

## PAT CTN Phantom Analysis

The CTN Phantom Analysis is meant to provide three measures of scanner performance.

1. Recovery Coefficient Curve (Partial volume vs. size)
2. Coefficient of Variation (Noise)
3. Lesion Detectability

The CTN phantom (Figure 1) is a simple anthropomorphic chest phantom meant to be a clinical simulation phantom. It contains 12 spherical lesions ranging in size from 7 mm to 37 mm. The sphere sizes were chosen to match those of the NEMA image quality phantom, although an additional 7mm sphere was included to challenge the imaging system's lesion detection capability. The phantom additionally has two 10 mm lesions in the lung field virtually contiguous to one another. This is designed to be a second image quality feature with the intent of testing a scanner system's ability to identify these proximal spheres as two distinct objects. The inside of the phantom is inhomogeneous in that two asymmetric lung fields with slightly less than half the density of water are included to challenge both scatter and attenuation correction algorithms.

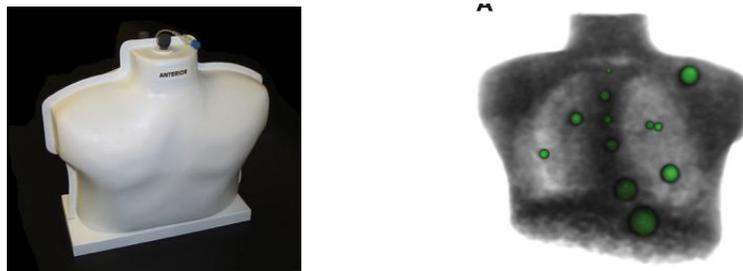


Figure 1: the CTN Phantom

By virtue of having a range of sphere sizes, the CTN phantom is designed to generate a recovery coefficient curve – which is a standard measure of the partial volume effects of the PET scanner using the chosen reconstruction.

When the phantom is filled as per instructions, the lesion:background contrast will be approximately 4:1. The fill activities can be changed to simulate different noise levels and contrasts for special purposes.

### How the Phantom Data is Acquired and Reconstructed

This phantom study is meant to automatically generate several measures of scanner performance under simulated clinical conditions. These measures include the Recovery Coefficient curve (a standard measure of partial volume effect as a function of object size), and a coefficient of variation measure taken from several regions of uniform background to assess background noise.

The reconstructed images themselves are designed for a technologist, physicist, or physician to gauge image quality through an assessment of whether, and/or how obviously the 7 mm lesion is visualized (many systems are incapable of visualizing this lesion at this contrast), and assessing the ability of the scanner to differentiate the two contiguous 10 mm lesions. These are not automated functions and they are meant to be performed by site personnel, or a qualified physicist.

To get accurate measures this test is meant to be performed using:

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1. A multi-bed position scan to fully image the phantom using your standard clinical acquisition duration.
2. Your standard clinical oncology reconstruction to get an accurate assessment of your clinically-used reconstruction algorithm and parameters.

## How the Software Works

The recommended approach expects the CTN phantom data to be acquired at the standard clinical acquisition duration, although the acquisition time can be adjusted for special purposes. The software understands the geometry of the phantom, and the inside is 3D printed for high reproducibility of structures. So even if the phantom is not centered in the gantry or is imaged at an oblique angle, the software should be capable of matching the phantom model to the image data. It has been tested extensively using many different scanner models, reconstructions, and noise levels.<sup>1</sup>

- The software first automatically detects the location of the detected lesions from the image data and calculates the physical distance of the centroids of each of the lesions to each of the others.
- The software then compares the relative positions of each of the lesions to its mathematical model of the manufactured phantom and performs an optimal rotation and translation of the mathematical model data to match the image data.
- Spherical volumes of interest (VOI) of the exact size of each sphere are automatically applied for the quantitative analysis.
- $SUV_{max}$ ,  $SUV_{peak}$ , and  $SUV_{mean}$  values are calculated for each of the spheres.
- Six additional spherical VOIs are then placed in known uniform regions inside the phantom. The mean, and more importantly, the standard deviations of the voxels inside these regions are calculated to generate the average Coefficient of Variation, a simple measurement of image noise.
- As a check that the model has correctly identified the location of all spheres, the scanner report generates a coronally-oriented MIP image with the detected spheres with their respective VOIs and centroids superimposed. (Figure 3)

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## Understanding the Report

### Report Header

The header of the report is at the top of the first page. Example below (Figure 2).

Facility: University of Iowa	Phantom: CTN	Contrast: 3.9:1
Scanner Model: SIEMENS Biograph64_mCT	Scan: 04/20/2018	Time Per Bed: 5.3min.
Reconstruction: OSEM3D+TOF 2i21s Gauss5.00		

Figure 2. Report header

This Section reads the facility name, scanner make and model, reconstruction, scan date, and time per bed position from the DICOM tags. It also reports the actual contrast in the phantom based upon the reported activity injected into the phantom, spheres, and the phantom volume.

### Recovery Coefficient Curve

The automated analysis results are presented in a box below the header information. Four pieces of information are reported. The first is the previously mentioned MIP image with VOIs superimposed (Figure 2 & 3). This should always be checked to assure that the model has correctly identified lesions and their relative locations.

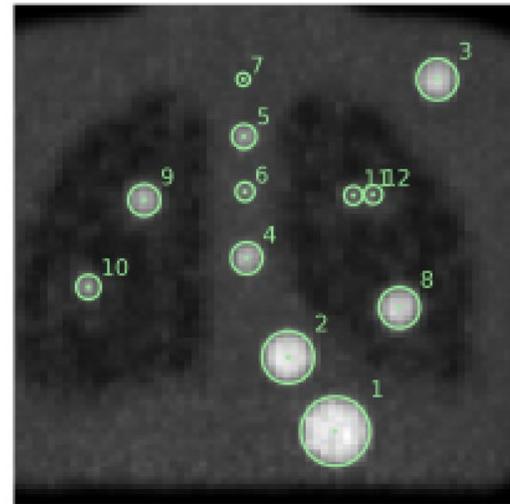


Figure 3. Coronally oriented MIP image of the CTN phantom with automatically defined spherical regions of interest.

Next the Recovery Coefficient curve is displayed (Figure 4). This is based upon  $SUV_{max}$  values. There is a solid black curve which represents the minimum allowable values associated with the EANM EARL program as a benchmark. This is not meant to be an acceptance criterion but simply a visual reference. However, since this is a baseline performance level, most values should be above this line, particularly when using a modern scanner. The two values at 10 mm should ideally be similar as they correspond to the two 10-mm spheres. The blue points represent spheres that are in the uniform background region, while the red points are those in the lung field (with a lower background than the uniform background region of the phantom). The Recovery Coefficient data are reported in the tables underneath the plot (Figure 5), separated into uniform background regions and lung background regions.

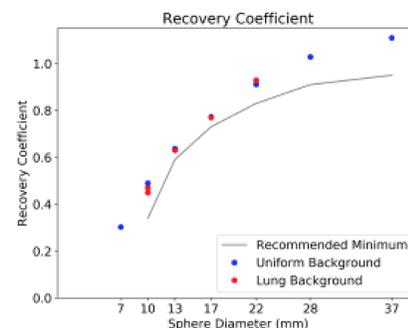


Figure 4: Recovery Coefficient curve

It should be noted that although the curve is generated by  $SUV_{max}$  values, the  $SUV_{peak}$  values are calculated and available in a separately downloadable Microsoft Excel formatted file. It should also be noted that the Recovery Coefficients are the values that are reported in the plot and the table below it. There is a separate metric called the “Contrast Recovery Coefficient” (CRC) which accounts for the contrast at which the data is acquired (Equation 1, below). The software also calculates this, but the results are embedded at the

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end of a JSON file that is also available for download. It can also be easily calculated from the data provided in the report tables given the actual contrast (radioactivity concentration ratio). The classic NEMA defined definition of CRC follows the

Equation 1 below where  $C_{hot}$  and  $C_{bkgd}$  are the average of the counts measured in the hot sphere ROI and the average of the counts in all background ROIs, respectively, and  $a_{hot} / a_{bkgd}$  is the ratio of the activities in the hot sphere and background.

$$CRC_{hot} = \frac{(C_{hot}/C_{bkgd} - 1)}{(a_{hot}/a_{bkgd} - 1)} \quad (1)$$

## Noise Assessment

Lastly, the Background Coefficient of Variation is calculated and displayed (Figure 6). Six spherical regions of interest in different areas of the phantom of known uniform background concentration are chosen. The Coefficient of Variations of the six regions are averaged to generate a global estimate of background noise. This is an admittedly simplistic noise measure, but it does give a meaningful assessment of image “roughness”. We typically like to see this number <10%, although this is not a formal acceptance criterium. COV’s less than 5% are sometimes indicative of overly smoothed images, although current advanced reconstructions with noise-controlling components can sometimes achieve this without compromising resolution. Steps like increasing acquisition time, using a PET scanner with Time-of-Flight capability, increasing Gaussian filtration, or using advanced reconstructions with noise suppressing properties are all means to reduce image noise.

	<b>Value</b>	<b>Recommended Range</b>
<b>Background Coefficient of Variation</b>	<b>9.0%</b>	<b>&lt;10%</b>

Figure 6: Background Coefficient of Variation

## Image Quality/Lesion Detectability

Two image quality/lesion detectability features are embedded in the phantom. The first is a 7mm sphere in the upper mediastinum. This is small enough that most non-Time-of-Flight scanners cannot visualize the lesion at 4:1 contrast with clinical acquisition times. By increasing contrast or increasing imaging time this feature becomes more evident. Most Time-of-Flight scanners are capable of detecting the 7 mm sphere. If it does not it is possible the images are being excessively smoothed with the Gaussian filter or imaged for too short a period of time. Alternatively, a lower Gaussian cutoff filter (i.e. 2-3 mm) can result in enough image noise that the sphere, although visualized, is not easily discriminated from noise.

A 5-point Likert Scale described below in Figure 7 and illustrated in Figure 8 was developed to help grade levels of lesion detectability. Although this is a subjective reader assessment and is not

Uniform Background Lesions			Lung Background Lesions		
Lesion Number	Lesion Size	Recovery Coefficient	Lesion Number	Lesion Size	Recovery Coefficient
7	7.0mm	0.30	12	10.0mm	0.47
6	10.0mm	0.49	11	10.0mm	0.45
5	13.0mm	0.64	10	13.0mm	0.63
4	17.0mm	0.77	9	17.0mm	0.77
3	22.0mm	0.91	8	22.0mm	0.93
2	28.0mm	1.03			
1	37.0mm	1.11			

Figure 5: Recovery Coefficient curve data

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performed automatically, the results can be fairly consistent across readers when the images are scored in reference to the example images.

**Optional** results to be completed by expert reader, if desired:

Lesion Detectability		
Criteria	Detectability	Recommended Range
7mm lesion <sup>1</sup>		≥0
10mm lung lesions <sup>2</sup>		≥1

- 0=not visualized, 1=barely visualized, but wouldn't call, 2=equivocal, 3=probably visualized above noise, 4=certainly visualized above noise
- 0=not distinguishable as two spheres, 1=distinguishable as two oblong objects, with small activity decrease between, 2=distinguishable as two objects, likely spherical, with no definite break between, 3=distinguishable as two clearly separated spheres with definite separation between the two, 4=distinguishable as two clearly separated spheres with clear lack of activity between the two.

Figure 7: Lesion Detectability measures

A second image quality feature consists of two adjacent, nearly contiguous 10 mm spheres in the left lung. This is another subjective assessment and describes the ability of the imaging system to discern the two spheres as distinct lesions. A different 5-point Likert Scale was defined to describe different levels of discrimination. These are described in Figure 7 and illustrated in Figure 9.

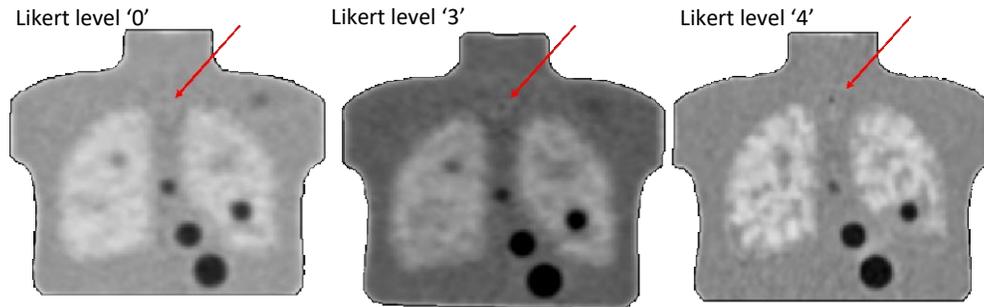


Figure 8: Examples of lesion detectability for 7mm sphere

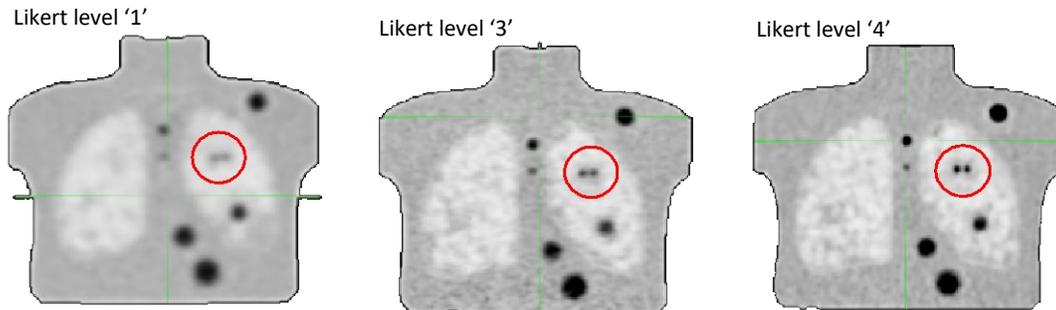


Figure 9: Examples of discerning contiguous 10mm spheres.

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## DICOM and Fill Information

Relevant DICOM header and fill information is displayed in fourth box and is illustrate in Figure 10. This is provided to provide a simple means to check the fill and reconstruction information.

Name	Value
Institution	University of Iowa
Phantom	CTN
Series Description	PET WB TOFVIA on.F1
Scan Date	04/20/2018
Scan Time	16:34:43
Assay Time	15:34:00
Background Volume	9507.0g
Background Activity	2.27
Uptake Time	60.72
Sphere Solution Volume	1000.0g
Sphere Activity	0.94
Actual Contrast	3.92:1
Minutes per Bed	5.26
Voxel Dimensions	3.18x3.18x2.03mm
Matrix Dimensions	256x256x171
Scanner Make and Model	SIEMENS Biograph64_mCT
Reconstruction Method	OSEM3D+TOF 2I21s
Reconstruction Parameters	
Reconstruction Filter	XYZ Gauss5.00

Figure 10: Phantom fill and DICOM data

## References

Ulrich EJ, Sunderland JJ, Smith BJ, Mohiuddin I, Parkhurst J, Plichta KA, Buatti JM, Beichel RR. Automated Model-Based Quantitative Analysis of Phantoms with Spherical Inserts in FDG PET Scans. *Med Phys*. 2017 Nov 1.