CT Image Quality, Radiation Dose and Clinical Applications

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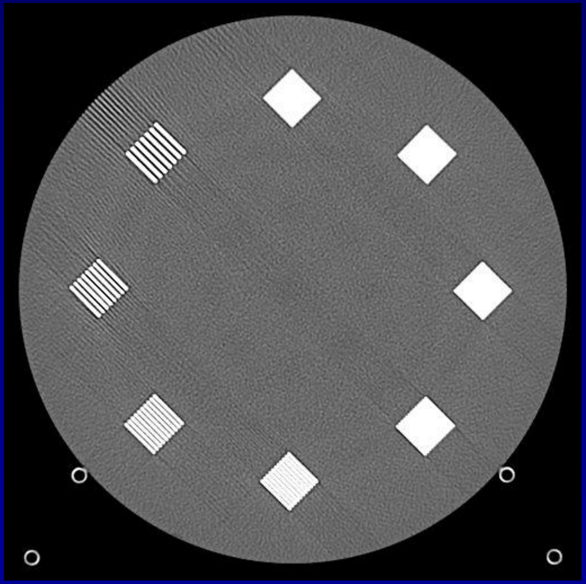
Learning Objectives

- CT Image Quality Metrics
- CT Dose and Reduction Techniques
- CT Clinical Applications

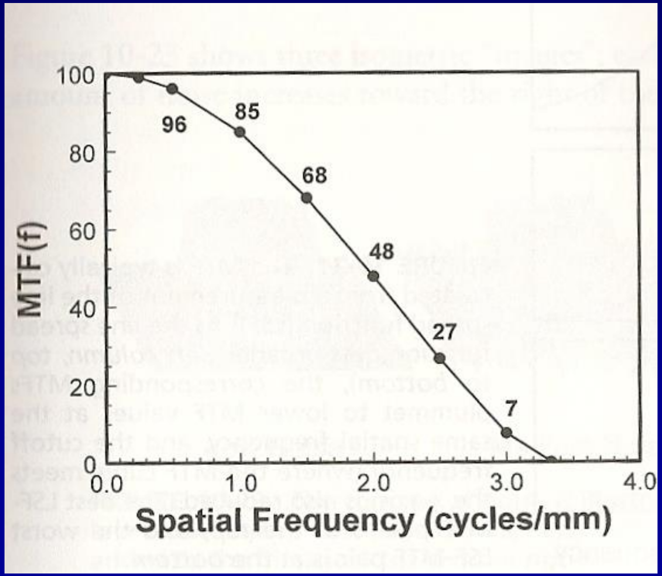
CT Image Quality Metrics

CT Spatial Resolution

- **Spatial resolution is the ability to resolve small but "high contrast" objects, such as bones, stent, small vessels with IV contrast.**
  - **In-plane (X-Y) by bar patterns or Modulation Transfer Function**
  - **Cross plane (Z) by Slice Sensitivity Profile or slice thickness**



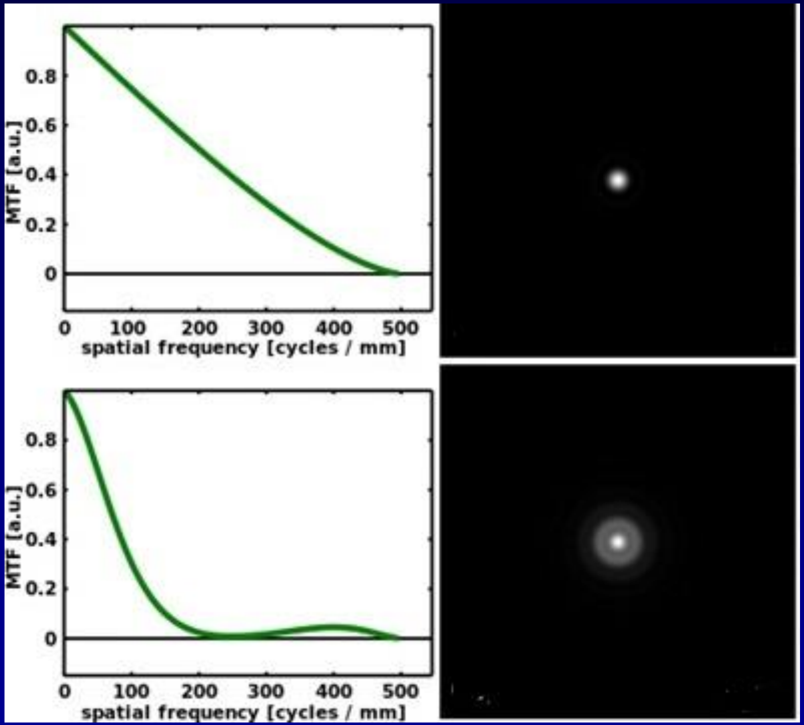
ACR Phantom



Modulation Transfer Function

MTF vs. Point Spread Function (PSF)

Wire Phantom



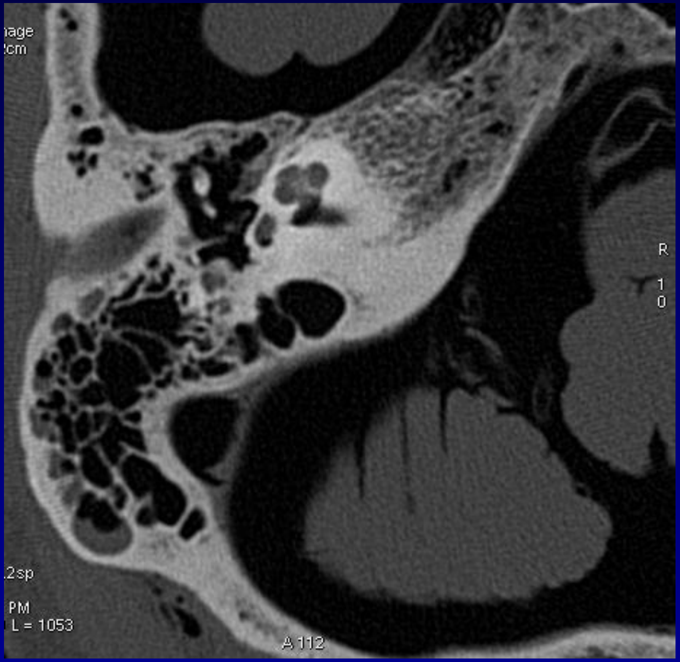
High Res

Low Res

MTF

PSF

Acquisition and Recon Parameters vs. Spatial Resolution

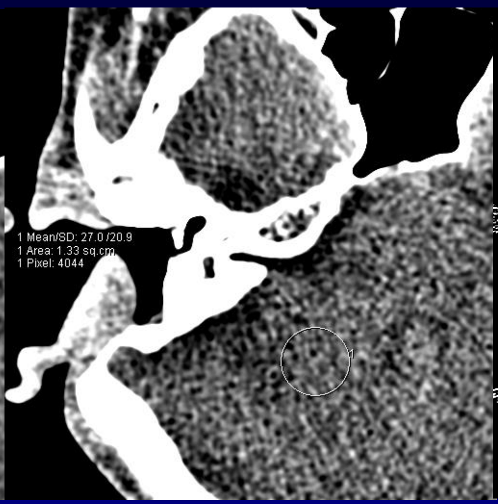


High Resolution CT Image of IAC

- Tube focal spot size
- Detector width
- Post-patient collimation
- Recon kernel
- Recon Field of View (FOV)

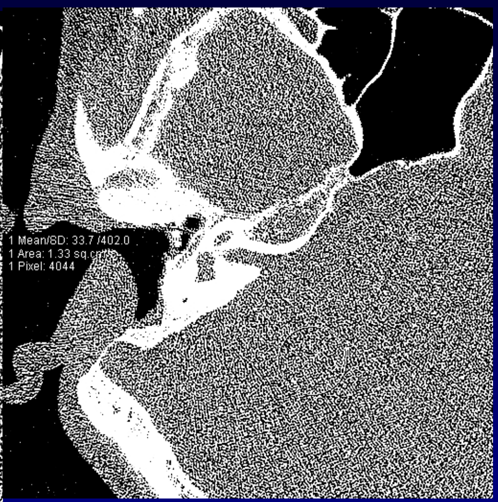
Siemens Ultra High Res Kernels

U30



U40

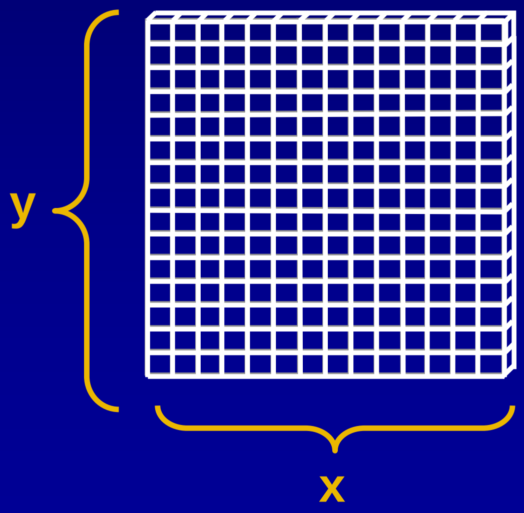
U80



U90

Display Image Matrix

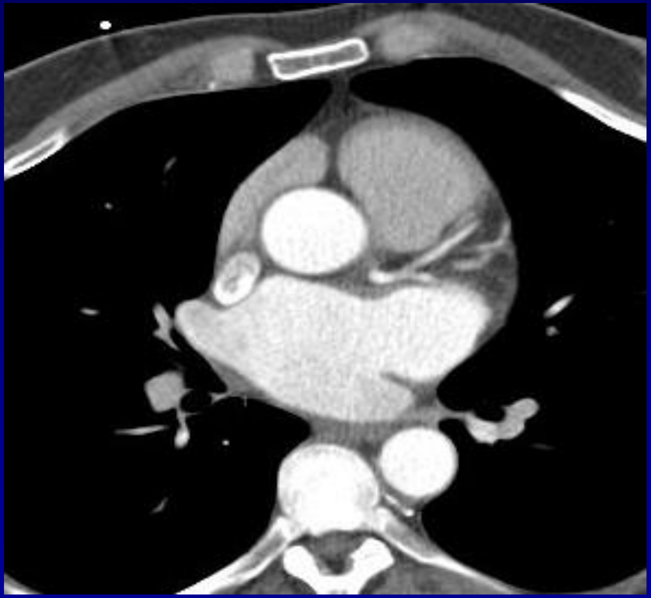
- Defines number of voxels into which cross-section of the body is divided
- Typically square with number of elements in x and y equal to a power of 2 (e.g., 512 x 512, 1024 x 1024)



Reconstructed Field of View

- **Defines in-plane (x and y) dimensions of an image**
- **5cm x 5cm ≤ Recon FOV ≤ 50cm x 50cm**
- **Smaller FOV improves visual resolution**

Large FOV



Small FOV

CT Image Noise

Image noise = 31.6

Image noise = 10.3

CT Image Noise

- **As a rule of thumb, CT image noise is a function of:**

$$noise \sim \frac{1}{\sqrt{mAs} \times \sqrt{slice\_thickness} \times \sqrt{(kVp)^n}}$$

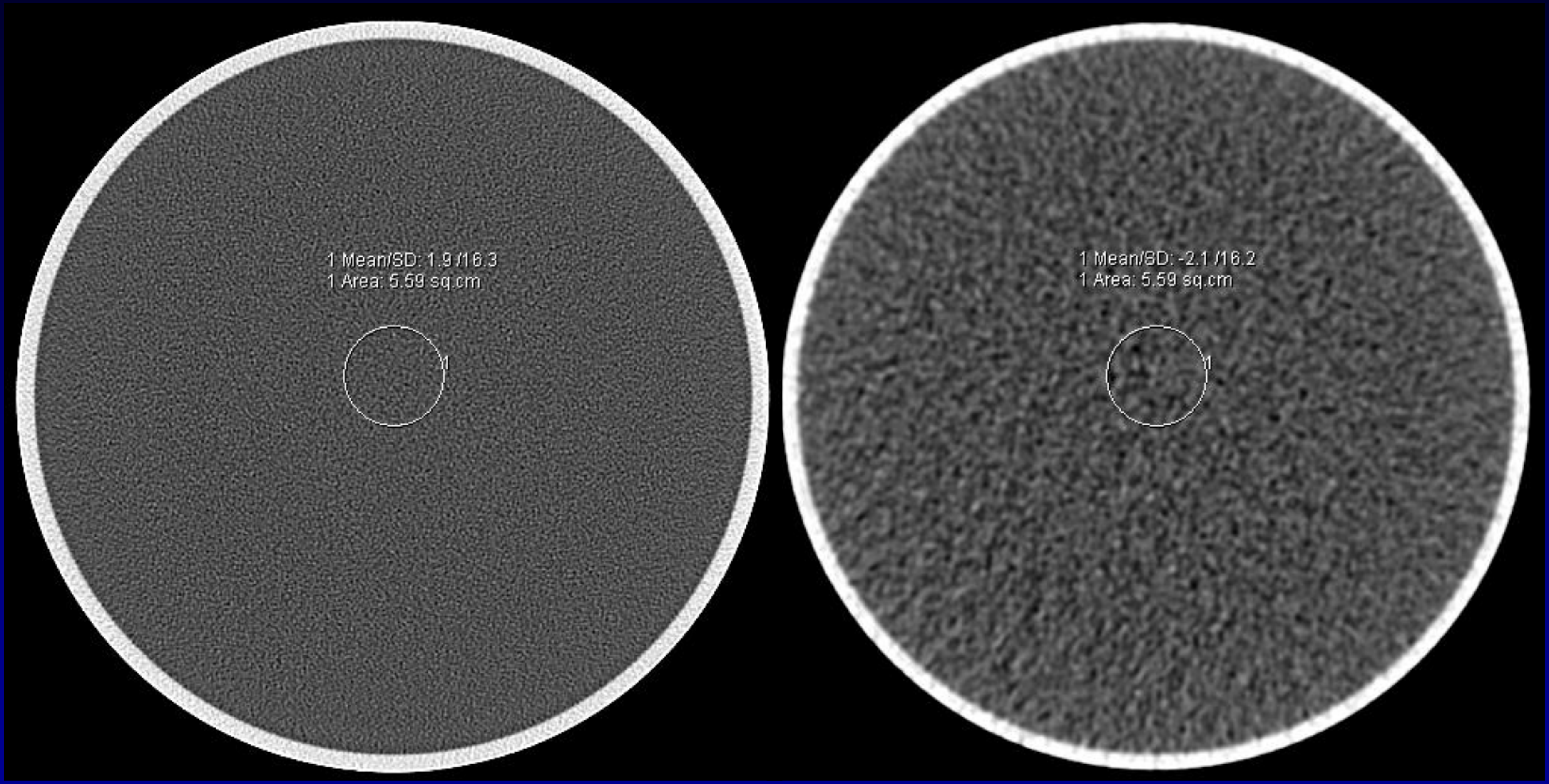
n = 2.5 ~3.0

Siemens Ultra High Res Kernels

U30	U40	U80	U90
Noise=14	Noise=21	Noise=203	Noise=402

Image noise increases significantly with high res kernels

Same Noise Mag but Different Texture



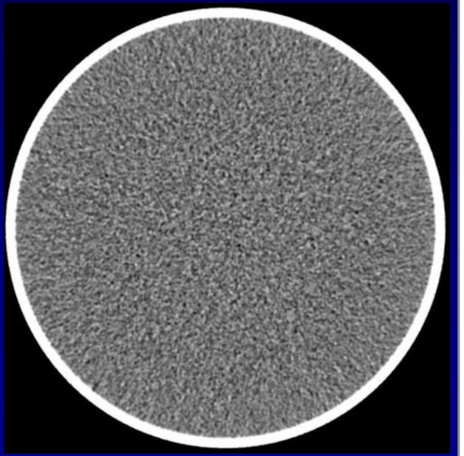
120 kV, 1000 eff mAs, B70
Noise =16

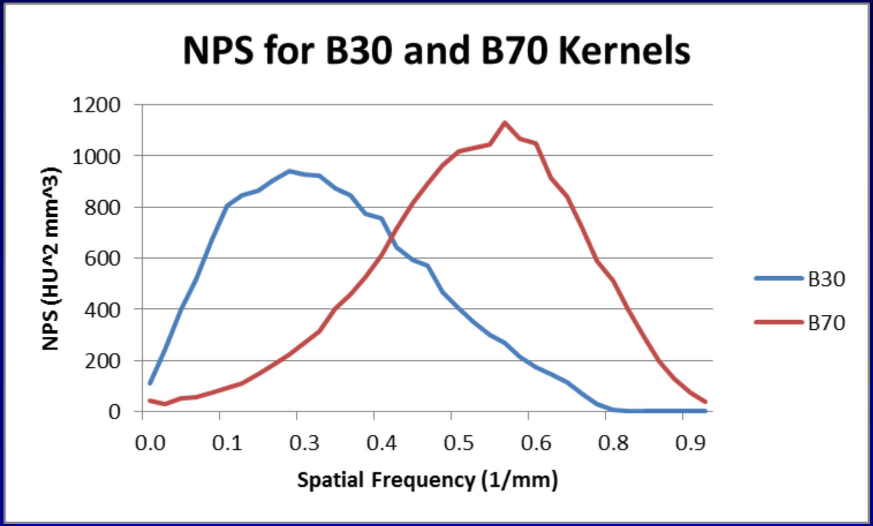
120 kV, 10 eff mAs, B10
Noise =16

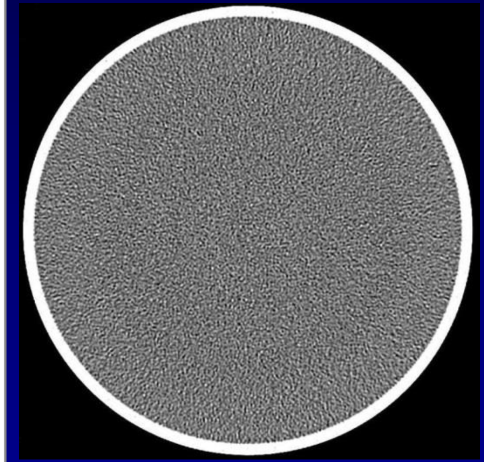
Noise Power Spectrum (NPS)

- Noise (standard deviation) only measures the magnitude.
- Noise power spectrum measures not only the magnitude but also the spatial correlation of noise properties (“texture”).

Images w/ Same noise Magnitude Different Noise Texture







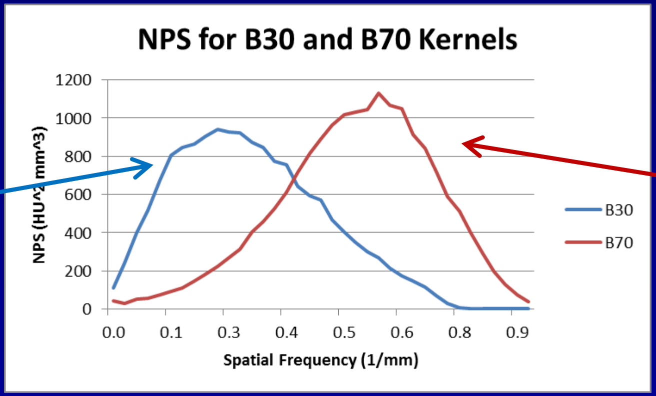
B30

B70

NPS Contains More Info

- Area under NPS curve is equal to the square of noise (magnitude)
- Mean and peak frequencies are related to the noise texture (“ noise grain size”).
- Fine texture usually indicates NPS has higher mean and peak frequencies

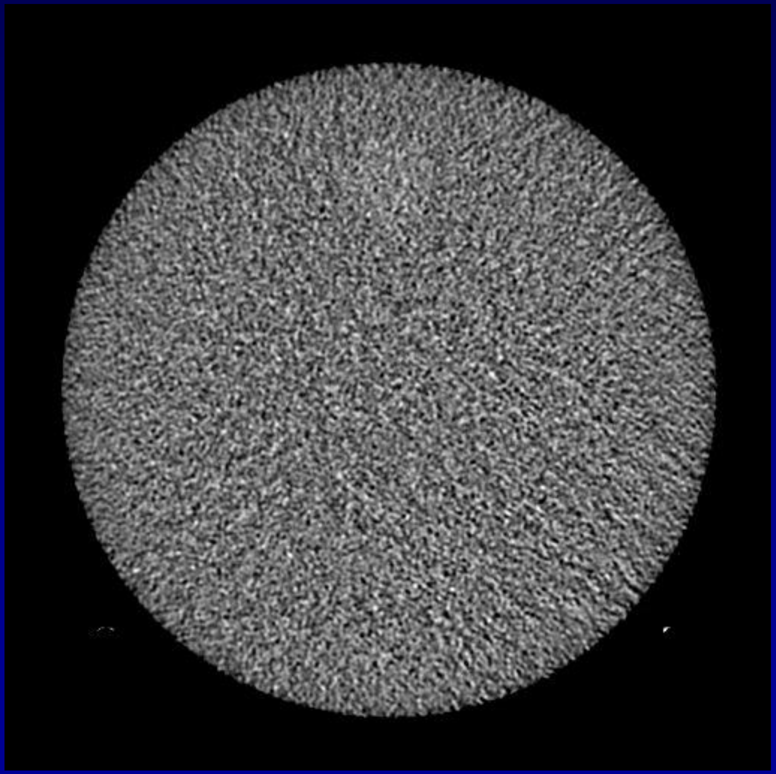
Mean freq: 3.2 lp/cm
Peak freq: 2.5 lp/cm



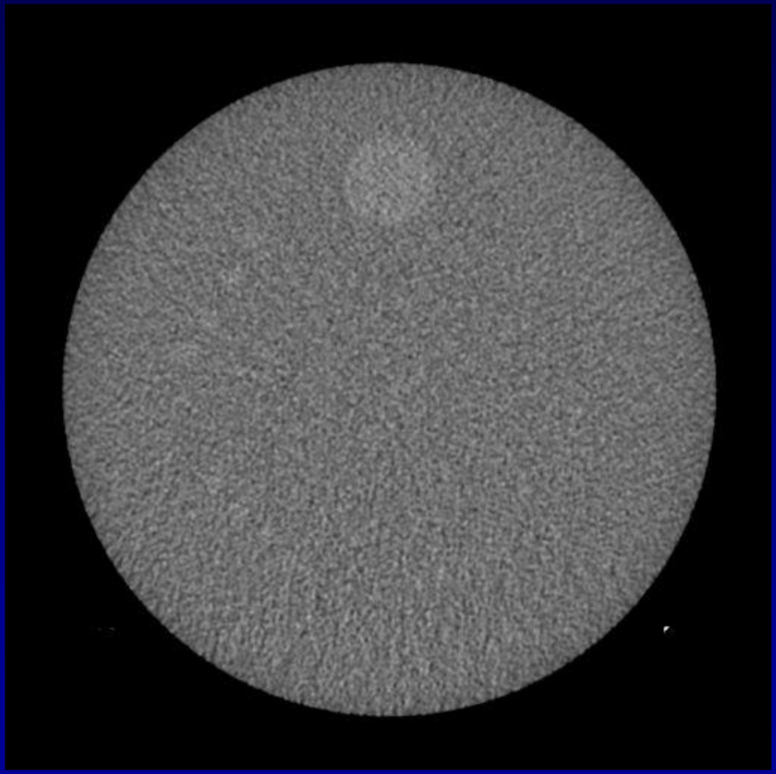
Mean freq: 5.4 lp/cm
Peak freq: 6.3 lp/cm

Low Contrast Resolution

- Ability to resolve low contrast objects, such as liver lesions
- mAs ↑, low contrast resolution ↑



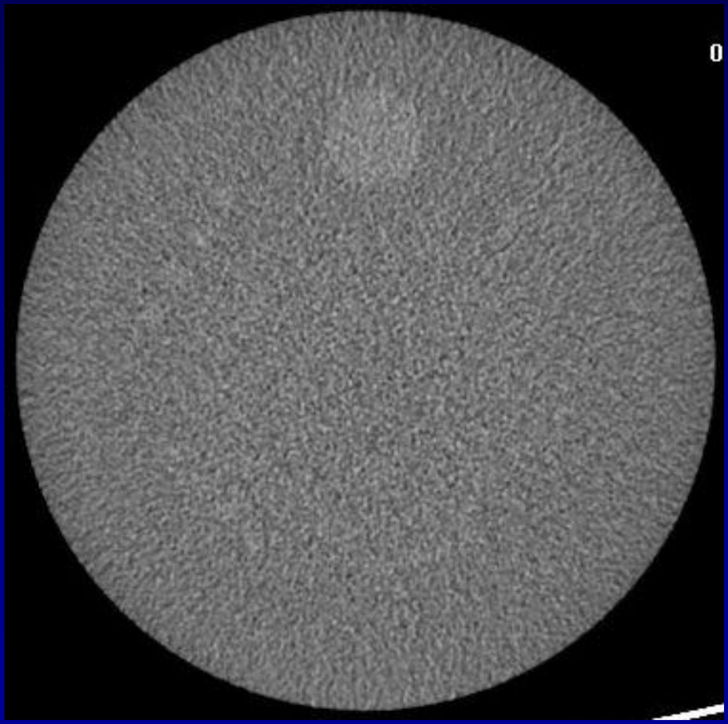
50mAs



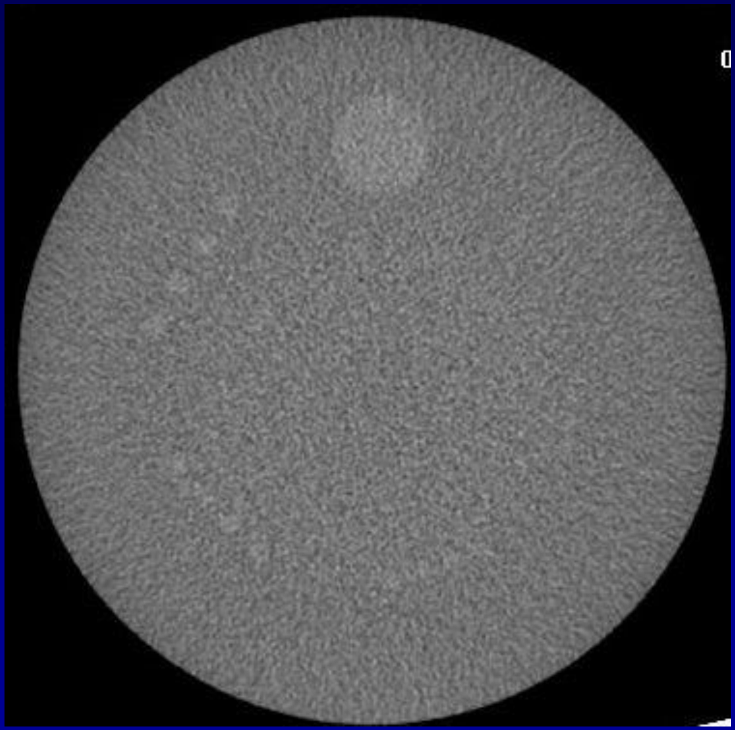
400mAs

Low Contrast Resolution

- Image thickness ↑, low contrast resolution ↑
- Smooth recon kernel-> better low contrast resolution



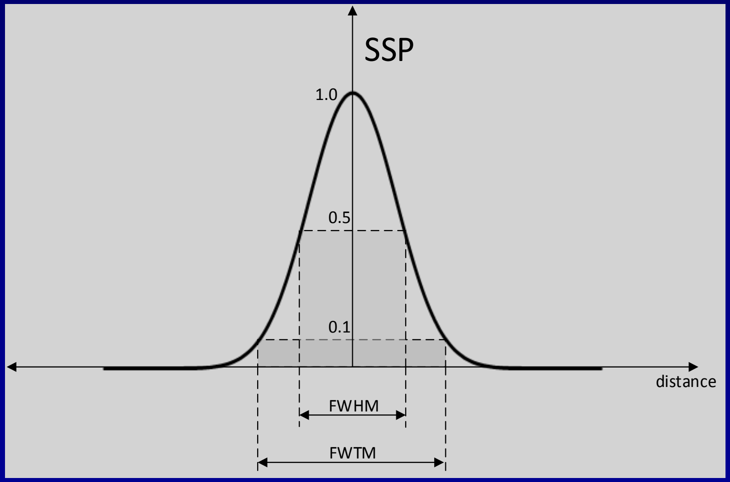
2mm



4mm

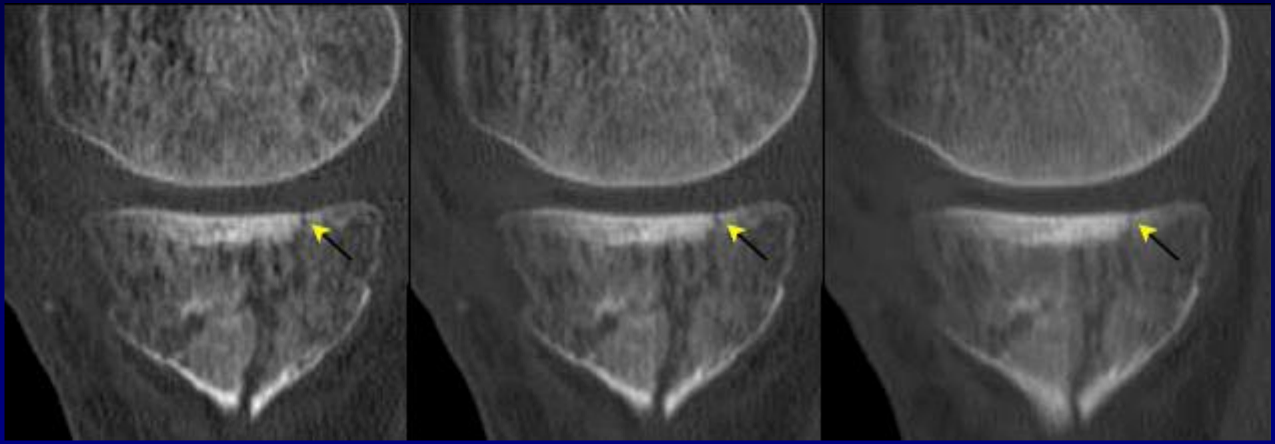
Slice Sensitivity Profile (SSP)

- SSP or Slice thickness is related to cross-plane resolution (or Z-axis resolution)
- Sharpness of reformat images
- Partial volume effect



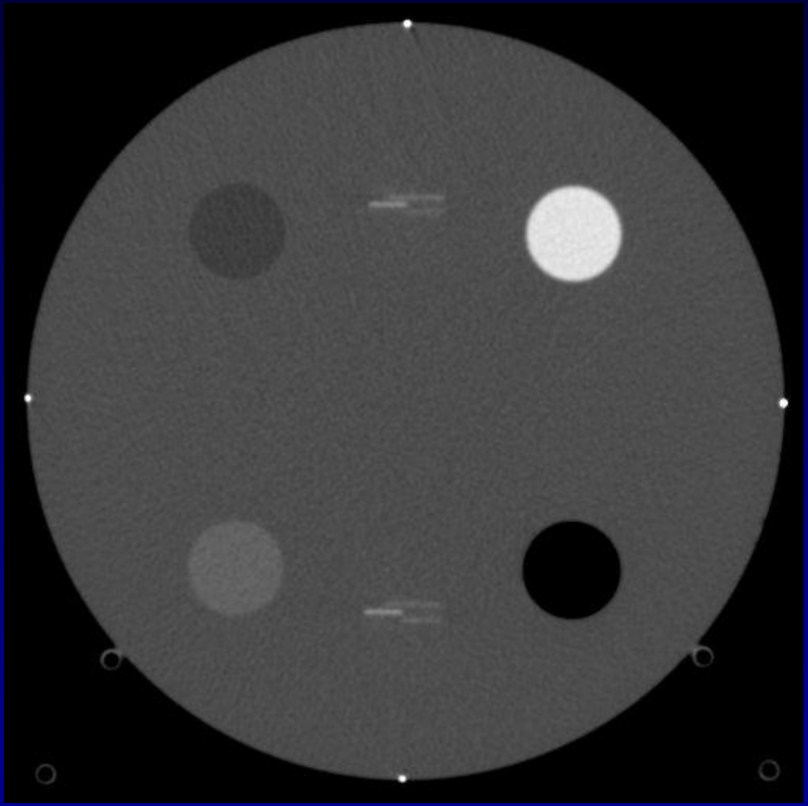
SSP Phantom and SSP profile with FWHM and FWTM

Slice thickness vs. Reformat Resolution

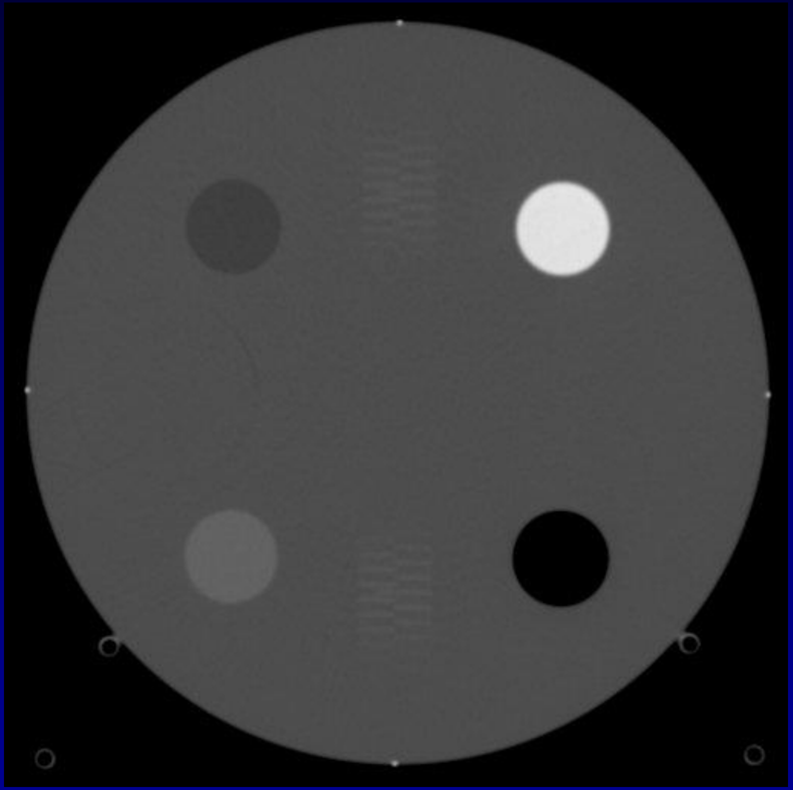


0.625mm 2mm 4mm

Image thickness vs. Partial volume



0.6mm

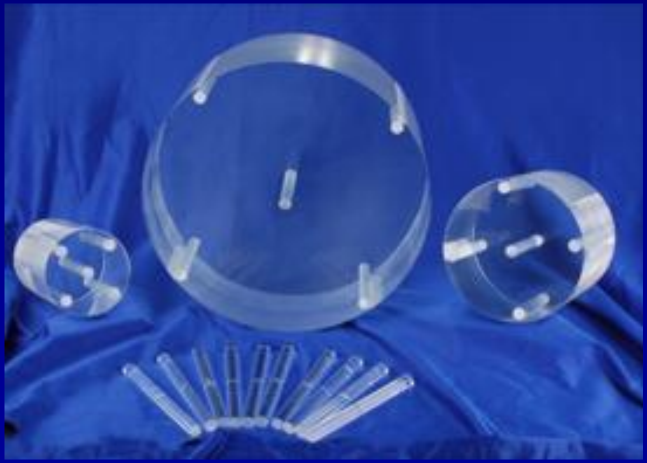


6mm

CT Dosimetry

CT Dose Index (CTDI)

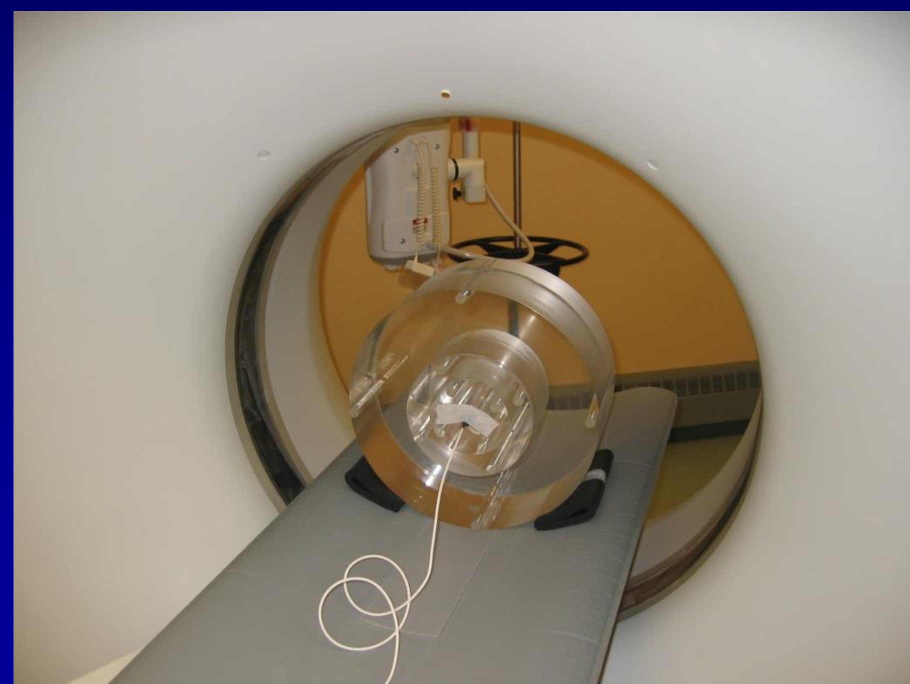
- Computed Tomography Dose Index” (CTDI) is a standardized dose metric for CT
- Common unit for CTDI is mGy
- CTDI is measured on 2 PMMA (Acrylic) phantoms
  - 16cm diameter “head” phantom
  - 32cm diameter “body” phantom



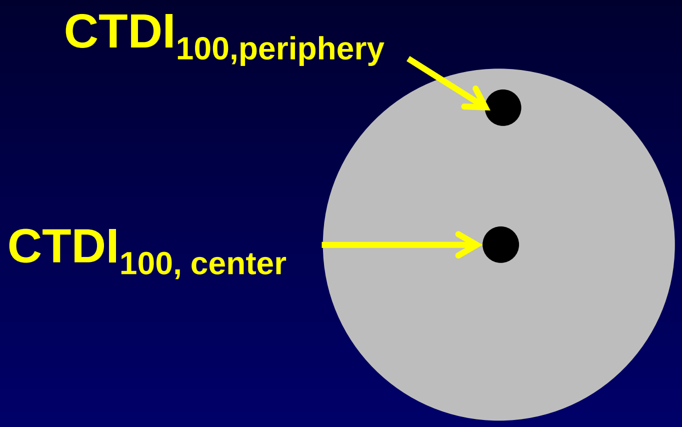
$CTDI_{100}$

- Using pencil ionization probe
- In axial scan mode without table movement
- Active probe length is 100mm ->$CTDI_{100}$

100-mm
pencil ion chamber



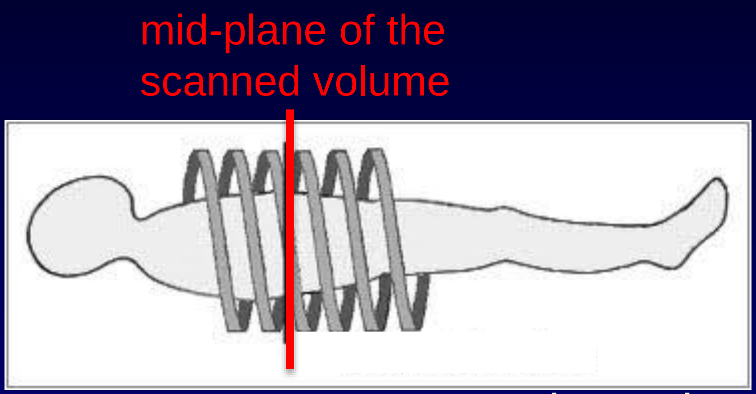
Weighted CTDI ($CTDI_w$)



$$\mathbf{CTDI_w = 1/3}\ CTDI_{100,\ center} + \mathbf{2/3}\ CTDI_{100,\ periphery}$$

- **$CTDI_w$ represents the average dose over the entire cross-sectional area (i.e., the average dose across the field-of-view (FOV)) in the central plane of the scanned volume.**
- **The weighting factors of 1/3 and 2/3 approximate to the relative areas represented by the central and peripheral $CTDI_{100}$.**

Volume CTDI ($CTDI_{vol}$)



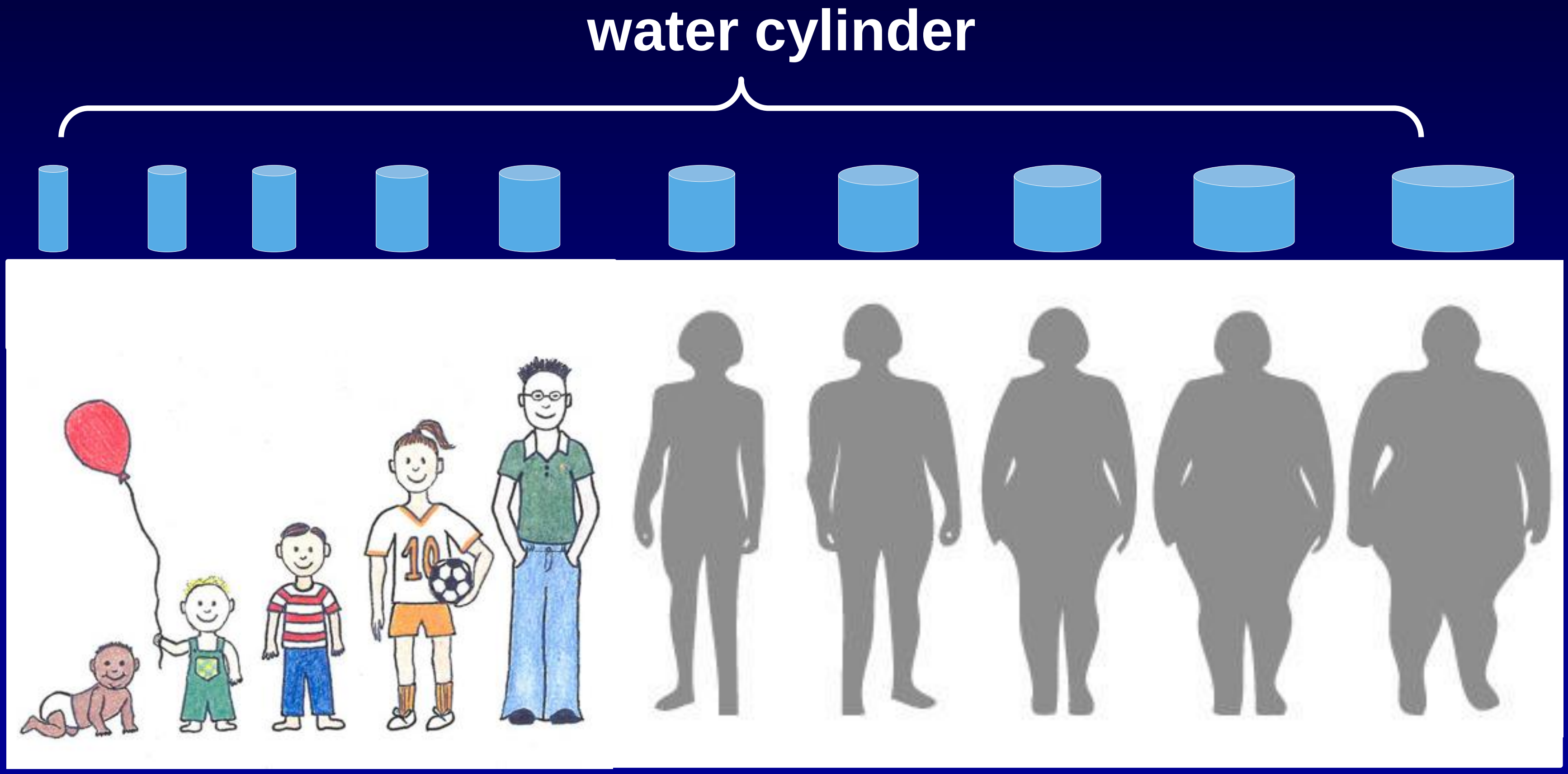
snmjournals.org

$$CTDI_{vol} = \frac{CTDI_W}{pitch}$$

- To account for the fact that, in helical CT, dose is inversely related to pitch
- **$CTDI_w$** represents the average dose across the field-of-view (FOV) in the mid-plane of the scanned volume – for axial scans
- **$CTDI_{vol}$** represents the average dose across the field-of-view (FOV) in the mid-plane of the scanned volume – for helical scans

Size-Specific Dose Estimate (SSDE)

$$\mathrm{SSDE} = \mathrm{CTDI}_{\mathrm{vol}} \times f(d)$$



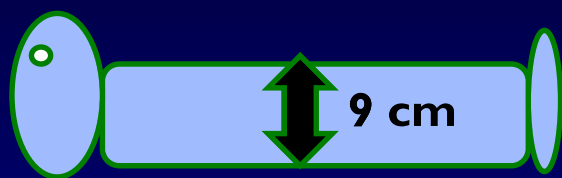
for-your-child.blogspot.com

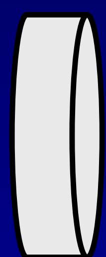
halftimefit.com

Courtesy of Dr. Xiang Li, Cleveland Clinic

CTDI$_{vol}$ vs. SSDE

120 kVp at 100 mAs

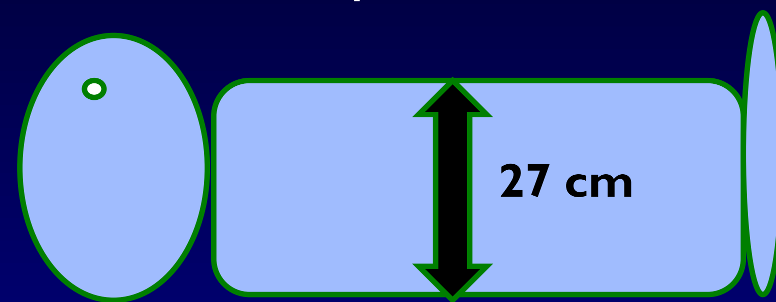


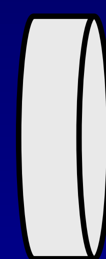


32 cm
Phantom

CTDI$_{vol}$ = 10 mGy
SSDE = 13.2 mGy

120 kVp at 200 mAs





32 cm
Phantom

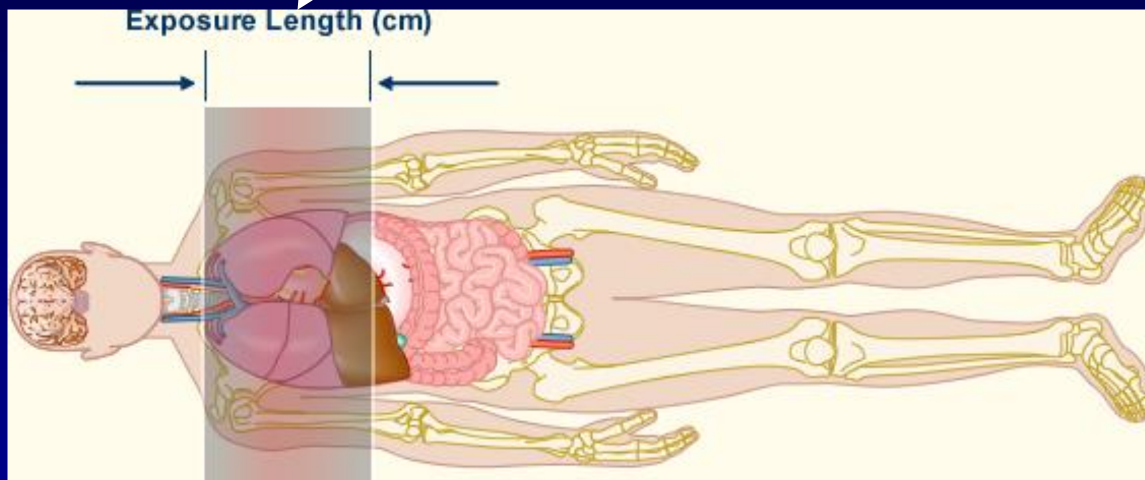
CTDI$_{vol}$ = 20 mGy
SSDE = 13.2 mGy

Patients have equivalent SSDE

Dose Length Product (DLP)

DLP = exposure length x CTDIvol

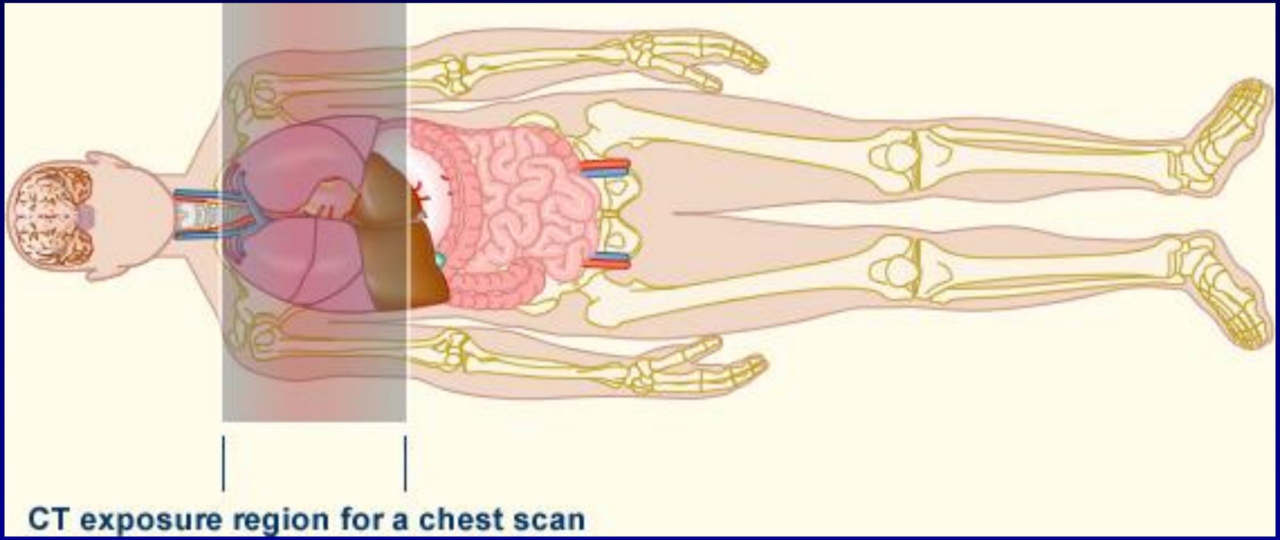
(mGy*cm) (cm) (mGy)



- DLP approximates the integrated dose along the scan range, therefore, clinically DLP is often used to indicate “total energy deposited.”

Organ Dose (D_T)

- **A CT scan is usually a partial body exposure with dose to certain organs in the scan range. Organs may be entirely or partially irradiated.**

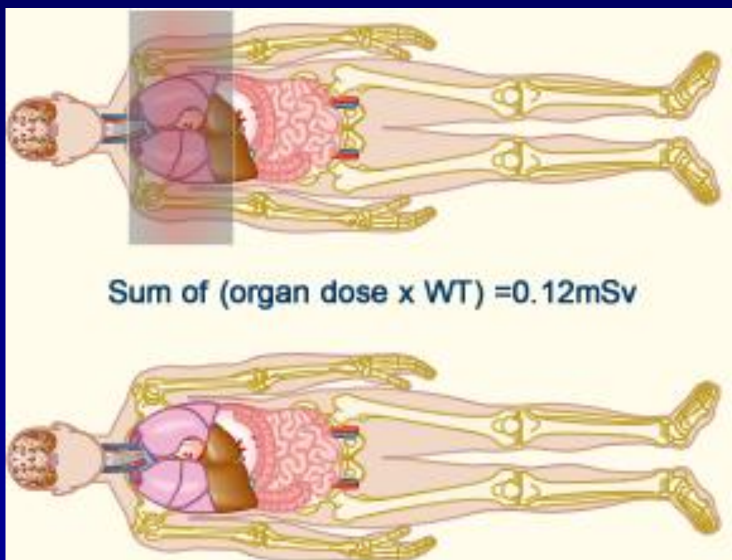


Organs irradiated: lung, breast, heart, bones, vessels and skins

Effective Dose E(mSv)

- Converts organ doses to an effective whole body dose
- Use tissue weighting factors from ICRP Report. 103

$$E\ (mSv) = \sum_T W_T * D_T$$



ICRP Tissue Weighting Factors W_t

Tissue or Organ	W_t
Bone marrow, Breast, Colon, Lung, Stomach	0.12
Bladder, Esophagus, Gonads, Liver, Thyroid	0.05
Bone Surface, Brain, Kidneys, Salivary, Glands, Skin	0.01
Remainder Tissues (Nominal W_t applied to the average dose to 14 tissues)	0.10

From ICRP Report 103 (2007)

Estimating Effective Dose

- Effective dose can be estimated using anatomic region specific conversion factors (k-factor):

$$E(mSv) = DLP * k$$

Table 3. Normalized effective dose per dose-length product (DLP) for adults (standard physique) and pediatric patients of various ages over various body regions. Conversion factor for adult head and neck and pediatric patients assume use of the head CT dose phantom (16 cm). All other conversion factors assume use of the 32-cm diameter CT body phantom[78,79]

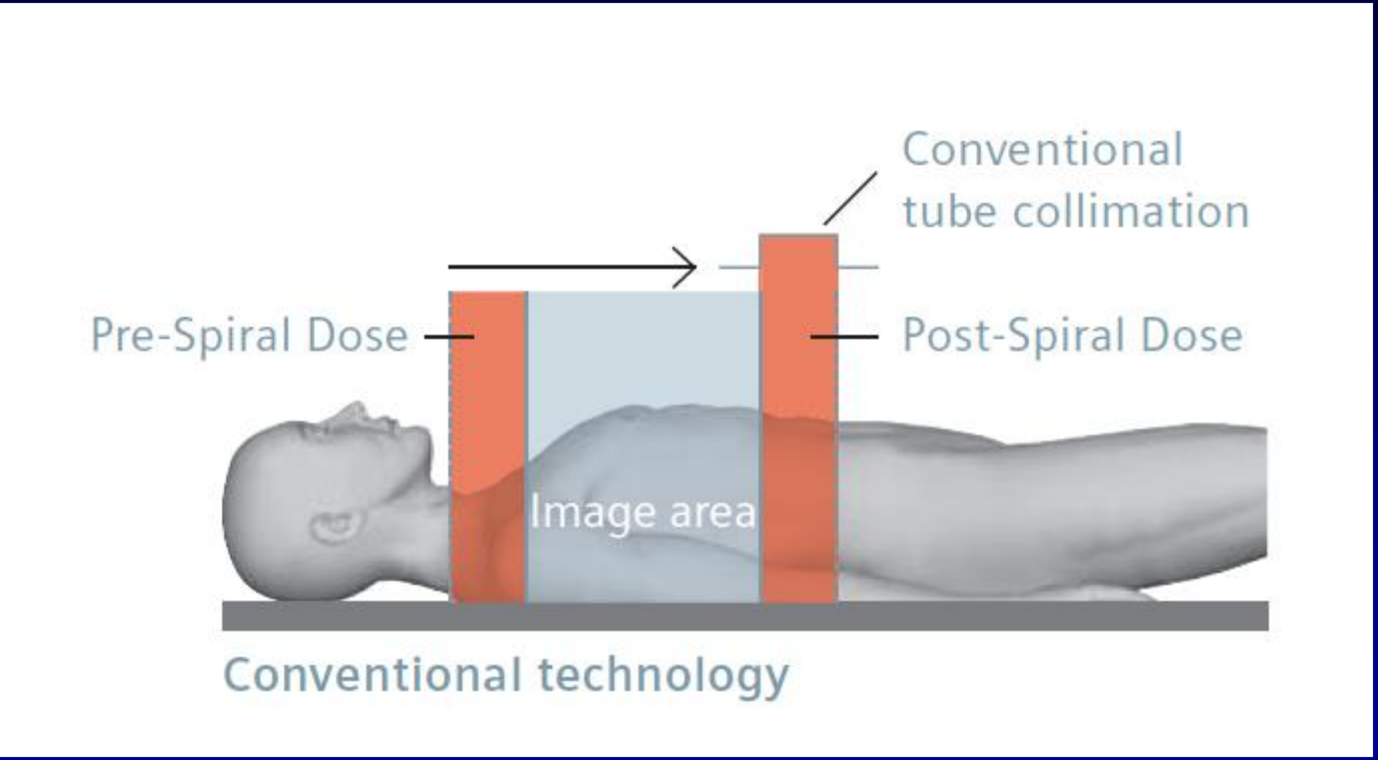
Region of Body	*k (mSv mGy⁻¹ cm⁻¹)*				
	0 year old	*1 year old*	*5 year old*	*10 year old*	*Adult*
Head and neck	0.013	0.0085	0.0057	0.0042	0.0031
Head	0.011	0.0067	0.0040	0.0032	0.0021
Neck	0.017	0.012	0.011	0.0079	0.0059
Chest	0.039	0.026	0.018	0.013	0.014
Abdomen ≈& pelvis	0.049	0.030	0.020	0.015	0.015
Trunk	0.044	0.028	0.019	0.014	0.015

AAPM Report No. 96, " The measurement, Reporting, and Management of Radiation Dose in CT"

Dose Reduction Techniques

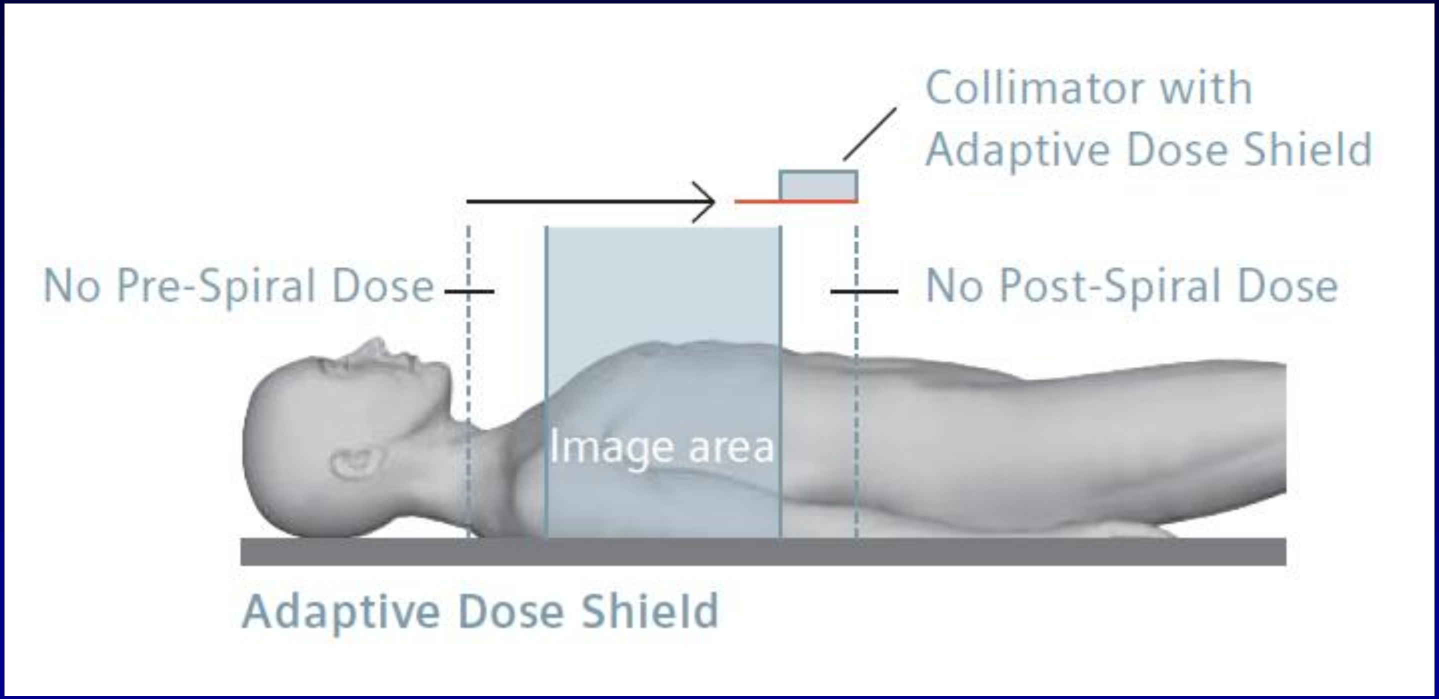
- Automatic tube current modulation (ATCM)
- Organ specific dose modulation
- Iterative Reconstruction
- Adaptive beam collimation

Conventional Beam Collimation



Courtesy of Siemens Healthcare, USA

Adaptive Beam Collimation



Courtesy of Siemens Healthcare, USA

CT Clinical Applications

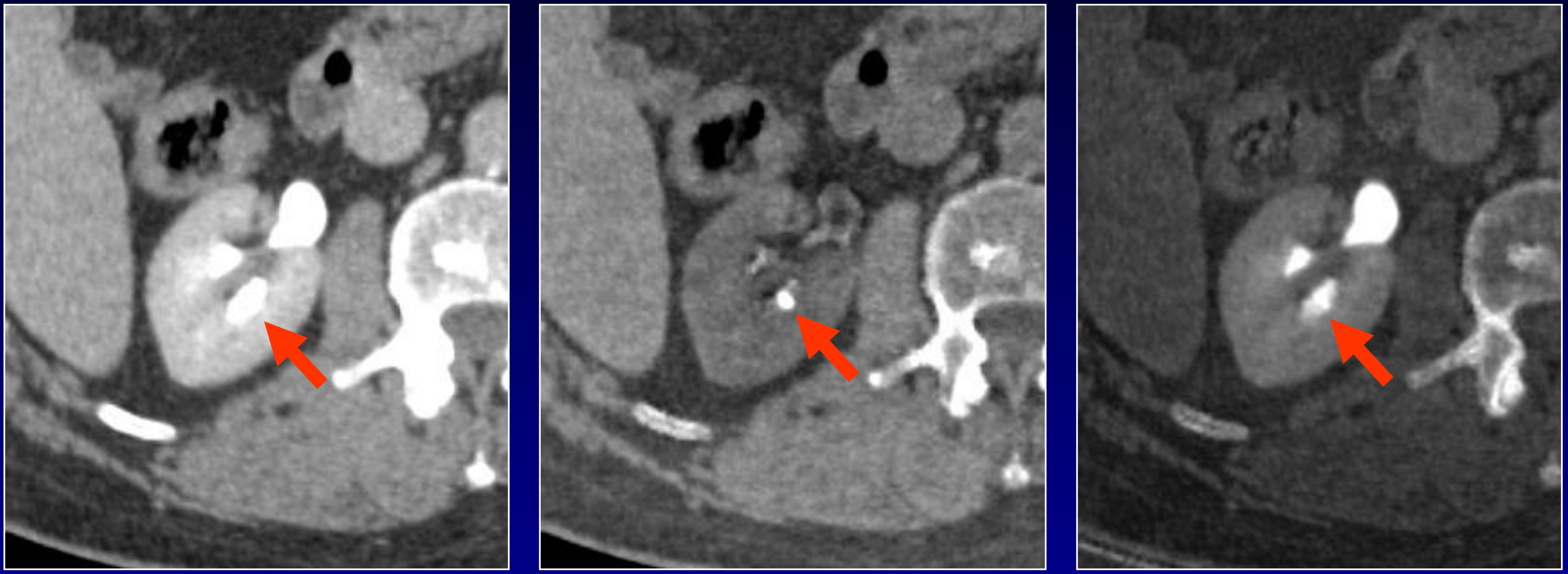
- Dual Energy Imaging
- CT Lung Cancer Screening
- One heart beat Cardiac CT
- Mobile CT Stroke Unit

Dual Energy CT

Dual Energy CT

- Acquire signals containing low and high energy photons separately,
  - FastkV switching (GE)
  - Dual source (Siemens)
  - TwinBeam dual energy (Siemens)
  - Dual layer detector (Philips)
- Combining low and high energy signals using a pre-calibrated coefficients to generate material specific images and/or monochromatic images

Virtual Non-contrast (VNC) Image



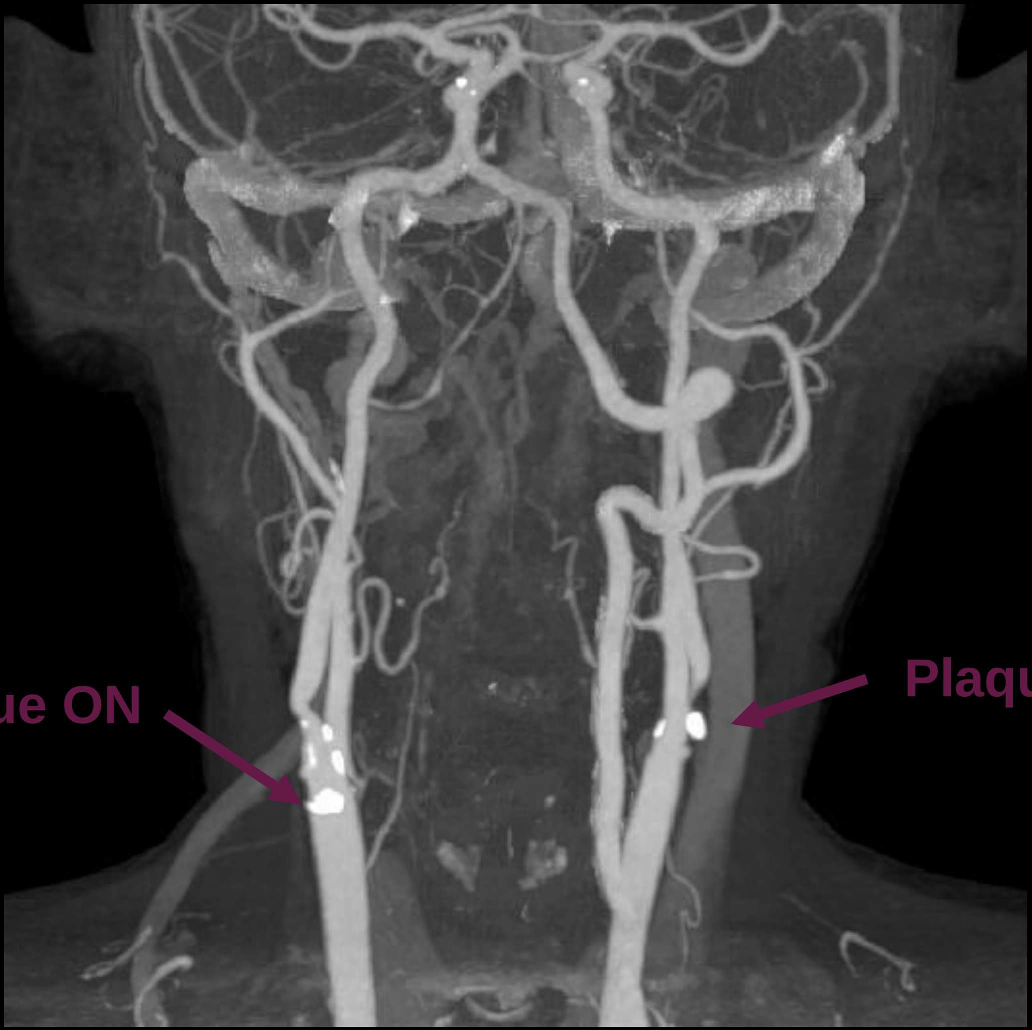
140kVp w/ contrast

Water-only (renal calculi visible)

Iodine-only

Courtesy of GE Healthcare

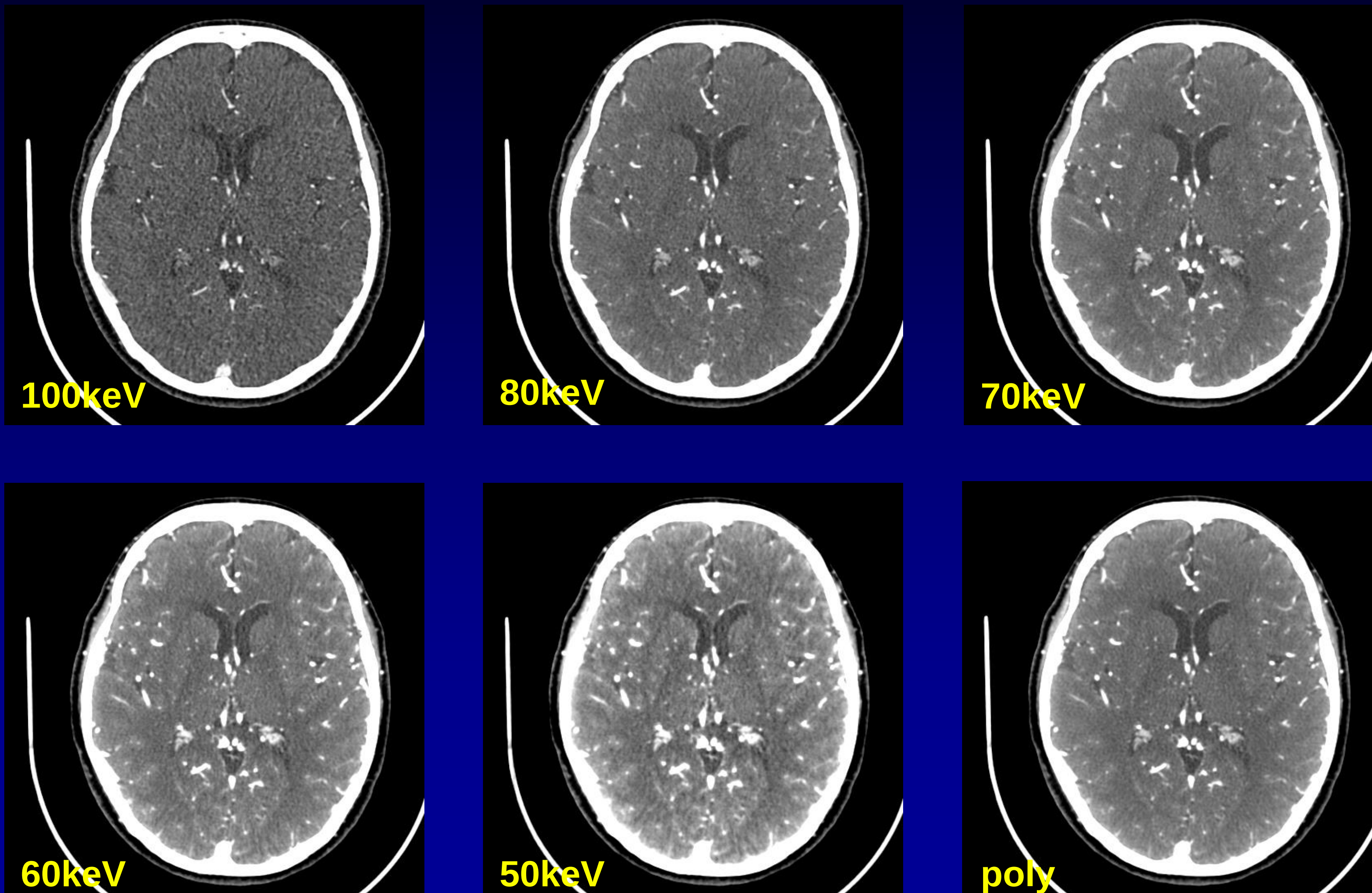
Bone Removal



Plaque ON

Plaque ON

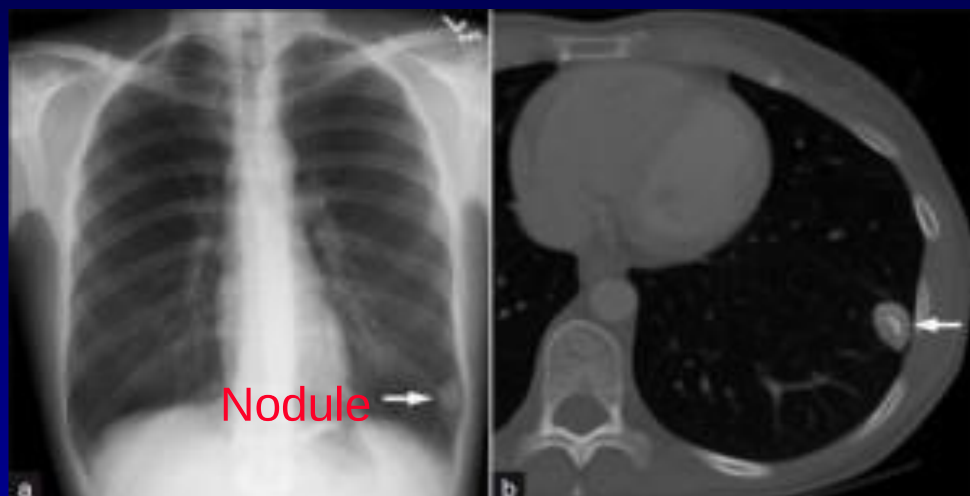
Monochromatic Brain Images w/ Contrast



Courtesy of GE Healthcare

CT Low Dose Lung Cancer Screening (LCS)

Chest X-ray vs. CT



Nodule

Chest X-ray

Chest CT

CT Lung Cancer Screening Scan Parameters

- Scanner
  - Gantry rotation period: ≤0.5s
  - Recon Slice thickness: ≤2.5mm (≤1.0mm is recommended)
  - No. of physical detector rows: ≥16 rows are preferred
- Low Radiation Dose
  - CTDIvol <3mGy for a standard sized patient (5’7” and 155lbs)
  - CTDIvol ↓ for smaller patients and ↑ for larger patients
  - Use Automatic Exposure Control system if available
  - Manual technique charts to adjust mA and/or kVp based on patient size

AAPM CT Lung Screening Protocols (GE Protocols)

	LightSpeed 16 BrightSpeed 16	Optima 660	LightSpeed VCT	Discovery CT750 HD
Scan Type	Helical	Helical	Helical	Helical
Rotation Time (s)	0.5	0.6	0.5	0.5
Beam Collimation (mm)	10/20	40	40	40
Detector Configuration	16x0.625/ 16x1.25	64x0.625	64x0.625	64x0.625
Pitch	1.375	1.375	0.969	0.969
Speed (mm/rot)	13.75/ 27.50	55.0	19.375	39.37
kV*	120	120	120	120
mA*	60	50	50	50
SFOV	Large Body	Large Body	Large Body	Large Body
CTDIvol*	2.3/ 2.0 mGy	1.8 mGy	1.9 mGy	1.9 mGy
RECON 1				
Plane	Axial	Axial	Axial	Axial
Algorithm	Bone or Lung	Bone or Lung	Bone or Lung	Bone or Lung
Recon Mode	Full	Full	Full	Full
Thickness (mm)	1.25	1.25	1.25	1.25
Interval (mm)	1.25	1.25	1.25	1.25
ASIR (if used)	SS50	SS50	SS50	SS50
RECON 2				
Plane	***Axial DMPR-create Sag/Cor reformats	**Axial DMPR-create Sag/Cor reformats	**Axial DMPR-create Sag/Cor reformats	**Axial DMPR-create Sag/Cor reformats
Algorithm	Bone or Lung	Bone or Lung	Bone or Lung	Bone or Lung
Recon Mode	Full	Full	Full	Full
Thickness (mm)	0.625	0.625	0.625	0.625
Interval (mm)	0.625	0.625	0.625	0.625
ASIR (if used)	SS50	SS50	SS50	SS50

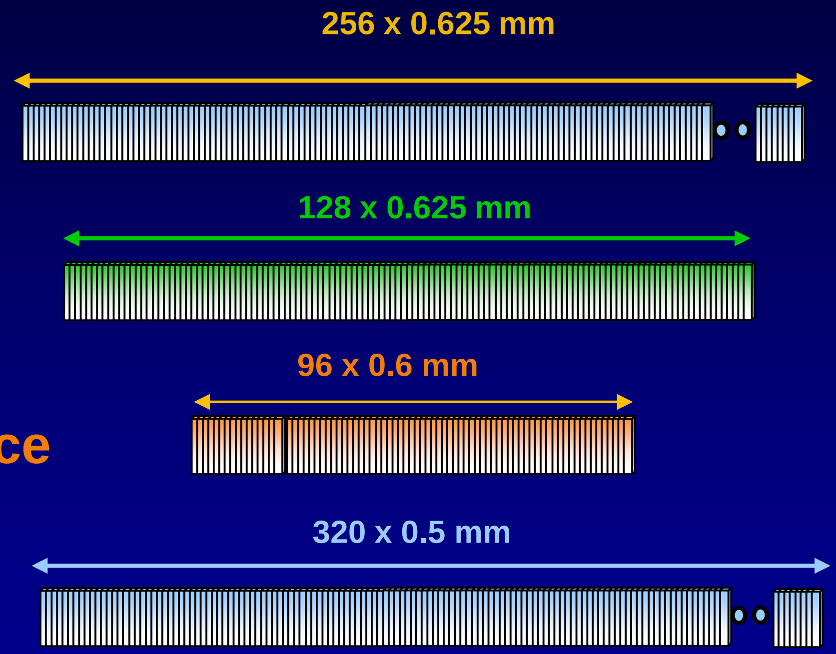
http://www.aapm.org/pubs/CTProtocols/documents/LungCancerScreeningCT.pdf

Cardiac Imaging within A Single Heartbeat

Single Heartbeat Cardiac Imaging

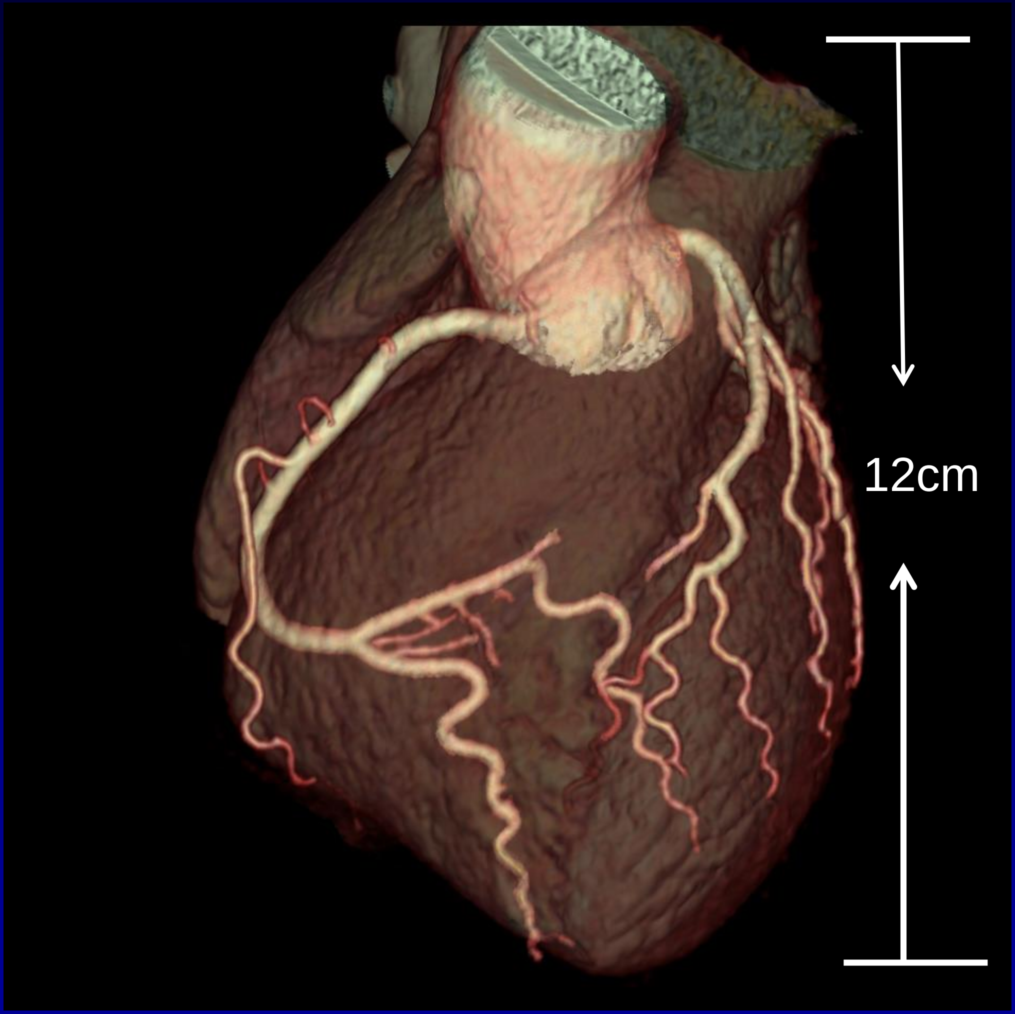
- Wide area CT detector
- Dual source CT for exceptional temporal resolution
- High pitch spiral/helical scan mode

Major Vendors’ CT Detector Configuration

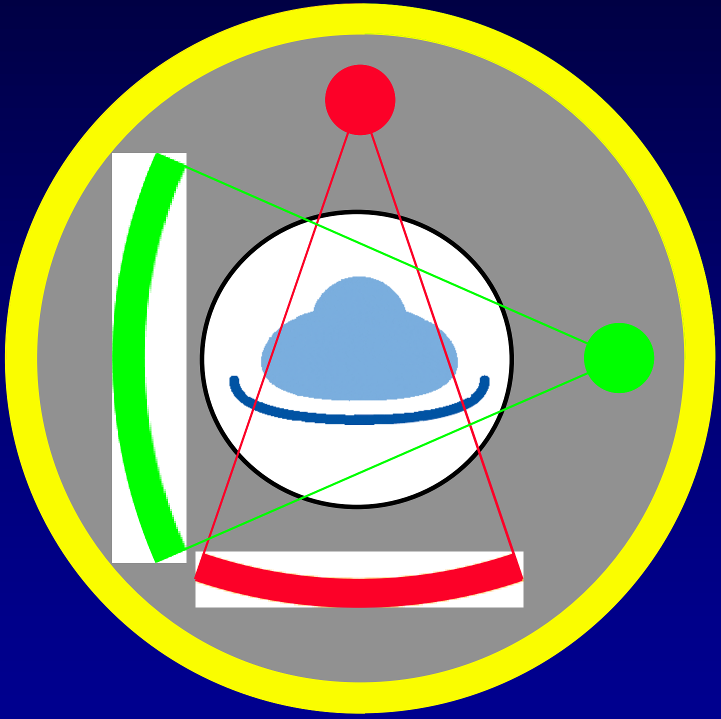


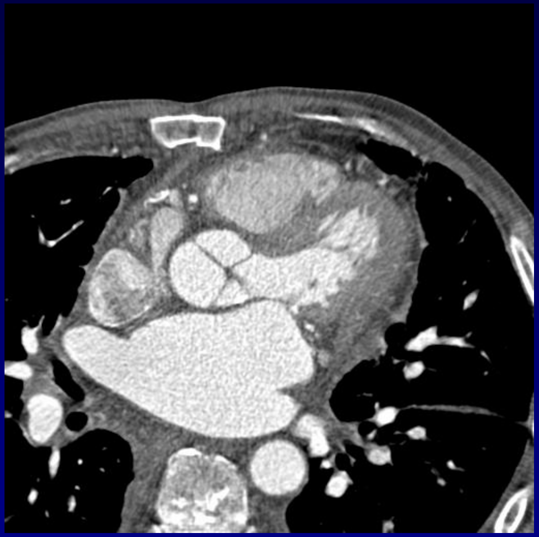
GE Revolution CT	160 mm/rot
Philips Brilliance iCT	80 mm/rot
Siemens Definition Force	57.6 mm/rot
Toshiba AquilionONE	160 mm/rot

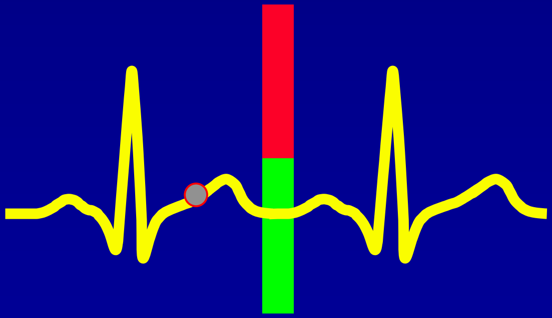
Single Heartbeat cardiac CT w/o Beta Blocker



Dual Source Recon



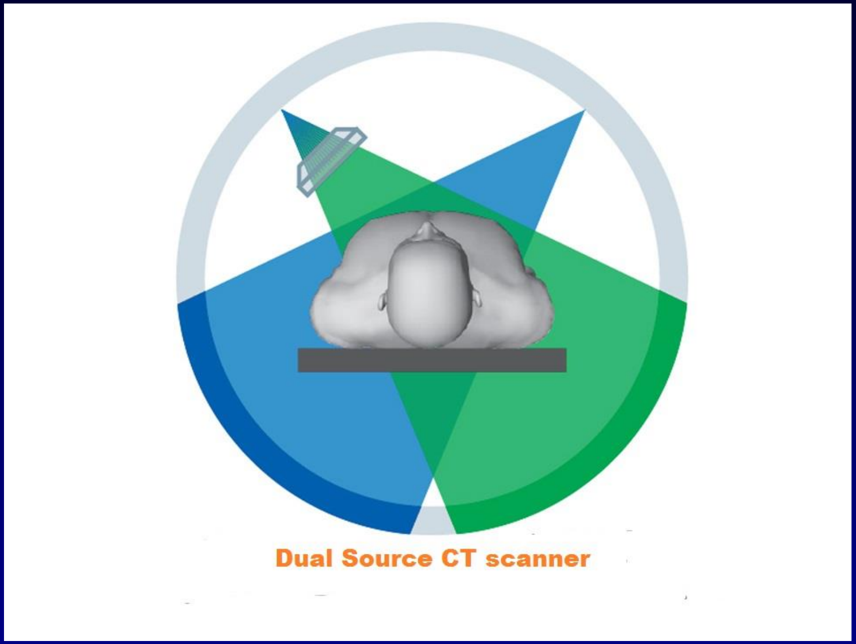


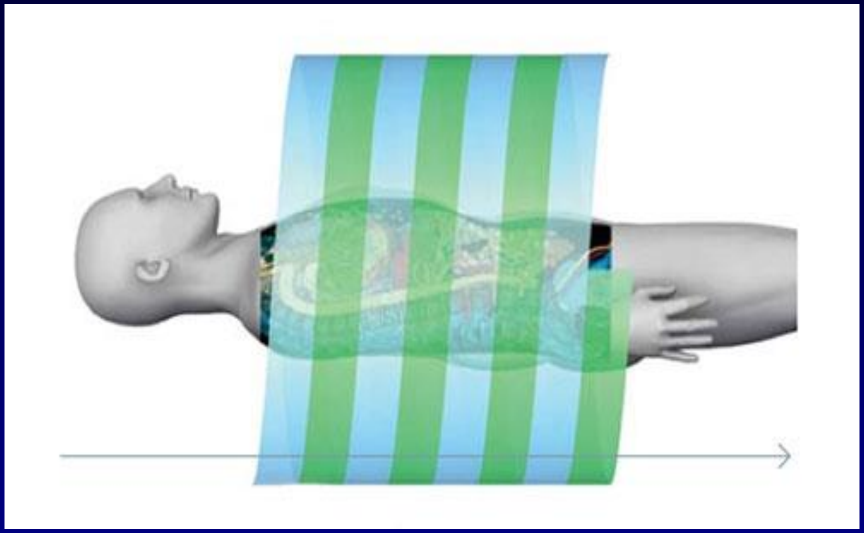


Temporal Resolution: $\frac{0.25s}{\sim 4}$ **= 63 ms**

Courtesy of Siemens Healthcare, USA

High Pitch Flash Mode





Data gap from one tube is filled in by the data from 2nd tube

- Single source CT spiral pitch <1.5
- Dual source CT spiral pitch ~3.2!
- Table speed up to 737 mm/s (Siemens Force).

Mobile Stroke CT Unit: Treatment on the Road

Stroke is the **5th** leading cause of death in the U.S.

It is the No. **1** cause of disability in the U.S.

1 in 5 women and **1 in 6** men will have a stroke in their lifetime.

Courtesy of Stacey Winners, Cleveland Clinic

Time is Brain!

	Neurons Lost	Synapses Lost	Accelerated Aging
Per Stroke	1.2 billion	8.3 trillion	36 yrs
Per Hour	120 million	830 billion	3.6 yrs
Per Minute	1.9 million	14 billion	3.1 weeks
Per Second	32,000	230 million	8.7 hrs

(Total number of neurons in the average human brain is 130 billion)

Stroke 2006;37:263-266

TIME GOALS

Door to physician

10 minutes

Door to neurologist

15 minutes

Door to CT complete

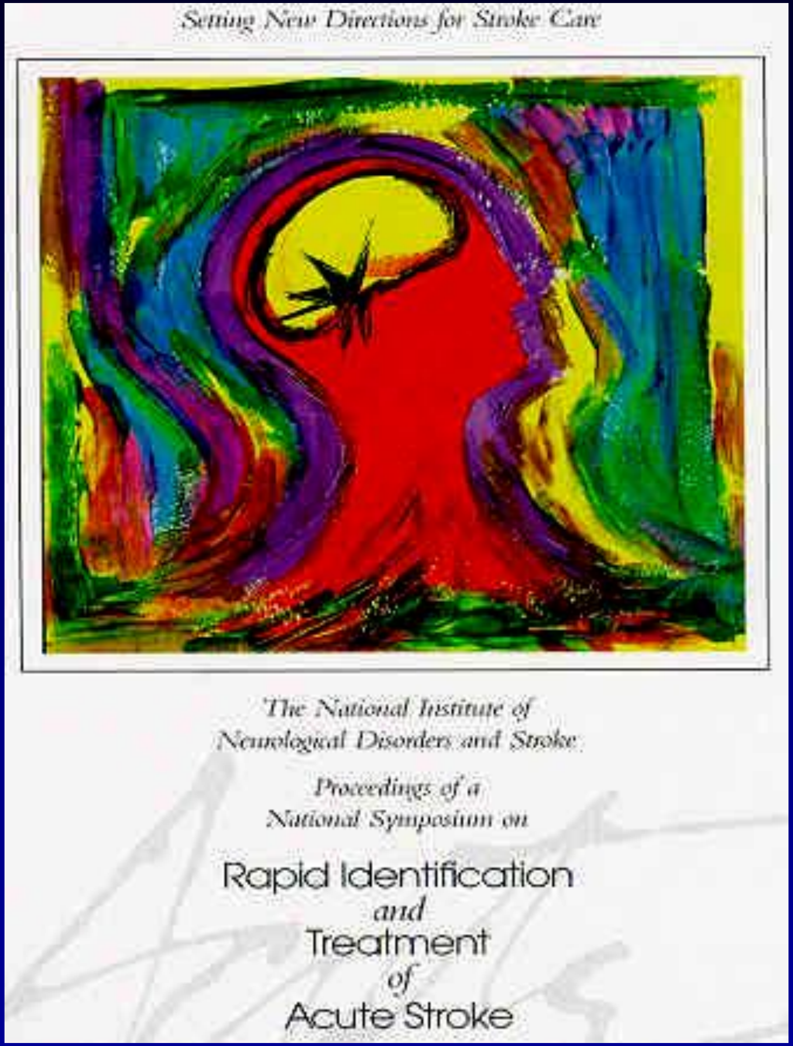
25 minutes

Door to CT read

45 minutes

Door to needle

60 minutes

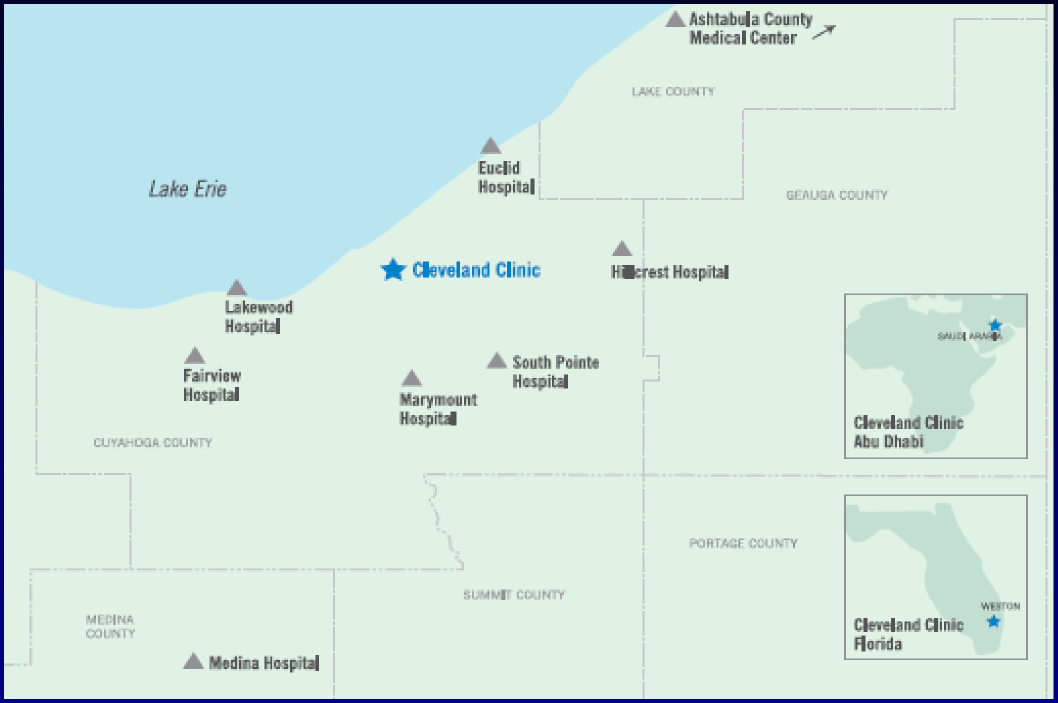


Stroke 2013;44;870-987

Cleveland Clinic Stroke System (Pre-Mobile Stroke)

Devastating Problem	Yearly Discharge Volume
Cuyahoga County	5,600

	Yearly Discharge Volume	Vol inc past 6 yrs
CC Main	1,600	+10%
Rest of CCHS	1,400	
UH main	1,200	



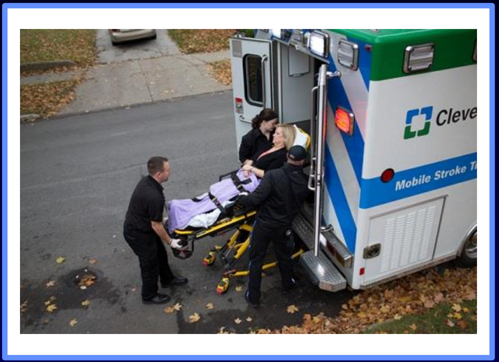
CC Slow to Improve	Hosp A	Hosp B	Hosp C	Hosp D	Hosp E	Hosp F	Hosp G	Hosp H	Hosp I
IVtPA delivery rate	17%	10%	11%	4%	7%	6%	18%	10%	0%
Door to Drug in 60 min	56	67	109	107	74	-	78	88	-

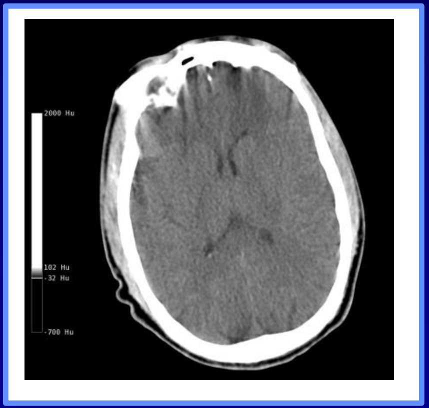
Mobile Stroke Unit: Diagnosis and Emergency Care

- Don’t wait for the patient to go to ER
- Bring the ER to the patient (CT and stroke expertise)
- Initiate treatment at the scene
    - Onboard Staff: EMT, Paramedic, CT Technologist, Critical Care RN and Virtual Stroke Neurologist enablement
- Dramatically cut time-to-treatment decisions

Courtesy of Stacey Winners, Cleveland Clinic

Mobile Stroke Unit Operation





Courtesy of Stacey Winners, Cleveland Clinic

Cleveland Clinic Telestroke (First 100 patients treated)

Variable	MSTU (n = 100)	Controls (n = 56)	*P* Value
Age, median (IQR), y	62 (53-76)	64 (57-79)	.22
Female sex, No. (%)	54 (54.0)	32 (57.1)	.70
Race/ethnicity, No. (%)			
African American	63 (63.0)	38 (67.9)	.12
Non-Hispanic white	29 (29.0)	9 (16.1)	
Other	8 (8.0)	7 (12.5)	
Initial National Institutes of Health Stroke Scale score, median (IQR)[a]	6.0 (2-12)	6.5 (2-13)	.70
IV-tPA, No. (%)	16 (16.0)	13 (23.2)	.30
Process time, median (IQR), min			
MSTU activation to scene arrival	12 (8-14)	NA	NA
On-scene time until entry into the MSTU[b]	8 (5-11)	NA	NA
Door to CT completion	13 (9-21)	18 (12-26)	.003
Door to CT read	25 (20-29)	25 (19-35)	.59
Door to international normalized ratio result	13 (7-18)	44 (36-61)	<.001
Door to IV-tPA	32 (24-47)	58 (53-68)	<.001
Door to video log-in	11 (7-17)	NA	NA
Video duration	20 (14-27)	NA	NA
Total MSTU use from activation until arrival at destination hospital per episode	86 (78-93)	NA	NA

Itrat A, et al. *JAMA Neurol*. 2016;73(2):162-168.