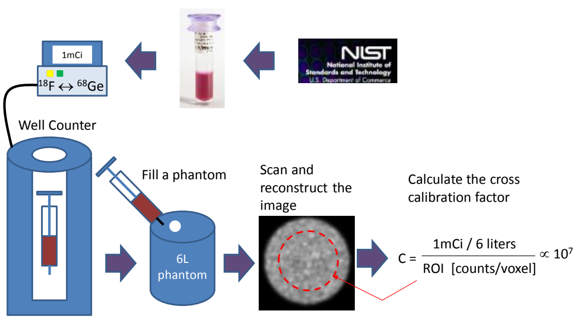
Measurement of Contrast Recovery Coefficients and Their Analytical Solutions

Jonathon A. Nye PhD
Emory University
Atlanta, GA

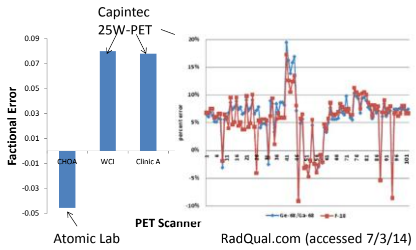
Outline

- Limits of quantization and resolution in PET
- Analytical representation of contrast recovery
- Simulations of contrast recovery
- Calculating resolution from measured contrast recovery coefficients



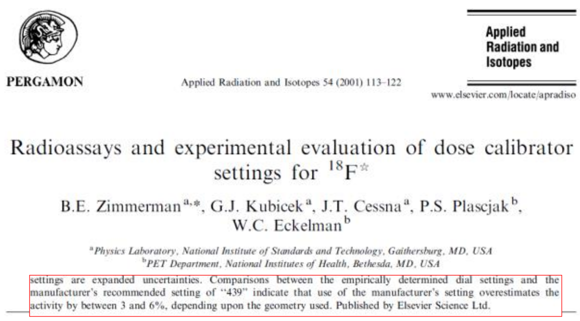
C = cross calibration factor
Relates scanner counts/voxel to radioactivity/cm^3

One Institution's Dose Calibrators for PET (F-18)



~2009 Capintec issued a press release that several of their models were +6.4% error on the F-18 setting

Zimmerman et al., Radioassays and experimental evaluation of dose calibrator settings for F-18. J. Applied. Rad. Isot. 2001: p. 113-22


PERGAMON
Applied Radiation and Isotopes 54 (2001) 113–122
Applied Radiation and Isotopes
www.elsevier.com/locate/apradiso

Radioassays and experimental evaluation of dose calibrator settings for ^{18}F☆

B.E. Zimmerman[a,*], G.J. Kubicek[a], J.T. Cessna[a], P.S. Plascjak[b], W.C. Eckelman[b]

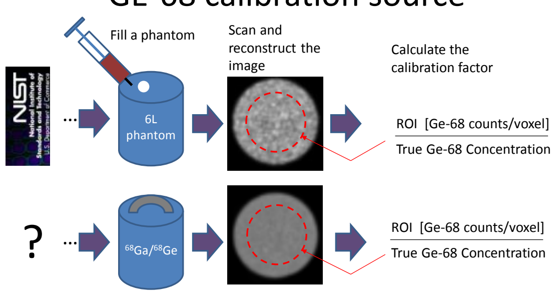
[a] Physics Laboratory, National Institute of Standards and Technology, Gaithersburg, MD, USA
[b] PET Department, National Institutes of Health, Bethesda, MD, USA

settings are expanded uncertainties. Comparisons between the empirically determined dial settings and the manufacturer's recommended setting of "439" indicate that use of the manufacturer's setting overestimates the activity by between 3 and 6%, depending upon the geometry used. Published by Elsevier Science Ltd.

- Dose calibrator setting
  - Depends strongly on the geometry of the sample (±10% variability)
  - Sensitive to the type of container (glass vial, 5mL plastic syringe,…)

Zimmerman et al., Correct use of dose calibrator values. J. Nucl. Med. 1998: p. 575-76

GE-68 calibration source



Scanner	^{68}Ge phantom	^{18}F phantom	Well-counter
CHOA	1.00	1.05	0.96
Clinic A	0.99	1.04	1.08

Does this matter? Depends…

- Use the same geometry (same time of day?)
- Use the same container (syringe, vial, …)
- Exact calibration may not matter for internal consistency between scanners

  …but it is important for cross-institutional consistency
- Check dose calibrator settings at quarterly

What is the purpose of scanner cross calibration with a dose calibrator?

17%	1.	To relate scanner counts/voxel to absolute concentration
17%	2.	To relate CT voxels to known HU values
37%	3.	To provide accurate scatter correction
30%	4.	To provide accurate attenuation correction

What is the purpose of scanner cross calibration with a dose calibrator?

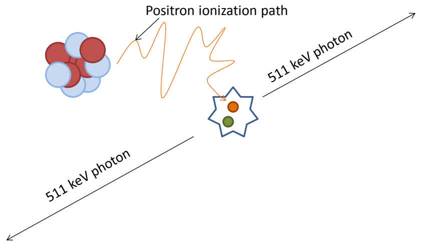
1. **To relate scanner counts/voxel to absolute concentration**
2. To relate CT voxels to known HU values
3. To provide accurate scatter correction
4. To provide accurate attenuation correction

Ref: Cherry, Sorenson and Phelps. 2013. Physics and Nuclear Medicine, 3rd edition. Elsevier. p. 357

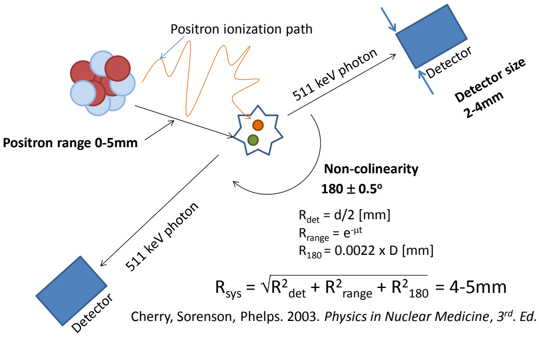
What else affects quantitation in PET

- Factors to consider
  - Scanner calibration
    - Reference to an internal, manufacturer or national standard?
  - Point spread functions (fixed)
    - Range from ~4-6mm
  - Iterative updates
    - Updates = iterations x subsets
    - Range from 30 to 90
  - Post-reconstruction filter
    - Range from 4 to 7mm FWHM
  - Pixel size
    - Could be sampling appropriately in image space
    - Pixels sizes are typically 3-4mm for FWHM of 6-7mm, may need to be a bit smaller

Ideal



Reality



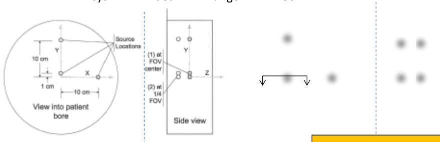
$R_{det} = d/2$ [mm]
$R_{range} = e^{-\mu t}$
$R_{180} = 0.0022 \times D$ [mm]

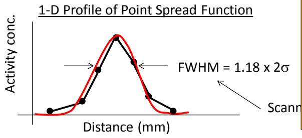
$$R_{sys} = \sqrt{R^2_{det} + R^2_{range} + R^2_{180}} = 4\text{-}5\text{mm}$$

Cherry, Sorenson, Phelps. 2003. *Physics in Nuclear Medicine*, 3rd. Ed.

Measuring Scanner Resolution

$$R_{sys} = \sqrt{R^2_{det} + R^2_{range} + R^2_{180} + \ldots R^2_n} = 4\text{-}6mm$$





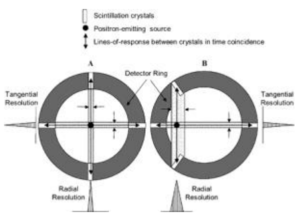
Best case scenario
1. Sources are measured in air
2. Measured at scanner isocenter
3. Data are reconstructed to pixel sizes << resolution
4. No scatter/attenuation effects

Scanner Resolution

Model	Maker	Isocenter Trans	Isocenter Axial	10 cm of isocenter Trans	10 cm of isocenter Axial	Ref.
Biograph 40	Siemens	4.6	5.1	5.3	5.9	Brambilla et al. 2005, JNM
Discovery ST (BGO)	GE	6.1	6.0	6.8	6.7	Mawlawi et al. 2004, JNM
Discovery 690	GE	4.7	4.8	4.7	5.6	Bettinardi et al. 2011, Med.Phys
Discovery 600 (BGO)	GE	4.9	5.6	5.6	6.4	De Ponti et al. 2011, Med. Phys
Biograph HiRez	Siemens	4.1	4.7	5.0	5.7	Jakoby et al. 2009, TNS
mCT	Siemens	4.4	4.4	4.7	5.9	Jakoby et al. 2011, PMB

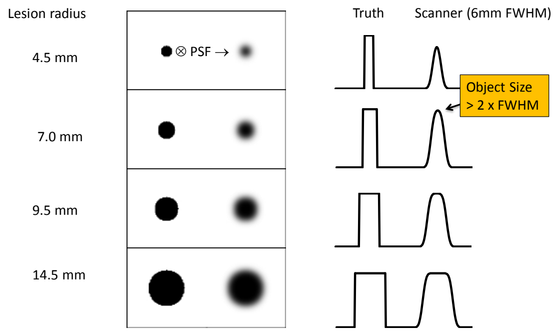
Depth of Interaction

- Crystal thickness > cross-section, needed to stop 511keV photons
- Close to scanner edge the cross-section increases
- Similar effect for interactions across rings (3D mode)

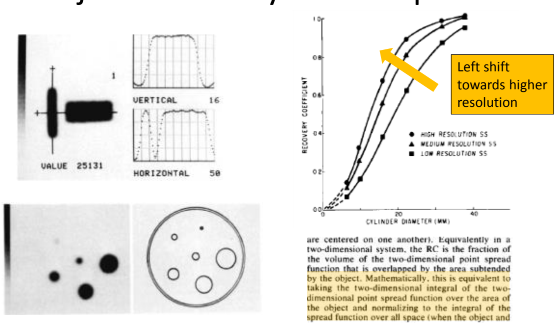


Pomper et al., Experimental evaluatin of depth-of-interaction correction in a small animal positron emission tomography scanner. 2012. Molecular Imaging. P 1536

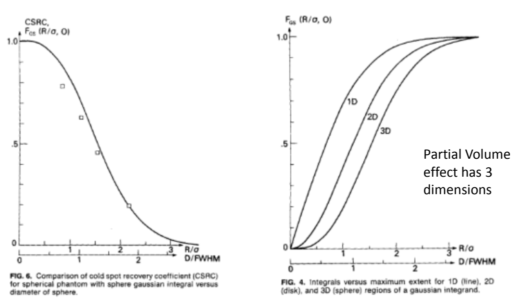
Partial Volume



Object size vs. System Response



Hoffman et al., Quantitation I Position Emission Computed Tomography: 2. Effect of Object Size. J. Compt. Assist. Tomo. 1979 **3**: p.299-308



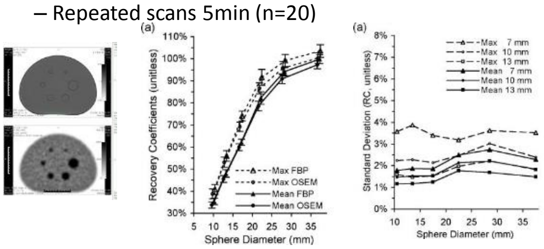
Kessler et al., Analysis of Emission Tomographic Scan Data: Limitations Imposed by Resolution and Background. 1984: p. 514-522

Contrast Recovery Coefficient

- Recovery Coefficient (RC, Hoffman et al., 1979)
  RC = (measured concentration) / (True concentration)
- Contrast Recovery Coefficient (CRC, Kessler et al., 1984)
  CRC = (Hot spot conc. – bkgd) / (truth – bkgd)
- NEMA percent contrast ($Q_{H,j}$)
  $Q_{H,j} = [(C_{H,j} / C_{B,j}) - 1] / [(a_H / a_B) - 1]$
  - No partial volume in bkgd, so if $C_{B,j} = a_B$
  - $Q_{H,j} = (C_{H,j} - C_{B,j}) / (a_H - a_B)$
- If bkgd is cold, then CRC = RC

NEMA Contrast Phantom

- Non-uniform phantom
  - Repeated scans 5min (n=20)



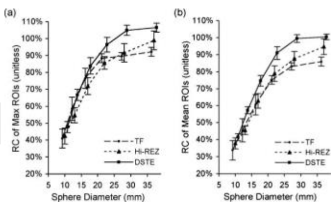
Doot et al., *Instrumentation factors affecting PET measure variance and bias*. J. Nucl. Med., 2010 **37**: p.6035-46

NEMA Contrast Phantom

- Non-uniform phantom
  - Repeated scans with positioning error
  - A look at 3 different manufactures (GE, Siemens, Philips)

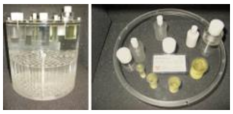
TF – Philips
Hi-REZ – Siemens
DSTE – GE

Each scanner has a unique recovery coefficient curve.

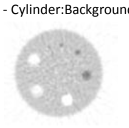


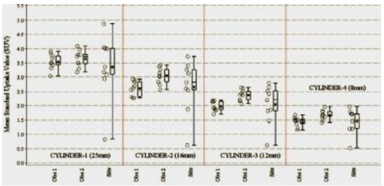
Variability across institutions

- ACR PET Phantom



4:1 - Cylinder:Background





Central read - ~10-15%
Institution read - ~30-43%

Fahey et al., *Variability in PET quantitation within a multicenter consortium.* Med. Phys. 2010 **37**: p.3660-66

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What is the cause of underestimation of the activity concentration with decreasing sphere size?

13%	1. Non-colinearity
3%	2. Positron range
20%	3. Partial volume
33%	4. Increased noise

What is the cause of underestimation of the activity concentration with decreasing sphere size?

a. Non-colinearity
b. Positron range
c. **Partial volume**
d. Increased noise

Ref: Cherry, Sorenson and Phelps. 2013. Physics and Nuclear Medicine, 3rd edition. Elsevier. p. 357

Contrast Recovery Coefficients

- An analytical prediction of CRC can be made for an imaging system with a gaussian PSF scanning simple objects

$$f\left(\frac{R}{\sigma},\frac{Z_p}{\sigma}\right)=\frac{1}{\left(\sqrt{2\pi}\sigma\right)^3}\int_{-R}^{R}dz\int_0^{2\pi}d\theta\int_0^{\sqrt{R^2+Z^2}}rdr\,e^{-\left(\frac{R^2+\left(Z^2-Z_p{}^2\right)}{2\sigma^2}\right)}$$

$$f\left(\frac{R}{\sigma},\frac{Z_p}{\sigma}\right)=erf\left(\left(R-Z_p\right)/\sqrt{2}\sigma\right)-\mathrm{erf}\left(\frac{\left(-R-Z_p\right)}{\sqrt{2}\sigma}\right)-\left(1/\sqrt{2\pi}\right)\cdot\left(\sigma/Z_p\right)\cdot e^{\left(-\left(R^2-Z_p^2\right)/2\sigma^2\right)}\left(e^{\left(R\cdot Z_p/\sigma^2\right)}-e^{\left(-R\cdot Z_p/\sigma^2\right)}\right)$$

$$A_{meas} = A_{true} * f(R,Z_p)$$

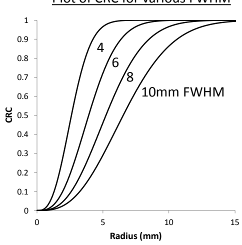
Solution for a 3D Gaussian integrated over a sphere

Assumption
The FWHM is the same in all directions

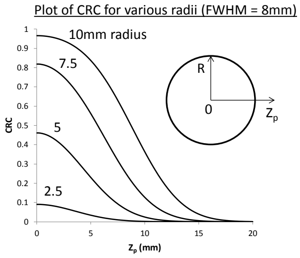
Kessler et al., *Analysis of Emission Tomography Scan Data: Limitations Imposed by Resolution and Background*. J. Comp. Assist. Tomo., 1984 **8**: p.514-22

Contrast Recovery Coefficients

Plot of CRC for various FWHM



Plot of CRC for various radii (FWHM = 8mm)

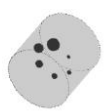


R – Object radius
Z_p – Distance from the center of the Gaussian kernel
For the max CRC, set Z_p equal to zero

CRC Simulations

1. 20 cm cylinder + sphere elements of 10, 13, 17, 22, 28, 37mm dia.
2. Simulate resolution by convolving image with 4, 6, 8 and 10mm Gaussian kernels
3. Calculate CRC for each element and fit to analytical function

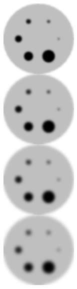
NEMA style Digital Phantom

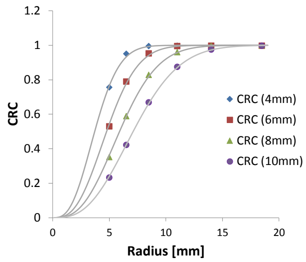


Prieto et al., *Evaluation of spatial resolution of a PET scanner through the simulation and experimental measurement of the recovery coefficient*. Comp. Biol. Med. 2010 **40**: p 75-80

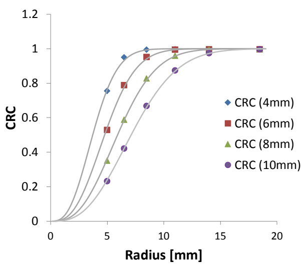
CRC Simulations

4 mm
6 mm
8 mm
10 mm





CRC Simulations

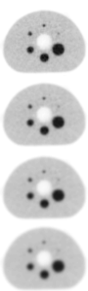


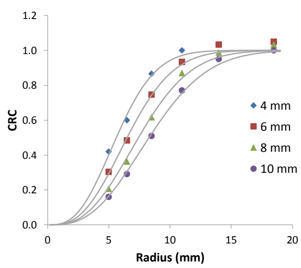
$$R_{meas} = \sqrt{R^2_{sys} + R^2_{filter}}$$

R_{meas}	R_{filter}	R_{sys}
4.32	4	~4.12
6.36	6	6.10
8.39	8	8.10
10.32	10	10.1

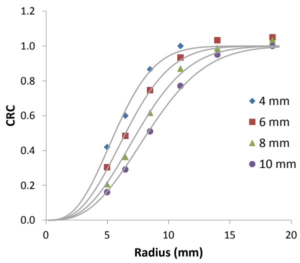
CRC Measurements

4 mm
6 mm
8 mm
10 mm





CRC Measurements



$$R_{meas} = \sqrt{R^2_{sys} + R^2_{filter}}$$

R_{meas}	R_{filter}	R_{sys}
6.83	None	6.83
7.58	4	6.44
9.10	6	7.00
10.63	8	6.69
12.03	10	6.83

6.79 ± 0.21 mm

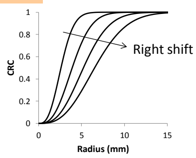
What will cause the contrast recovery curve measured in a NEMA phantom to shift rightward when plotted against increasing sphere size?

17% 1. Increase in system sensitivity

7% 2. Increase in sphere diameter

3% 3. Decrease in pixel size

13% 4. Decrease in system resolution



What will cause the contrast recovery curve measured in a NEMA phantom to shift rightward when plotted against increasing sphere size?

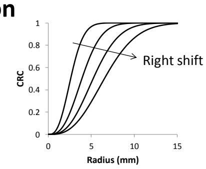
a. Increase in system sensitivity

b. Increase in sphere diameter

c. Decrease in pixel size

d. **Decrease in system resolution**

Ref. Kessler et al., Analysis of Emission Tomographic Scan Data: Limitations Imposed by Resolution and Background. 1984: p. 514-522



Contrast Recovery Coefficients (Cylinders)

$$f\left(\frac{R}{\sigma}, Z_P = 0\right) = \frac{1}{\left(\sqrt{2\pi}\sigma\right)^3}\int_{-L/2}^{L/2} dz \int_0^{2\pi} d\theta \int_0^{\sqrt{R^2+Z^2}} r dr\, e^{-\left(\frac{r^2+z^2}{2\sigma^2}\right)}$$

$$f\left(\frac{R}{\sigma}\right) = \left[1 - e^{(1/2)(R^2/\sigma^2)}\right]\cdot\left[1 - 2\cdot erfc\left(L/(2\cdot\sqrt{2}\sigma)\right)\right]$$

Some differences compared to the spherical case

1. Axial direction is infinite relative to the FWHM, CRC is 1.0 in axial direction of ACR phantom
2. CRC for a cylindrical element will be higher than a spherical element of the same radius

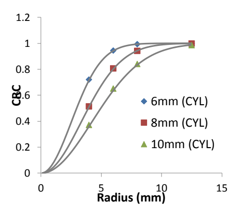
Kessler et al., *Analysis of Emission Tomography Scan Data: Limitations Imposed by Resolution and Background*. J. Comp. Assist. Tomo., 1984 **8**: p.514-22

CRC Simulations

1. 20 cm cylinder + cylindrical elements of 8, 12, 16, 25 dia.
2. Simulate resolution by convolving image with 6, 8 and 10mm Gaussian kernels
3. Calculate CRC for each element and fit to analytical function

ACR Style Digital Phantom

CRC Simulations (cylindrical elements)

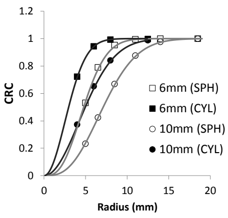


R_{filter}	R_{meas}
6	5.9
8	7.8
10	9.9

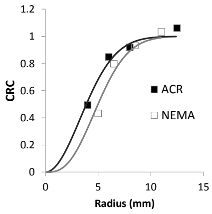
Spherical vs Cylindrical Elements

- Contrast recovery is greater with cylindrical than spherical resolution elements

Simulations



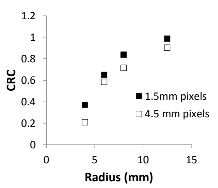
Measurements



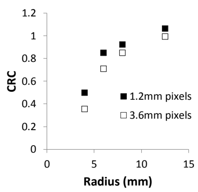
Contrast Recovery vs Pixel Size

- Patient reconstruction protocols generally have pixel sizes larger than NEMA documents specify

Simulations

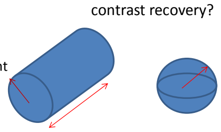


Measurements



Comparing the cylindrical ACR and spherical NEMA resolution elements of the same radius, why do the cylindrical ACR resolution elements show higher contrast recovery?

Cylindrical element

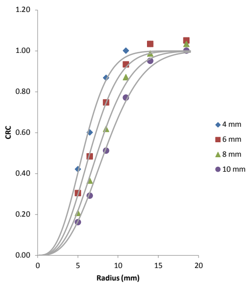


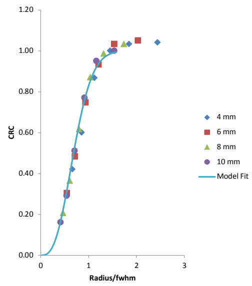
Spherical element

a. CRC in z-direction is higher
b. Total activity is larger in element
c. NEMA has more background
d. ACR is smaller in diameter

Kessler et al., Analysis of Emission Tomographic Scan Data: Limitations Imposed by Resolution and Background. 1984: p. 514-522

CRC vs Radius/FWHM





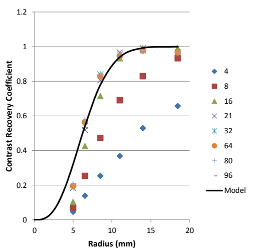
What else affects quantitation in PET (Revisited)

- Factors include
  - Scanner calibration — Shifts CRC curve up and down (no effect on system resolution)
    - Reference to an internal, manufacturer or national standard?
  - Point spread functions — Fixed by scanner geometry (not much you can do here)
    - Range from ~4-6mm
  - Iterative updates
    - Updates = iterations x subsets
    - Range from 30 to 90
  - Post-reconstruction filter
    - Range from 4 to 7mm FWHM
  - Pixel size
    - Could be under-sampling in image space — Set to appropriate size
    - Pixels sizes are typically 3-4mm for FWHM of 6-7mm

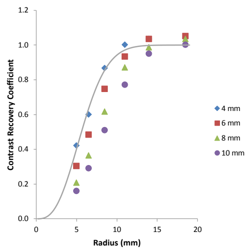
Two biggest variables (likely cannot be analytically separated in CRC curve)

Iterations/post-filtering on CRC

Iterations

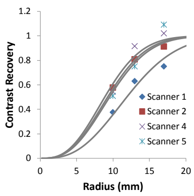


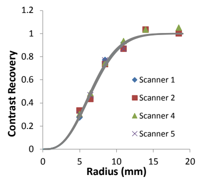
Post-filtering



Comparison at one institution

- Verify all PET scanners have cross-calibrations to their well-counters
  - All well-counters are on the same calibration
- Adjust recon parameters of lower CRC curve to improve contrast recovery





What is the affect on the appearance of phantom images when too few iterative updates (iterations x subsets) are performed in the reconstruction?

10%	1. Attenuation errors
13%	2. Image smoothness
17%	3. Pixel aliasing
20%	4. Excessive noise

What is the affect on the appearance of phantom images when too few iterative updates (iterations x subsets) are performed in the reconstruction?

a. Attenuation errors
b. Image smoothness
c. Pixel aliasing
d. Excessive noise

Ref: Cherry, Sorenson and Phelps. 2013. Physics and Nuclear Medicine, 3rd edition. Elsevier. p. 293

Summary

- Each scanner can be characterized by a contrast recovery curve
- Contrast phantoms account for resolution losses do physical factors of the instrument , isotope properties, and corrections
- Analytical solutions to contrast recovery can be used to estimate scanner resolution from phantoms
- Long cylindrical elements have higher contrast recovery than a sphere of the same size

Thank you!