Optimizing CT Dose and Image Quality for Different Patient Sizes

Dianna D. Cody, Ph.D., DABR, FAAPM
UT MD Anderson Cancer Center

Michael F. McNitt-Gray, Ph.D., DABR
David Geffen School of Medicine at UCLA

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- $ Michael McNitt-Gray, Ph.D.
  - UCLA Department of Radiology has a Master Research Agreement with Siemens Medical Solutions

Learning Objectives

- Understand how radiation dose for CT studies is currently estimated
- Understand the trade-offs of dose and image quality, especially for large (obese) patients and in pediatric patients
- Review of the manufacturers’ dose modulation methods and how these affect dose in different patients

Talk Outline

1. Radiation Dose Basics
2. Image Quality Basics
3. Patient Size and Its Relationship to Radiation Dose
4. The Effect of Patient Size on Radiation Dose and Image Quality
5. Tube Current Modulation Methods
6. Monte Carlo Simulation Methods for Radiation Dose
7. Summary and Practical Issues on how to balance image quality and radiation dose as a function of patient size

Radiation Dose Basics: Why Care About CT Dose?

There have been significant improvements in CT technology over the past decade

- Multidetector CT (4 -> 320 rows)
- Improved temporal resolution (1 sec -> .3 sec per rotation)
- Cardiac CT
- Dual source CT
- Dual energy CT

This has led to increase in clinical utilization

- Approx 10% per year

Increased utilization has led to concerns over radiation dose

Radiation Dose Basics: Why Care About CT Dose?

- CT has recently been identified as one of the leading contributors to medical radiation exposure (Mettler et al 2008)
  - 15% of diagnostic radiology procedures
  - 50% of medical exposure
  - 25% of total exposure

Radiation Dose Basics:
How do we currently measure dose in CT?

Conventional Computed Tomography Dose Index (CTDI)

- Measure exposure in phantom (16 or 32 cm diameter) in 100 mm long pencil ionization chamber
- Using an axial scan (even if protocol is helical scan)
- Calculate

$$CTDI_{100} = \frac{fCEL}{NT}$$

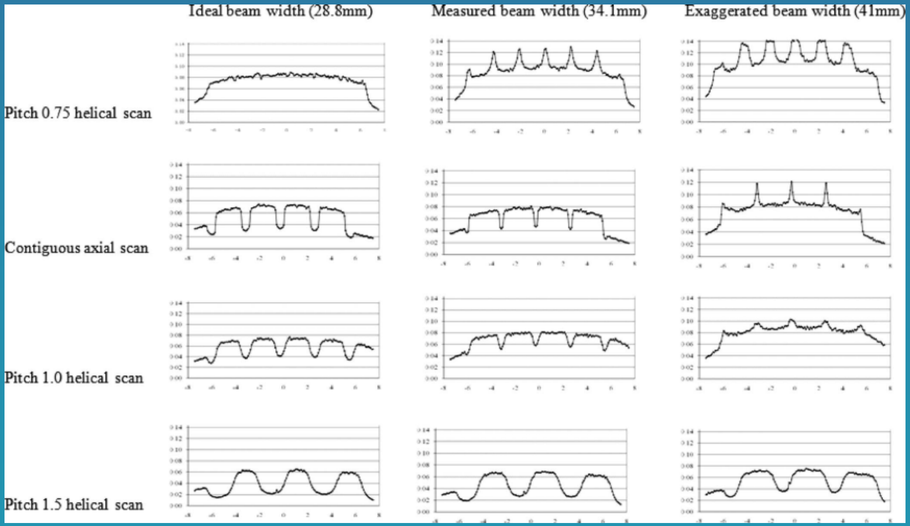
$$CTDI_{w} = [(\frac{1}{3}CTDI_{center}) + (\frac{2}{3}CTDI_{periphery})]$$

$$CTDI_{vol} = \frac{CTDI_{w}}{p}$$

Radiation Dose Basics: AAPM TG 111

AAPM TG 111 is proposed a revised methodology

- Use small (Farmer) ionization chamber
- Scan helically if protocol is helical (scan axially if protocol is axial)
- In this way, the small chamber integrates dose received from entire scan (both primary and scatter from adjacent images)
- Attention paid to adjustment of pitch when **measuring surface dose** in helical protocol (surface dose variations)



- Zhang et al Med Phys March 2009

- Some important details (phantom, which measurements to make/report, etc.) to be ironed out. TG 200

Radiation Dose Basics: Organ Dose

- BEIR VII report (2005), ICRP 103 (2007) and previous ICRP reports all use dose to radiosensitive organs (in mGy; also known as equivalent dose, expressed in mSv) as a basis for estimating metrics that relate to risk
- BEIR VII estimates risk based on organ, dose to that organ, age, gender, etc.
- ICRP 103 uses organ dose to estimate effective dose

Effective Dose

Tissue	ICRP 60 weighting factor (w_T)	ICRP 103 w_T
Gonads	0.20	.08
Red Bone Marrow	0.12	.12
Colon	0.12	.12
Lung	0.12	.12
Stomach	0.12	.12
Bladder	0.05	.04
Breast	0.05	.12
Liver	0.05	.04
Esophagus	0.05	.04
Thyroid	0.05	.04
Skin	0.01	.01
Bone Surface	0.01	.01
Brain	(Remainder)	.01
Salivary Glands	(Remainder)	.01
Remainder (Adrenals, etc.)	0.05	.12

Radiation Dose Basics: Summary

- CT provides tremendous diagnostic information
- Increased utilization and radiation dose are concerns
- Currently measure dose with CTDI in phantoms
- Methods proposed to revise this, but still use phantoms
- Risk is best indicated via organ dose
- ? Some way to link these two (organ dose and CTDI)?

Image Quality Basics

- Basic Descriptors
- Examples
- More detailed/complete descriptors

Image Quality Basic Descriptors

- Noise
- Spatial Resolution
- Low Contrast Resolution

Noise – Part 1

- In its *simplest* definition
  - is the measured standard deviation of voxel values in a homogenous (typically water) phantom
- Influenced by many parameters:
  - kVp
  - mA
  - Exposure time
  - Collimation/Reconstructed image Thickness
  - Reconstruction algorithm
  - Helical Pitch/Table speed
  - Helical Interpolation Algorithm
  - Others (Focal spot to isocenter distance, detector efficiency, etc.)

Reducing mAs Increases Noise

$$Noise \propto \frac{1}{\sqrt{mAs}}$$

- If mAs is reduced by ½,
  - noise increases by $\sqrt{2}$ =1.414 → (40% increase)

Reducing image Thickness Increases Noise

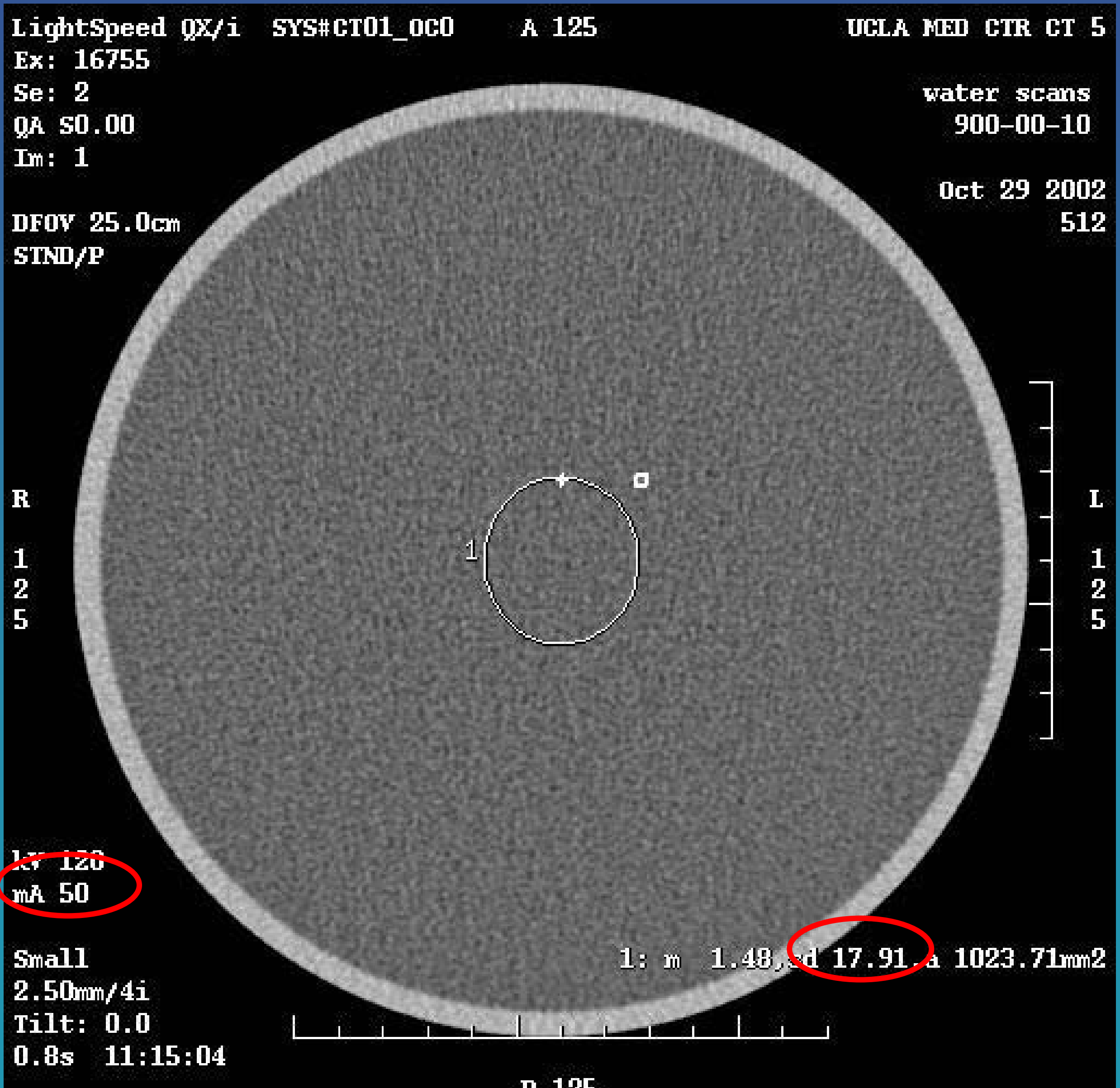
$$Noise \propto \frac{1}{\sqrt{image\,thickness}}$$

- If image thickness is reduced by ½,
  - noise increases by $\sqrt{2}$ =1.414 →(40% increase)

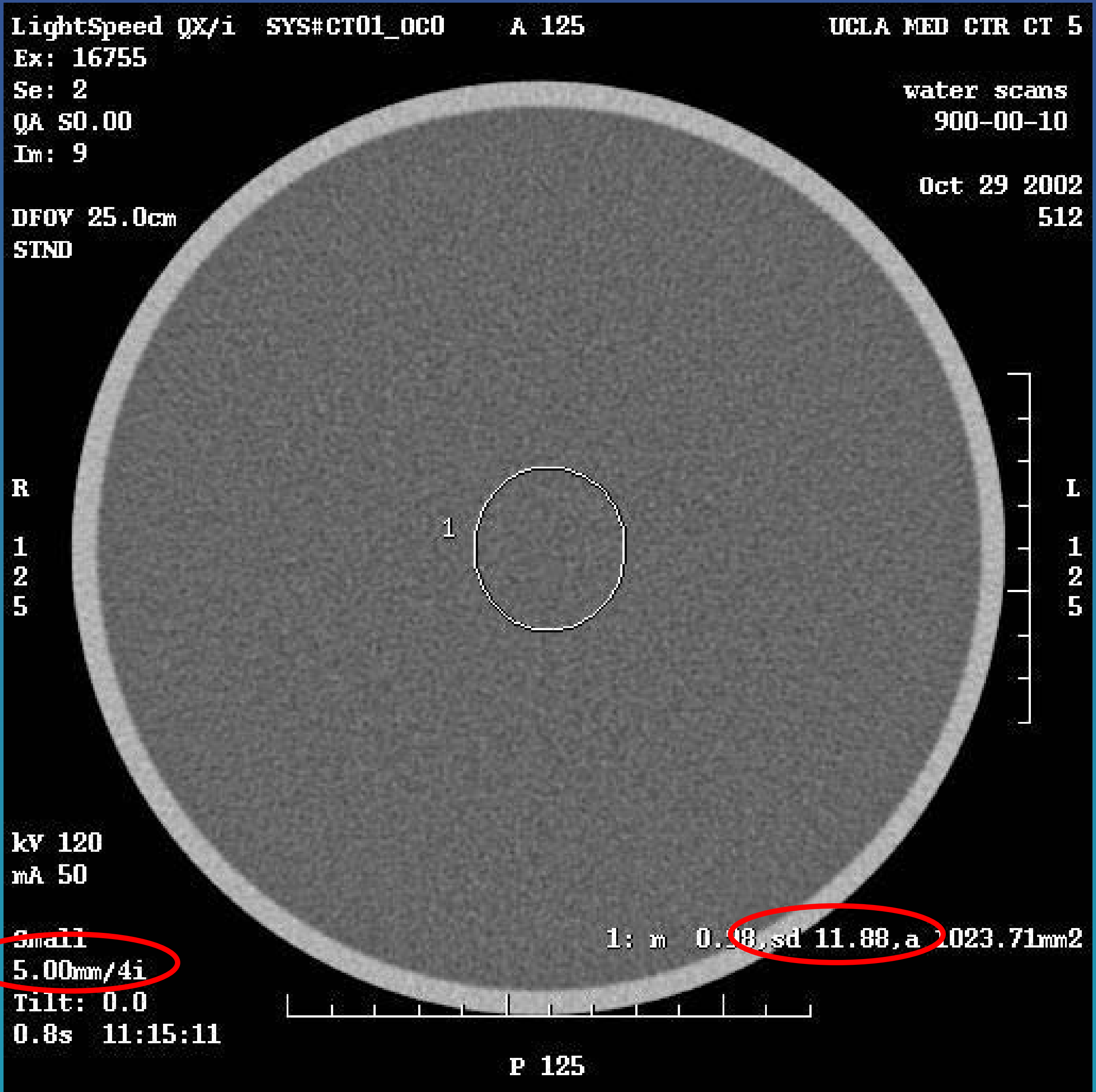
- Reducing image thickness (without making any other adjustments) has same effect on noise as reducing mAs

Reducing mAs Increases Noise

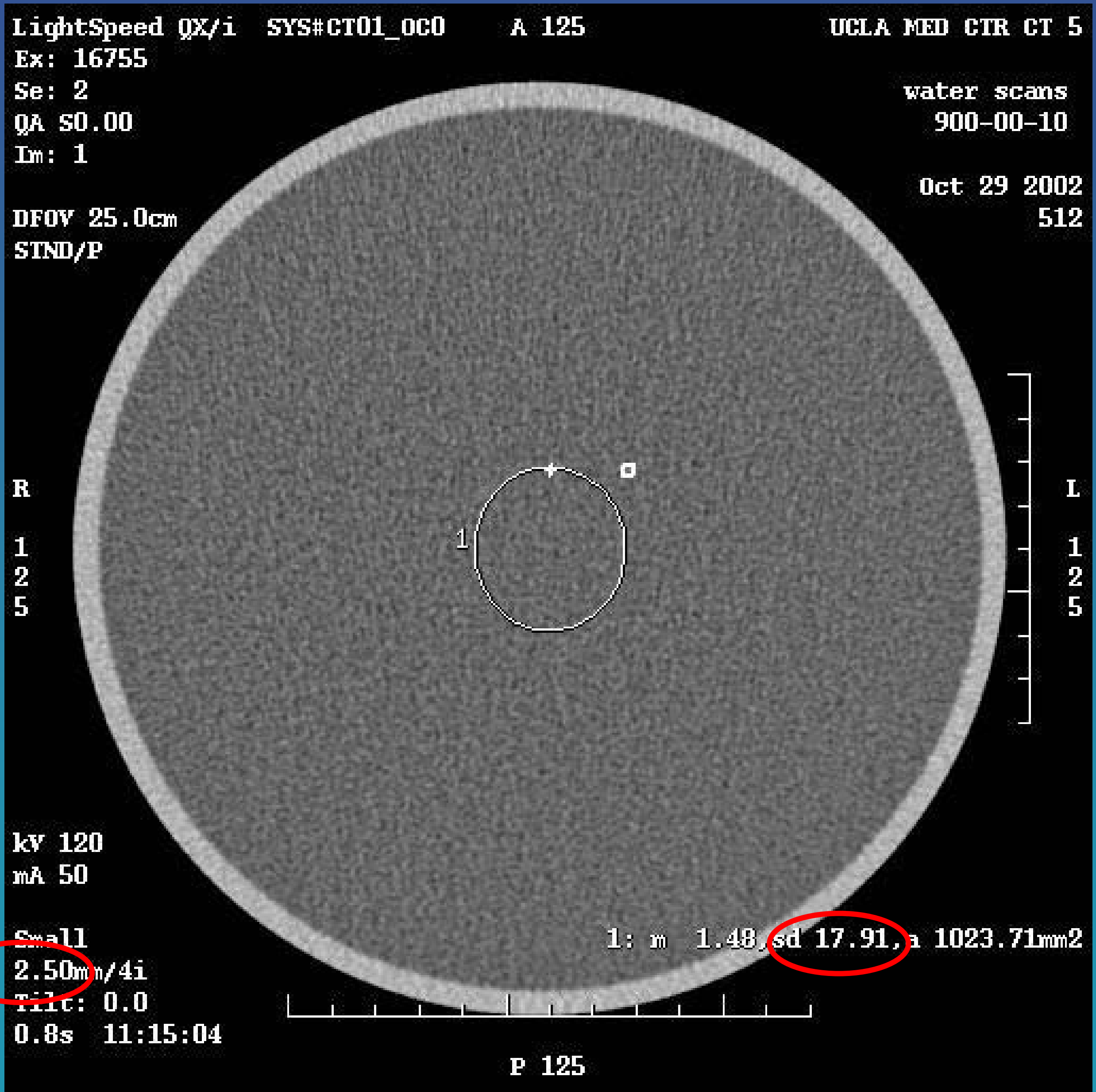
Reducing mAs Increases Noise



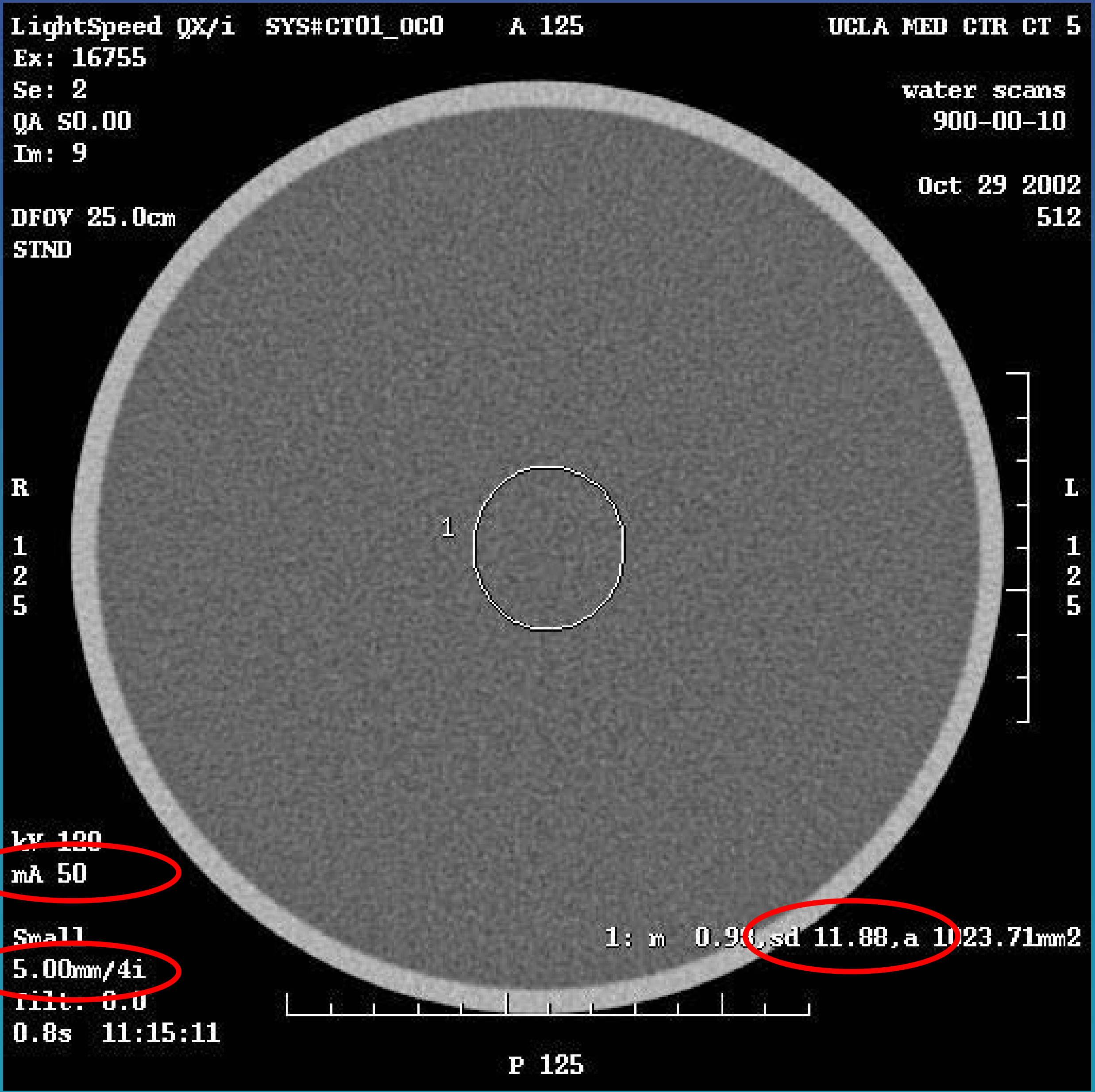
Reducing image Thickness Increases Noise



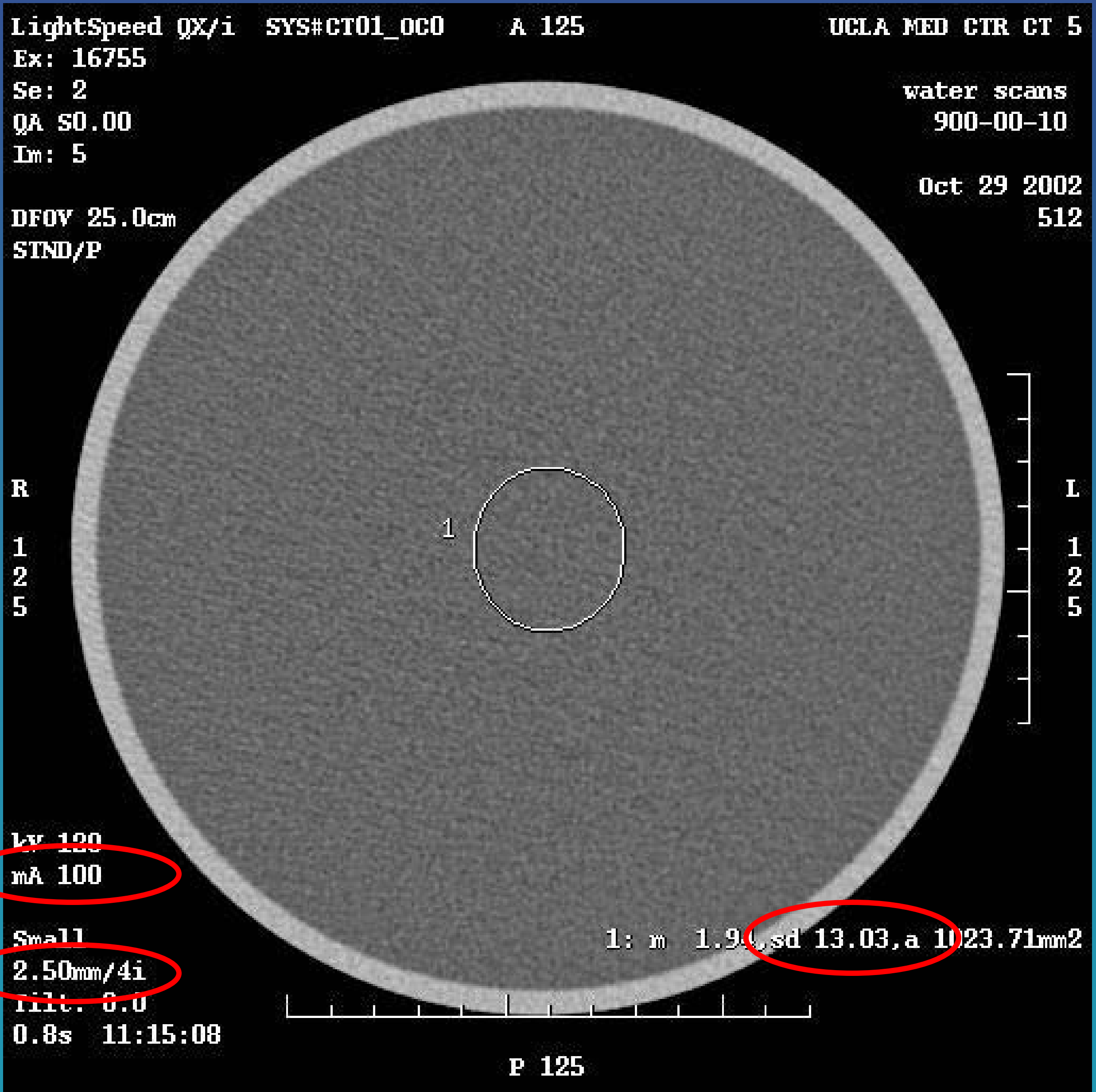
Reducing image Thickness Increases Noise



Increasing mAs to Offset Reduced image Thickness



Increasing mAs to Offset Reduced image Thickness



The radiologist would like to decrease the image thickness for a particular exam from 5mm to 2.5mm and maintain the same image quality. This will require what change in radiation dose?

0%	1.	Radiation dose will have to be doubled (200%)
0%	2.	Radiation dose will have to be tripled (300%)
0%	3.	Radiation dose can stay the same
0%	4.	Radiation dose will have to be decreased by 40%
0%	5.	Radiation dose will not be affected if current modulation is utilized in this case.

The radiologist would like to decrease the image thickness for a particular exam from 5mm to 2.5mm and maintain the same image quality. This will require what change in radiation dose?

0%	1.	Radiation dose will have to be doubled (200%)
0%	2.	
0%	3.	
0%	4.	
0%	5.	

Ref: Anthony, Brinton, Wolbarst. Physics of Radiology (2nd Edition). Medical PhysicsPublishing, Madison, WI, 2005, p.413

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High Contrast (Spatial) Resolution

- High contrast or spatial resolution within the scan plane - determined using objects having a large signal to noise ratio.
- This test measures the system’s ability to resolve high contrast objects of increasingly smaller sizes (increasing spatial frequencies).
- Several quantitative methods have been described
  - E.g. MTF using a thin wire

High Contrast (Spatial) Resolution

- High contrast spatial resolution is influenced by factors including:
  - System geometric resolution limits
    - focal spot size
    - detector width
    - ray sampling,
  - Pixel size
  - Properties of the convolution kernel /mathematical reconstruction filter


LightSpeed QX/i SYS#CT01_OC0 A 125 UCLA MED CTR CT 5
Ex: 23873
Se: 3
QA S2.50
Im: 3
TEST IMAGES
9000010
Aug 06 2003
512
DFOV 25.0cm
STND
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mA 260
Small
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Tilt: 0.0
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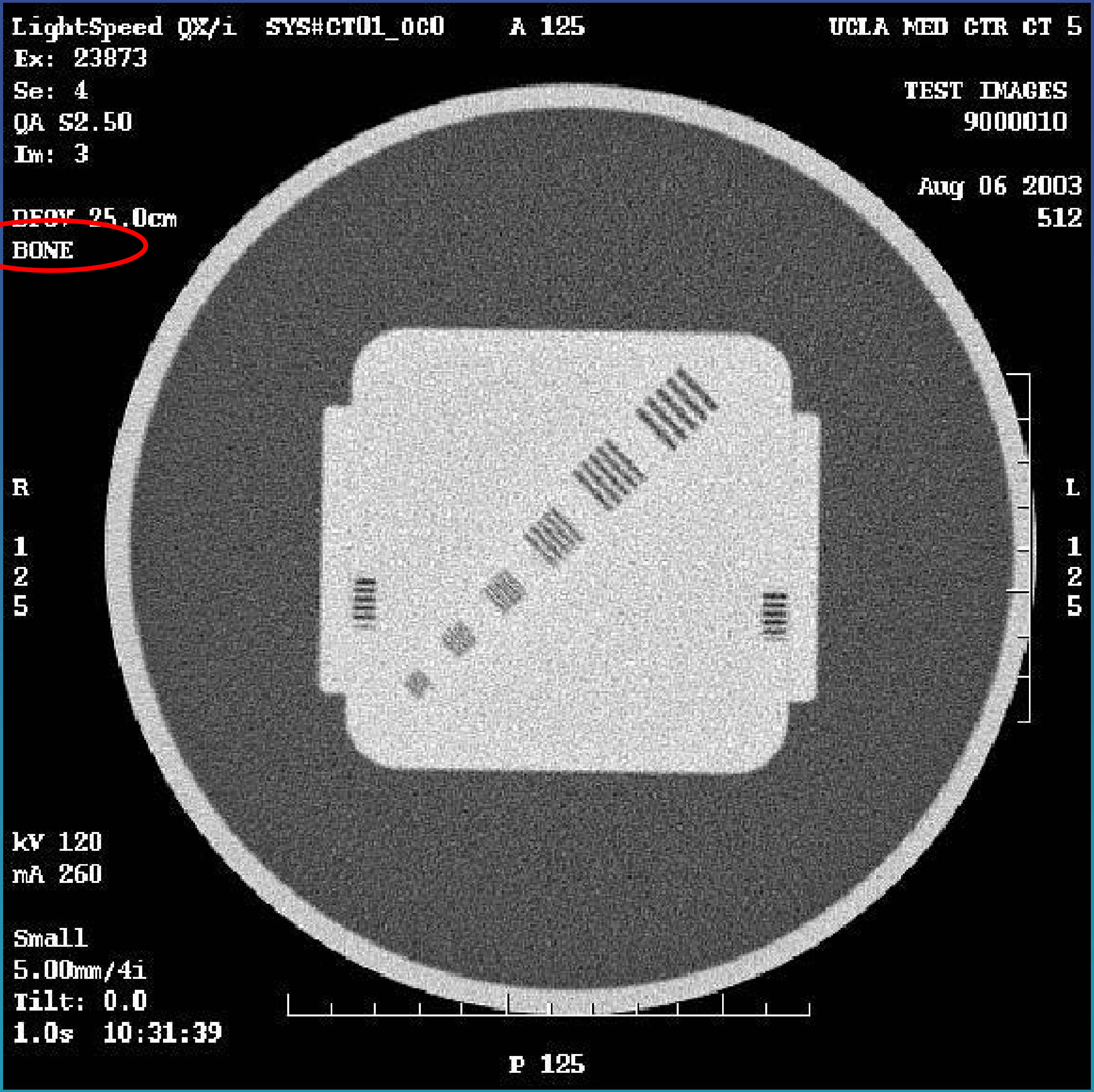
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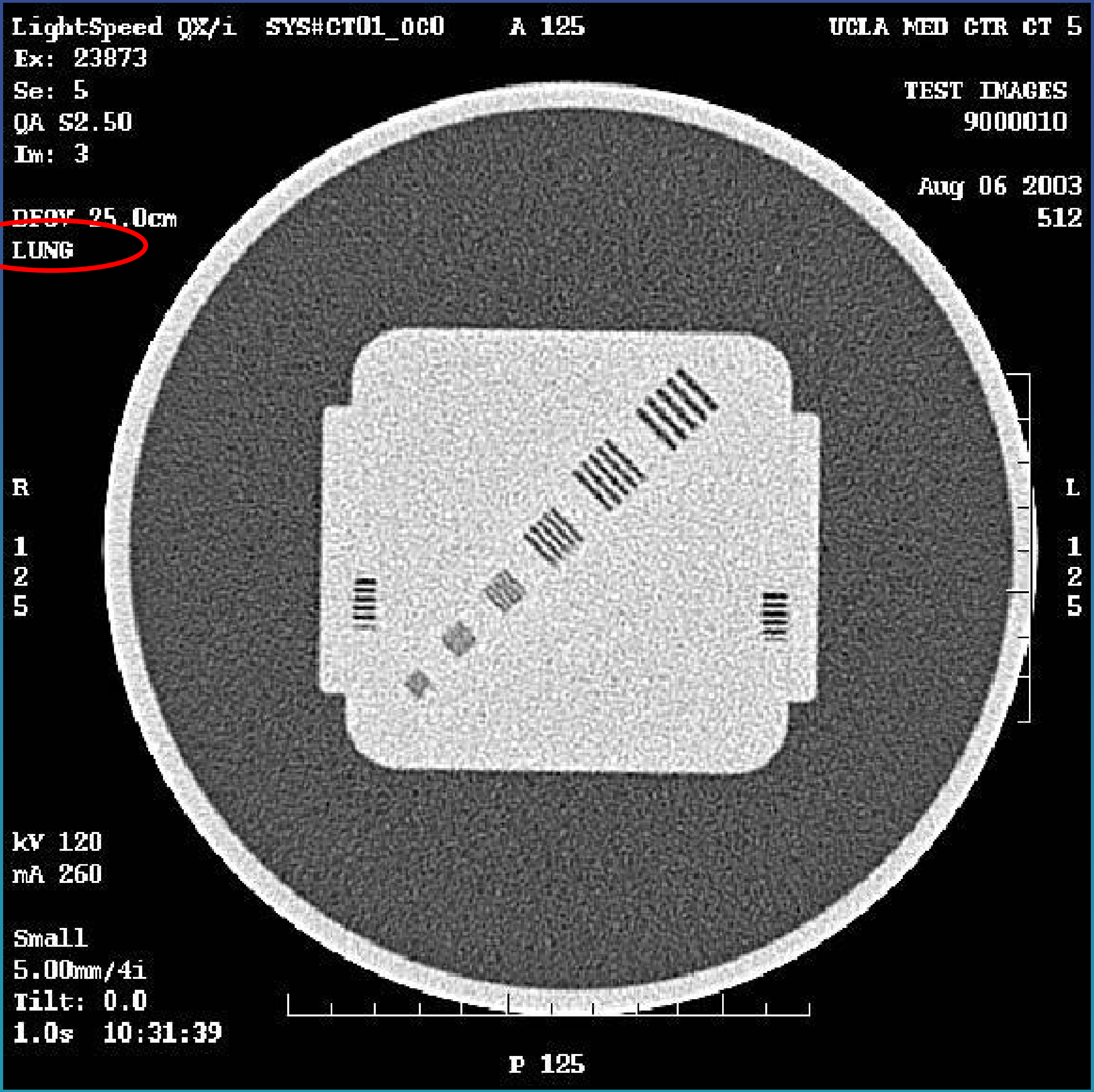
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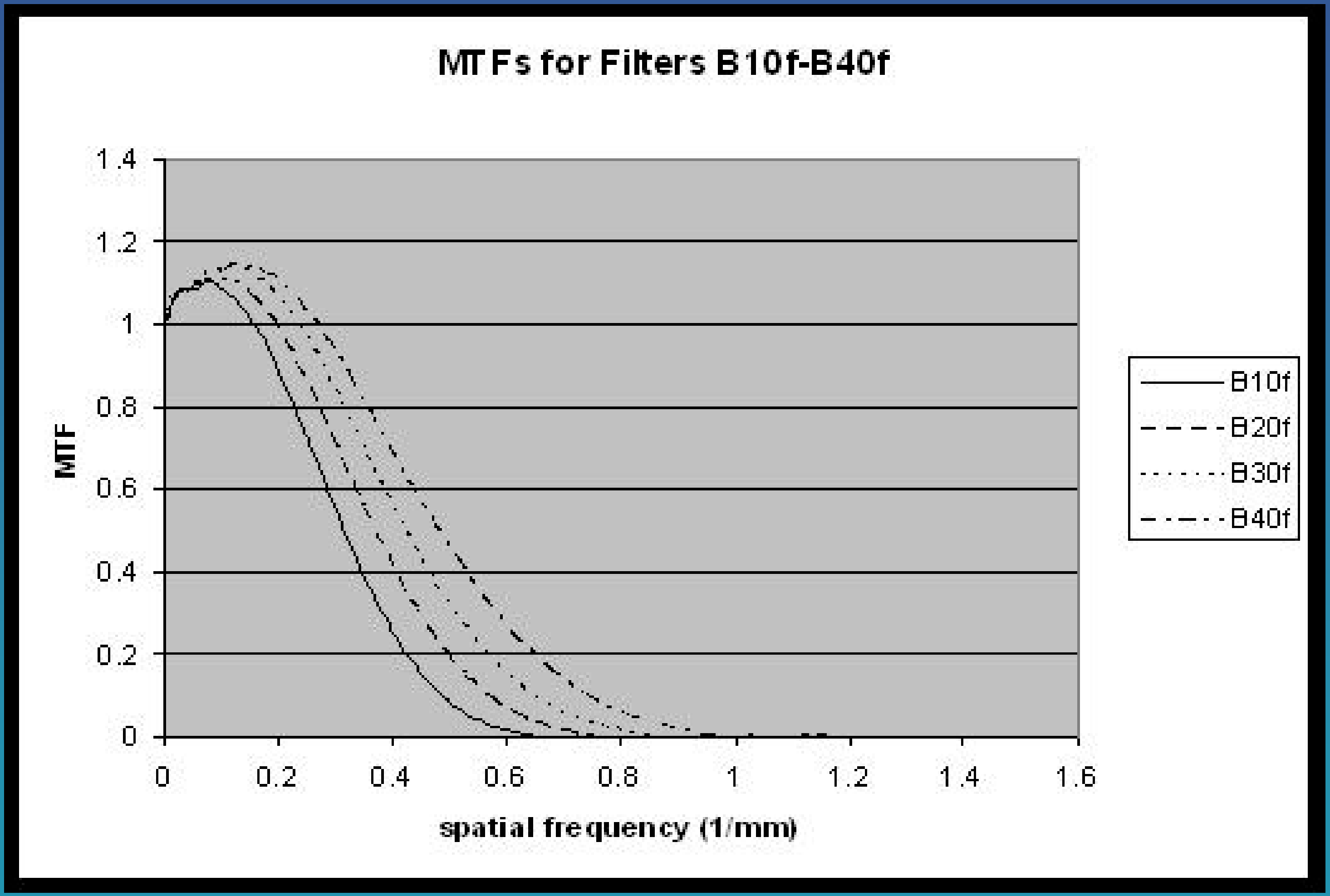
Effect of Reconstruction Filter

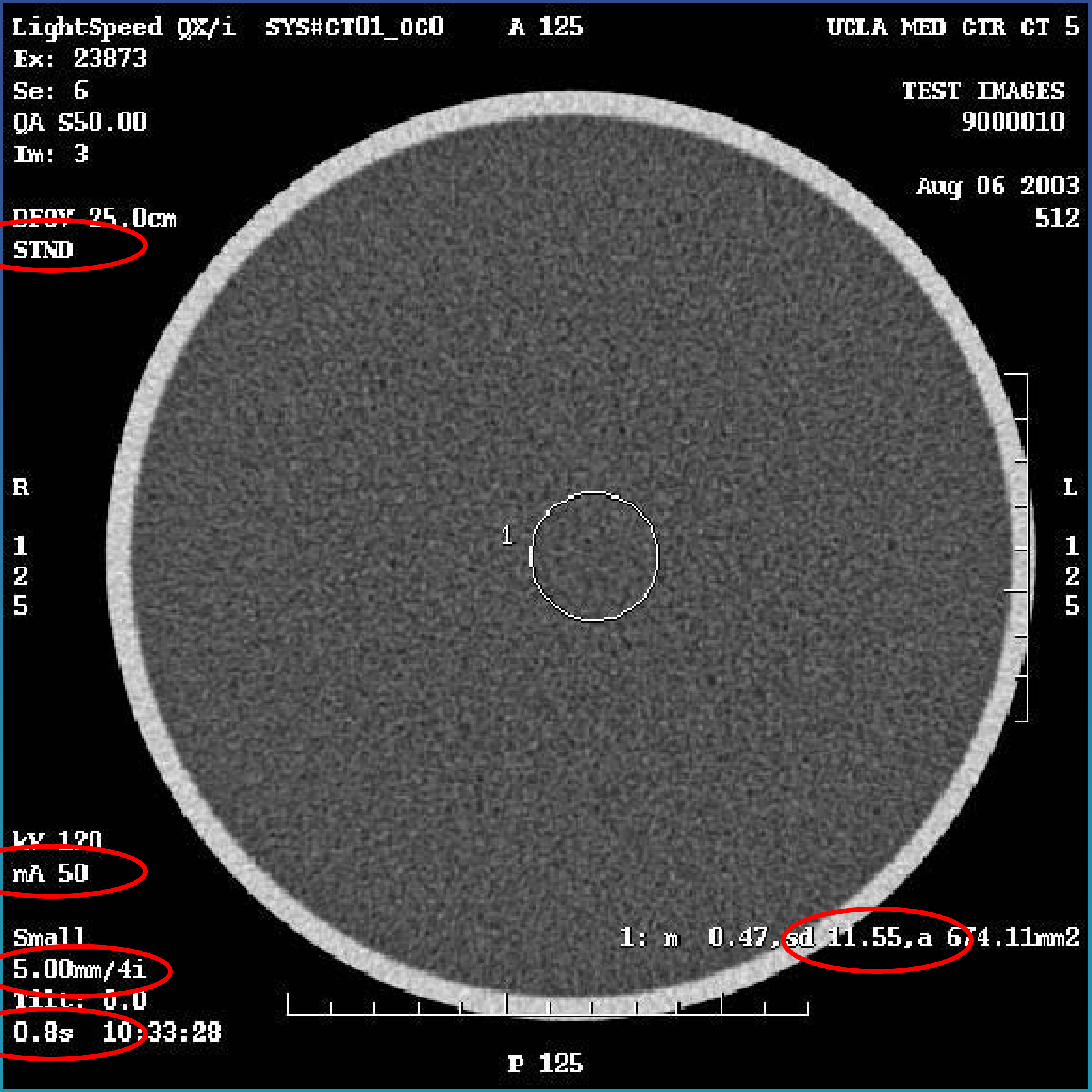


High Contrast (Spatial) Resolution

- However, increasing x-y plane resolution by via reconstruction algorithm can result in a TRADEOFF with a nominal increase (certainly a change) in noise
  - Increase in x-y plane resolution vs. Change in Noise

Noise – Part 2

- Standard deviation does not tell the whole story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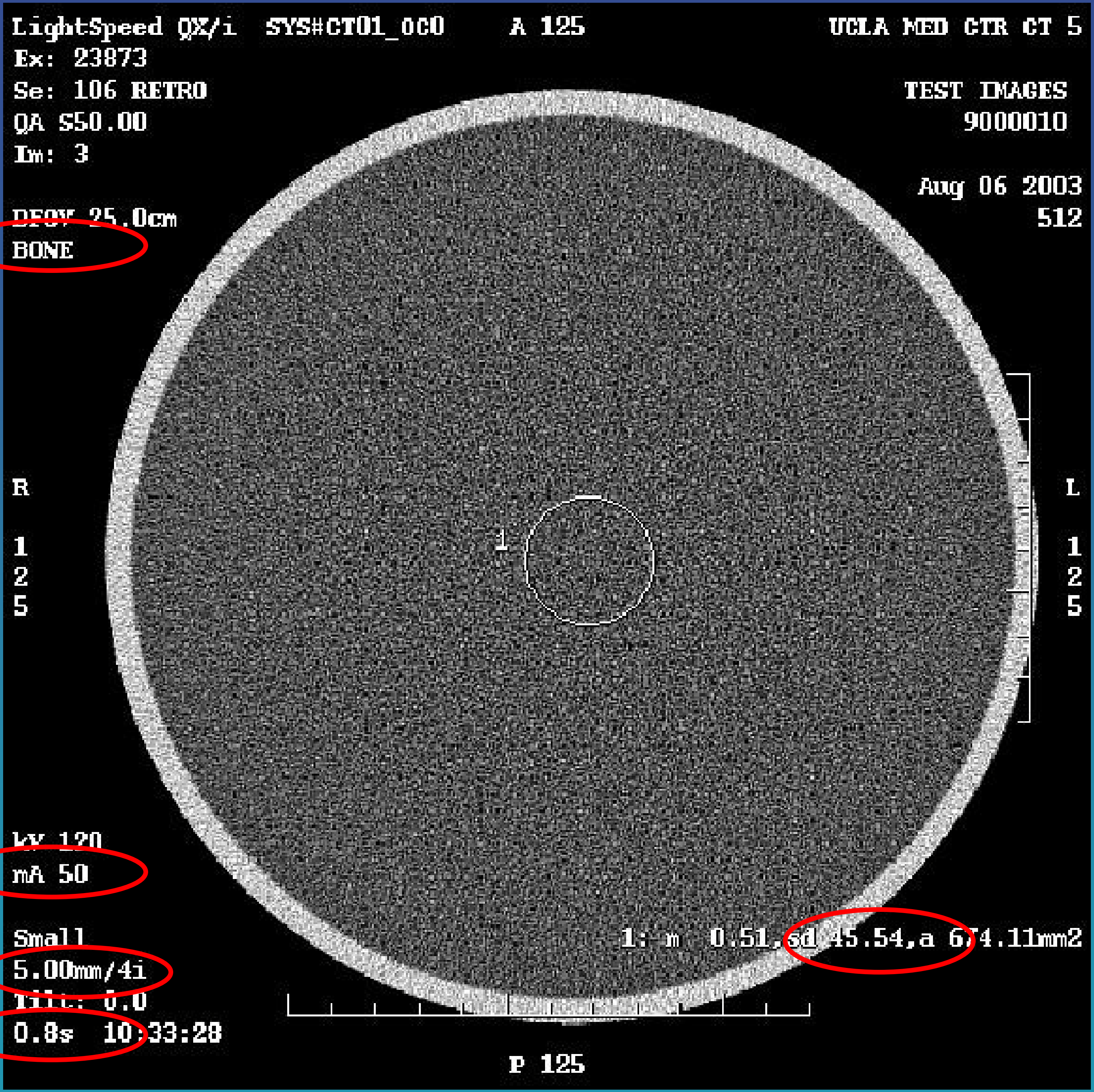
1: m 0.47, sd 11.55, a 674.11mm2
P 125



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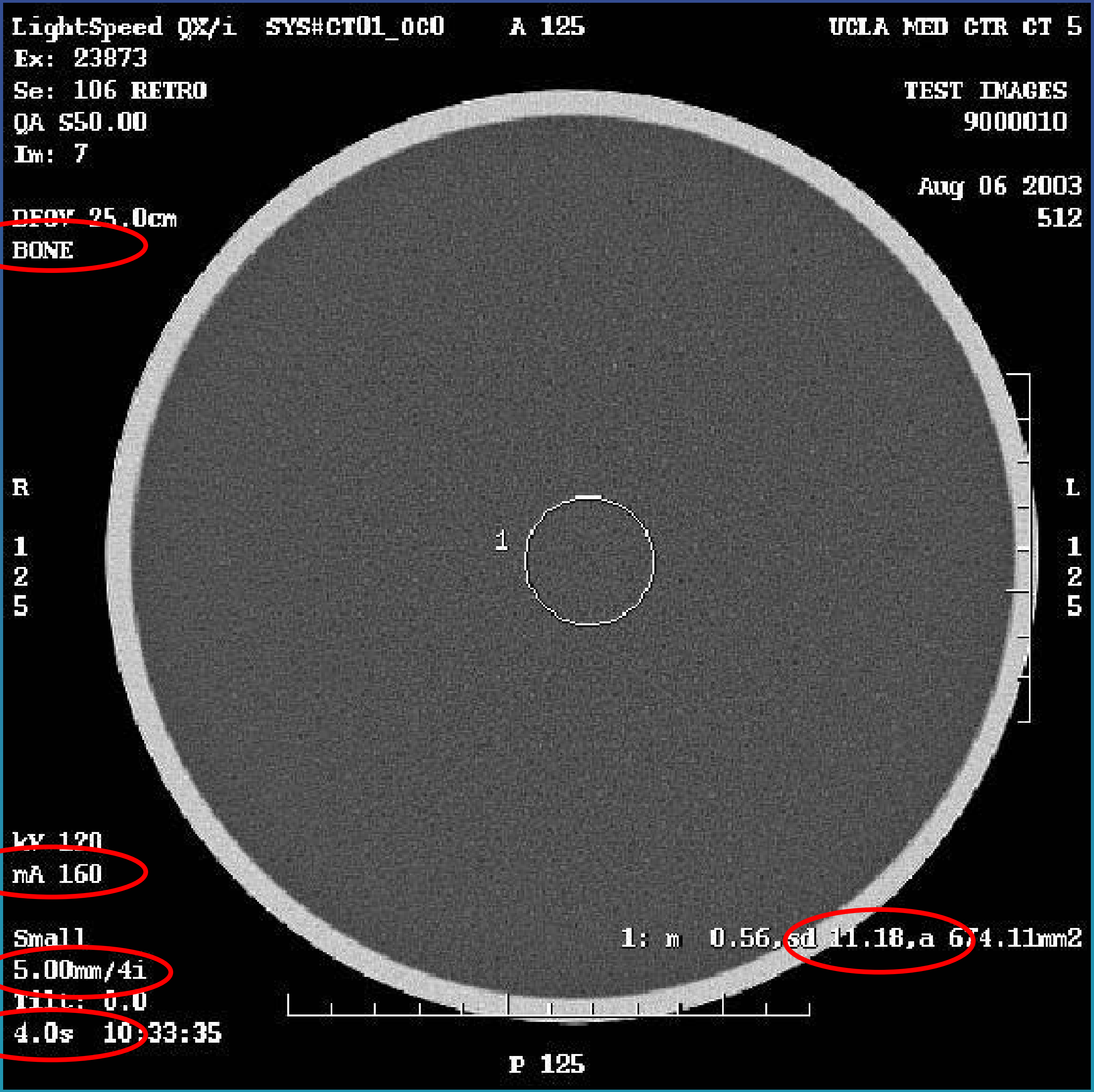
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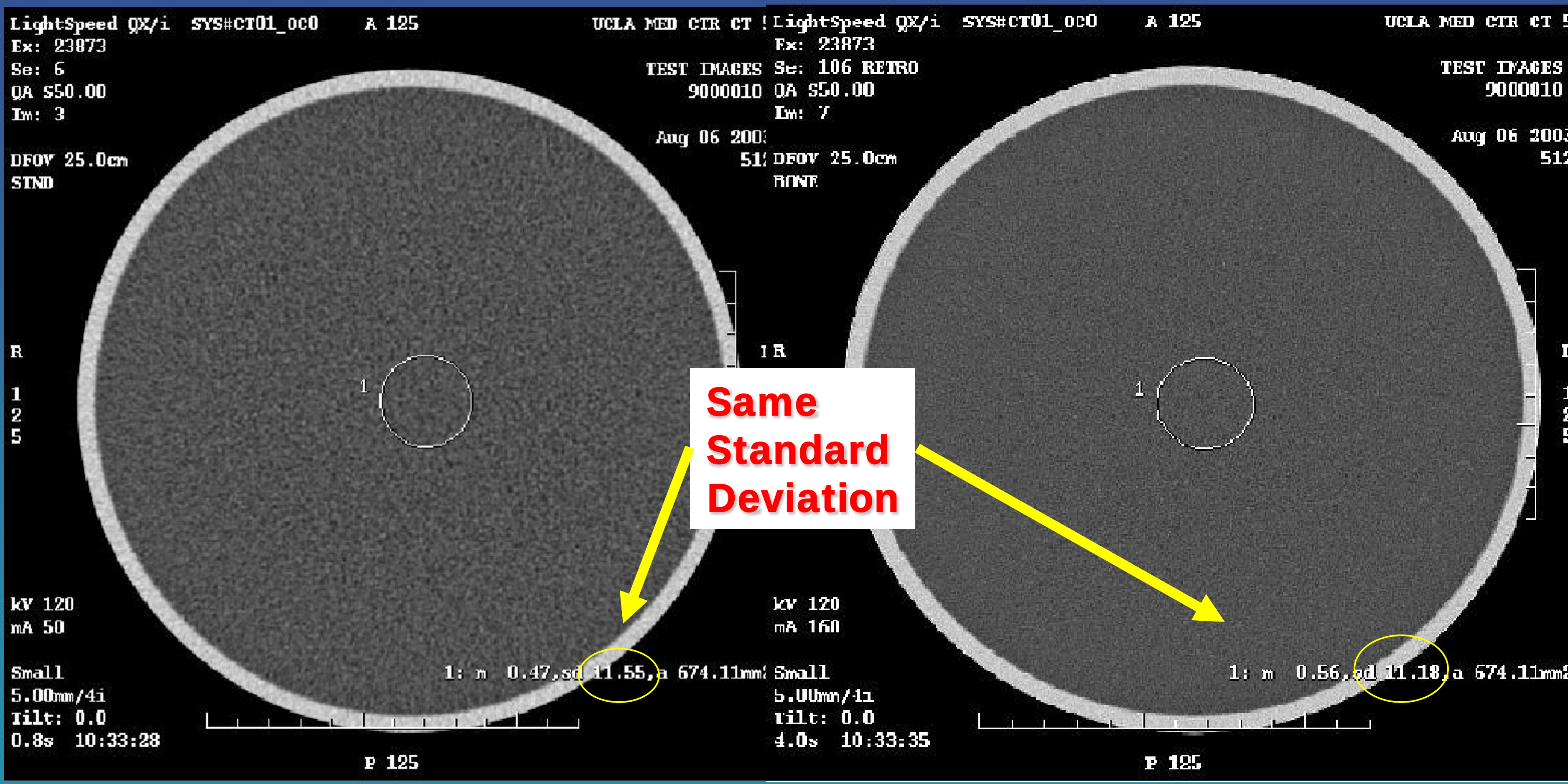
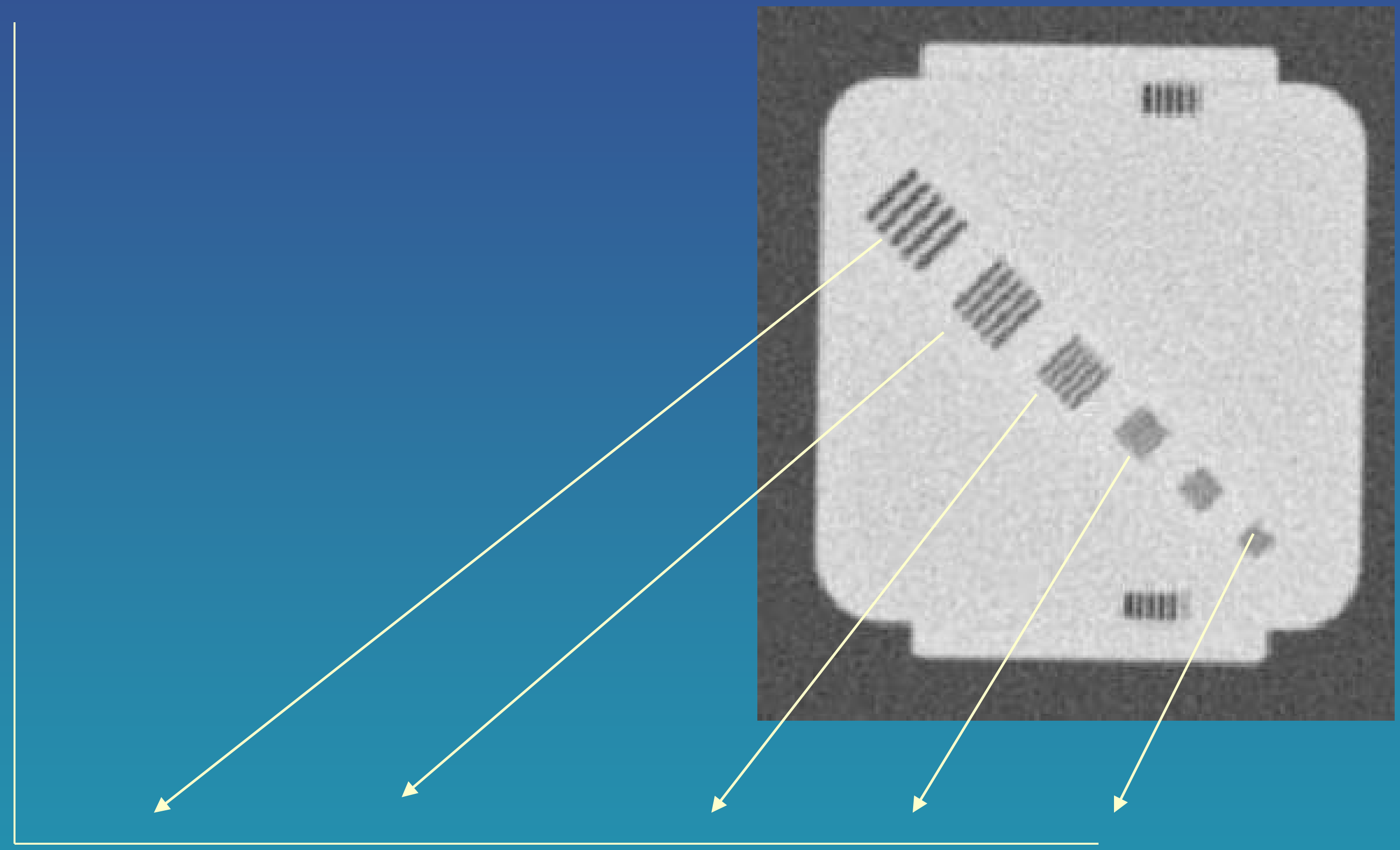


120 kVp, 40mAs, Standard

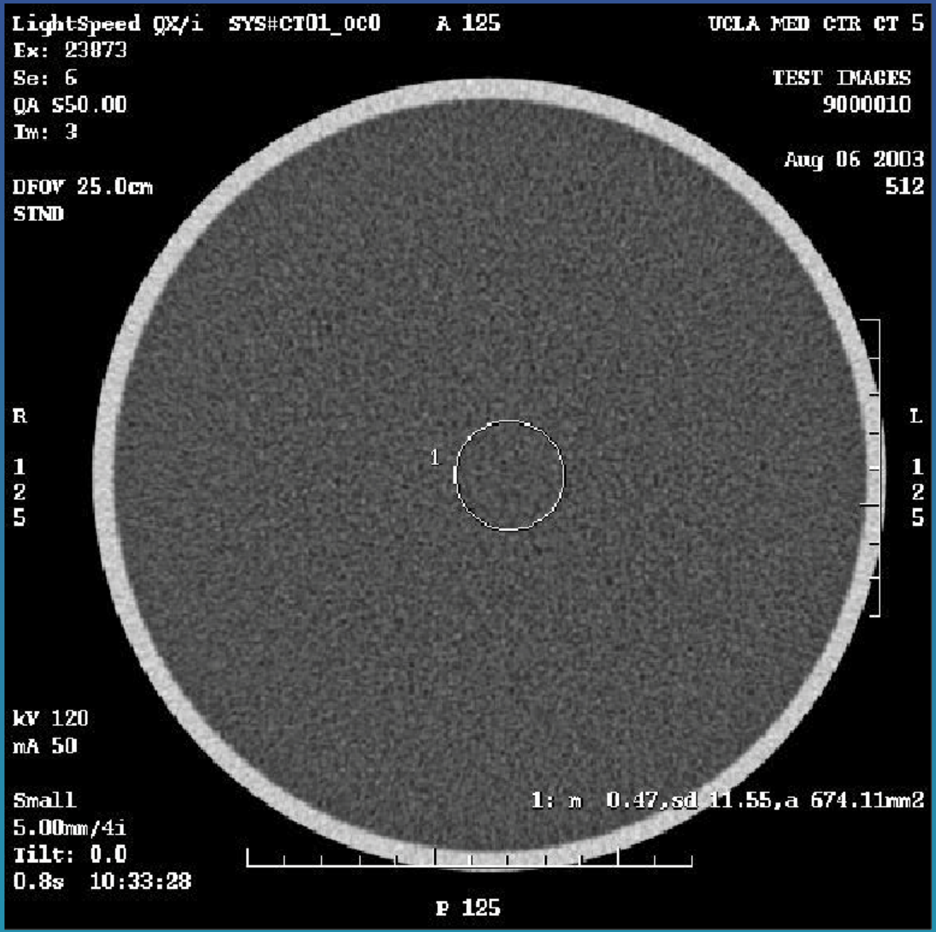
120 kVp, 640 mAs, Bone

Spatial Frequency



Low spatial frequencies – large objects

High spatial frequencies – small objects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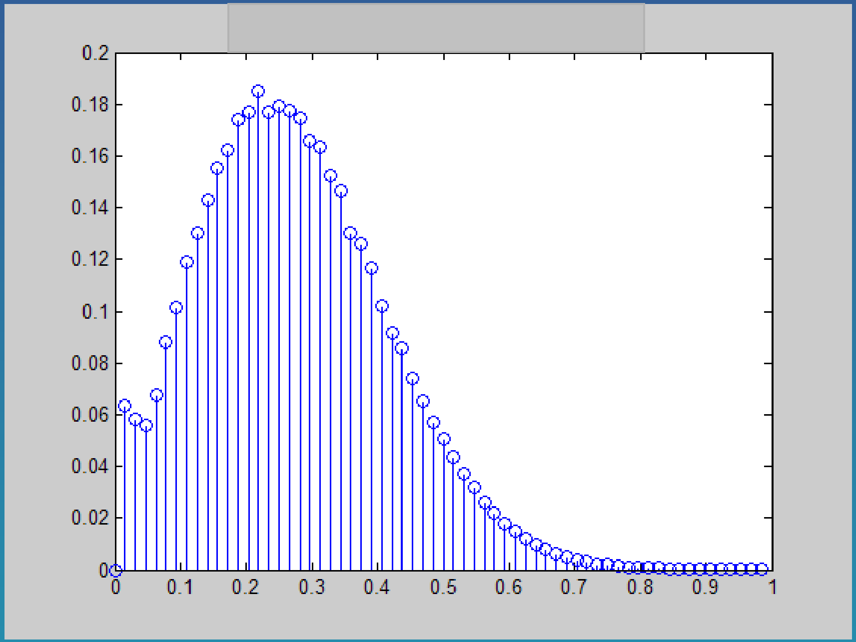
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LightSpeed QX/i SYS#CT01_OC0 A 125 UCLA MED CTR CT 5
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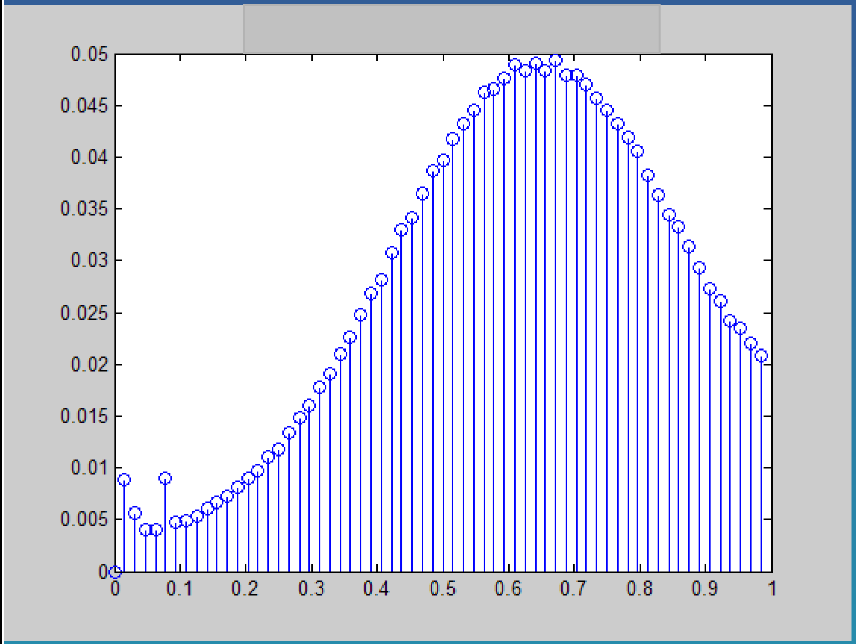
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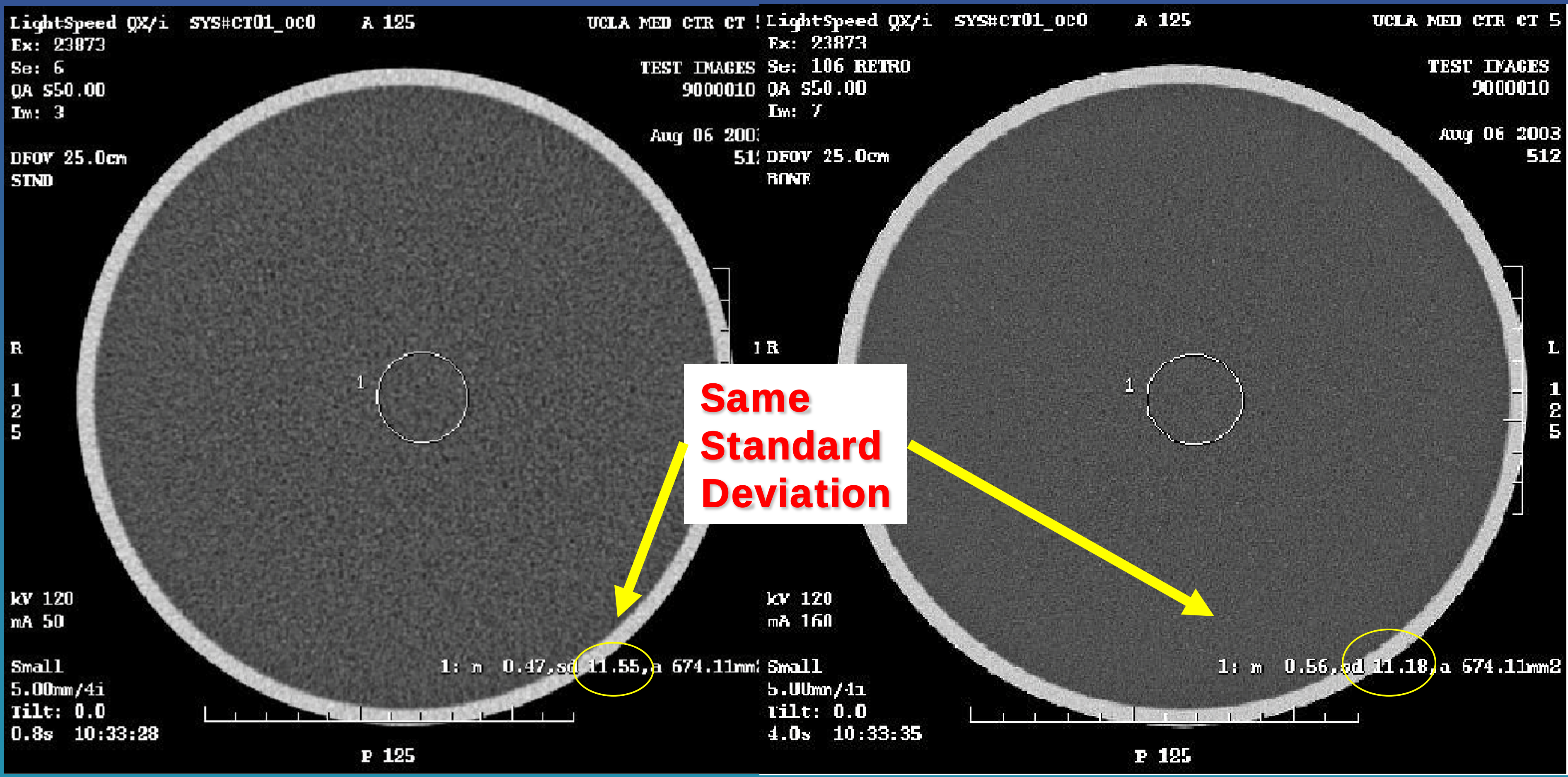
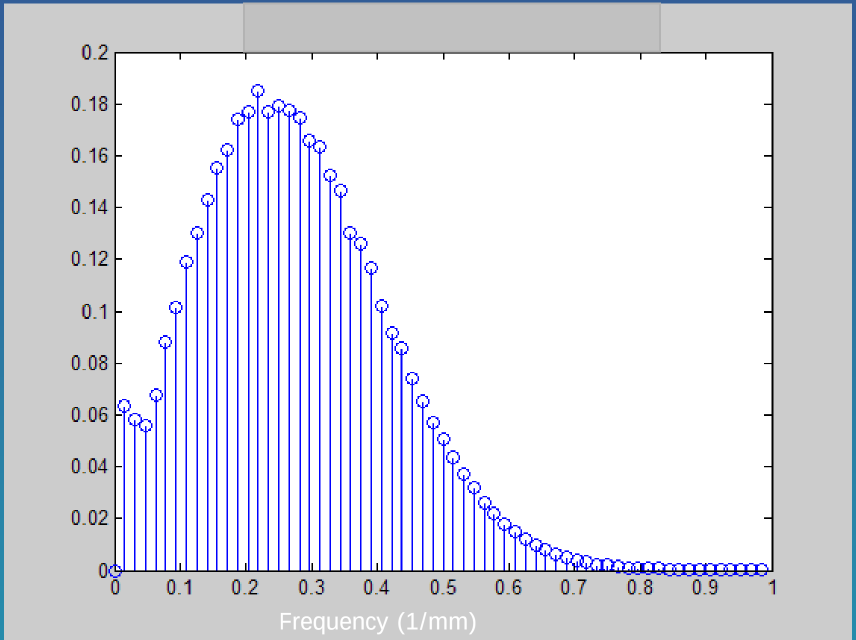
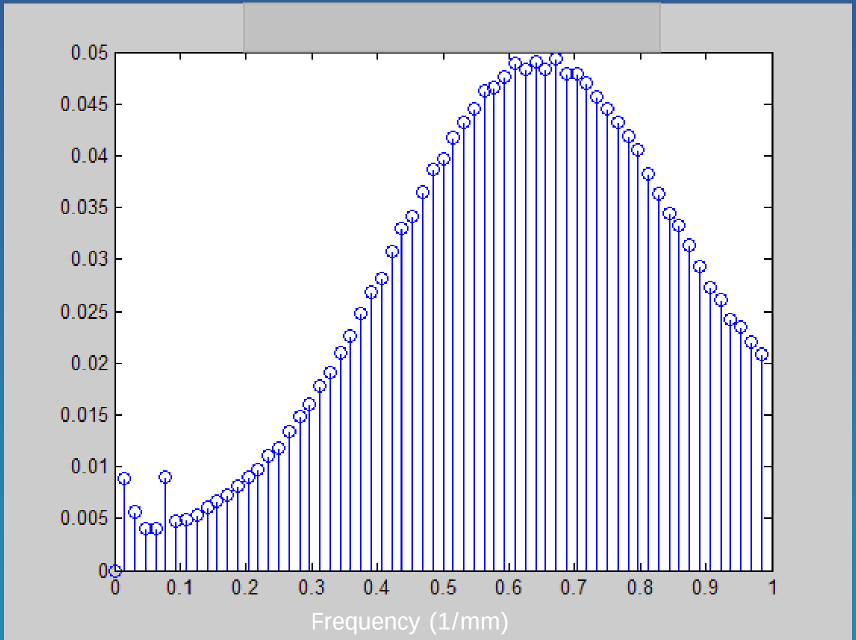


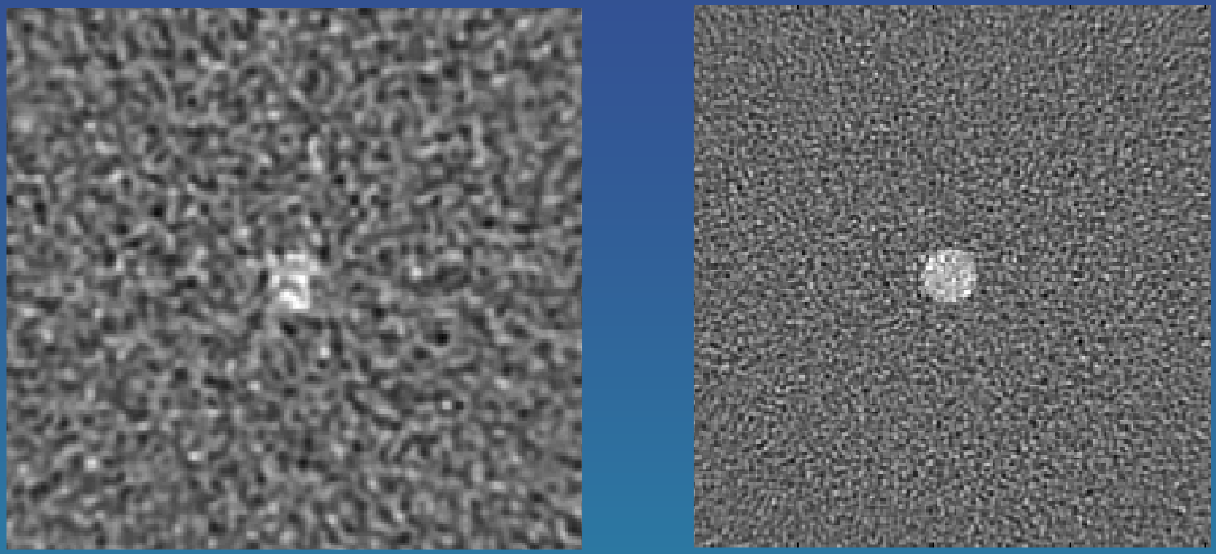
120 kVp, 40mAs, Standard

120 kVp, 640 mAs, Bone

Noise Power Spectrum







Simulated 2 mm image of a sphere 55 HU from background. The standard deviation of noise in both images is 21.5 HU. Part (a) was reconstructed with filter B10. Part (b) was reconstructed with filter B50.

Boedeker and McNitt-Gray PMB **52** 2007

Low Contrast Resolution

- Low contrast resolution is often determined using objects having a very small difference from background (typically from 4-10 HU difference).
-
- Because the signal (the difference between object and background) is so small, noise is a significant factor in this test.

Low Contrast Resolution

- This test measures the system’s ability to resolve low contrast objects of increasingly smaller sizes (increasing spatial frequencies).

- Influenced by many of the same parameters as noise

Low Contrast Resolution

- An example of a low contrast resolution phantom is that in used by the ACR CT Accreditation program.
- This phantom consists of:
  - A single 25mm rod for reference and measurements,
  - Sets of 4 rods, each is decreasing in diameter from:
    - 6mm,
    - 5mm,
    - 4mm
    - 3mm
    - 2mm (typically not visible unless a very, very high technique is used).
  - All approximately 6 HU from background

ACR Phantom Low Contrast Resolution

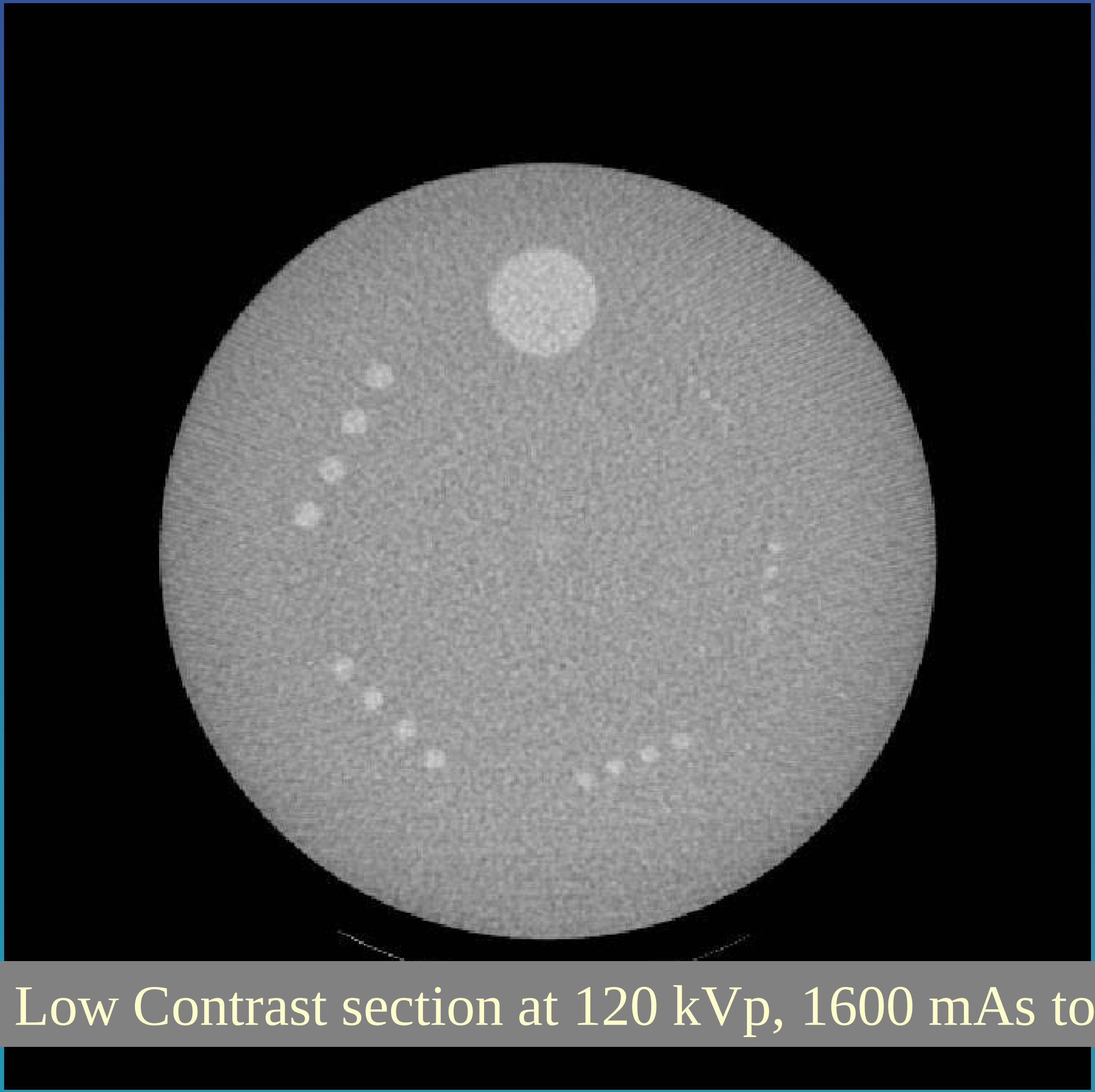
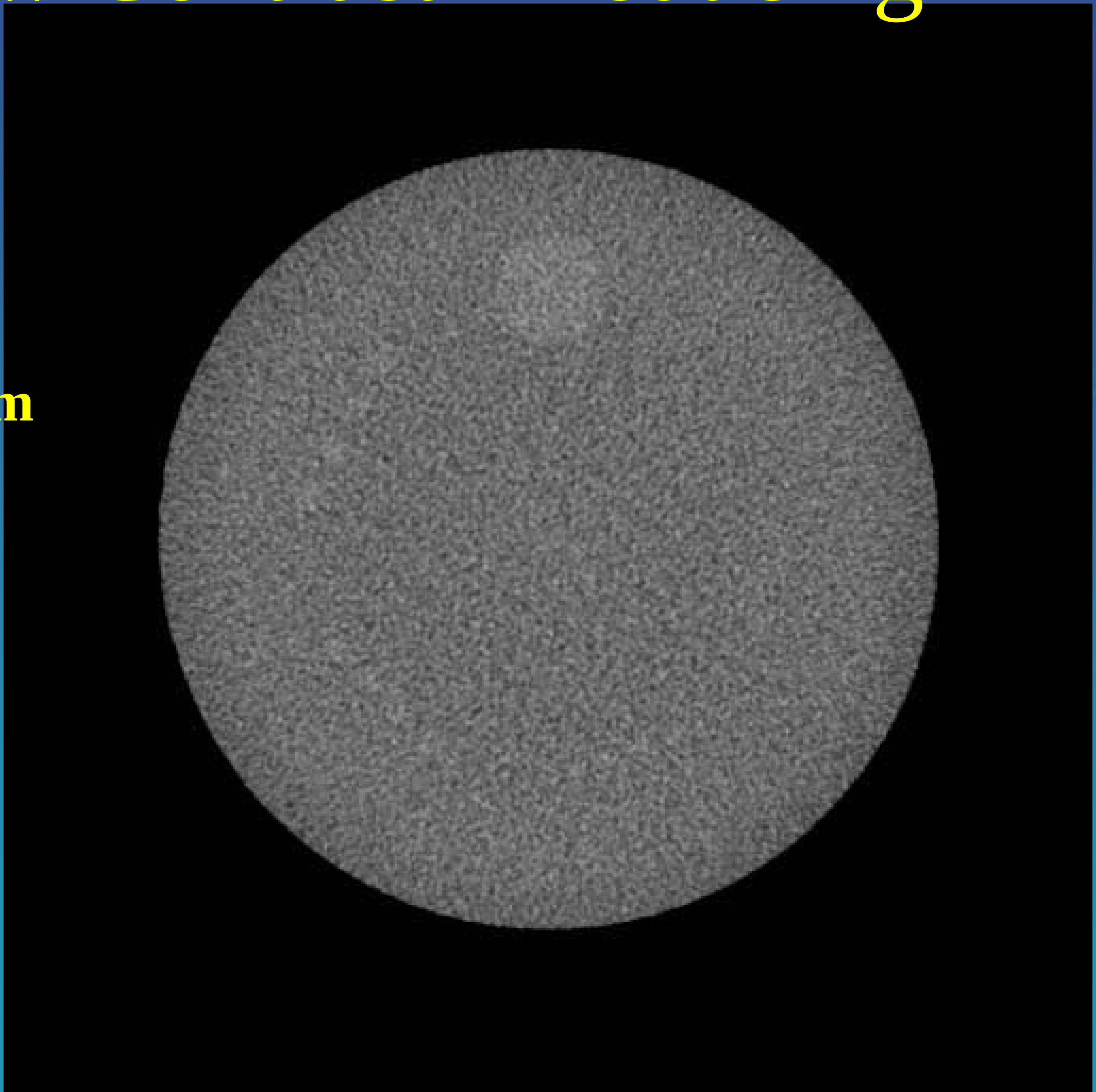


Image of Low Contrast section at 120 kVp, 1600 mAs to show all rods;

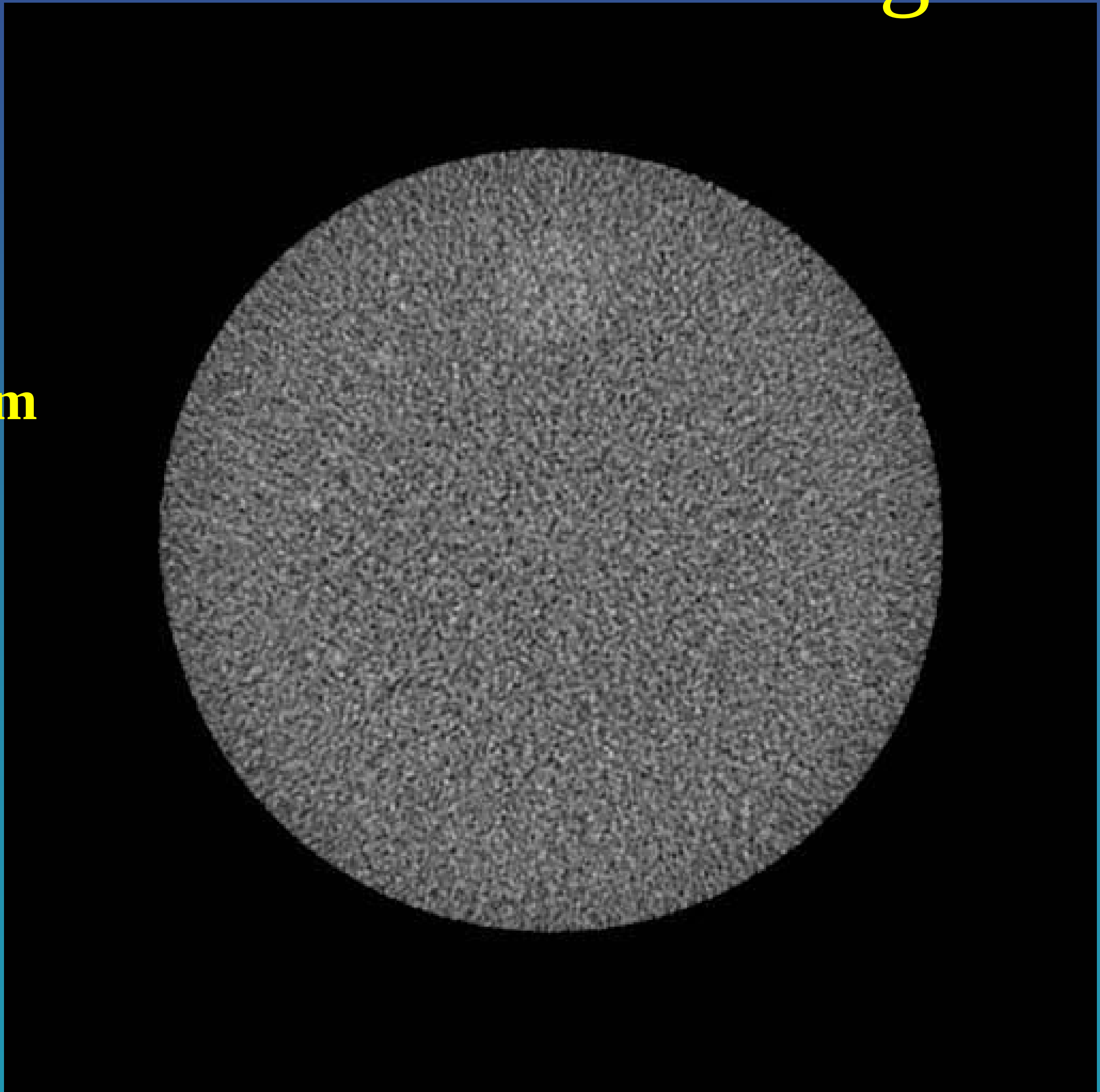
Low Contrast - Reducing mAs

120 kVp
240 mAs
5 mm
Std Algorithm



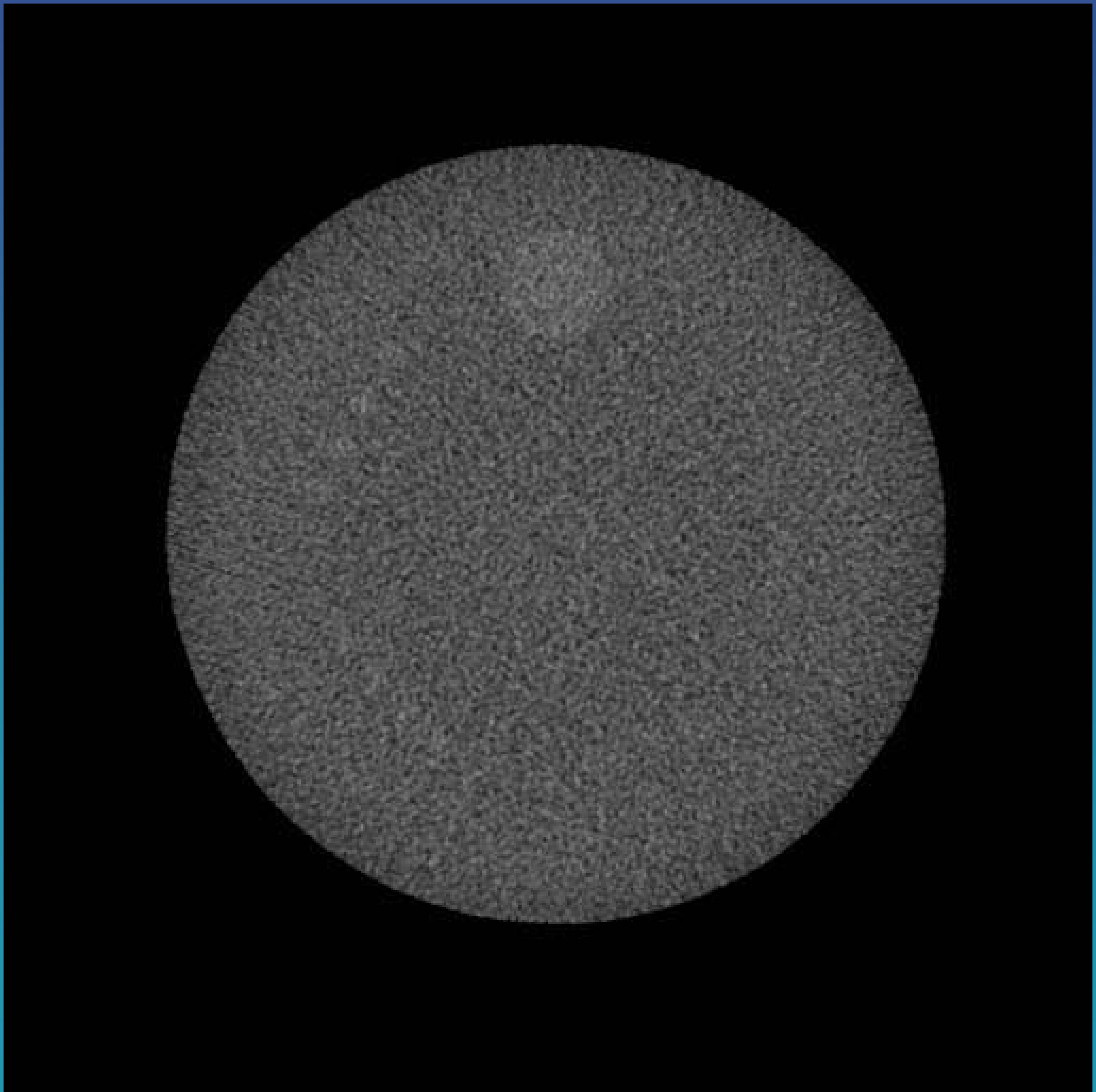
Low Contrast - Reducing mAs

120 kVp
80 mAs
5 mm
Std Algorithm



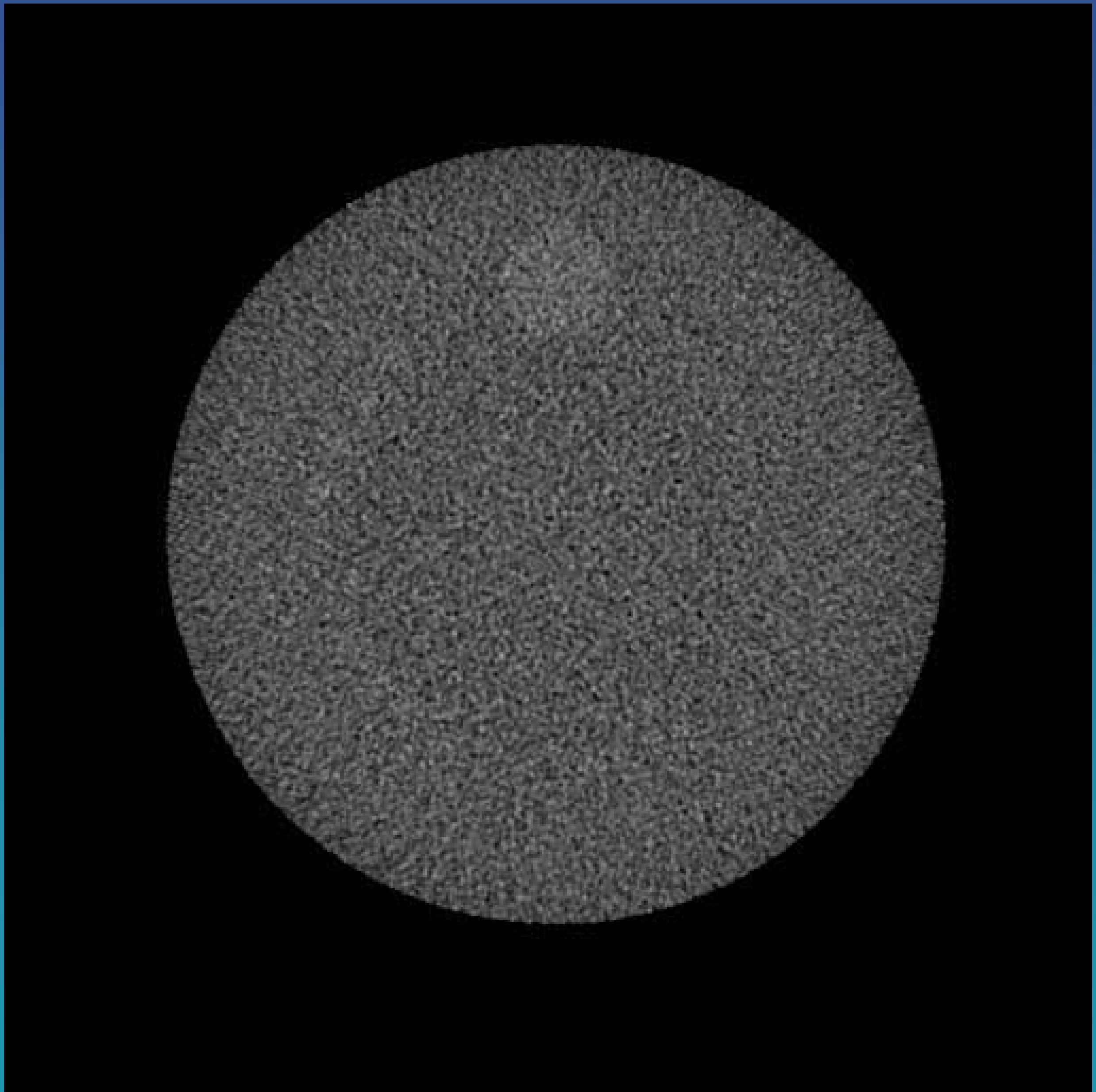
Low Contrast – Thinner images

120 kVp
240 mAs
5 mm
Std Algorithm



Low Contrast – Thinner images

120 kVp
240 mAs
2.5 mm
Std Algorithm



Impact for Clinical Images

- Some simulated lower dose exposures

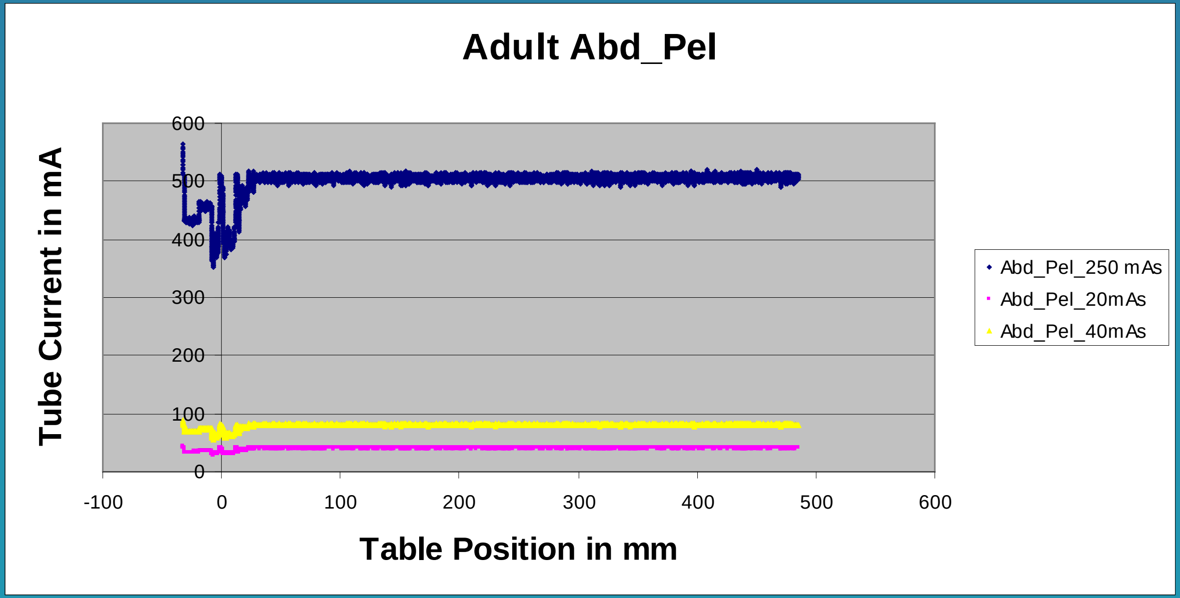
Subject 1

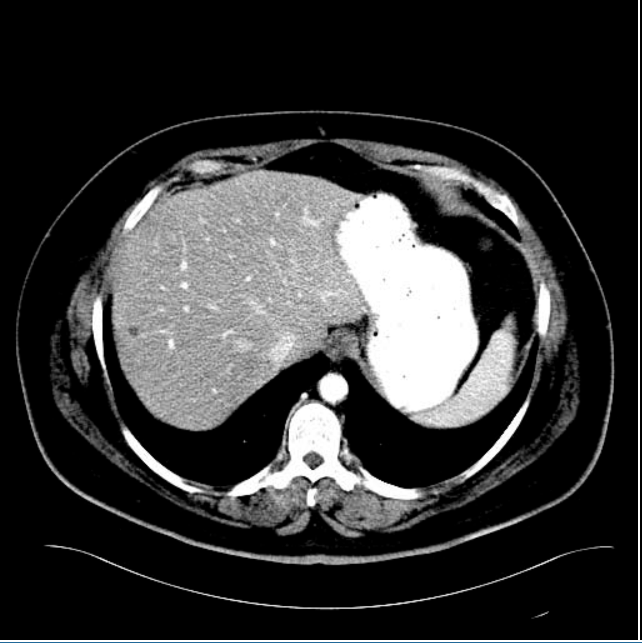
- Adult Abdomen Pelvis
- Constant Tube Current

250 eff. mAs
Std dev = 18.3

40 eff. mAs
Std dev = 42.2

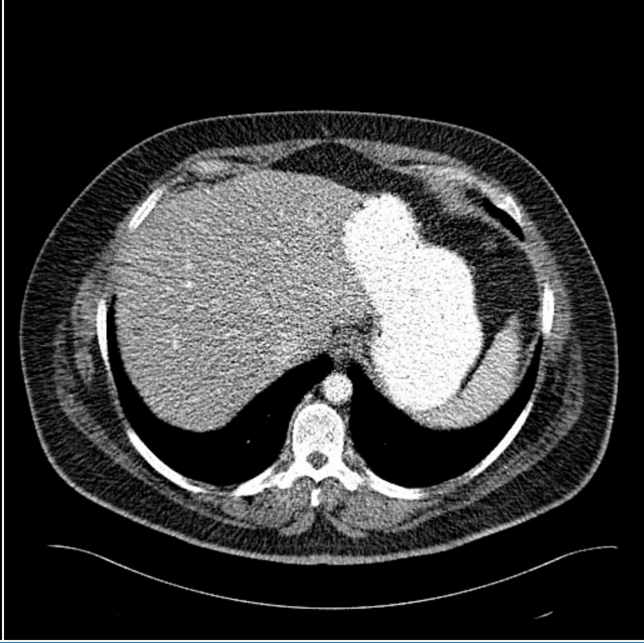
20 eff. mAs
Std dev = 60.0





250 eff. mAs

40 eff. mAs

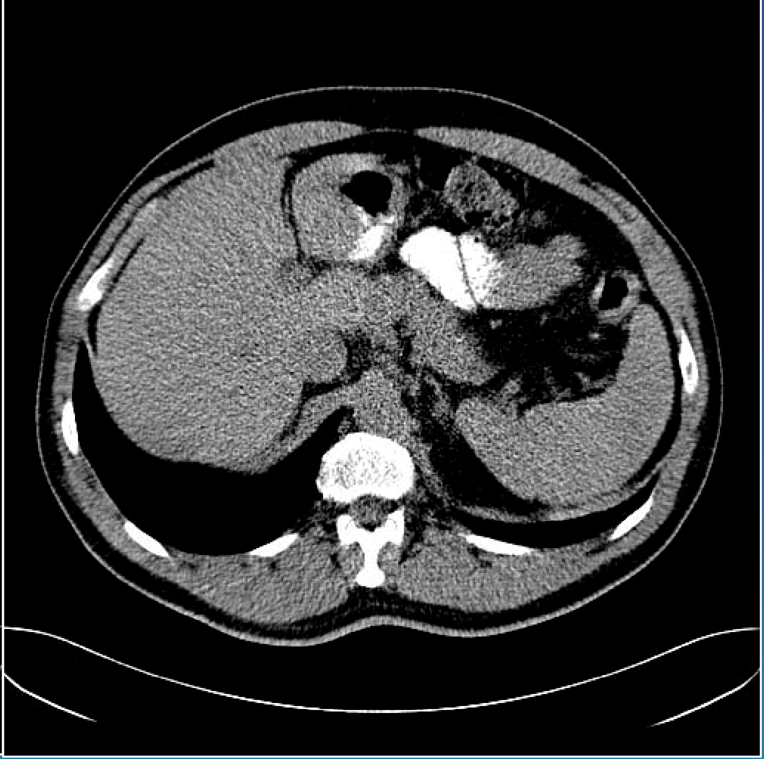


20 eff. mAs

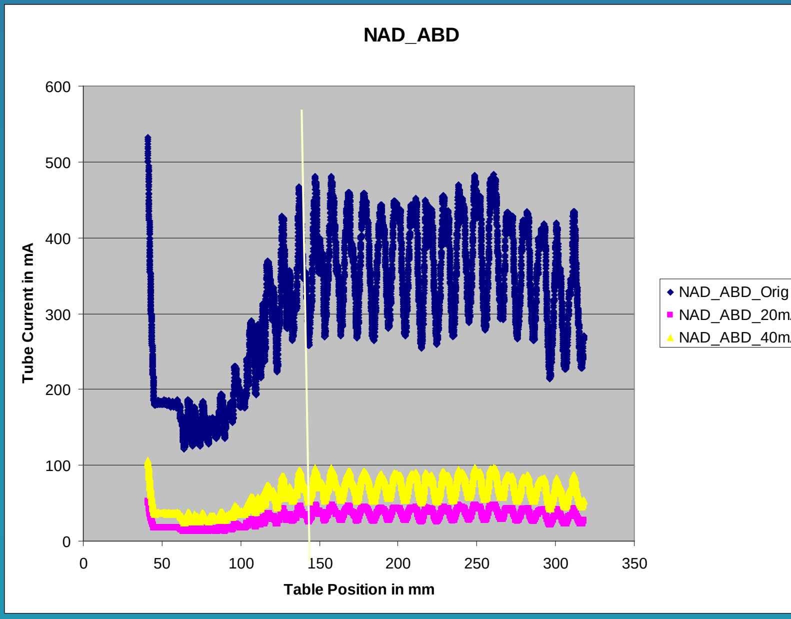
Subject 2

- Adult Abdomen
- Tube Current Modulation (CareDose4D)

250 eff mAs

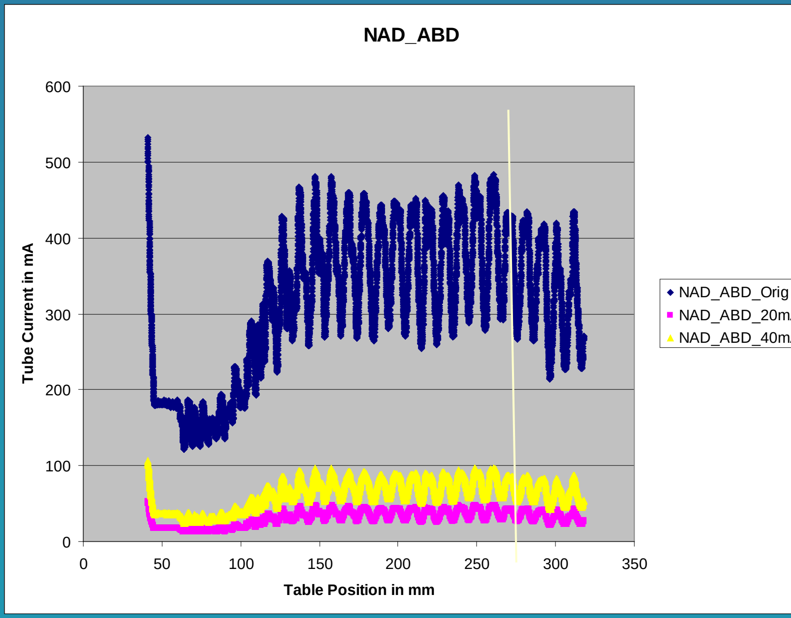


20 eff. mAs



250 eff mAs

20 eff. mAs



Summary

- Noise
  - Affected by many factors, including mAs and image thickness (influences z-axis resolution)
  - Not just standard deviation
    - It has magnitude and frequency content
- Spatial Resolution
  - In plane resolution affected by recon kernel
    - Which also impacts noise (magnitude and frequency content)
  - Z-axis resolution affected by image thickness
    - Which also impacts noise
- Low Contrast Resolution
  - Also affected by many factors, including noise

Current/Future Questions

– Dose Reduction Technologies

– Impacts of tube current modulation on noise

  - Should reduce dose but maintain noise
  - How to assess in the field? How to assess the dose reduction? How to ensure the noise is maintained?

Patient Size

Centers for Disease Control

BRFSS, Behavioral Risk Factor Surveillance System. http://www.cdc.gov/brfss/

Mokdad AH, et al. The spread of the obesity epidemic in the United States, 1991—1998 *JAMA* 1999; 282:16:1519–1522.

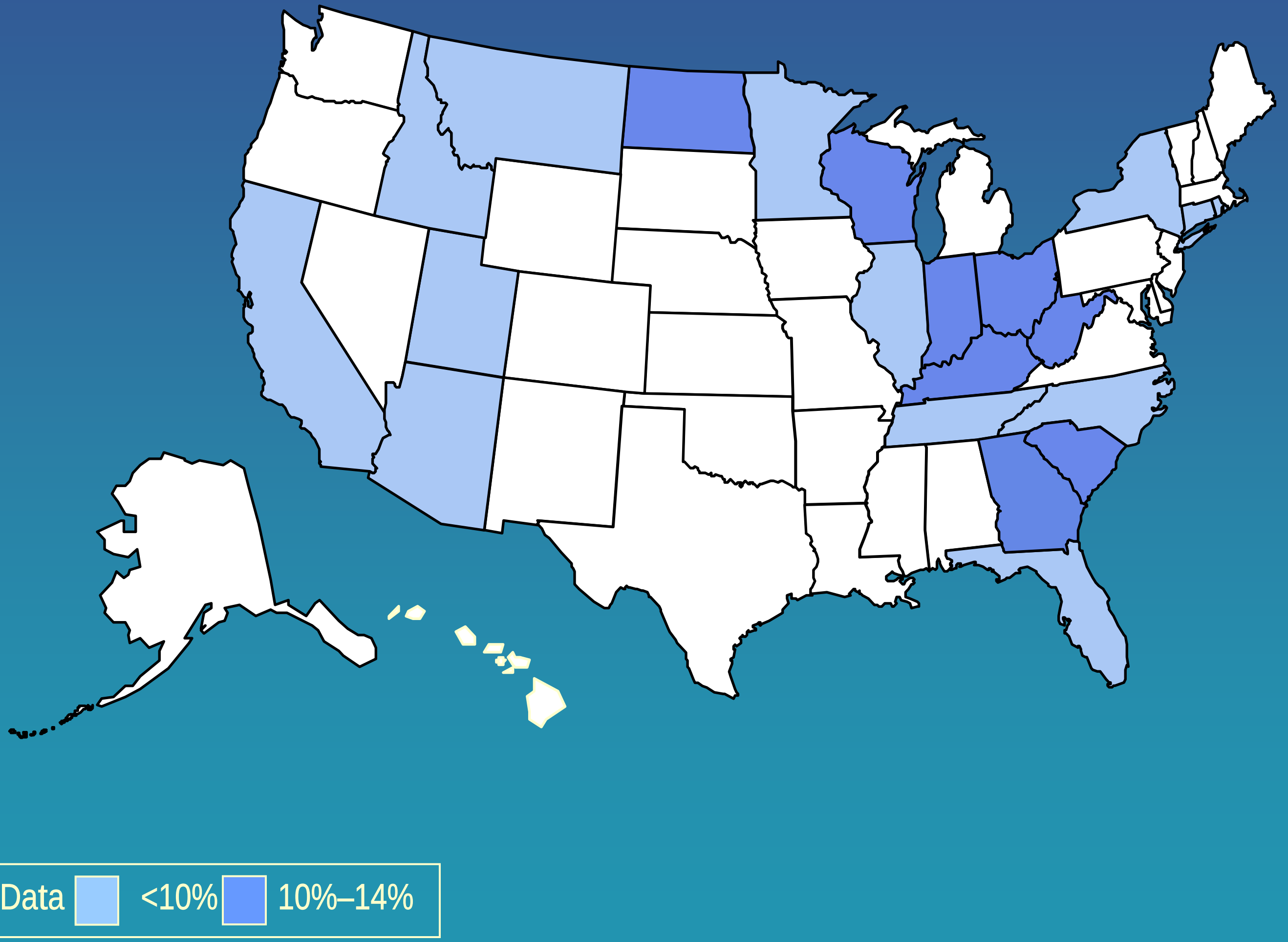
Mokdad AH, et al. The continuing epidemics of obesity and diabetes in the United States. *JAMA*. 2001; 286:10:1519–22.

Mokdad AH, et al. Prevalence of obesity, diabetes, and obesity-related health risk factors, 2001. *JAMA* 2003: 289:1: 76–79

CDC. State-Specific Prevalence of Obesity Among Adults — United States, 2005; MMWR 2006; 55(36);985–988

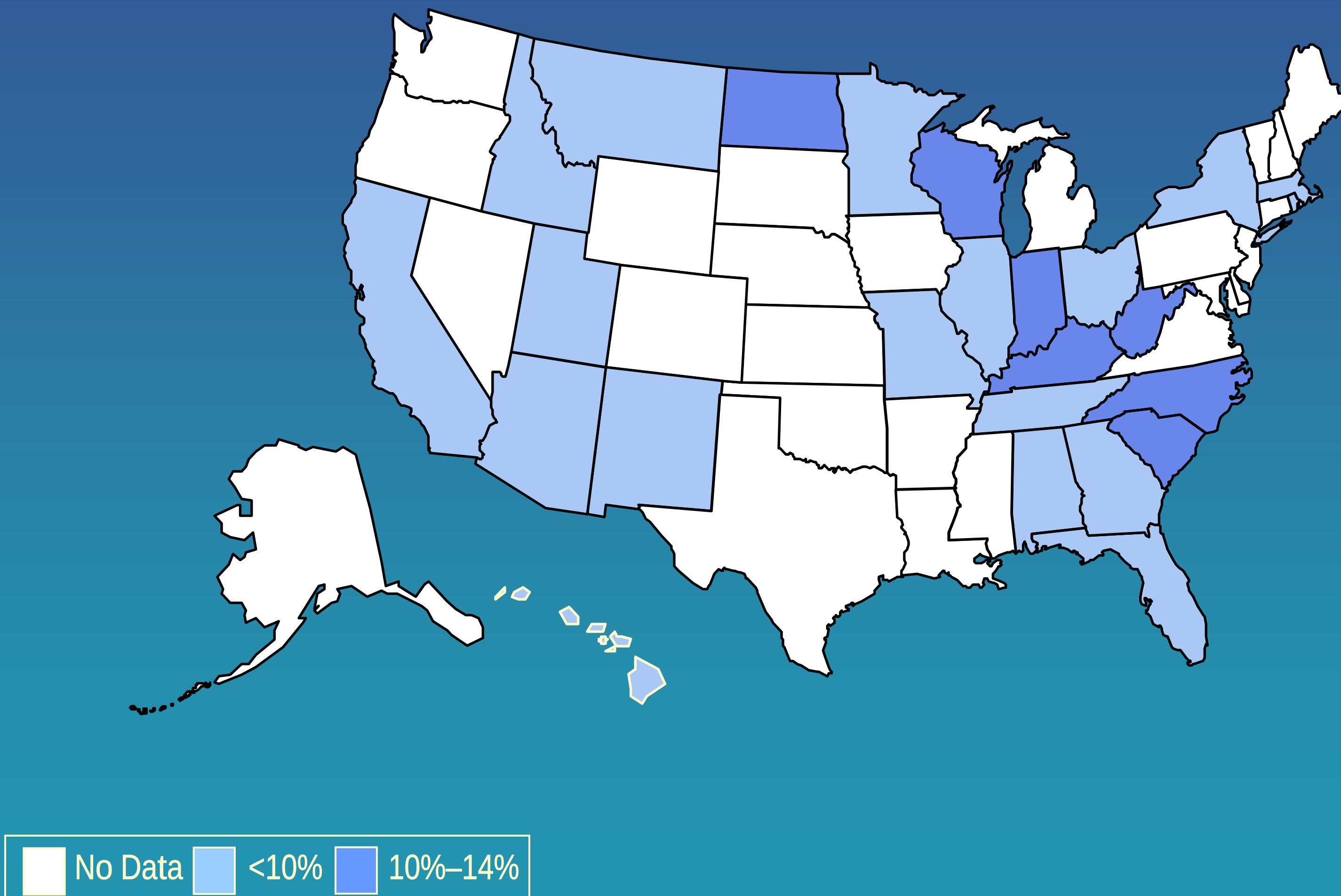
Obesity Trends* Among U.S. Adults
BRFSS, 1985

(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)



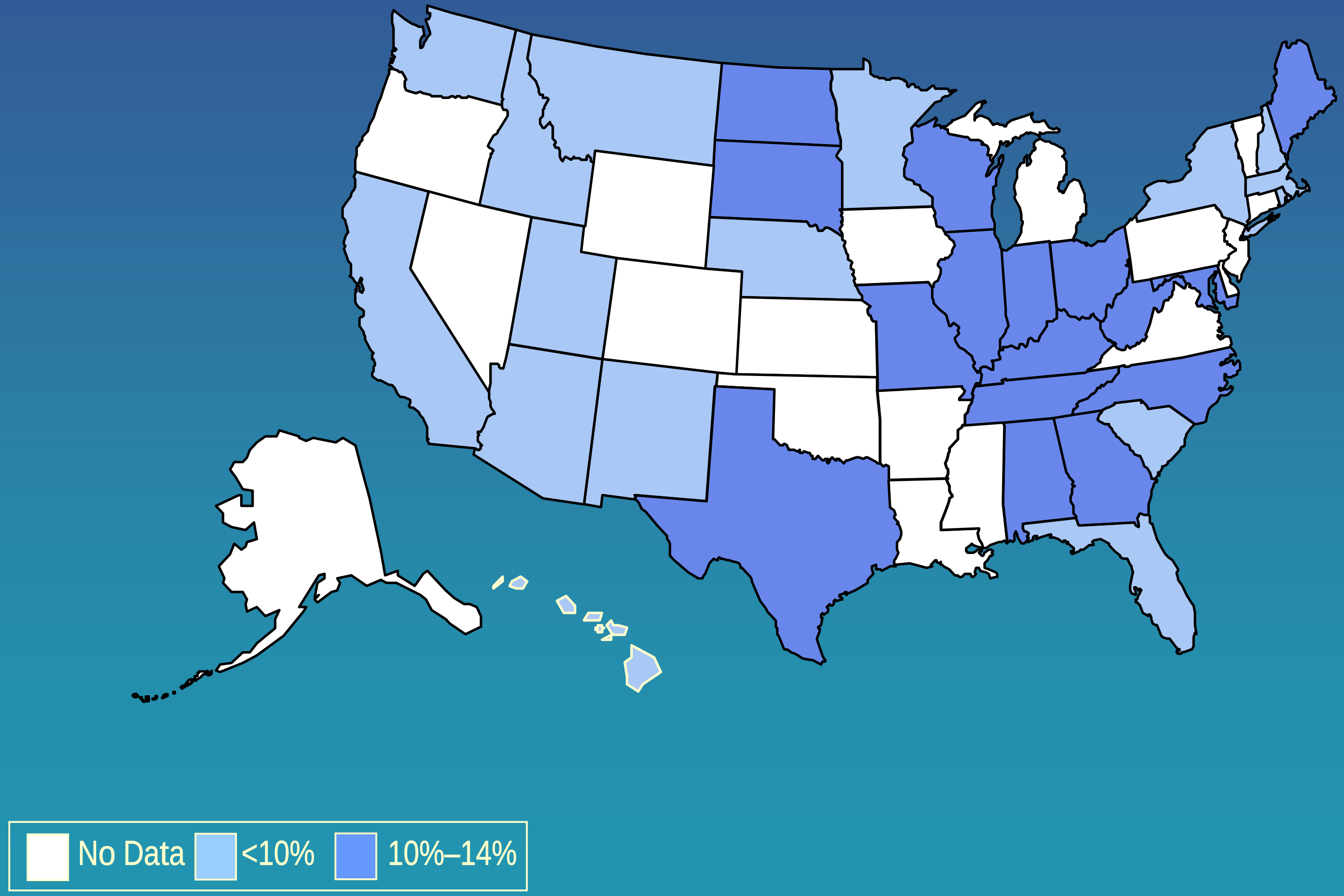
Obesity Trends* Among U.S. Adults
BRFSS, 1986

(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)



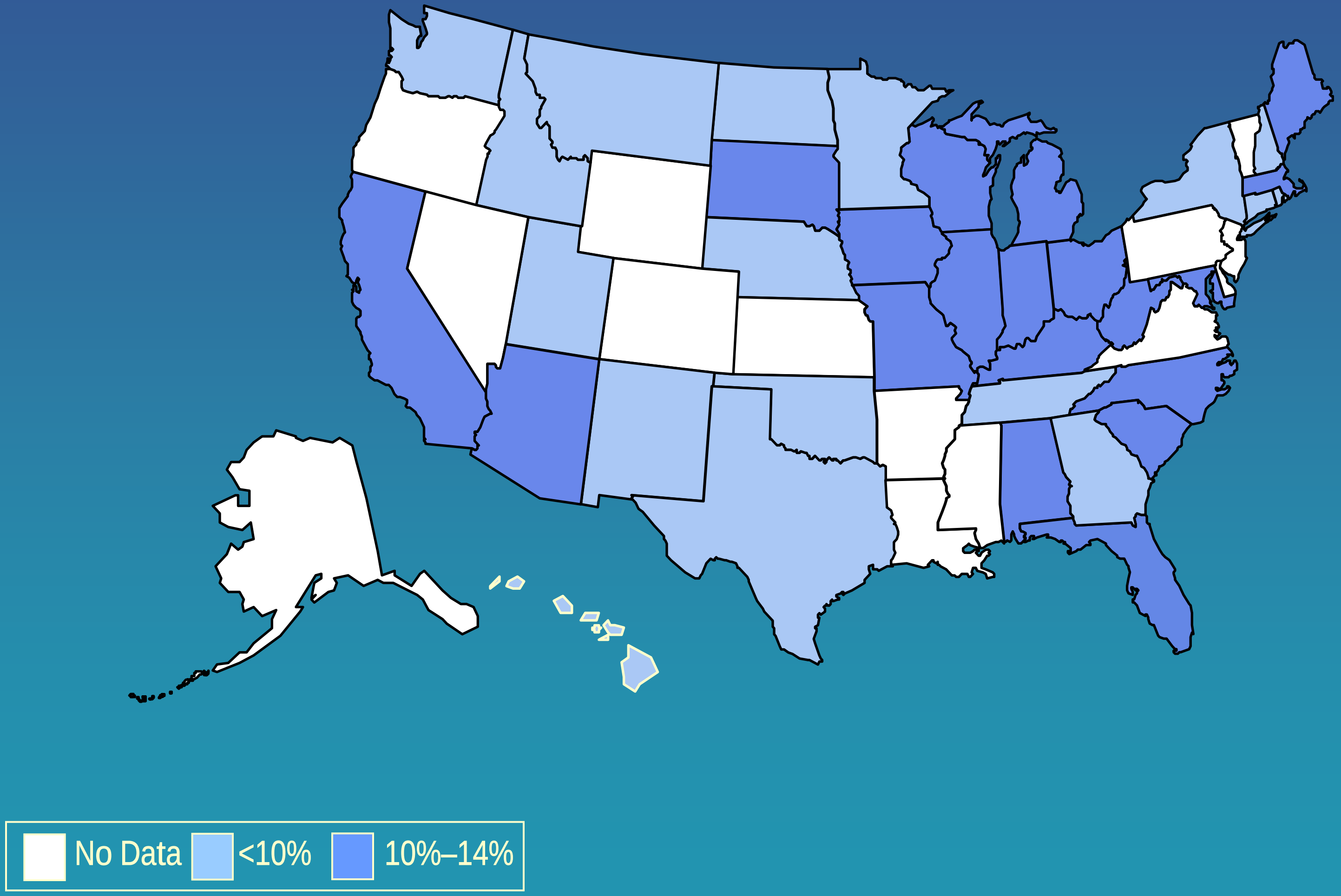
Obesity Trends* Among U.S. Adults
BRFSS, 1987

(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)



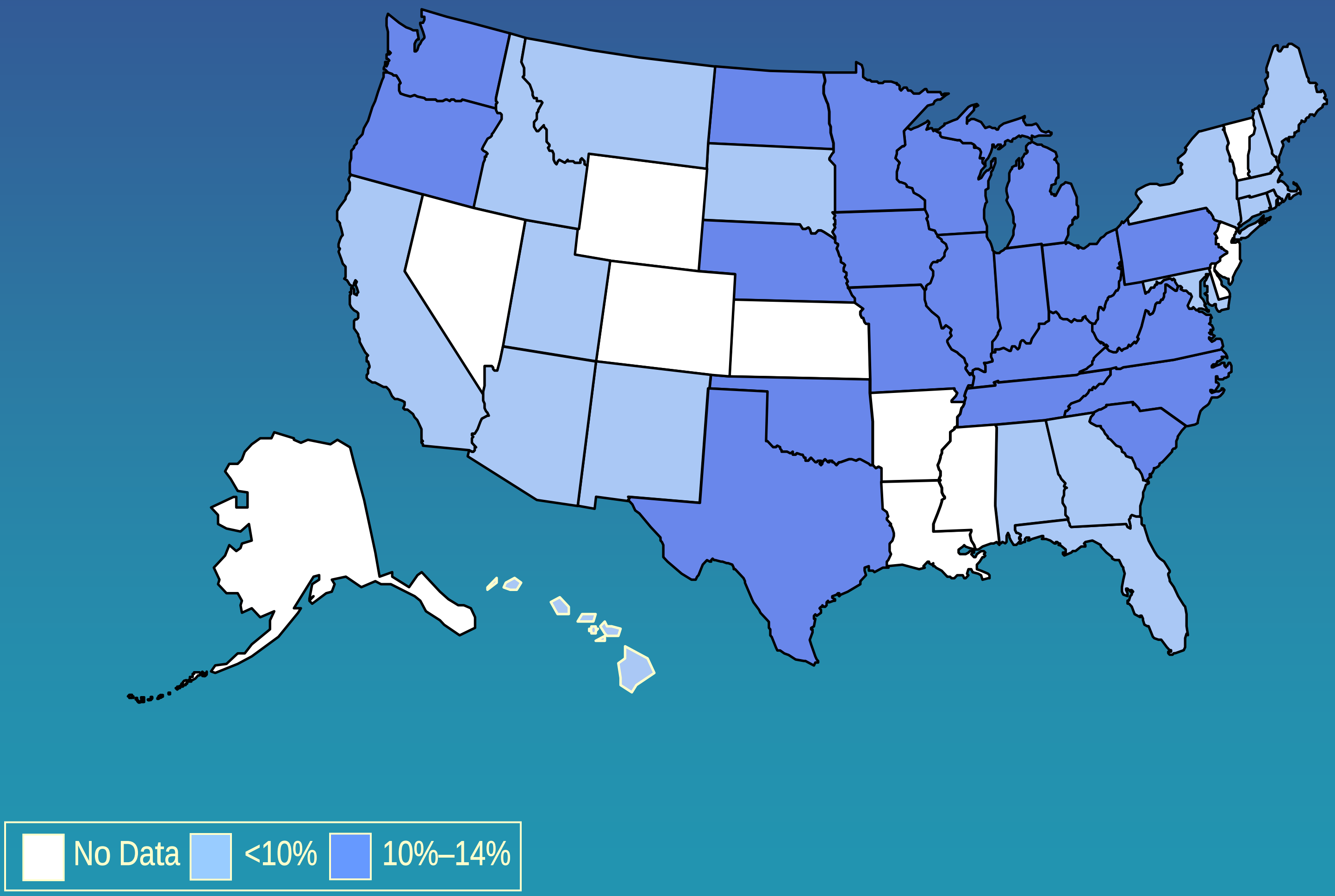
Obesity Trends* Among U.S. Adults
BRFSS, 1988

(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)



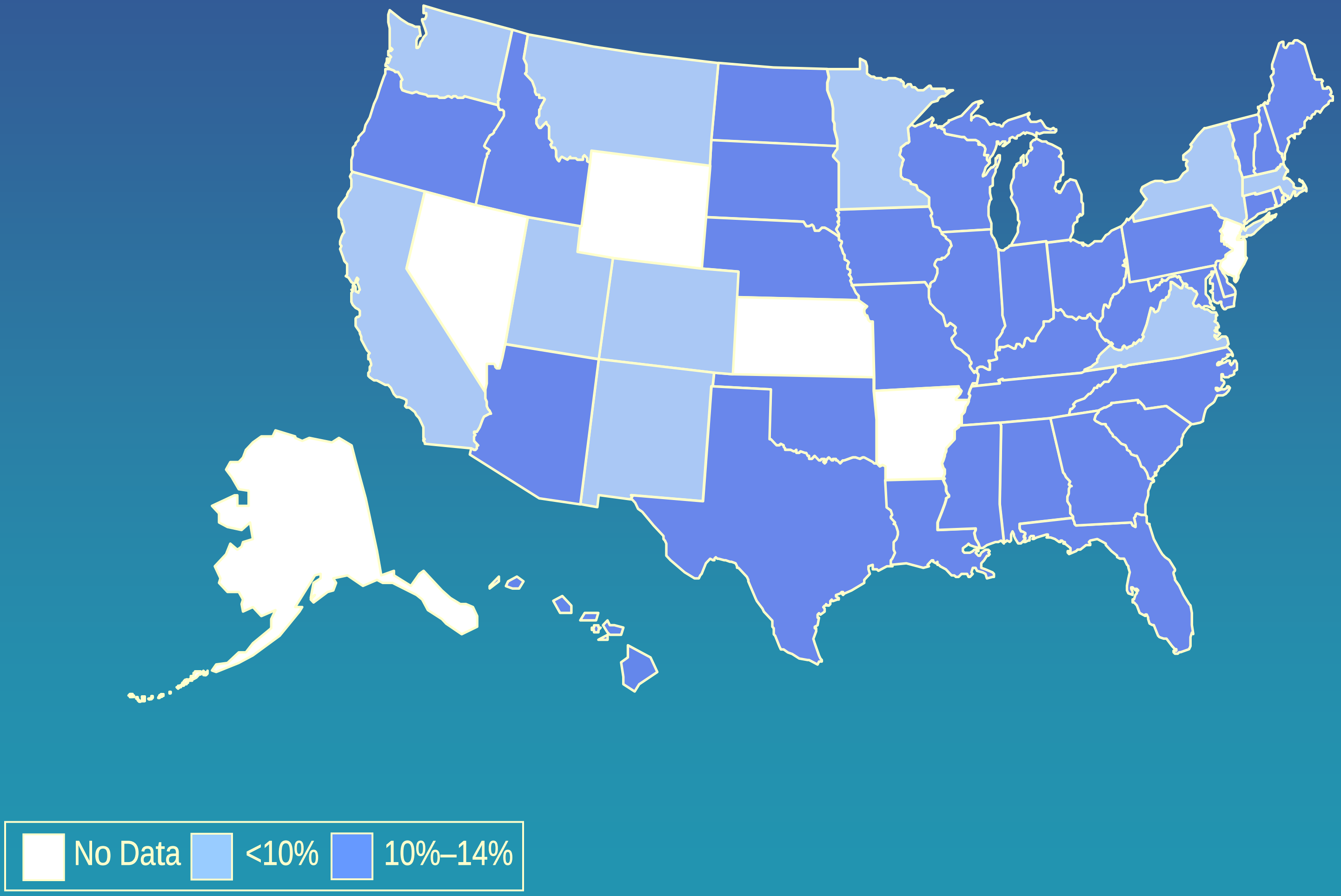
Obesity Trends* Among U.S. Adults
BRFSS, 1989

(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)



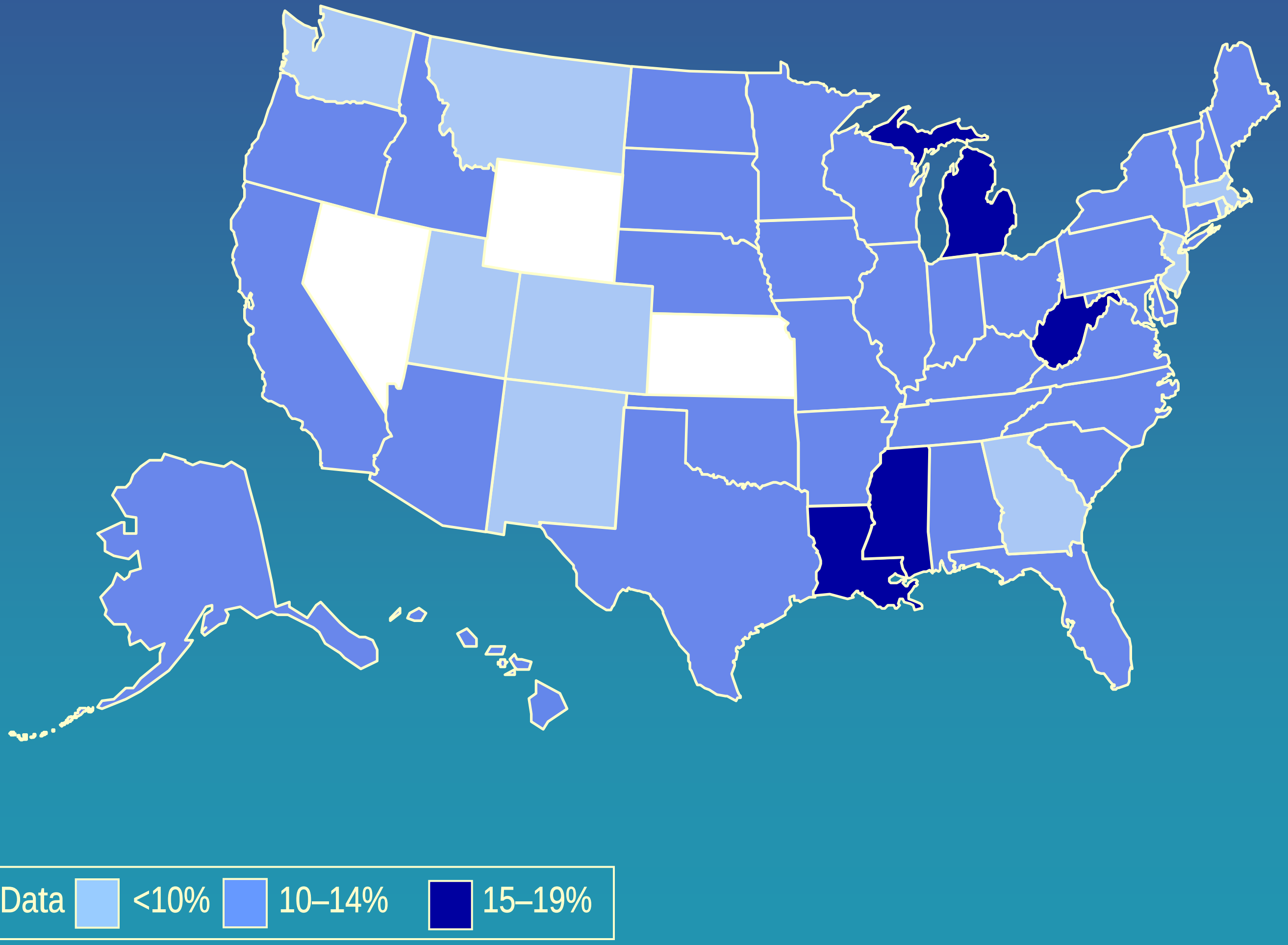
Obesity Trends* Among U.S. Adults
BRFSS, 1990

(*BMI ≥30, or ~ 30 lbs. overweight for 5' 4" person)



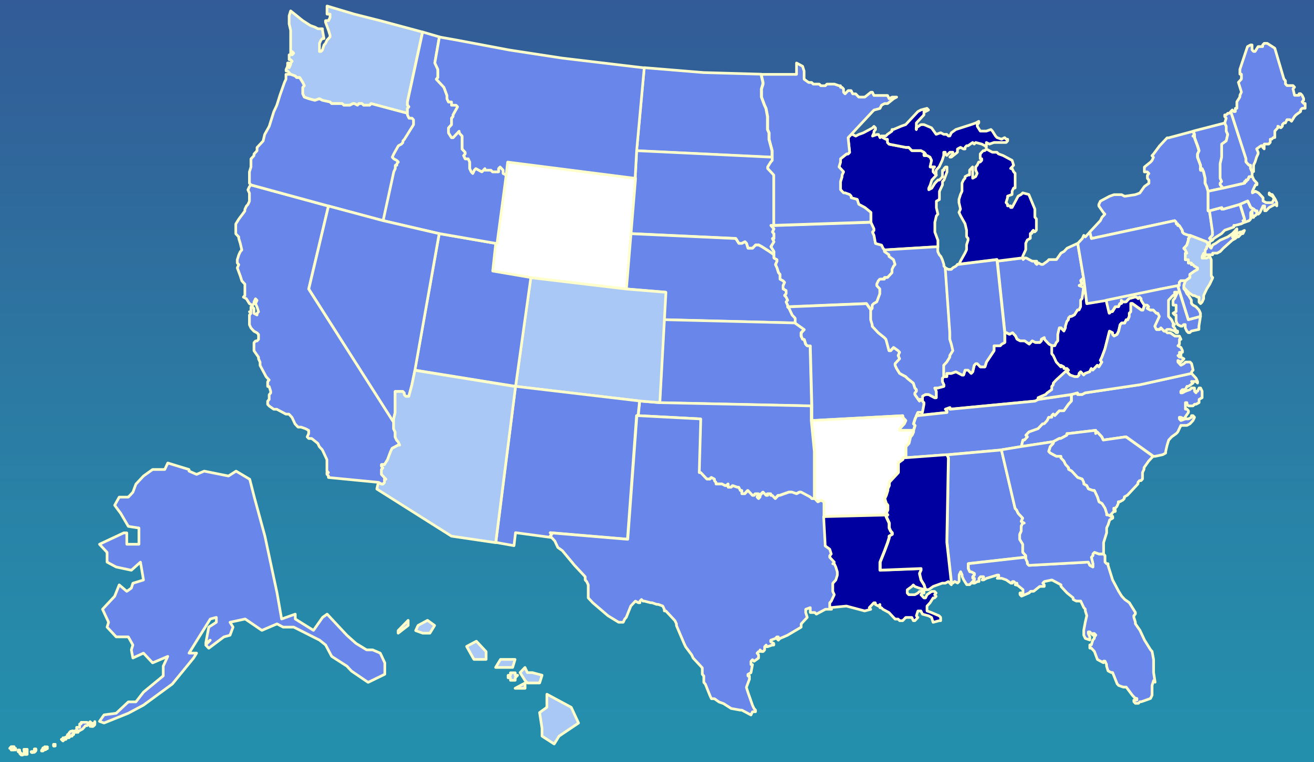
Obesity Trends* Among U.S. Adults
BRFSS, 1991

(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)



Obesity Trends* Among U.S. Adults
BRFSS, 1992

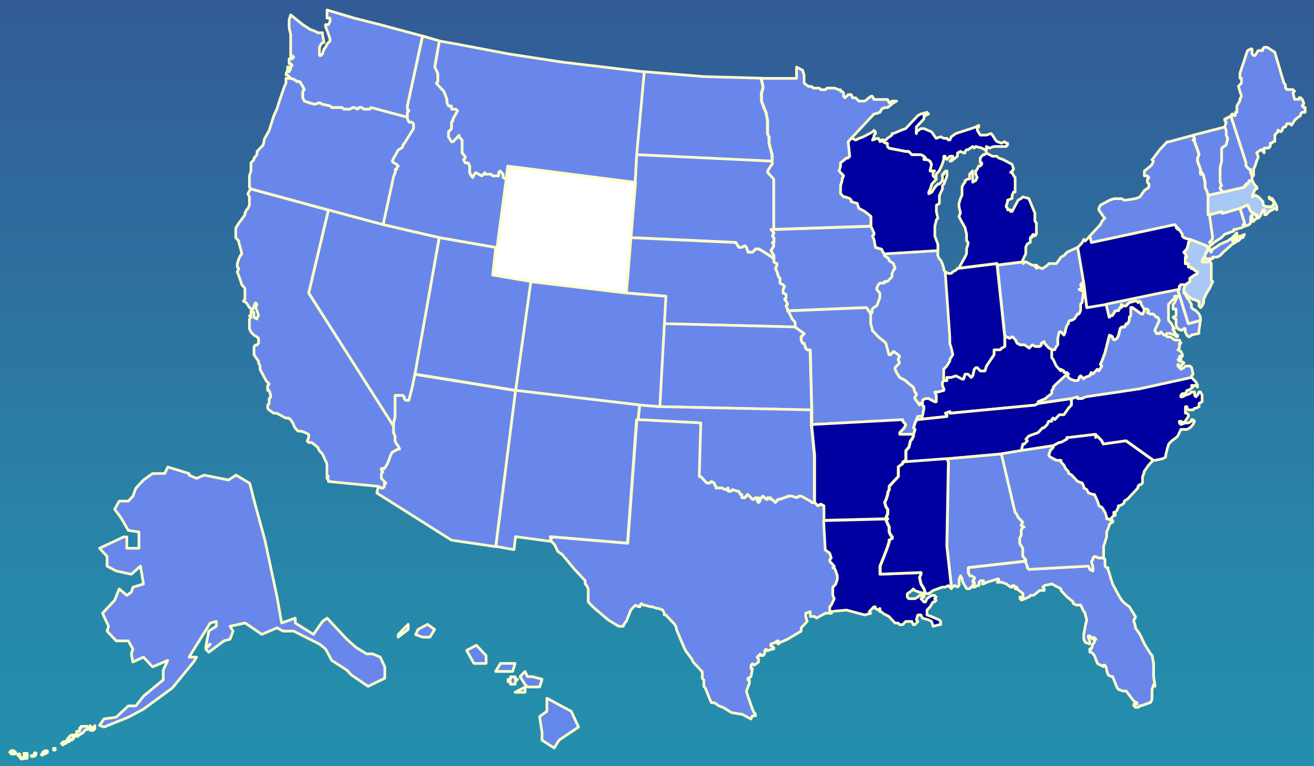
(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)



No Data | <10% | 10 –14% | 15–19%

Obesity Trends* Among U.S. Adults
BRFSS, 1993

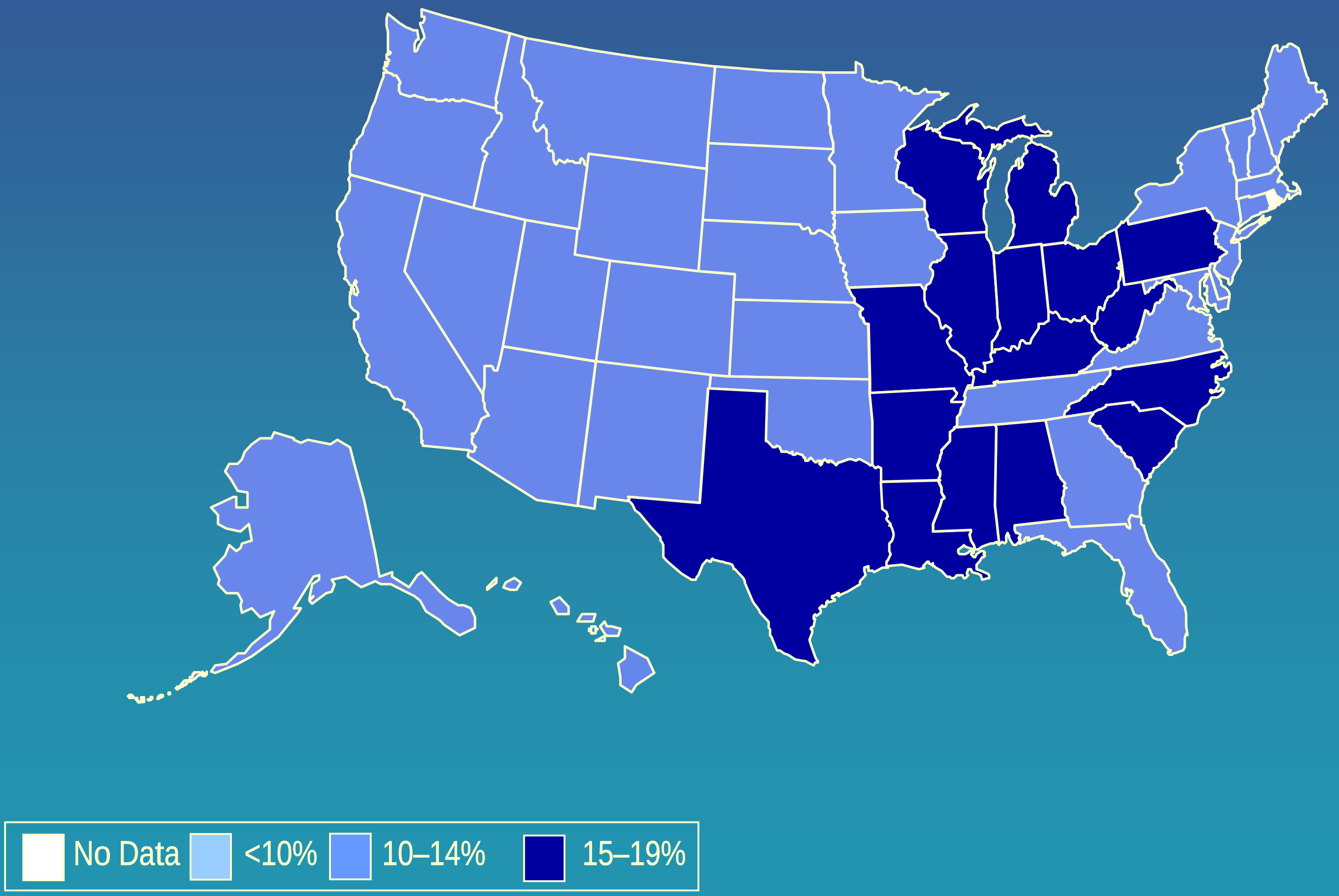
(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)



No Data | <10% | 10–14% | 15–19%

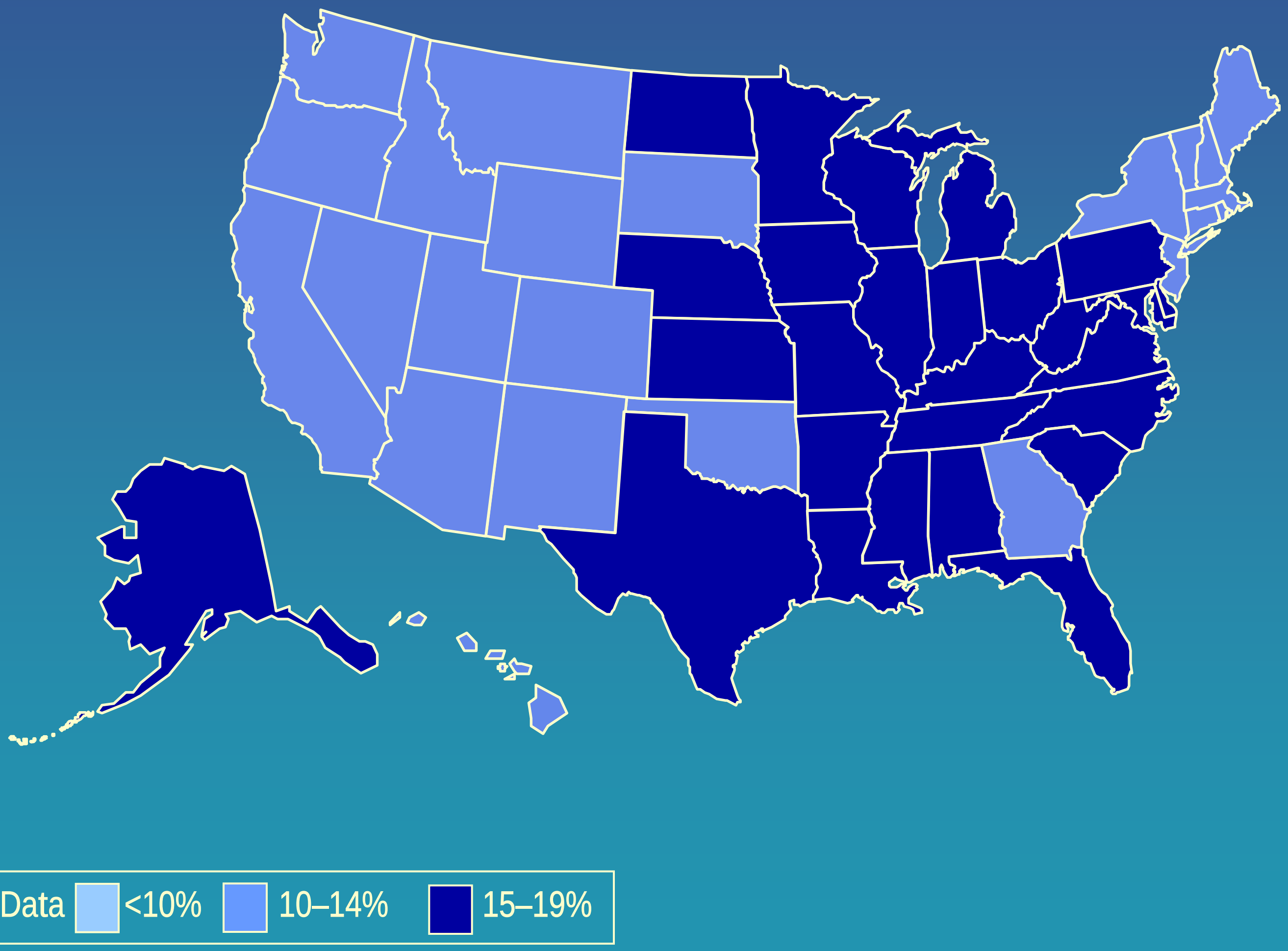
Obesity Trends* Among U.S. Adults
BRFSS, 1994

(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)



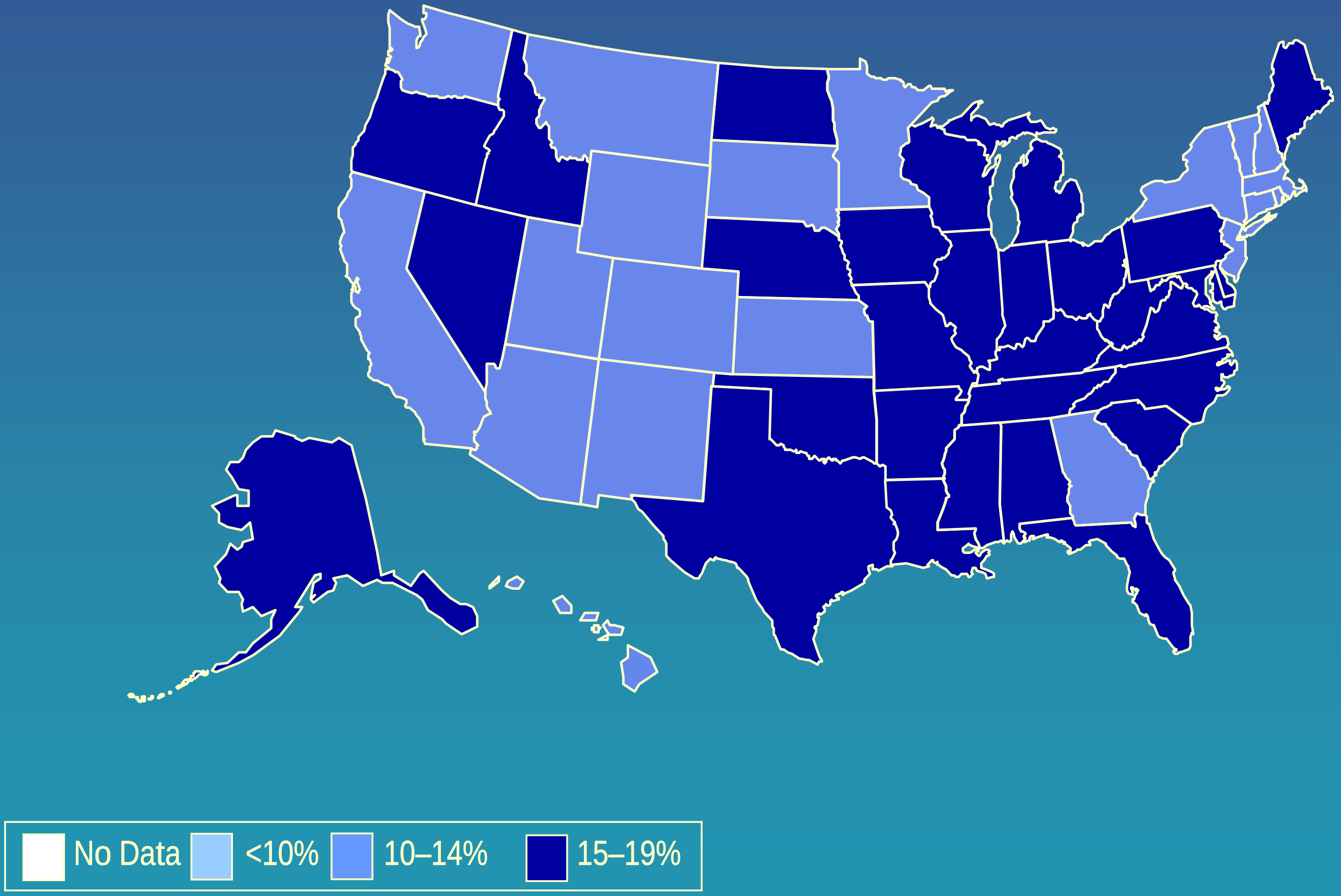
Obesity Trends* Among U.S. Adults
BRFSS, 1995

(*BMI ≥30, or ~ 30 lbs. overweight for 5' 4" person)



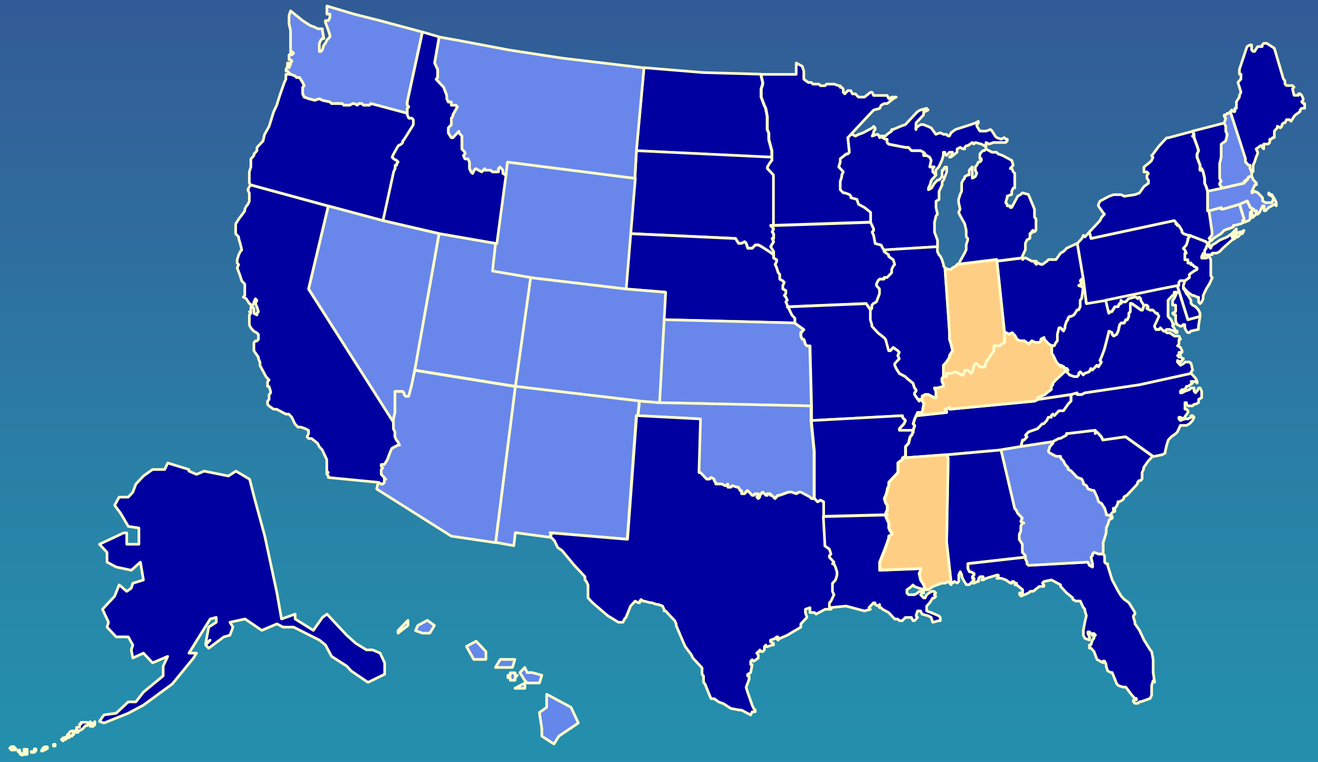
Obesity Trends* Among U.S. Adults
BRFSS, 1996

(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)



Obesity Trends* Among U.S. Adults
BRFSS, 1997

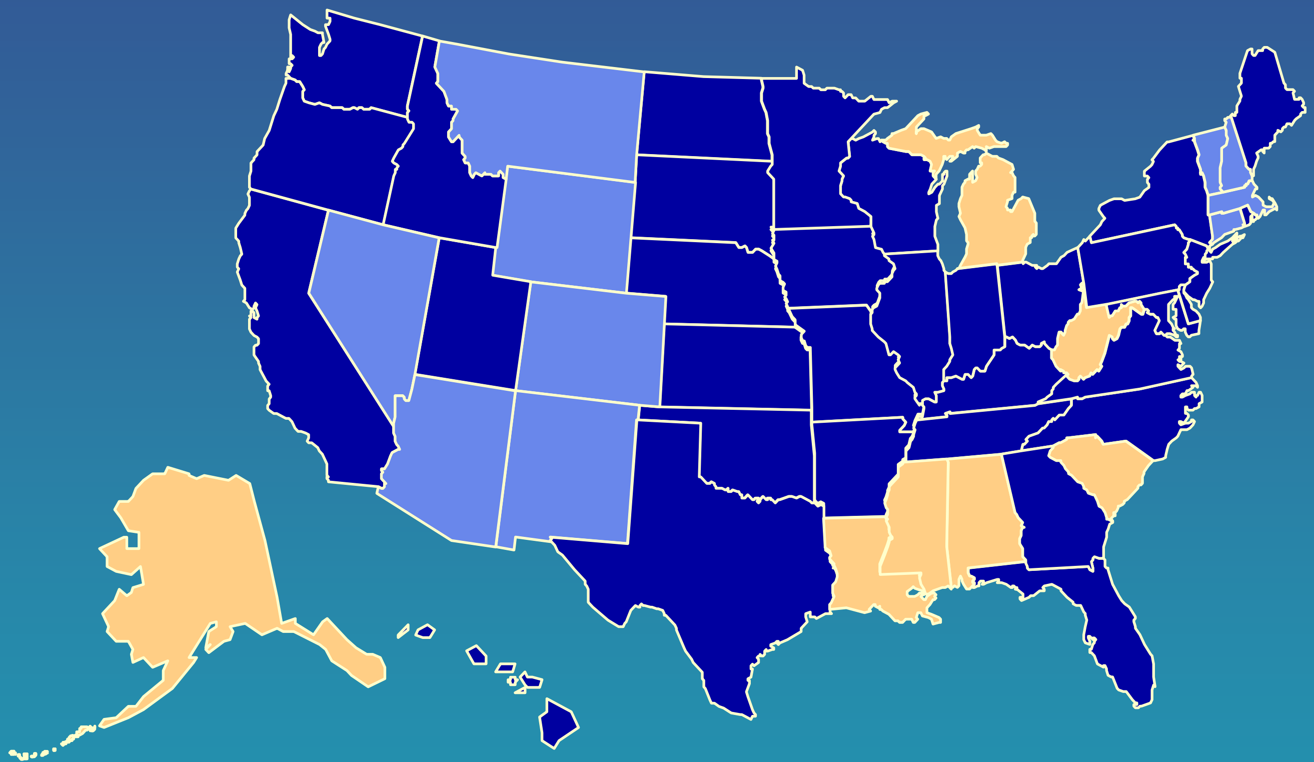
(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)

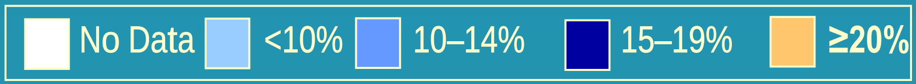


No Data | <10% | 10–14% | 15–19% | ≥20%

Obesity Trends* Among U.S. Adults
BRFSS, 1998

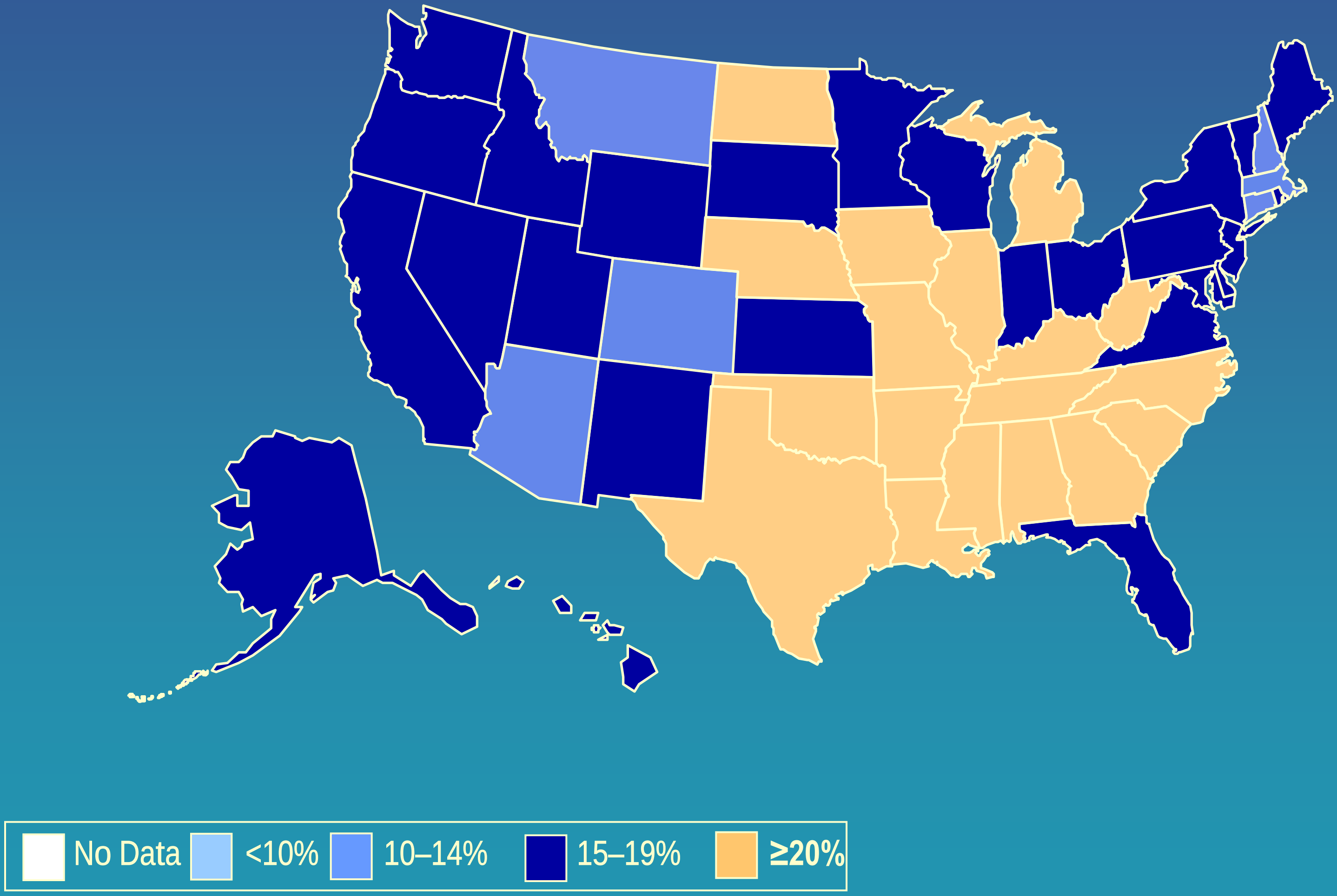
(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)





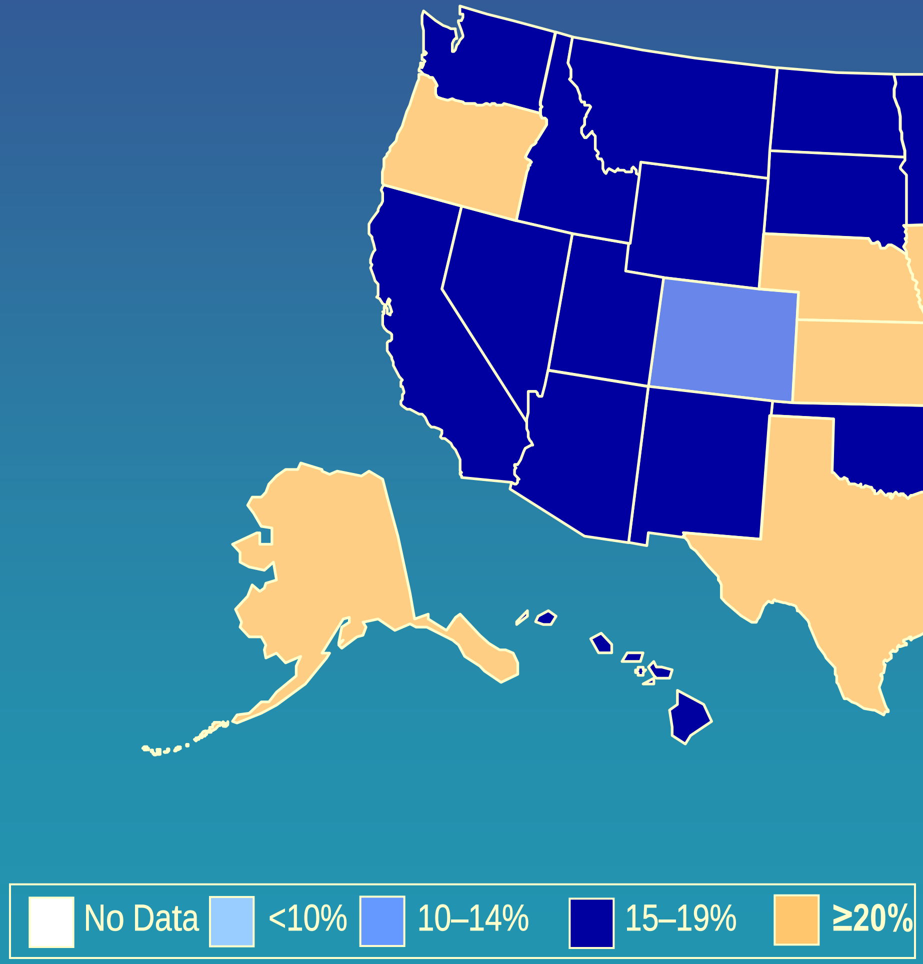
Obesity Trends* Among U.S. Adults
BRFSS, 1999

(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)



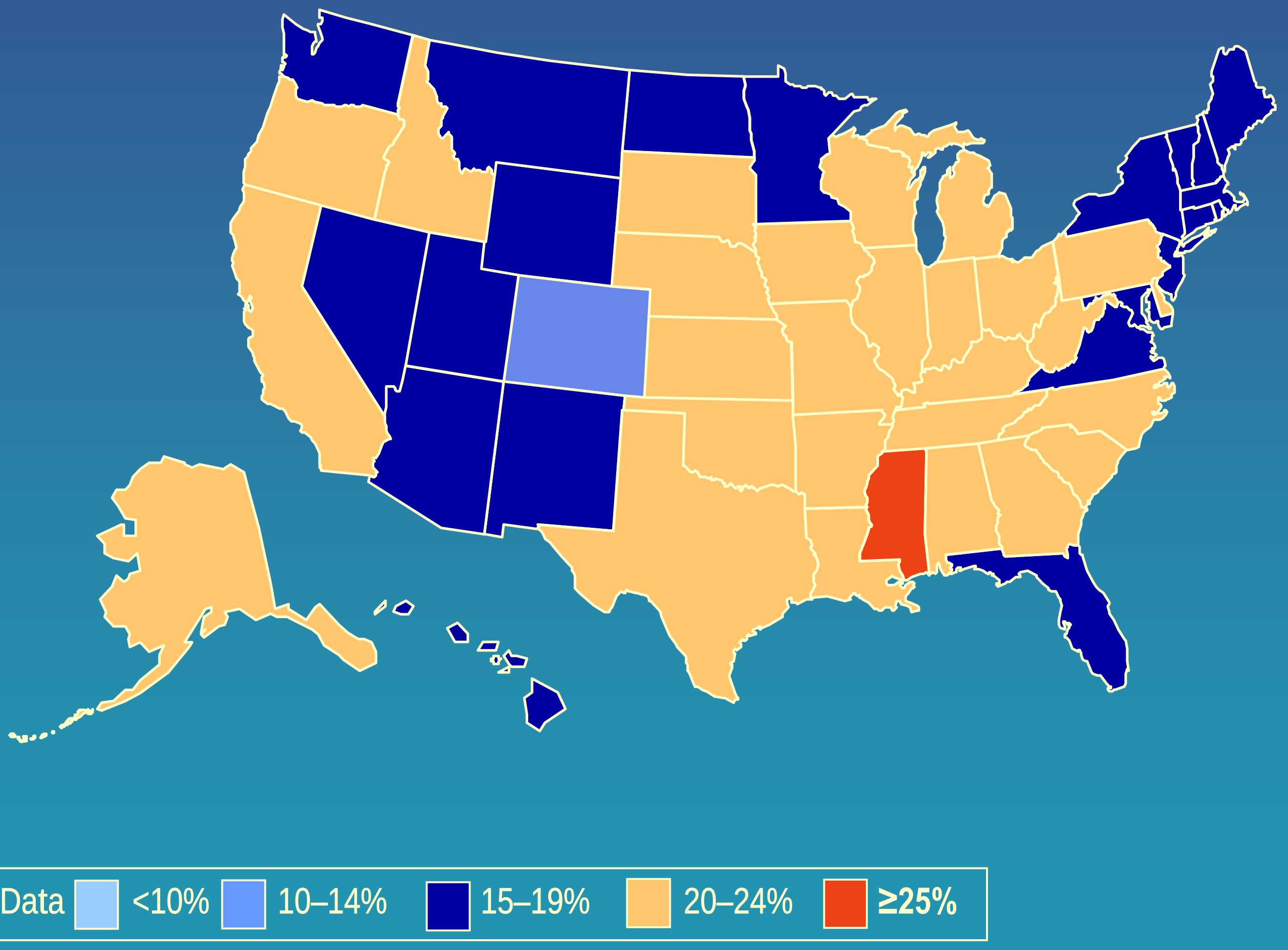
Obesity Trends* Among U.S. Adults
BRFSS, 2000

(*BMI ≥30, or ~ 30 lbs. overweight for 5' 4" person)



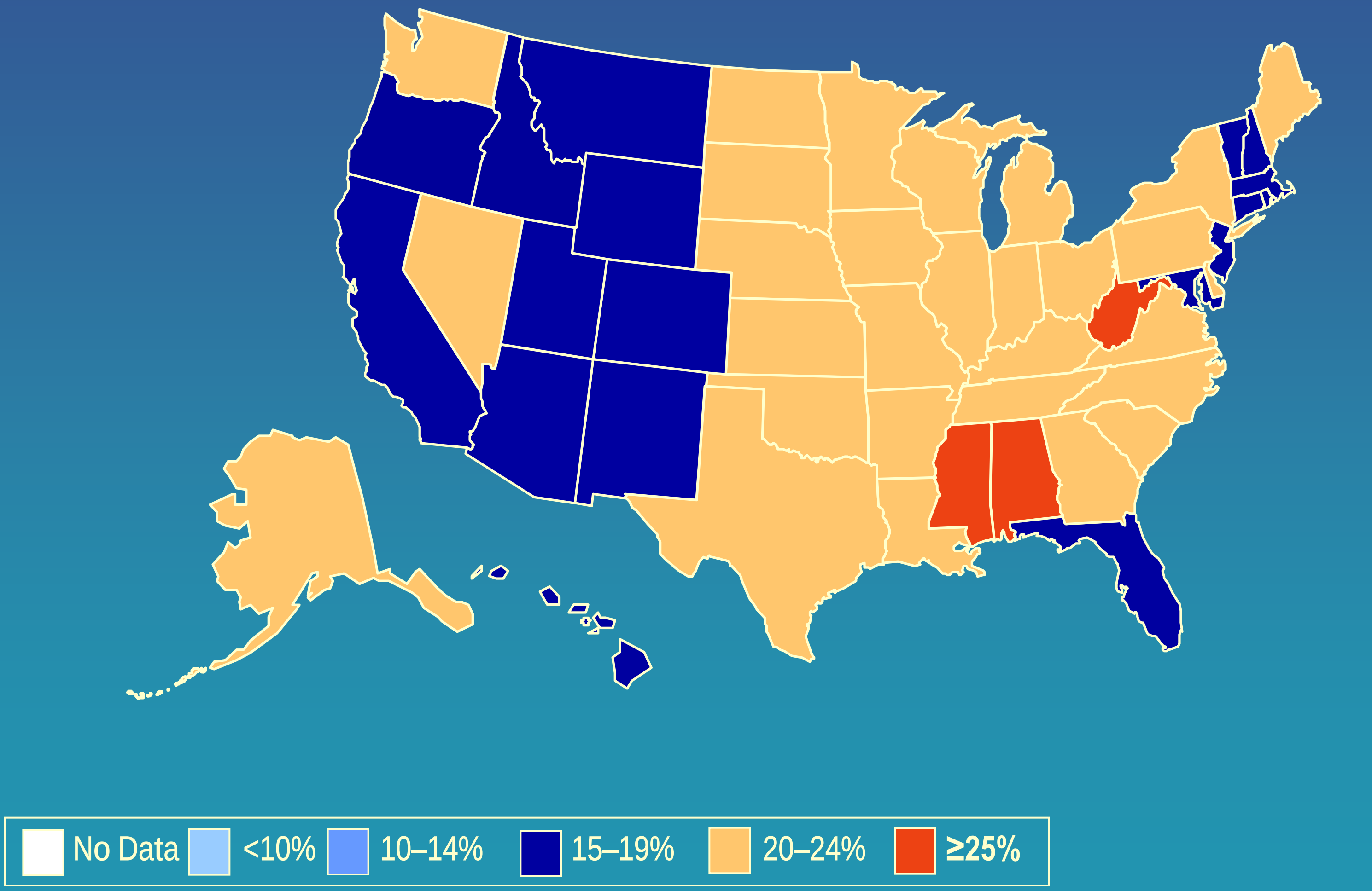
Obesity Trends* Among U.S. Adults
BRFSS, 2001

(*BMI ≥30, or ~ 30 lbs. overweight for 5' 4" person)



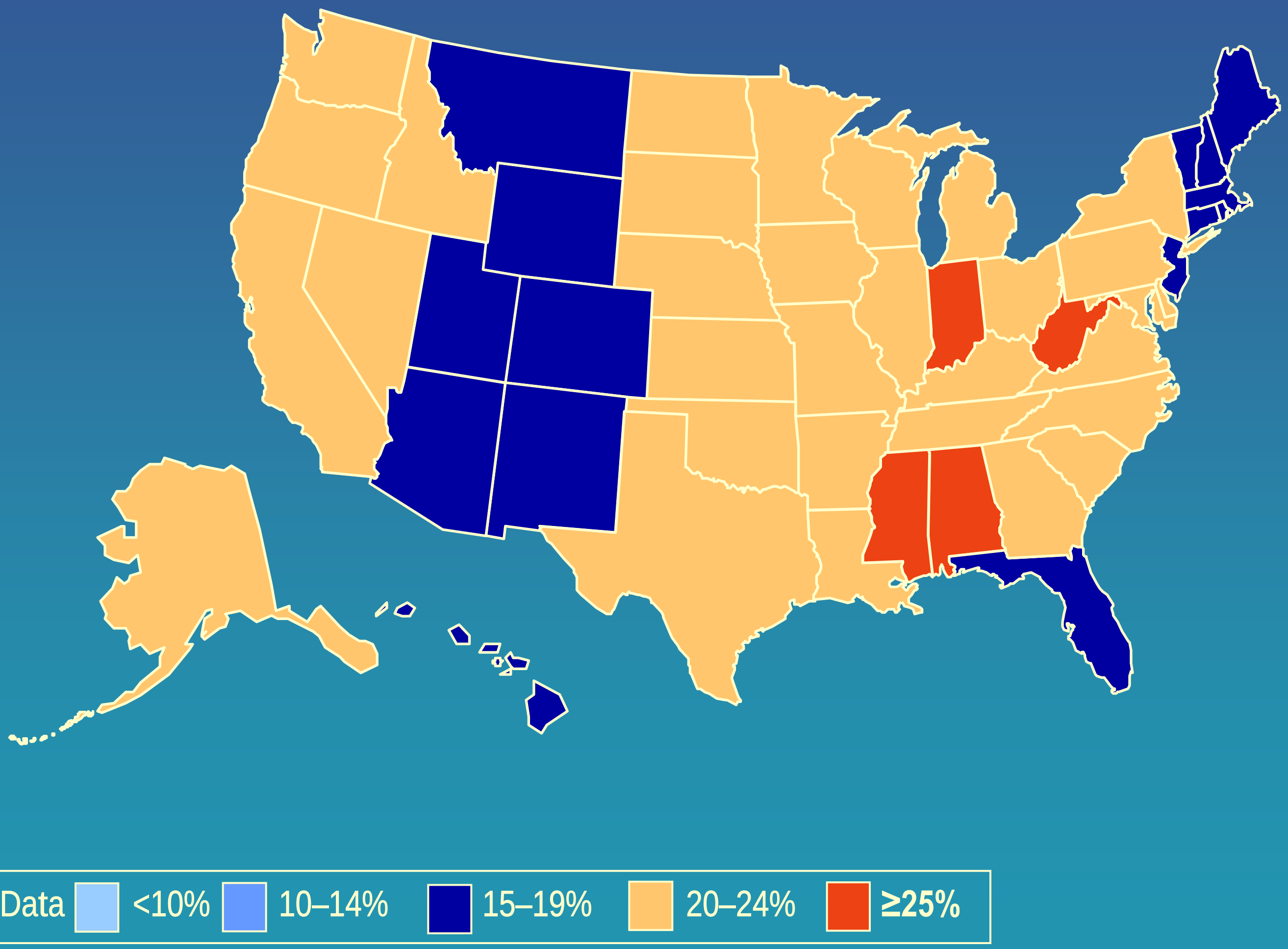
Obesity Trends* Among U.S. Adults
BRFSS, 2002

(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)



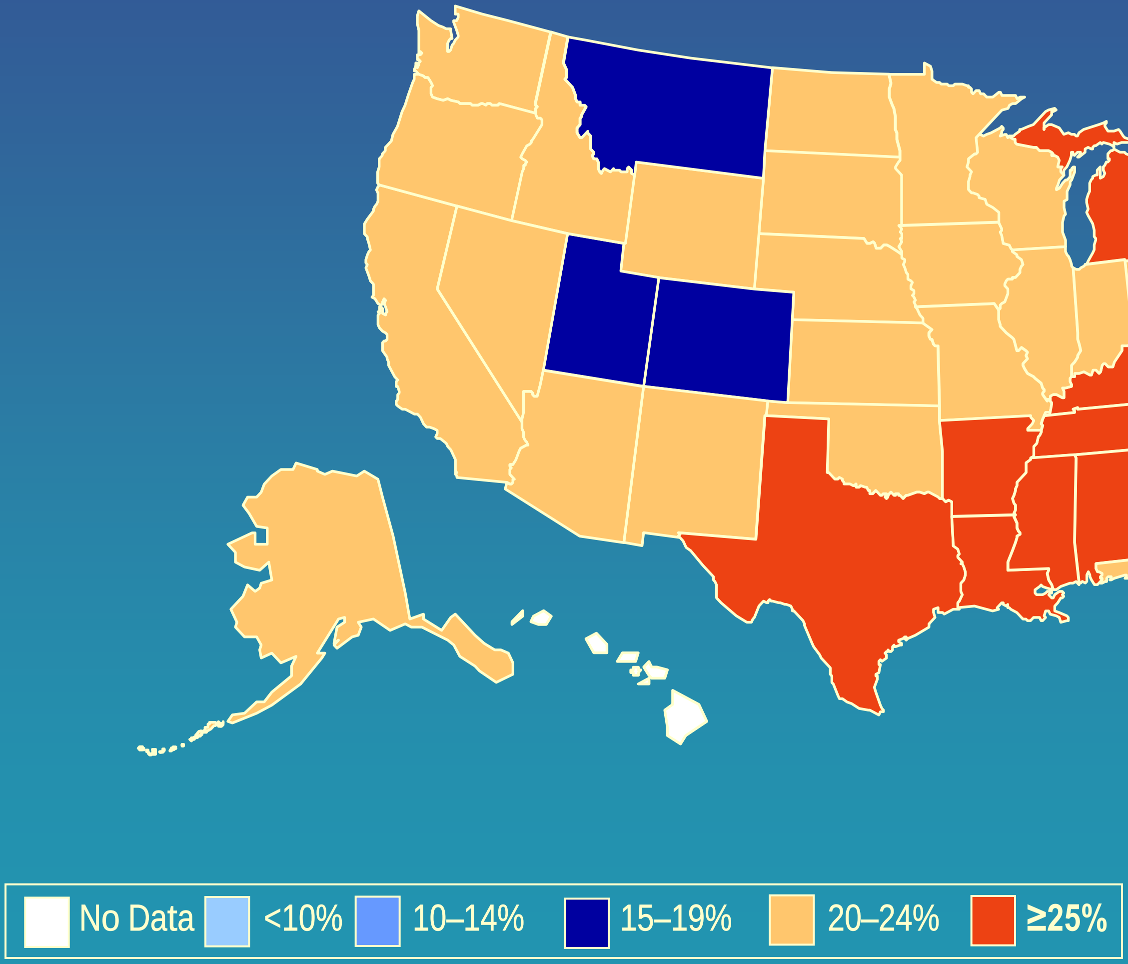
Obesity Trends* Among U.S. Adults
BRFSS, 2003

(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)



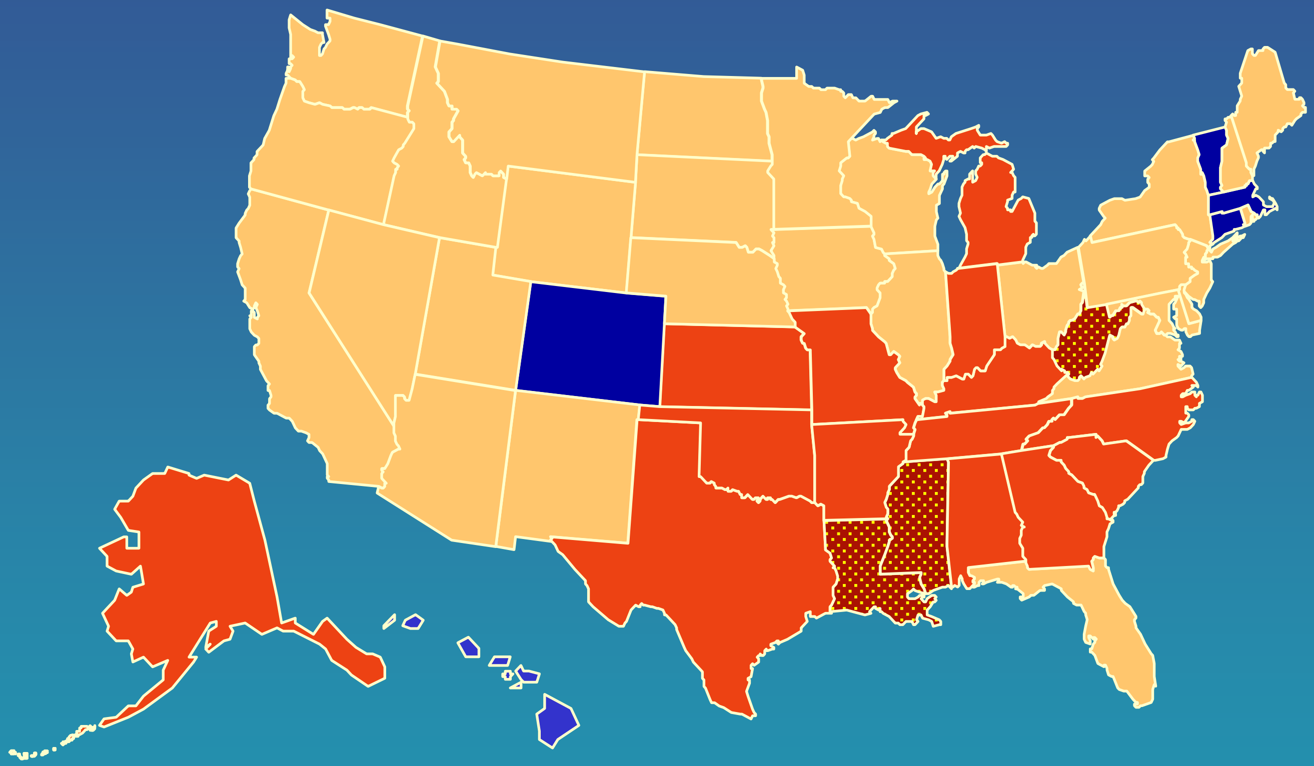
Obesity Trends* Among U.S. Adults
BRFSS, 2004

(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)



Obesity Trends* Among U.S. Adults
BRFSS, 2005

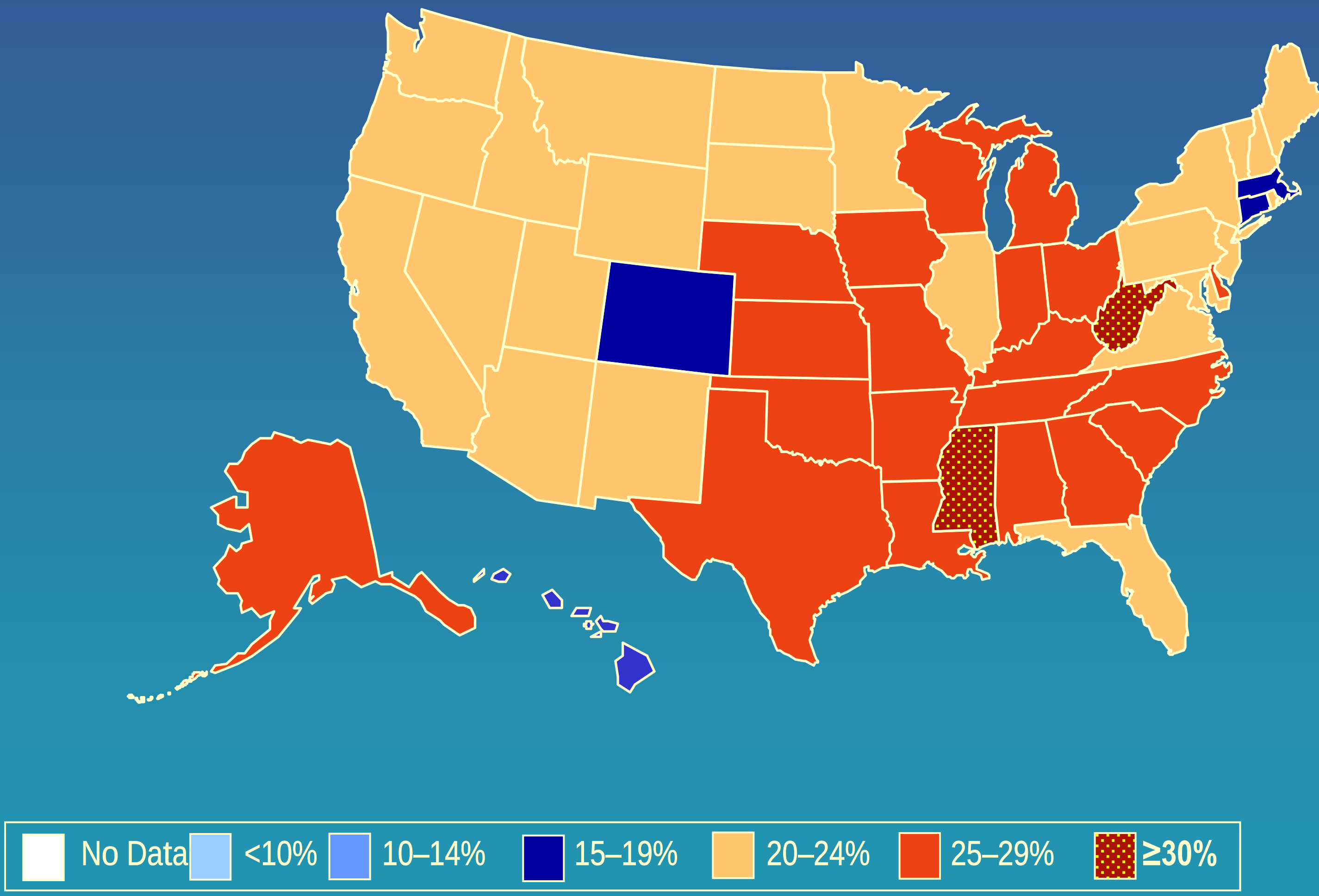
(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)



No Data | <10% | 10–14% | 15–19% | 20–24% | 25–29% | ≥30%

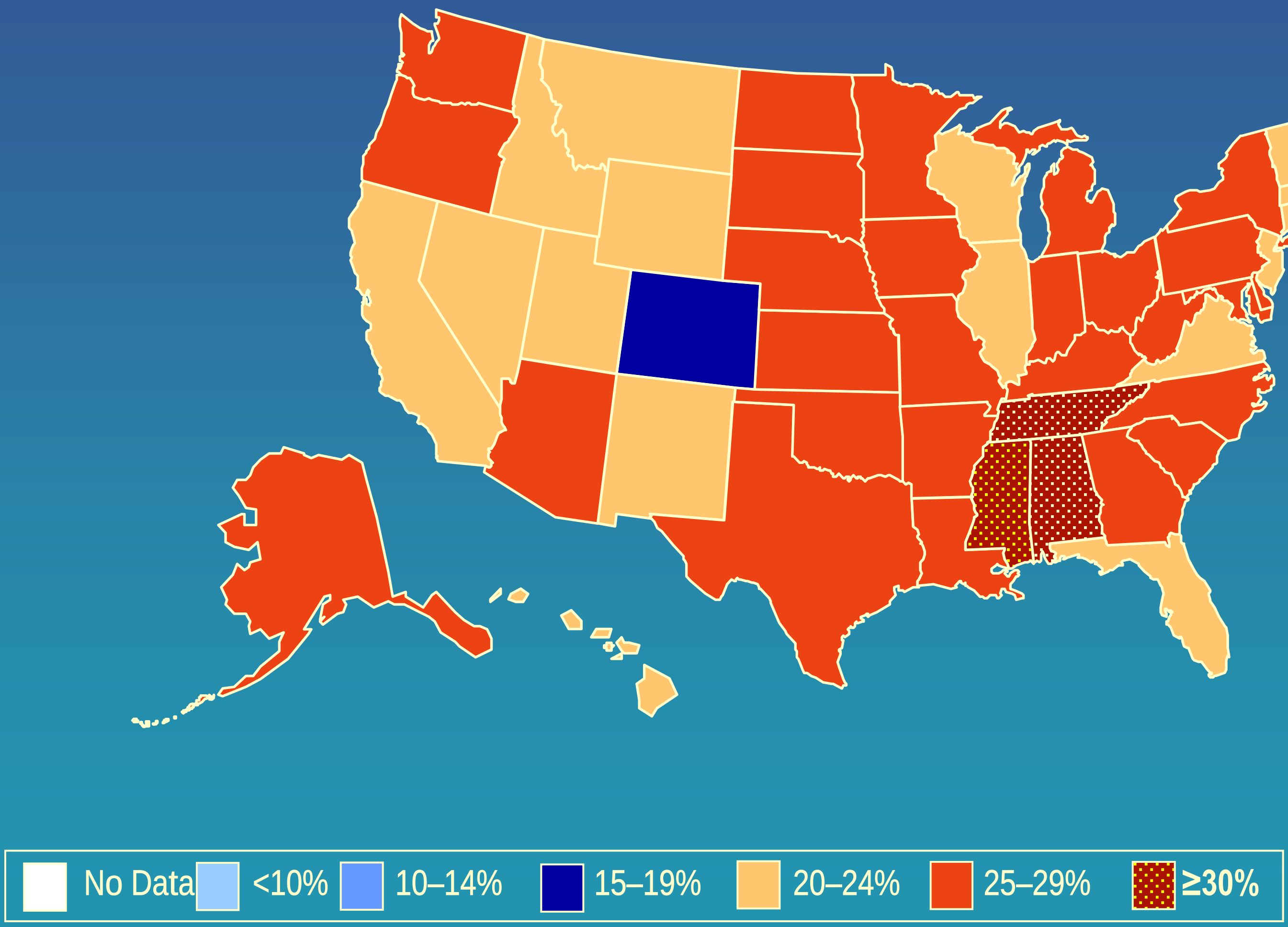
Obesity Trends* Among U.S. Adults
BRFSS, 2006

(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)

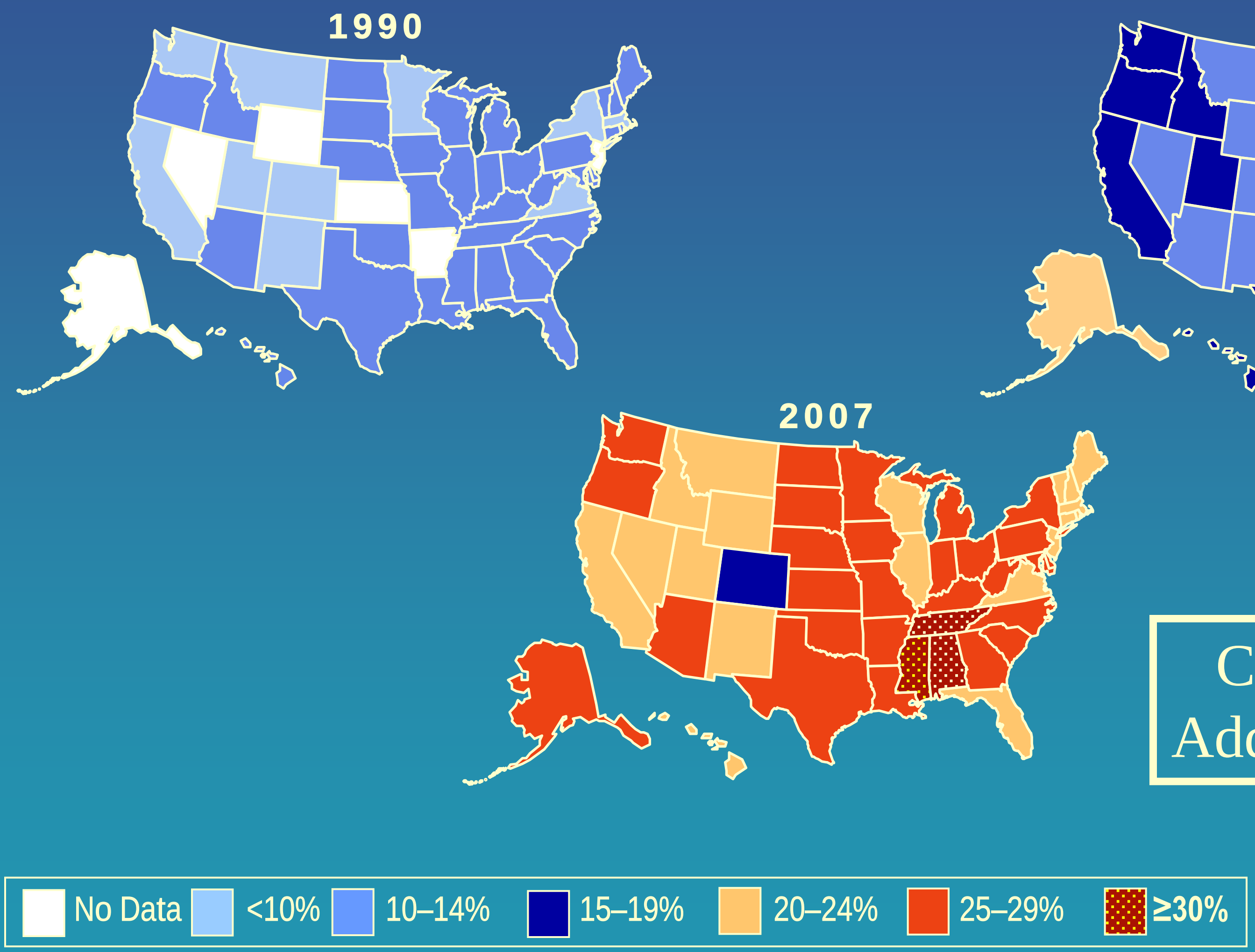


Obesity Trends* Among U.S. Adults
BRFSS, 2007

(*BMI ≥30, or ~ 30 lbs. overweight for 5' 4" person)



Obesity Trends* Among U.S. Adults
BRFSS, 1990, 1998, 2007
(*BMI ≥30, or about 30 lbs. overweight for 5’4” person)



Cody BMI ~24
Add 35lbs, BMI 30

How do we design CT protocols?

- Initially for “standard” size patients
- Sooner rather than later, “large” size patients
- Maybe – “small” size patients?

How do we assess risk?

- Assumption: “standard” size patients
- May be ok for larger patients
  - Tend to use higher techniques on larger patients, who have more tissue to dissipate energy
  - Intensity of beam more gradually decreased, reduced risk to DNA?
- Underestimated for smaller adult patients

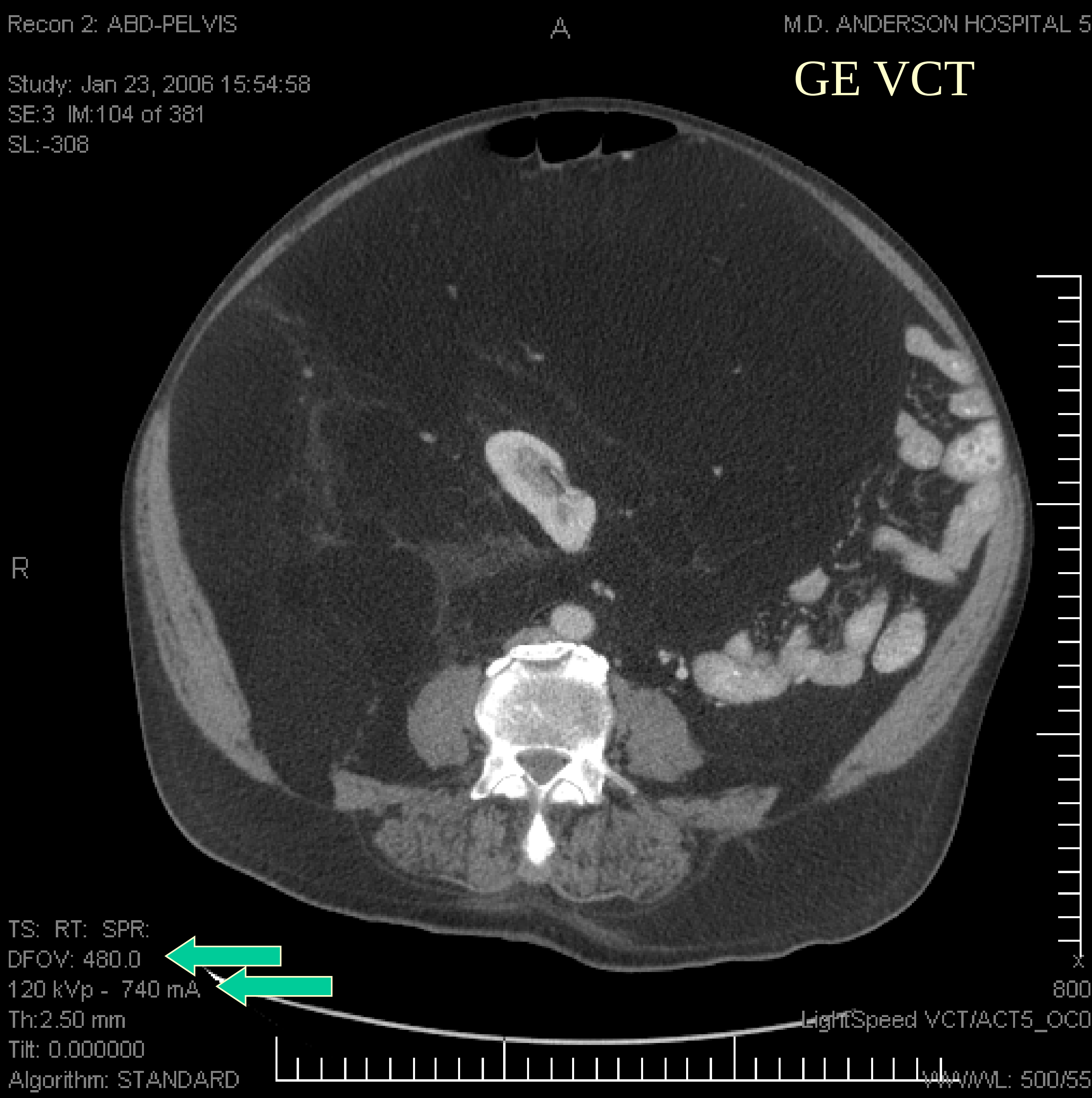
What is “standard” size?

- “Standard” man (dose models)
- Size: 5’9” 160 pound male
- Size: 5’4” 132 pound female
- How many roughly “standard” size folks here?
- How many larger than standard size?
- How many smaller than standard size?

Adjust protocols for large size patients?

- Tube current modulation
- Tube heat capacity may limit this approach
- Technique chart
  - Increase effective mAs by ~30%*
  - Select a size criteria
  - DFOV $\geq$ 42cm*

* MD Anderson approach



DFOV 48cm

120 kV

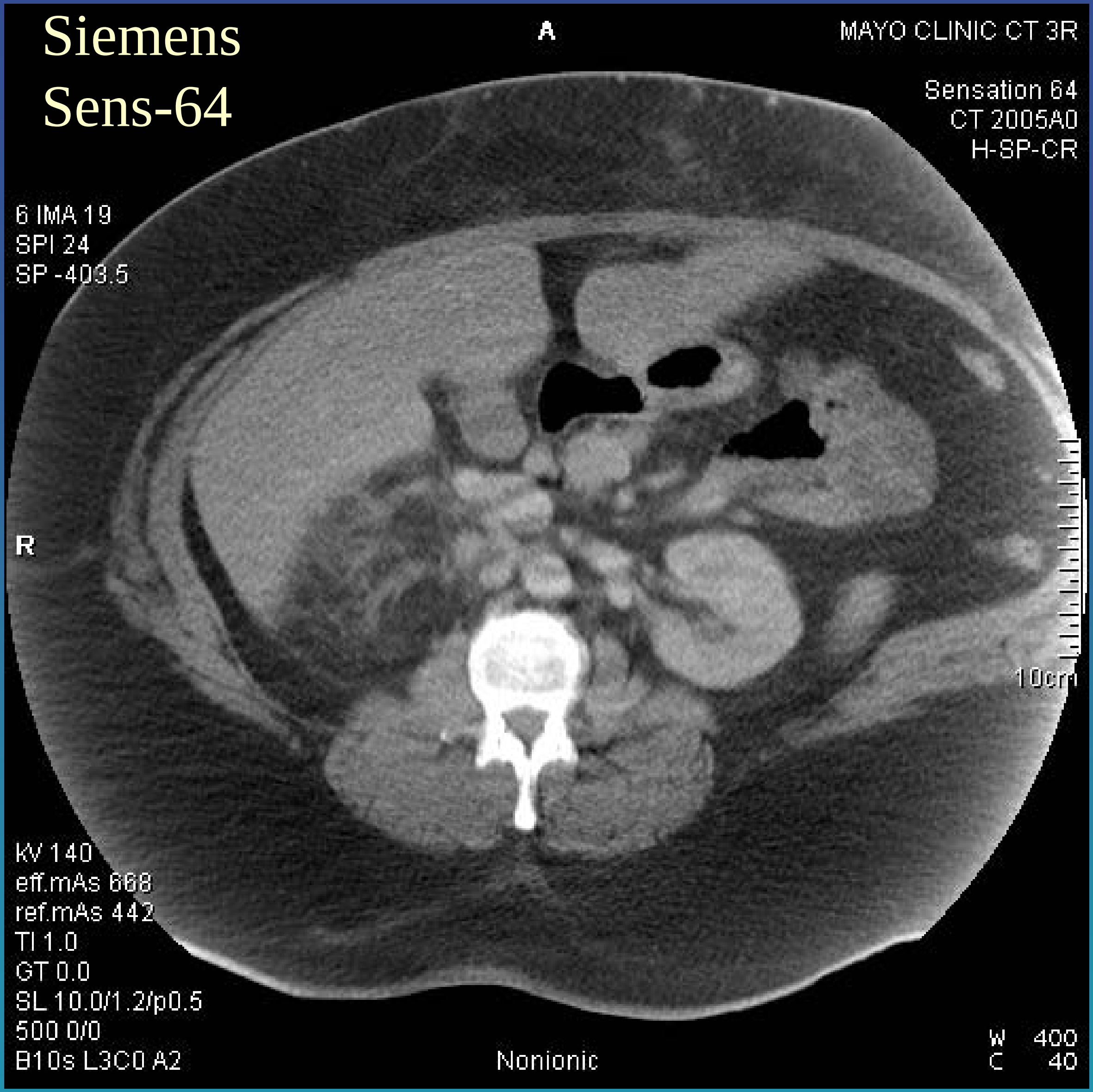
740 mA

0.8 sec/rotn

Pitch .984

600 eff mAs

Image quality for large patients sensitive to miscentering (truncation)

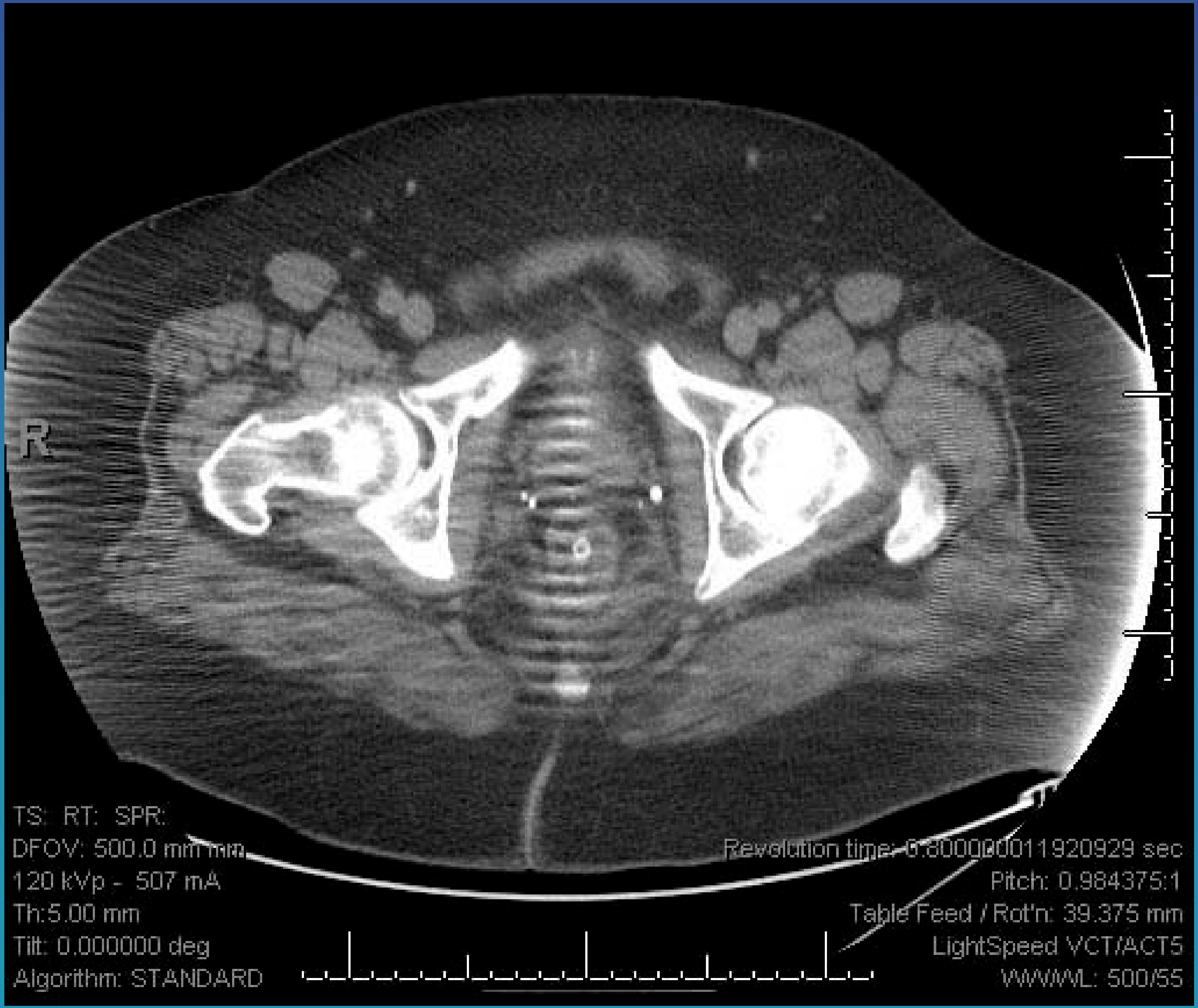


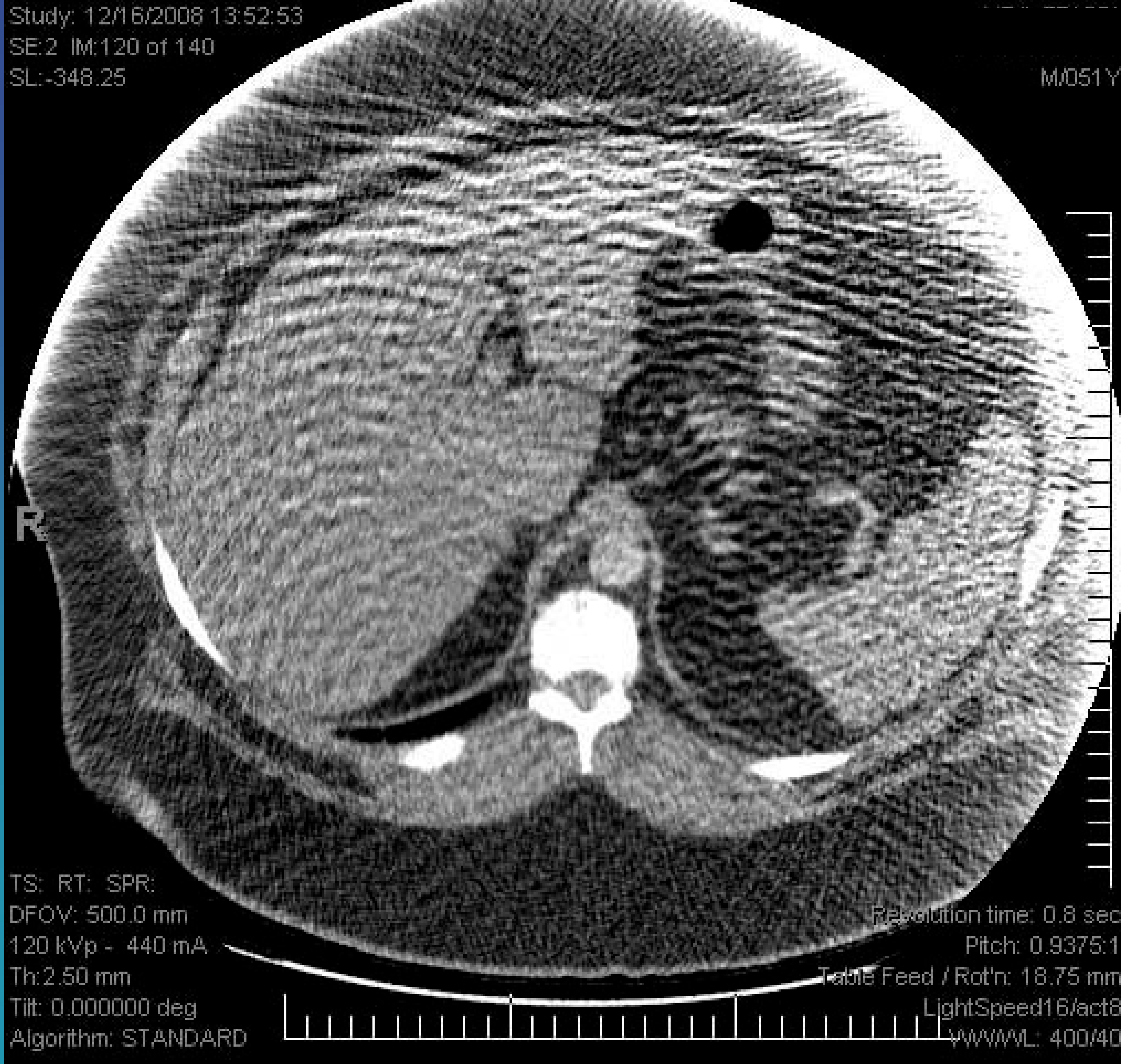
DFOV 50cm
140 kV
334 mA
1.0 sec/rotn
Pitch 0.5
10mm images

668 eff mAs

Mayo Clinic
James Kofler, Ph.D.

Blocked reference detector?




Study: 12/16/2008 13:52:53
SE:2 IM:120 of 140
SL:-348.25
M/051Y
R
TS: RT: SPR:
DFOV: 500.0 mm
120 kVp - 440 mA
Th:2.50 mm
Tilt: 0.000000 deg
Algorithm: STANDARD
Revolution time: 0.8 sec
Pitch: 0.9375:1
Table Feed / Rot'n: 18.75 mm
LightSpeed16/act8
WW/WL: 400/40

Patient size thresholds

•**Lateral width** the best predictor of acceptable image quality

We used DFOV in place of lateral width

< 36 cm => 80 kV imaging acceptable

< 41 cm => 100 kV imaging acceptable

> 42 cm => 120 kV

•Larger patients may not be able to undergo low kV imaging

•Patient size selection only insures good quality

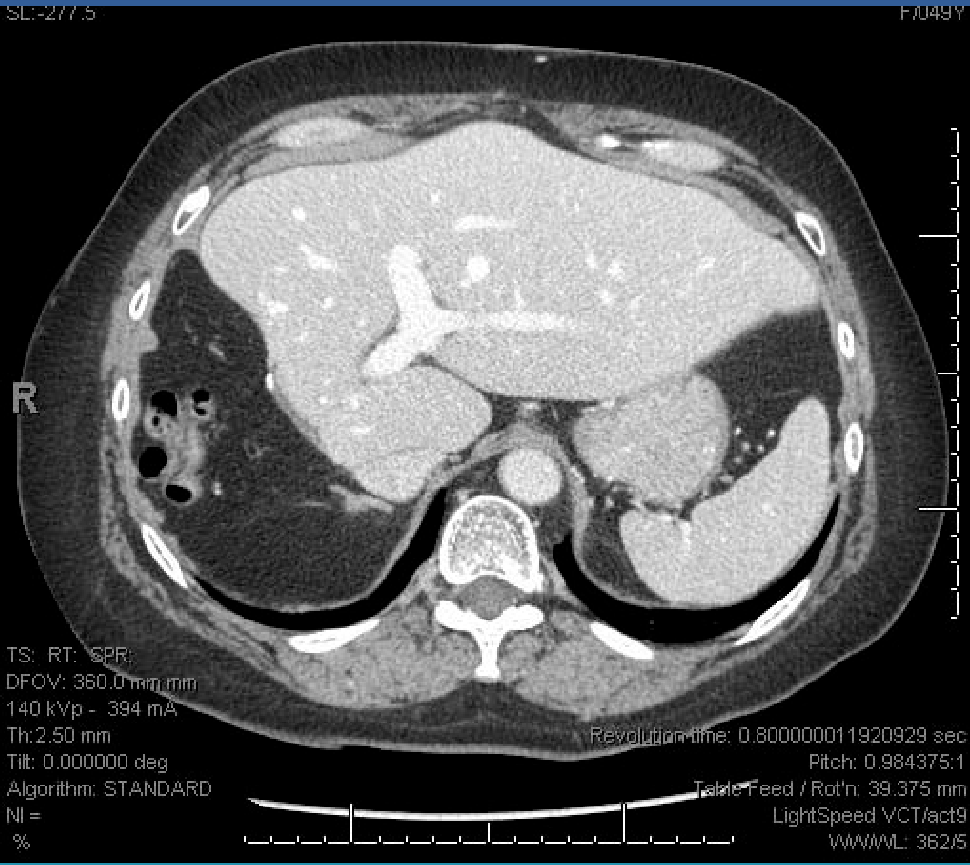
JG Fletcher, MD
Mayo Clinic

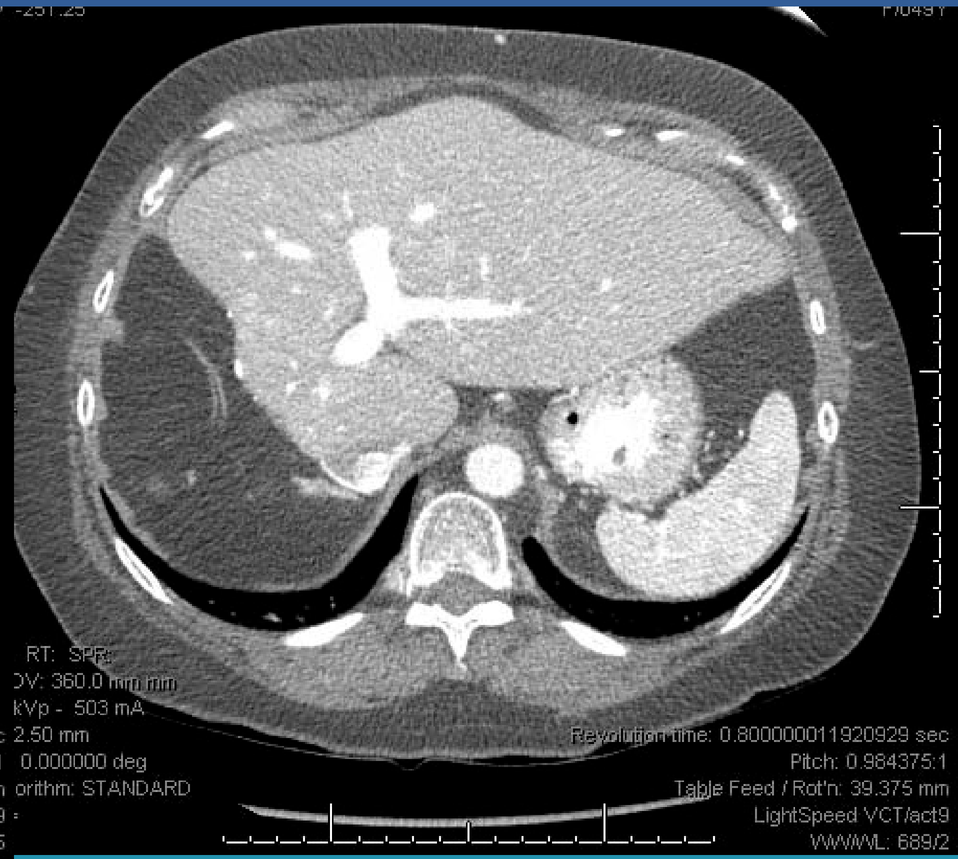
Liver Protocol

- Multiple scan phases
- Prior Settings
  - 140 kVp
  - NI: 10 - 13

- Same multiple scan phases
- Trial Settings
  - kVp according to DFOV
  - NI unchanged (goal)

Patient Example





140 kVp NI = 10 **80 kVp NI = 10**

Exam Description: CAP W CON-- LIVER

Dose Report

Series	Type	Scan Range (mm)	CTDIvol (mGy)	DLP (mGy-cm)	Phantom cm
1	Scout	-	-	-	-
2	Helical	I193.500-I463.500	26.19	827.72	Body 32
200	Axial	I332.250-I332.250	10.58	5.30	Body 32
4	Helical	I195.000-I405.000	41.86	1071.95	Body 32
4	Helical	I195.000-I405.000	41.85	1071.70	Body 32
4	Helical	I406.500-I711.500	54.39	1909.35	Body 32
7	Helical	I30.000-I360.000	19.13	720.20	Body 32
7	Helical	I195.000-I445.000	33.40	988.86	Body 32
7	Helical	I530.000-I645.000	37.58	605.41	Body 32
			Total Exam DLP:	7200.49	

140 kVp effective dose 108 mSv
80 kVp effective dose 26 mSv

LIV)

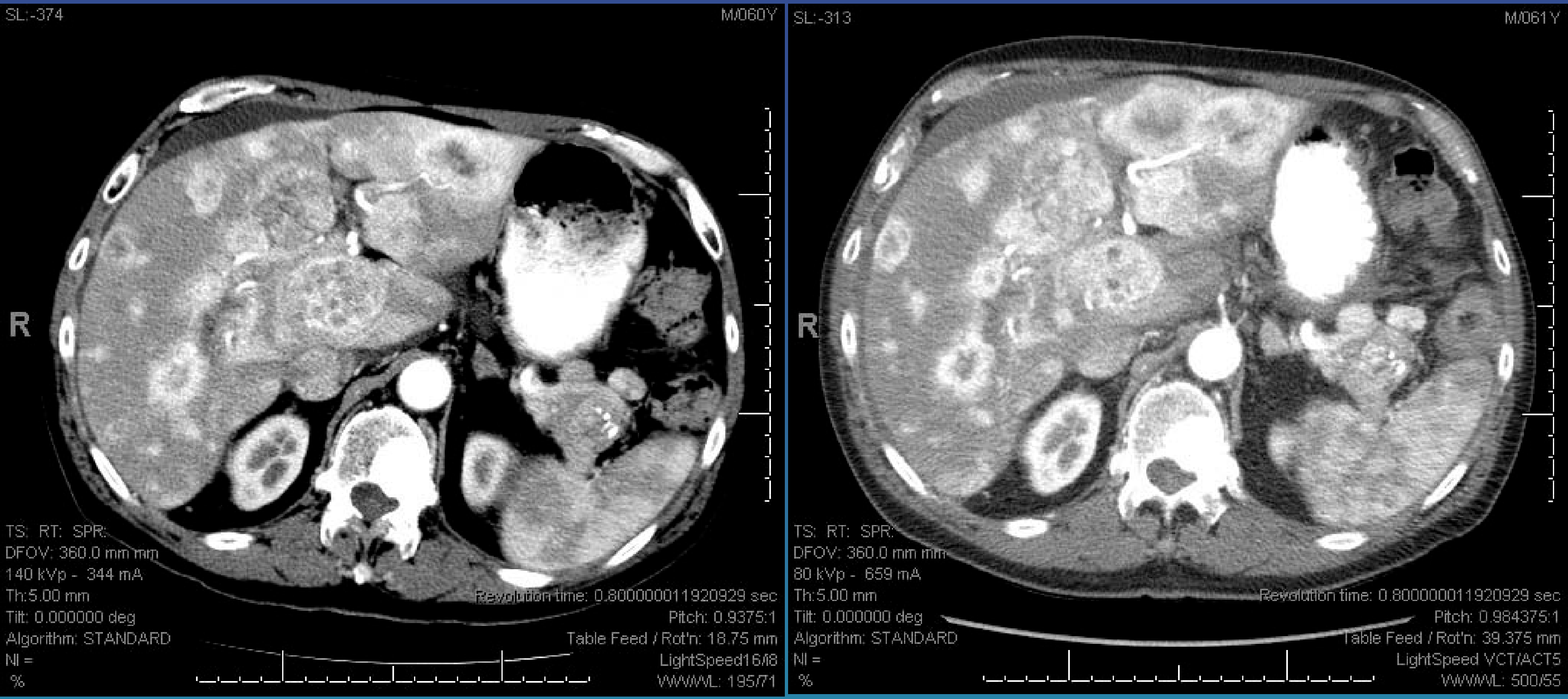
Dose Report

Series	Type	Scan Range (mm)	CTDIvol (mGy)	DLP (mGy-cm)	Phantom cm
1	Scout	-	-	-	-
2	Helical	I175.500-I390.500	8.32	217.28	Body 32
200	Axial	I285.000-I285.000	2.34	1.18	Body 32
4	Helical	I178.750-I343.750	10.40	219.58	Body 32
4	Helical	I178.750-I343.750	10.40	219.58	Body 32
4	Helical	I345.000-I640.000	8.32	283.86	Body 32
7	Helical	I1.250-I331.250	11.86	446.53	Body 32
7	Helical	I181.500-I406.500	8.32	225.60	Body 32
7	Helical	I538.000-I613.000	8.32	100.77	Body 32
			Total Exam DLP:	1714.38	

140 kV

80 kV

Another example of a small patient (36cm DFOV)
No dose report available on prior exam.



When **appropriate window/levels are used**, the contrast difference is somewhat mitigated.

Preliminary Conclusions regarding lower kV for multi-phase liver CT

- May have great potential to reduce dose (and improve IQ) in SMALLER patients
- May improve IQ in larger patients but substantial dose benefit is unlikely

What about smaller patients?

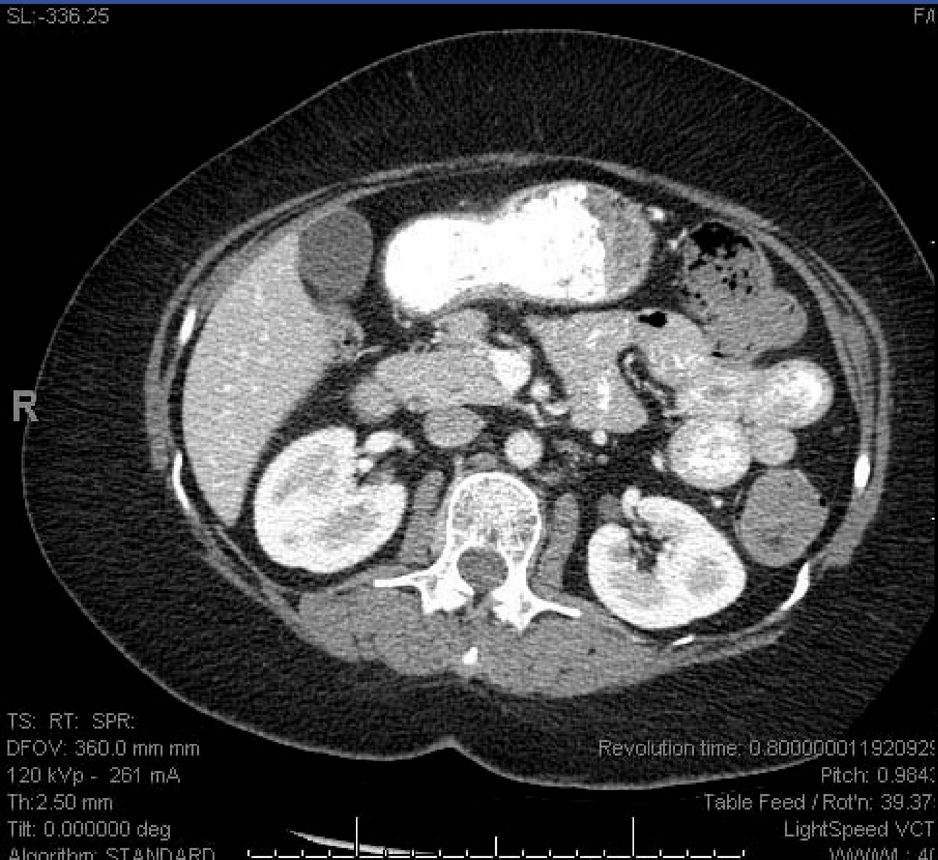
- Pediatric patients become adult patients
  - On specific birthday (18 years?)
  - Big size change before and after birthday?
- Some adult patients are small
- Don’t benefit from extra radiation dose delivered from “standard” size protocols!

Adjust protocols for smaller size patients?

- Use tube current modulation
- For some TCM schemes, need to adjust noise target for smaller patients
- Technique chart
  - Decrease effective mAs by ~30%*
  - Select patient size criteria
  - DFOV $\leq$ 38cm*

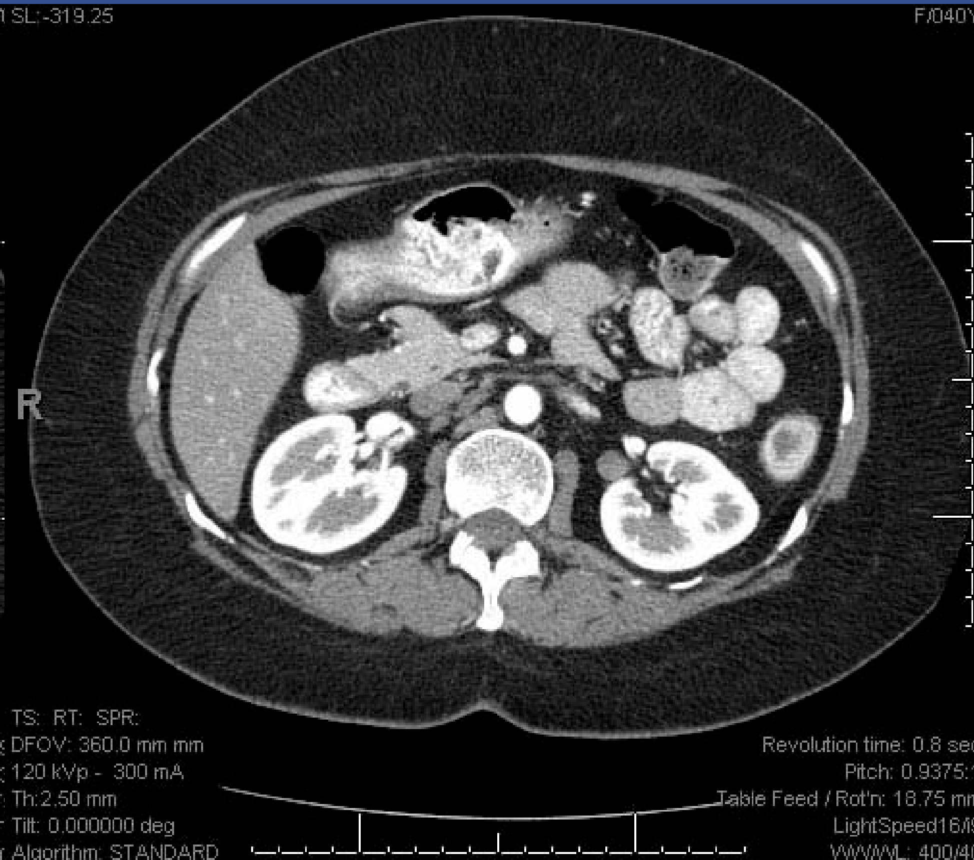
*MD Anderson approach

212 eff mAs



VCT TCM w/reduced max mA

255 eff mAs

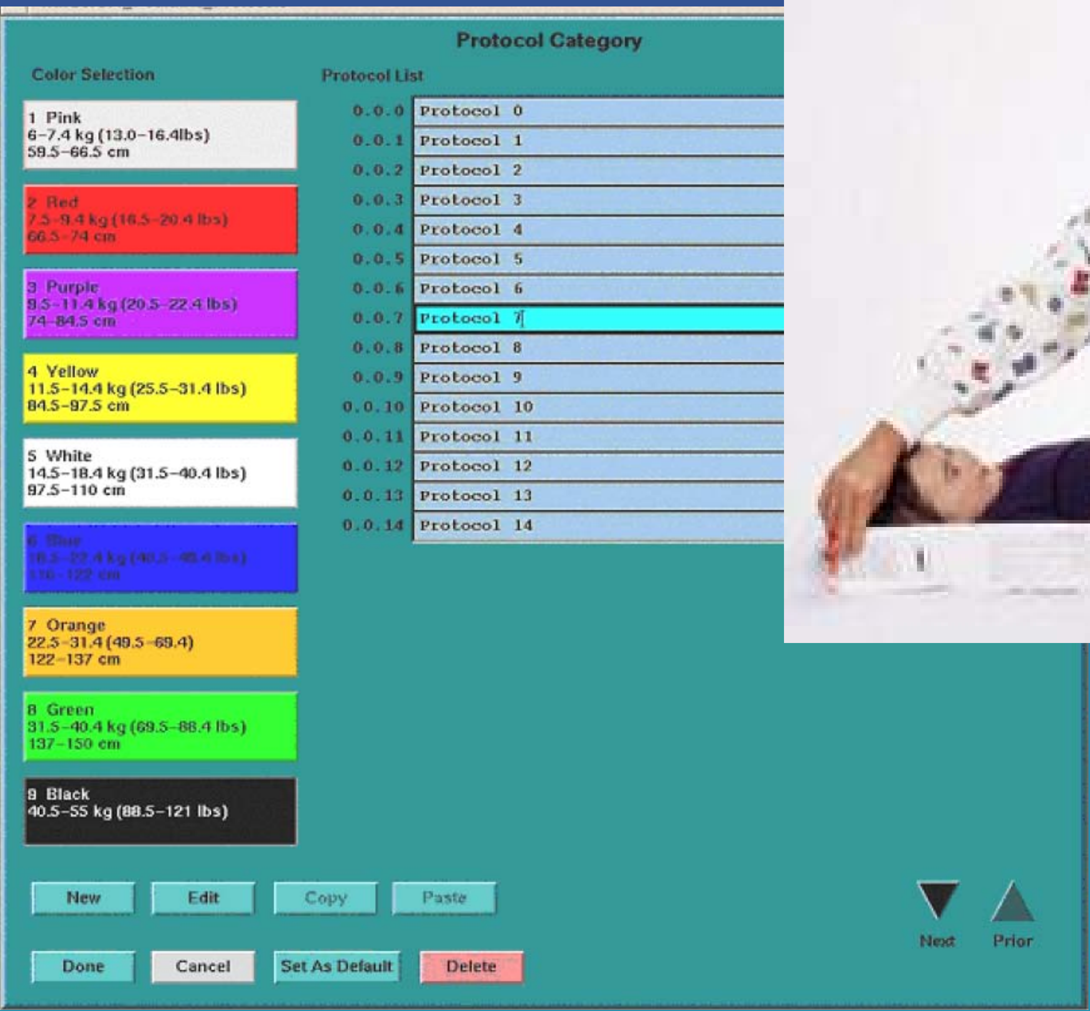


LS-16 manual technique

Pediatric Patients?

- Use tube current modulation
- For some TCM schemes, need to adjust noise target for smaller patients (as well as small adults)
- Technique chart
  - Select size criteria
  - Scale effective mAs for size
  - Consider using 80 & 100 kVp

Color Coding for KIDS



February 2008
Volume 63, Issue 2

ACR BULLETIN

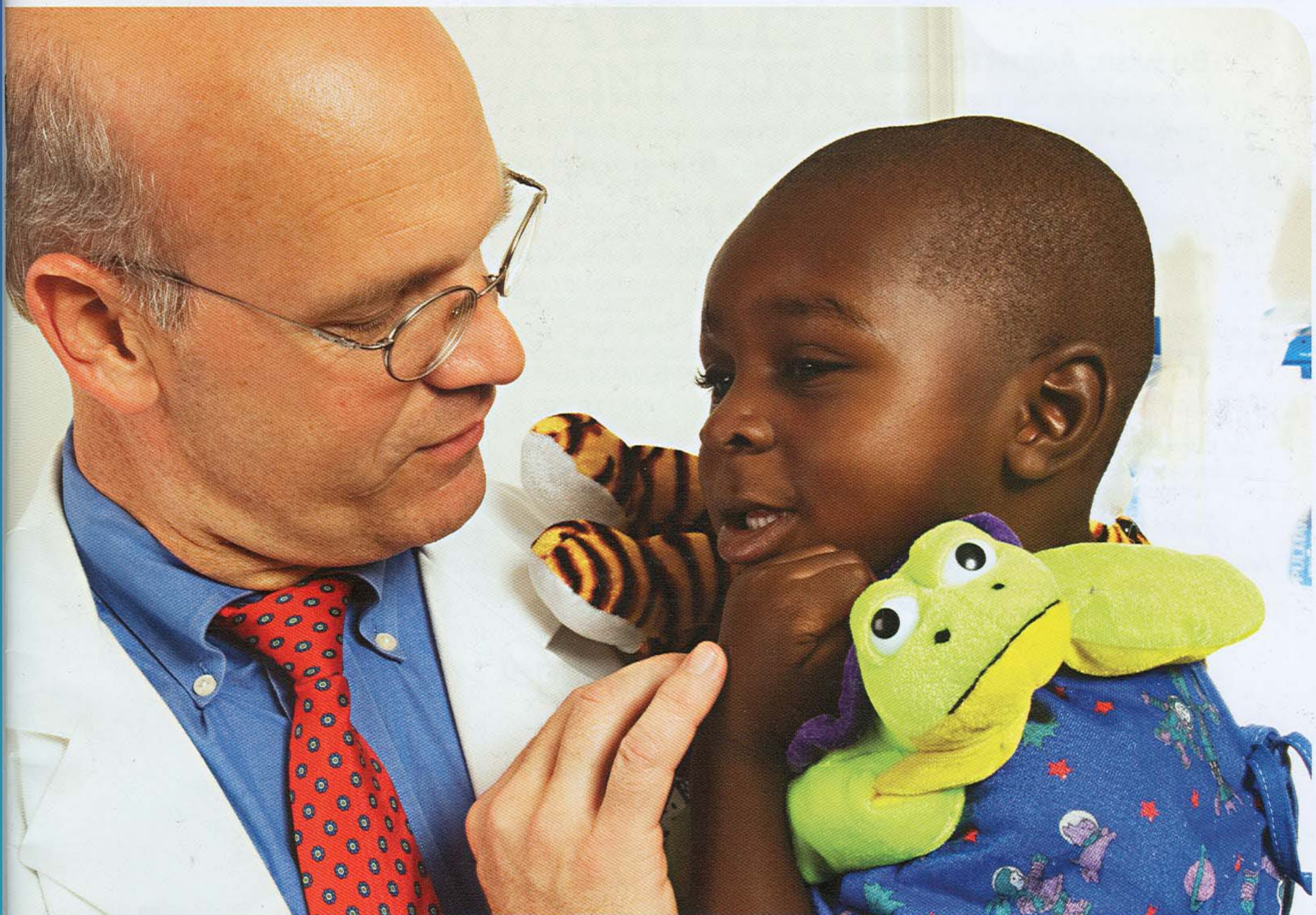


Image Gently and Protect Our Greatest Resource

Zone	Wt	Length	Age	Chest	Abd Pelvis
PINK	5.5 – 7.4 kg	60-67 cm	2.5 – 5.5 mo	9.5	6.5
RED	7.5 – 9.4 kg	67-75 cm	5.5 – 11.5 mo	10.0	7.5
PURPLE	9.5 – 11.4 kg	75-85 cm	11.5 – 22 mo	10.5	8.5
YELLOW	11.5 – 14.4 kg	85-97 cm	22 mo – 3yr, 2 mo	11	9.5
WHITE	14.5 – 18.4 kg	97-109 cm	3 ys, 2 mo – 5 yr, 2 mo	12	10.5
BLUE	18.5 – 23.4 kg	109-121 cm	5 yr, 2 mo – 7 yr, 4 mo	13	11.5
ORANGE	23.5 – 29.4 kg	121-133 cm	7 yr, 4 mo – 9 yr, 2 mo	14	12.5
GREEN	29.5 – 36.4 kg	133-147 cm	9 yr, 2 mo – 13 yr, 6 mo	15	13.5
BLACK	36.5 – 55 kg	>147 cm	>13 yr, 6 mo	16	14

Courtesy of Don Frush, M.D.

Noise Index

Zone	Wt	Length	Age	Chest	Abd Pelvis
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Noise Index

Courtesy of Don Frush, M.D.

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WHITE	14.5 – 18.4 kg	97-109 cm	3 ys, 2 mo – 5 yr, 2 mo	12	10.5
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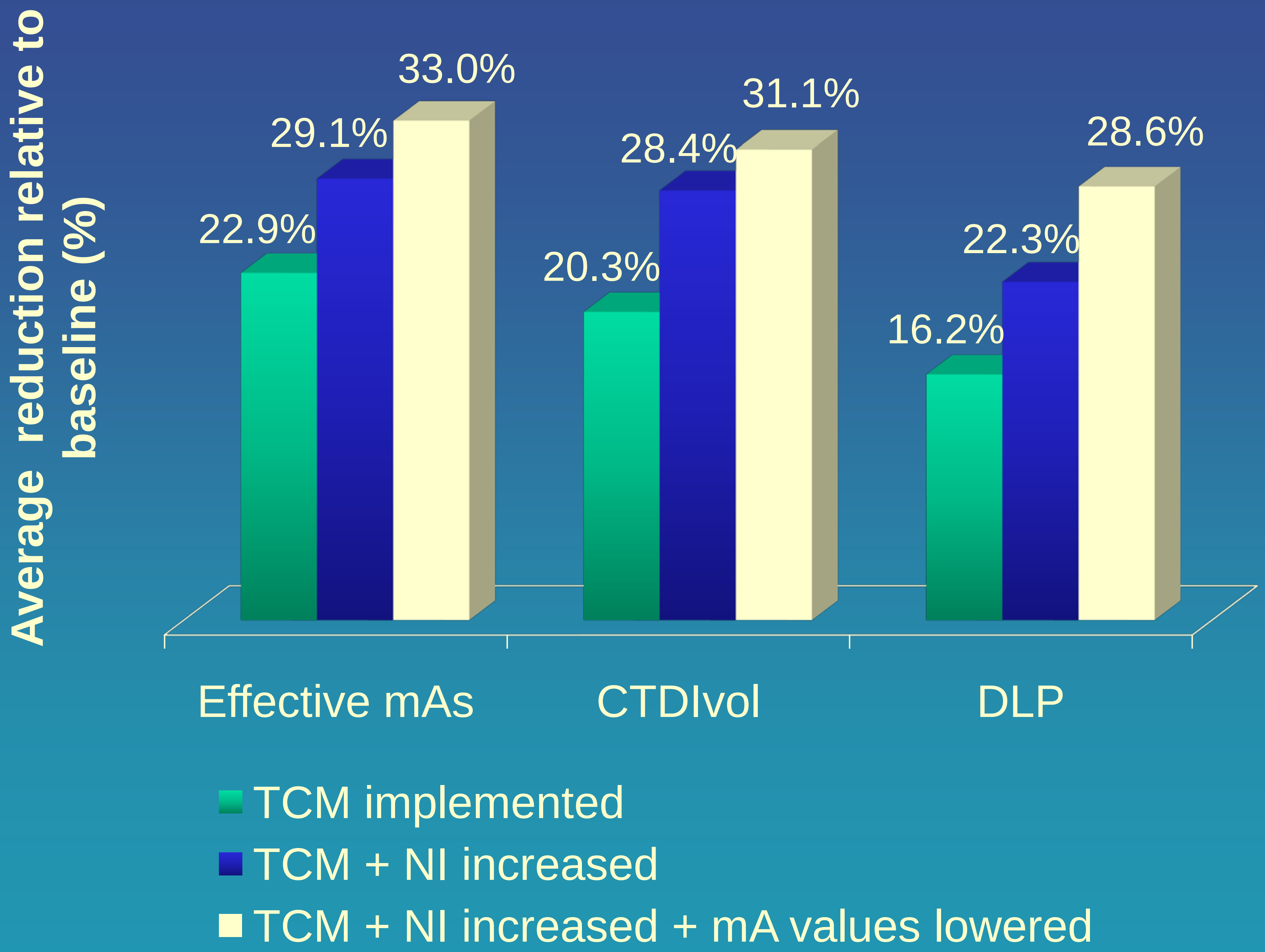
BLACK	36.5 – 55 kg	>147 cm	>13 yr, 6 mo	16	14

Noise Index

Courtesy of Don Frush, M.D.



Average reduction relative to baseline (%)
33.0%
29.1%
22.9%
31.1%
28.4%
20.3%
28.6%
22.3%
16.2%
Effective mAs
CTDIvol
DLP
TCM implemented
TCM + NI increased
TCM + NI increased + mA values lowered

Faster Acquisitions

- **Multiple images per gantry rotation**
- **Reduce motion artifact**
  - **Peristalsis, cough, crying, voluntary motion …**
- **Enable reduction in pediatric sedations**
  - **Safer for children (no shields during scout!!)**
  - **Money and time savings**

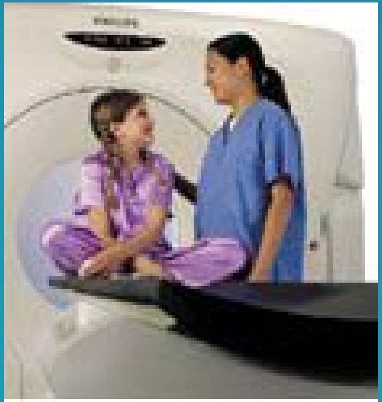
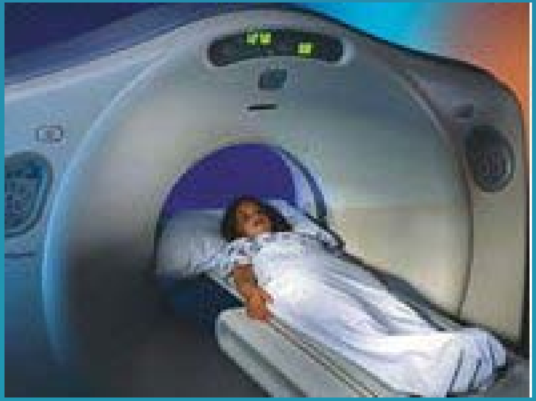



image gently℠

The Alliance for Radiation Safety in Pediatric Imaging

- Program sponsored by several professional organizations
- Goal is to remind staff to always use size specific radiographic techniques for kids
- Guidelines for designing pediatric CT protocols
  - Manual techniques – doesn’t have guidelines for tube current modulation
- New materials helpful for parents

www.imagegently.com

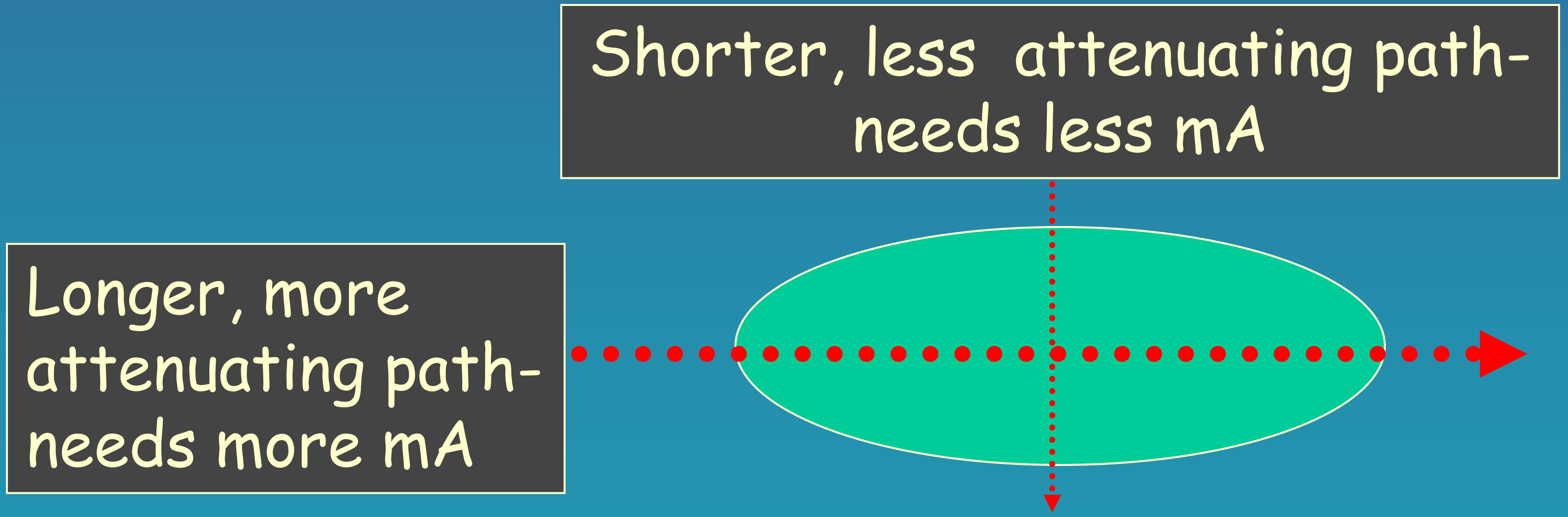
Pediatric Protocols for Siemens S64
Using Tube Current Mod. (CareDose4D) and changing kVp w/ size

Weight	Chest		Abdomen	
	kVp	Qref mAs	kVp	Qref mAs
< 5 kg	80	45	80	45
6-15 kg	80	55	80	55
16-60 kg	100	55	100	65
> 60 kg	120	55	120	65

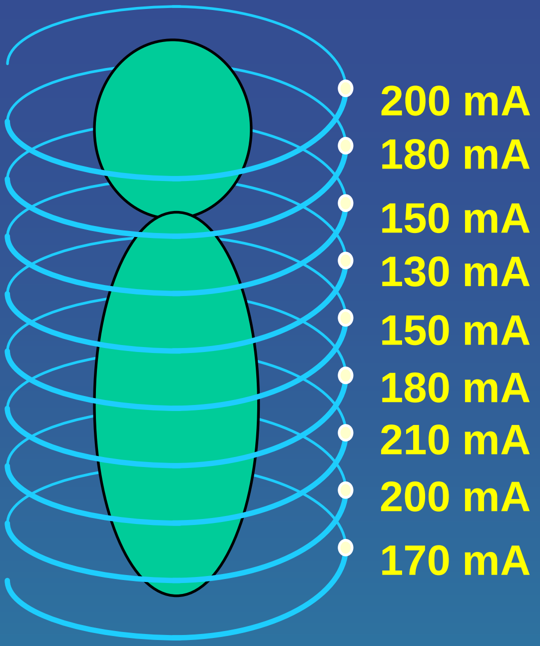
Based on Kim and Newman *AJR 2010; 194:1188–1193*

Dose Reduction Options

- Some Scanners offer capability to vary mA as tube rotates around patient
  - *Currently*, based on predicted values of attenuation (from 2 planning views)
  - *Future*, adjust mA to essentially perform AEC



Dose Reduction Options



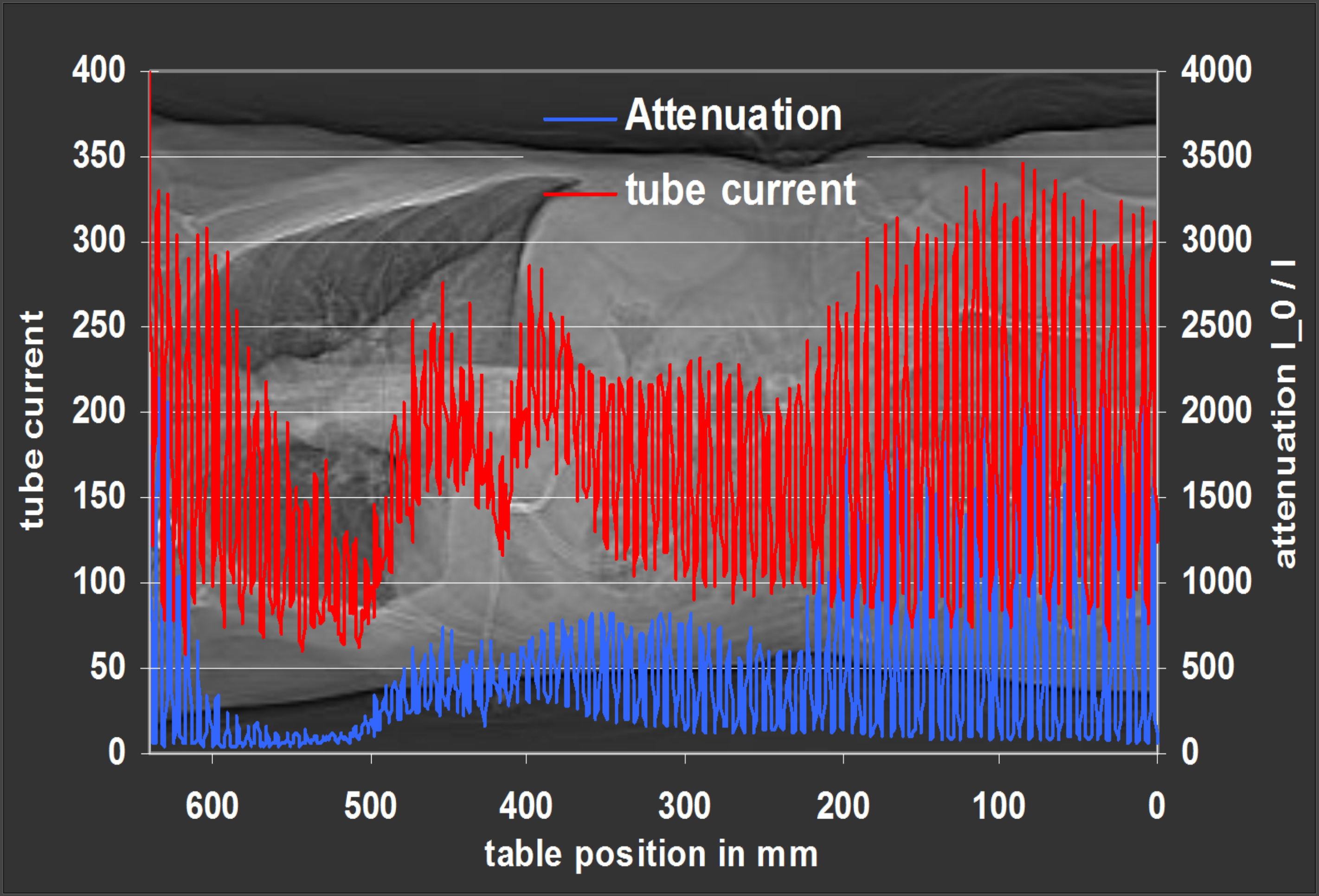
- Dose reduction based on patient anatomy
- Lower mA in AP, higher mA in lateral directions

Methods

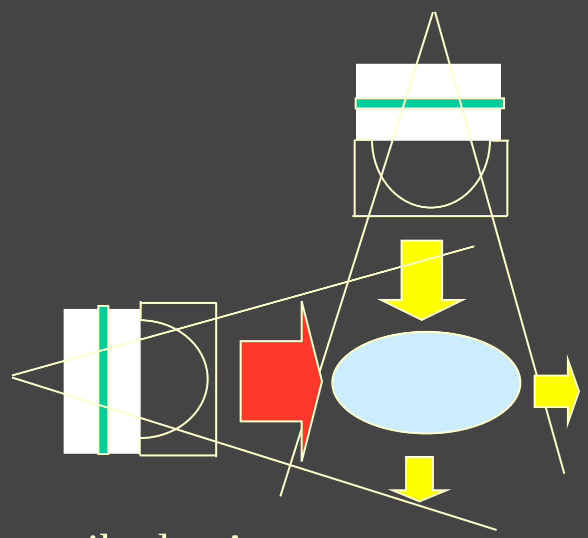
- Patient attenuation measured during scout scan (AP & Lat) and alter mA for each gantry rotation (Smart mA[1], Sure Exposure[2], Z-DOM[3] and/or "on-the-fly" (Care dose[4])
- Use same kV in scout as in helical sequence [1,2,3]
- Dose reduction of 20-40% has been reported

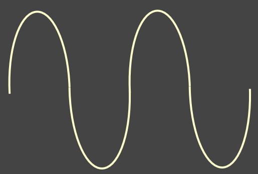
[1] GE, [2] Toshiba, [3] Philips, and [4] Siemens MDCT

Optimal mA for a.p. and lat. Views:
On-line mA modulation



AutomA and SmartmA automatically adjust tube current



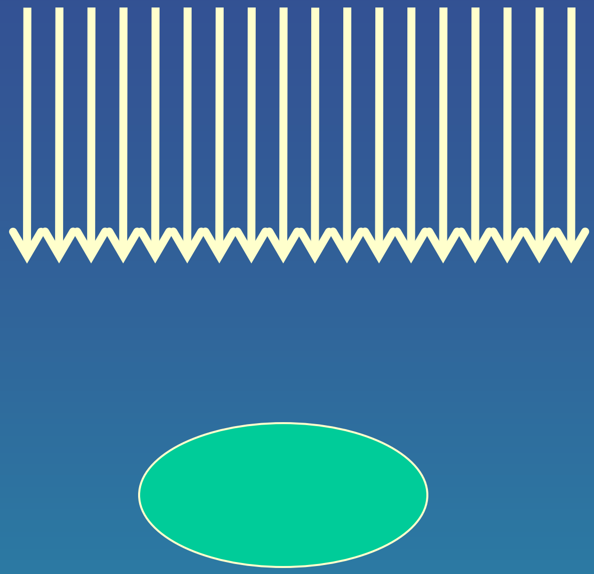


Incident X-ray flux decreased vs angle depending on patient asymmetry

- AutomA (Z) reduces noise variation allowing more predictable IQ. Dose reduction depends on User (Noise index = image noise)

- Smart mA (X,Y) reduces dose without significantly increasing image noise

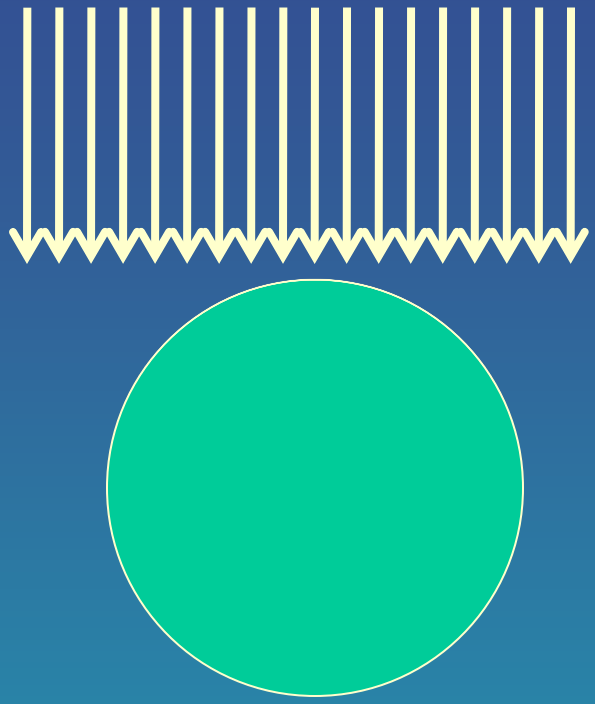
Use of Scout Image for TCM



Att’n pattern

↓

Patient shape & size



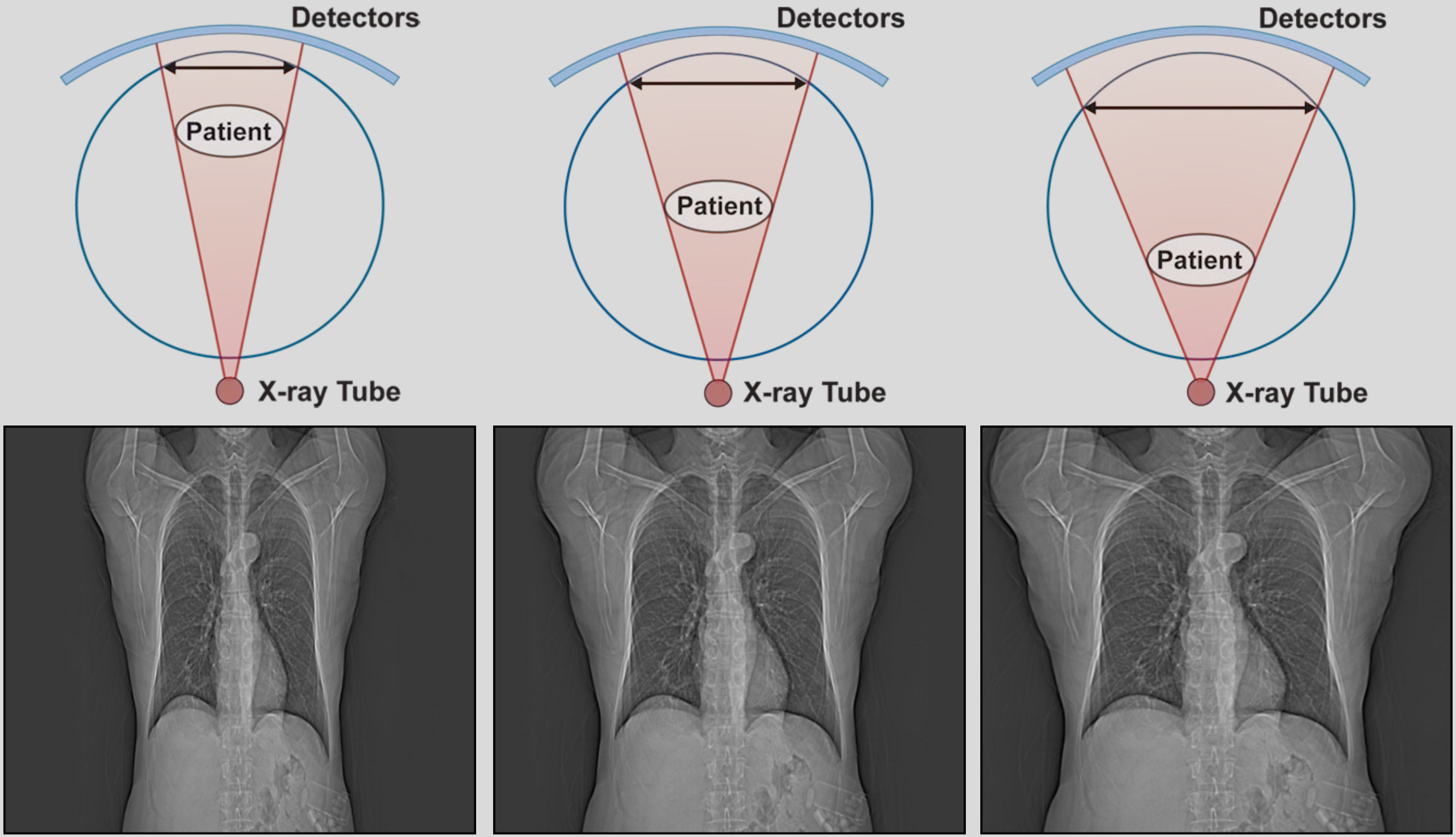
Att’n pattern

↓

Patient shape & size

mA Modulation Scout Scans

Jim Kofler, Ph.D.



Tube Current Modulation

- Set noise target (or reference mAs)
- Set **minimum** & **maximum** mA limits
- Be sure the final scout is the one with the best image quality (AP vs Lateral)

Current Modulation Schemes

Manufacturer	**Parameter**	**Reference**
GE	Noise Index	SD water phantom
Philips	Reference Image	Raw data, scout, SD in acceptable patient image
Siemens	Quality Ref. Eff. mAs	Adult - Eff. mAs for 70kg Peds – Eff. mAs for 25 kg
Toshiba	SD	SD water phantom

Tube Current Modulation methods may vary the tube current:

0% 1. In the x-y plane only

0% 2. Along the longitudinal direction only

0% 3. Along time such as at different patient visits

0% 4. In the x-y plane as well as longitudinal direction

0% 5. In the x-y plane, longitudinal direction and across time

10

Tube Current Modulation methods may vary the tube current:

0% 1.

0% 2.

0% 3.

0% 4. In the x-y plane as well as longitudinal direction

0% 5.

McCollough CH, Bruesewitz MR, Kofler JM Jr. CT dose reduction and dose management tools: overview of available options. Radiographics. 2006 Mar-Apr;26(2):503-12

10

Tube Current Modulation methods may be able to take into account patient size:

0%
0%
0%
0%
0%

1. For pediatric and adult patients, including obese patients
2. Only for morbidly obese patients
3. Only for pediatric patients
4. Only for Abdominal Scans
5. Only for Thoracic Scans

10

Tube Current Modulation methods may be able to take into account patient size:

0% 1. For pediatric and adult patients, including obese patients

0% 2.

0% 3.

0% 4.

0% 5.

McCollough CH, Bruesewitz MR, Kofler JM Jr. CT dose reduction and dose management tools: overview of available options. Radiographics. 2006 Mar-Apr;26(2):503-12

10

Under what condition does Tube Current Modulation fail (produce images that radiologists find unacceptable for interpretation)?

0%	1.	When X-ray tube has inadequate tube performance (output)
0%	2.	When a minimum mA setting is used that is too low
0%	3.	When a poor scout image is used for modulation planning
0%	4.	When the patient table is either way too low or way too high in the gantry opening
0%	5.	All of these conditions can cause tube current modulation schemes to produce images that would be considered unacceptable by an interpreting radiologist.

10

Under what condition does Tube Current Modulation fail (produce images that radiologists find unacceptable for interpretation)?

0%	1.
0%	2.
0%	3.
0%	4.
0%	5. All of these conditions can cause tube current modulation schemes to produce images that would be considered unacceptable by an interpreting radiologist.

McCollough CH, Bruesewitz MR, Kofler JM Jr. CT dose reduction and dose management tools: overview of available options. Radiographics. 2006 Mar-Apr;26(2):503-12

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Bismuth Shields???

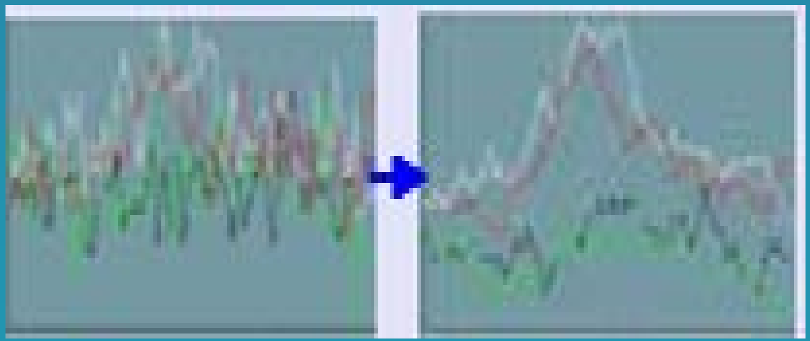
- Becoming ‘red’ state vs ‘blue’ state issue…
- If staff decide to use them:
  - Place on patient AFTER scouts are completed
  - If placed before scout, dose **increased** by ~15%
  - Coursey, et al. AJR 190:2008
  - Shield alone decreased breast dose by 26%
  - Shield + TCM decreased breast dose by 52%
  - IMAGE QUALITY IMPACT

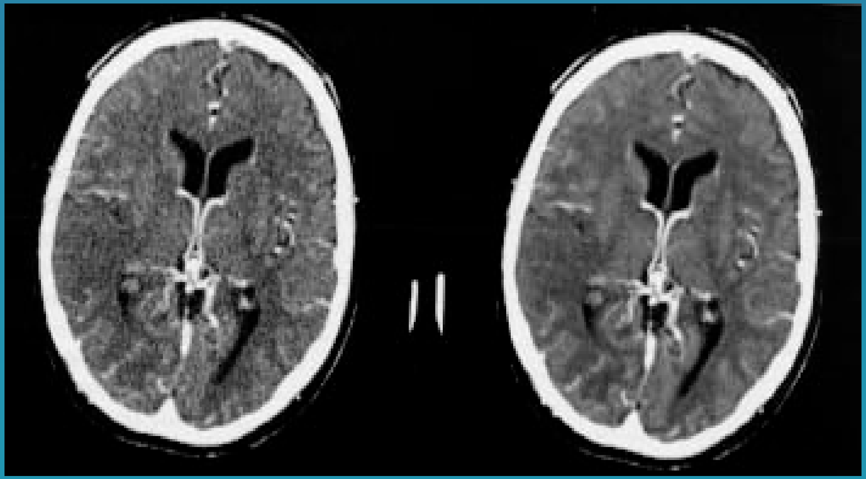
Advanced Image Reconstruction

- Several Approaches with Goals of:
  - Reducing Noise
  - Preserving Image Quality
- Non-linear Image Processing
    - Reduce Noise in smooth regions, preserve edges
- Iterative Reconstructions
  - Usually take longer and so have been employed on a limited basis.
  - faster computing may make these more popular.

Advanced Image Processing Algorithms

- Adaptive filtering at the projection level reduces noise as a function of attenuation
- Non-linear image processing algorithms reduce noise image while maintaining sharpness

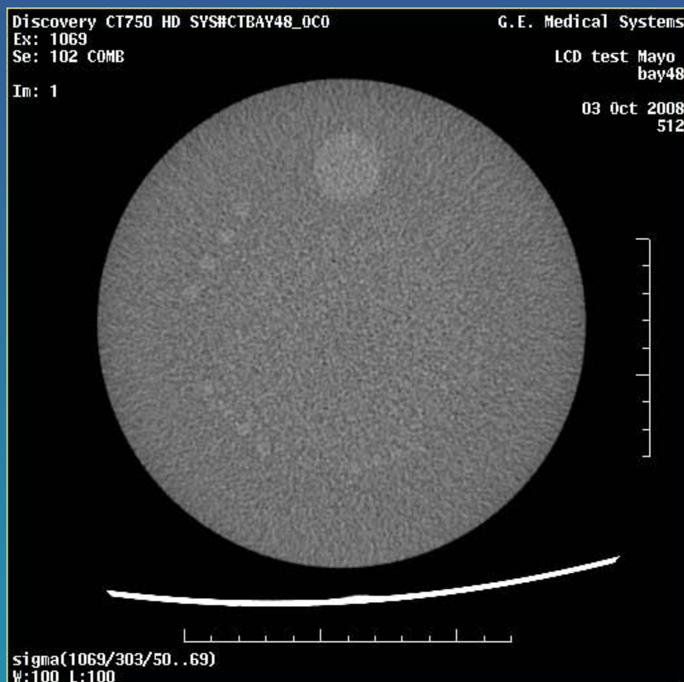




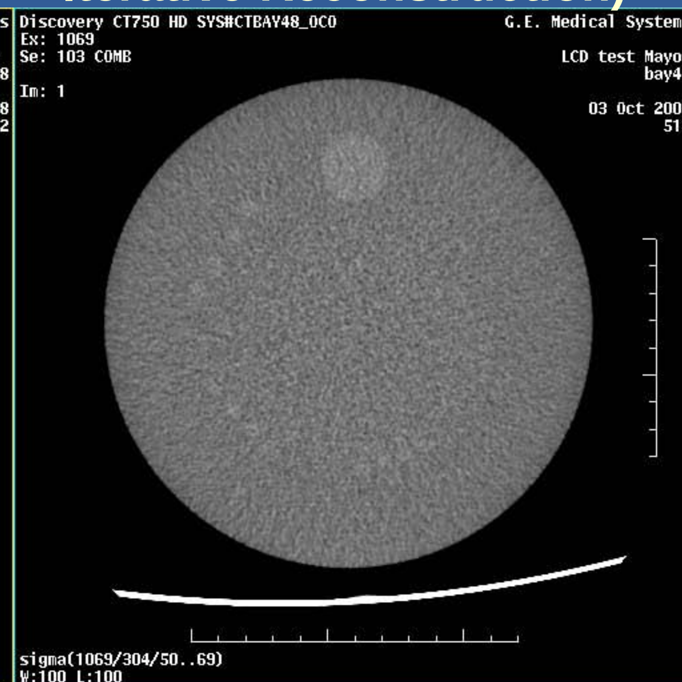
Unprocessed Image **After Filtering**

LCD Phantom (50% Dose Reduction)

Conventional FBP



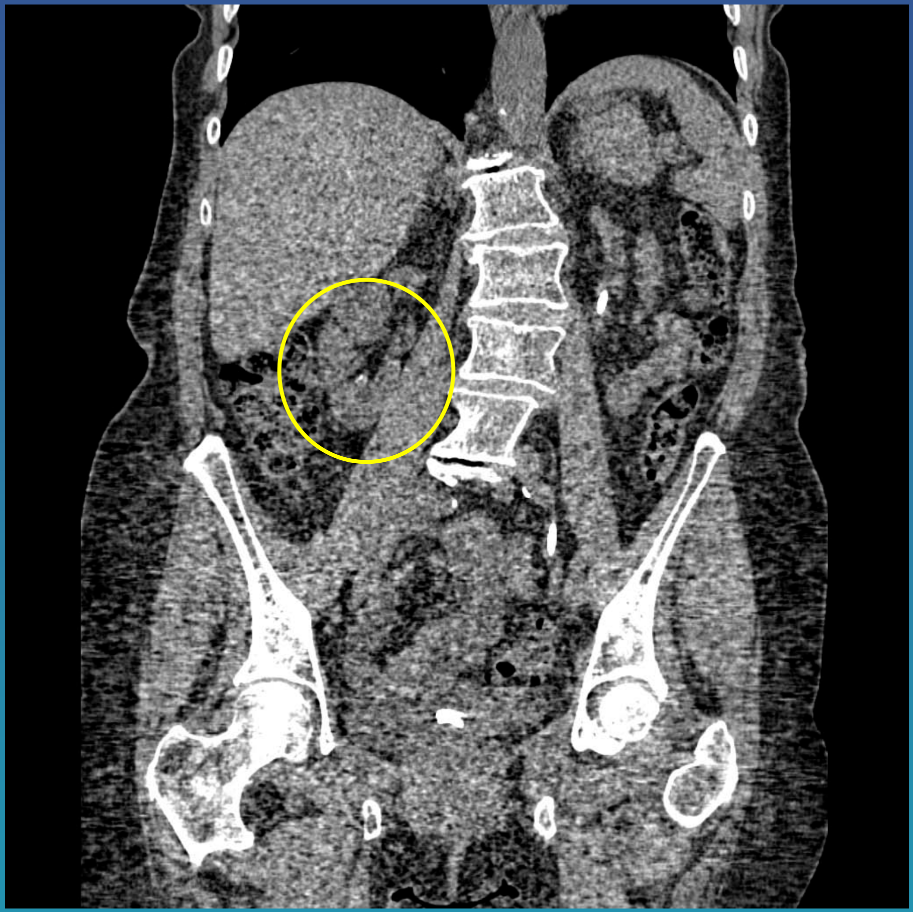
ASIR
(Advanced Statistical Iterative Reconstruction)



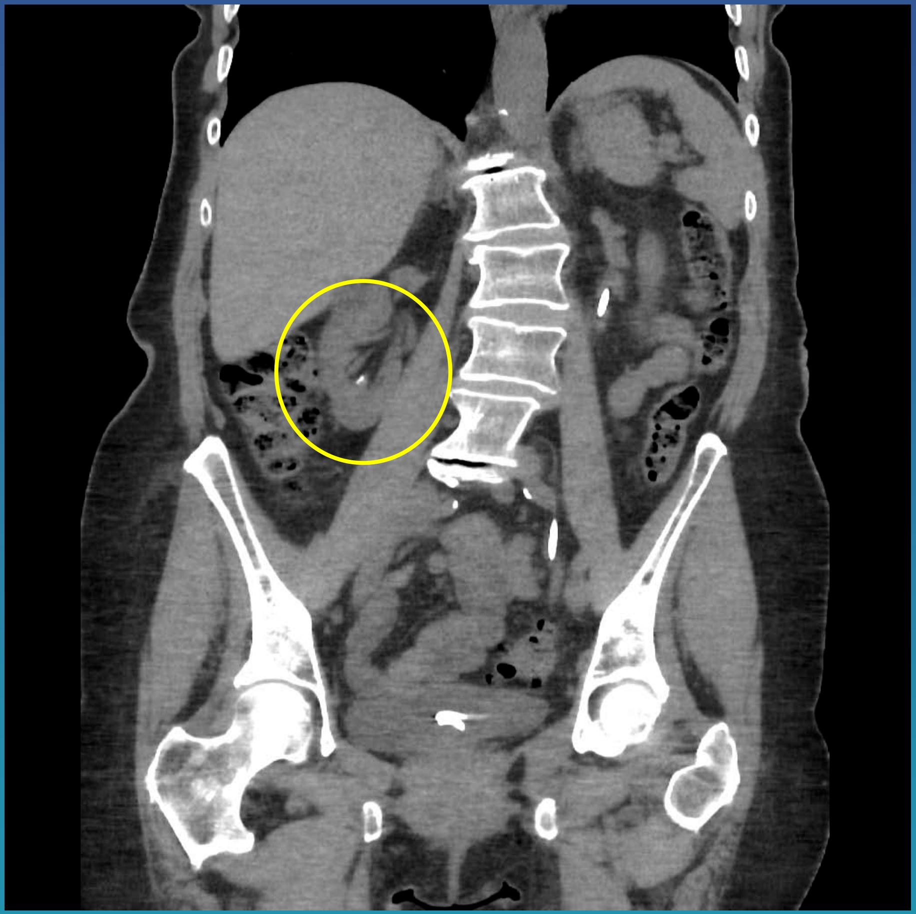
Full dose: CTDIvol= 25.08mGy 10mm slice thickness

Half dose: CTDIvol= 12.42mGy, 50% Volume ASIR, 10mm slice

Noise Reduction



FBP



ASIR

When compared to conventional Filtered Back Projection techniques, Iterative Reconstructions techniques can result in:

0%	1. An increase in radiation dose.
0%	2. Lower spatial resolution
0%	3. An increase in image noise
0%	4. A decrease in temporal resolution
0%	5. A decrease in low contrast resolution

10

When compared to conventional Filtered Back Projection techniques, Iterative Reconstructions techniques can result in:

0%	1.
0%	2. Lower spatial resolution
0%	3.
0%	4.
0%	5.

Ref: Hara AK, Paden RG, Silva, AC, Kujak JL. Lawder HJ, Pavlicek W. Iterative Reconstruction Technique for Reducing Body Radiation Dose at CT: Feasibility Study. AJR 2009; 193:764–771

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Iterative Reconstruction Techniques result in a reduction in radiation dose by:

0%	1. Scanning the patient multiple times with reduced radiation mA and then iterating by minimizing errors in pixel values.
0%	2. Iterating through different mA values until the ideal image quality is obtained
0%	3. Scanning at a lower mA technique and then applying a smoothing and edge preserving function multiple times
0%	4. Scanning at two different kVp levels until noise levels are obtained that are similar to conventional dose images.
0%	5. Scanning at a lower mA technique and then iterating through different patient models until the ideal noise level is reached.

10

Iterative Reconstruction Techniques result in a reduction in radiation dose by:

0% 1.

0% 2.

0% 3. Scanning at a lower mA technique and then applying a smoothing and edge preserving function multiple times

0% 4.

0% 5.

Ref: Hara AK, Paden RG, Silva, AC, Kujak JL. Lawder HJ, Pavlicek W. Iterative Reconstruction Technique for Reducing Body Radiation Dose at CT: Feasibility Study. AJR 2009; 193:764–771

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What should sites use for CT radiation dose limit guidance?

0%
0%
0%
0%
0%

1. AAPM Report 96 for head, chest, abd, pelvis exams only.
2. Most recent NEXT survey for CT.
3. AAPM Report 39 for head, chest, abdomen exams only.
4. FDA equipment performance standard for CT
5. American College of Radiology CT Accreditation dose limits for adult chest, adult abdomen, and pediatric abdomen exams only.

10

What should sites use for CT radiation dose limit guidance?

0%	1.
0%	2.
0%	3.
0%	4.
0%	5. American College of Radiology CT Accreditation dose limits for adult chest, adult abdomen, and pediatric abdomen exams only.

McCollough CH, Bruesewitz MR, McNitt-Gray MF, Bush K, Ruckdeschel T, Payne JT, Brink JA, Zeman RK; American College of Radiology.
The phantom portion of the American College of Radiology (ACR) computed tomography (CT) accreditation program: practical tips, artifact examples, and pitfalls to avoid. Med Phys. 2004 Sep;31(9):2423-42.

10

Lessons learned (the hard way)…

- Monitor every protocol parameter, including **min mA**
- Caution techs regarding **changing patient orientation after scout/topogram**
- Scanner may revert to default manual technique (yet another set of parameters to set and monitor)
- **End of Section on Patient Size**

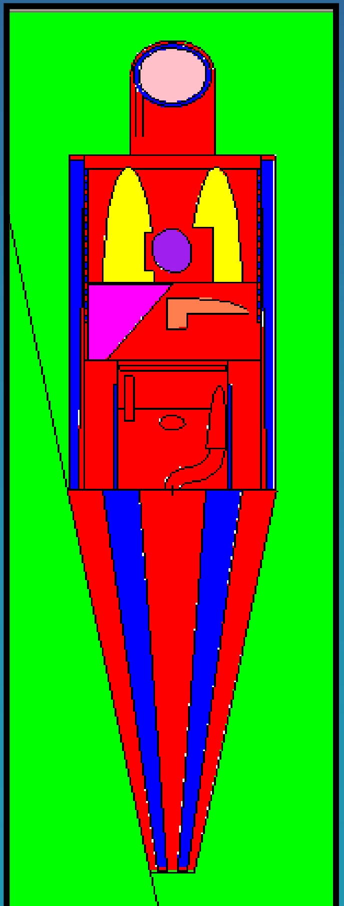
Monte Carlo Simulation Methods for Estimating Radiation Dose

Monte Carlo Simulation Methods for Estimating Radiation Dose

- Monte Carlo methods
  - Used in CT for some time
    - NRPB report 250 (1990)
    - GSF (Zankl)

Background

- These early reports used:
  - Detailed Models of Single Detector, Axial Scanners
  - Idealized (Nominal) collimation
  - Standard Man Phantom
    - MIRD V (geometric model) →
    - Eva, Adam



Background

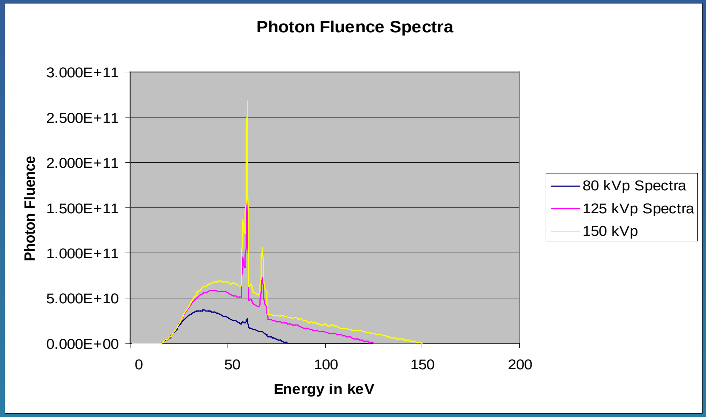
- These form the basis for:
  - CT Dose computer program
  - CT Expo
  - ImPACT dose calculator
  - k factor approach (Effective dose = k* DLP), which was derived from NRPB simulated data

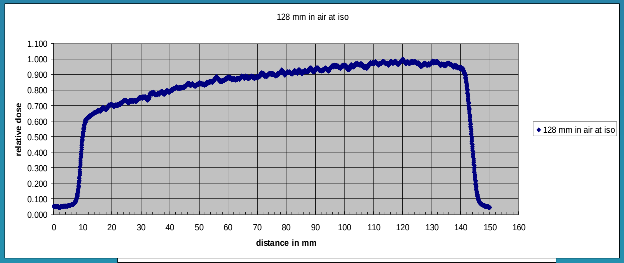
Current Approaches

- Model Scanner (e.g MDCT) in detail
- Model Patient (Geometric, Voxelized)
- Simulate Scan
- Tally Organ Dose

Modeling the CT scanner

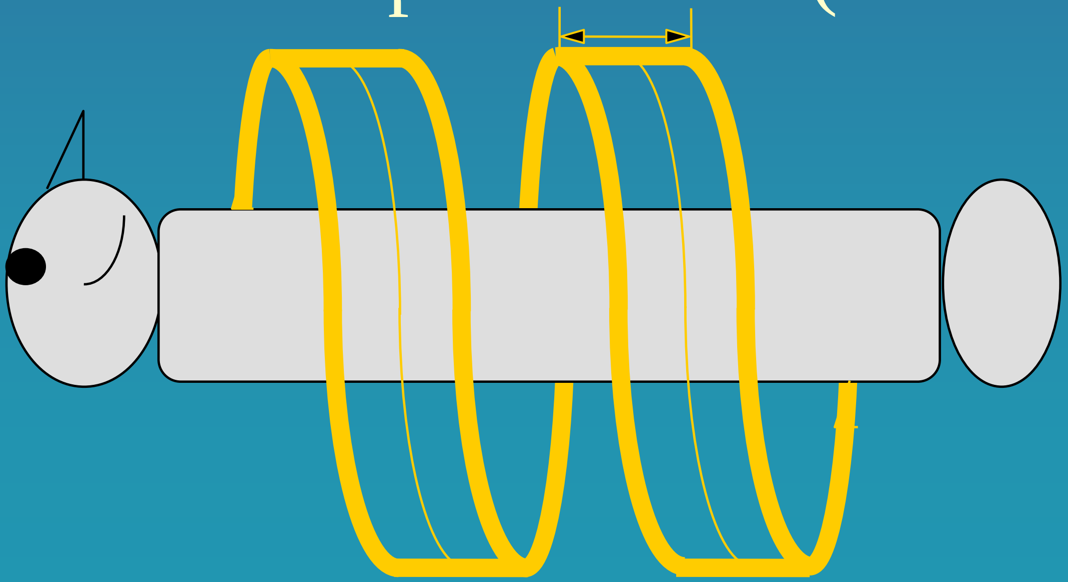
- Spectra
  - Function of beam energy
- Geometry
  - Focal spot to isocenter, fan angle
- Beam Collimation
  - Nominal or actual
- Filtration
  - Bowtie filter (typically proprietary)
  - Other add'l filtration (also proprietary)
- Tube Current Modulation Scheme
  - x-y only, z-only, x-y-z, etc.



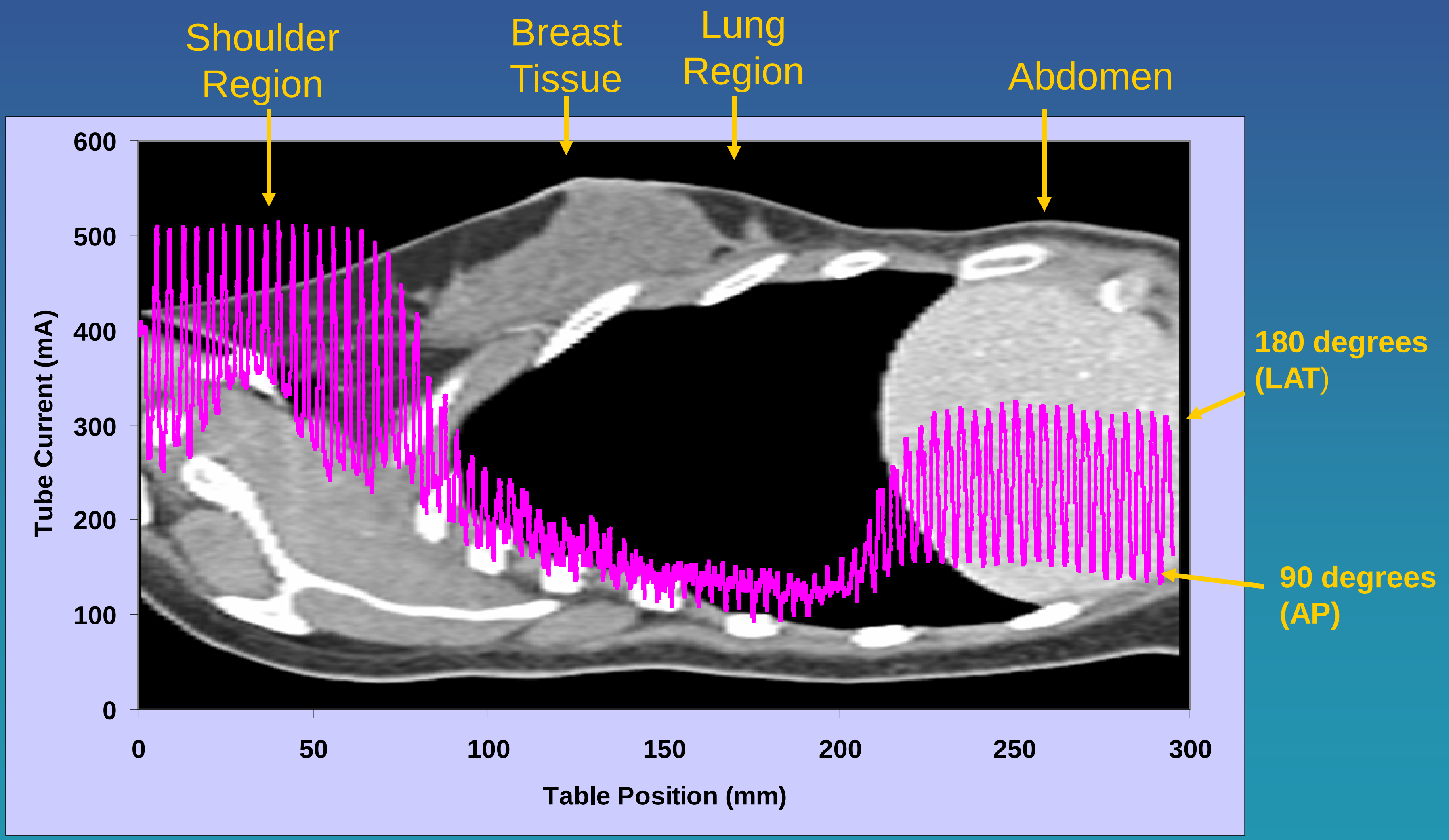


Modeling the CT scanner

- Source Path - dependent on scan parameters:
  - Nominal collimation
  - Pitch
  - Start and Stop Locations (of the source)

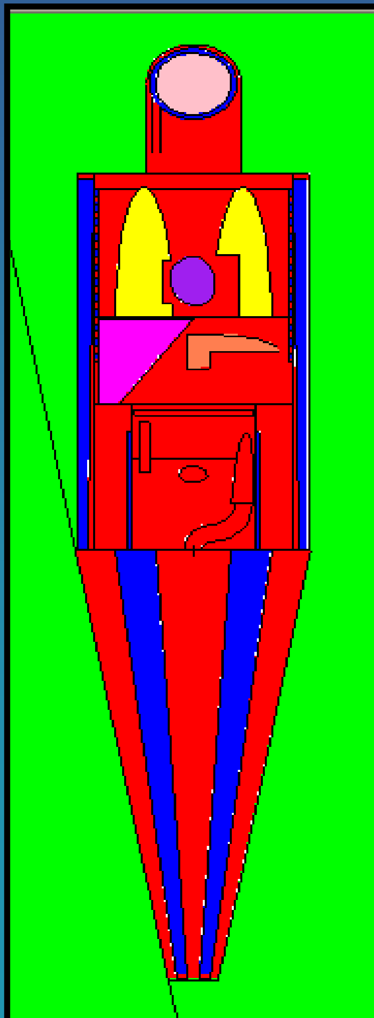


Long Axis Modulation



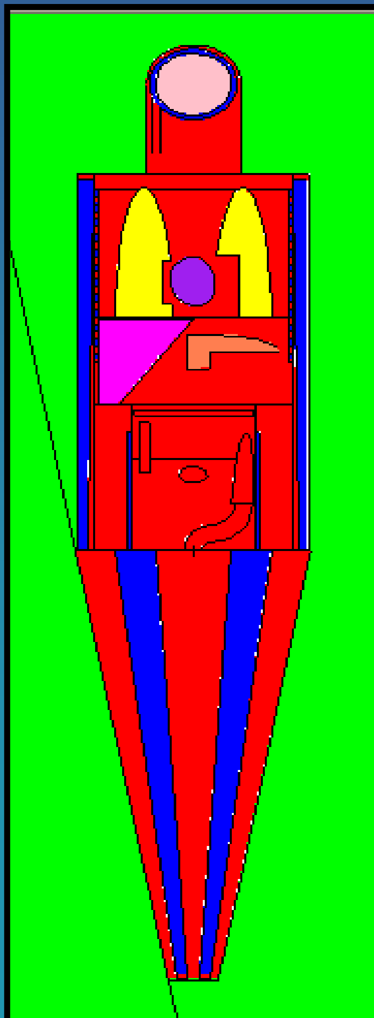
Modeling the Patient

- Geometric
  - e.g MIRD
  - Standard man
  - Often androgynous (male/female organs)
  - Usually single size
- Size and age variations
  - newborn, ages 1, 5, 10, and 15 years
  - adult female, and adult male
  - Including pregnant patient



Modeling the Patient

- All radiosensitive organs identified
  - Location
  - Size
  - Composition and density

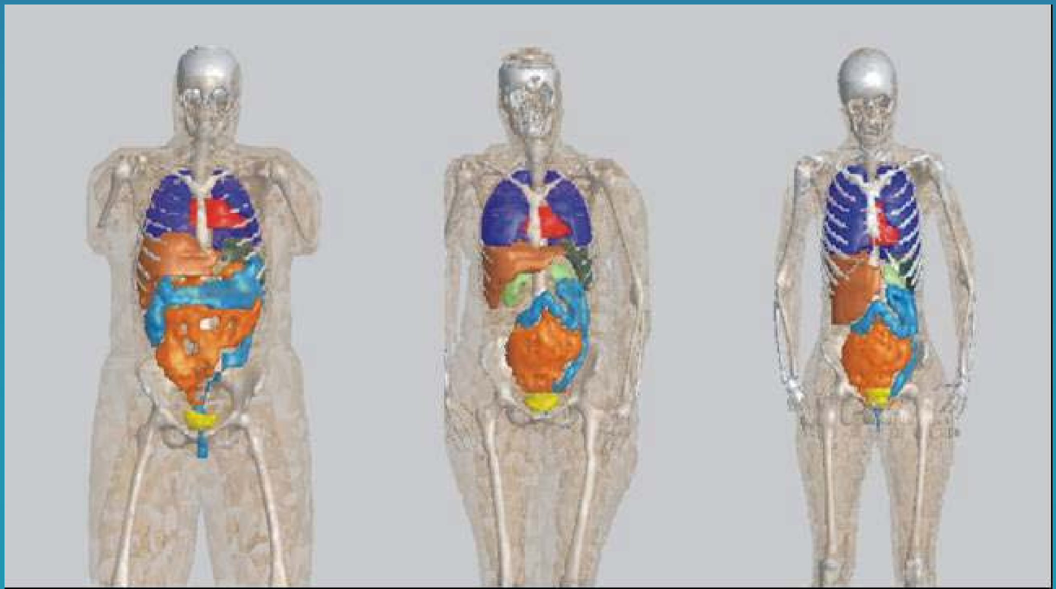


Modeling the Patient

- Voxelized Models
  - Based on actual patient scans
  - Identify radiosensitive organs – usually manually
  - Non-geometric
- Different age and gender
- Different sizes

Modeling the Patient

- GSF models (Petoussi-Henss N, Zankl M et al, 2002)
  - Baby, Child, three adult females (shown), two adult males, Visible Human
  - All radiosensitive organs identified manually (ugh!)



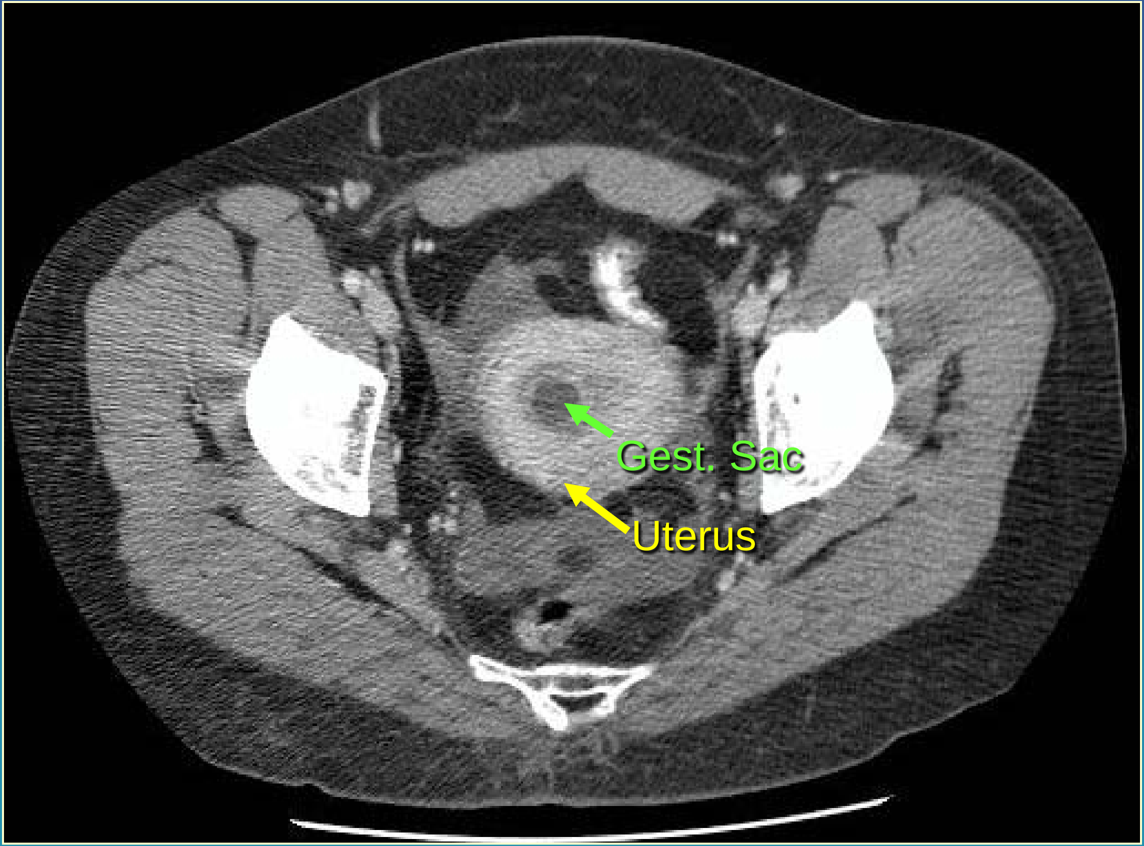
Modeling the Patient

- Xu – pregnant patient, RPI-AM, RPI-AF
- Bolch – UF Phantoms
- Zubal – Adult male phantoms
- Several others (see http://www.virtualphantoms.org/)

Modeling (Parts of) the Patient

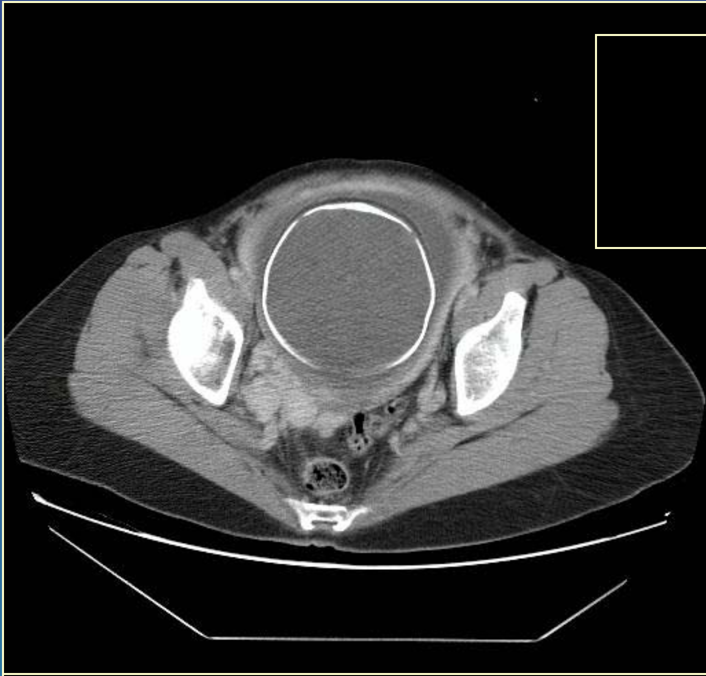
- Embryo/Fetus
- Breast

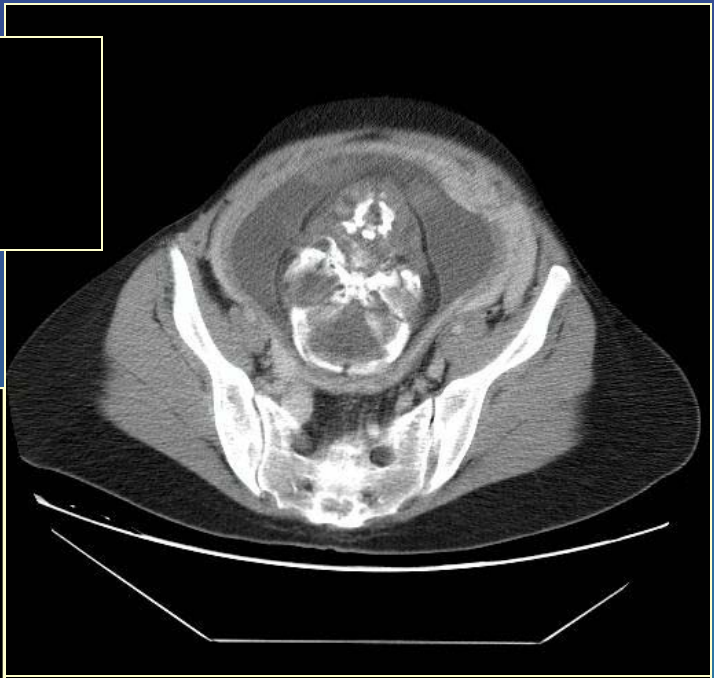
7 weeks (embryo not visible)

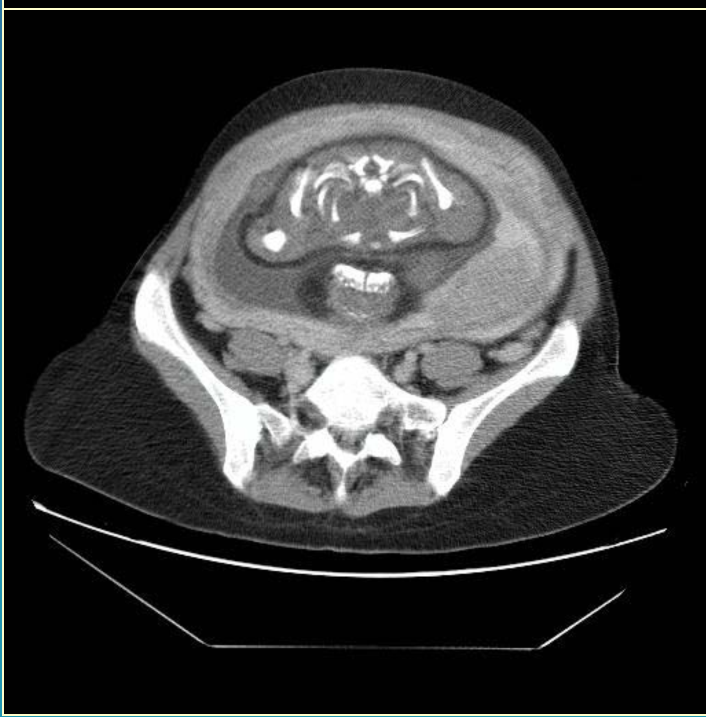


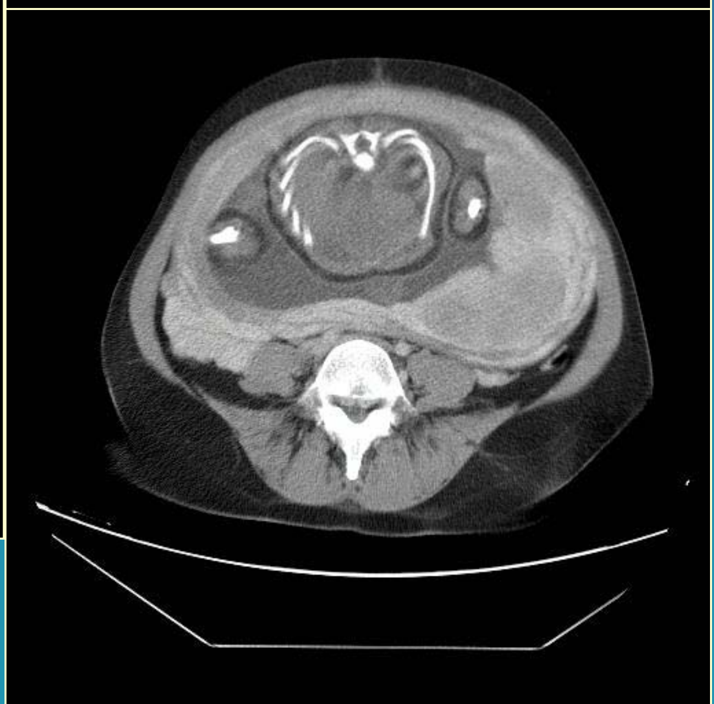
Mature Fetus:

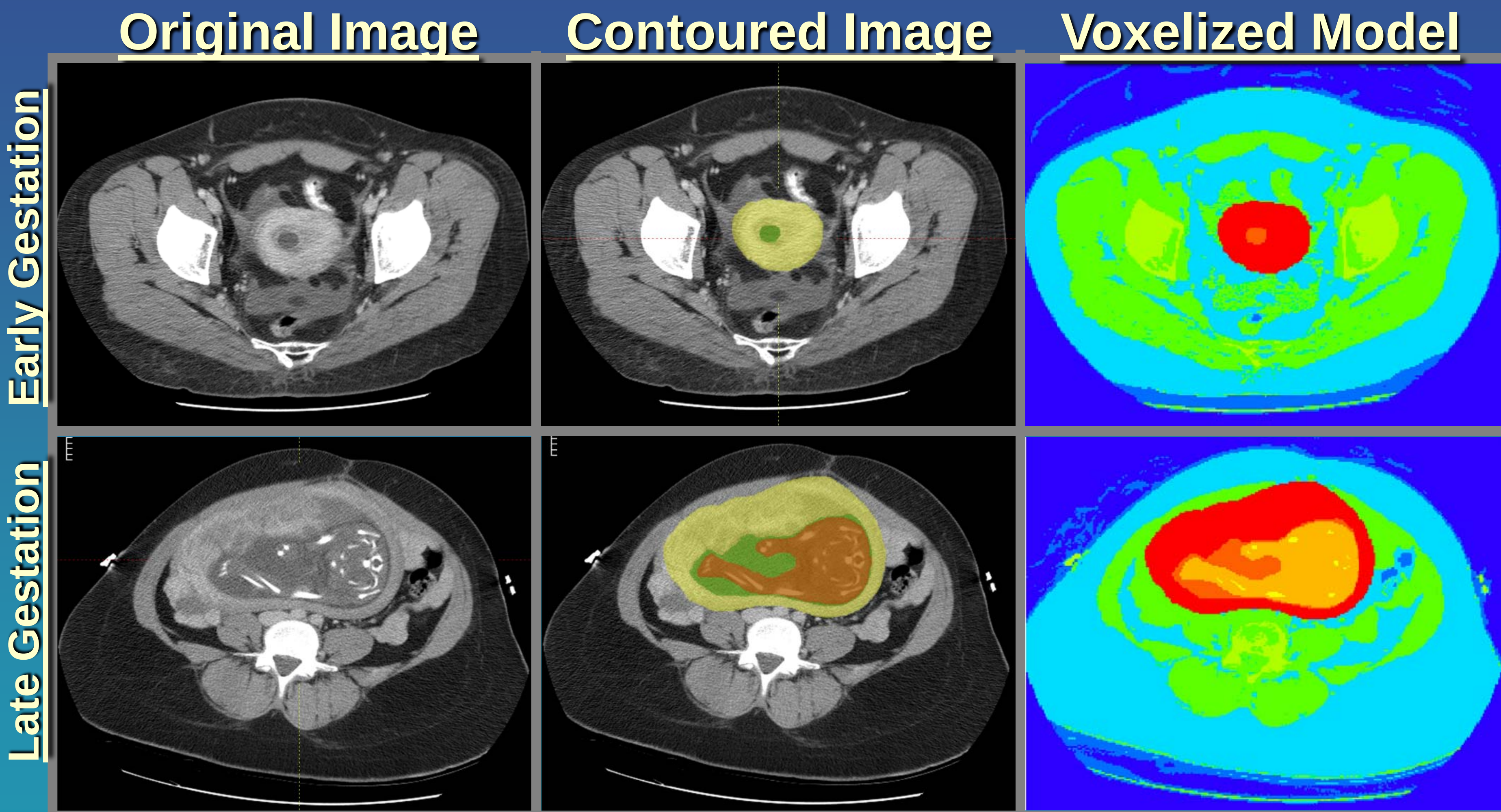
36 weeks



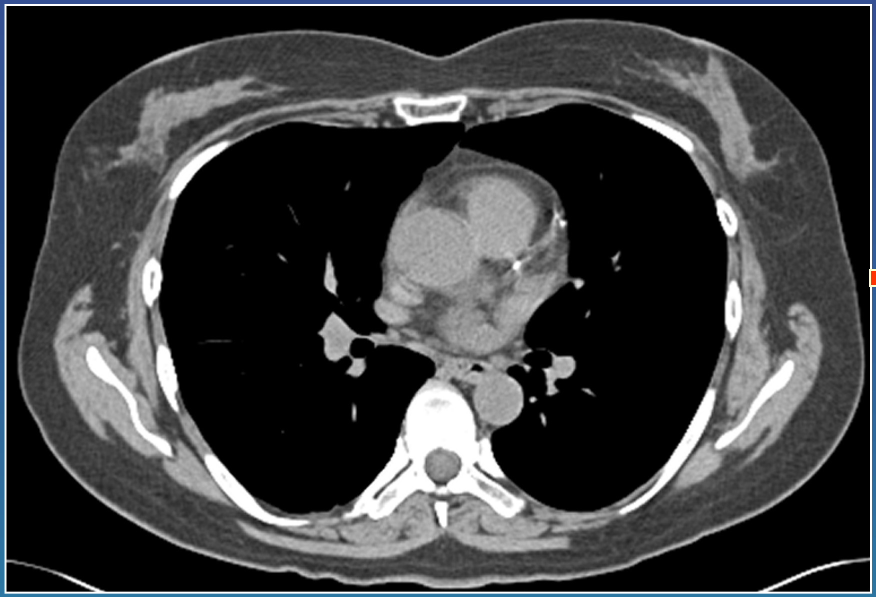




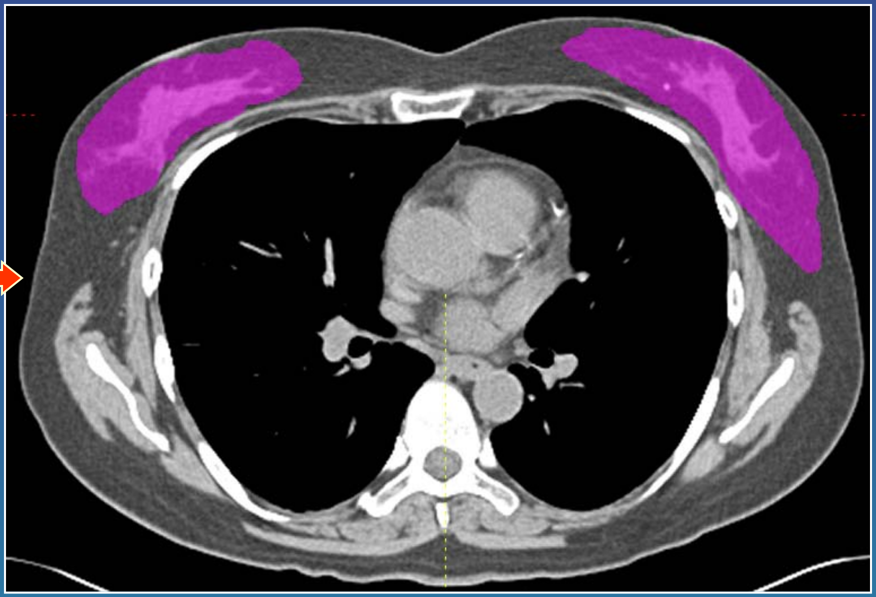



Original Image
Contoured Image
Voxelized Model
Early Gestation
Late Gestation

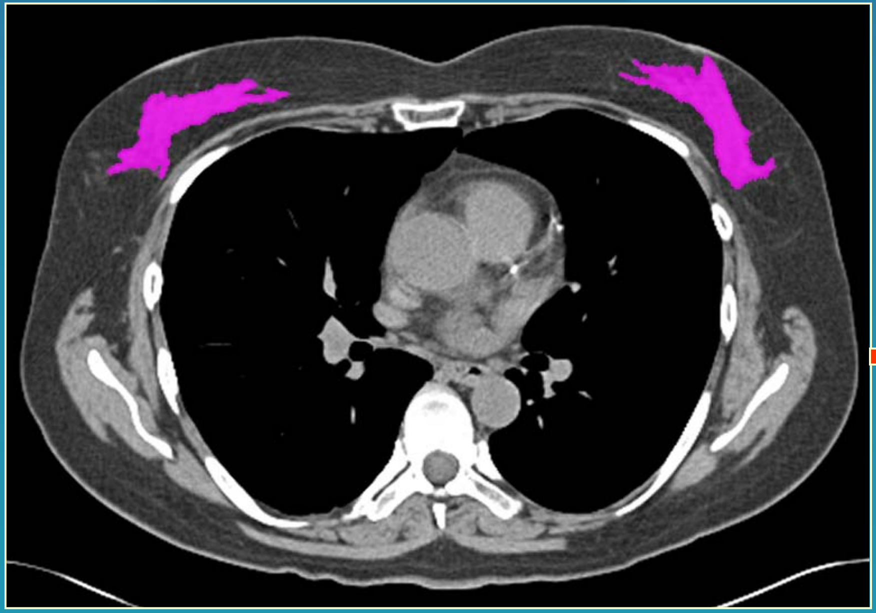
Original Image



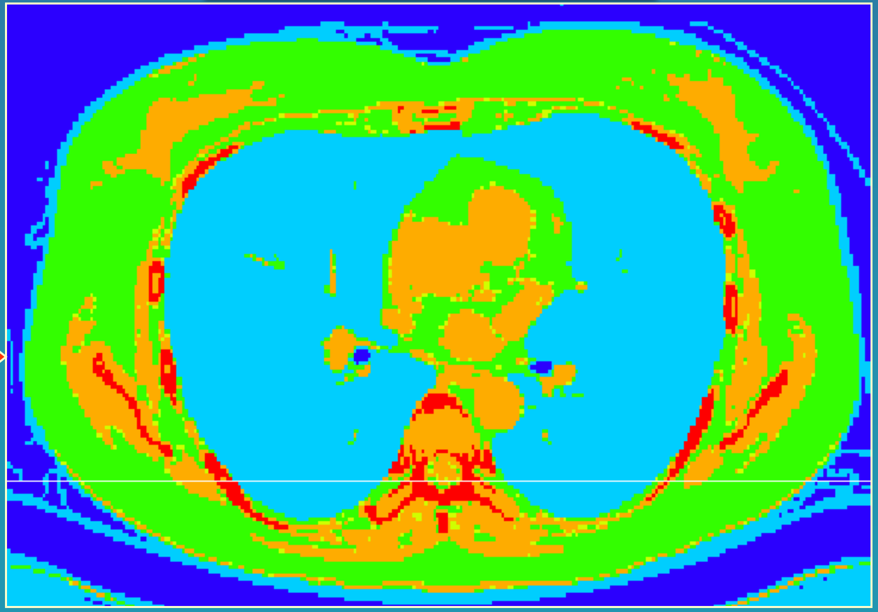
Contoured Image



Threshold Image



Voxelized Model



Simulating the Scan

- Select Technical Parameters
  - Type of scan (helical, axial)
  - Beam energy
  - Collimation
  - Pitch
  - Tube Current/rotation time (or tube current modulation)
- Select Anatomic Region
  - Head/Chest/Abdomen/Pelvis/etc.
- Translate this to:
  - Start/stop location -> Source Path

Monte Carlo for CT Dose - Details

- Monte Carlo Packages
  - MCNP (Los Alamos)
  - EGS
- Model Transport of Photons from modified (CT) source
- Probabilistic interactions of photons with Tissues
  - Photoelectric, Compton Scatter, Coherent Scatter
- Tissues need detailed descriptions
  - Density
  - Chemical composition (e.g. from NIST web site)

Validating the CT Scanner Model

- Benchmark MC Model against physical measurements
  - CTDI Phantoms
    - Head and Body
    - Simulate a tally in a pencil chamber
    - Each kVp and beam collimation combination
    - Measured vs. Simulated
  - Aim for < 5% difference between Simulated and Measured

Monte Carlo Methods

- Used to Estimate Organ Doses
- MDCT scanner details
- Scan protocol details
- Different patient models

- Extendable to new geometries/methods
- Evaluate effectiveness of dose reduction methods on organ dose (and not just dose to phantoms)
- Detailed organ dose approach ->basis for simpler relationships (curve fits, regression equations, etc.)

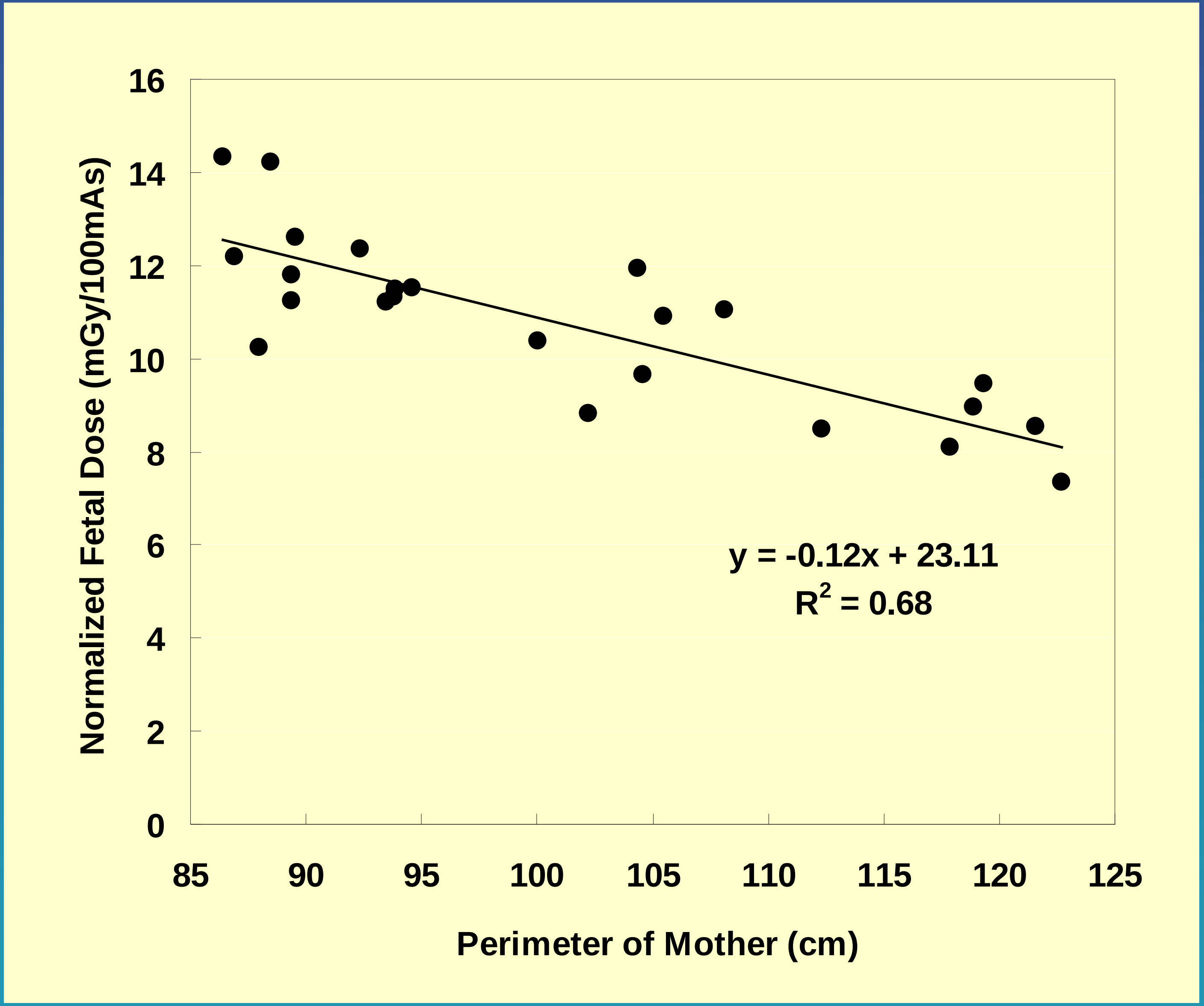
Monte Carlo Methods and Patient Size

Fetal Dose (mGy/100 mAs) for Different Sized Moms and Gestational Age

	Gestational Age (weeks)	Maternal Perimeter (cm)	Fetal Depth (cm)	Normalized Fetal Dose (mGy/100mAs)
	< 5	123	10.6	7.3*
	5.0	89	4.2	11.8**
	5.0	88	7.6	10.3**
	6.6	102	10.9	8.8**
	7.1	90	5.9	12.6**
	12.1	88	4.6	14.2
	14.3	105	6.5	10.9
	14.9	93	7.1	11.2
	17.0	94	7.7	11.3
	17.1	87	6.7	12.2
	18.5	87	5.6	14.3
	20.3	112	8.0	8.5
	22.0	108	4.7	11.1
	23.7	118	6.3	8.1
	24.0	95	5.6	11.5
	24.4	94	6.6	11.5
	25.0	92	2.5	12.3
	27.0	89	9.0	11.2
	27.4	104	3.6	11.9
	27.4	122	6.0	8.6
	28.3	119	5.5	9.5
	29.4	105	3.5	9.7
	35.0	100	5.1	10.4
	35.9	119	3.4	8.9
Mean:	*19.7*	*101*	*6.1*	*10.8*

Angel et al
Radiology
Oct. 2008

Fetal Dose as a Function of Patient Perimeter



The Monte Carlo approach to estimating radiation dose from CT is most often used to：

0% 1. Measure CTDI for each scanner

0% 2. Estimate the limitations of CTDI

0% 3. Estimate dose to radiosensitive organs

0% 4. Determine detector efficiencies

0% 5. Determine which MDCT scanner is the most dose-efficient

10

The Monte Carlo approach to estimating radiation dose from CT is <u>most often</u> used to:

0%	1.
0%	2.
0%	3. Estimate dose to radiosensitive organs
0%	4.
0%	5.

DeMarco JJ et al. Estimating radiation doses from multidetector CT using Monte Carlo simulations: effects of different size voxelized patient models on magnitudes of organ and effective dose.
Phys Med Biol. 2007 May 7;52(9):2583-97.

McNitt-Gray MF AAPM/RSNA Physics Tutorial for Residents: Topics in CT. Radiation dose in CT. Radiographics. 2002 Nov-Dec;22(6):1541-53.

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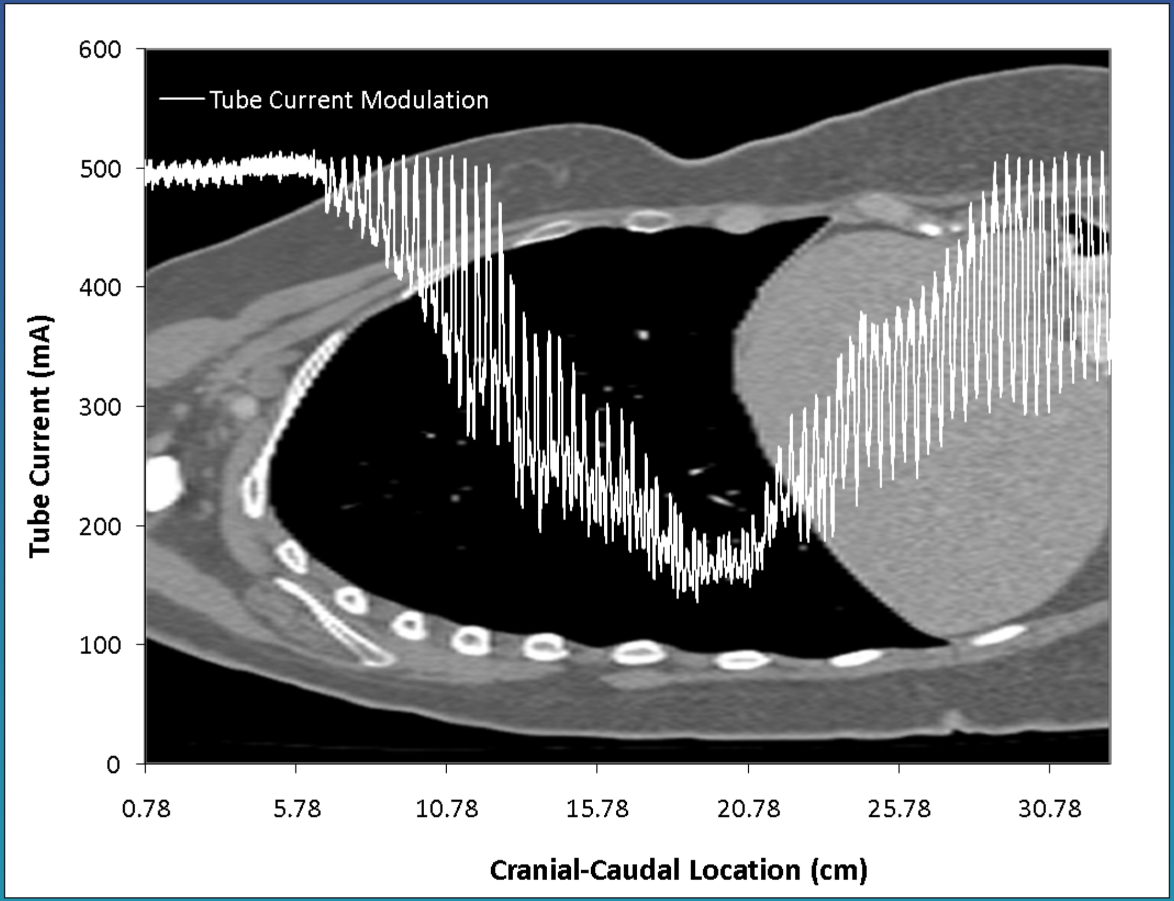
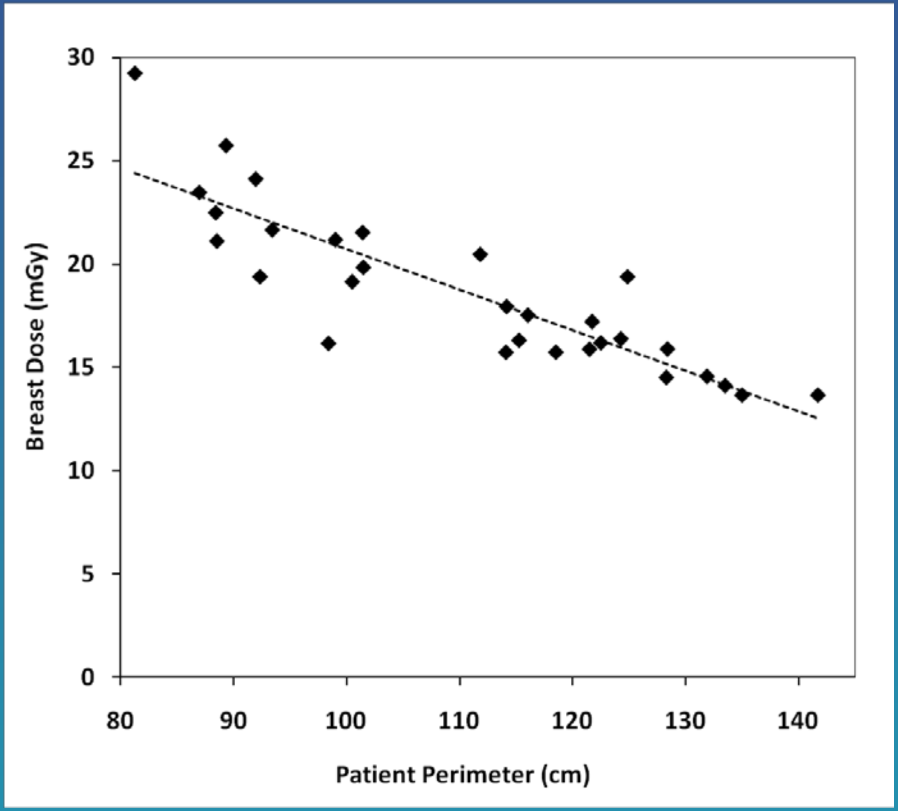
Angel et al, PMB Feb 2009



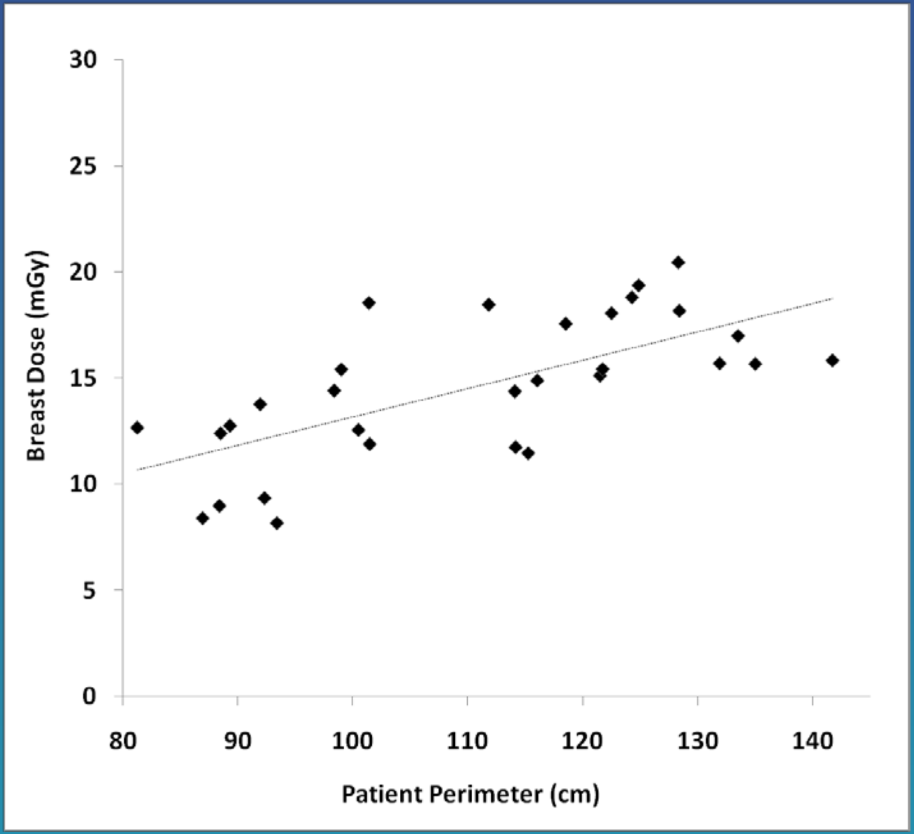
Tube current versus x-axis location of the TCM schema for a patient model with a perimeter of 125cm. Background is a sagittal view of the patient.

Angel et al, PMB Feb 2009



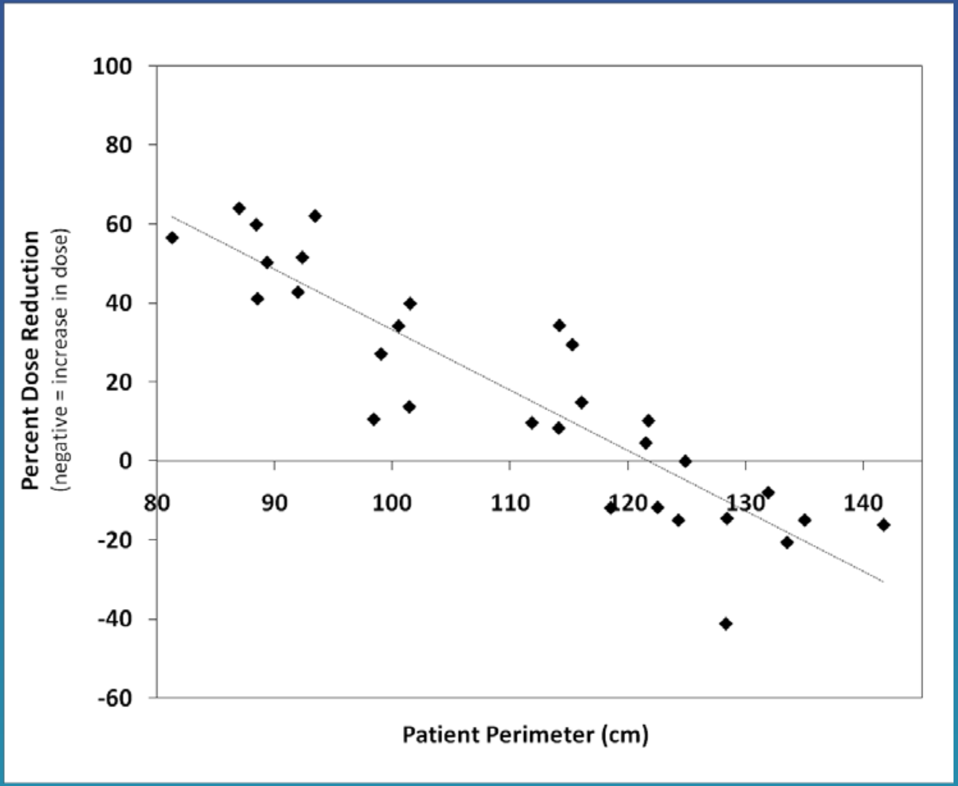
Breast dose versus patient perimeter for all 30 patient models in the fixed tube current simulations. Breast dose decreases linearly with an increase in patient perimeter (R2=0.76).

Angel et al, PMB Feb 2009



Breast dose versus patient perimeter for all 30 patient models in the TCM simulations. Breast dose increases linearly with an increase in patient perimeter (R2=0.46).

Angel et al, PMB Feb 2009



Dose Savings

Dose Increase

Percent dose reduction for the TCM simulations as compared to the fixed tube current simulations. Dose reduction decreases linearly with an increase in patient perimeter (R2=0.81).

When Tube Current Modulation methods are employed in thoracic scans of adult female patients and compared to fixed tube current scans:

0%	1. Radiation dose to glandular breast tissue is always reduced
0%	2. Radiation dose to glandular breast tissue is always increased
0%	3. Radiation dose to glandular breast tissue remains the same
0%	4. Radiation dose to glandular breast tissue is reduced only for large patients
0%	5. Radiation dose to glandular breast tissue is reduced only for small patients

10

When Tube Current Modulation methods are employed in thoracic scans of adult female patients and compared to fixed tube current scans:

0%
0%
0%
0%
0%

1.
2.
3.
4.
5. Radiation dose to glandular breast tissue is reduced only for small patients

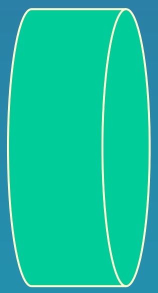
Angel E, Yaghmai N, Jude CM, Demarco JJ, Cagnon CH, Goldin JG, Primak AN, Stevens DM, Cody DD, McCollough CH, McNitt-Gray MF. Monte Carlo simulations to assess the effects of tube current modulation on breast dose for multidetector CT.Phys Med Biol. 2009 Feb 7;54(3):497-512

$CTDI_{vol}$ and DLP

- $CTDI_{vol}$ currently reported on the scanner
  - (though not required in US)
- Is Dose to one of two phantoms
  - (16 or 32 cm diameter)
- Is NOT dose to a specific patient
- Does not tell you whether scan was done “correctly” or “Alara” without other information (such as body region or patient size)
- MAY be used as an index to patient dose with some additional information (later)

Scenario 1: **No adjustment** in technical factors for patient size

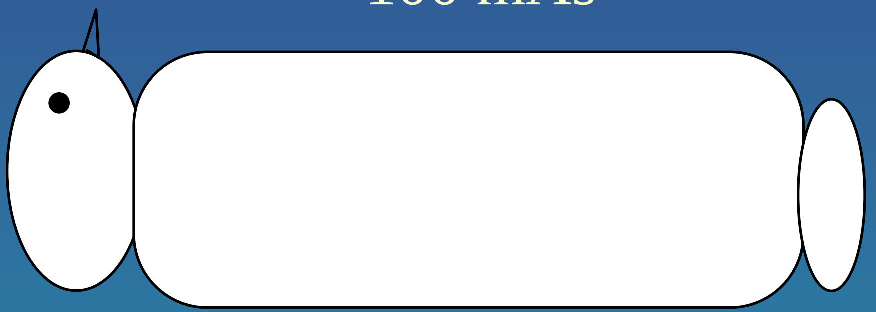
100 mAs

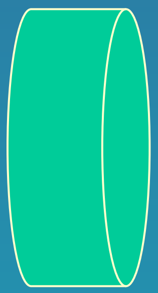


32 cm phantom

$\mathrm{CTDI}_{vol} = 20$ mGy

100 mAs





32 cm phantom

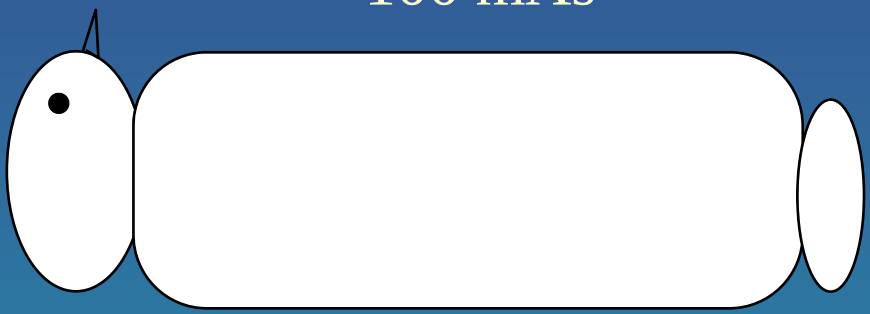
$\mathrm{CTDI}_{vol} = 20$ mGy

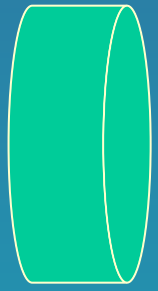
The CTDI_{vol} (dose to phantom) for these two would be the same

Scenario 2: **Adjustment** in technical factors for patient size

50 mAs

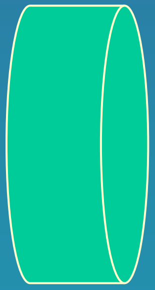
100 mAs





32 cm phantom

$CTDI_{vol}$ = 10 mGy



32 cm phantom

$CTDI_{vol}$ = 20 mGy

The $CTDI_{vol}$ (dose to phantom) indicates larger patient received 2X dose

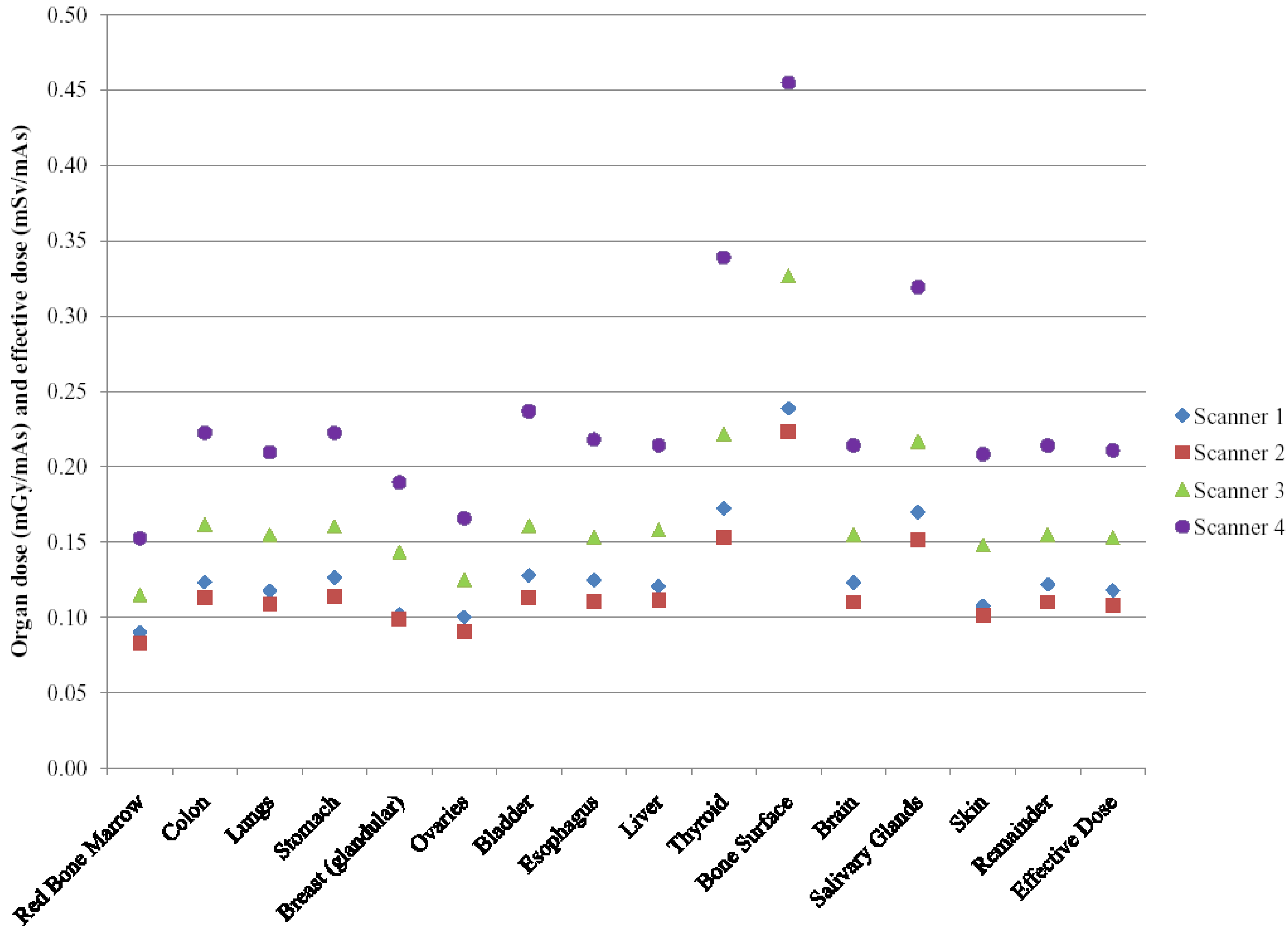
Did Patient Dose Really Increase ?

For same tech. factors, smaller patient absorbs more dose

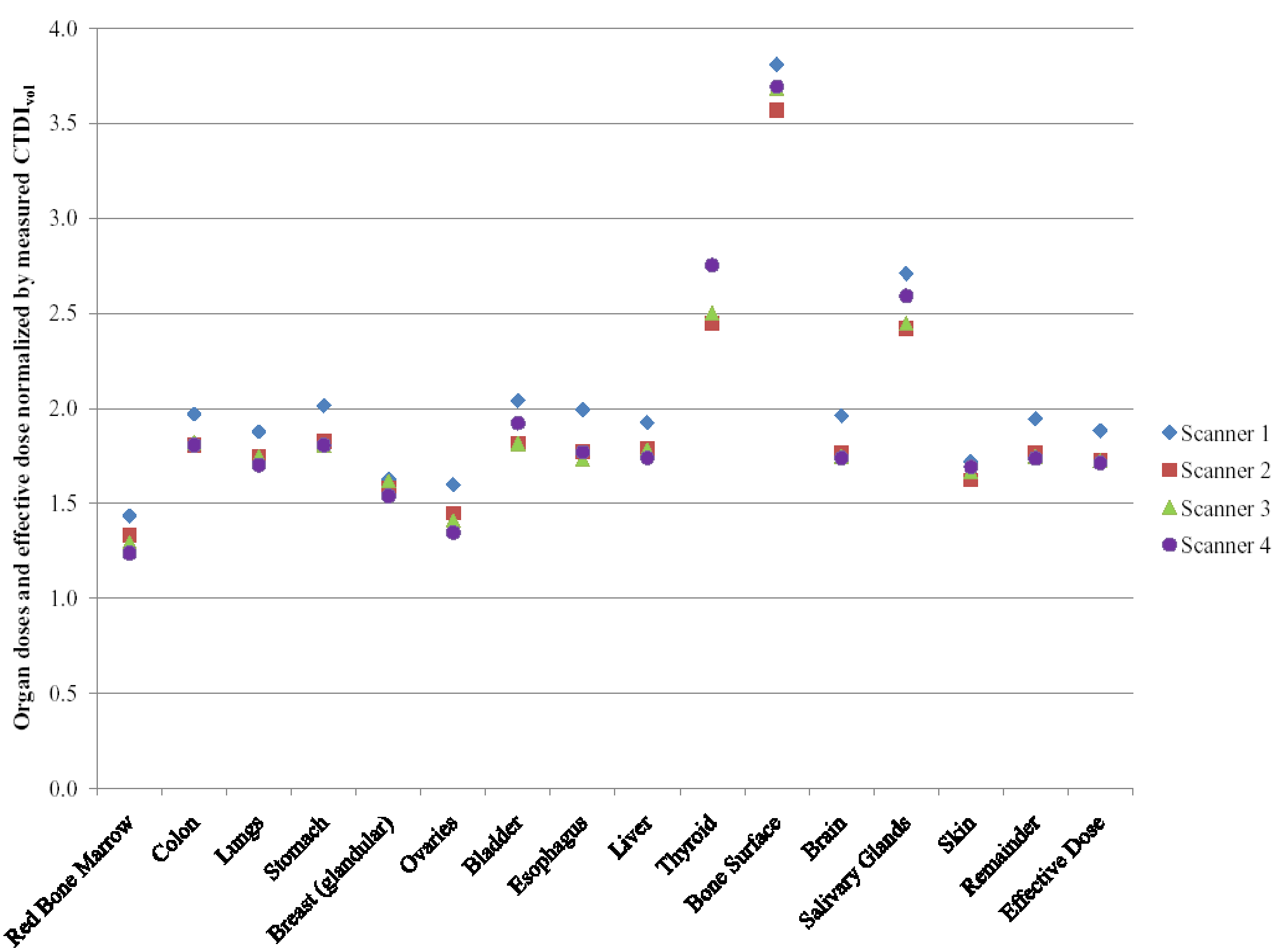
- Scenario 1: CTDI is same but smaller patient’s dose is higher
- Scenario 2: CTDI is smaller for smaller patient, but patient dose is closer to equal for both.

Organ Dose Independent of Scanner

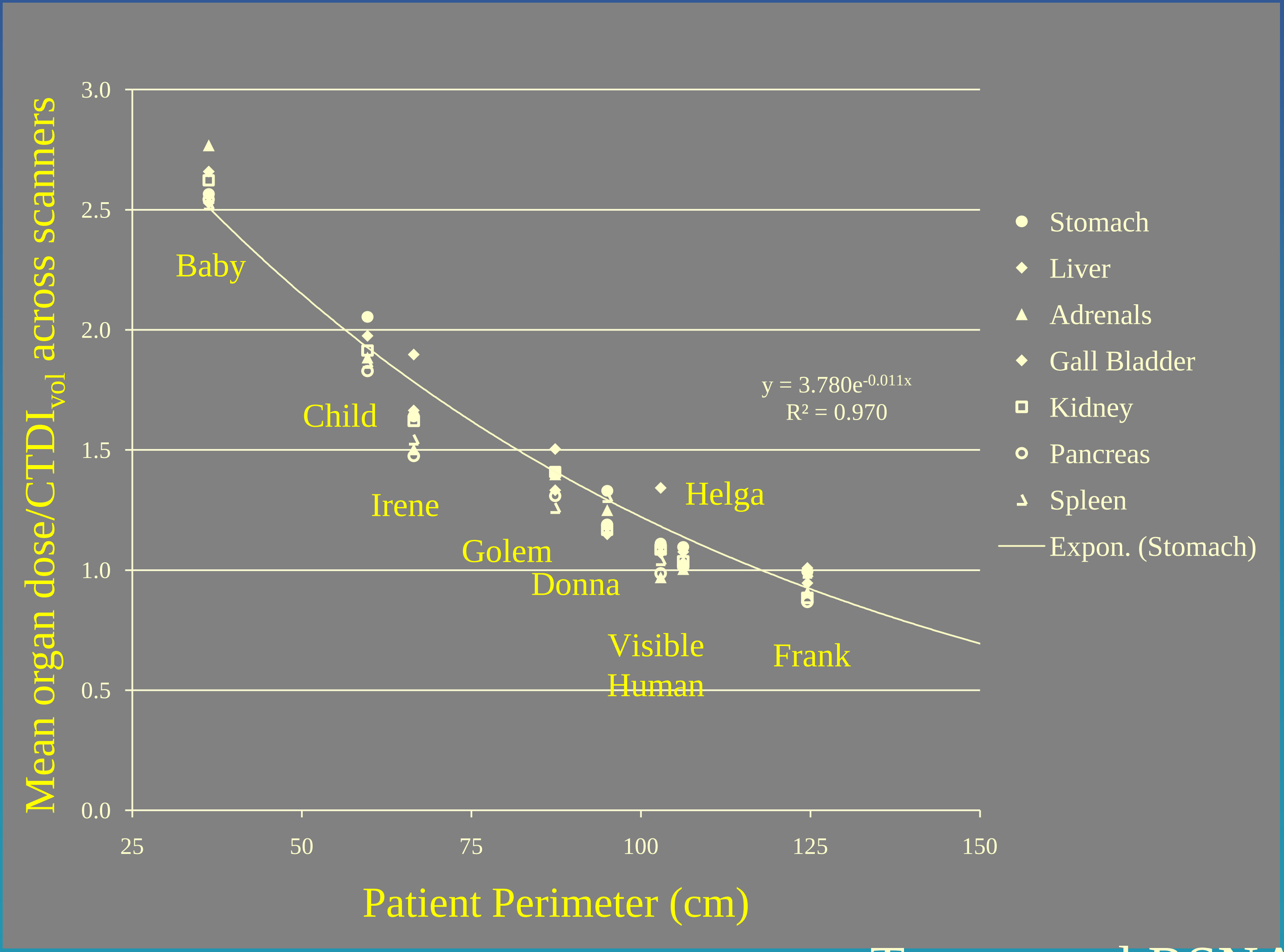
Organ dose (in mGy/mAs) and effective dose (in mSv/mAs) for GSF model Irene resulting from a whole body scan with similar parameters for each scanner



Organ dose and effective dose **normalized** by measured CTDIvol for GSF model Irene resulting from a whole body scan.



Normalized Organ Dose as function of Pt. Size (Abdomen Scans for each Patient)



Turner et al RSNA 2009

Future of Dosimetry?

Patient
Size info

Size
Coefficients

$CTDI_{vol}$
(or TG 111)

Patient Organ Dose
- Accounting for patient size
- Accounting for scanner
- Accounting for anatomic region

Summary

- There are trade-offs of dose and image quality in CT
- These can be especially important for large (obese) patients and in pediatric patients
- Lots of methods being developed to help with these tradeoffs:
  - Dose Reduction methods such as TCM
  - Image Recon methods such as Iterative Methods (ASIR, etc.) to reduce noise (and allow lower dose scans)

Summary

- Not always straightforward solutions
  - Informed Physicist input can help tremendously to obtain best results across all situations (Is there really a “routine” scan?)
- Methods being developed to provide realistic estimates of patient dose
- Movement to use Quantitative Methods for Image Quality (e.g. Noise Power Spectrum)