

Aim:

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

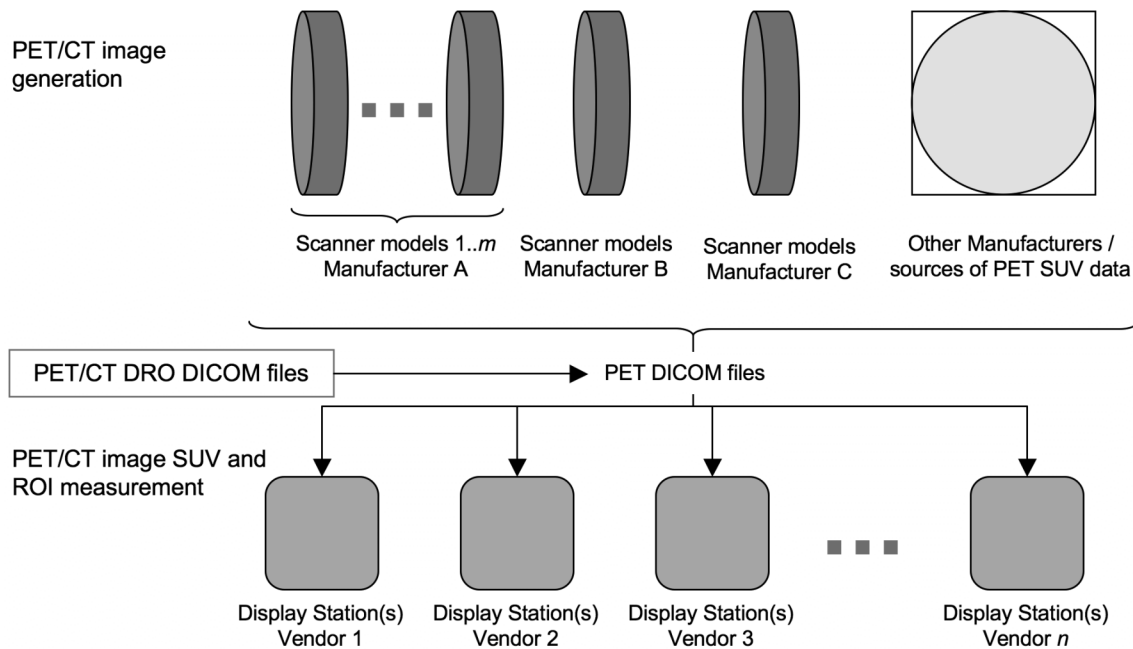


Figure 1. Data flow for DICOM PET/CT images, showing insertion of the QIBA Digital reference Object (DRO) as a testing device.

To we have constructed a common reference test object as illustrated in Figure 2 below, based on the NEMA NU-2 Image Quality phantom (without the central 5 cm air cylinder).

Properties of the DRO include

- Parametrically defined
- Contrast, noise and smoothing are adjustable
- Paired anatomical (CT) and functional (PET) objects

There are five phases to the project, as listed below, and we are in phase 3 and 4

1. Completion of extensions to DRO generation
2. DICOM validity testing
3. Vendor specific DRO generation

4. Testing DRO on multiple display stations with assistance of QIBA FDG-PET TC members
5. Communication of results to manufactures. 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 user guide (attached)
- Requested TC member feedback using a testing survey (attached)
- Completed development of the first vendor-specific DRO (using GE formats), which is currently undergoing testing

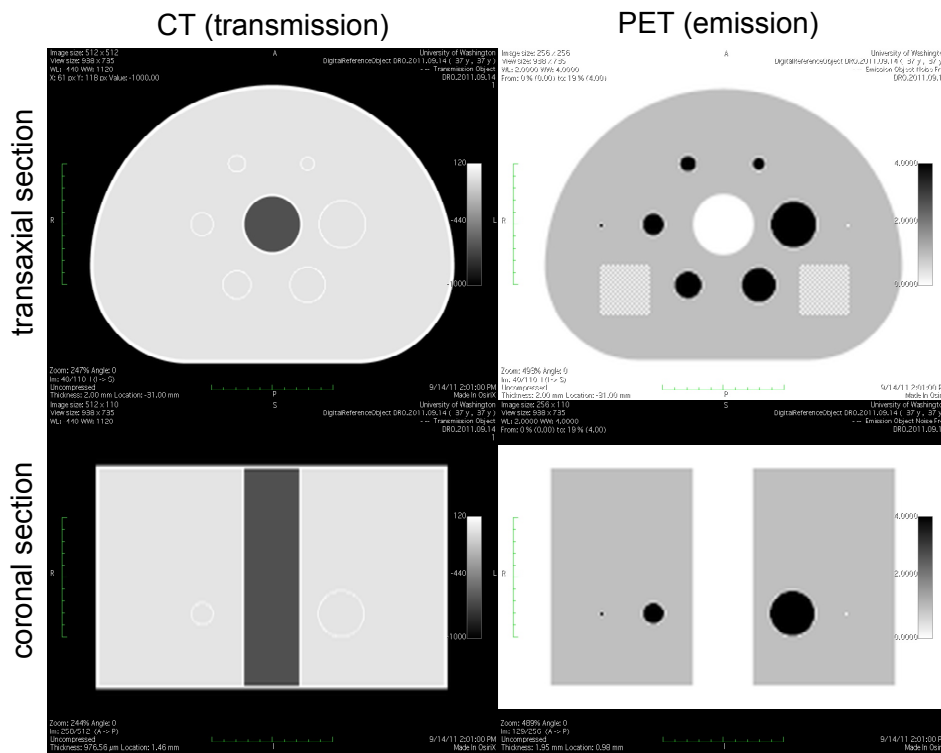


Figure 2: PET/CT Digital Reference Object for testing DICOM-based SUV measures
 Top: Measured NEMA image quality phantom. Bottom: Representations of the Digital Reference Object

PET/CT Digital Reference Object

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³ CoreLab Partners

Version 10/31/2011

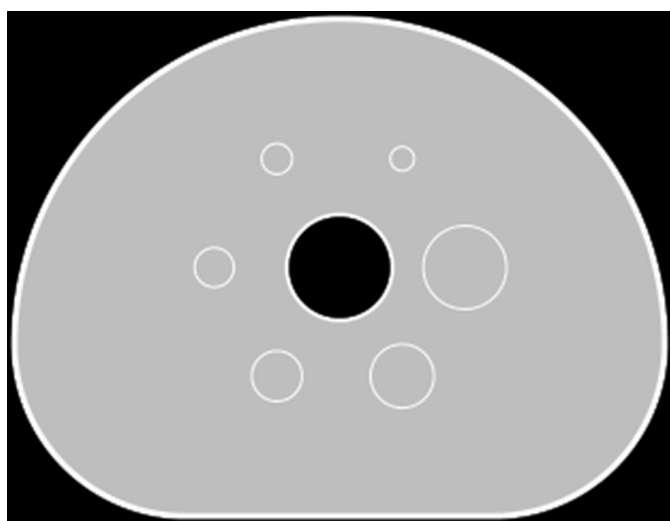
1 Project Description

The PET/CT Digital Reference Object (DRO) is a QIBA and RSNA sponsored artificially generated set of PET and CT DICOM files (a DICOM stack) of known voxel values and DICOM fields. The DRO is intended to check SUV computation fidelity and region of interest (ROI) analysis performance. This is motivated by the vendor-specific variations in the standardized uptake value (SUV) calculations as illustrated in Figure 2.

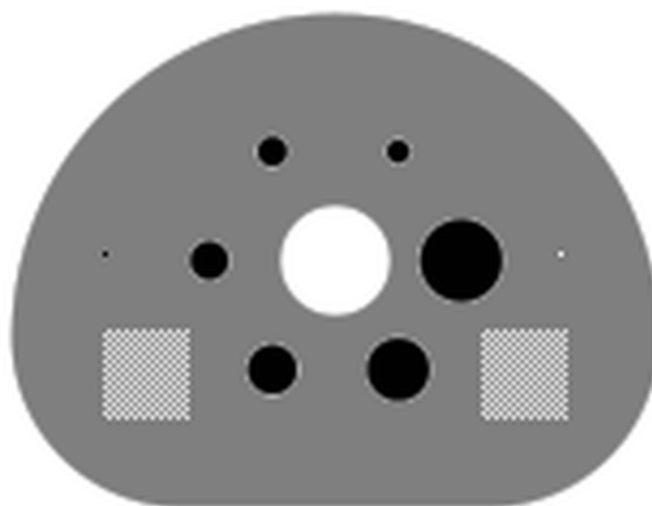
The primary goals and objectives of the PET/CT Digital Reference Object are to support the QIBA FDG-PET Technical Validation efforts, including NIBIB tasks 1-3. This will be done by (1) evaluation and validation of SUV calculations in PET images, (2) evaluation and validation of ROI calculations and (3) providing a common reference standard that can be adopted and modified by PET/CT scanner and display station manufacturers.

Users of the DRO are asked to download the package, import the PET and CT objects into their viewing software, perform several region of interest (ROI) analyses, and submit the results, as detailed in Section 2.2.

Two DICOM stacks are provided in the 10/31/2011 DRO package: a PET object and a CT object. Each image volume is modeled after the NEMA Image Quality (IQ) Phantom described in [1]. The PET object has added “test voxels” together with 2D and 3D “test patterns”. Axial and coronal views of the PET object are shown in Figure 3. Detailed descriptions of the CT and PET DROs are given in sections 3.1 and 3.2.



(a) Slice 40 of the CT DRO



(b) Slice 40 of the PET DRO

Figure 1: Slice 40 of the CT and PET DROs

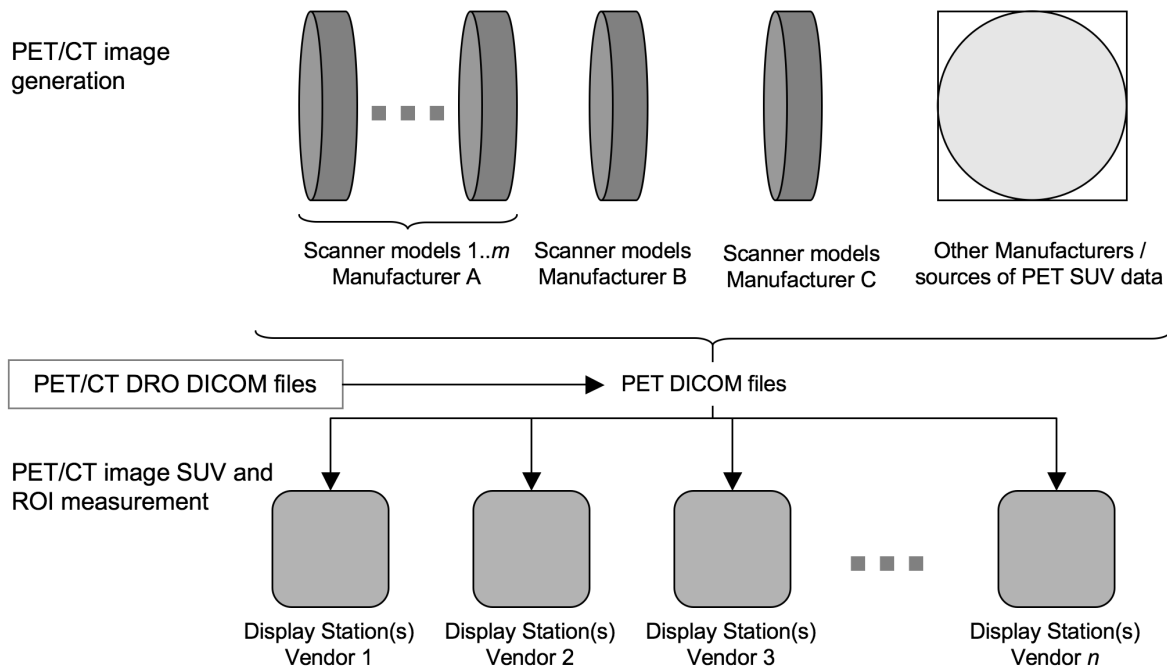


Figure 2: Flow of PET/CT DICOM image files in a heterogeneous manufacturer and vendor network. The insertion of digital reference objects (DROs) for testing validity of SUV and ROI analysis is also indicated.

2 Using the Digital Reference Object

Users of the Digital Reference Object are requested to:

1. Download the DRO (or import from CD) and the user report, as described in Section 2.1.1.
2. Verify the DRO files (Section 2.1.2).
3. Import the DRO into your viewing software (Section 2.1.3).
4. Perform ROI analysis of the DRO (Section 2.2).
5. Submit the completed report (Section 2.3).
6. Submit feedback on the DRO, the report, or general comments (Section 2.4).

2.1 Obtaining, Verifying, and Importing the DRO

2.1.1 Getting the 10/31/2011 DRO Package

The 10/31/2011 DRO package is named **DRO_20111031.zip** and can be downloaded from the DRO website:

<http://depts.washington.edu/petctdro/>

Alternatively, you can order a copy of the DRO on compact disk (CD) and have it mailed to you by sending an email request to the Imaging Research Laboratory at: petctdro@uw.edu

2.1.2 Verifying the DRO Package

1. Create a new folder and place the file **DRO_20111031.zip** in that folder.
2. Unzip the file **DRO_20111031.zip**
3. Verify that all files and directories are present:
 - The User Report pdf: **DRO_REPORT_20111031.pdf**
 - The User Report MS Excel Spreadsheet: **DRO_REPORT_20111031.xls**

- A directory named **DRO_CT_20111031** containing One Hundred Ten files numbered files named **000001.dcm** through **000110.dcm**
- A directory named **DRO_PET_20111031** containing One Hundred Ten files numbered files named **000001.dcm** through **000110.dcm**
- The user guide (this document): **DRO_USER_GUIDE_20111031.pdf**

2.1.3 Importing the DRO into your Software

1. Use your viewing software to import all DICOM (.dcm) files in the folder **DRO_CT_20111031**
2. Use your viewing software to import all DICOM (.dcm) files in the folder **DRO_PET_20111031**
3. Quickly scroll through the CT and PET DRO objects to verify that they have been properly imported.

2.2 Performing the ROI Analysis and Completing the Report

Open the DRO user report pdf: **DRO_REPORT_20111031.pdf** . Choose one of the following options to complete the DRO report:

1. Record your answers directly in the pdf document using annotations or a pdf editor.
2. Open the MS Excel file **DRO_REPORT_20111031.xls** and record your answers directly in the Excel spreadsheet. (Each line on the pdf document corresponds to a row on the MS Excel spreadsheet.)
3. Print the user report and write your answers on the printed report.

Follow the instructions in the report and record your answers. Save the completed report.

2.3 Submitting the Report

If you printed the report, scan the completed report to a .pdf file.

Email the completed pdf form or Excel spreadsheet and any screenshots to petctdro@uw.edu with subject: "Completed DRO Report". Include your name and institution in the body of the email.

Alternatively, you may mail the completed form to:

Digital Reference Object
Imaging Research Lab
222 Old Fisheries Building
Campus Mail Stop: 357987
1500 NE Boat St.
University of Washington
Seattle, WA. 98195

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

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

2.4 User Feedback

A primary purpose of this project is to evaluate the display statistics of various hardware and software configurations used in medical imaging. Its known that these systems vary (often in a number of subtle ways), but to what extent, how, and what impact this could potentially have on patient care is not well understood in the field. As a result your feedback is critical to helping establish reference material describing the display characteristics of the equipment that your institution operates with. We hope this study will improve understanding of how patient information is presented to service providers such as yourself, and as such we greatly value your input and feedback.

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 $500/512 \times 500/512 \times 2$ ($0.9765625 \times 0.9765625 \times 2.0$) millimeters³.

The interior of the phantom body and the interiors of the hot spheres have voxels with values of 0 Hounsfield 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 $500/256 \times 500/256 \times 2$ ($1.953125 \times 1.953125 \times 2.0$) millimeters³.

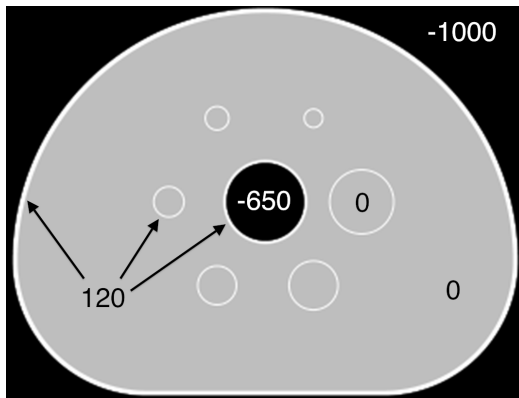
The voxels interior to the phantom body are set to an SUV value of 1.00. The voxels interior to the six hot spheres are set to an SUV_{bw} value of 4.00. The voxels corresponding to the polymethylmethacrylate shell and the exterior of the phantom body and interior to the lung insert are set to an SUV_{bw} 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.

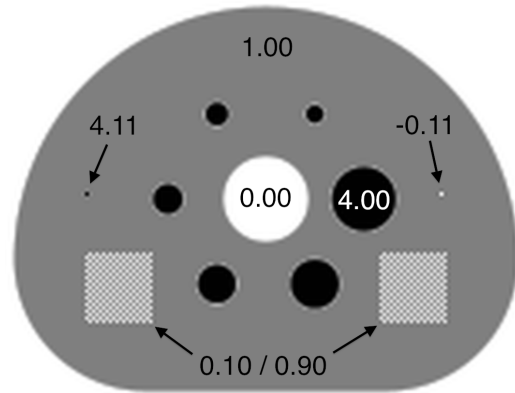
There are two test patterns in the PET DRO, a square (2D) checkerboard pattern in slice 40, and a cubic (3D) checkerboard pattern centered in slice 40. The 3D cubic test pattern appears closest to the largest hot sphere in an axial view of slice 40.

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.

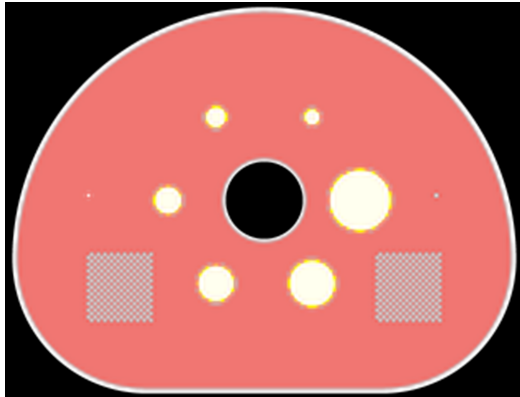
The SUV_{bw} values of each region of the PET DRO are shown in Figure 3(b).



(a) The CT DRO showing Hounsfield 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

20110914: 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.

20111031: 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) **dcenvfy**: 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

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

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

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

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

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

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 Hounsfield 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

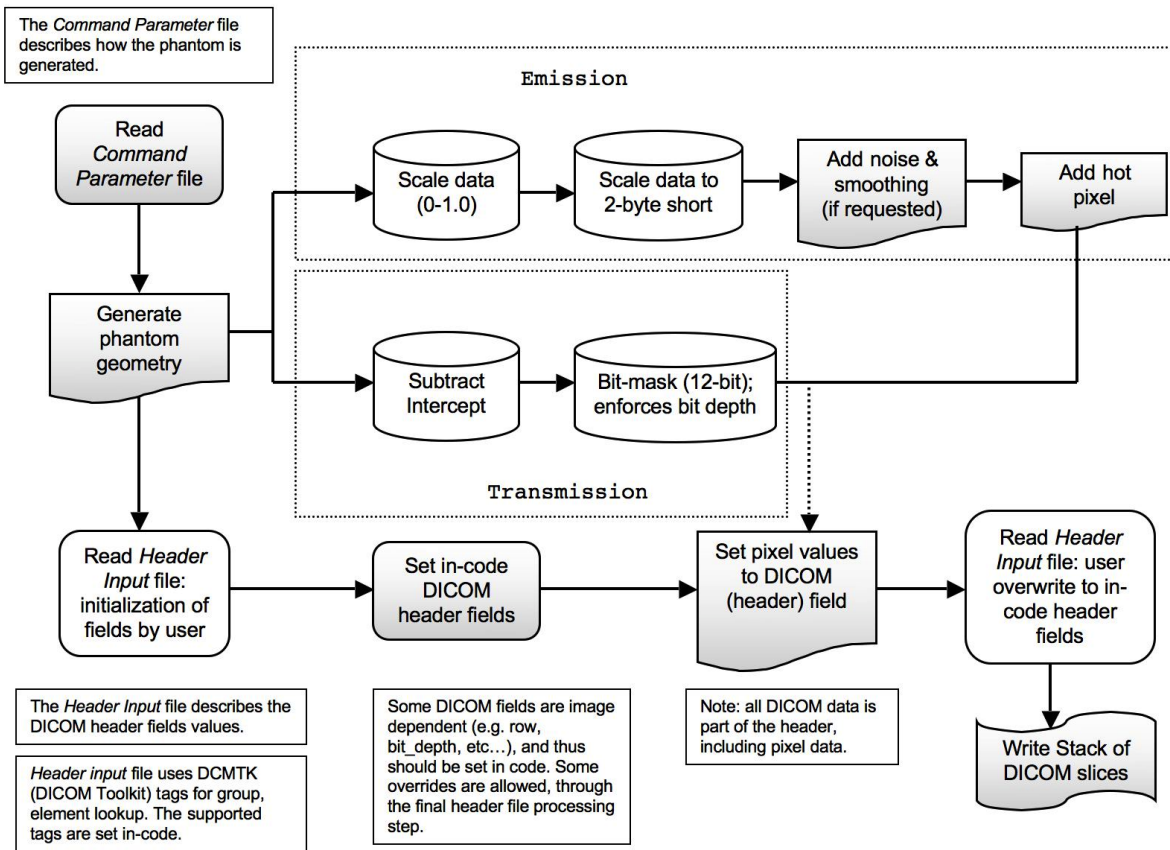


Figure 4: Workflow Diagram of the DRO creation process

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

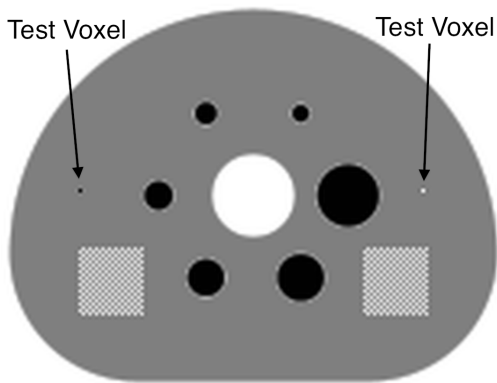
You may record your answers directly on this form or by filling out the accompanying Excel spreadsheet. The numbers on each line indicate the corresponding rows and columns of the Excel spreadsheet. Alternatively, you may print and mail the completed form to the address at the end of this document.

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..



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?	

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

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 $2,600 \text{ mm}^3$ (diameter 25 mm), centered within the 3D block test pattern nearest the cold test voxel.

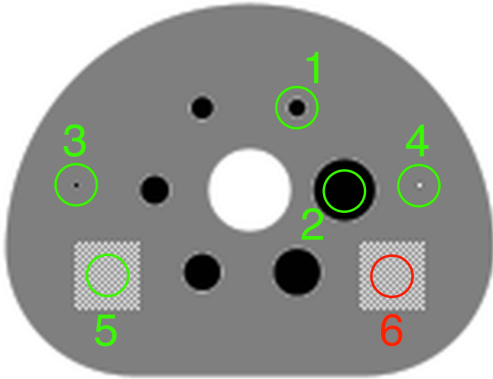


Figure 2: ROIs for the DRO analysis. The cross-section of the sphere in the 3D test pattern (on the right) is shown in red.

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.

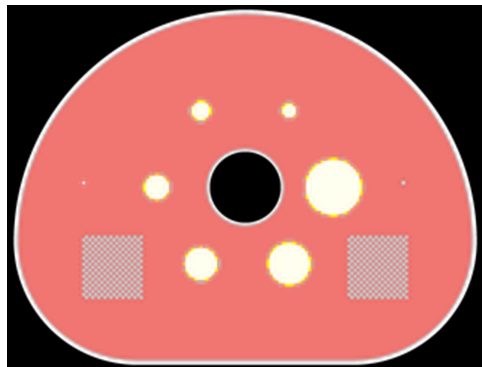


Figure 4: Image fusion of the emission and transmission DROs

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
