An Overview of PET Quality Assurance Procedures: Part II: Understanding the Results

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Objective: Computer-generated PET quality assurance data are only useful if they are fully understood by the technologist who should be able to rely on the scanner's performance without question.
Methods: This paper reviews the various results generated by the quality control procedures and the acceptance tests for the Siemens ECAT 951/31 scanner.
Results: Although the data presented are from the Siemens scanner, they can be easily applied to other PET cameras and should give users a point of reference.
Conclusions: The technologist's confidence and comprehension of the quality control and acceptance procedures is important in understanding PET quality assurance.
Key Words: quality assurance procedures; PET; calibration; normalization; acceptance testing; spatial resolution

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The computer-generated data from daily scans and weekly calibrations of nuclear medicine scanners are of the greatest value if they are understood by the technologist operating the system. It is the technologist who has primary contact with the scanner and needs to have confidence in the scanner's performance.

The results reviewed here are generated by the quality control procedures and the acceptance tests for the Siemens ECAT 951/31 (Siemens Medical Systems, Inc., Hoffman Estates, IL). All PET systems have some standard quality control and acceptance procedures. Understanding these results should assist the technologist in a basic understanding of PET quality assurance.

QUALITY CONTROL RESULTS

Daily Results

The Siemens ECAT 951/31 prints out the system's quality results of the daily check scan. The results compare each individual detector response to the average of all the detector's responses (Table 1).

The difference value checks for a uniform detector response. Equation 1 shows how the difference value is determined. Detectors that fall outside the difference range need to have their energy discriminators adjusted.

$$\% \text{ Difference} = \frac{\text{No. of cts for a particular block}}{\text{Avg. no. of cts a block should detect}} \times 100. \quad \text{Eq. 1}$$

The root mean square (RMS) that appears in Table 1 relates the difference between each individual block and compares it to an average block.

Equation 2 is used to calculate the average efficiency for each crystal to remove any differences in block efficiency. The RMS is the square root of the sum of all the means squared of all the crystals within a block. The RMS is used to calculate and compare the difference between a specific crystal in a block to a crystal in the same position on an average block (*1*).

TABLE 1
Daily Quality Control Computer Generated Output

Bucket: 16	Block: 0	Difference: −1.31%	RMS: 15.79%
Bucket: 22	Block: 3	Difference: −2.14%	RMS: 18.01%
Bucket: 28	Block: 2	Difference: 2.00%	RMS: 15.26%

The standard deviation for the normalized scan is: 1.83%

Theoretical minimum is: 0.75%

There were 25 crystals out of 8192 with efficiencies outside of three standard deviations.

The crystals with the maximum and minimum efficiency were:

Bucket: 00	Block: 1	Crystal: 05 is 109.27%
Bucket: 00	Block: 1	Crystal: 07 is 88.51%

Detector check was run: 12-Nov-89

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Average efficiency for each crystal

$$= \frac{\text{individual crystal cts}}{\text{avg. crystal cts} \in \text{that block}}. \quad \text{Eq. 2}$$

If a crystal in a block is out of range, the entire block will register out of range. Blocks that fall outside the RMS range can be corrected by adjusting the gain (*2*).

The standard deviation and the theoretical minimum are derived from the normalization. This multiplication factor is applied to the crystals so they should all read evenly. Due to noise and the randomness of radioactivity, this is not always true. The percent of the variation from the theoretical evenness is published as the standard deviation from the normalization for the crystal efficiencies. The crystals that fall outside three standard deviations are listed on the results along with the amount of difference. Their location is also recorded (Table 1).

In a normal distribution, less than 1% of all crystals will have efficiencies outside three standard deviations from the mean (*1*). On a system with 8192 crystals, approximately 82 crystals could be out and still be within normal range.

The theoretical minimum is the signal-to-noise ratio. This is calculated in Equation 3. The lower the percent theoretical minimum, the better the signal-to-noise ratio.

Theoretical minimum =

$$\frac{1}{\sqrt{(\text{average crystal counts})}} \times 100. \quad \text{Eq. 3}$$

If a detector pair is not functioning properly, but the standard deviation is 2.5% or less, the system could still be used for that day.

To reference how well the scanner is functioning from day to day, hard copy images of the daily quality control sinograms or the results should be kept. This also helps the technologist to be aware of how temperature and humidity changes affect the system.

System Calibration

The system calibration or setup makes coarse and fine gain adjustments to the photomultiplier tubes (PMTs). When a PMT is failing, the gain will have to be turned up higher to allow the PMT to see the scintillation in the crystal.

In the ECAT 951/31, the gain settings can be reviewed by examining the feature called bucket gains. All PET systems should have a function similar to this. The technologist can quickly review the hardware so any problems in this area can be accurately reported. Bucket gain will list the gain settings for each PMT (Table 2). The theoretical perfect gain is 114, however, as long as a PMT gain can still be adjusted so it responds the same as the other PMTs, it is in working condition. The higher the number, the more adjustment needed. The tube with a high gain value may also begin to quickly

TABLE 2
Gains Listed for Each Photomultiplier Tube in Each Bucket

Gains for bucket	0 are:	127, 112, 132, 101
		134, 174, 129, 138
		120, 123, 124, 136
		89, 124, 144, 139
Gains for bucket	1 are:	135, 139, 149, 129
		128, 113, 149, 122
		141, 114, 196, 132
		142, 139, 139, 131
Gains for bucket	2 are:	145, 134, 141, 129
		144, 131, 175, 146
		109, 104, 118, 116
		139, 147, 145, 139
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Gains for bucket	31 are:	132, 127, 133, 137
		124, 118, 130, 112
		139, 116, 133, 122
		120, 120, 142, 127

drift out of alignment. The gain cannot be calibrated above 255. A tube requiring higher adjustment cannot be aligned and will need to be replaced by service personnel.

The ECAT 951/31 will automatically print out all blocks that were not able to be adjusted. This report will state: Bucket 1 Block 3 completed with an S1 response. An S1 response indicates that within that block a PMT is above adjustment. To find the failing PMT, a histogram could be acquired (Fig. 1). The histogram will display the counts seen by each crystal in an entire block. The counts will vary, but if a PMT is out, one whole quadrant of the image will record very few to no counts because the tube's gain could not be

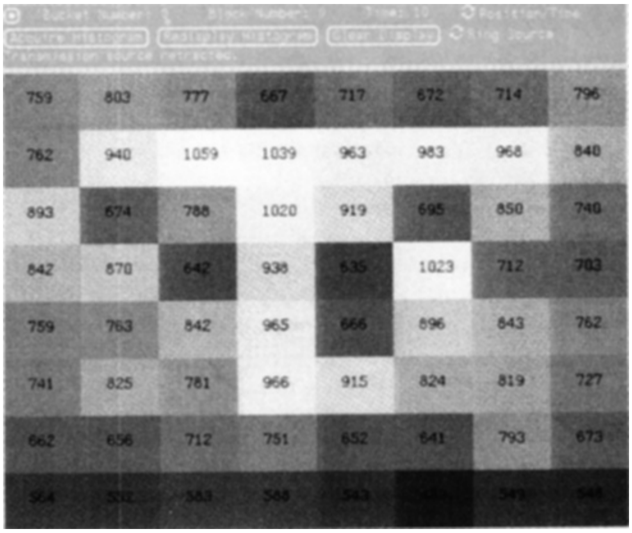

FIGURE 1. Histogram to assist in finding a PMT.

TABLE 3
Normalization Detector Check Results

```
Processing matrix  1 1 1 0 0  of file /sd0/nrmscntmp.scn
  Total counts for this sinogram = 2779278, average counts per
    detector = 10856.55
  Bucket 8  Block 1 crystal Row 5 : sum = 16584 dev = 152.76
  1 detector was outside a range of 50 and 150
Processing matrix  1 2 1 0 0  of file /sd0/nrmscntmp.scn
  Total counts for this sinogram = 5329749, average counts per
    detector = 20819.33
  0 detectors were outside a range of 50 and 150
Processing matrix  1 3 1 0 0  of file /sd0/nrmscntmp.scn
  Total counts for this sinogram = 7793033, average counts per
    detector = 30441.54
  0 detectors were outside a range of 50 and 150
*
*
*
Processing matrix  1 31 1 0 0  of file /sd0/nrmscntmp.scn
  Total counts for this sinogram = 2766008, average counts per
    detector = 10804.72
  0 detectors were outside a range of 50 and 150
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set high enough to see the scintillations. Using a histogram, the technologist can precisely pinpoint the tube in question.

Plane Efficiency

The plane efficiency scan sets factors for each plane so the hardware variation from plane to plane is corrected. The plane efficiency information is used during reconstruction to adjust the data so that each plane has an equivalent efficiency.

Normalization

The normalization balances individual crystal sensitivity to the lines of responses. The normalization calculates a crystal correction coefficient for each defector pair which is then applied to the sinograms.

$$\text{Norm} = \frac{\text{avg. counts for entire scanner}}{\text{measured counts for LOR}}. \quad \text{Eq. 4}$$

The normalization scan collects data from a uniform plane source from six different angles. The data are then compiled into a single normalized sinogram for each plane. Each of these sinograms can be visually inspected for defects.

A detector check can be run on the normalization scan to give the technologist detailed information on the performance of individual detectors. To identify anomolous detectors, the number of events for each detector is compared to the average counts per detector for each plane. Any detector that has a count number >150% or <50% of the mean for that plane can be considered suspicious (Table 3).

TABLE 4
Spatial Resolution Test

Plane	Max	Center of matrix	y FWHM mm	y FWTM mm	x FWHM mm	x FWTM mm	x off set	y off set
1	32894	(126,128)	4.63	10.39	4.51	10.03	0.01	0.00
2	32894	(126,128)	4.69	10.58	4.59	10.18	0.01	0.00
3	32894	(126,128)	4.76	10.92	4.71	10.49	0.01	0.00
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.								
.								
29	32894	(126,128)	4.68	10.41	4.67	10.33	0.01	0.00
30	32894	(126,128)	4.61	10.58	4.63	10.27	0.01	0.00
31	32894	(126,128)	4.62	10.45	4.71	19.43	0.01	0.00

x offset = 0.07 cm; y offset = 0.00 cm
Total x FWHM: Average = 4.77 STD = 0.25 (5.08%)
Total y FWHM: Average = 4.71 STD = 0.28 (5.89%)

ACCEPTANCE TESTS

Spatial Resolution Results

Spatial resolution is a measure of the scanner's ability to accurately distinguish between two close objects and observe their detail (*3*). The values of full-width at half-maximum (FWHM) and full-width at tenth maximum (FWTM) for each plane's x-axis and y-axis in the stationary and wobble positions, if available, are reported. Two source positions are acquired for each mode; one in the center of the field of view and one at 10 cm offset from the center.

Table 4 is an example of the information available from the computer data sheet for spatial resolution. The FWHM and FWTM for all planes are listed in millimeters. The shorter the distance of the width of the curve, the better the scanner resolution. The millimeter measurement is a function of crystal size. The smaller the crystal size, the better the resolution.

When measuring spatial resolution on the ECAT 951/31 using the wobble function, the FWHM at the center of the gantry should be approximately 5.5 mm and the FWHM 10 cm offset from the center will be larger. For a stationary acquisition for spatial resolution, the FWHM at the center of the gantry should be approximately 6.4 mm and will be larger for 10 cm offset from the center (*4*).

If only one plane is above the specified value, the scan should be repeated. If several planes are above the range or repeating the test does not improve the results, it should be verified that the system is operating properly by the daily detector check. If a system is properly calibrated and normalized, it should provide good resolution. The inherent resolution is controlled by the unchanging detector geometry.

The average for all the FWHM measurements for each x-axis and y-axis is reported. The maximum number is another coordinate system for the center of the matrix. The center of the matrix is where the line source curve is formed on the matrix for each plane. The x and y offset is the

TABLE 5
Axial Resolution Test*

Plane	Absolute	Plane center relative	FWHM	FWTM
1	125.59	49.99	4.28	9.61
2	122.48	46.88	4.75	10.93
3	119.41	43.82	4.55	11.93
†				
†				
†				
15	79.04	3.45	4.32	11.05
16	75.59	0.00	4.28	11.67
17	71.93	−3.67	4.48	12.24
†				
†				
†				
29	31.78	−43.82	4.65	11.50
30	28.55	−47.05	4.58	10.65
31	25.44	−50.15	4.42	9.07

Total axial width = 109.49 mm
FWHM: Average = 4.64 STD = 0.23 (4.87%)

*196 points read
†Plane data omitted to save space

physical location of the line source in the gantry. The standard deviation from the means measures plane-to-plane difference.

Axial Resolution Results

The results from the axial resolution will yield a report of FWHM and FWTM data per plane for all 31 planes (Table 5). Axial resolution checks for accurate sampling on the scanner's z-axis.

The Siemens ECAT 951/31 will operate in the absolute or relative position of the bed in the field of view of the scanner.

The absolute position is that position of the patient couch in the gantry (in millimeters based on zero) with the bed fully retracted. The patient couch holds the point source which is then incremented by 0.7 mm from one edge of the field of view to the other. The center point of each couch position for each plane is then recorded.

The relative bed location is the position of the patient couch in relation to the center of the field of view. Plane 16 is set as zero and each patient couch position in the center of each plane is then recorded as either a positive number for places 1–15, or a negative number for places 17–31.

The FWHM and FWTM of the response curves are then printed. The axial resolution test will acquire a minimum of 196 five-second acquisitions. This allows for approximately six points for each plane. Each point is then plotted to form a response curve for that plane. The peak of the response curve should correspond to the center of that plane. The FWHM of the response curve should intersect with approximately the same place on the next plane's response curve (Fig. 2). The results are reported in millimeters. For the ECAT 951/31, the ideal FWHM for the center of the field of view should be less than 5.5 mm and the ideal FWHM for the 10-cm offset position should be less than 6.5 mm (*4*). The ideal results will change as scanner hardware continues to improve.

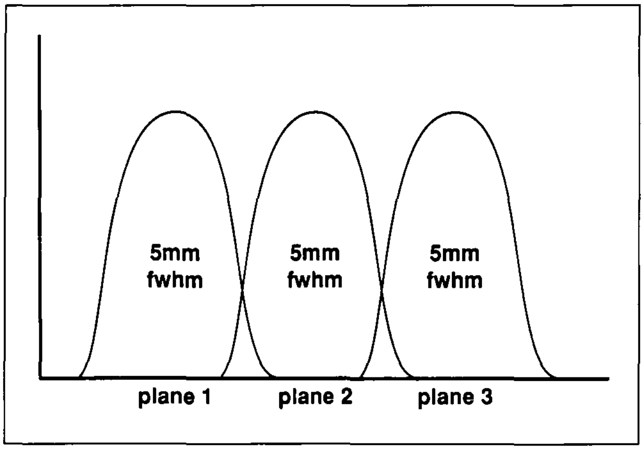

FIGURE 2. Axial response curves for each plane.

No gap between the response curves' half maximums of the planes is desired. This measurement is to ensure that there is no error in partial volume assessment.

The total axial width of the field of view, the FWHM average of all the planes and the standard deviation from the mean are all printed for quick reference.

Count Rate Results

The count rate test measures the scanner's ability to accurately correct for dead time over a range of radioactivity. The count rate results are count rate data per plane for thirty, 5-min acquisitions (Table 6). The results will list the actual time each 5-min scan began with the calculated activity in μCi/ml at the time acquired based on the initial activity in the phantom being greater than 5 μCi/ml at the start of the initial acquisition (*6*). For the ECAT 951/31, the corrected true coincidence count rate should be within ±10% of the expected coincidence rate for an activity of 5 μCi/ml.

The calculation starts from frame 30, which has the lowest number of true counts recorded from the smallest amount of activity concentration, and corrects the dead time back to the beginning of the count rate test (total true counts/microcurie). A straight ascending diagonal line would represent the ideal progression of isotope decay to recorded true counts.

Dead time in hardware systems prevents equipment from performing to ideal standards. The count rate tests acquire true counts collected from the system and corrects the true counts to the ideal. The true count rate ratio is figured at 100% when the radioactivity is at its lowest concentration. Dead time remains relatively constant for radioactivity levels until they get high enough to cause electronic saturation. At this point, dead time increases and the acquired true count rates begin to level out and then decrease as the electronics of the scanner begin to saturate from too many

TABLE 6
Count Rate Test

Frame	Acquisition	Time-activity (μC/ml)	Corrected trues	Trues ratio	Corrected %ROI integral	ROI ratio (%)
Plane 1						
1	Wed. Nov. 20 16:39:56	7.1667	2.397076e+06	91.0	2.124969e+02	93.2
2	Wed. Nov. 20 17:05:01	6.1171	2.419514e+06	91.8	2.109359e+02	92.5
3	Wed. Nov. 20 17:30:03	5.2230	2.427959e+06	92.1	2.104885e+02	92.3
*						
*						
*						
15	Wed. Nov. 20 22:30:23	0.7844	2.580554e+06	97.9	2.213877e+02	97.1
16	Wed. Nov. 20 22:55:24	0.6698	2.573997e+06	97.7	2.207402e+02	96.8
17	Wed. Nov. 20 23:20:26	0.5719	2.585267e+06	98.1	2.218804e+02	97.3
*						
*						
*						
28	Wed. Nov. 21 03:55:50	0.1005	2.627551e+06	99.7	2.261664e+02	99.2
29	Wed. Nov. 21 04:20:51	0.0858	2.636638e+06	100.1	2.276456e+02	99.9
30	Wed. Nov. 21 04:45:52	0.0733	2.634981e+06	100.0	2.279940e+02	100.0

*Plane data omitted to save space.

random and true count rates. The dead time correction factor corrects for this decline in counts. The corrected counts should be within ±10% (90%–110%) of the ideal for 5 μCi/cc.

Corrected region of interest (ROI) integral and ROI ratio percents use the same data acquired during the count rate test. A circular ROI is drawn in the center of the count rate image. The pixel counts are then used to perform the decay correction back to the start.

This provides image statistics and compares these results for dead time correction. The ROI integral and ROI ratio percent should also be within ±10% (90%–110%) at 5 μCi/cc (*5*).

Counting Efficiency Scan

The results from the counting efficiency scan will list the efficiency of each plane and the entire scanner's efficiency (Table 7). The total counts for each plane, the corrected true counts and the efficiency are recorded. The corrected counts are the true coincident counts plus multiples and scatter counts (randoms are excluded). The corrected counts are then converted into counts per second. It is the corrected counts per second for each plane that is divided by the source-specific activity which results in the counting efficiency for each plane. Equation 4 calculates the specific positron activity that is necessary for the counting efficiency to be calculated in Equation 5 (*4*).

$$SA = \mu Ci/ml \times {}^{a}0.967 sec * \exp[-0.693 * (T_L + T/T_{1/2})]$$

$$= \mu Ci/cc, \quad \text{Eq. 5}$$

where SA is specific positron activity; t is the scan length in seconds; T_L is the time in seconds from when activity was calibrated to when the scan was started; $T_{1/2}$ is half-life of

TABLE 7
ECAT Efficiency Test Results

Isotope: ^{18}F
Calibrated activity: 1.74 mCi
Phantom volume: 6283.00 ml
Calibration date: Tue. Feb. 25 14:10:00 1992
Measurement time: Tue. Feb. 25 14:15:53 1992
Source specific activity: 0.2423 μCi/ml
[a]Isotope branching ratio: 0.9670
Planes measured: all
Acquisition time: 1200 sec

Plane	Total counts	Corrected counts/sec	Efficiency
1	336806	296.83	1225.27
2	659957	581.83	2401.69
3	979368	861.91	3557.87
4	1243721	1093.03	4511.92
5	1059527	930.99	3843.03
*			
*			
*			
16	1234275	1092.50	4509.70
17	1001887	886.81	3660.65
18	1234219	1092.42	4509.38
19	1003945	886.61	3659.83
20	1247602	1100.08	4541.00
*			
*			
*			
27	1084409	955.56	3944.44
28	1222416	1077.50	4447.80
29	966954	853.63	3523.67
30	653849	578.20	2386.73
31	327443	289.38	1194.52
		System efficiency =	119248.08

*Plane data omitted to save space.

activity used; and [a] is the branching ratio of ^{18}F (from the *Nuclear data sheet*, Academic Press, 1968).

$$\text{Efficiency} = \frac{\text{total coincidence cnts}}{\text{time}} \times \text{Specific activity } (\mu\text{Ci/ml}). \quad \text{Eq. 6}$$

The alternating pattern of counts per plane has to do with the cross planes and direct planes. The direct planes will record a lower number of counts than cross planes. In cross planes, the crystals form coincidences with other crystals in the adjacent detector ring. In direct planes, the crystals form coincidences with only one detector ring. The end planes have a reduced number of counts due to their position in the field of view.

The system efficiency is the total of all the plane efficiencies and its results should meet the manufacturer's acceptance specifications for plane efficiency. Failure of the counting efficiency of the system to meet this specification indicates a hardware problem and service personnel should be called.

Image Uniformity Result

The image uniformity test verifies that the scanner system can produce a uniform image from a homogeneous source (Table 8). The plane efficiency correction factors correct for the hardware variances of line of response detection so an image will appear uniform. The test measures the variation for the same ROI in each plane. The average deviation should meet the manufacturer's acceptance specification.

CONCLUSION

These tests apply to the Siemens Ecat 951/31 scanner but serve as a very useful tool for all PET users to use as a reference. Quality control procedures should be performed and results reviewed and understood to make certain that the equipment is functioning to meet acceptance criteria. In the future, National Electrical Manufacturers Association (NEMA) will make requirements for all PET manufactures so there will be a uniform measurement of quality control for all scanner equipment.

TABLE 8
Stationary Uniformity Test

Plane	STD	Mean
1	26.44%	1.313561e-02
2	18.88%	1.322724e-02
3	15.10%	1.325272e-02
4	13.56%	1.329124e-02
5	14.54%	1.334218e-02
*		
*		
*		
16	13.62%	1.313220e-02
17	14.88%	1.316753e-02
18	13.98%	1.312172e-02
19	15.54%	1.315019e-02
20	13.94%	1.318834e-02
*		
*		
*		
27	14.41%	1.338874e-02
28	13.75%	1.335655e-02
29	15.50%	1.327951e-02
30	18.30%	1.324717e-02
31	25.37%	1.326661e-02
Average deviation = 15.35%		

*Plane data omitted to save space.

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