2 a | 25 mm | 4.81 cm^2 | 25.0 | 443.7 mm^2 | 22 mm | R = 12.3 | 25.0 mm | 25 | 4.888cm | 0.991821 | 4.900146cm | " | 490 mm2 | 484 |
| **ROI 6 Max** | 0.9 | 0.9 | 0.9 | NA | 0.9 | 0.9 | 0.8999599 | 0.9 | 0.9 | 0.90 | 0.9 | 0.89999 | 0.9 | 0.499 | 0.9 | 0.90 |
| **ROI 6 Min** | 0.1 | 0.1 | 0.1 | NA | 0.1 | 0.1 | 0.10000705 | 0.1 | 0.1 | 0.10 | 0.1 | 0.099977 | 0.1 | 0.499 | 0.1 | 0.10 |
| **ROI 6 Mean** | 0.5 | 0.5 | 0.5 | NA | 0.5 | 0.5 | 0.49820703 | 0.505 | 0.5 | 0.50 | 0.5 | 0.489707 | 0.5026 | 0.5 | 0.5 | 0.51 |
| **ROI 6 STD** | | | 0.53 | NA | 0.4 | 0.4 | 0.39997247 | 0.4 | 0.4 | 0.40 | 0.4 | 0.399874 | 0.4013 | 0 | N/A | 0.40 |
| **ROI 6 Diam / Area** | 24mm diame | 492.1 mm2 a | 25 mm | NA | 25.0 | 5.52 cm^3 | 22 mm | 25.0 | 25.0 mm | 27 | 5.11cm | 7.720947 | 1.7986cm^3 | " | 490 mm2 | 8360 |

## 4.2 Comments on Viewer Performance

Squared or pixelated hot sphere borders

Slight horizontal and vertical streaks at hot sphere border

Asymmetry of circle - cannot assess whether fully due to asymmetry of synthetic data or partially application.

When you zoom in the small sphere appears warped.  The large sphere appears to have 4 black spots not easily observed

No anomalies were observed that generated any ring around the wall of the spheres.

No anomalies and excellent PET/CT fusion.

Our system does not display STD at the same time as ROI parameters.

Note apparent problem in our ROI 4 SUVmin.

The CT to PET fusion ratio may need to be specified.

Hybrid viewer does not allow drawing of fixed size VOI so used as close as possible

Checkerboard seen in the first and last couple of slices of objects but not throughout the volume - appears uniform. Also rapid scrolling makes checkerboard appear. Some complex ringing etc as your figs show. The spheres seem OK for SUV but black and white voxels are off ! Checkerboard values are also off!

The .... software performed extremely well with this phantom and absolutely no anomalies were identified.

## 4.3 Comments on DRO Design and Process

The .... software is used in multi-center trials and the DRO was a good test for this ... ... software.

Congratulations on an excellent digital phantom

The image sets have different spatial dimensions. You should explain what you want done with image fusion. I have choices to reformat the emission image to fit the transmission image and vice versa.

Maybe you should ask for Number of Voxels since some programs, like mine, know that there is always depth to a pixel making even a single voxel, a volume measurement.

Also, to define circular/spherical objects I have to define a radius - not a diameter, which may affect the resulting shape.

On the main web page, you should highlight (maybe with a section header) a request for users to analyze the image data prior to the sentence at the bottom of the page. A header like "DRO Analysis: Request for User Input", in the same format as "DRO Description" at the top of the page.  ALSO . . . link the word download in the sentence to the download page.

In the download page please add a separate link for the DICOM files.

## 5. Summary

The QIBA FDG-PET/CT Digital Reference Object (DRO) provides a method for testing the SUV based calculations performed by PET/CT display software platforms. It is not intended as a ranking approach, but rather to verify nominal performance in a transparent and objective  manner. The anecdotal evidence of failures (or otherwise) during evaluation of new software versions is a demonstration that the DRO has already succeeded in this manner.  Even so, initial DRO tests have identified some variation in performance.

## 6. Future Directions and Recommendations

1. The potential for errors during DRO testing, as well as the number of vendors, platforms, and versions of PET/CT display software, indicate the need for broader testing to accumulate consensus results for any specific combination of vendor, platform, and version.

2. The DRO testing process should be made available as a centralized service by QIBA. This could potentially be accomplished as part of the proposed QIBA/RIC database server and potentially in conjunction with the QIBA DCE-MRI DRO.

3. Additional capabilities for the DRO have been requested. These include, but are not limited to the following:

- Features that properly tests calculation of SUVpeak, such as a sphere with radially-varying intensity.

- A dynamic PET DRO for testing PET analysis software.

- CT-specific DRO tests.

- A DRO with unknown true values, i.e. for site specific testing where the measured results are reported back to QIBA for verification.

- Open-source software for producing DROs, i.e. to allow users to generate their own DROs with unique UIDs.

4. The role, availability, and value of the DRO should be publicized. An abstract on the DRO has been submitted to the SNM annual meeting and to the 2012 RSNA Quantitative Imaging Reading Room.

## 7. Acknowledgements

## 8. References

[1] Daube-Witherspoon ME et al., "PET Performance Measurements Using the NEMA NU 2-2001 Standard" J Nucl Med 2002 43:1398-1409

[2] The NEMA DICOM standard: http://medical.nema.org

[3] DICOM FAQ: http://www.dclunie.com/medical-image-faq/html/index.html

[4] QIBA Pseudocode for computing SUVbw. http://qibawiki.rsna.org/images/e/e8/SUV_vendorneutral_pseudocode_20091106_DAC.doc

## 9. Appendices

1. Digital Reference Object Analysis Sheet

2. Description of the CT and PET DROs

3. Version Identification and DICOM Field Assignment in the DRO

4. DRO Verification and Quality Control

5. How SUVbw is Calculated

6. Creation of the DRO

7. Software Process Flow

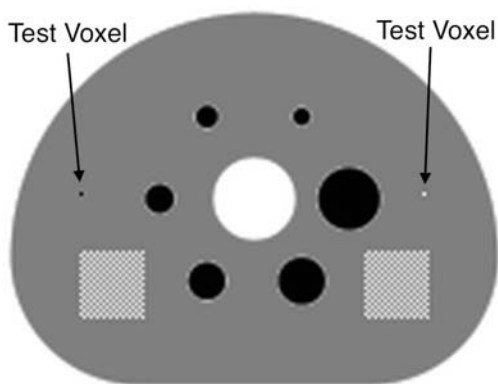**Digital Reference Object Analysis Sheet - Version 10/31/2011**

You may record your answers directly on this form or by filling out the accompanying Excel spreadsheet. The numbers on each line indicate the corresponding rows and columns of the Excel spreadsheet. Alternatively, you may print and mail the completed form to the address at the end of this document.

# 1   Basic Information

Fill out the basic information for the test. Include a brief description of the workstation and its hardware, the software being tested, and the makes and models of the primary scanners that supply the images viewed on the workstation used for this test.

| ROW | Item | Value |
|---|---|---|
| 6 | Name of Institution | |
| 7 | Name of person testing software | |
| 8 | Email or Phone contact | |
| 9 | Date of test | |
| 10 | Workstation used for test (Serial #) | |
| 11 | Description of hardware (Hardware Version) | |
| 12 | Make and model of monitor | |
| 13 | Software Manufacturer | |
| 14 | Name of software being tested | |
| 15 | Version of software | |
| 16 | Makes and models of primary scanners | |

Load the DRO into your viewing software. Using an axial view, advance to **slice 40**, which contains the two test voxels and both test patterns as shown in Figure 1. Record the type of SUV that you are measuring (or 'Unknown') and the number of decimal places that the software reports for the SUV value. Record the type of ROI that your software uses (2D or 3D). Record the ROI measurement units and indicate if it is a diameter, an area, a volume, etc..



Figure 1: You should see both the hot and cold test voxels and the two square test patterns in slice 40.

| ROW | Item | Value |
|---|---|---|
| 20 | SUV Type (BW, LBM, BSA) | |
| 21 | Number of decimal places | |
| 22 | ROI Type (2D, 3D) | |
| 23 | Recording ROI Area or Diameter? | |

## 2 ROI Analysis of the DRO

For each of the following six ROIs (shown in Figure 2), record the maximum, minimum, mean, standard deviation for the voxel SUV values. Also record either the diameter or area of each ROI (if recording area, record the volume for ROI 6).

(1) Draw a circular ROI with an area of 490 mm$^2$ (diameter=25 mm), concentric with the smallest hot sphere.
(2) Draw a circular ROI with an area of 490 mm$^2$ (diameter 25 mm), concentric with largest hot sphere.
(3) Draw a circular ROI with an area of 490 mm$^2$ (diameter 25 mm), concentric with the hot test voxel.
(4) Draw a circular ROI with an area of 490 mm$^2$ (diameter 25 mm), concentric with the cold test voxel.
(5) Draw a circular ROI with an area of 490 mm$^2$ (diameter 25 mm), centered within the single plane test pattern nearest the hot test voxel.
(6) Draw a spherical (3D) ROI with a volume of 2,600 mm$^3$ (diameter 25 mm), centered within the 3D block test pattern nearest the cold test voxel.
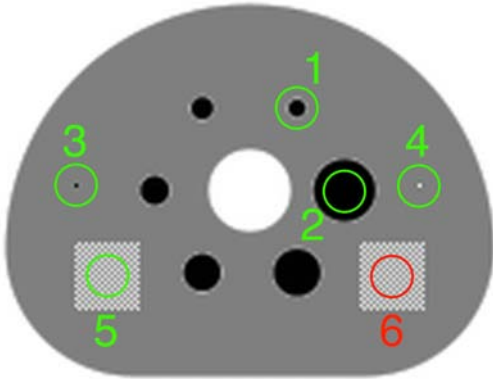


Figure 2: ROIs for the DRO analysis. The cross-section of the sphere in the 3D test pattern (on the right) is shown in red.

| COL: | C | D | E | F | G |
|---|---|---|---|---|---|
| ROW ROI | Max | Min | Mean | STD | Diam or Area |
| 28 ROI 1 | | | | | |
| 29 ROI 2 | | | | | |
| 30 ROI 3 | | | | | |
| 31 ROI 4 | | | | | |
| 32 ROI 5 | | | | | |
| 33 ROI 6 | | | | | |

# 3    Imaging Software Zoom Characteristics

Zoom in on the smallest hot sphere (sphere 1) until it fills as much of the screen as possible as shown in Figure 3(a). Repeat this for the largest hot sphere (sphere 6). Note any anomalies or enter 'None'. If the anomalies are too complex to describe, enter 'Complex'. If possible, take a screenshot of any anomalies encountered.

> **36 Zoom Anomalies:**
>
>
>
>

Scroll through the entire DRO volume (axial, coronal, and sagittal). Report any anomalies that you find or enter 'None'. If the anomalies are too complex to describe, enter 'Complex'. If possible, take a screenshot of any anomalies encountered.

> **Other Anomalies:**
> **39** Axial:
>
>
> **40** Coronal:
>
>
> **41** Sagittal:
>
>
>



(a) Zoomed view of the smallest hot sphere (sphere 1). Slight spacial distortions and slight ringing artifacts are apparent. A complex ringing perpendicular to the sphere wall and a horizontal/vertical streaking has been observed on some displays.

(b) Zoomed view of the largest hot sphere (sphere 6). Ringing artifacts are apparent outside the wall of the sphere, and the top and bottom of the sphere wall appear to be truncated. A complex ringing perpendicular to the sphere wall has been observed on some displays.

Figure 3: Zoomed-in views as described in Section 3.

# 4    Imaging Software Fusion Characteristics

Use image fusion to fuse the emission and transmission DRO as shown in Figure 4. Scroll through the image volume (axial, coronal, and sagittal) and report any anomalies that you encounter or enter 'None'. If the anomalies are too complex to describe, enter 'Complex'. If possible, take a screenshot of any anomalies encountered.
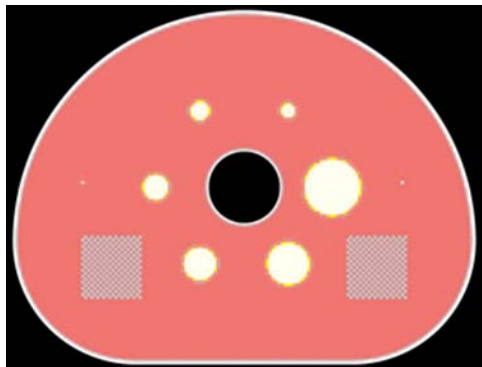


Figure 4: Image fusion of the emission and transmission DROs

**Fusion Anomalies:**
**45** Axial:

**46** Coronal:

**47** Sagittal:

# 5    User Feedback

We appreciate any feedback that you have to offer in improving these tests. If you have any comments or suggestions about the design of the test, the layout, submission process, etc., please let us know or write 'None'.

**51 Feedback:**

# 6    Submit the Report

Email the completed Excel spreadsheet or pdf document and any screenshots taken to **petctdro@uw.edu** with subject line **DRO report**. Include your name and the name of your institution in the body of the email.

Contact the Imaging Research Laboratory at the University of Washington with any questions or comments:

email: petctdro@uw.edu
Phone: 206-543-0517
Fax: 206-543-8356

# 3 Description of the CT and PET DROs

There are two DROs in the 10/31/2011 package: a CT object, and a PET object. Screenshots of these objects can be seen in Figure 3.

Each image volume is modeled after the NEMA Image Quality (IQ) Phantom [1], as described in **NEMA Standards Publication NU 2-2006 ; Performance Measurements of Positron Emission Tomographs**. In each object, the thickness of the exterior shell is 3 mm, the thickness of the hot sphere walls is 1 mm, and the thickness of the lung insert wall is 2mm.

## 3.1 The CT Object

The CT object is $512 \times 512 \times 110$ voxels, and is stored in 110 DICOM files named **000001.dcm** through **000110.dcm** , numerically ordered so that **000001.dcm** corresponds to slice 1 in the image volume.

The CT object has a reconstruction diameter of 500 millimeters and an axial extent of 220 millimeters, resulting in a voxel size of $500/512 \times 500/512 \times 2$ ($0.9765625 \times 0.9765625 \times 2.0$) millimeters$^3$.

The interior of the phantom body and the interiors of the hot spheres have voxels with values of 0 Houndsfield Units (HU), simulating water in the body and the interior of the hot spheres. The shell of the body, lung insert wall, and hot sphere walls have voxels set to 120 HU, simulating polymethylmethacrylate. The voxels interior to the lung insert are set to -650 HU, simulating lung attenuation material. The voxels exterior of the phantom body are set to -1000 HU, simulating air. These values are indicated in Figure 3(a). **NOTE:** Partial volume effects will alter the voxel values near the borders of different regions.

## 3.2 The PET Object

The PET object consists of a $256 \times 256 \times 110$ voxel image volume stored in 110 DICOM files named **000001.dcm** through **000110.dcm**, similar to the CT object described above.

The PET object has a reconstruction diameter of 500 millimeters and an axial extent of 220 millimeters, resulting in a voxel size of $500/256 \times 500/256 \times 2$ ($1.953125 \times 1.953125 \times 2.0$) millimeters$^3$.
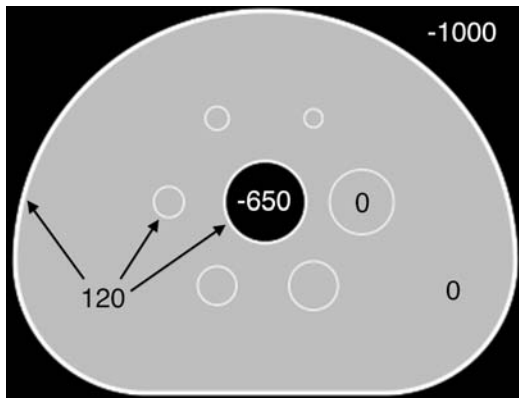
The voxels interior to the phantom body are set to an SUV value of 1.00. The voxels interior to the six hot spheres are set to an $SUV_{bw}$ value of 4.00. The voxels corresponding to the polymethylmethacrylate shell and the exterior of the phantom body and interior to the lung insert are set to an $SUV_{bw}$ value of 0.00. **NOTE:** Partial volume effects will alter the voxel values near the borders of different regions.

There are two test voxels in slice 40 of the DRO. The test voxel furthest from the largest hot sphere in slice 40 is set to an $SUV_{bw}$ value of 4.11. The test voxel closest to the largest hot sphere in slice 40 is set to an $SUV_{bw}$ value of -0.11. **NOTE:** There is no polymethylmethacrylate shell surrounding the test voxels in the PET object, and no partial volume effects surrounding the test voxels.
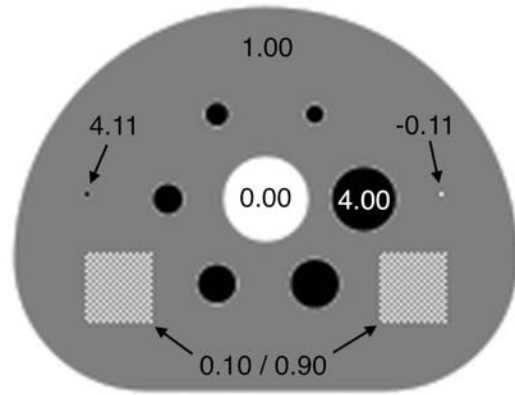
There are two test patterns in the PET DRO, a square (2D) checkerboard pattern in slice 40, and a cubic (3D) checkerboard pattern centered in slice 40. The 3D cubic test pattern appears closest to the largest hot sphere in an axial view of slice 40.

Each test pattern consists of a checkerboard of voxels with alternating $SUV_{bw}$ values of 0.10 and 0.90 Both the 2D square and 3D cubic test patterns have edge measurements of 40 mm.
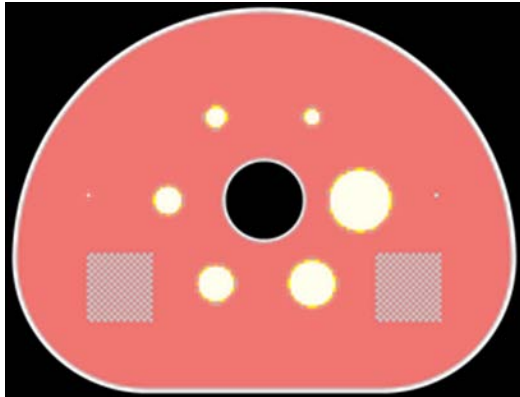
The $SUV_{bw}$ values of each region of the PET DRO are shown in Figure 3(b).

(a) The CT DRO showing Houndsfield Units of each structure.



(b) The PET DRO with the $SUV_{bw}$ values of each structure.



(c) Image fusion of the CT and PET DROs.



(d) Coronal view of the PET DRO showing the 2D test pattern in slice 40 (left) as well as the 3D cubic test pattern (right).

Figure 3: Views of the CT and PET DROs.

# 4 Future Plans

- Creation of vendor-specific DROs
- Open source code release (including unique developer UIDs)
- Publication of design methodology and results

# 5 Acknowledgements

This work was supported by a grant from the RSNA Quantitative Imaging Biomarkers Alliance (QIBA).

# References

[1] Daube-Witherspoon ME et al., "PET Performance Measurements Using the NEMA NU 2-2001 Standard" *J Nucl Med* 2002 43:1398-1409

[2] The NEMA DICOM standard: `http://medical.nema.org`

[3] David Clunie's DICOM FAQ: `http://www.dclunie.com/medical-image-faq/html/index.html`

[4] Pseudocode for computing $SUV_{bw}$ from QIBA: `http://qibawiki.rsna.org/images/e/e8/SUV_vendorneutral_pseudocode_20091106_DAC.doc`

# APPENDICES

# A Version Identification and DICOM Field Assignment in the DRO

Each IRL-released version of the DRO is differentiated by inserting an official "Version Date" into the five DICOM fields:

| | |
|---|---|
| StudyDate | (0008,0020) |
| SeriesDate | (0008,0021) |
| AcquisitionDate | (0008,0022) |
| Manufacturer | (0008,0070) |
| StudyDescription | (0008,1030) |

The official version date of each DRO is given in the YYYYMMDD DICOM DateTime format. This is done to differentiate versions of the DRO while allowing multiple instances of each version (with different UID) for debugging purposes.

The version date is user-editable in the source code header files (see Section D) along with Patient Information and other fields. Users can change the version date format to fit their own identification purposes.

## A.1 Released Versions of the DRO

**<u>20110914</u>:** The September 14, 2011 version of the DRO was released in October of 2011. It was found to have numerous errors in the DICOM fields, and was promptly removed from the website. An email notice was sent to inform users of the errors.

**<u>20111031</u>:** The October 31, 2011 version of the DRO was released in November of 2011 and is an update and correction to the 20110914 version. Alterations to the 20110914 version include:

1. Fixes made to incorrectly reported and repeated DICOM fields from the Sept. 14, 2011 version
2. New UID structure implemented
3. New DRO versioning structure implemented (see Section A)
4. New software versioning implemented
5. Implementation of a DRO verification checklist for DICOM validity and Quality Control (see Section B)

# B DRO Verification and Quality Control

Starting with the October 31, 2011 version of the DRO (20111031), a quality control checklist was implemented in order to ensure the validity and compatibility of the DRO. This checklist was signed off by Brian Elston, Larry Pierce, and Paul Kinahan and the records filed at the Imaging Research Laboratory.

This checklist includes:

1. Testing all DRO slices (each DICOM file) from the PET and CT objects using a bash script and the dicom3tools package provided by David Clunie (`http://www.dclunie.com/dicom3tools/dciodvfy.html`). Each of these PET and CT DICOM files is tested using:

   (a) **dcentvfy**: To ensure entry-level attribute consistency.
   (b) **dciodvfy**: To ensure that no errors are reported.
   (c) **dctable**: Critical attributes (InstanceNumber, SliceLocation, ImagePositionPatient, SeriesTime, AcquisitionTime, FrameReferenceTime) are tabulated for manual review.

2. Several DICOM files are chosen from both the PET and CT objects and **andump** is used to manually review all DICOM fields and ensure that each field is accurate and that the length of each DICOM field matches the length of the intended value.

3. Visual checks of the DRO, including verification of the pixel values in various slices of the PET and CT objects. This includes testing of the test voxel and test pattern SUV values and scrolling through the PET and CT DRO in the axial, sagittal, and coronal dimensions.

4. Fusing the PET and CT objects and scrolling through the fused image in the axial, sagittal, and coronal dimensions in order to look for anomalies in the DRO and ensure proper image fusion.

5. Testing the DRO by performing the ROI analysis in Section 2.2 and verifying that the reported numbers are within the expected range.

6. Sending the DRO files to David Clunie for additional verification.

# C  How SUV$_{bw}$ is Calculated

For a given voxel value measured in Becquerels per milliliter, the SUV$_{bw}$ value for that voxel is defined as

$$\text{SUV}_{bw} = \frac{(\text{Bq/mL}) \times w \times 1,000}{\text{Decayed Dose}} \tag{1}$$

and Bq/mL is computed from the DICOM stored data by

$$(\text{Bq/mL}) = m\,(d + b) \tag{2}$$

where $d$ is the stored voxel data (from DICOM field (7FE0,0010)), $m$ is the rescale slope (DICOM field (0028,1053)), $b$ is the rescale intercept (DICOM field (0028,1052)), and $w$ is the patient's weight in kilograms (DICOM field (0010,1030)). The decay corrected dose given to the patient is computed as

$$\text{Decayed Dose} = (\text{Injected Dose}) \times 2^{-\text{Decay Time/Half Life}}$$

The Decay Time is computed as the difference in time from when the radiopharmaceutical was injected into the patient (DICOM field (0018,1072)) to when the scan began (DICOM field (0008,0031)). The radiopharmaceutical half life is measured in seconds and is stored in DICOM field (0018,1075). The injected dose is stored in DICOM field (0018,1074).

In an ideal setting, the software process flow would look like this:

1. Software retrieves the voxel data stored in DICOM stack

2. Software reads the DICOM fields needed to convert voxel data to SUV (rescale slope, patient weight, etc.)

3. Software converts stored voxel values into SUV values according to Equations 1 and 2 above

4. Software correctly displays the converted voxel values in SUV units on the screen

5. Software correctly computes and reports the max, min, mean, SD, and any other statistics for an ROI drawn on the image

Using the DRO gives known data for step one of this process.

For more information on DICOM fields and SUV calculations from DICOM fields, see:

- The NEMA DICOM standard: `http://medical.nema.org`

- David Clunie's DICOM FAQ: `http://www.dclunie.com/medical-image-faq/html/index.html`

- Pseudocode for computing SUV$_{bw}$ from QIBA: `http://qibawiki.rsna.org/images/e/e8/SUV_vendorneutral_pseudocode_20091106_DAC.doc`

# D  Creation of the DRO

The size, position, and shapes (i.e. physical geometry) in the NEMA IQ phantom are saved as exact mathematical formulae, and are hard-coded in the DRO algorithm.

The parameters of the creation process are defined in three input files to the executable program. The Command Parameter File defines characteristics of the physical geometry and SUV$_{bw}$ (PET) or Housefield Units (CT). A Header Input File specifies DICOM header field values for the generated voxel geometry, though a subset of these are image dependent (e.g. Rows, PixelSpacing, RescaleSlope, etc.) and thus are set in-code in the application. A read-only UID file contains a uniquely assigned DICOM UID prefix, and is used to assure the DRO has unique DICOM header fields where appropriate. The UID prefix is assigned from a sub-range that has been specifically allocated for your use, and thus is stored in a read-only file that should not be modified.

Both the PET and CT DROs are created using the same two-step process. The first step is to generate the voxel values for the image volume. Values for each object in the phantom are defined by the user (in the Command Parameter file). For example, the user can designate the Houndsfield Units of the polymethylmethacrylate shell of the CT DRO or the SUV$_{bw}$ measure of the six hot spheres in the PET DRO.

In the PET object, the user can control the SUV$_{bw}$ values for:

- The six spheres (all have the same activity)

- The background

- The body

- The center rod lung insert (usually set to zero)

- An optional single hot voxel

- An optional single cold voxel

In the CT DRO, the user can designate the Houndsfield Units of:

- The interior of the spheres (usually set to water)

- The polymethylmethacrylate shell (includes sphere and lung insert walls)

- The lung insert

- The body (usually set to water)

Similarly, the user can define other fields that will affect the DROs image, and also will be reflected in the DICOM header. These include (but are not limited to):

- Reconstruction Diameter

- Image size (x,y, and z) (can be different for PET and CT DROs)

- Slice Thickness

- Number of fine-division oversampling for calculating voxel values

- Optional test pattern, placement, and extent (single slice area and volume)

From these values the algorithm then sub-divides the image volume into the user-defined voxel size and slice thickness. Each image voxel is oversampled, and the algorithm numerically integrates the hard-coded formulae to determine the value for that voxel.

In the second step, after the voxel values have been calculated, the image information (voxel size, slice thickness, etc.) is combined with user defined header values (from the Header Input file) to compute and populate all of the necessary DICOM header fields for the PET and CT modalities.

The Header Input File is composed of a series of key-value pairings specifying DICOM key header tags to be assigned a designated value. DICOM tags are preceded with '**DCM_**', which references a given (group, element) tag within the DCMTK DICOM toolkit. A subset of these tags (eg. **DCM_MediaStorageSOPInstanceUID**, **DCM_StudyInstanceUID**, etc.) are dependent on timestamps, slice information, or other programatic information, and thus cannot be set by the user through the Header Input file. There are also image dependent fields that should not be set by the user (but they are allowed to), which generate a warning.

There is support for sequences (both single level and nested) using a simple parsing mechanism. Key-value pairings are allowed to have an empty value. Private tags can be specified directly through (group, element) designations with a specified value and type (which defaults to 'LO' if not specified).

In this version, only strictly necessary DICOM fields are populated, with a few exceptions, such as kVP in the transmission object.

# DRO: Software process



The *Command Parameter* file describes how the phantom is generated.

Read *Command Parameter* file

Generate phantom geometry

**Emission**

Scale data (0-1.0)

Scale data to 2-byte short

Add noise & smoothing (if requested)

Add hot pixel

Subtract Intercept

Bit-mask (12-bit); enforces bit depth

**Transmission**

Read *Header Input* file: initialization of fields by user

Set in-code DICOM header fields

Set pixel values to DICOM (header) field

Read *Header Input* file: user overwrite to in-code header fields

Write Stack of DICOM slices

The *Header Input* file describes the DICOM header fields values.

*Header input* file uses DCMTK (DICOM Toolkit) tags for group, element lookup. The supported tags are set in-code.

Some DICOM fields are image dependent (e.g. row, bit_depth, etc...), and thus should be set in code. Some overrides are allowed, through the final header file processing step.
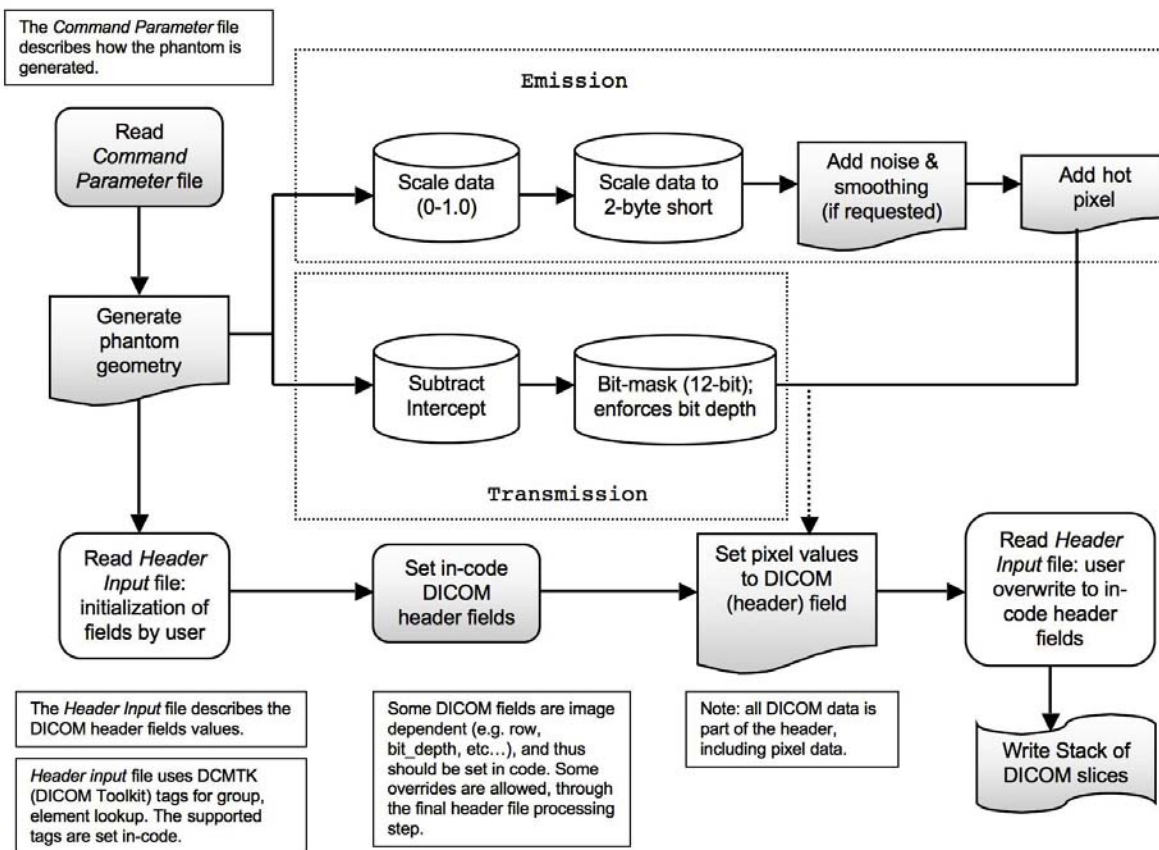
Note: all DICOM data is part of the header, including pixel data.

Figure 4: Workflow Diagram of the DRO creation process