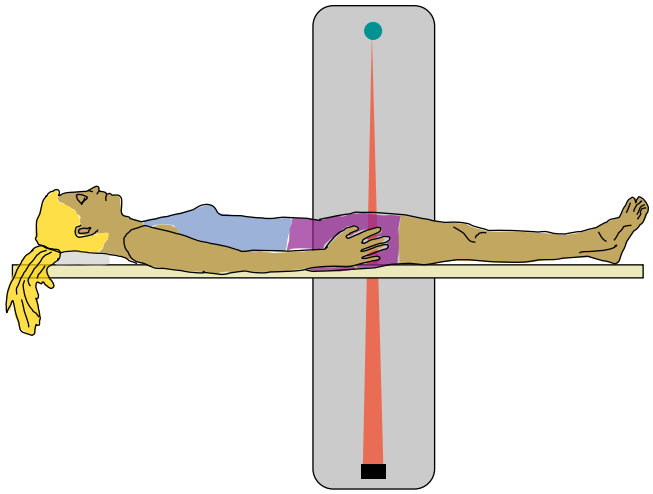
Relationship between Photon Count, Dose, and Image Quality



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University of California Davis Medical Center
Sacramento, California

Disclosure of Conflicts (required by UC Davis):

- Varian Imaging Systems, Consultant
- Artemis, Consultant
- Varian Imaging Systems, Research Funding
- Hologic Corporation, Research Funding
- Fuji Medical Systems, Research Funding
- Siemens Medical Systems, Research Funding
- Stanford Research Institute, Research Funding (R21 subcontract)
- Creativ Microtech, Research Funding (R21 subcontract)

Relationship between Photon Count, Dose, and Image Quality

- Introduction

  An Integrated CT Image Quality / Dosimetry Phantom

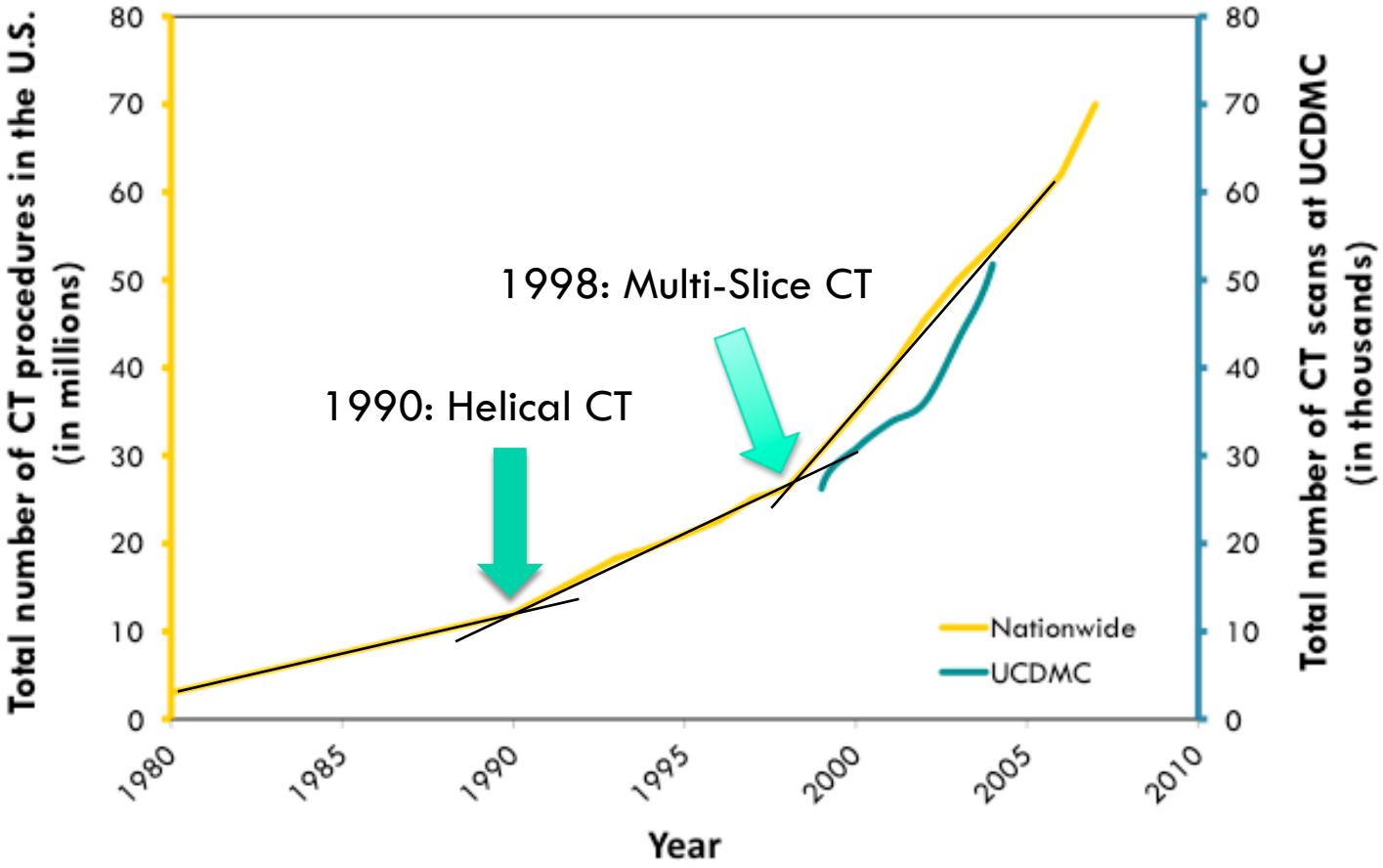
  Beyond $CTDI_{100}$ - including scan length dependence

  Beyond $CTDI_{vol}$ – including patient size dependence

  Energy Integrating versus Photon Counting CT Detectors

  Summary

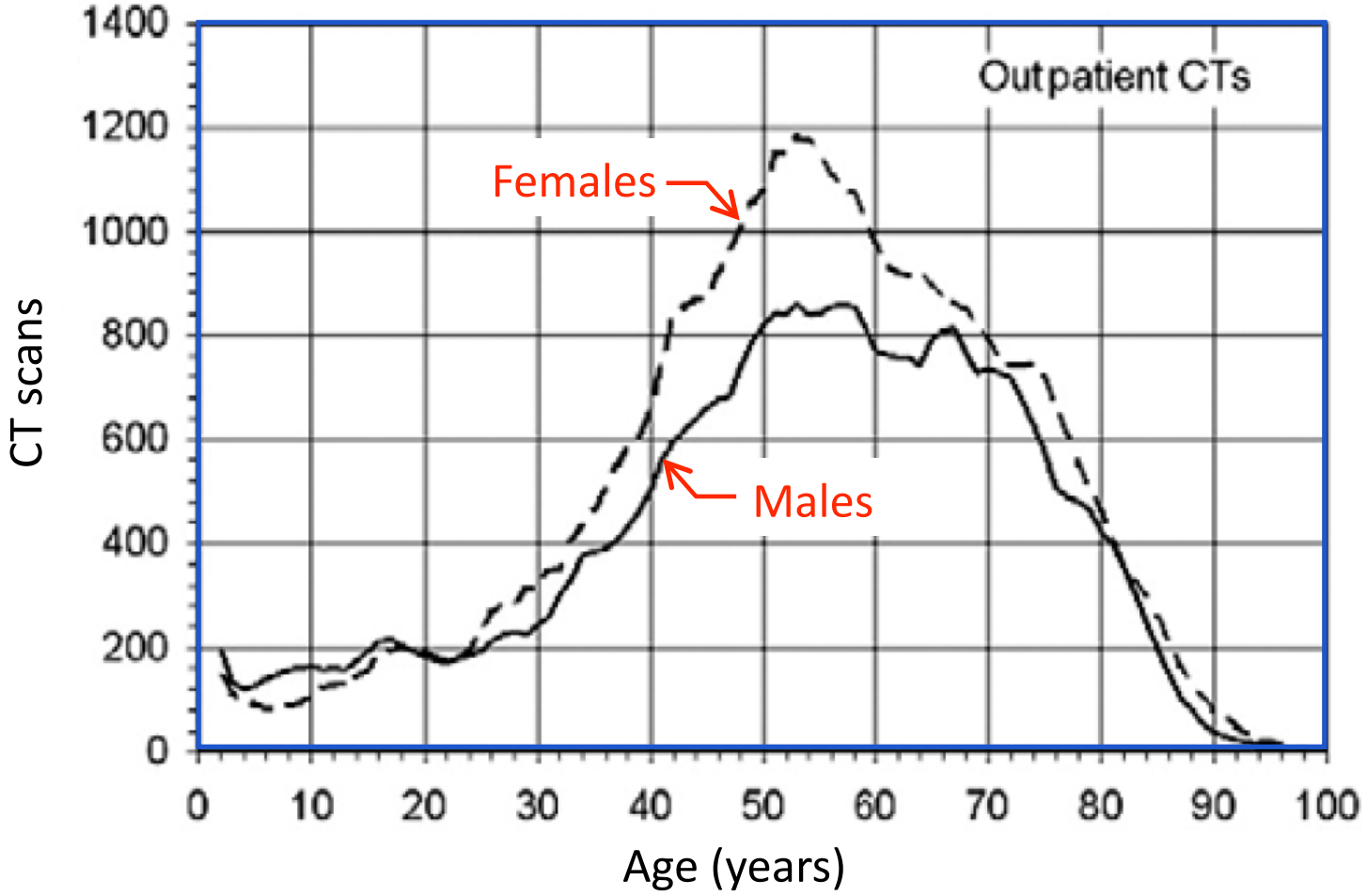
Use of CT: USA & UC Davis Trends



JM Boone, et al, *J Am Col Radiology*, 2008;5(2): 132–138
DJ Brenner, et al, *New Eng J Med*, 2007;357: 2277-2284

UCDAVIS
UNIVERSITY OF CALIFORNIA

Outpatient CT Usage – 1998-2005



JM Boone, et al, *J Am Col Radiology*, 2008;5(2): 132–138

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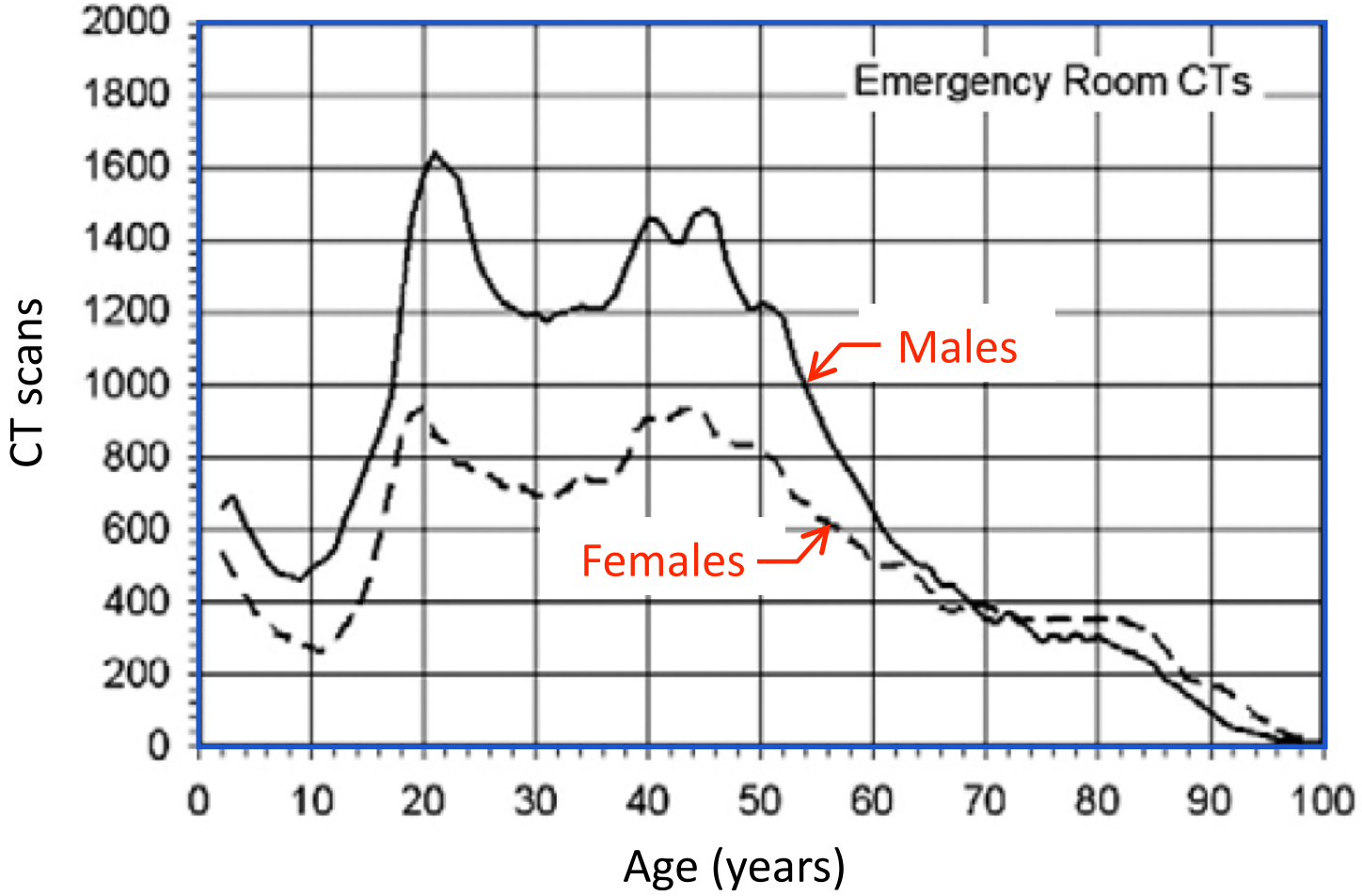
Emergency Room CT Usage –1998-2005



JM Boone, et al, *J Am Col Radiology*, 2008;5(2): 132–138

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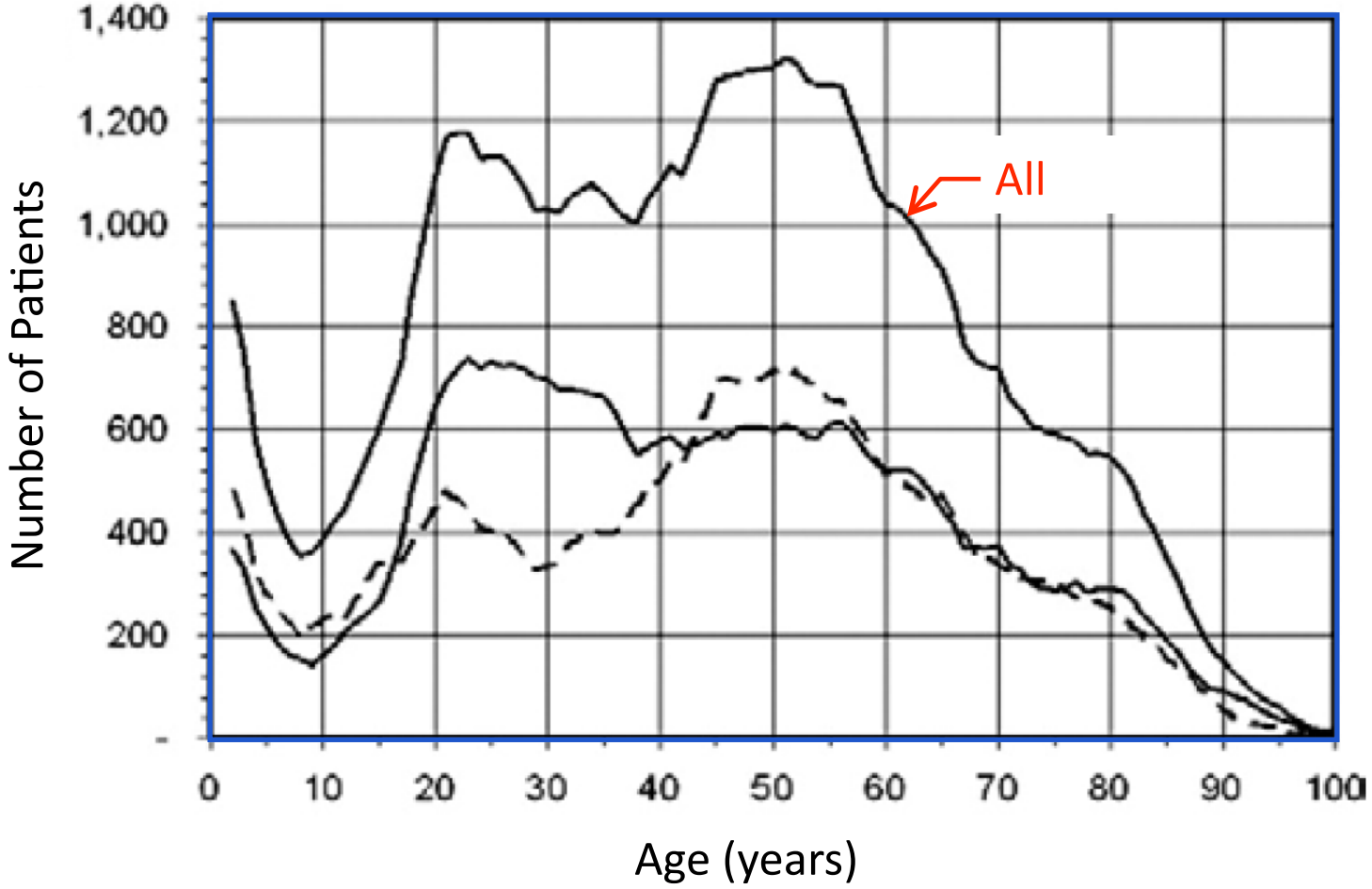
Total CT Usage –1998-2005



JM Boone, et al, *J Am Col Radiology*, 2008;5(2): 132–138

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The Summit on Management of Radiation Dose in Computed Tomography: *Toward the Sub-mSv Exam*

- **Opportunities to Improve**
  - Future Dose Reduction without Compromise of Image Quality

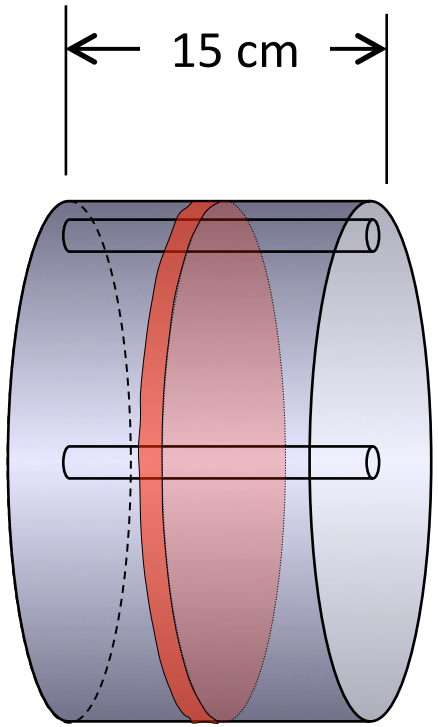
International Commission on Radiation Units and Measurements, Inc.

ICRU Committee on
Image Quality and
Patient Dose in CT

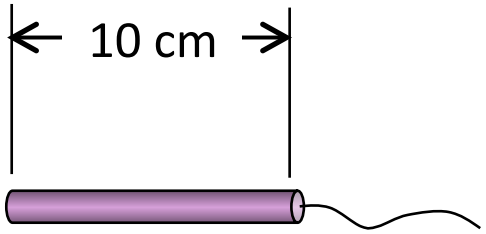
AAPM Task Group 204
Pediatric CT dosimetry

AAPM Task Group 200
CT phantom

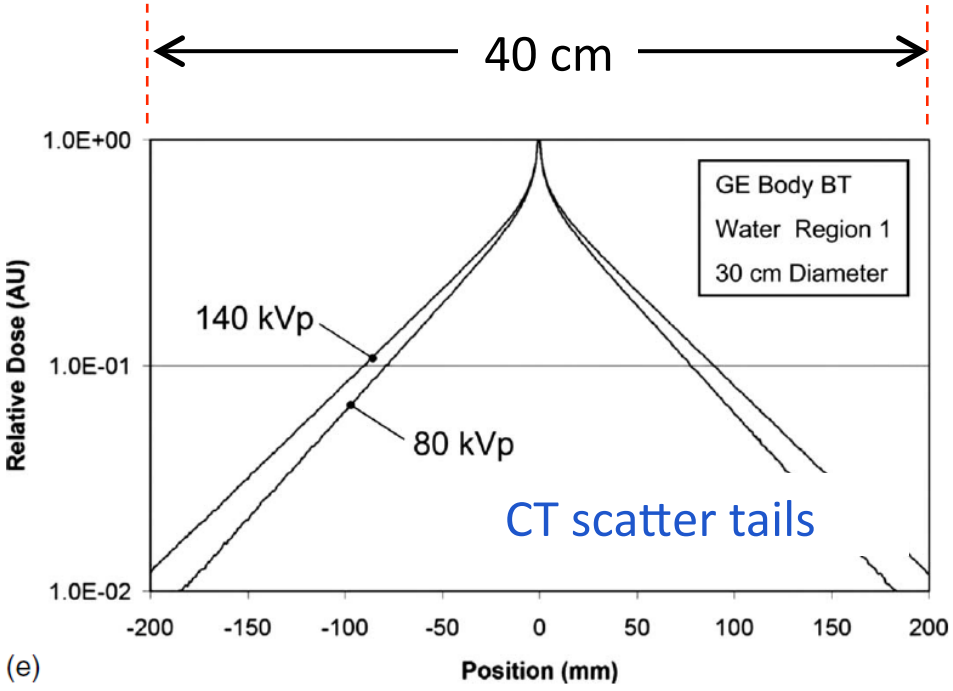
$CTDI_{100}$ Dose Metrics and Its Derivatives



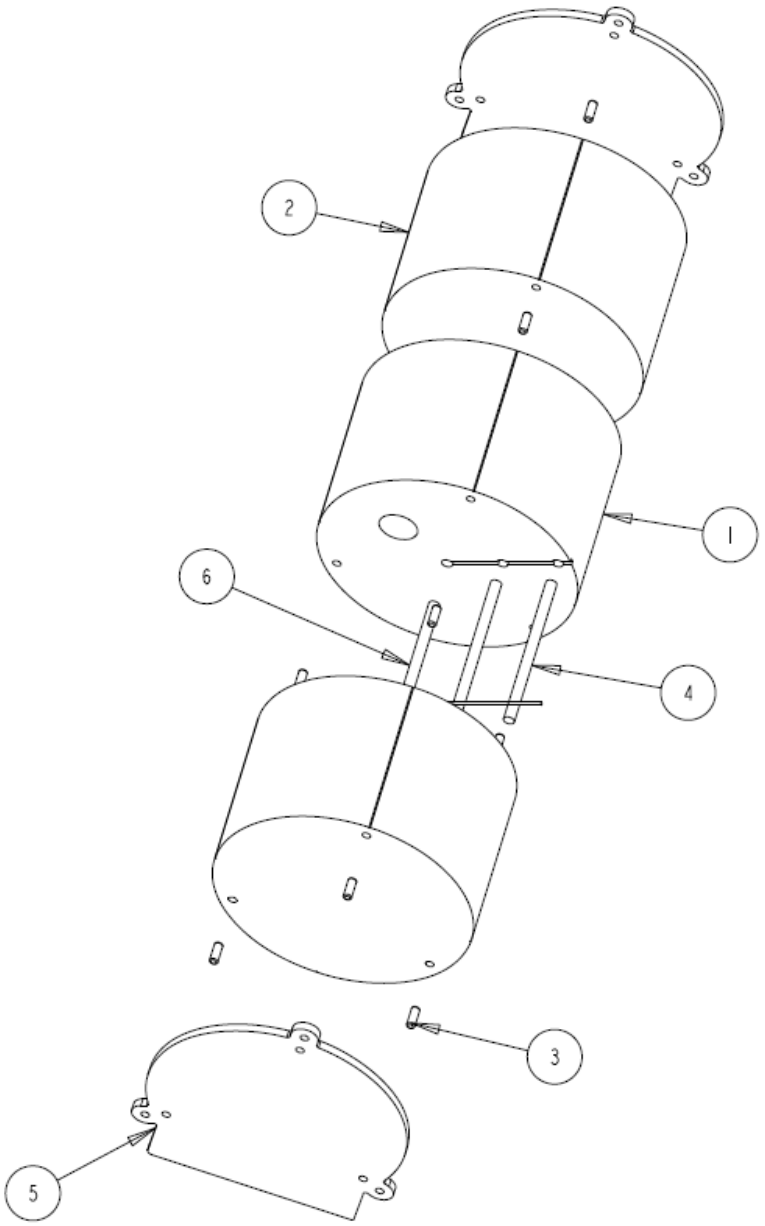
CT dosimetry phantom

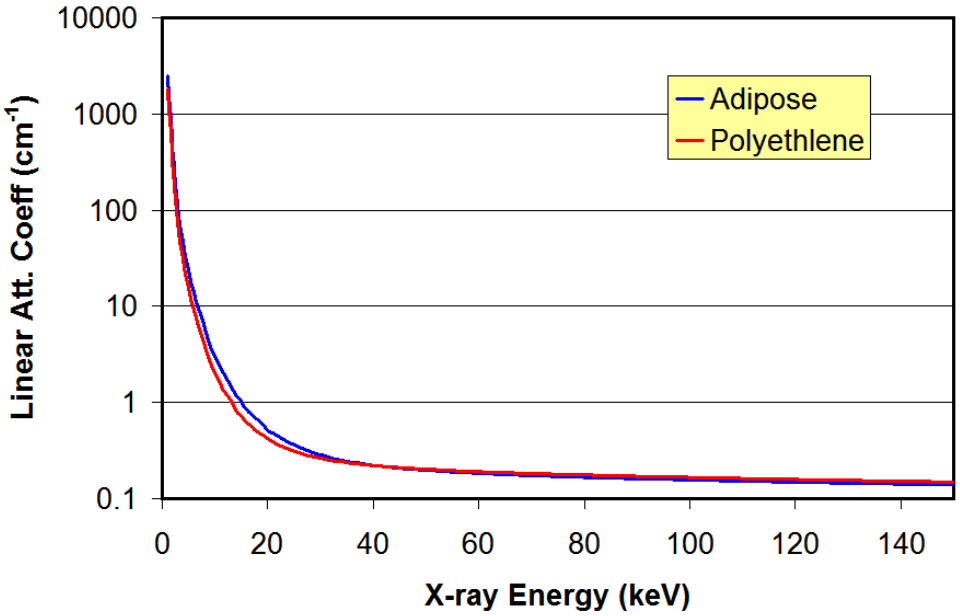


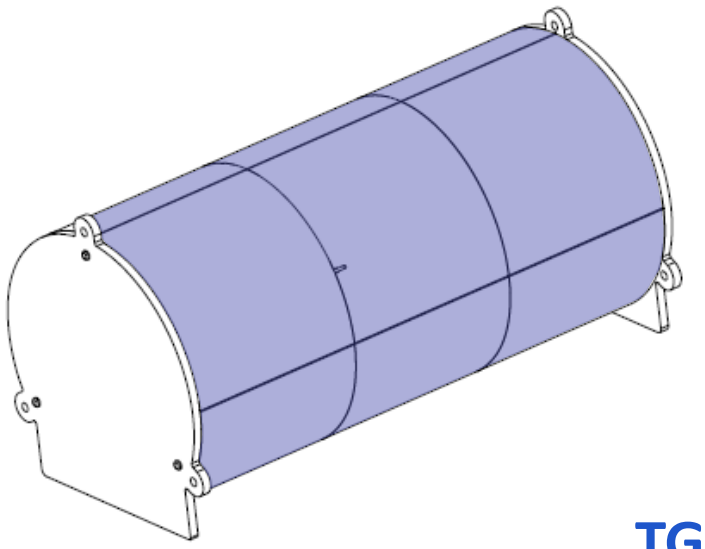
CT dosimetry probe



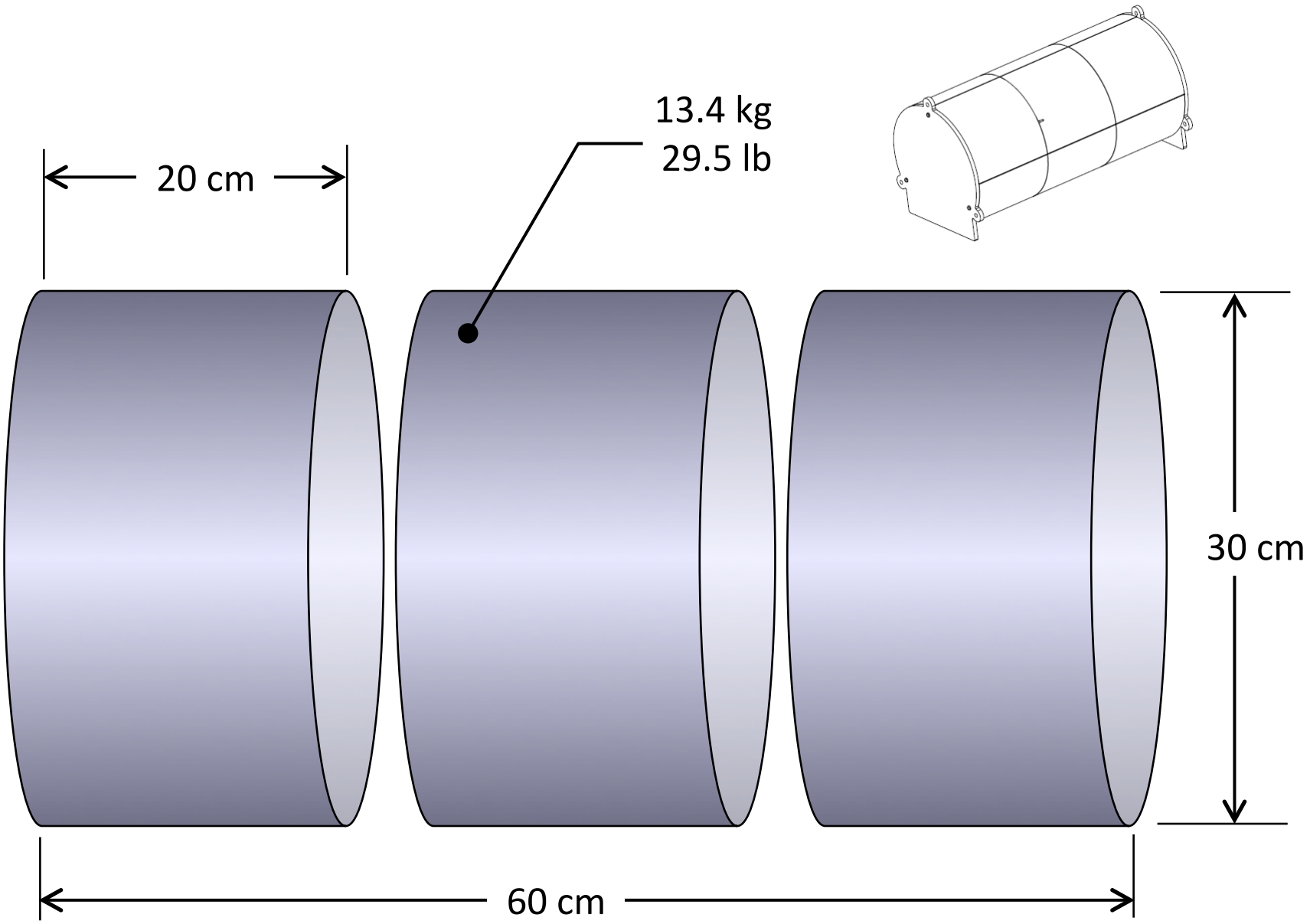
CT scatter tails

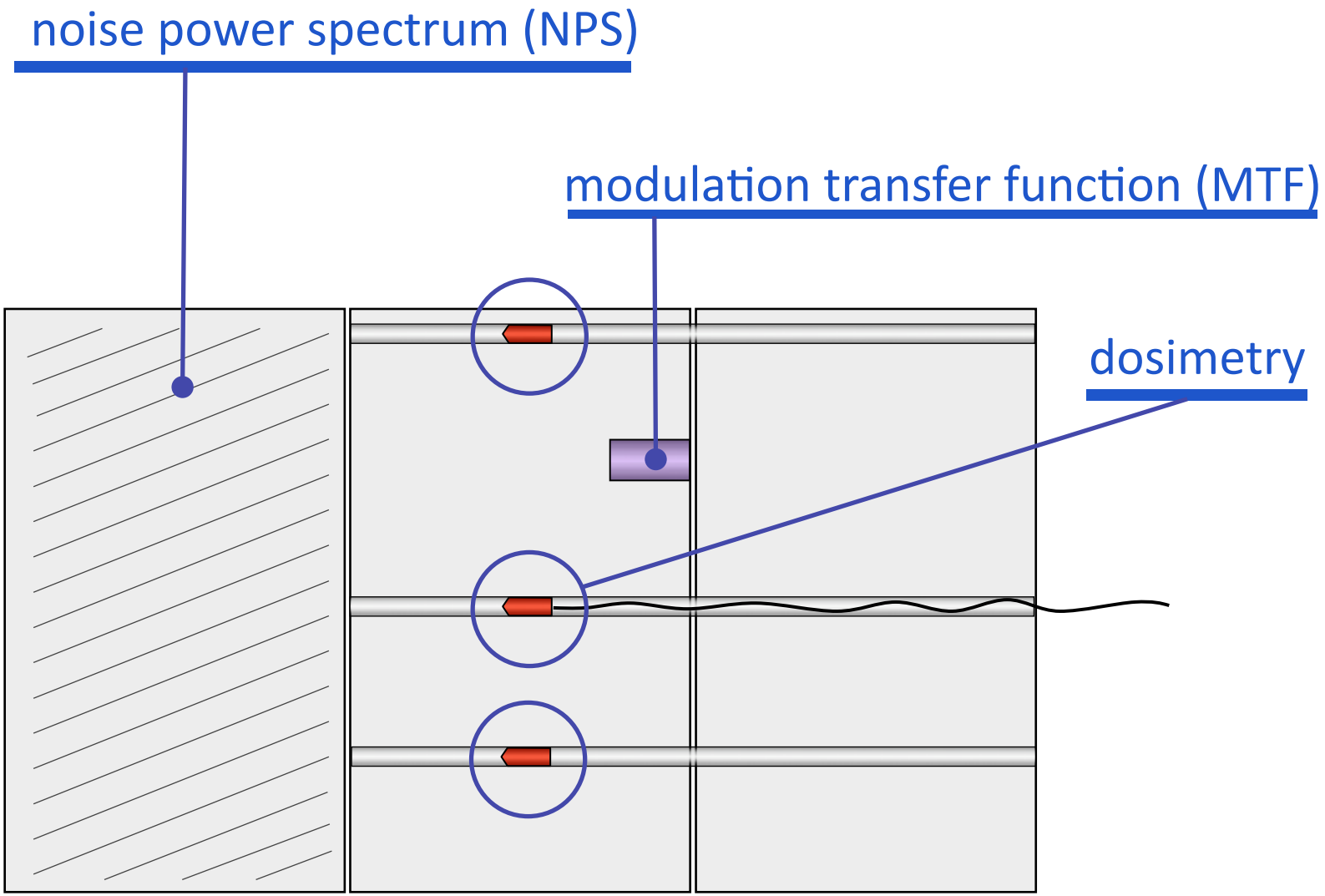

2
1
6
4
3
5


10000
1000
100
10
1
0.1
Linear Att. Coeff (cm-1)
0
20
40
60
80
100
120
140
X-ray Energy (keV)
Adipose
Polyethlene

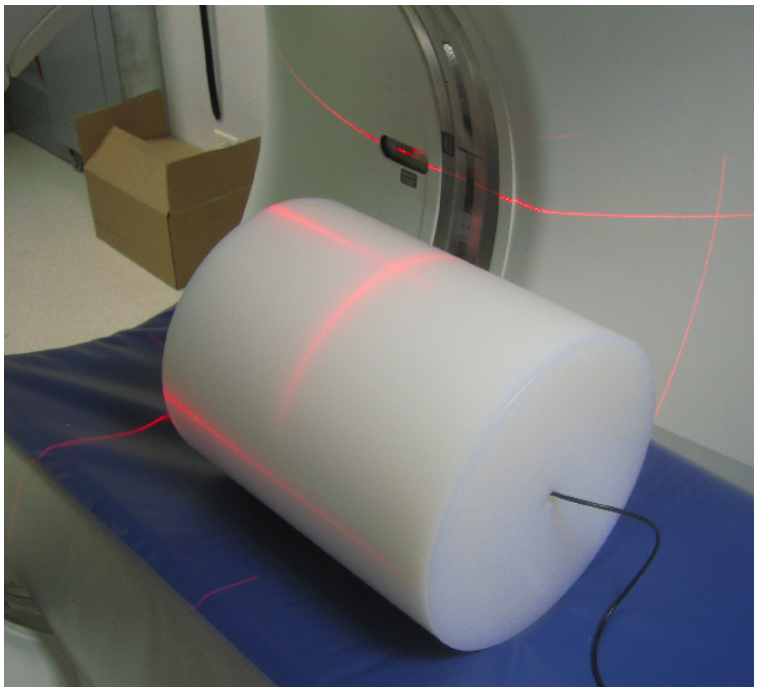


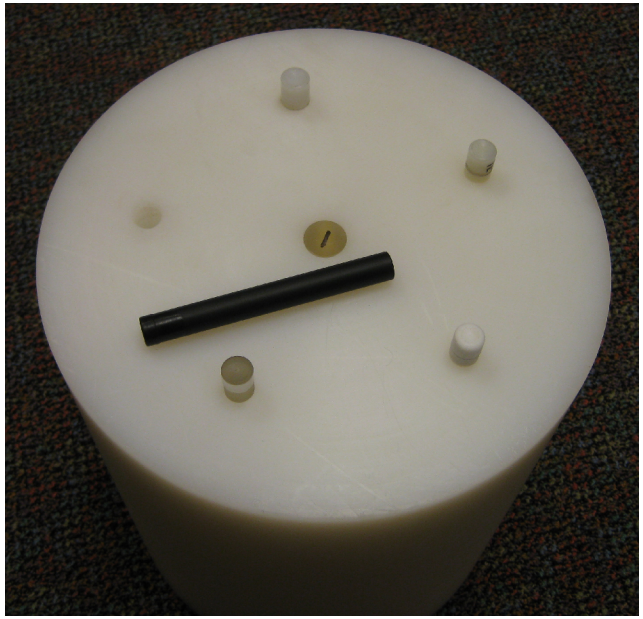
TG-200

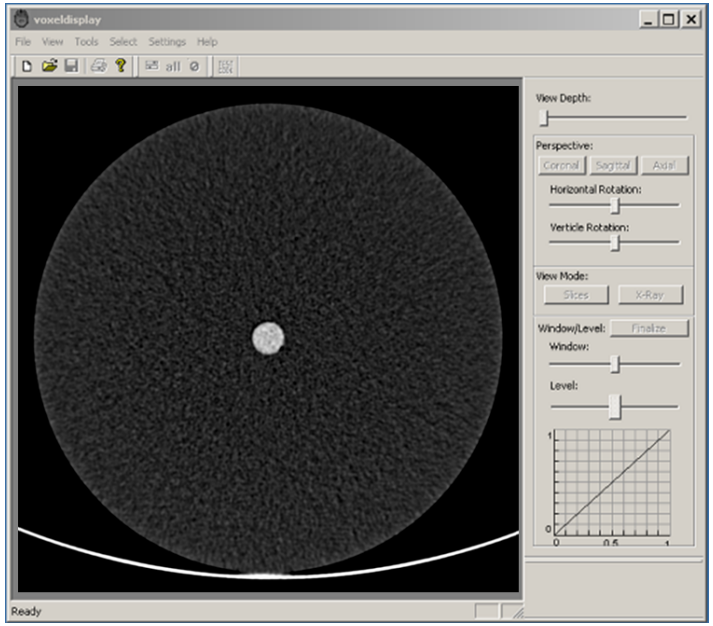

13.4 kg
29.5 lb
20 cm
30 cm
60 cm



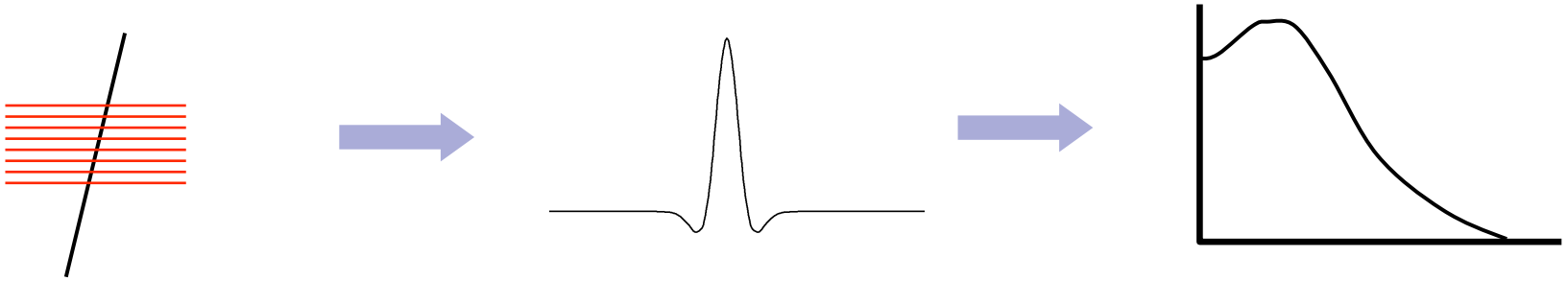
An Integrated CT Image Quality / Dosimetry Phantom



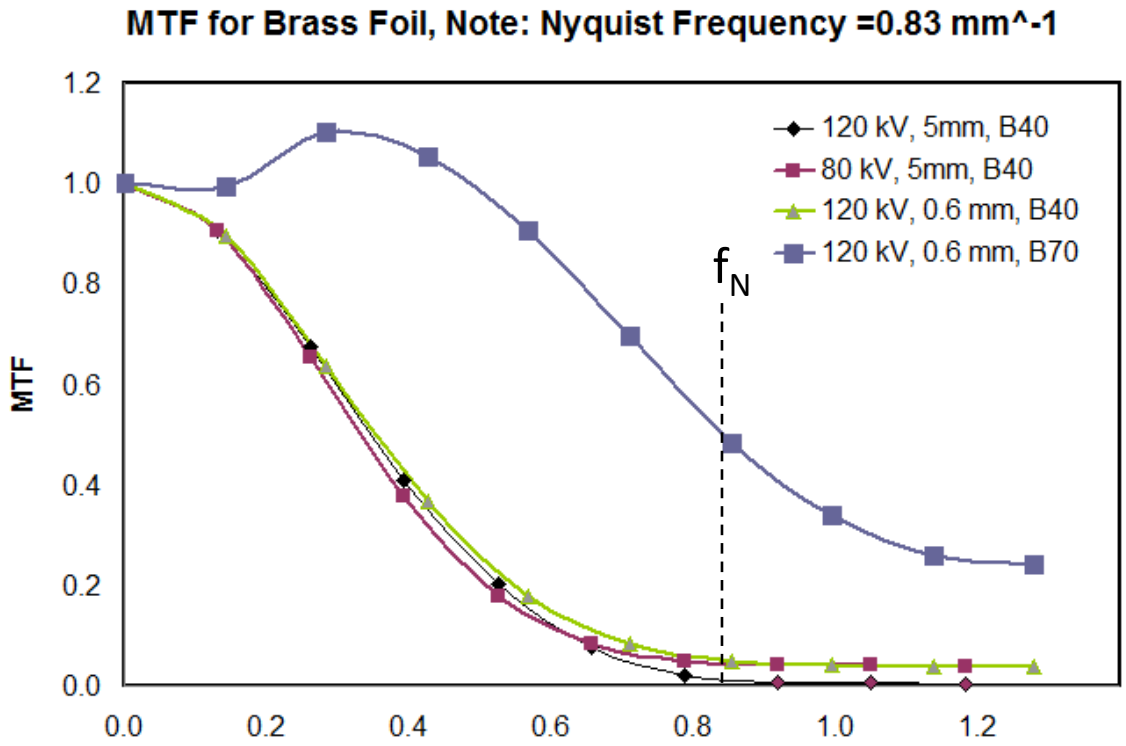



voxeldisplay
File View Tools Select Settings Help
all
View Depth:
Perspective:
Coronal
Sagittal
Axial
Horizontal Rotation:
Verticle Rotation:
View Mode:
Slices
X-Ray
Window/Level:
Finalize
Window:
Level:
1
0
0
0.5
1
Ready

Modulation Transfer Function Assessment in CT

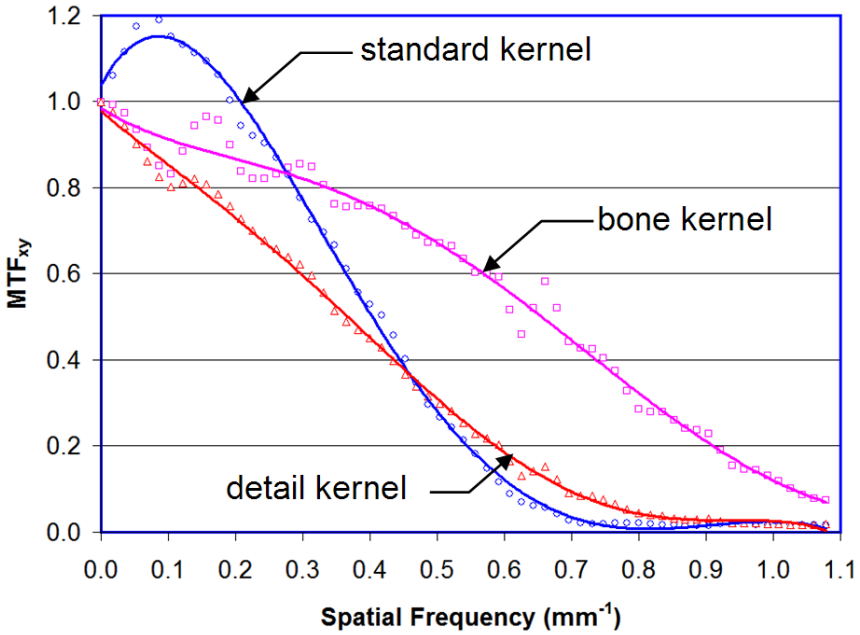


oversampled slit LSF MTF

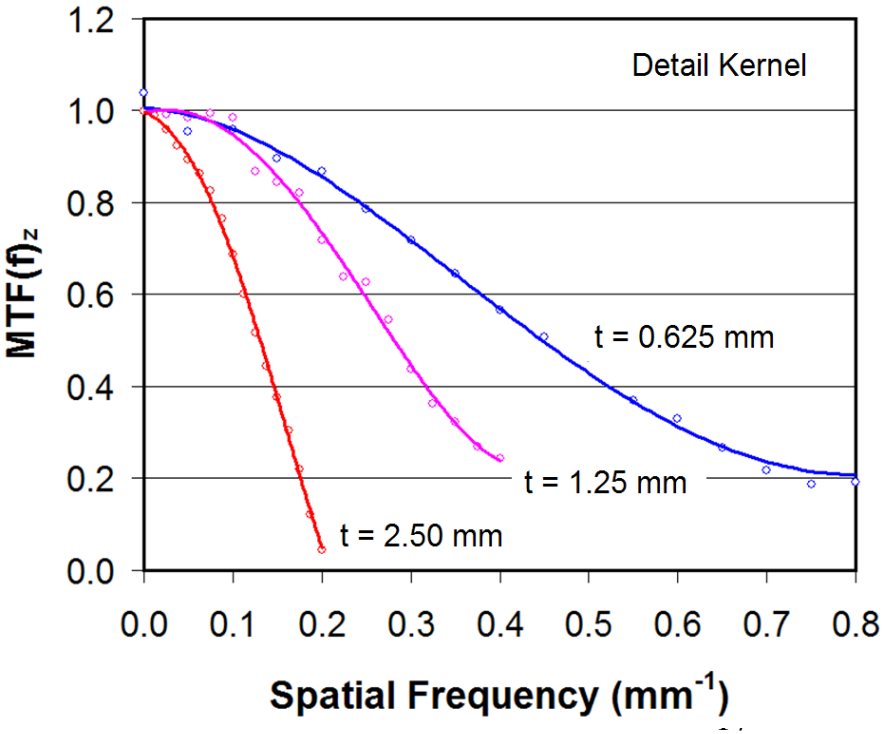


Modulation Transfer Function Assessment in CT

effect of kernel

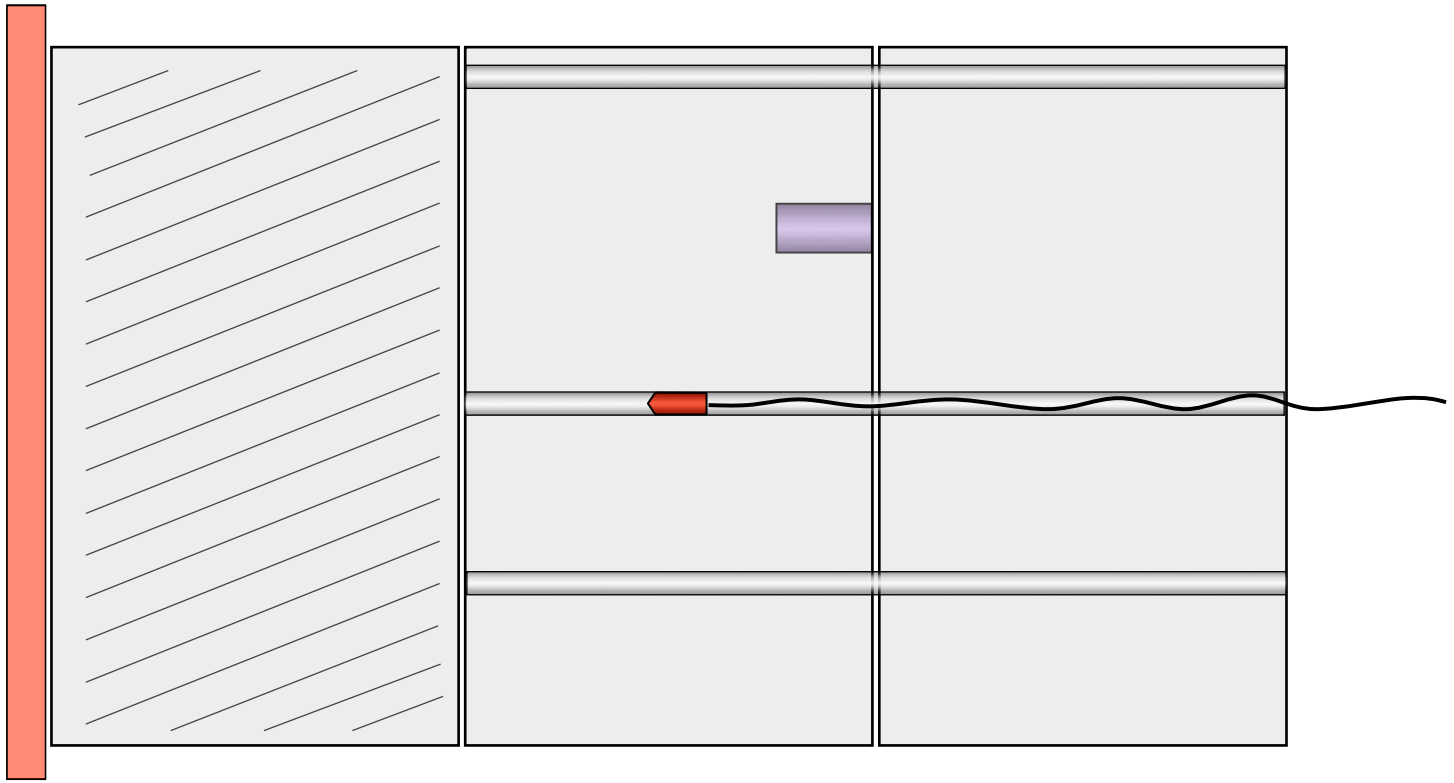


effect of slice thickness



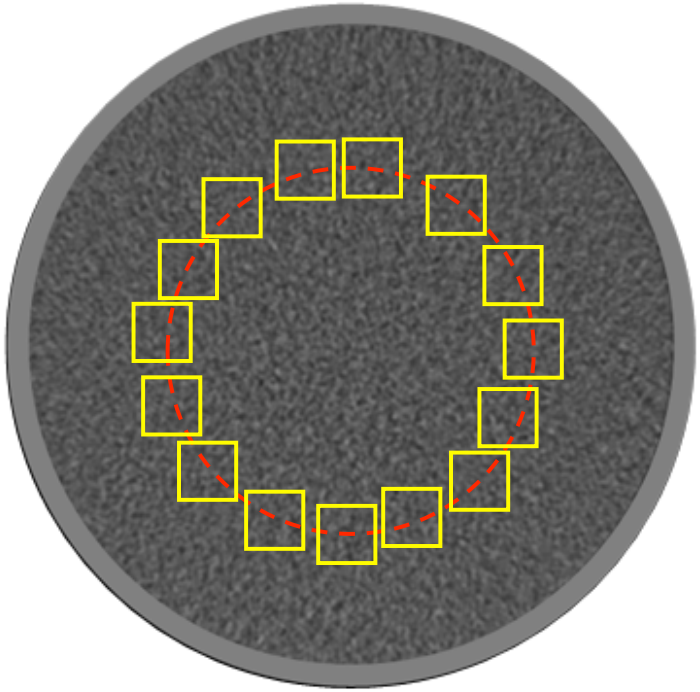
Noise Power Spectra Assessment of Noise in CT

$$CT\ Noise \propto \sqrt{Dose}$$

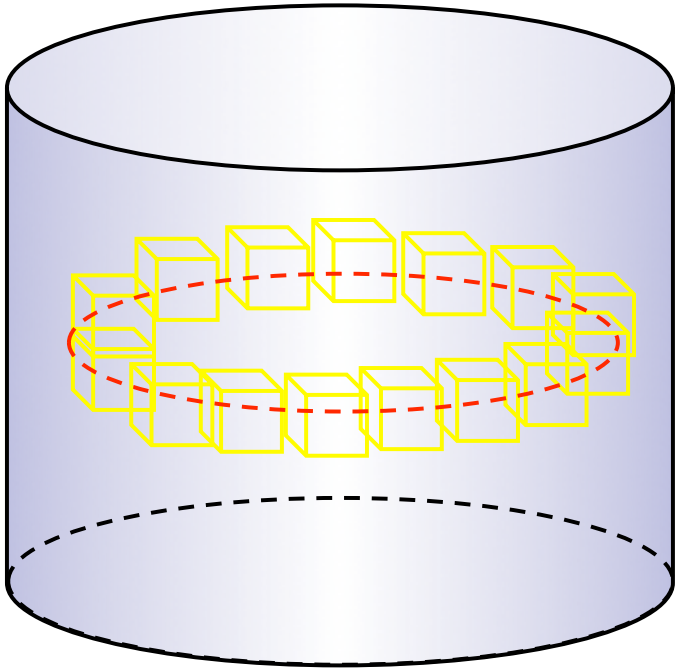


step 1:	step 2:	step 3:	step 4:
120 kV	**Read out dose**	**120 kV**	**Measure**
100 mAs	**adjust mAs**	**xxx mAs**	**NPS(f)**
Pitch ≈ 1.0	**20 mGy**	**Pitch ≈ 1.0**	

Noise Power Spectra Assessment of Noise in CT



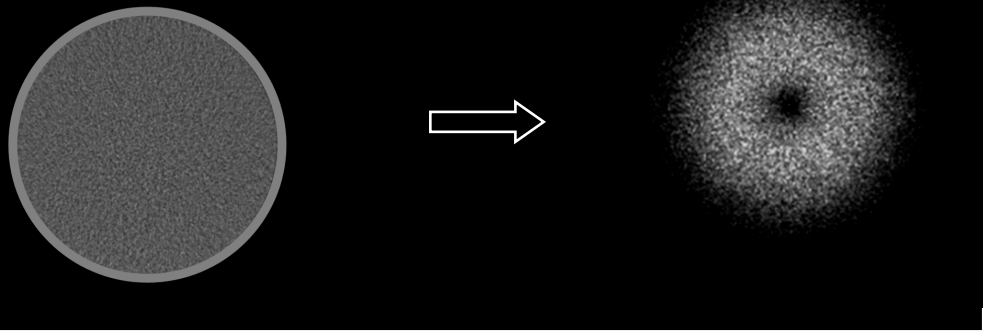
2D NPS

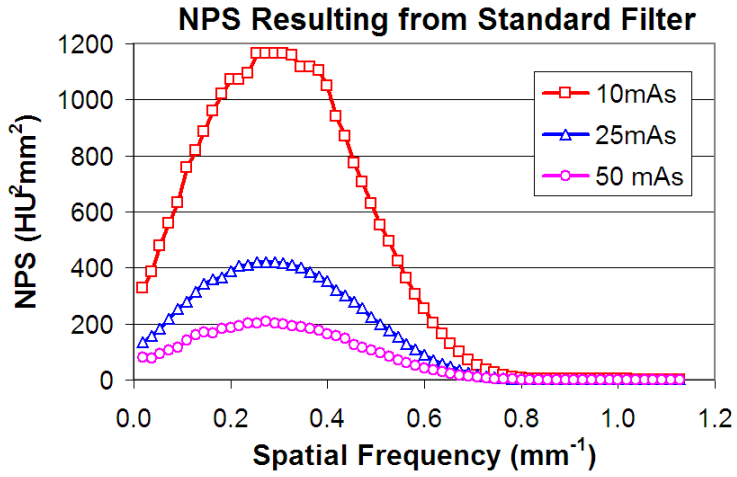


3D NPS

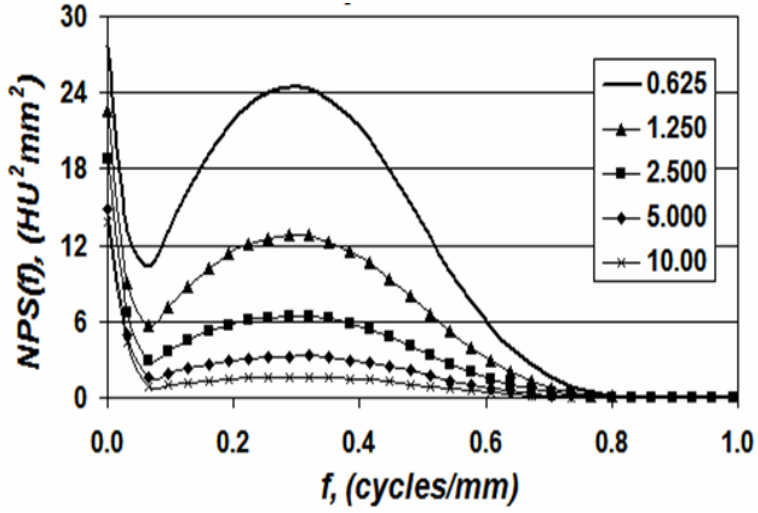
Noise Power Spectra Assessment of Noise in CT

$$NNPS_{2D}(u,v) = \frac{1}{N}\sum_{i=1}^{N}\frac{\left|DFT_{2D}[DI_i(x,y) - \overline{DI_i}\right|^2}{2}\frac{\Delta x}{N_x}\frac{\Delta y}{N_y}$$

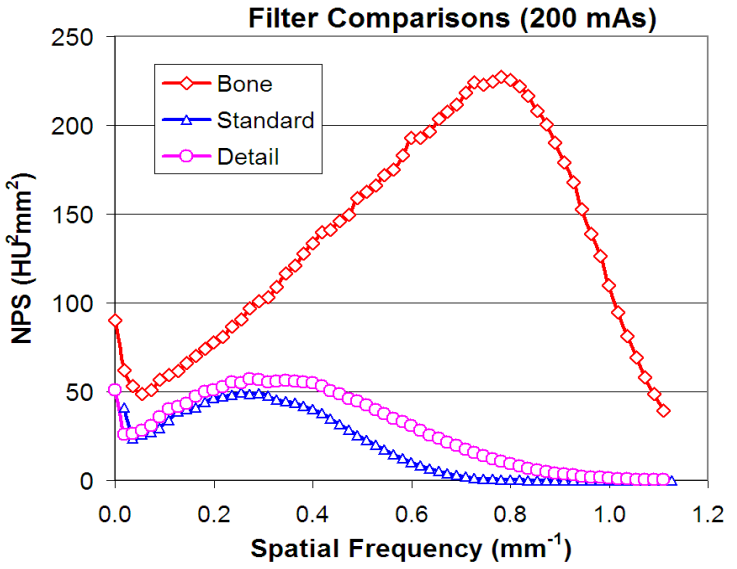




effect of technique

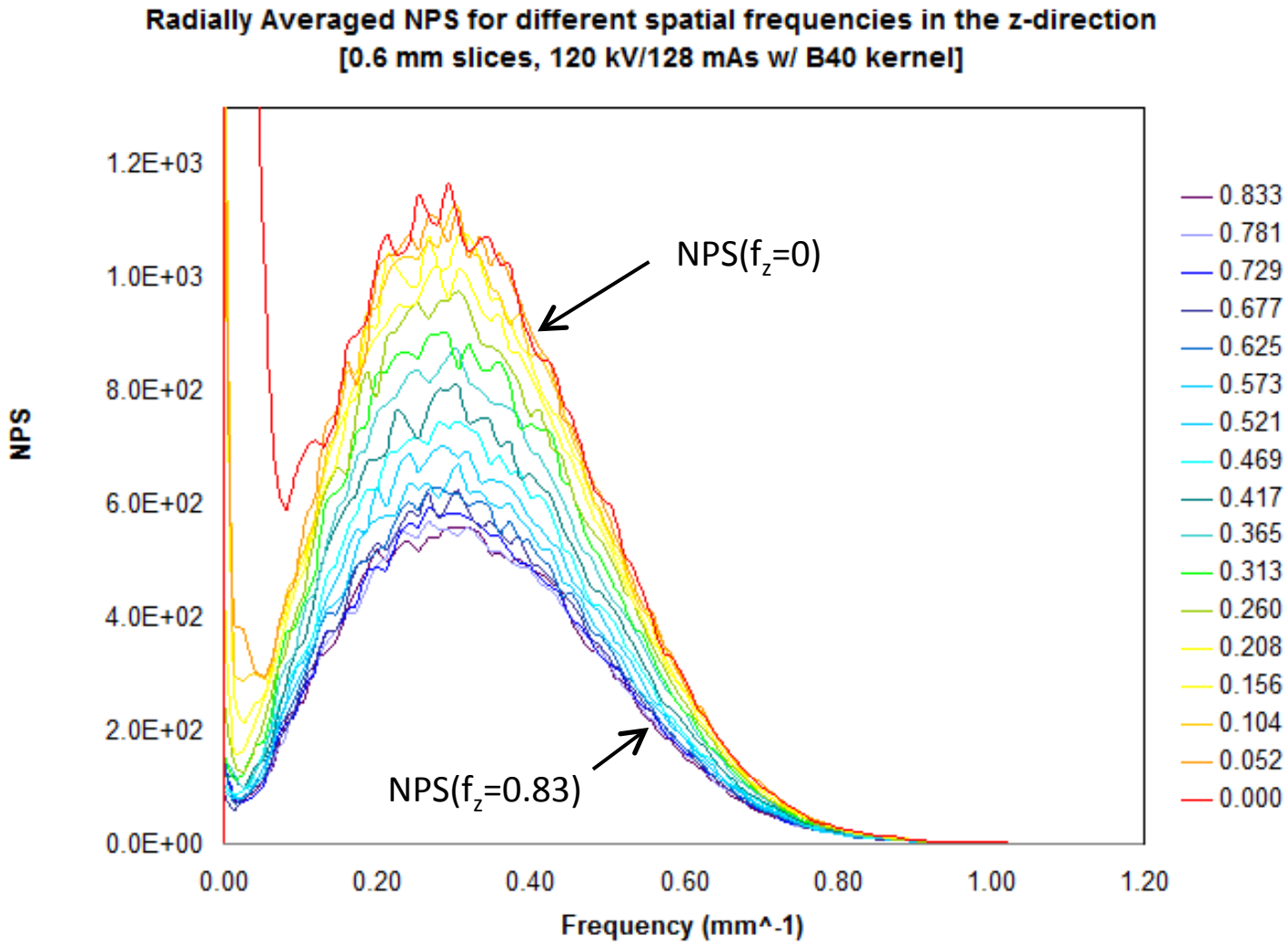


effect of slice thickness

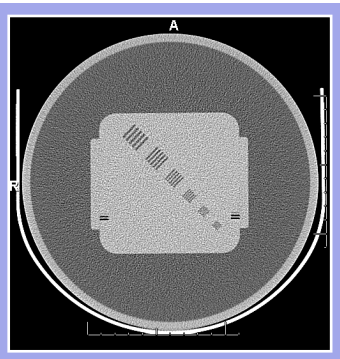
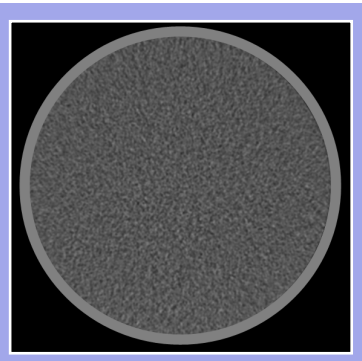
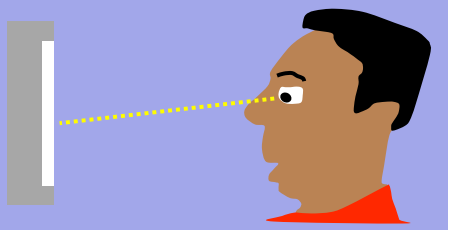


effect of kernel

Noise Power Spectra (3D)



CT image quality evaluation

	Old Era	New Era
phantom	 complicated	 basic
analysis	 simple	$MTF(f) = \frac{\int_{-\infty}^{\infty} LSF(x)\ e^{-2\pi i f x}\ dx}{\int_{-\infty}^{\infty} LSF(x)\ dx}$ more sophisticated
results	perfunctory	useful & quantitative

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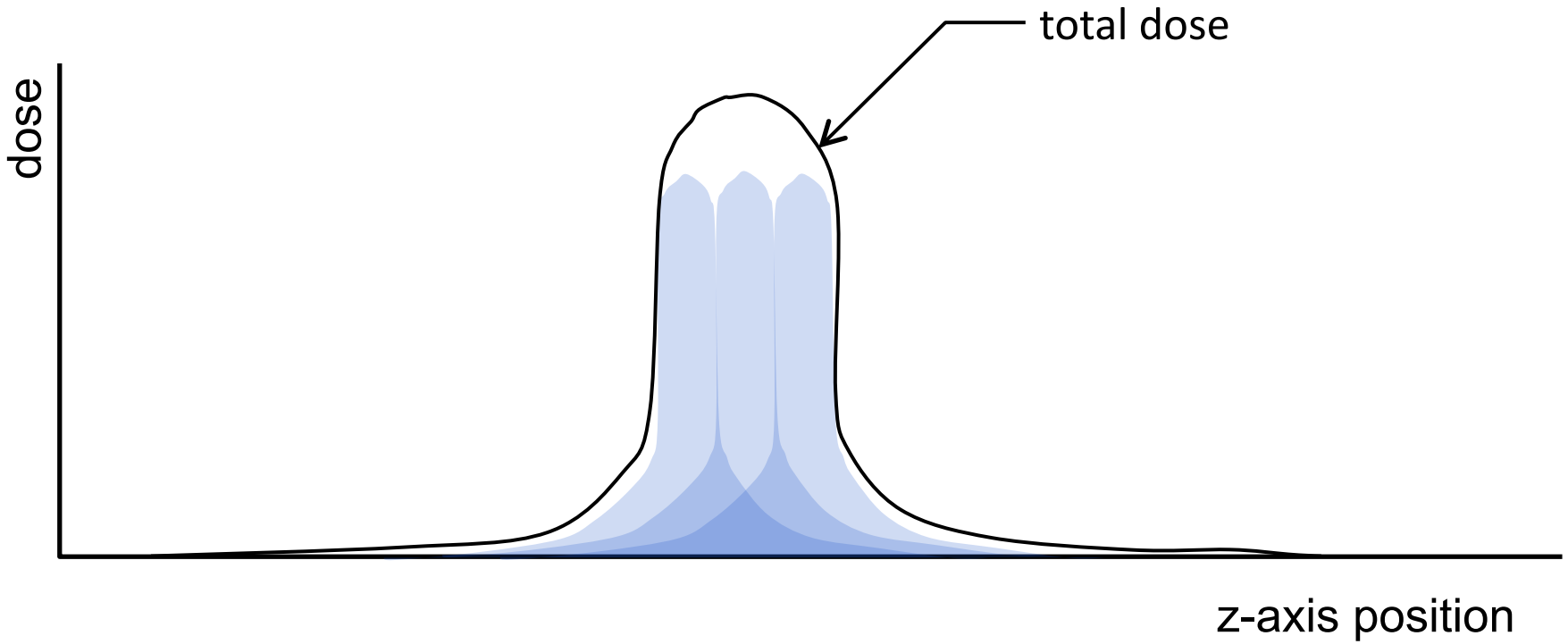
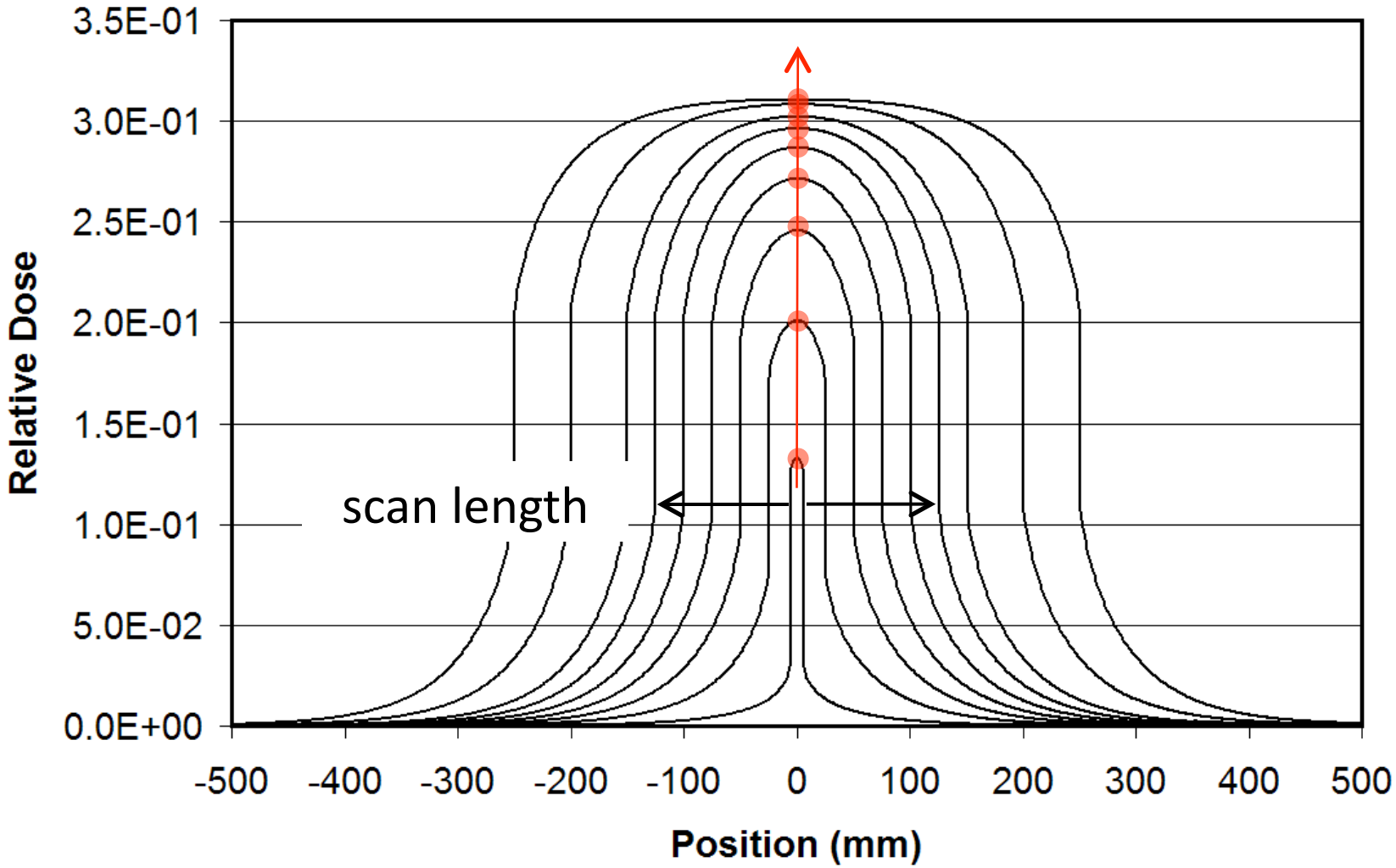
Energy Integrating versus Photon Counting CT Detectors

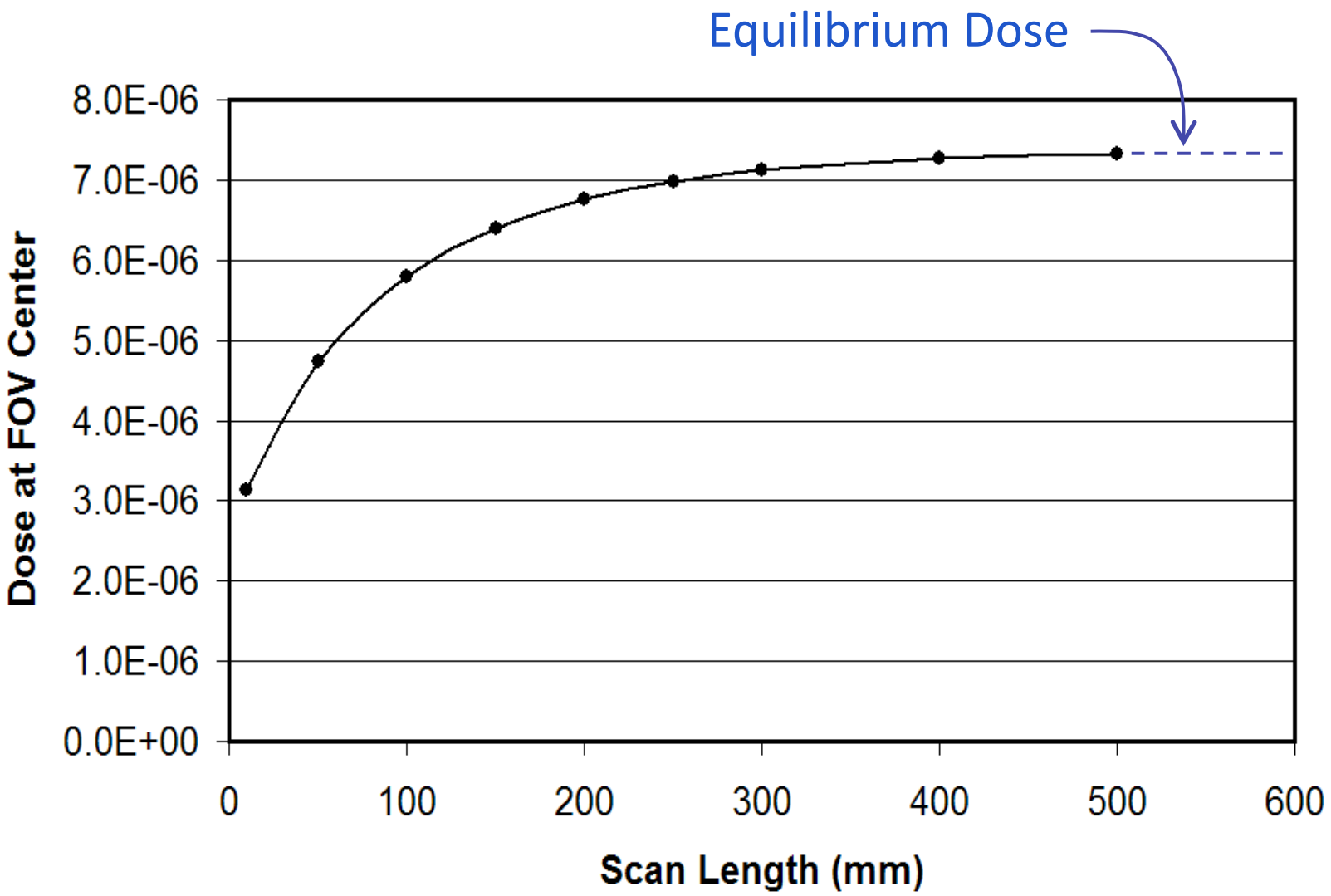
Summary


total dose
dose
z-axis position

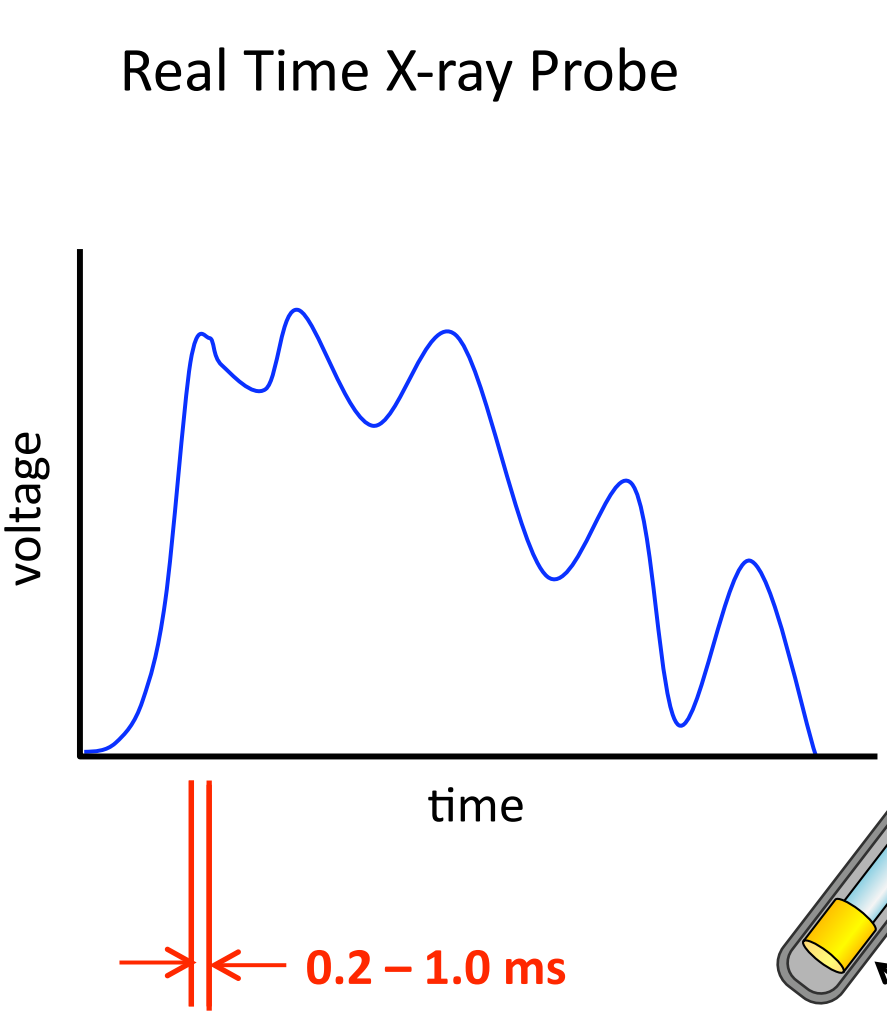
Dose profiles as a function of Scan Length

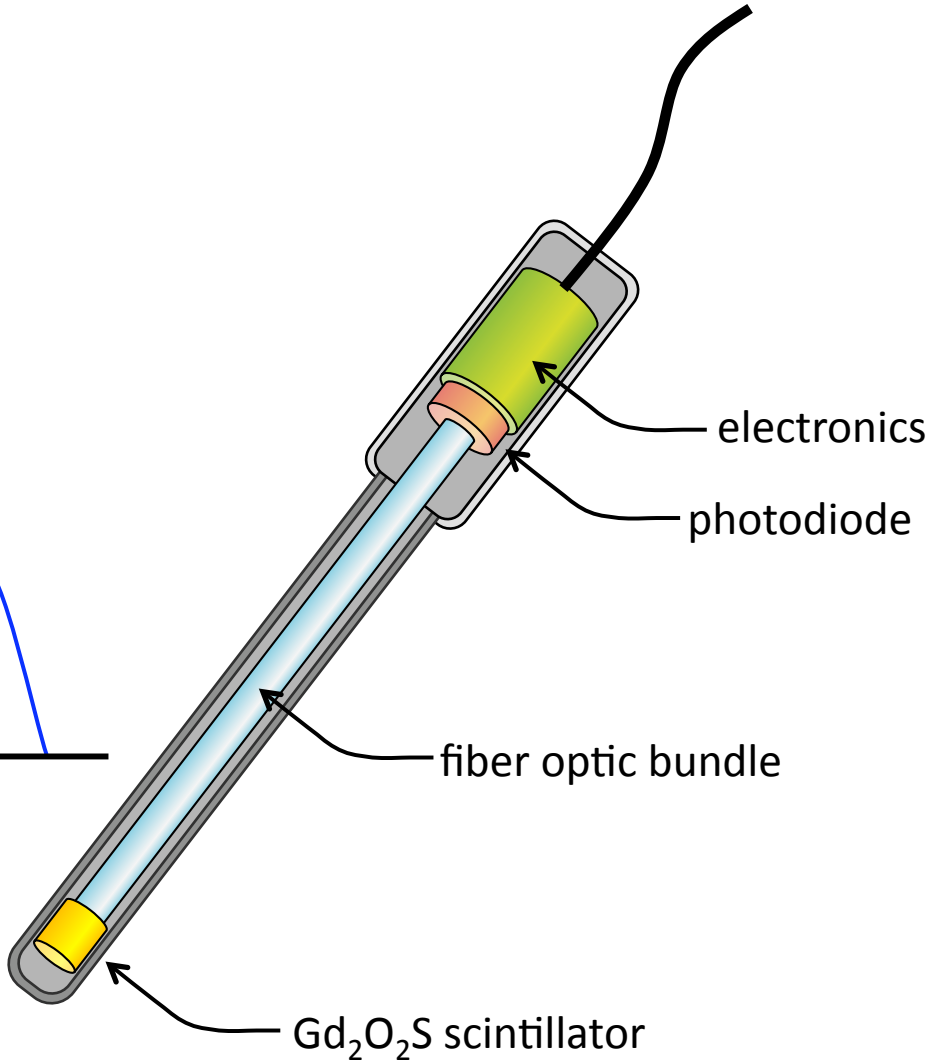


Dose as a function of Scan Length

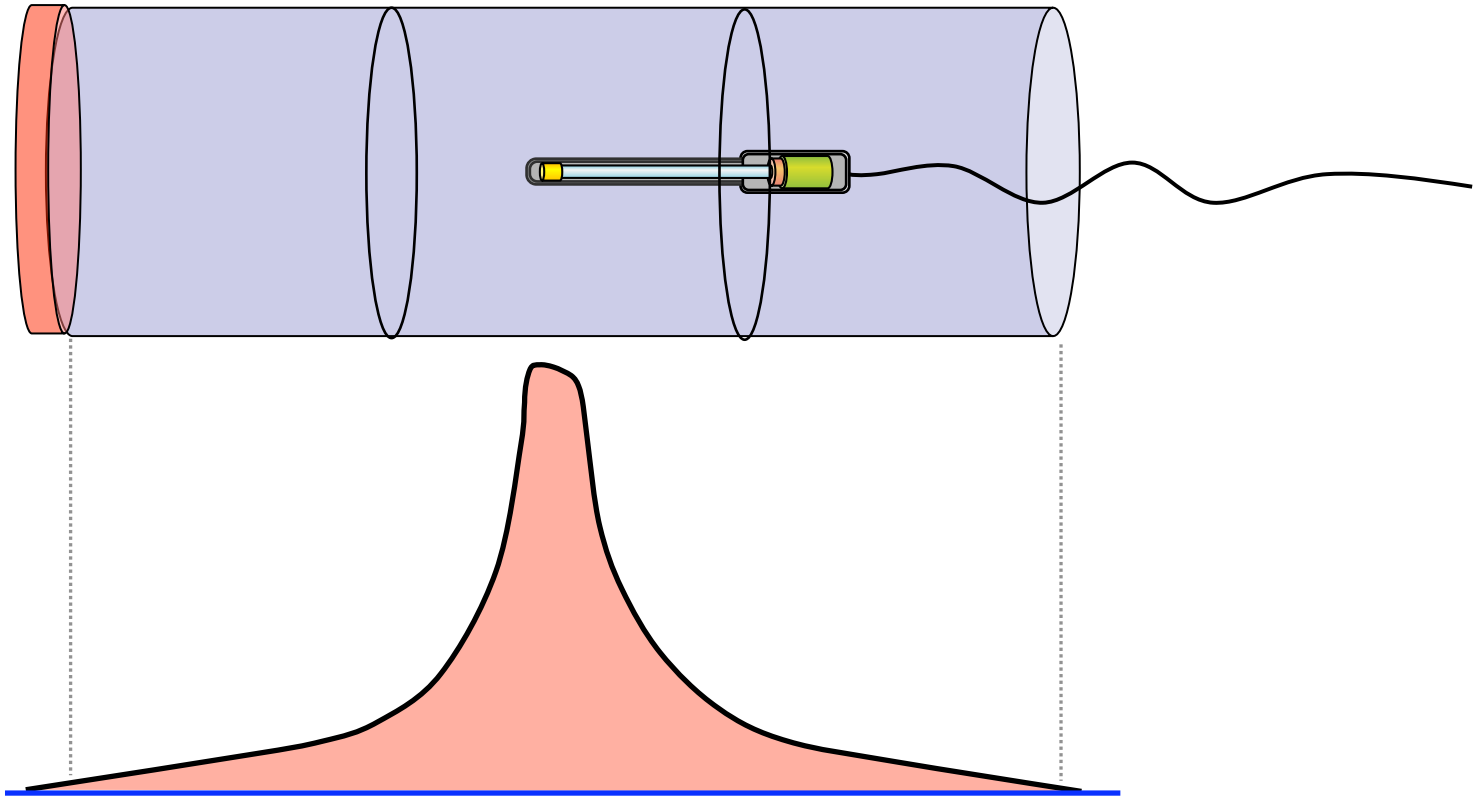


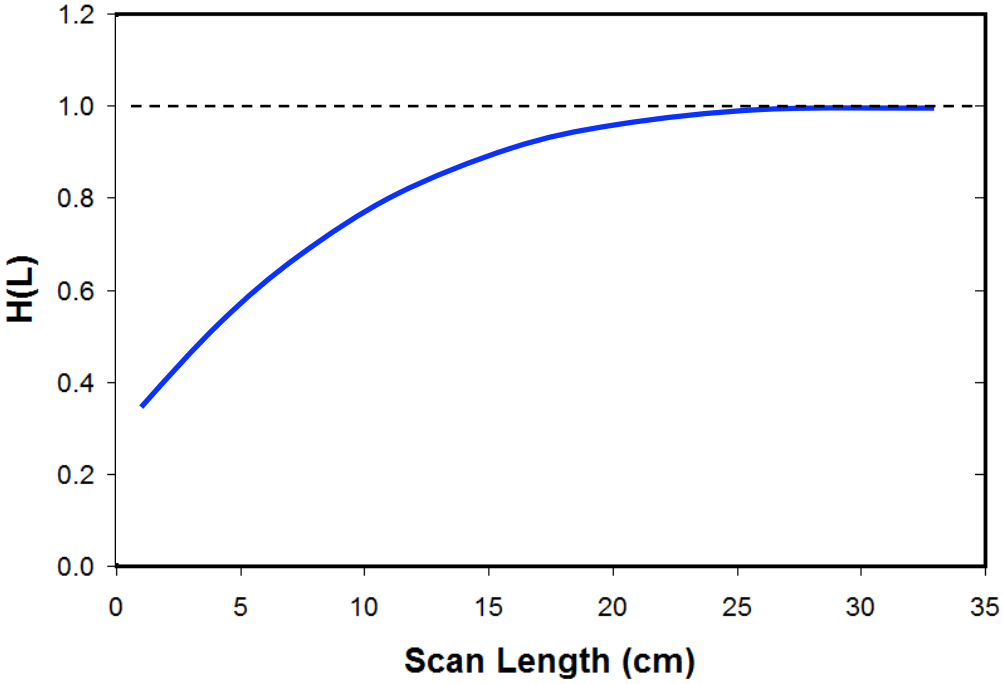
Real Time X-ray Probe

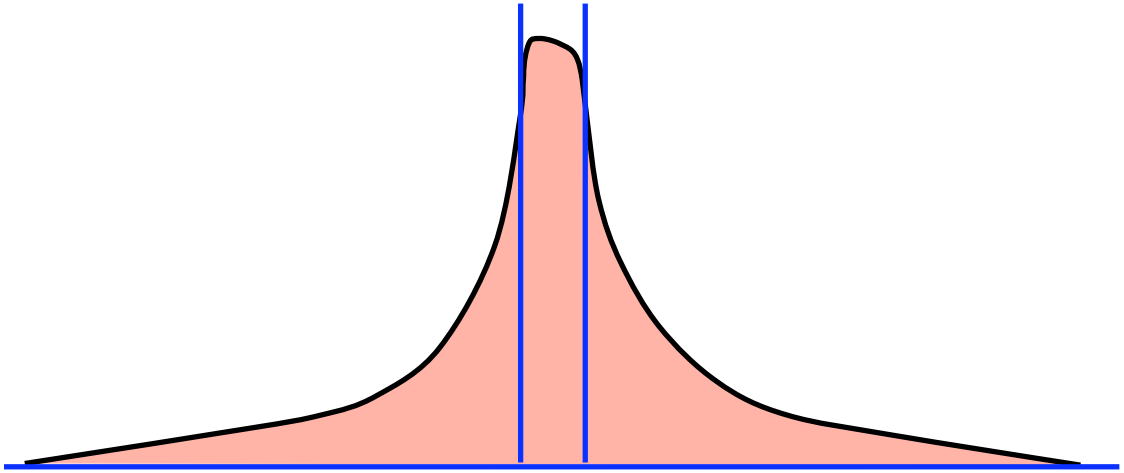




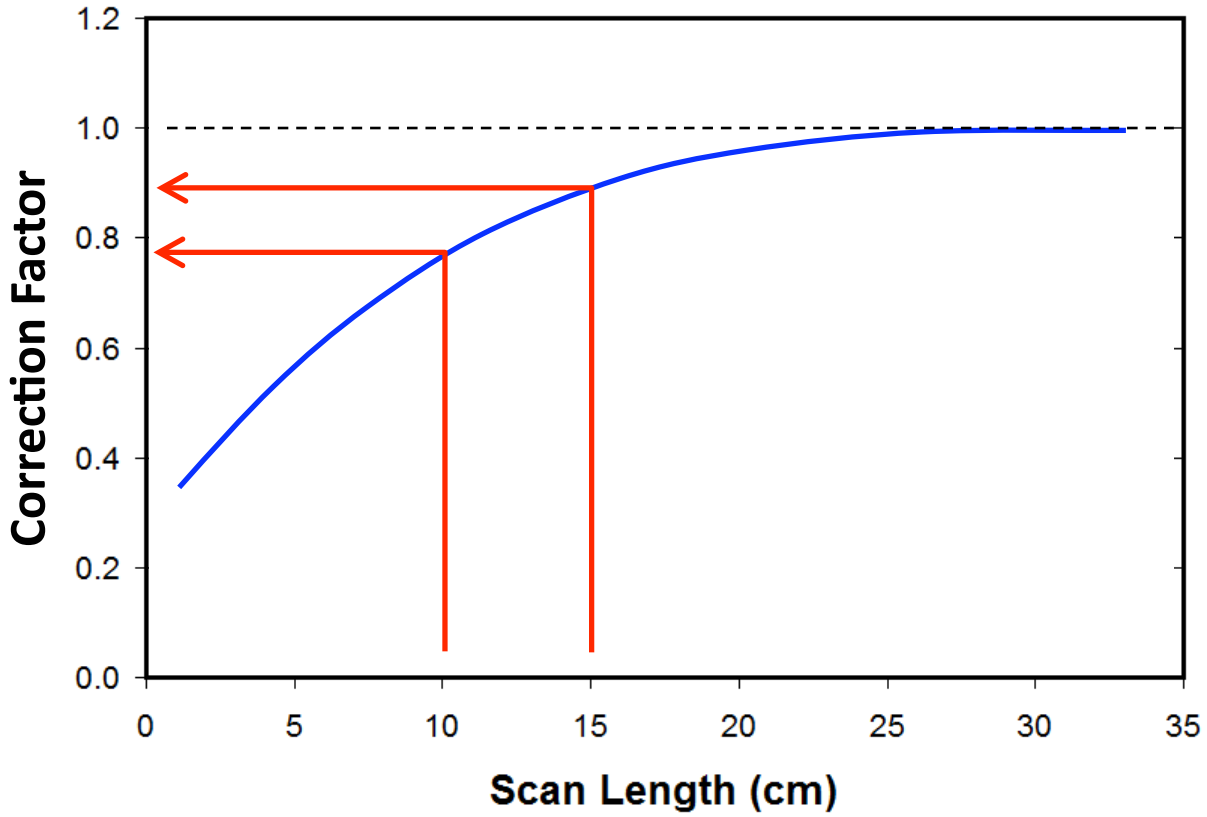
ICRU Method: beyond TG111







beam profile


Correction Factor
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
30
35
Scan Length (cm)

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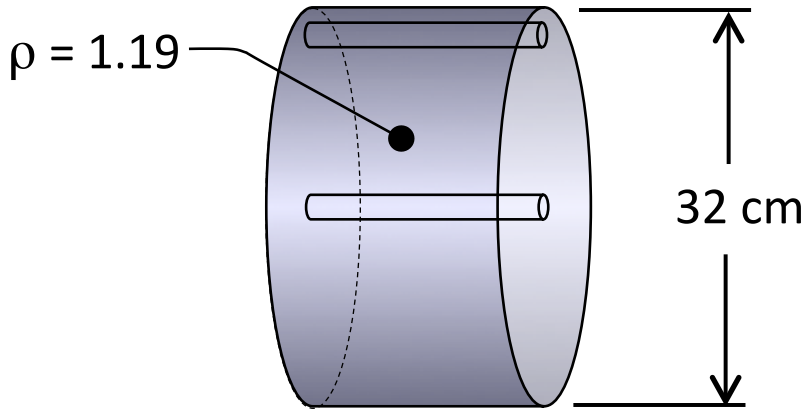
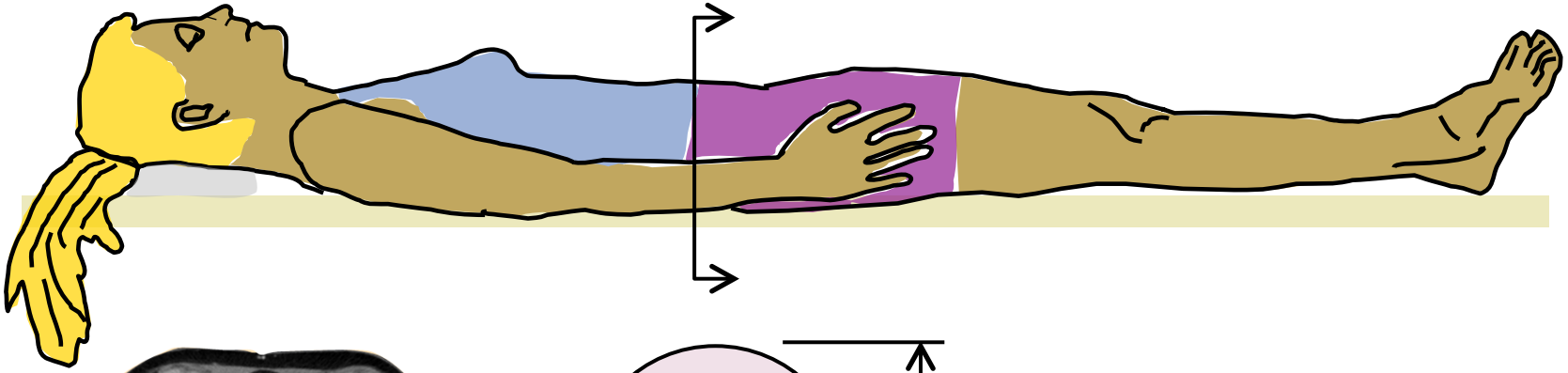
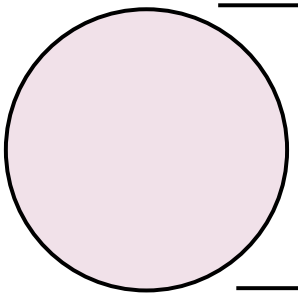


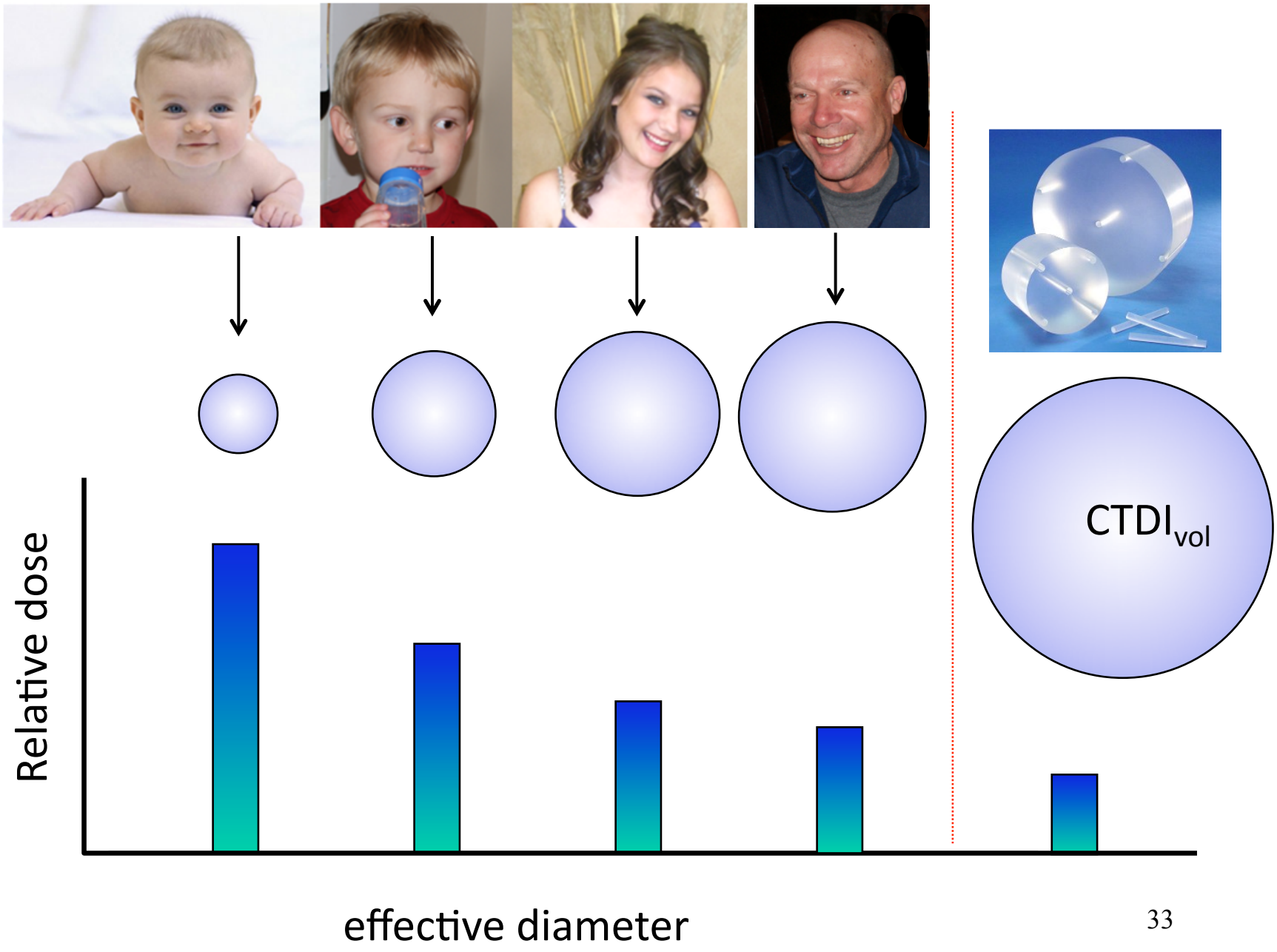
47”
119 cm
} waistline



≈



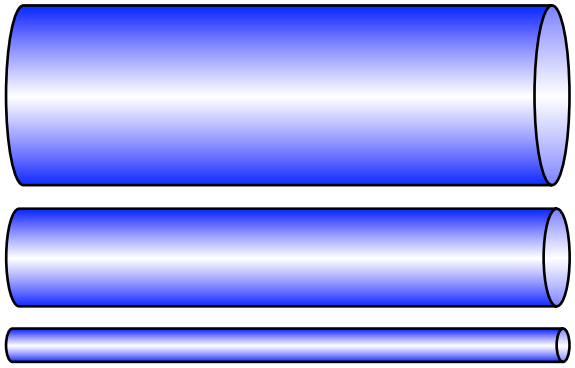
34”
86 cm
} waistline


Relative dose
effective diameter
CTDIvol

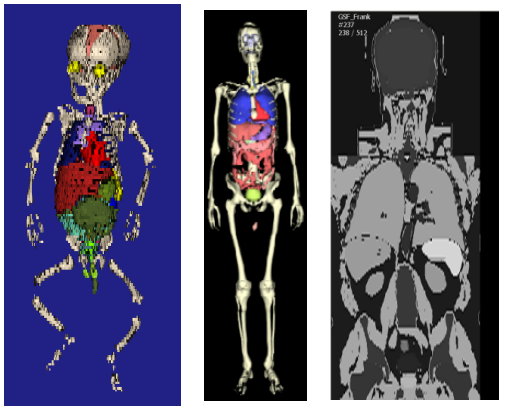
Family of physical phantoms
Cynthia McCollough, Mayo Clinic

standard phantoms
Tom Toth & Keith Strauss

AAPM Task Group 204 – Pediatric CT Dose

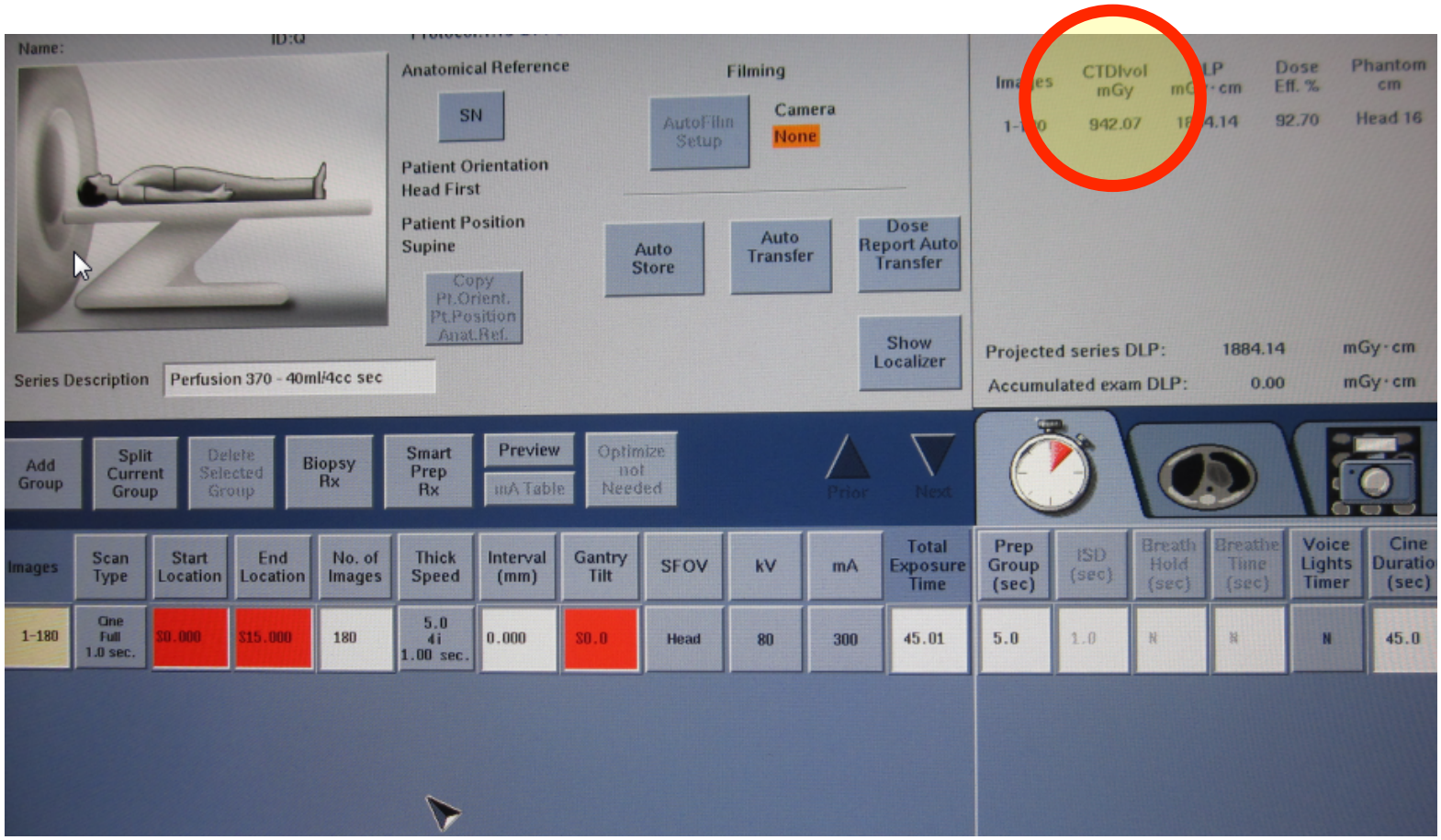


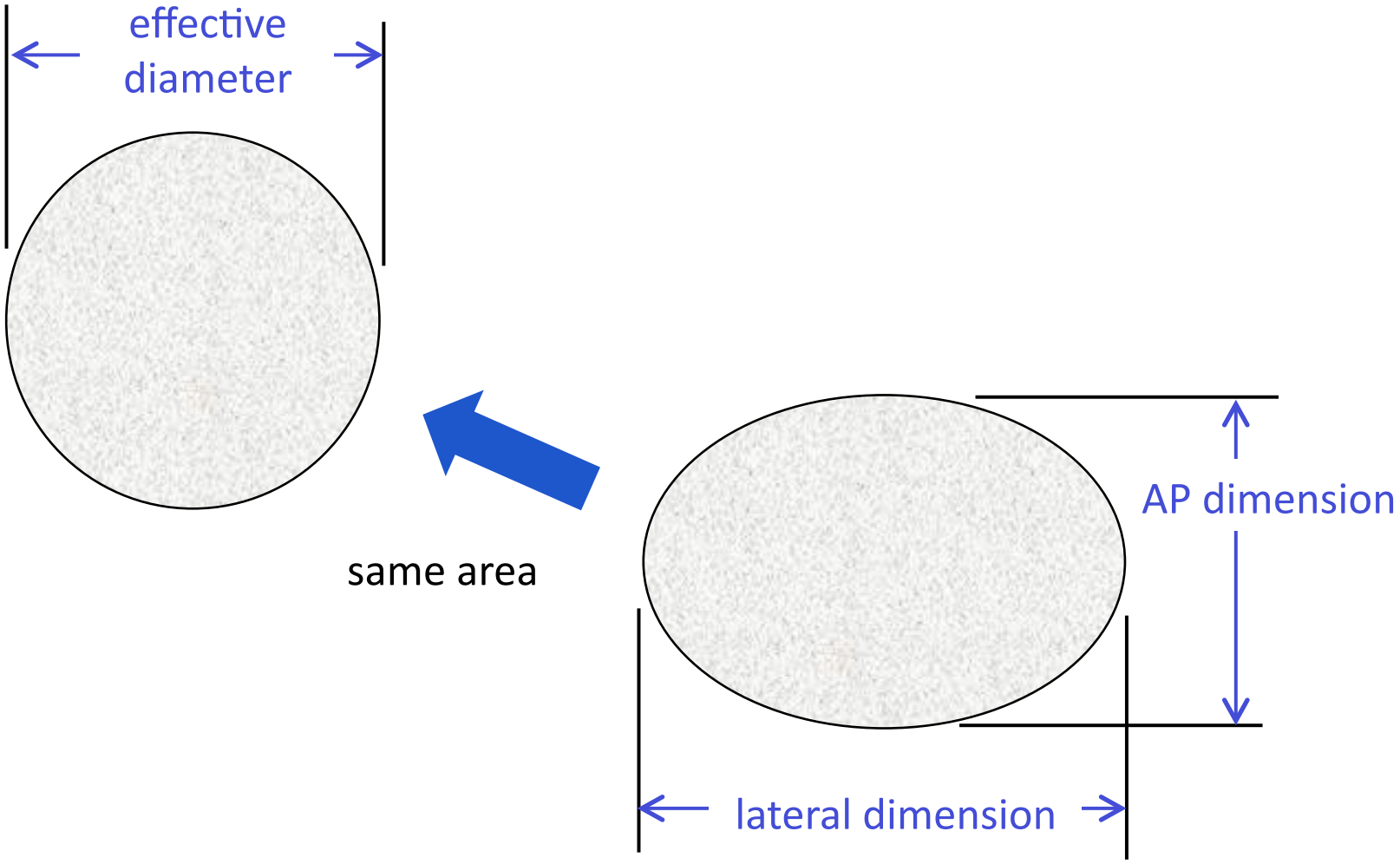
Monte Carlo phantoms (1 – 50 cm)
John M. Boone, UC Davis

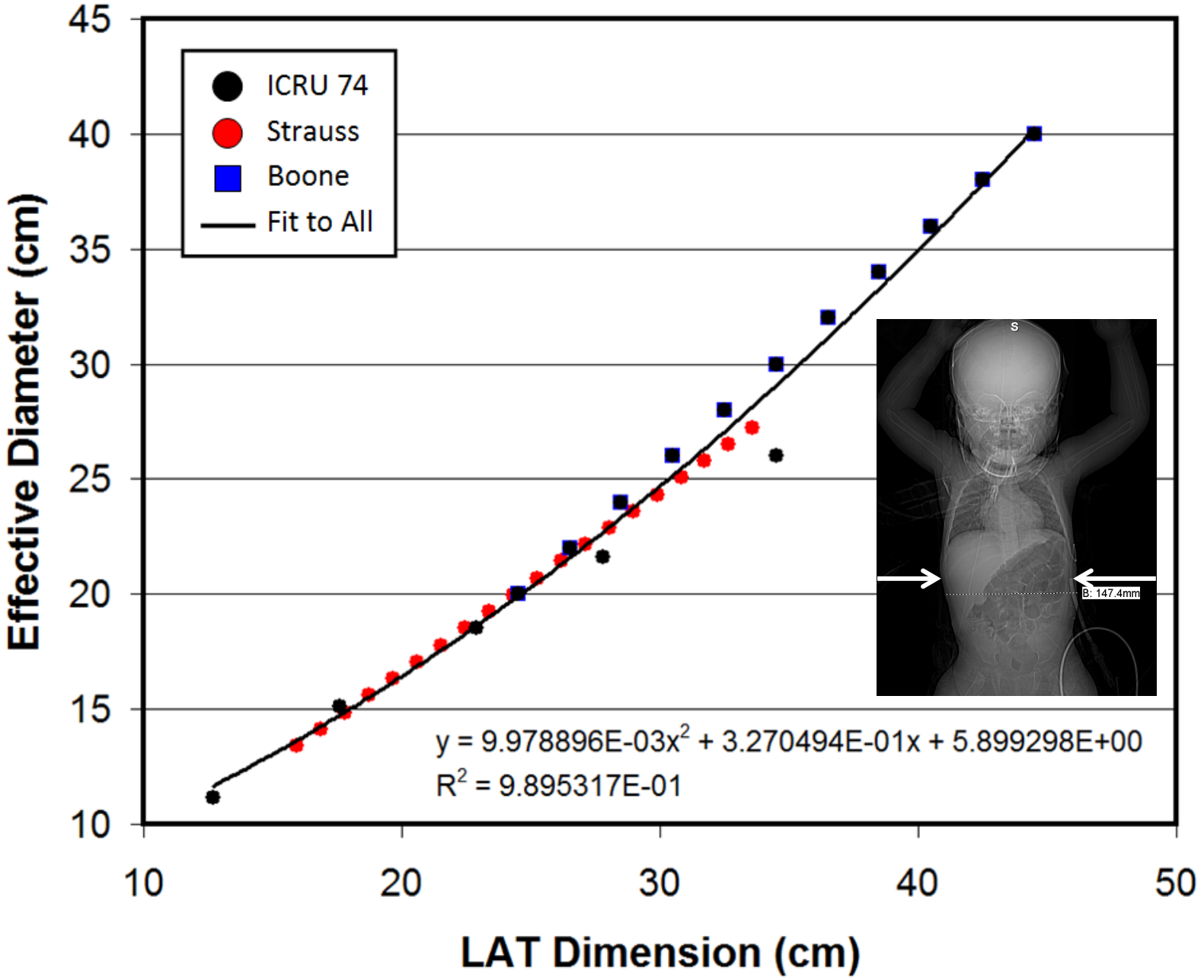


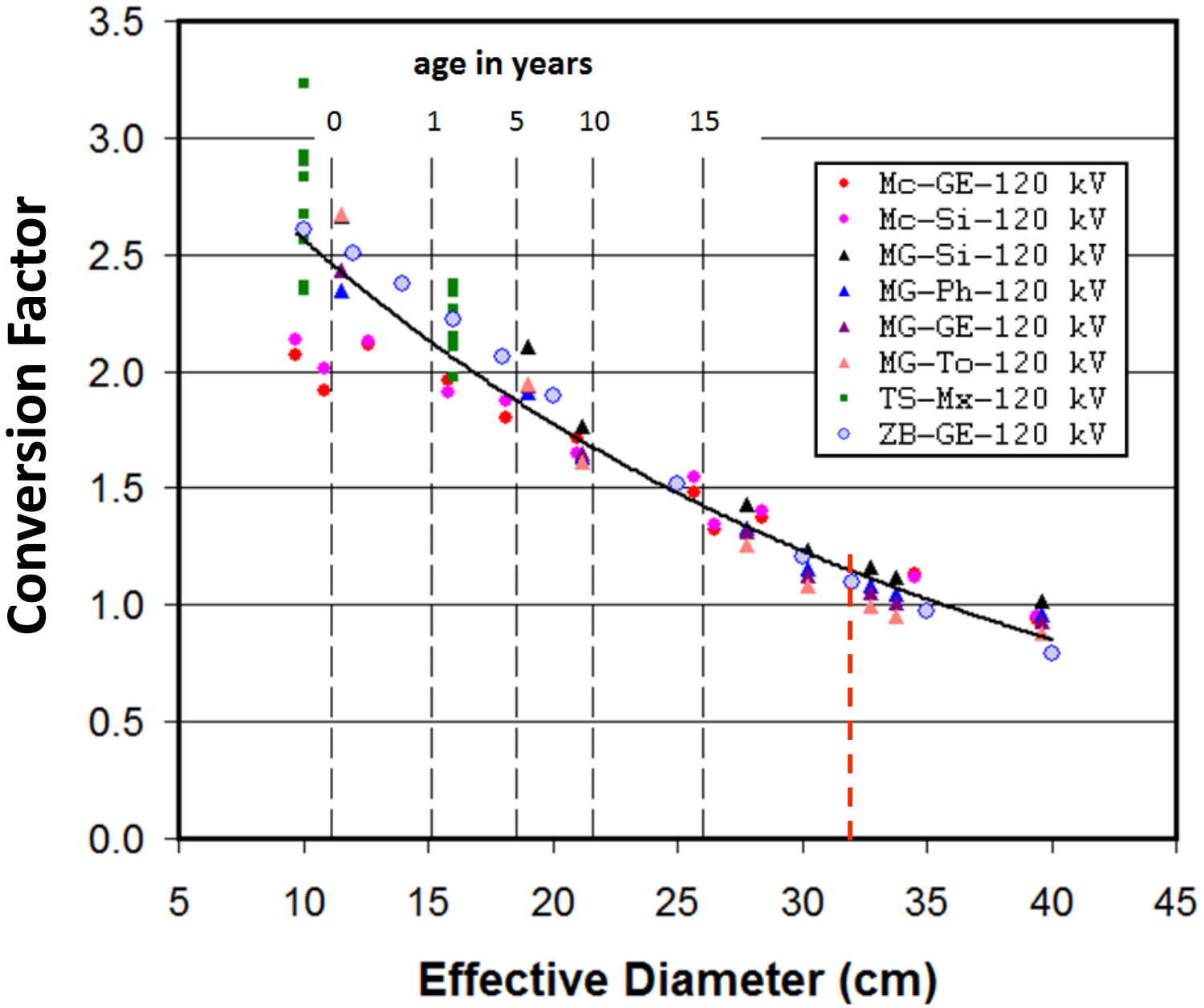
Anthropomorphic Monte Carlo phantoms
Mike McNitt-Gray, UCLA

Dose Index value ($CTDI_{vol}$) is on most scanners.....




effective
diameter
same area
AP dimension
lateral dimension


ICRU 74
Strauss
Boone
Fit to All
Effective Diameter (cm)
LAT Dimension (cm)
45
40
35
30
25
20
15
10
10
20
30
40
50
y = 9.978896E-03x2 + 3.270494E-01x + 5.899298E+00
R2 = 9.895317E-01
S
B: 147.4mm


age in years
0
1
5
10
15
Mc-GE-120 kV
Mc-Si-120 kV
MG-Si-120 kV
MG-Ph-120 kV
MG-GE-120 kV
MG-To-120 kV
TS-Mx-120 kV
ZB-GE-120 kV
Conversion Factor
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
5
10
15
20
25
30
35
40
45
Effective Diameter (cm)

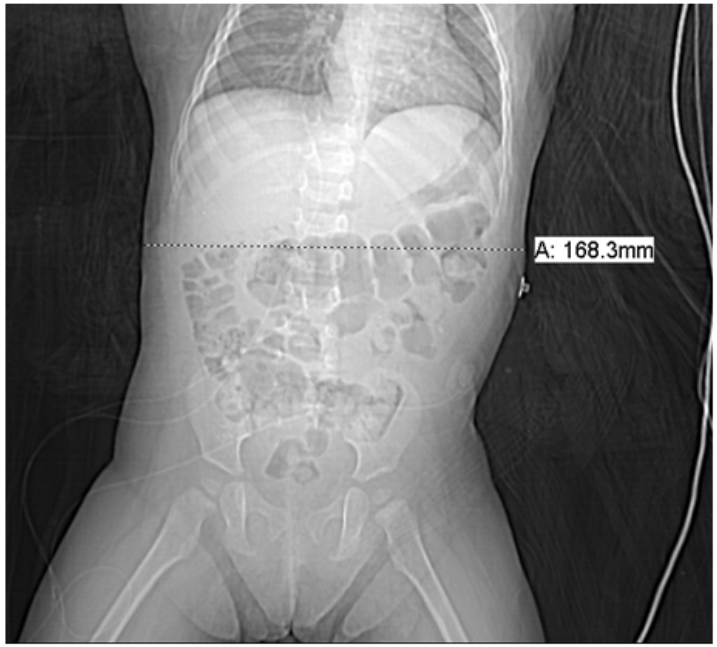
Tables of Conversion Factors: $CTDI_{vol}$ to Estimated Dose

Lat + AP Dim (cm)	Effective Dia (cm)	Correction Factor
16	7.7	2.79
17	8.2	2.74
18	8.7	2.69
19	9.2	2.64
20	9.7	2.59
21	10.2	2.55
22	10.7	2.50
23	11.2	2.46
24	11.7	2.41
25	12.2	2.37
26	12.7	2.32
27	13.2	2.28
28	13.7	2.24
29	14.2	2.20
30	14.7	2.16
31	15.2	2.12
32	15.7	2.08
33	16.2	2.05
34	16.7	2.01
35	17.2	1.97
36	17.6	1.94
37	18.1	1.90
38	18.6	1.87
39	19.1	1.83
40	19.6	1.80
41	20.1	1.77
42	20.6	1.74
43	21.1	1.71
44	21.6	1.67
45	22.1	1.64
46	22.6	1.62
47	23.1	1.59
48	23.6	1.56
49	24.1	1.53
50	24.6	1.50
51	25.1	1.47
52	25.6	1.45
53	26.1	1.42

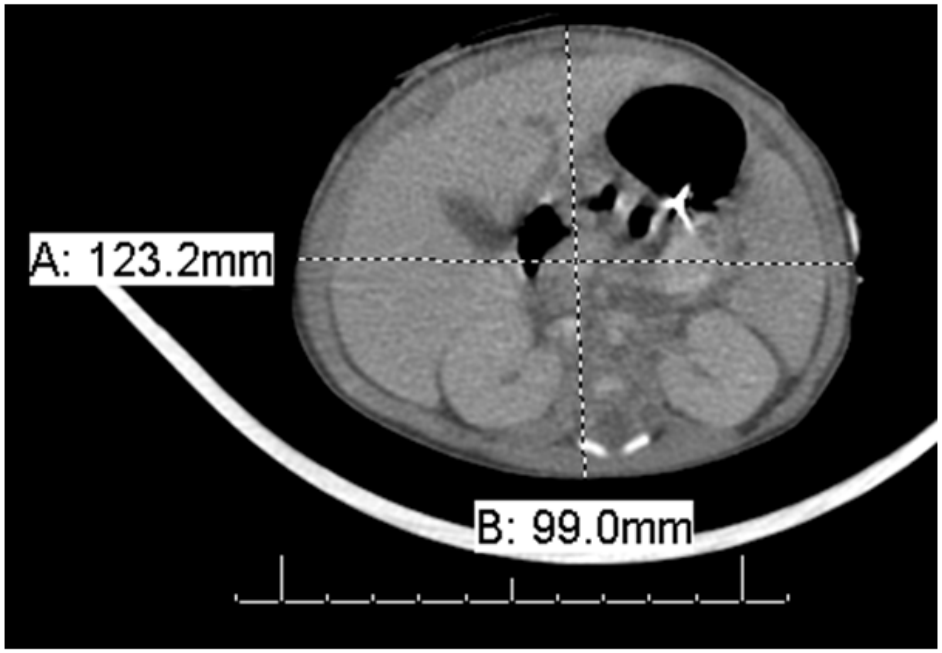
Lateral Dim (cm)	Effective Dia (cm)	Correction Factor
8	9.2	2.65
9	9.7	2.60
10	10.2	2.55
11	10.7	2.50
12	11.3	2.45
13	11.8	2.40
14	12.4	2.35
15	13.1	2.29
16	13.7	2.24
17	14.3	2.19
18	15.0	2.13
19	15.7	2.08
20	16.4	2.03
21	17.2	1.97
22	17.9	1.92
23	18.7	1.86
24	19.5	1.81
25	20.3	1.76
26	21.1	1.70
27	22.0	1.65
28	22.9	1.60
29	23.8	1.55
30	24.7	1.50
31	25.6	1.45
32	26.6	1.40
33	27.6	1.35
34	28.6	1.30
35	29.6	1.25
36	30.6	1.20
37	31.7	1.16
38	32.7	1.11
39	33.8	1.07
40	34.9	1.03
41	36.1	0.98
42	37.2	0.94
43	38.4	0.90
44	39.6	0.87
45	40.8	0.83

AP Dim (cm)	Effective Dia (cm)	Correction Factor
8	8.8	2.68
9	10.2	2.55
10	11.6	2.42
11	13.0	2.30
12	14.4	2.18
13	15.7	2.08
14	17.0	1.98
15	18.3	1.89
16	19.6	1.81
17	20.8	1.73
18	22.0	1.65
19	23.2	1.58
20	24.3	1.52
21	25.5	1.45
22	26.6	1.40
23	27.6	1.34
24	28.7	1.29
25	29.7	1.25
26	30.7	1.20
27	31.6	1.16
28	32.6	1.12
29	33.5	1.08
30	34.4	1.05
31	35.2	1.02
32	36.0	0.99
33	36.8	0.96
34	37.6	0.93
35	38.4	0.91
36	39.1	0.88
37	39.8	0.86
38	40.4	0.84
39	41.1	0.82
40	41.7	0.80
41	42.3	0.78
42	42.8	0.77
43	43.4	0.75
44	43.9	0.74
45	44.4	0.73

Effective Dia (cm)	Correction Factor
8	2.76
9	2.66
10	2.57
11	2.47
12	2.38
13	2.30
14	2.22
15	2.14
16	2.06
17	1.98
18	1.91
19	1.84
20	1.78
21	1.71
22	1.65
23	1.59
24	1.53
25	1.48
26	1.43
27	1.37
28	1.32
29	1.28
30	1.23
31	1.19
32	1.14
33	1.10
34	1.06
35	1.02
36	0.99
37	0.95
38	0.92
39	0.88
40	0.85
41	0.82
42	0.79
43	0.76
44	0.74
45	0.71



9.29 mGy = CTDIvol (16 cm phantom)



5.40 mGy = CTDIvol (32 cm phantom)

Relationship between Photon Count, Dose, and Image Quality

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Beyond $CTDI_{100}$ - including scan length dependence

Beyond $CTDI_{vol}$ – including patient size dependence

Energy Integrating versus Photon Counting CT Detectors

Summary

Photon Counting

1: Schmitzberger FF, Fallenberg EM, Lawaczeck R, Hemmendorff M, Moa E, Danielsson M, Bick U, Diekmann S, Pöllinger A, Engelken FJ, Diekmann F. Development of Low-Dose Photon-counting Contrast-enhanced Tomosynthesis with Spectral Imaging. Radiology. 2011 Feb 17. [Epub ahead of print] PubMed PMID: 21330558.

2: Acciavatti RJ, Maidment AD. A comparative analysis of OTF, NPS, and DQE in energy integrating and photon counting digital x-ray detectors. Med Phys. 2010 Dec;37(12):6480-95. PubMed PMID: 21302803; PubMed Central PMCID: PMC3016706.

3: Kuhls-Gilcrist A, Jain A, Bednarek DR, Rudin S. The Solid State X-ray Image Intensifier (SSXII) in Single Photon Counting (SPC) mode. Proc SPIE. 2010 Mar 22;7622(76221P). pii: 76221P (2010). PubMed PMID: 21243094; PubMed Central PMCID: PMC3021377.

4: Skakun VV, Engel R, Digris AV, Borst JW, Visser AJ. Global analysis of autocorrelation functions and photon counting distributions. Front Biosci (Elite Ed). 2011 Jan 1;3:489-505. PubMed PMID: 21196329.

5: Carton AK, Ullberg C, Maidment AD. Optimization of a dual-energy contrast-enhanced technique for a photon-counting digital breast tomosynthesis system: II. An experimental validation. Med Phys. 2010 Nov;37(11):5908-13. PubMed PMID: 21158303.

6: Carton AK, Ullberg C, Lindman K, Acciavatti R, Francke T, Maid Optimization of a dual-energy contrast-enhanced technique for a p digital breast tomosynthesis system: I. A theoretical model. Med Nov;37(11):5896-907. PubMed PMID: 21158302.

7: Taguchi K, Frey EC, Wang X, Iwanczyk JS, Barber WC. An analytical model of the effects of pulse pileup on the energy spectrum recorded by energy resolved photon counting x-ray detectors. Med Phys. 2010 Aug;37(8):3957-69. PubMed PMID: 20879558; PubMed Central PMCID: PMC2917451.

8: Fredenberg E, Hemmendorff M, Cederström B, Aslund M, Danielsson M. Contrast-enhanced spectral mammography with a photon-counting detector. Med Phys. 2010 May;37(5):2017-29. PubMed PMID: 20527535.

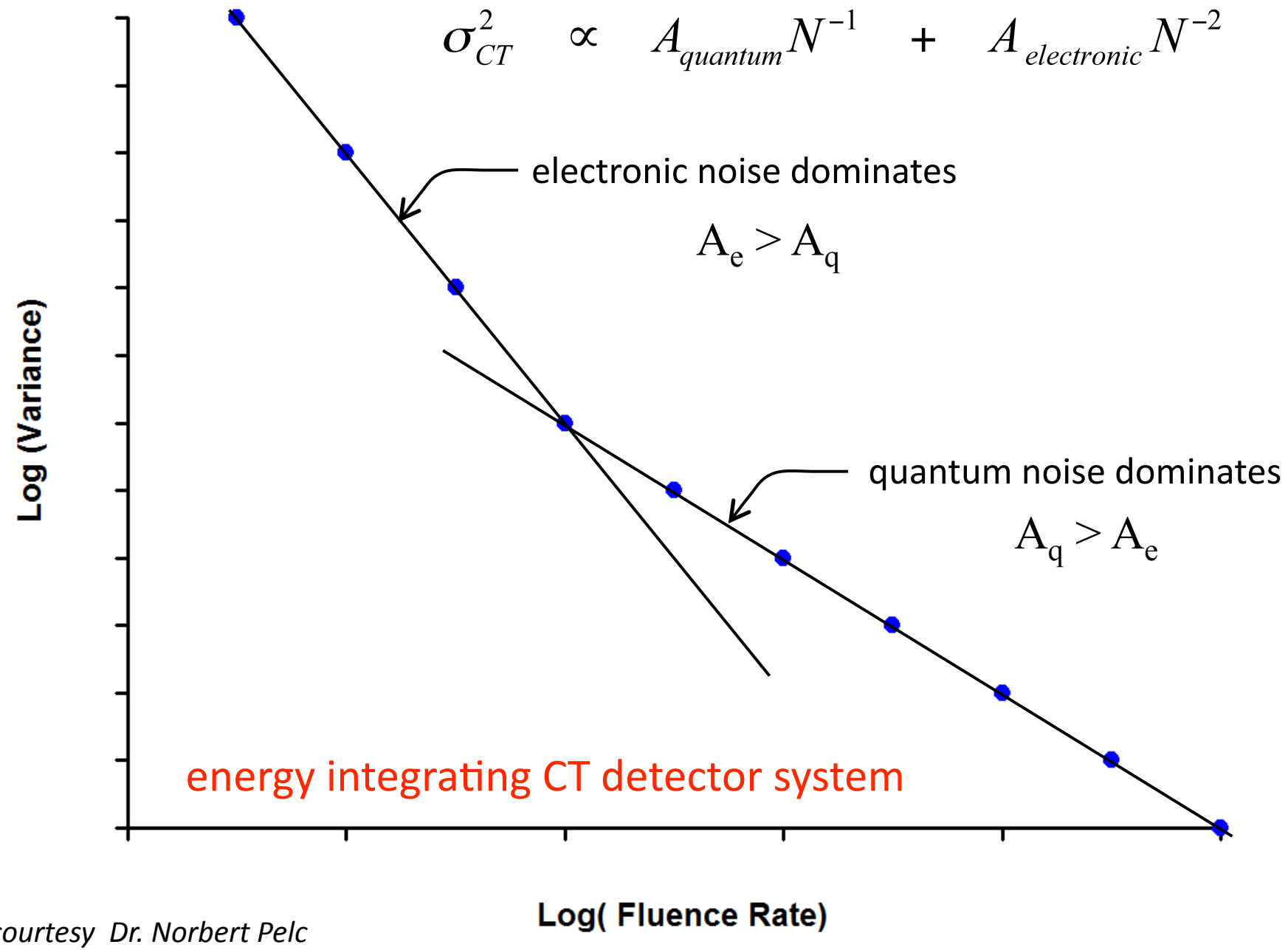
9: Bornefalk H, Danielsson M. Photon-counting spectral computed tomography using silicon strip detectors: a feasibility study. Phys Med Biol. 2010 Apr 7;55(7):1999-2022. Epub 2010 Mar 19. PubMed PMID: 20299720.

10: Fredenberg E, Cederström B, Danielsson M. Energy filtering with X-ray lenses: optimization for photon-counting mammography. Radiat Prot Dosimetry. 2010 Apr-May;139(1-3):339-42. Epub 2010 Feb 23. PubMed PMID: 20179073.

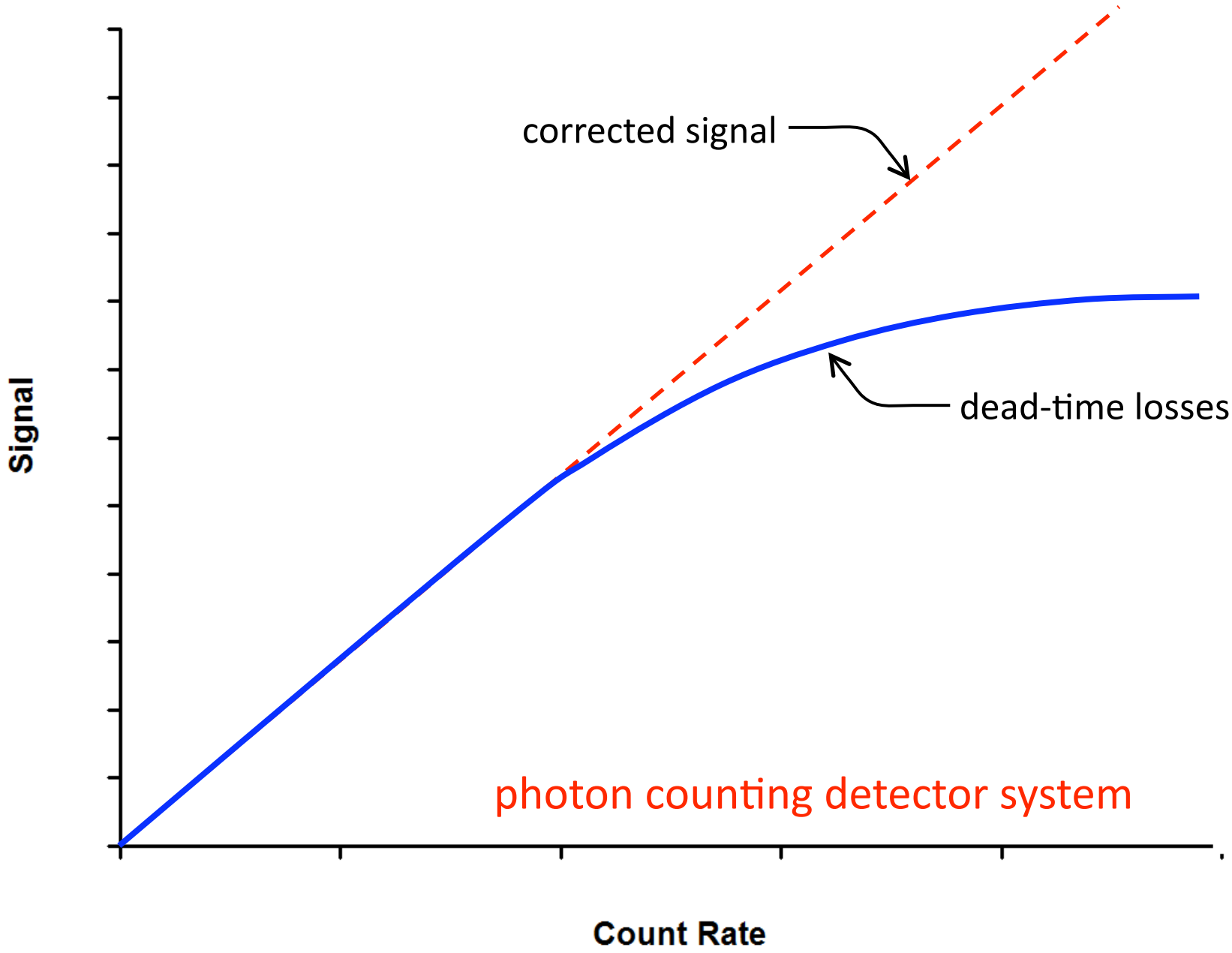
11: Narravula SR, Hayat MM, Javidi B. Information theoretic approach for assessing image fidelity in photon-counting arrays. Opt Express. 2010 Feb 1;18(3):2449-66. doi: 10.1364/OE.18.002449. PubMed PMID: 20174073.

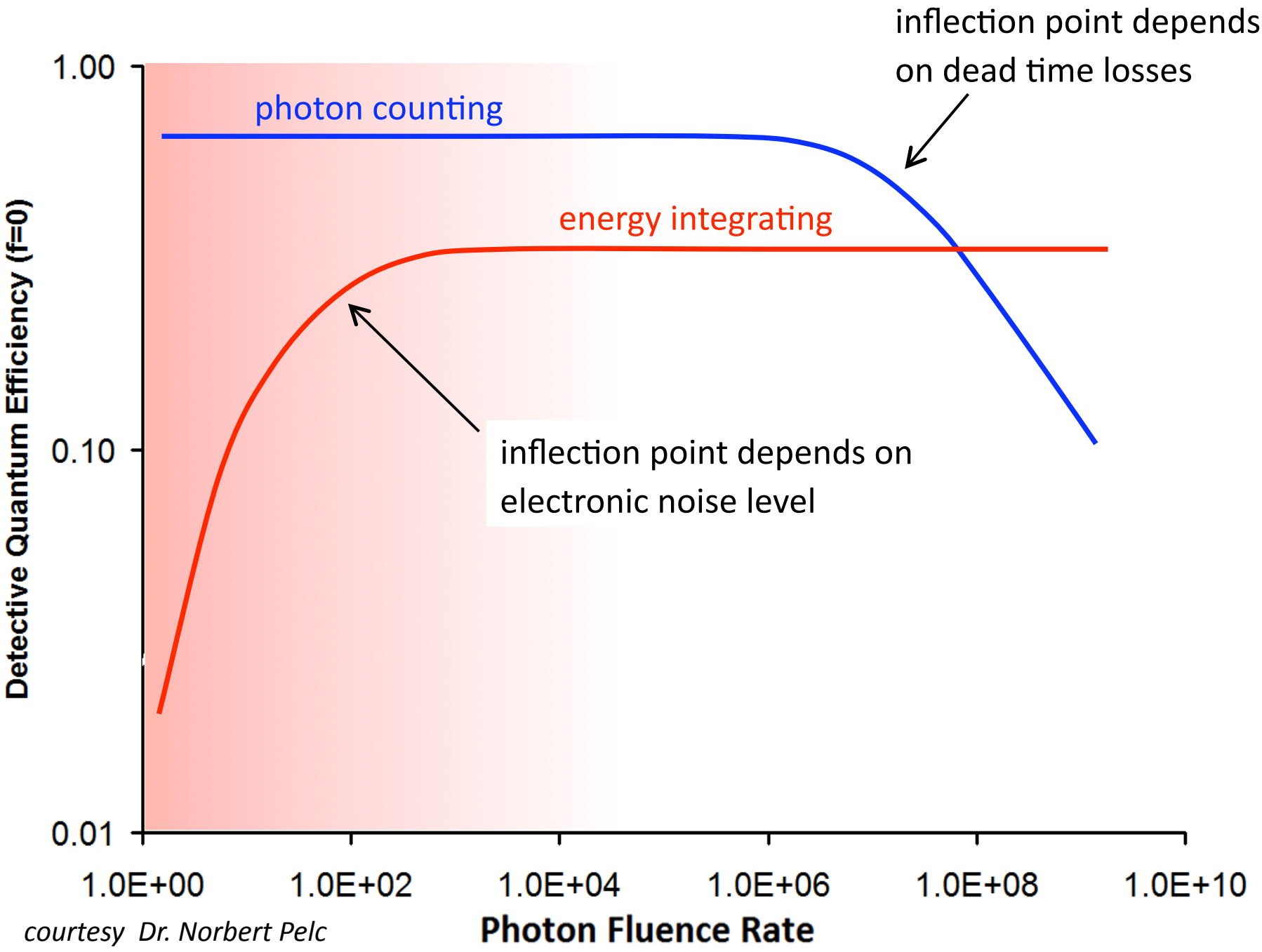
12: Boll DT, Patil NA, Paulson EK, Merkle EM, Nelson RC, Schindera ST, Roessl E, Martens G, Proksa R, Fleiter TR, Schlomka JP. Focal cystic high-attenuation lesions: characterization in renal phantom by using photon-counting spectral CT--improved differentiation of lesion composition. Radiology. 2010 Jan;254(1):270-6. PubMed PMID: 20032158.

Photon counting papers for x-ray imaging in 2010

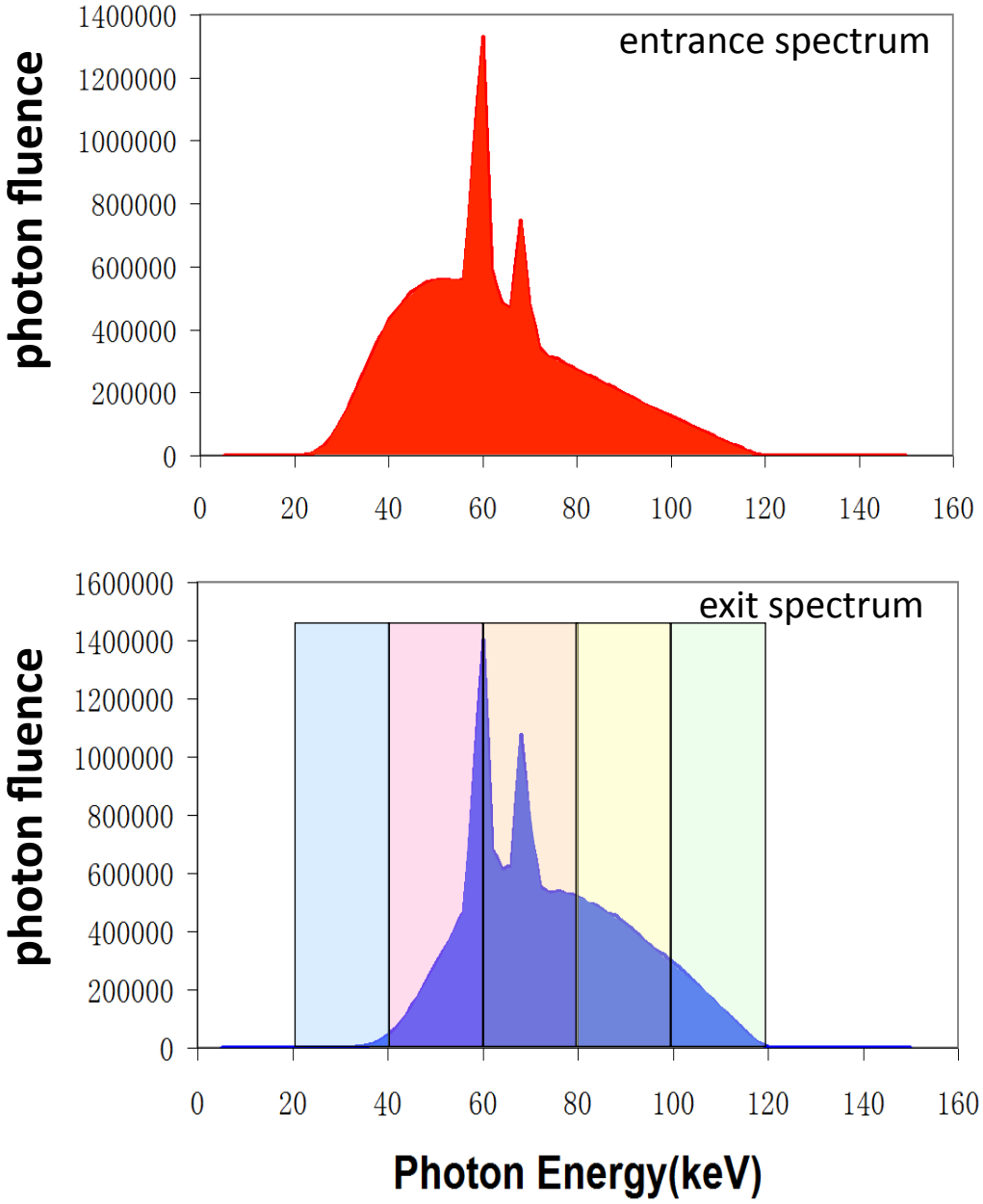


courtesy Dr. Norbert Pelc


corrected signal
dead-time losses
photon counting detector system
Signal
Count Rate

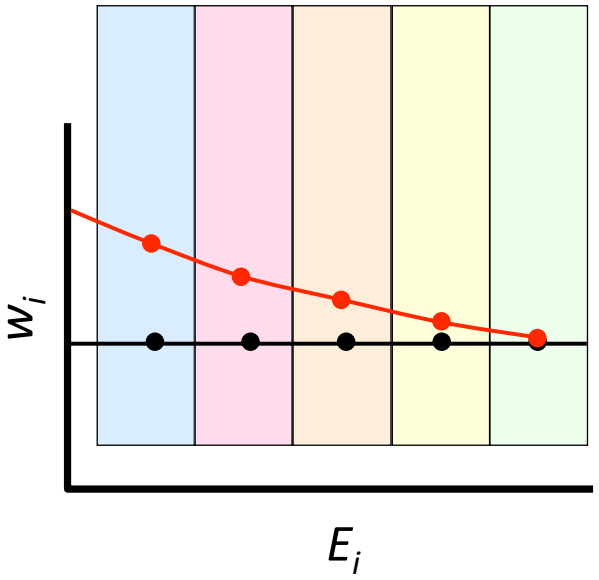


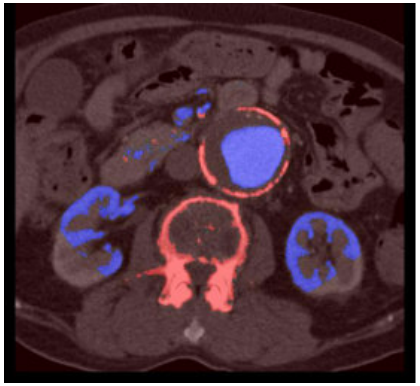
courtesy Dr. Norbert Pelc

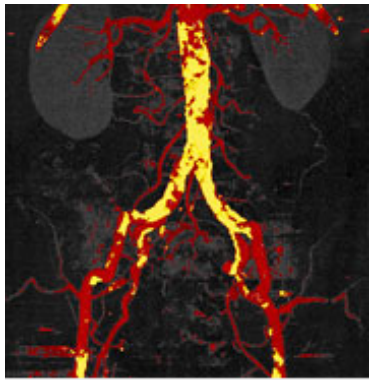


Energy Resolution

Energy Weighting



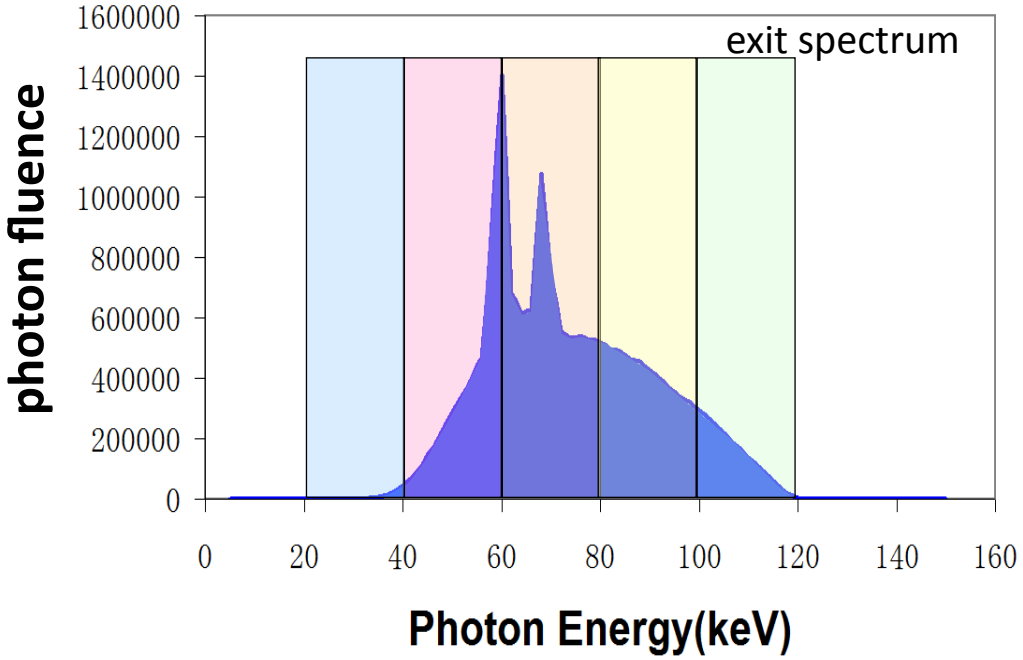




Energy Resolution

Energy Decomposition

$$DE(x,y) = LN[I_{hi}(x,y)] - w\,LN[I_{low}(x,y)]$$



Images courtesy various websites

Relationship between Photon Count, Dose, and Image Quality

Introduction

An Integrated CT Image Quality / Dosimetry Phantom

Beyond $CTDI_{100}$ - including scan length dependence

Beyond $CTDI_{vol}$ – including patient size dependence

Energy Integrating versus Photon Counting CT Detectors

Summary

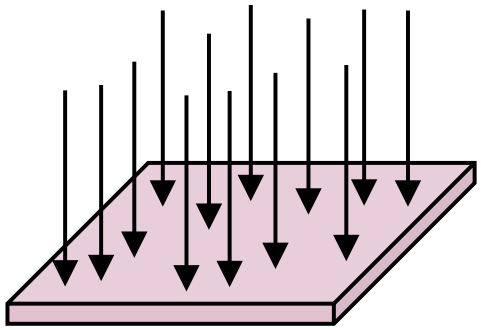
The path towards:

Future Dose Reduction without Compromise of Image Quality

An Integrated CT Image Quality / Dosimetry Phantom

planar x-ray detectors

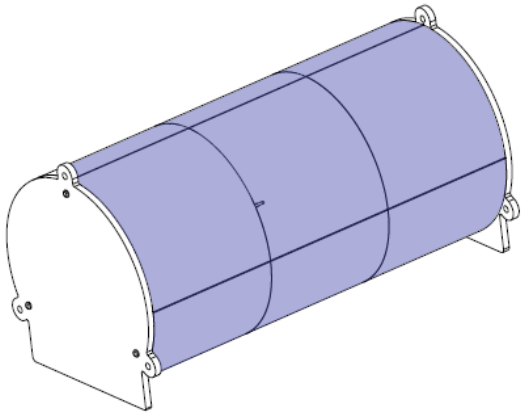
$$DQE(f) = \frac{MTF^2(f)}{q \quad NPS(f)}$$



CT detector systems

$$NEQ(f) = \frac{MTF^2(f)}{NPS(f)}$$

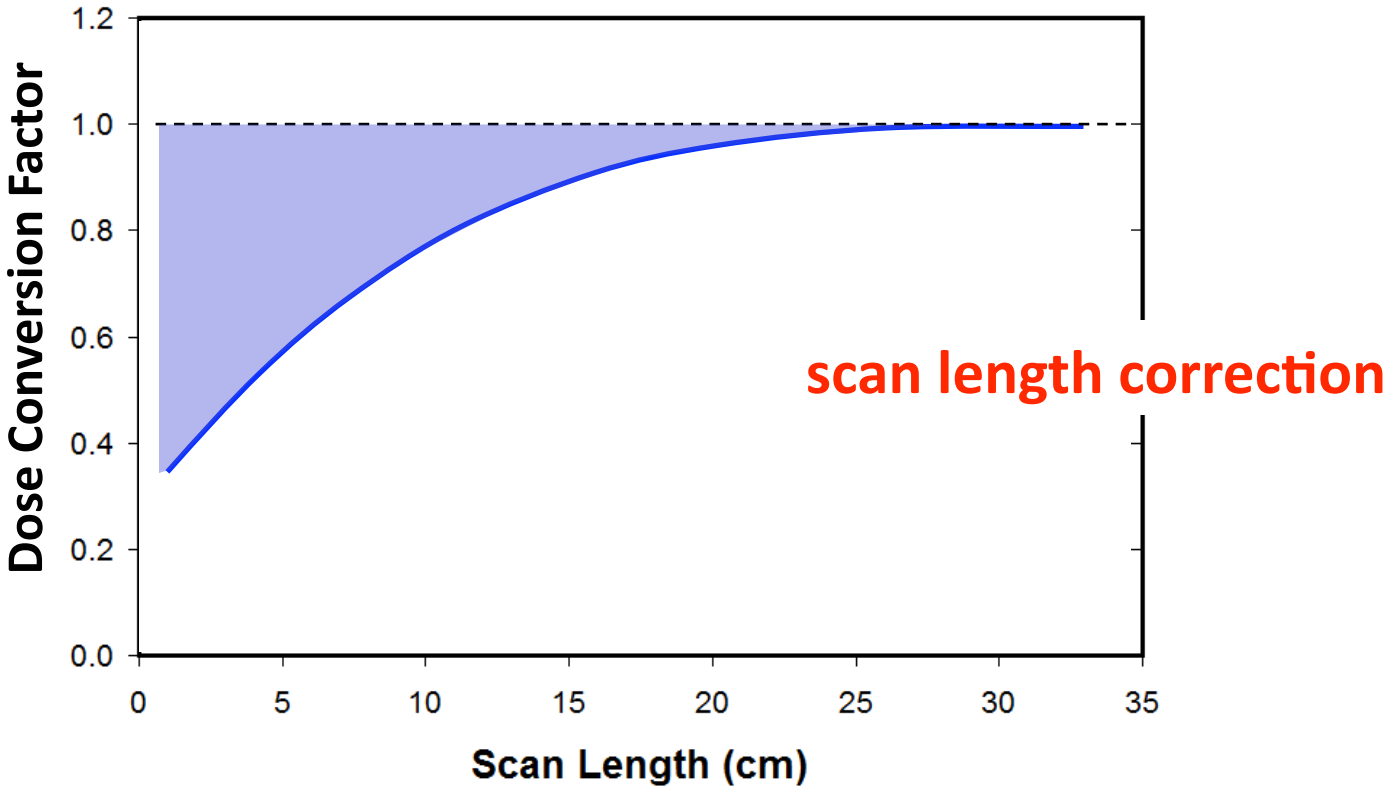
....at equal dose



The path towards:

Future Dose Reduction without Compromise of Image Quality

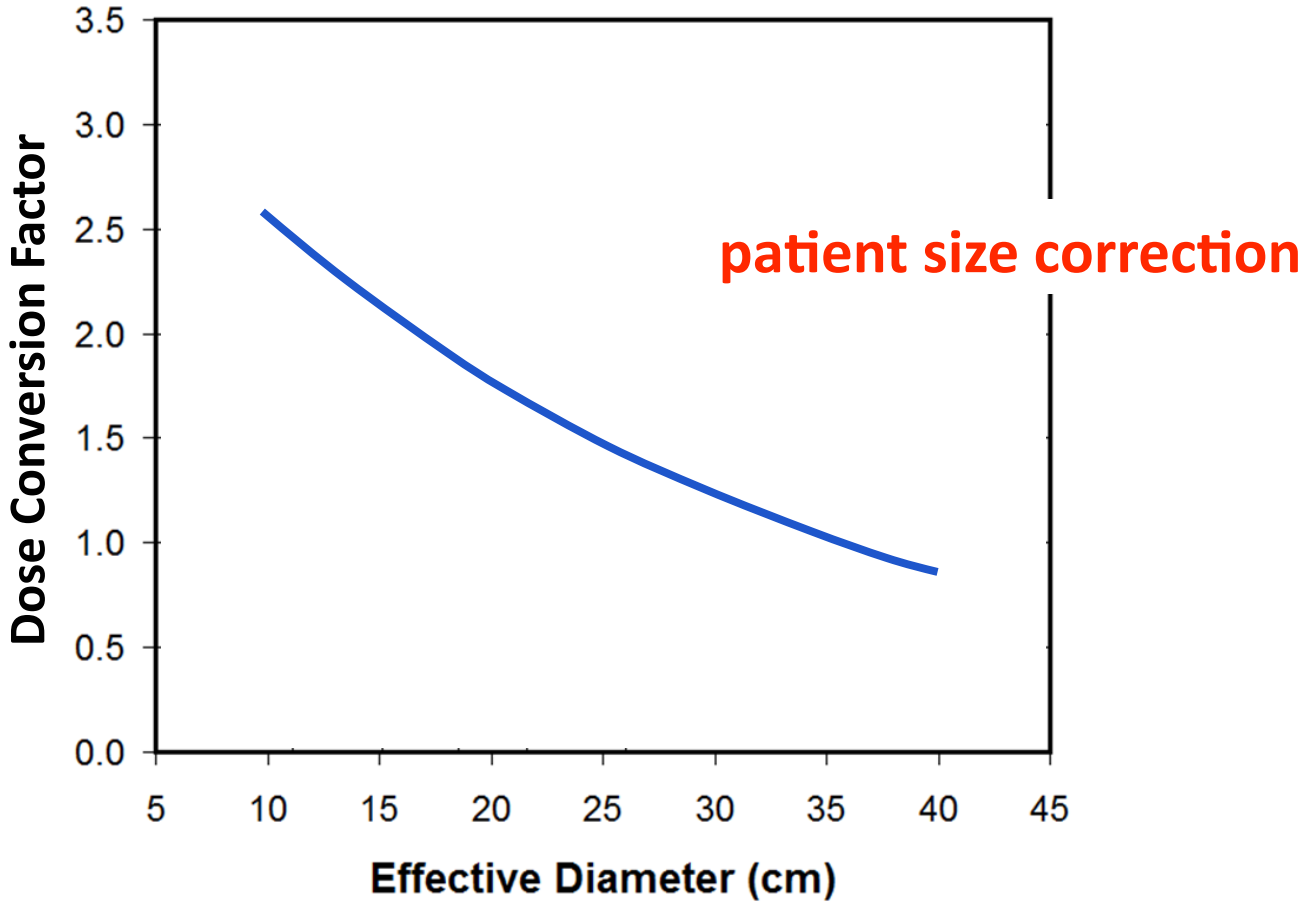
More accurate CT dosimetry tools



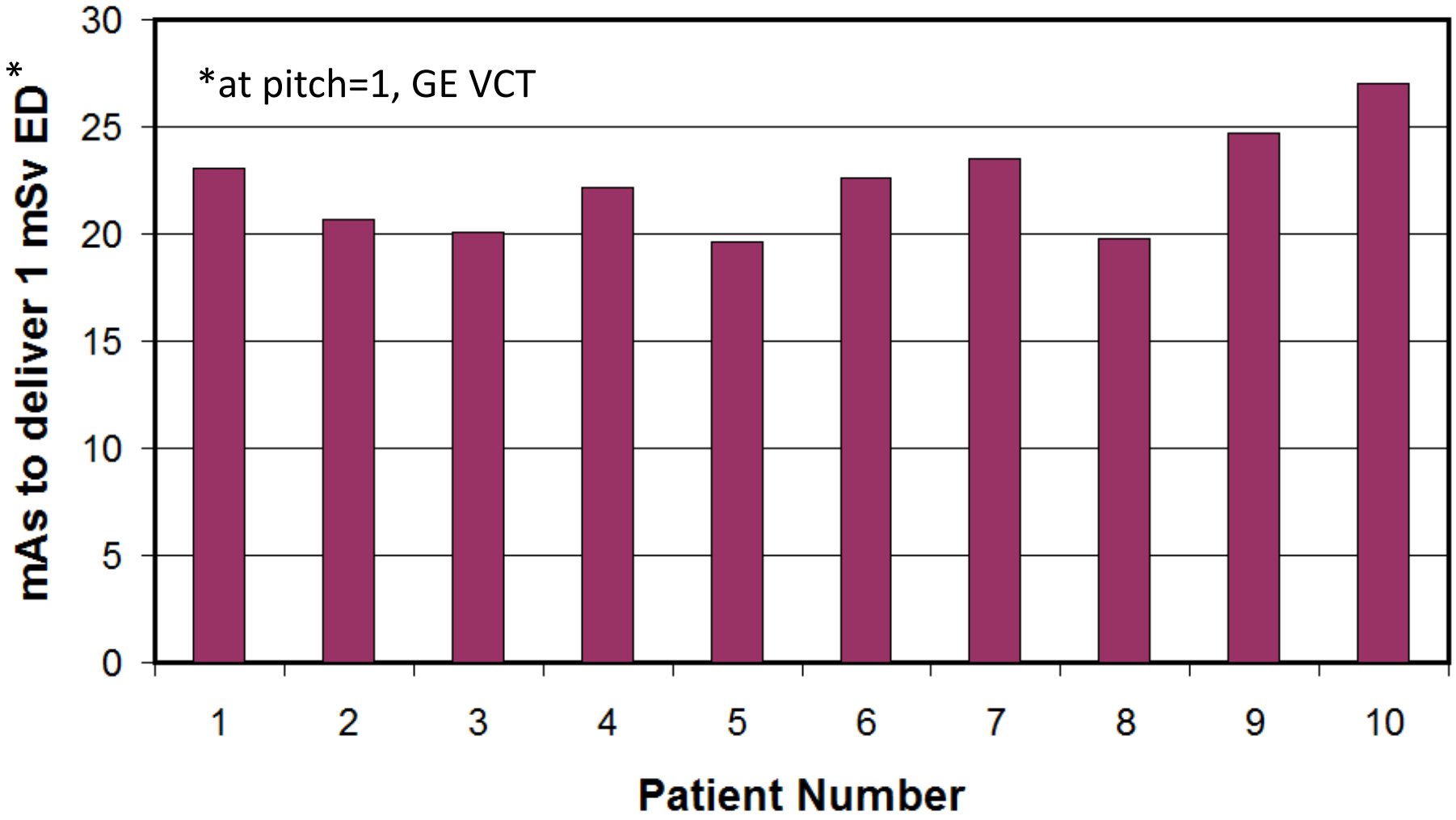
The path towards:

Future Dose Reduction without Compromise of Image Quality

More accurate CT dosimetry tools



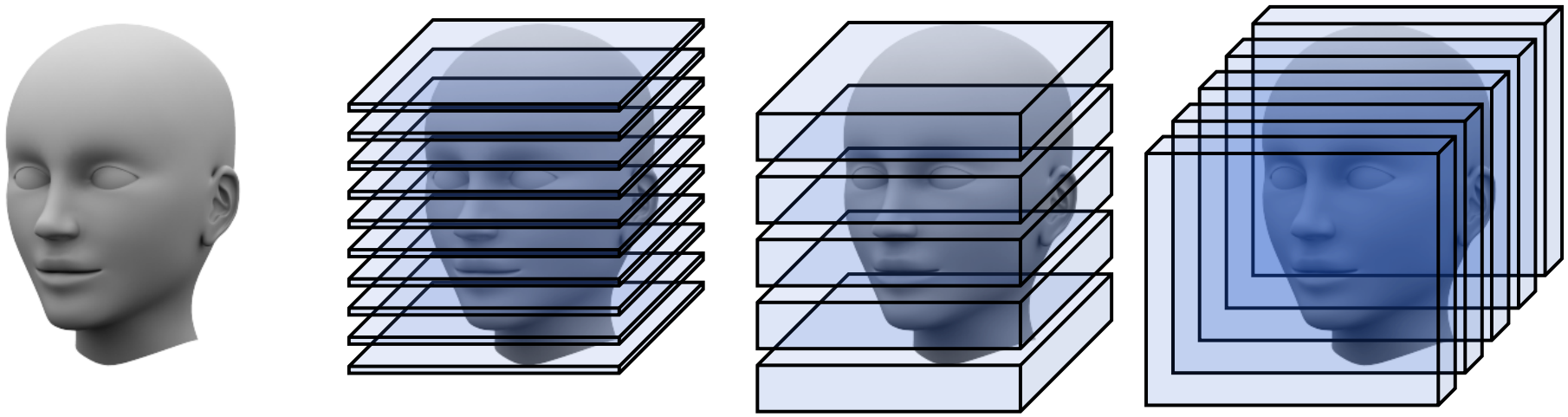
mAs necessary to achieve 1 mSv CT scan (abdomen or pelvis)



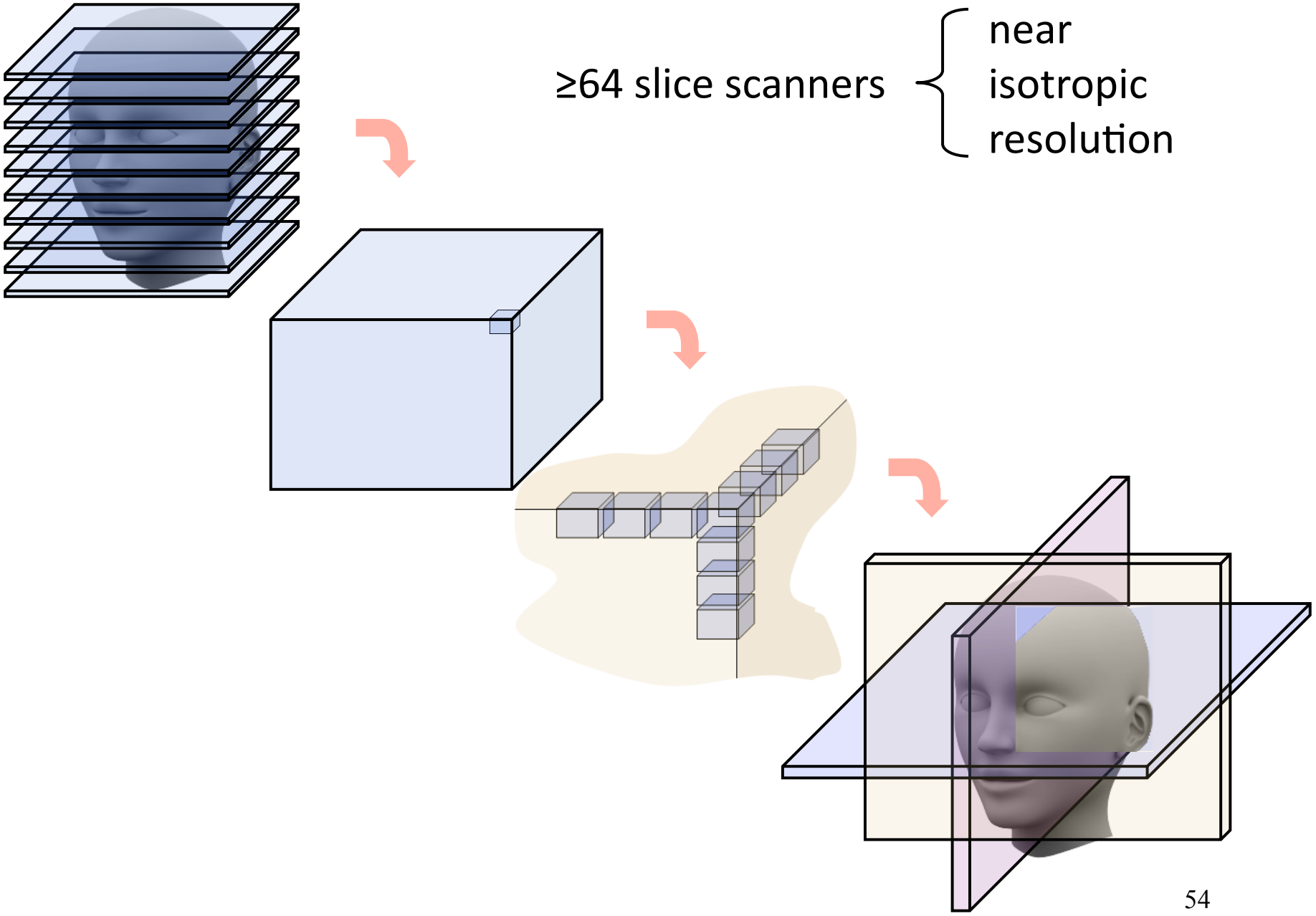
The path towards:

Future Dose Reduction without Compromise of Image Quality

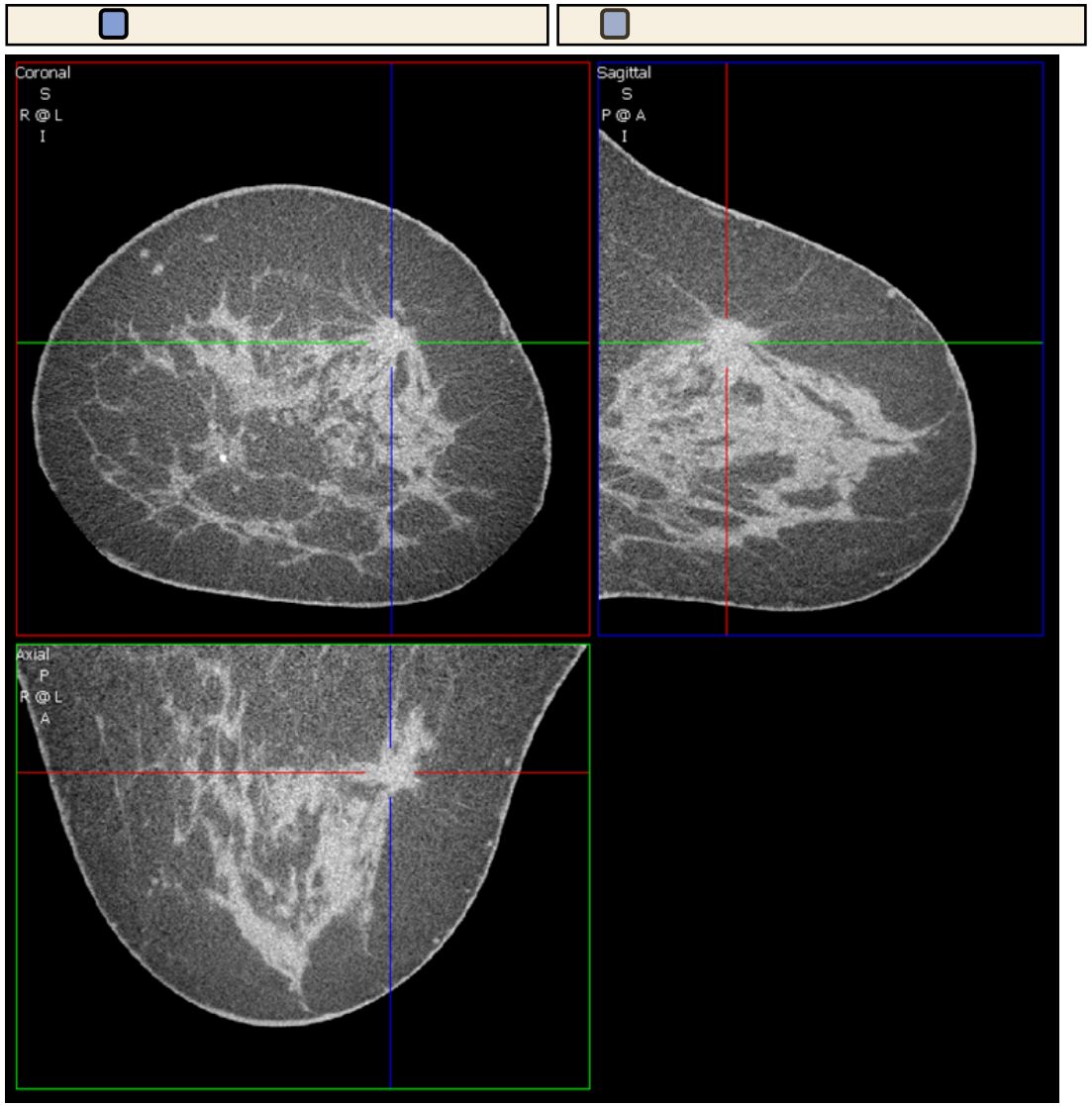
Work flow and image viewing capabilities



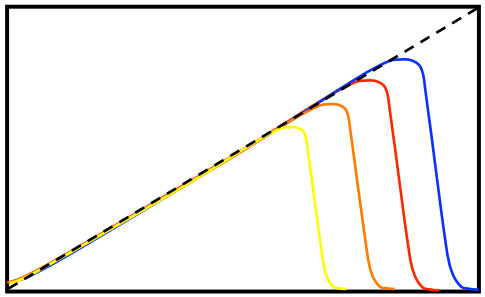
thin slice axial thick slice axial coronal


≥64 slice scanners
near
isotropic
resolution

true 2D orthogonal viewing



kernel control

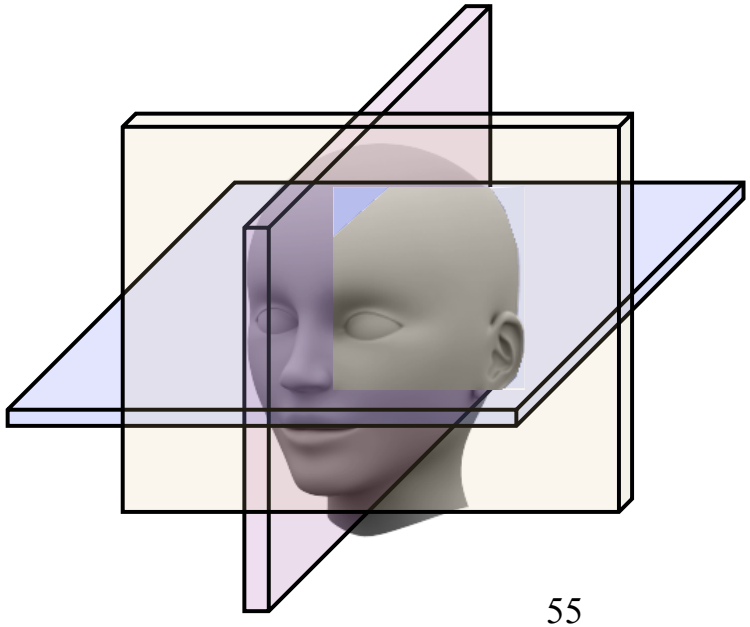


slice thickness control

2x thick = 2x mAs

4x thick = 2x mAs

8x thick = 8x mAs

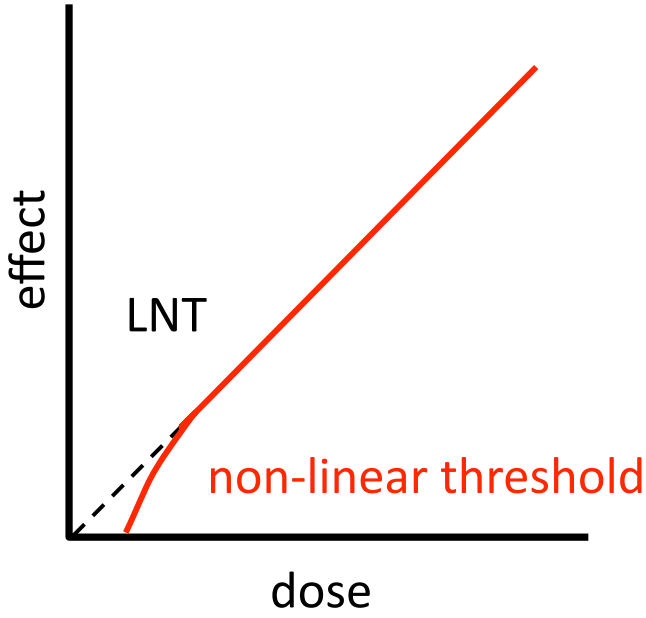


Some concepts courtesy Dr. Willi Kalender

Toward the Sub-mSv Exam

ICRP 103

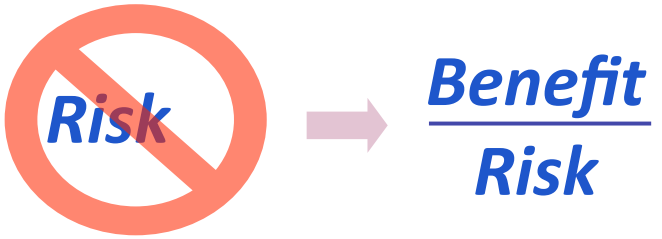
Organ	w_T	H_T (mGy)	$w_T.H_T$
Gonads	0.08	0.00	0.00
Bone Marrow	0.12	1.50	0.18
Colon	0.12	0.00	0.00
Lung	0.12	0.06	0.01
Stomach	0.12	0.00	0.00
Bladder	0.04	0.00	0.00
Breast	0.12	0.02	0.00
Liver	0.04	0.00	0.00
Oesophagus (Thymus)	0.04	0.04	0.00
Thyroid	0.04	1.20	0.05
Skin	0.01	1.30	0.01
Bone Surface	0.01	6.10	0.06
Brain	0.01	24.00	0.24
Salivary Glands (Brain)	0.01	24.00	0.24
Remainder	0.12	2	0.24
Not Applicable	0	0	0
Total Effective Dose (mSv)			**1**



HEALTH RISKS
FROM EXPOSURE TO
LOW LEVELS OF
IONIZING
RADIATION

BEIR VII PHASE 2

Toward the Low-Dose CT Exam



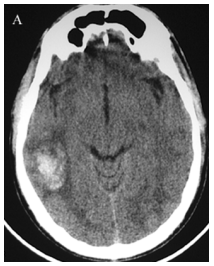
Significant Extra-colonic findings in CT colonography

54 cancers / 10,286 asymptomatic patients

5.2 cancers / 1000 cases • 0.5 fatal cancers / 1000 cases

10:1 Benefit to Risk ratio?

Significant Findings in Head CT in the ED



Head CT in the Emergency Department (~3000 studied)

~5% (50 / 1000) • 0.5 fatal cancers / 1000 cases

100:1 Benefit to Risk ratio?

* Pickhardt et al: Colorectal and extra-colonic cancers detected at screening CT colonography in 10,286 asymptomatic adults, Radiology 255: 2010; 83-88

**Rawson, Boone, Brunberg & Bobinski, in preparation

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