Dose Reduction and Artifacts in CT

Stephen E. Hale Jr., Ph.D.
Integrated Science Support, Inc.

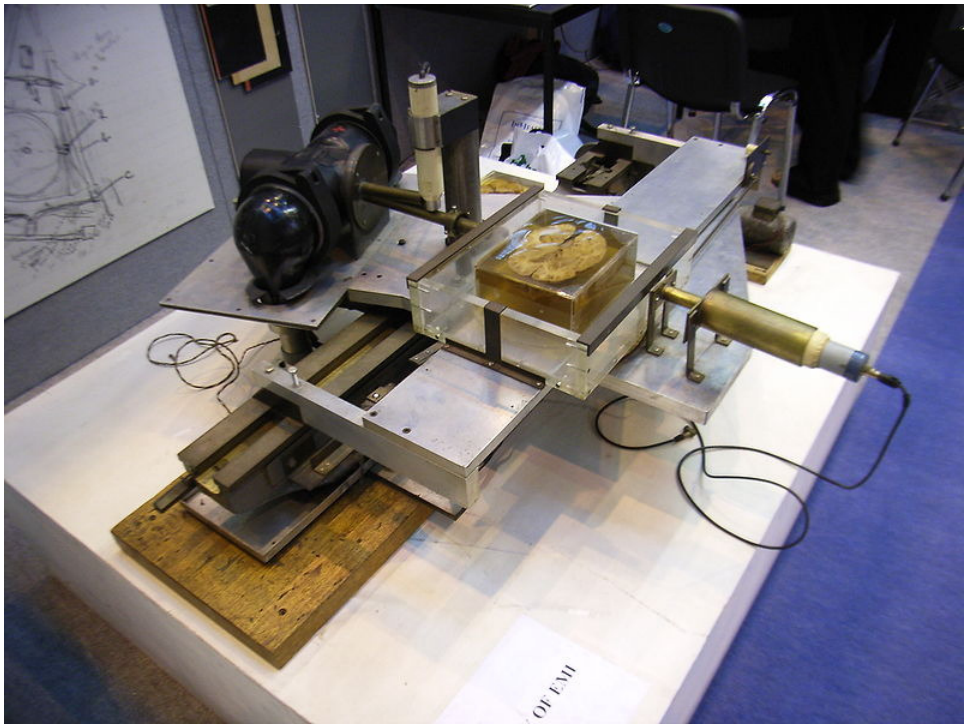
Outline

- Nature and History of CT
- CT Dose Issues
- Dose Reduction Capabilities
- Dose Management
- Artifacts in CT
- Summary

NATURE & HISTORY OF CT

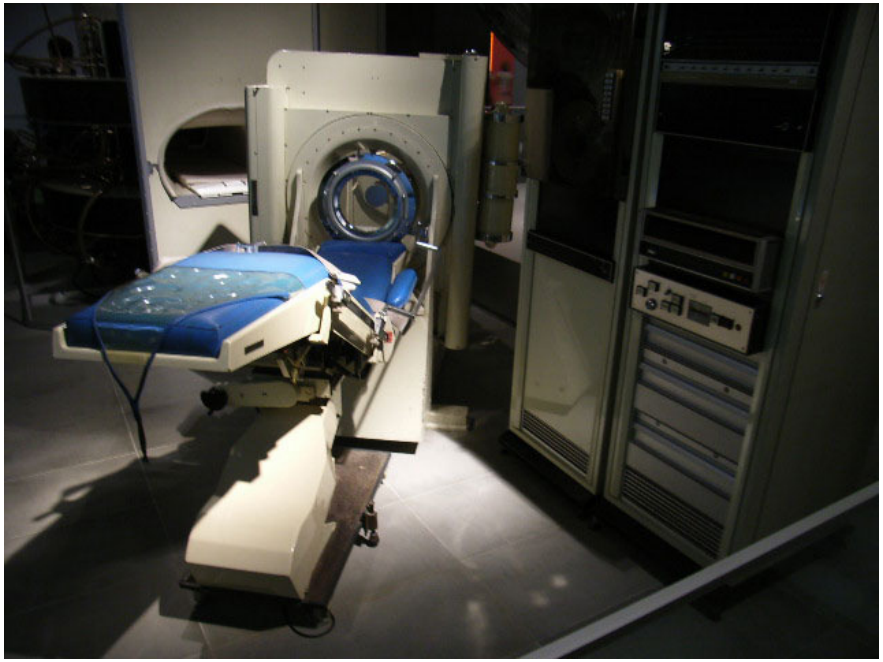
First CT - 1967

- 1st Generation
- Translate and Rotate
- Single detector
- Hounsfield in 1967 actually had 2 detectors



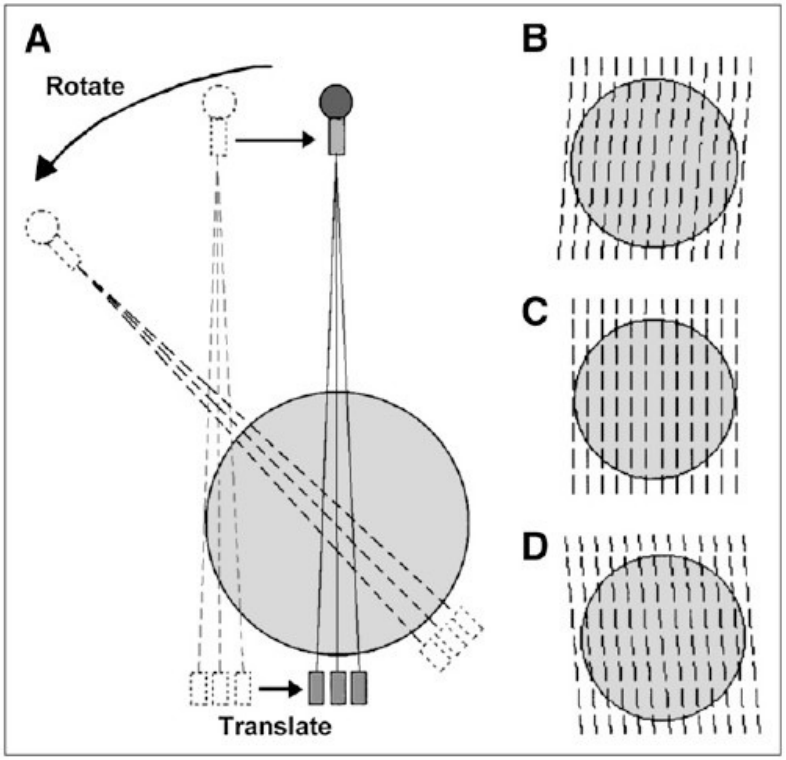
Clinical Introduction

- First patient head scan performed at Atkinson-Morley Hospital in England on 10/1/1967
- 160 rays @ each of 180 angles, 1° apart
- Scan took 5 minutes
- Reconstruction took 2.5 hours



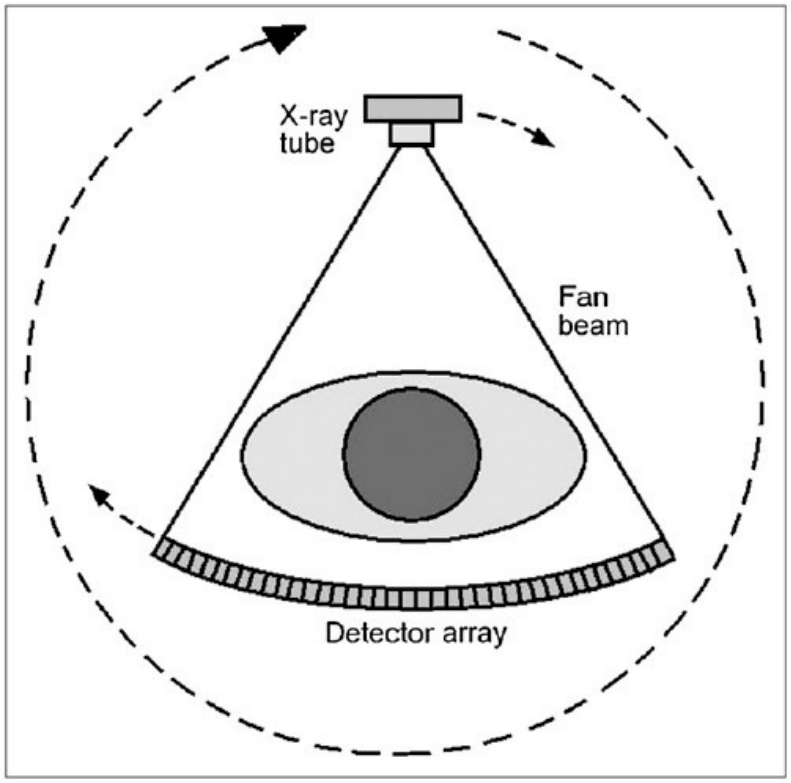
2nd Generation CT

- Still translate and rotate
- Multiple detectors with multiple beams (or a beam with width = fan beam)
- Scatter increased with wider beam



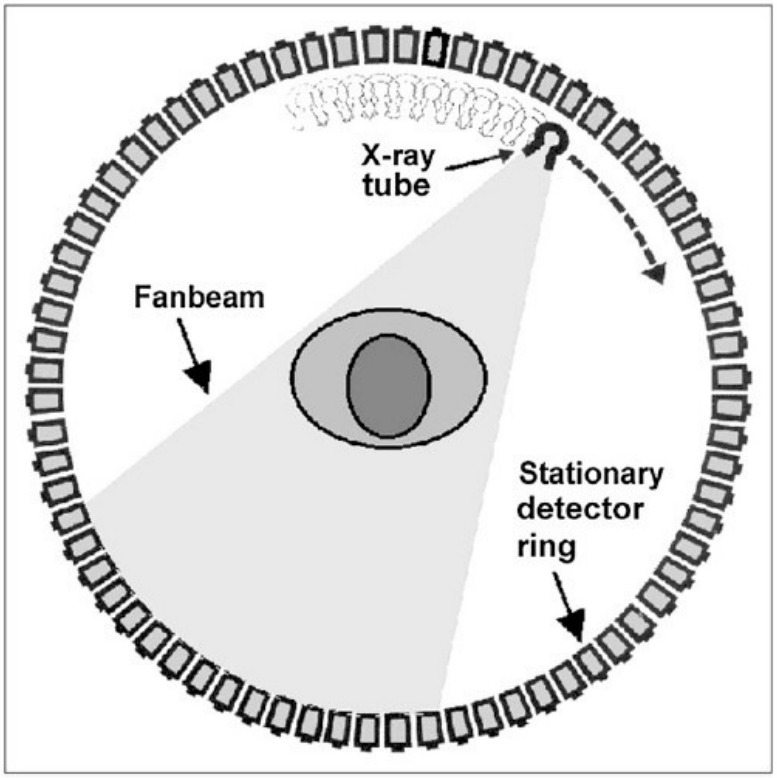
3rd Generation CT

- Widen x-ray beam to a fan beam
- Array of detectors
- Physically tie detectors and x-ray source onto same structure
- Complications – detector stability, matching responses, ring artifacts



4th Generation CT

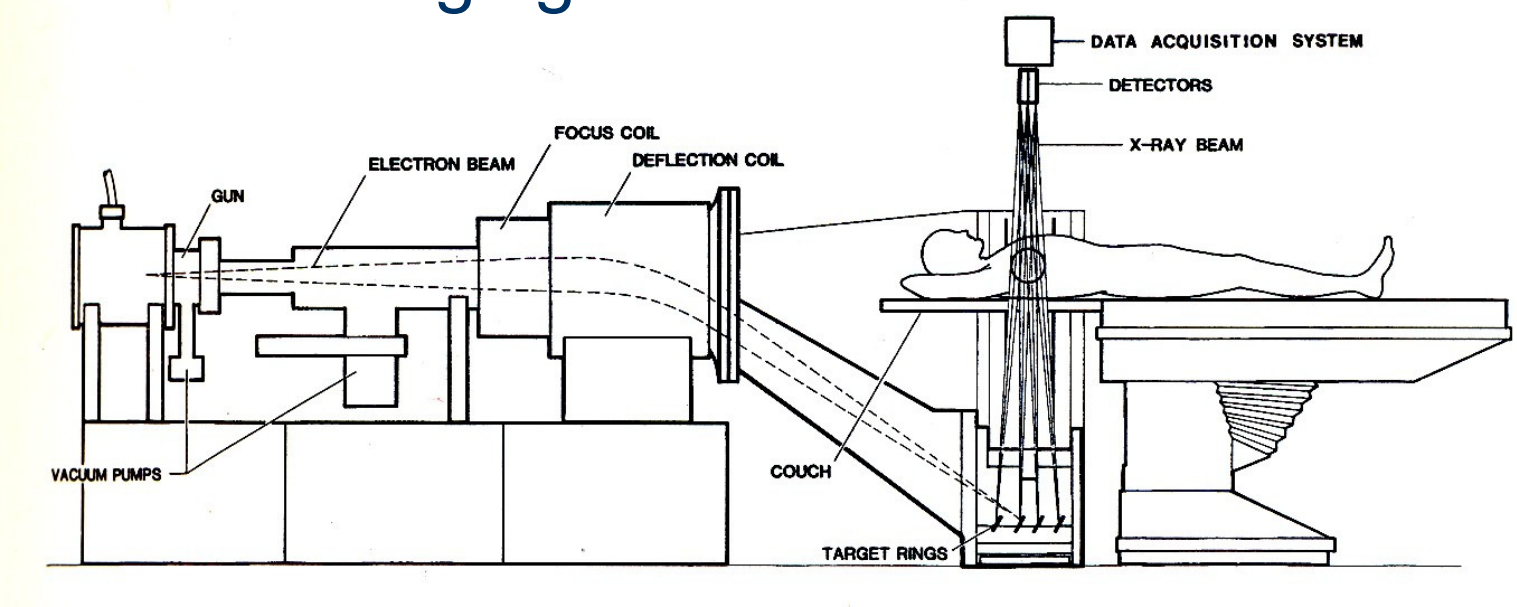
- Rotate/Stationary
- Fixed ring of detectors
- X-ray tube rotates inside of detector ring
- Issues
  - Size of system
  - Cost of detectors
  - Scatter removal



CT in Motion

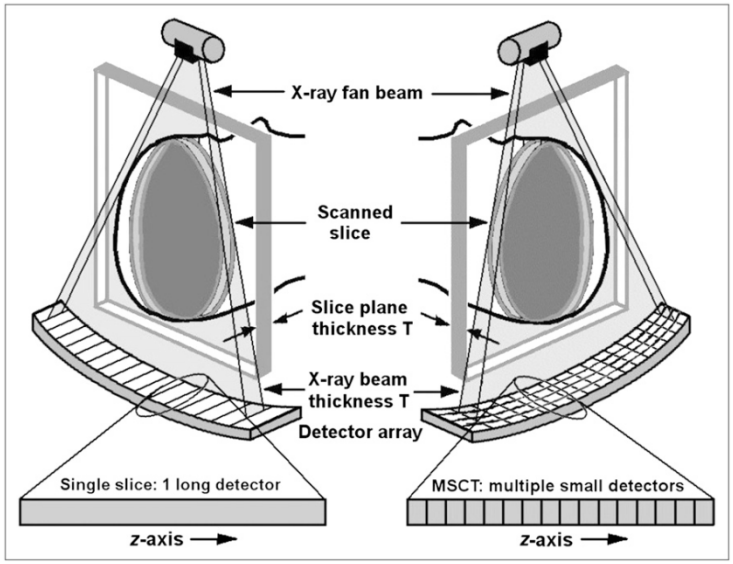
EBCT – 5th Generation

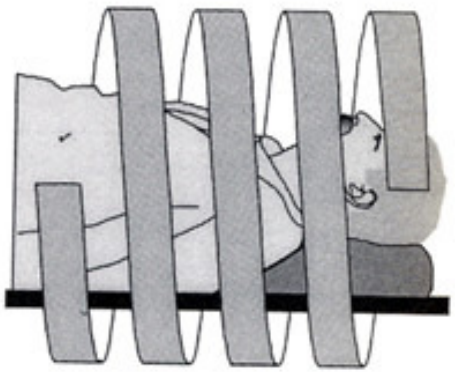
- Electron beam onto stationary target with stationary detector array
- 50 msec imaging times



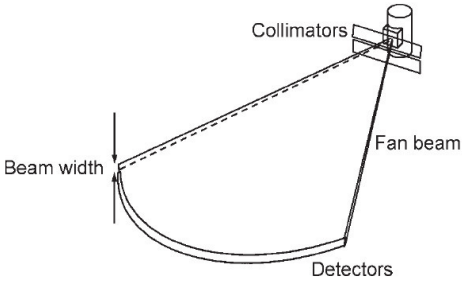
Developments

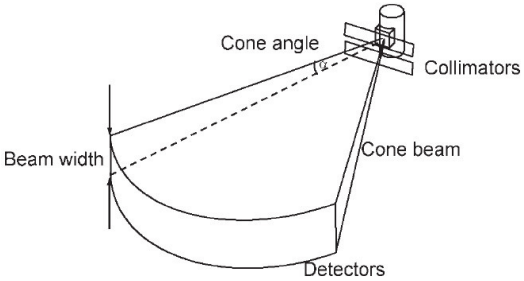
- Helical scans
  - Continuous table movement
- Arrays of detectors (multiple rows)
  - Cone beam acquisition required





helical x-ray tube path around patient

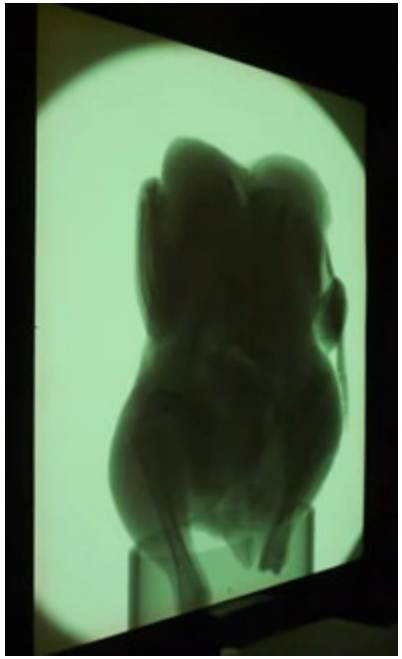


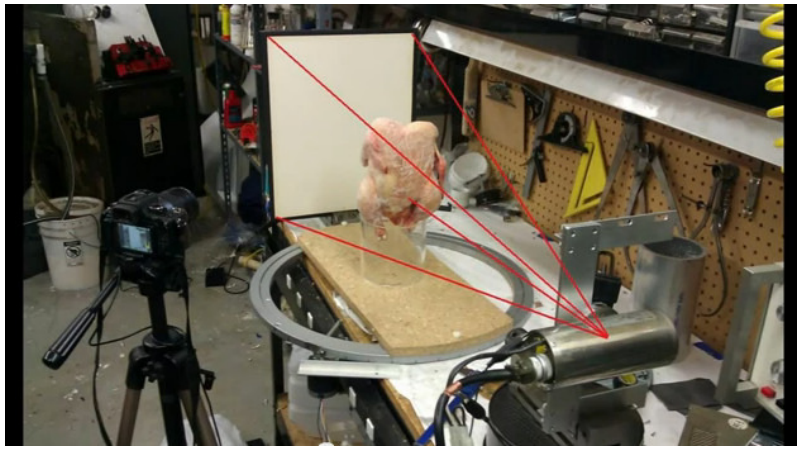


Costs & Benefits of CT

- Benefits
  - Tissues not superimposed
  - Improved low contrast resolution
  - Reformatting for different planes of images (MPR)
  - Surface and volume rendering
- Costs
  - HIGH dose modality
  - Patient reaction to contrast is possible
  - Possibility of cancer induction

Next?

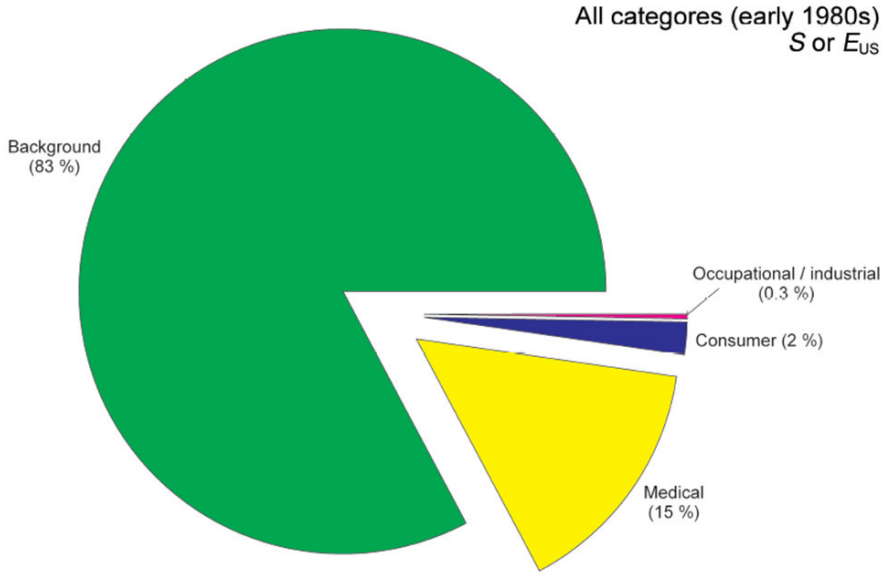


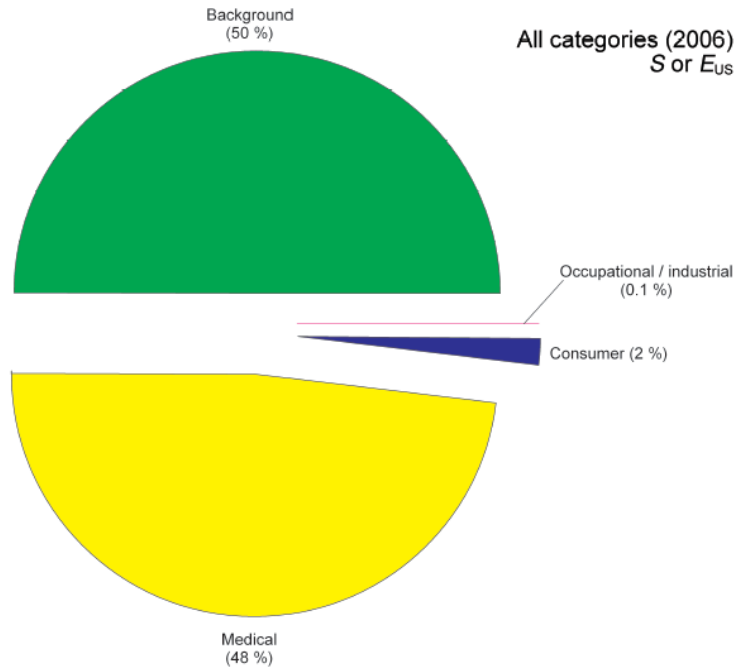


- Garage built CT
- X-ray tube from eBay, stepper motor, digital camera
- 45 images combined with FBP
- http://www.youtube.com/watch?v=hF3V-GHiJ78

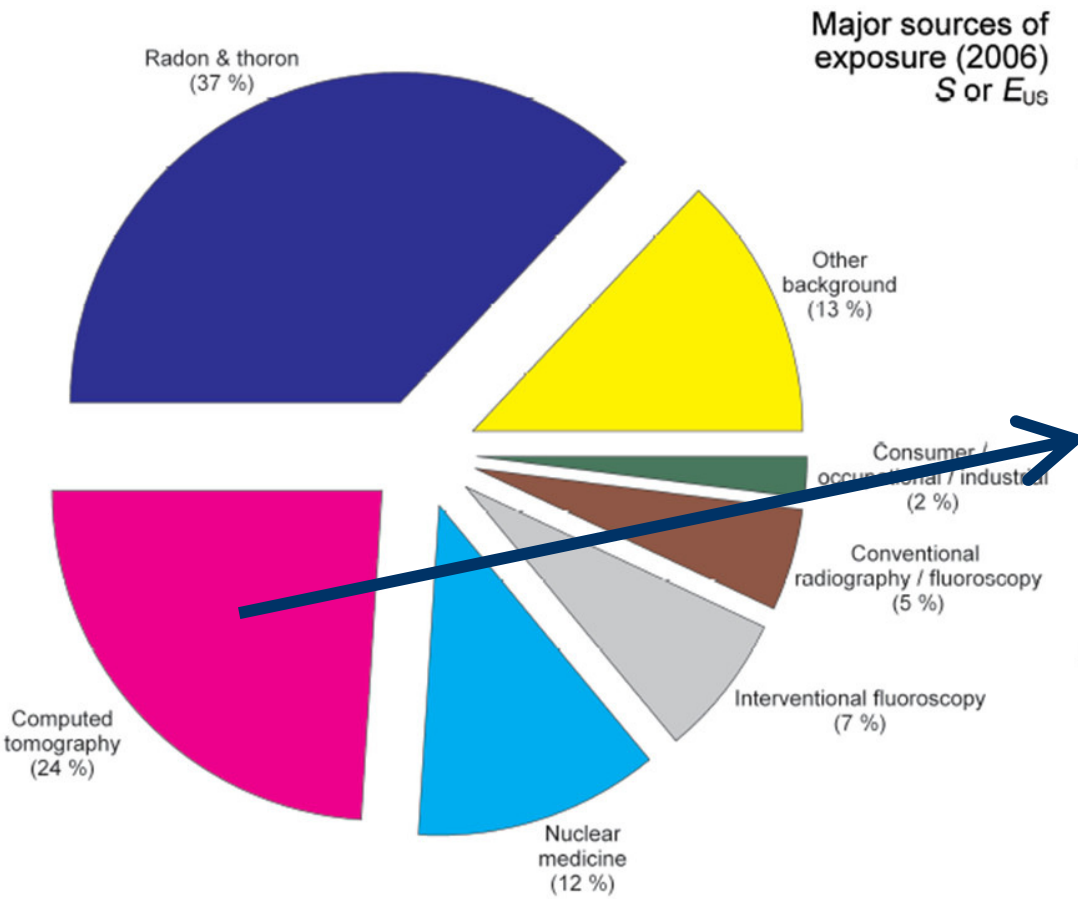
CT DOSE ISSUES

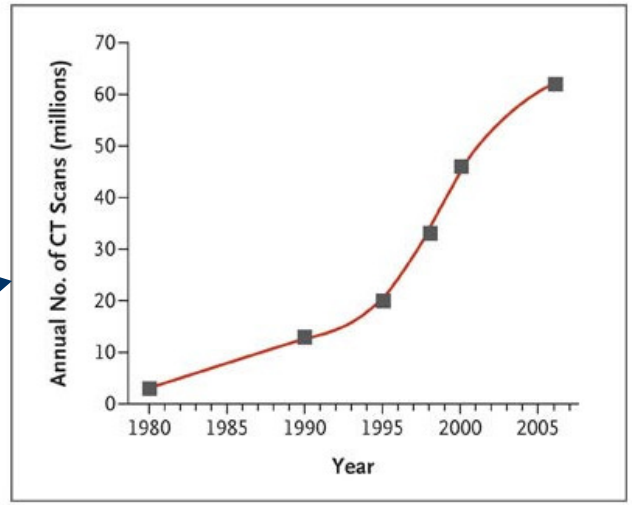
Exposure evolution





Source of exposure increase





“CT Dose”

Dose Report					
Series	Type	Scan Range (mm)	$CTDI_{vol}$ (mGy)	DLP (mGy-cm)	Phantom (cm)
1	Scout	—			
2	Helical	S30.000-S7.500	25	90	Body32
2	Helical	I72.500-I95.000	25	90	Body32
			Total Exam DLP: 180		

What is $CTDI_{vol}$?

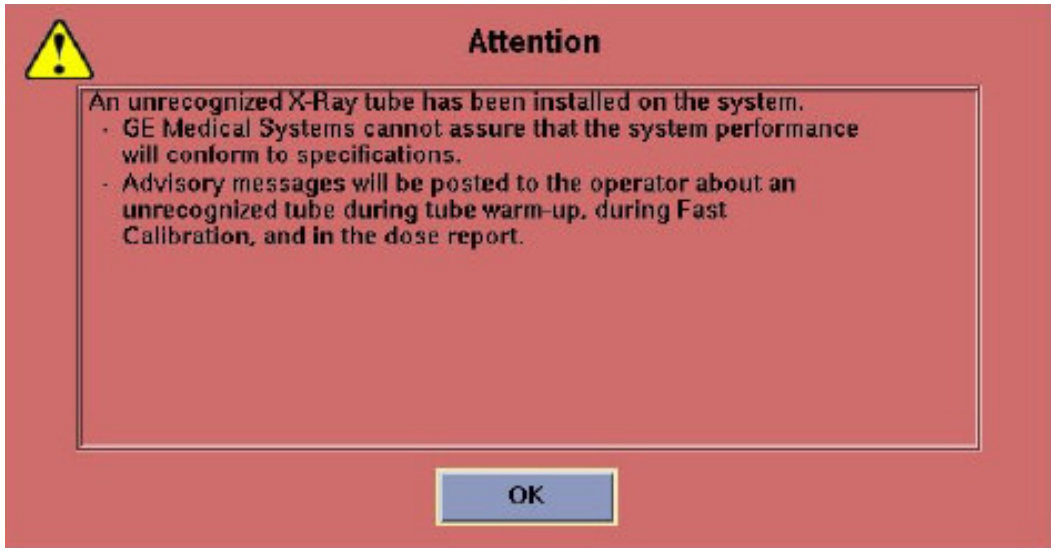
- CTD**I** = Computed Tomography Dose **Index**
  - **Not a Dose!**
  - The dose index is used for comparison purposes only
  - A standardized parameter to measure scanner radiation output
- For a true dose measurement/calculation, would need to know actual absorbed doses to organs & tissues being irradiated

Pesky Details of $CTDI_{vol}$

- $CTDI_{vol}$ reported in units of mGy, so it looks like a dose
- Scanner is reporting the value of radiation output distributed across a 16-cm or 32-cm diameter right cylinder acrylic phantom
  - For same techniques, $CTDI_{vol}$ for 16-cm phantom is approximately 2x that for a 32-cm phantom

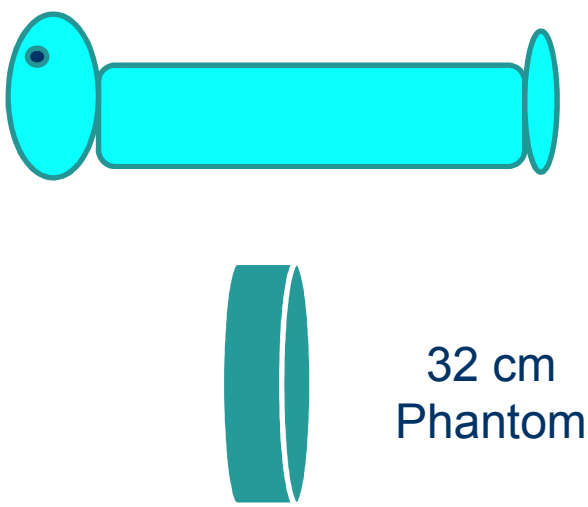
…and all is in a state of flux

- Reported value is based on measurements by the manufacturer
  - **THINGS CHANGE!**
  - **Physicists Test!**



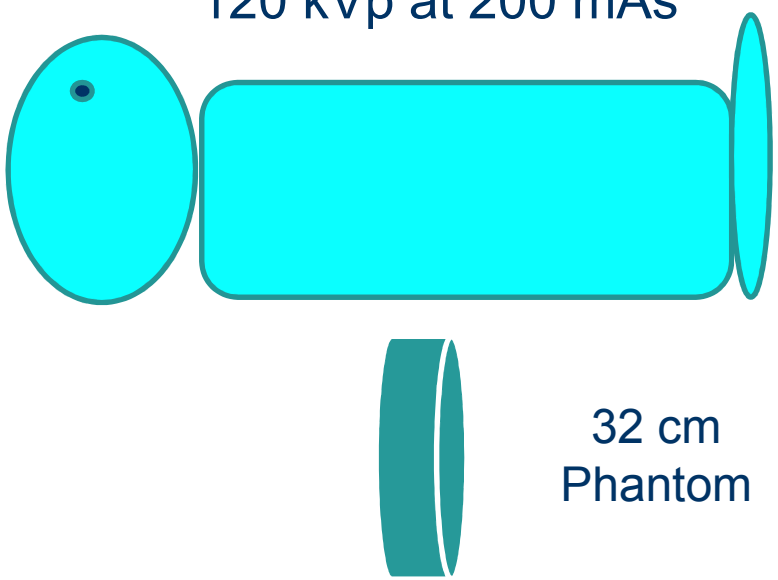
How is $CTDI_{vol}$ Related to Patient Dose

120 kVp at 200 mAs



$CTDI_{vol}$ = 20 mGy

120 kVp at 200 mAs



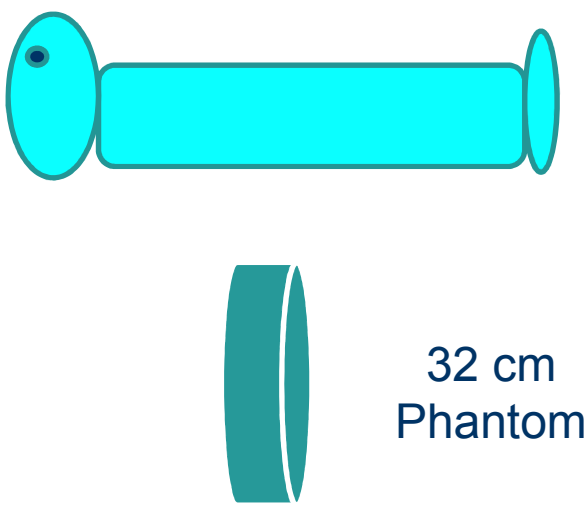
$CTDI_{vol}$ = 20 mGy

Both patients scanned with the same $CTDI_{vol}$

Patient dose will be higher for the smaller patient

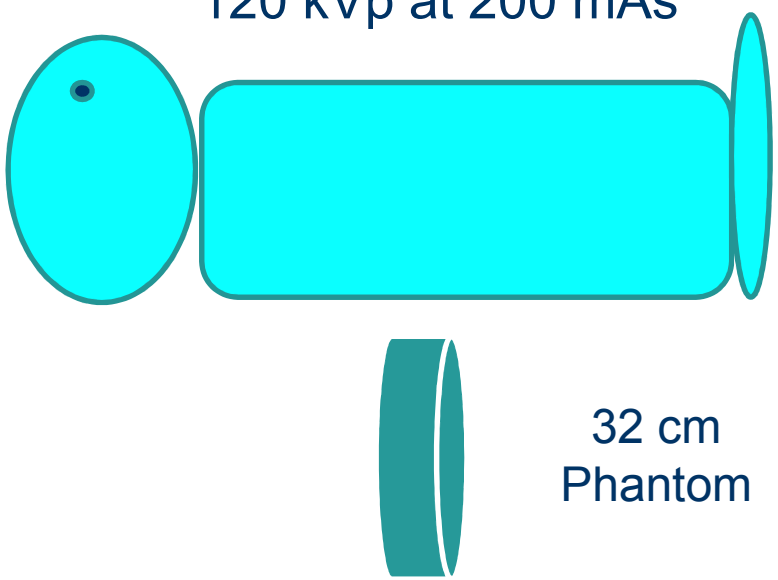
How is $CTDI_{vol}$ Related to Patient Dose

120 kVp at 100 mAs



$CTDI_{vol}$ = 10 mGy

120 kVp at 200 mAs



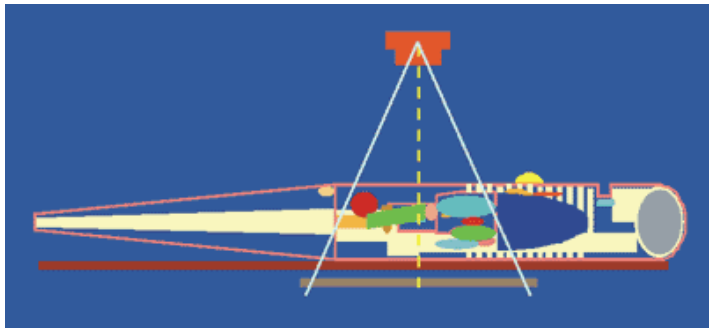
$CTDI_{vol}$ = 20 mGy

Smaller patient scanned with a lower $CTDI_{vol}$

Patient doses will be approximately equal

Determining Actual Dose from CT

- Boundaries of x-ray field
  - Completely or partially contain organ?
- Attenuation of overlying tissue
- Scatter calculation for organs outside the beam collimation
- Uncertainty in tissue properties
  - We're all the same but we're different!
- Deformation of organs



Why do we have $CTDI_{vol}$?

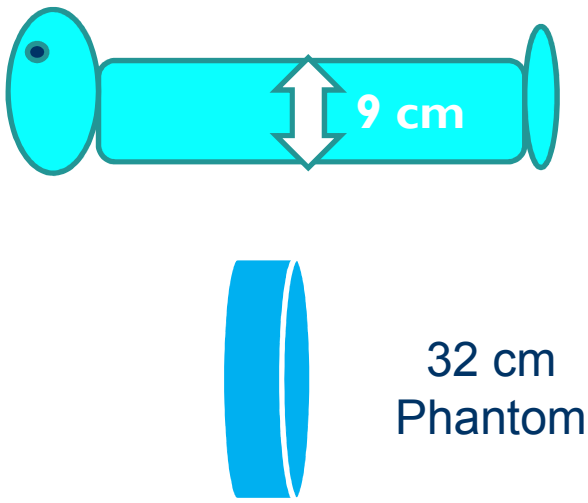
- It provides information about the amount of radiation used to perform the study
- It provides a way to track across patients and protocols for QC
- It allows for comparison between scanners and facilities

Anything Better than $CTDI_{vol}$?

- Current area of research and debate
- AAPM Report 204 – Size Specific Dose Estimate (SSDE)
  - Conversion factors based on patient size (AP or lateral dimension, or effective diameter)
  - SSDE is still not the exact patient dose, as factors such as scan length and patient composition may differ from the assumptions used to calculate SSDE
  - SSDE is not dose to any specific organ, but rather the mean dose in the center of the scanned volume

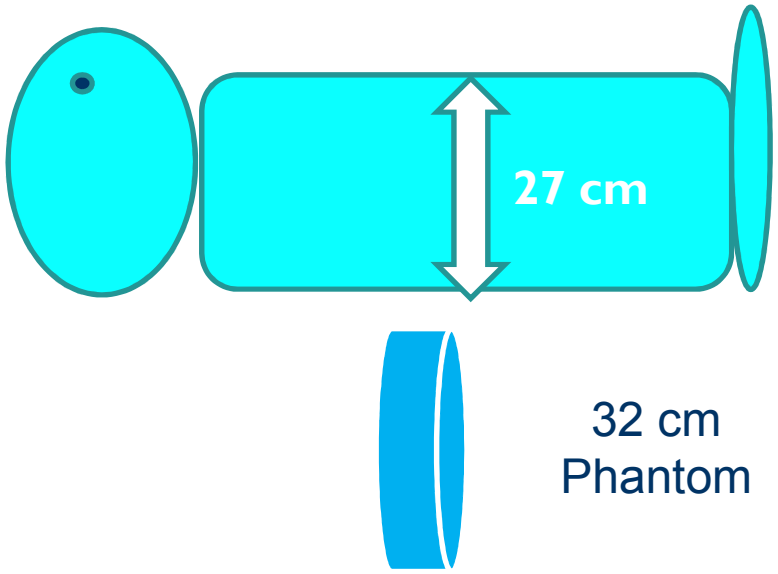
SSDE…

120 kVp at 100 mAs



$CTDI_{vol}$ = 10 mGy
SSDE = 13.2 mGy

120 kVp at 200 mAs



$CTDI_{vol}$ = 20 mGy
SSDE = 13.2 mGy

Patients have equivalent SSDE

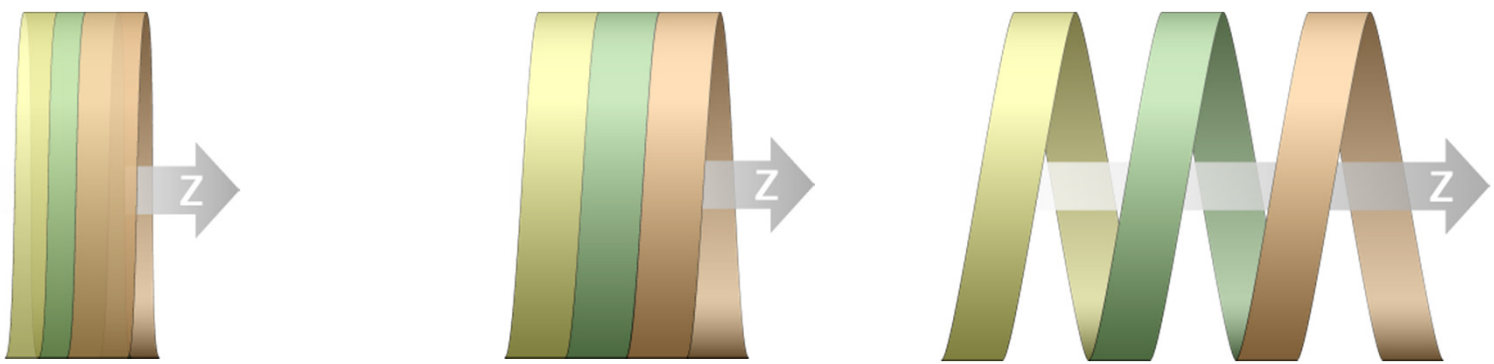
Dose Length Product

- Dose Length Product (DLP) is the product of the length of the irradiated volume and the average $CTDI_{vol}$ across that volume

- Units are mGy * cm

$CTDI_{vol}$ = f(protocol parameters)

- $CTDI_{vol} \propto 1/pitch$
- $CTDI_{vol} \propto$ exposure time per rotation (s)
- $CTDI_{vol} \propto$ tube current (mA)
- $CTDI_{vol} \propto$ tube current time product (mAs)
- $CTDI_{vol} \propto (kVp_1/kVp_2)^n$, n=2-3



Pitch < 1 Pitch = 1 Pitch > 1

CT Overexposures

- Starting around 2009, reports started appearing
- 206 patients @ Cedars-Sinai
- 8X expected exposure
- 18 months before noticed
- 3-4 Gy (300-400 rad)
- ≈ 40% experienced hair loss

Implications…

LawyersandSettlements.com
America's Premier Online Legal News Source

Home Page >> Emerging Issues >> CT Brain Scan

CT Brain Perfusion Scan Radiation Overdose FDA Investigation

The Food and Drug Administration (FDA) has notified health care professionals about radiation overexposure in patients who have undergone perfusion CT imaging (essentially, a **CT brain scan**), done to diagnose and treat strokes. According to the FDA alert, 206 patients in an 18-month period at Cedars-Sinai Medical Center received radiation doses that were approximately eight times the expected level, causing a **CT radiation overdose**. Now, patients who were affected by the excess **CT scan radiation** have filed lawsuits against Cedars-Sinai and the makers of the CT machine, GE Healthcare Inc. and GE Healthcare Technologies.

The New York Times

F.D.A. Urges Two Steps for Safer CT Scans

By WALT BOGDANICH
Published: November 9, 2010

March 7, 2011

npr

home | news | arts & life | music | program

News > Health

Twitter Facebook Share Comments

FDA Investigates Radiation Overdose At Hospitals

by PATTI NEIGHMOND

Lieff Cabraser Heimann & Bernstein
Attorneys at Law

About Us
Attorneys
Practice Areas
Case Center
Media Center

Hospital Radiation Overexposure

Issue: Radiation exposure

Hospital Radiation Therapy Safety Side Effects and Excessive Radiation

Goals with CT and Dose

- A CT study should use as little radiation as possible while still meeting the image quality needs of the exam

- A CT study that is non-diagnostic because the radiation dose is too low may require rescanning the patient – increasing the total patient dose

DOSE REDUCTION CAPABILITIES

Dose Reduction Methods

- Appropriate Protocol Selection and Usage
- Tube Current Modification (Manual)
- Automatic Tube Current Modulation (ATCM)
  - Longitudinal
  - Angular
  - Organ-based
  - ECG-based
- Automatic Tube Potential Selection
- Iterative Reconstruction

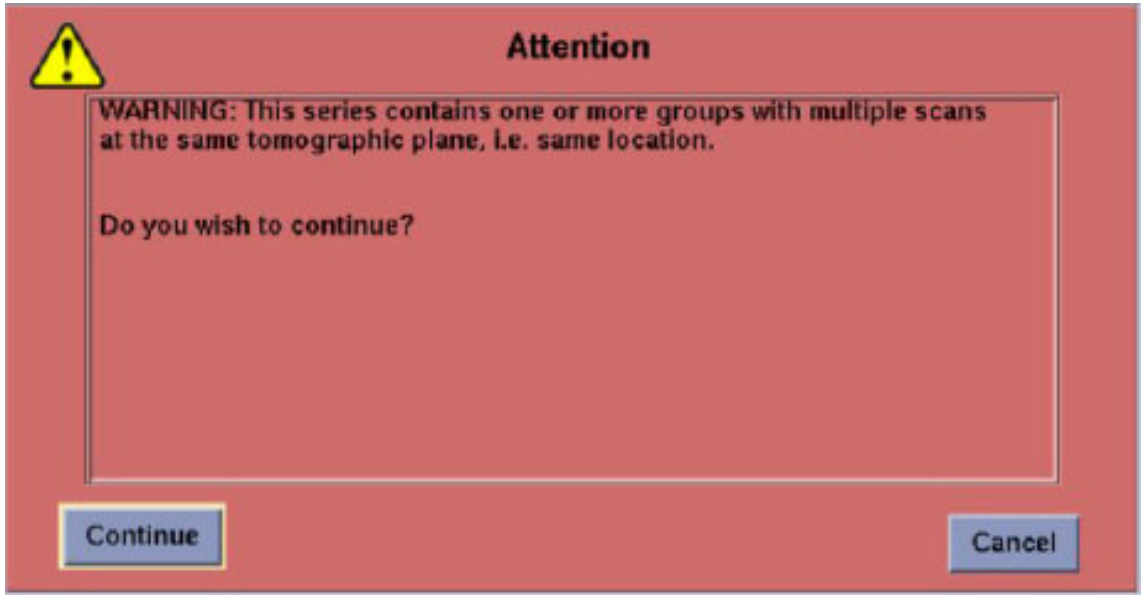
Protocol Selection

- Use pediatric protocols when appropriate
- Some systems allow fine gradations in protocol specifications

Pink 6.0 to 7.5 kg (13.2 to 16.5 lbs) 59.5 to 66.5 cm
Red 7.5 to 9.5 kg (16.5 to 20.9 lbs) 66.5 to 74.0 cm
Purple 9.5 to 11.5 kg (20.9 to 25.4 lbs) 74.0 to 84.5 cm
Yellow 11.5 to 14.5 kg (25.4 to 32.0 lbs) 84.5 to 97.5 cm
White 14.5 to 18.5 kg (32.0 to 40.8 lbs) 97.5 to 110.0 cm
Blue 18.5 to 22.5 kg (40.8 to 49.6 lbs) 110.0 to 122.0 cm
Orange 22.5 to 31.5 kg (49.6 to 69.5 lbs) 122.0 to 137.0 cm
Green 31.5 to 40.5 kg (69.5 to 89.3 lbs) 137.0 to 150.0 cm
Black 40.5 to 55.0 kg (89.3 to 121.3 lbs)

Protocol Usage

- Protocols stored with default parameters, but can be adjusted
- Be careful when adjusting!



Tube Current Modification

- Generally performed by manually adjusting mA/mAs based on patient size

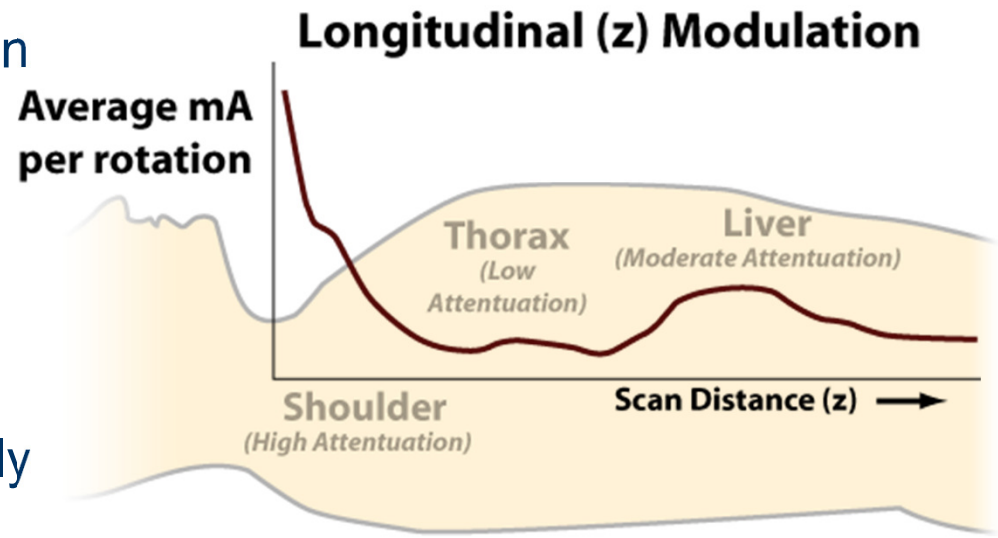
- Incumbent on the technologist to make the change

Auto Tube Current Modulation

- The system can automatically increase or decrease the mA of the tube during the exposure
- Takes into account patient attenuation
- Attempts to maintain a constant image quality as measured via a reference metric – vendor specific
  - Image Quality Reference mAs, Noise Index, Target Image Quality Level, etc.
- Centering the patient in the gantry is vital for most AEC systems to function correctly!

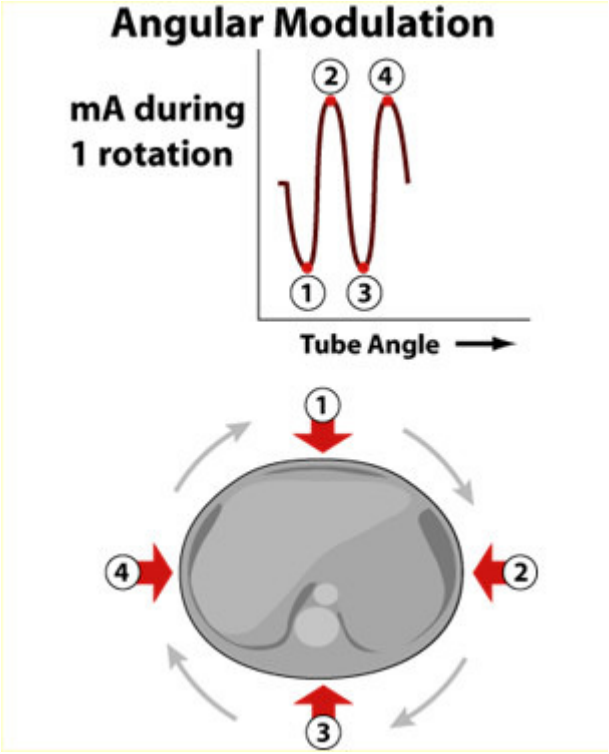
Longitudinal Tube Current Modulation

- Based on CT localizer radiograph of patient before scan begins
- Higher mA required through dense shoulders, less through lungs, slightly more through abdomen



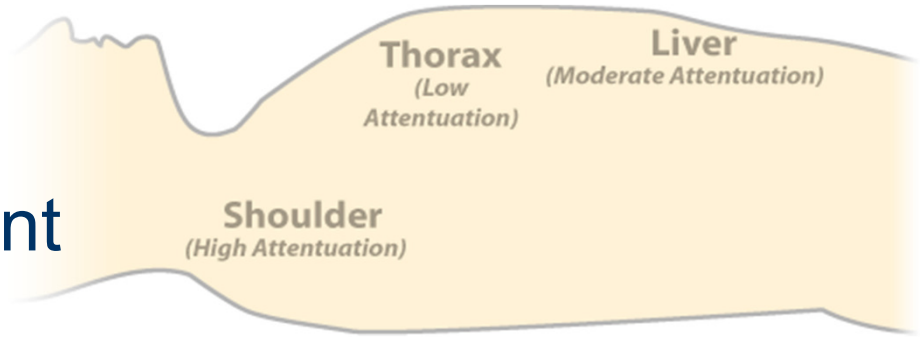
Angular Tube Current Modulation

- mA increased through thicker projections (e.g. laterally through shoulders)
- Typically performed on the fly, monitoring dose received at the detectors
- Changes in ¼ rotation increments



Combined Tube Current Modulation

- Superposition of longitudinal and angular tube current modulation
- Combines both capabilities
- Not available on every scanner



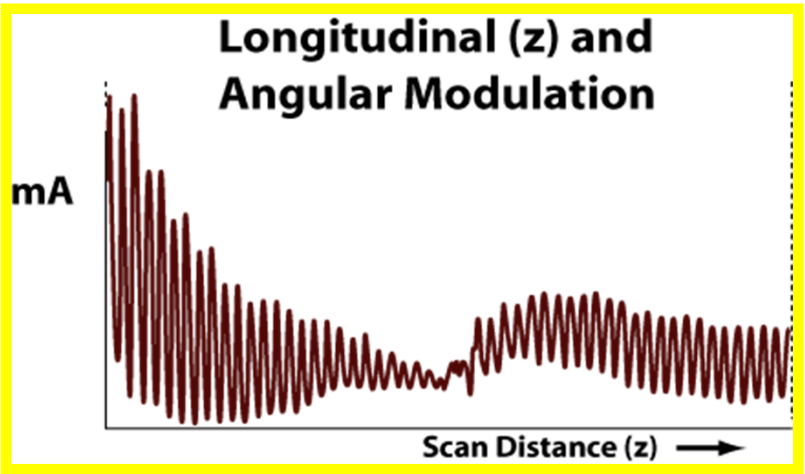


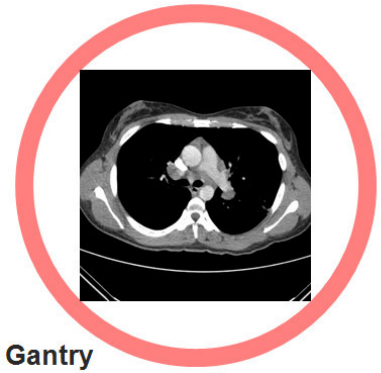
Table 1. AEC systems available from each of the major manufacturers [3]

Vendor	AEC System Name	Operator-Controlled Parameter	Parameter Explanation	Principles	Z-Axis Modulation	Angular (X-Axis, Y-Axis) Modulation?
Siemens	CAREDose4D	Image quality reference mAs	mAs that would be used for an average-sized patient	Angular modulation of tube current in the x, y, and z axes on the basis of patient size relative to the mAs specified by the user for a standard-sized reference patient	Yes	Yes
Philips	Dose Right	Reference image	Image quality expressed in terms of noise level of an existing optimal clinical image	Modulation of tube current on the basis of patient size to achieve the same image noise level as in a previously defined reference image	Yes	Yes
Toshiba	Sure Exposure 3D	Target image quality level	Standard deviation of pixel values in an image (higher standard deviation = higher noise)	User prespecifies image quality on the basis of a patient-equivalent water phantom, and mAs is modulated on the basis of patient size to maintain image quality	Yes	Yes
GE	Auto mA	Noise index	Measure of image quality/ noise level defined relative to uniform water phantom	Modulation of tube current only in the longitudinal direction to maintain a constant noise index	Yes	No
GE	Smart mA	Noise index	Measure of image quality/ noise level defined relative to uniform water phantom	Modulation of tube current in the x, y, and z axes to maintain a constant noise index	Yes	Yes

Note: mAs = tube current-time product.

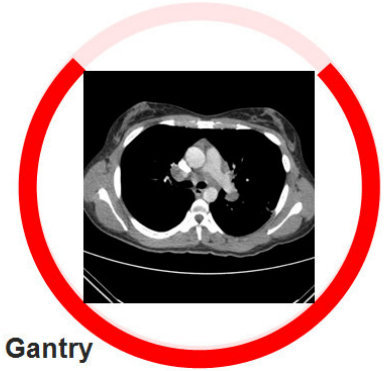
- CT Dose Reduction Applications, Raman et al., J Am Coll Radiol 2013;10:37-41.

Organ based tube current modulation



Conventional

Vs.



Organ-Based Modulation

Vs.

- AEC feature that decreases tube current over radiosensitive organs on patient's surface
  - Breast tissue
  - Eye lenses

Study Results

Bismuth Shielding, Organ-based Tube Current Modulation, and Global Reduction of Tube Current for Dose Reductio to the Eye at Head CT[1]

Table 1

Doses to the Eye Surface with Different Scanning Techniques

Scanning Technique	$CTDI_{vol}$ (mGy)*	Dose to the Eye (mGy)†	Mean Absolute Difference between Two Eyes (mGy)
Reference	38.18	32.16 ± 1.62	0.14
Bismuth shielding (one layer)	38.18	23.66 ± 0.41	0.38
Organ-based TCM	37.57	22.39 ± 0.47	0.51
Decreased tube current	27.19	22.44 ± 0.98	1.64
Bismuth shielding (two layers)	38.18	18.53 ± 0.66	0.79
Bismuth shielding and organ-based TCM	37.88	17.05 ± 0.44	0.68

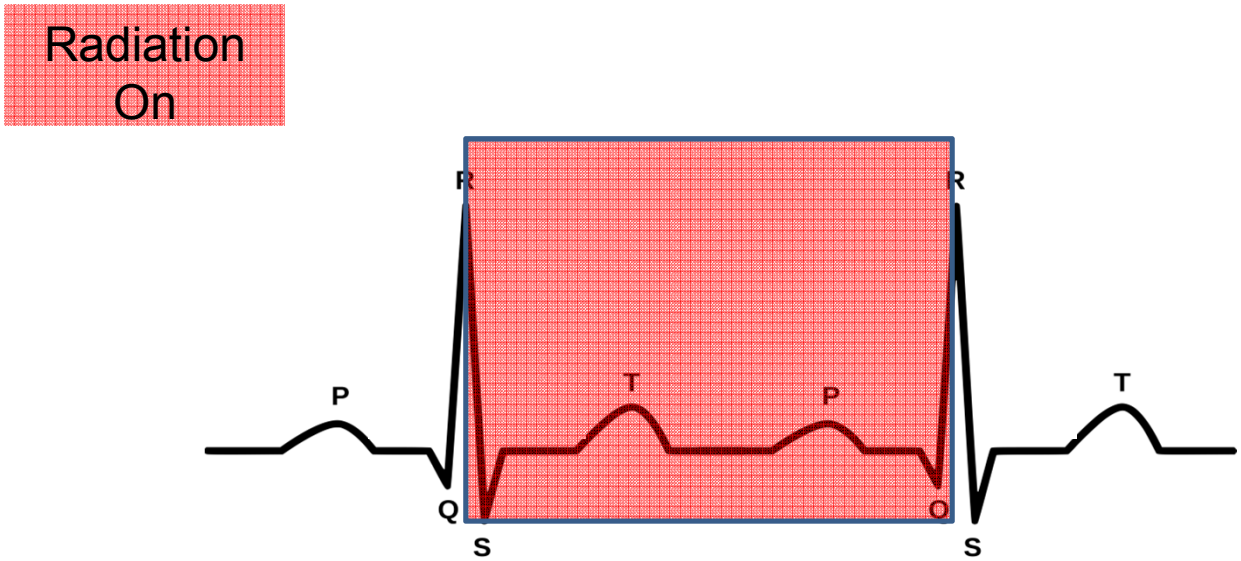
Conclusion: Organ-based TCM provided superior image quality to that with bismuth shielding while similarly reducing dose to the eye. Simply reducing tube current globally by about 30% provides the same dose reduction to the eye as bismuth shielding; however, CT number accuracy is maintained and dose is reduced to all parts of the head.

- ***Radiology:*** Volume 262: Number 1, January 2012

ECG-Based Tube Current Modulation

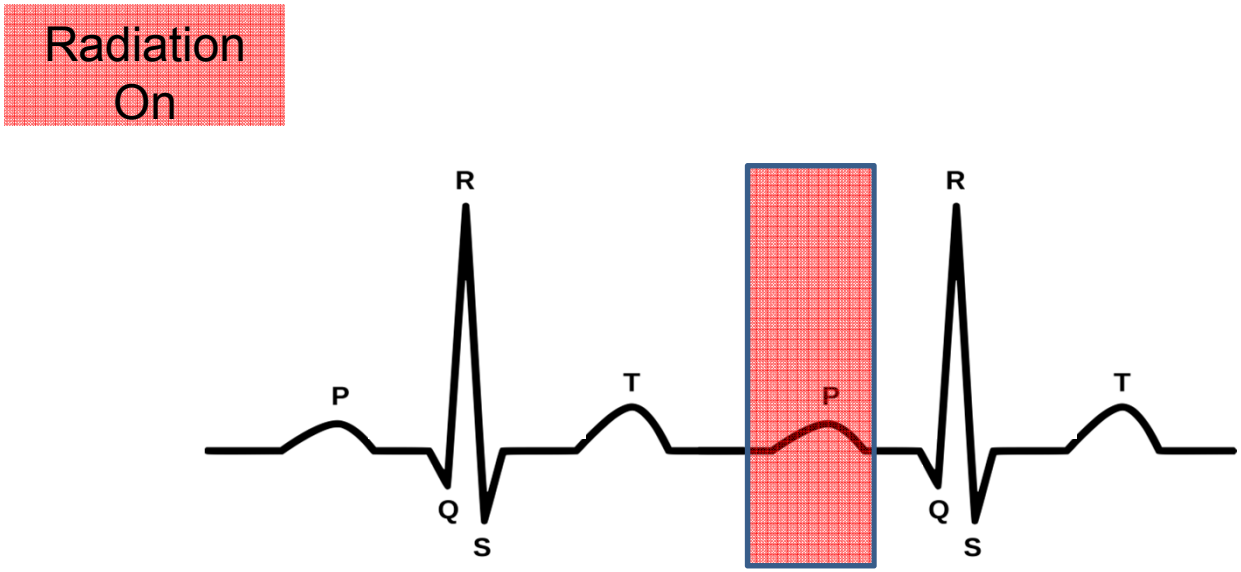
- Retrospective vs. Prospective Gating
  - Retrospective has no dose savings but acquisition is simple (beam always on)
  - Prospective has added complexity, but lowers dose to patient
- Prospective gating changes mA as a function of the phase within the heart's cycle

Retrospective Gating



- Multiple heart beats and table positions may be required to collect all of the data required to reconstruct the FOV including the heart

Prospective Gating



- Multiple heart beats and table positions may be required to collect all of the data required to reconstruct the FOV including the heart

Study Results

Prospective versus Retrospective ECG Gating for 64-Detector CT of the Coronary Arteries: Comparison of Image Quality and Patient Radiation Dose[1]

Figure 1

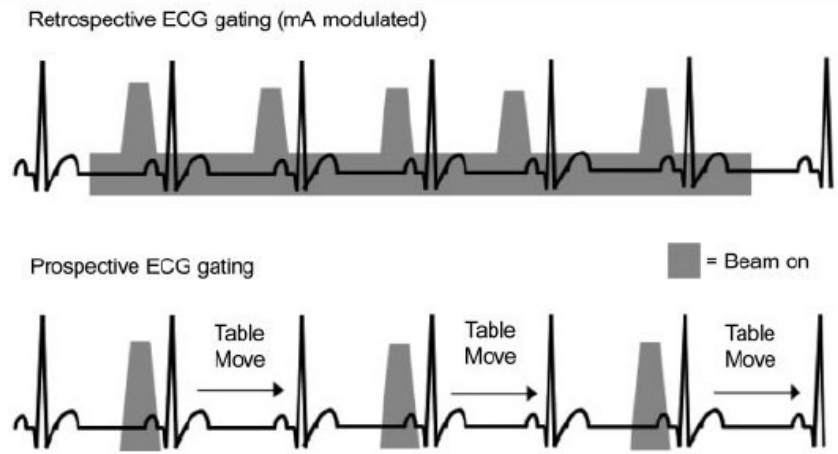


Figure 1: Model shows retrospective ECG gating versus prospective ECG gating. With retrospective gat- tirety of the R-R intervals during imaging. With pro- very other R-R interval.

Conclusion: Use of 64-detector CT coronary angiography performed with prospective ECG gating has similar subjective image quality scores but 77% lower patient radiation dose when compared with use of retrospective ECG gating.

- ***Radiology:*** Volume 248: Number 2—August 2008

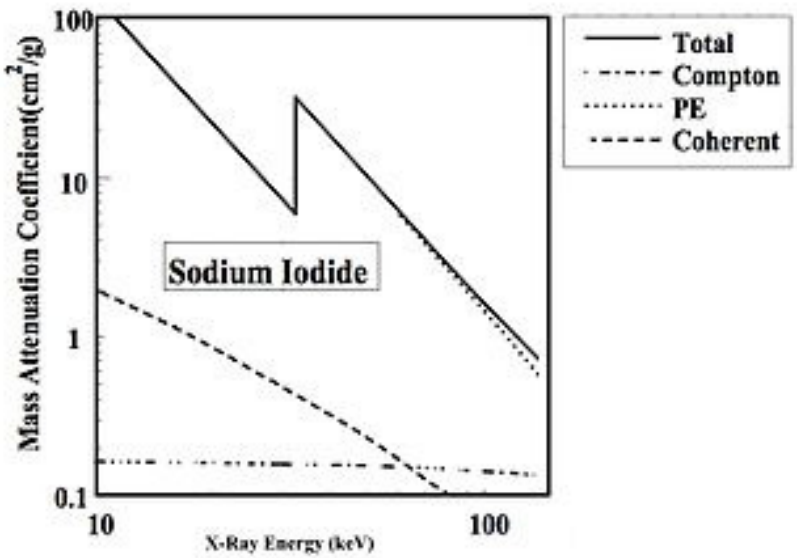
Auto kVp Selection

- Not modulated in same manner as mA

  $\neq f(\theta,z)$
- Selected for specific patient, anatomic region, and diagnostic task
- With constant mA:
  - 120 → 100 kVp = dose ↓ roughly 33%
  - 120 → 80 kVp = dose ↓ roughly 65%

kVp Reduction and Contrast

- Most x-ray beams have effective energy = ⅓ to ½ of the peak energy
  - 100 kVp → 33-50 keV
  - 80 kVp → 26-40 keV
- Just above absorption edge
  → GREAT CONTRAST!



Reconstruction Methodology

- Actual CT data are projections at different angles around the patient
- First clinical CT:
  - 160 detector readings at each angle
  - 180° of data, 1° apart
  - → 28,800 individual readings
- Modern CT:
  - 360° or greater angular range
  - More than 1 million individual measurements
- Data must be processed to reconstruct images

Iterative Reconstruction

- All major vendors support some form of non-FBP reconstruction

Vendor	Acronym	Name
Siemens	IRIS	Image Reconstruction Iterative Reconstruction
Siemens	SAFIRE	Sinogram Affirmed Iterative Reconstruction
GE	ASiR	Adaptive Statistical Iterative Reconstruction
Philips	iDose	iDose
Toshiba	ADIR/ADIR 3D	Adaptive Iterative Dose Reduction

DOSE MANAGEMENT

Tech Interactions with the Scanner

- Diagnostic Reference Levels
- Dose Notification Levels
- Dose Alert Levels
- Radiation Dose Structured Reports (RDSRs)

Diagnostic Reference Levels

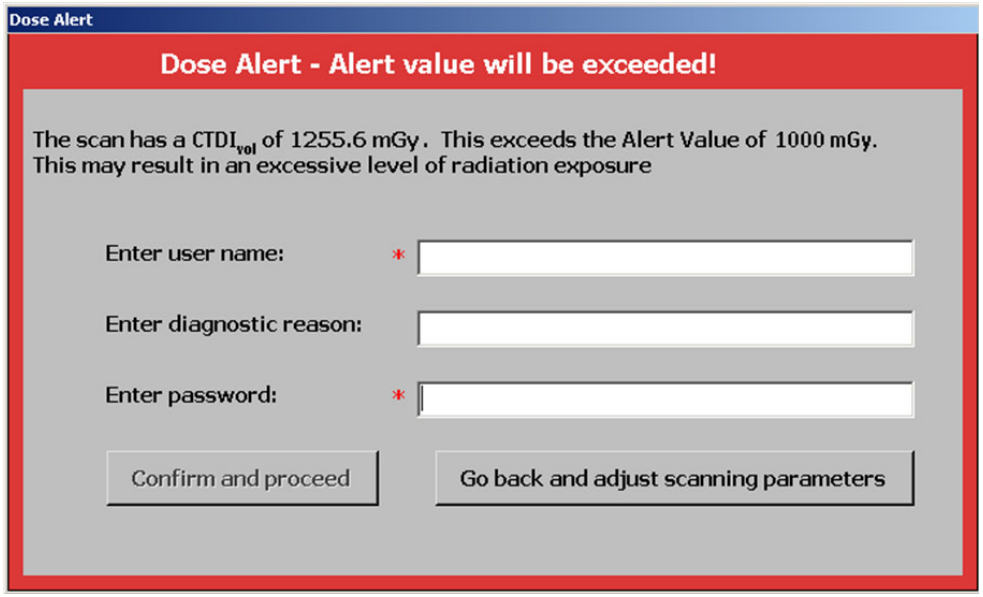
- Diagnostic Reference Levels (DRLs) are examination specific, patient-group specific metrics to be used as initial broad checks on dose appropriateness
- They are $CTDI_{vol}$ and DLP values for a given exam type and for a given patient demographic that, if exceeded, should cause facilities to question their protocol settings
- Typically set by 3rd-party organizations based on broad surveys
- Commonly set at 3rd quartile of reported values, so 25% of reported values are > the DRL value

	Head		Abdomen		Abdomen & Pelvis			
	Whole Exam		Whole Exam		Pelvis		Whole Exam	
	CTDIvol	DLP	CTDIvol	DLP	CTDIvol	DLP	CTDIvol	DLP
Sweden 2002 [12]	75	1200	25	-	-	-	-	-
UK 2003 [8]	65 - 100	930	14	470	-	-	14	560
Netherlands 2008 [13]	-	-	-	-	-	-	15	700
EC 2004 [14]	60	-	25	-	-	-	15	700
ACR 2008 [15]	75	-	25	-	-	-	-	-

EC = European Commission; ACR = American College of Radiology; UK = United Kingdom

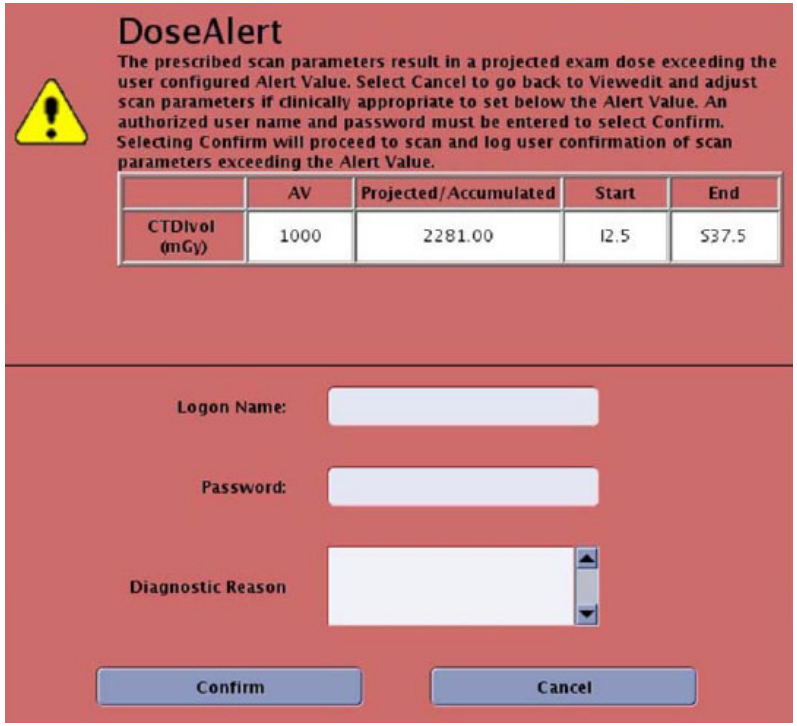
Dose Notification Levels

- Notification Levels may be set on a CT scanner **<u>for each series</u>** within an exam protocol
- If the planned $CTDI_{vol}$ is above the Notification Level and triggers the notification, the user has the opportunity to edit or confirm the technique settings
- Notification Levels may be exceeded when appropriate for a specific patient or diagnostic task (e.g., in very large patients or contrast bolus monitoring scans)



Dose Alert Levels

- Dose Alert Levels require specific action by the operator to continue scanning
- Dose Alert Levels are typically much higher than Notification Levels and take into account **all series within the exam**
- Triggering a Dose Alert requires that the operator confirm the protocol and settings are correct by entering in his or her name. Optionally, sites may require that the operator provide a brief explanation in the provided field



Radiation Dose Structured Reports

- Radiation Dose Structured Reports (RDSRs) are provided in newer software versions in a defined DICOM format
- They provide the most complete set of information regarding the irradiating events
- The reports are very detailed and require an RDSR viewer for easy visualization of relevant information
  - 3rd party vendors are currently providing solutions
  - RADIANCE - http://www.radiancedose.com/
  - Dose Utility - http://www.dclunie.com/pixelmed/software/webstart/DoseUtilityUsage.html

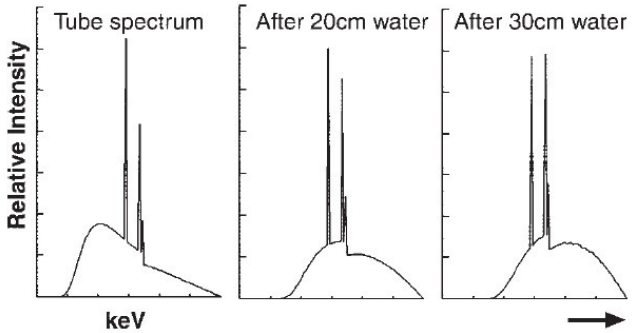
ARTIFACTS IN CT

Types of Artifacts

- Beam Hardening
- Partial Volume Averaging
- Motion
- Metallic Artifacts
- Edge Gradient
- Patient Positioning
- Step Artifact
- Equipment-Induced Artifacts

Beam Hardening

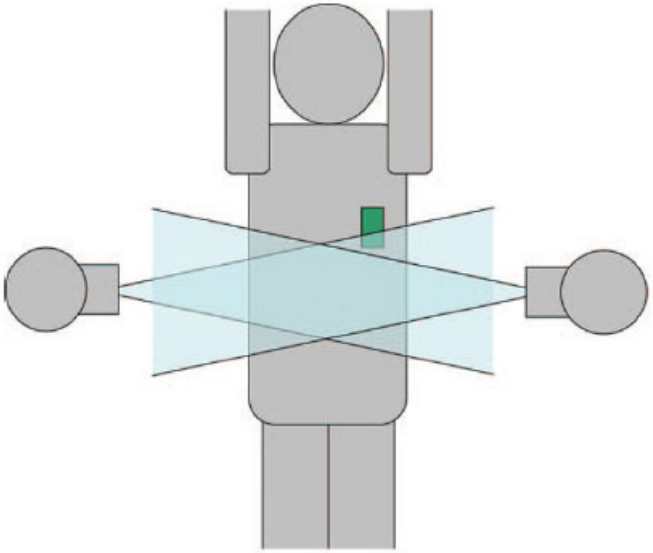
- Average photon energy increases as the x-ray beam travels through patient
- By the center of the patient, can change interaction enough for CT to be unable to correct it
- Dense bony areas surrounding soft tissue are problematical
- Mathematical corrections present in reconstruction can help
- Higher kVp techniques may help

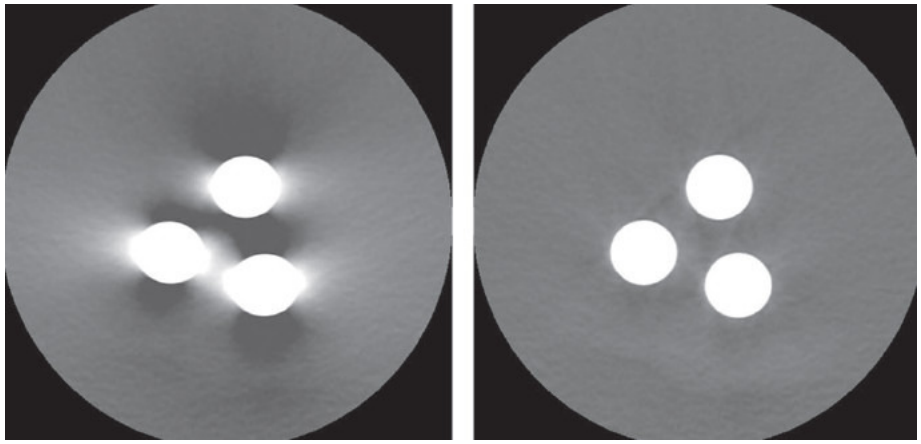


Partial Volume Averaging

- Occurs when an anatomic structure is only partially positioned within a voxel
- Mixtures of different attenuation constant material inside same volume
- Results in generalized haziness of borders and loss of contrast
- Very likely in areas of dramatic density differences (bone + soft tissue, e.g. in the head)
- Also likely in areas of potential pathology
  - Small masses, nodules, fractures
- Reduce the effect with thin sections and/or overlapping sections

Partial Volume Effect





Motion Artifacts

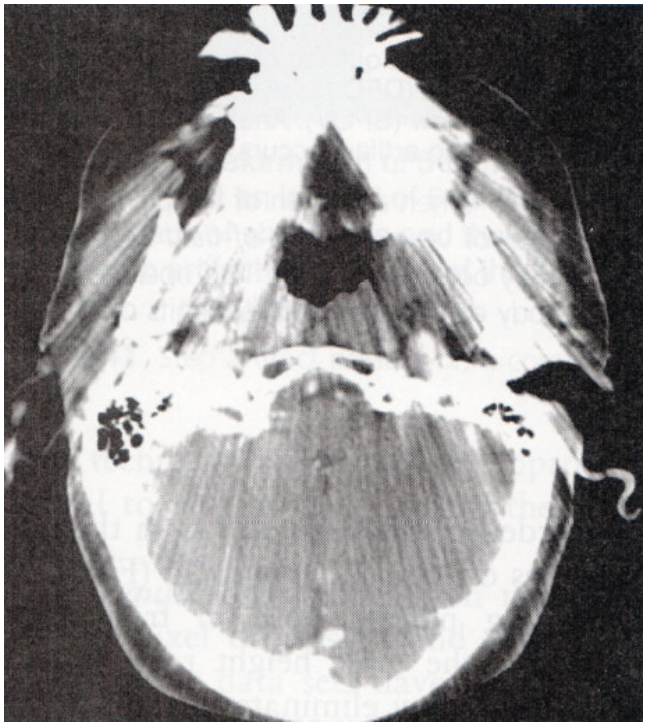
- Occurs when the patient moves during the scan
- Blurring and streaking are common occurrences
- Could also lead to step artifacts in 3D and MPR images
- Solutions:
  - Faster scan time
  - Physiologic gating (e.g. ECG)
  - Communication
  - Immobilization

Metallic Artifacts

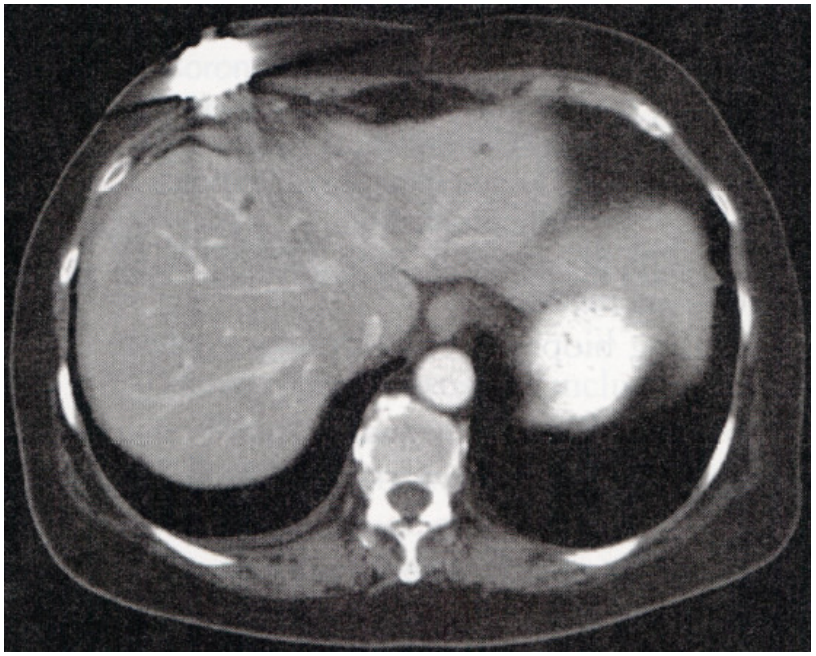
- Highly dense metal objects in and around patients cause significant image streaking
- Artifacts occur from combination of beam hardening and partial volume effect
- Solutions possible:
  - Remove metal object
  - Decrease section width
  - Increase kVp for better penetrability
  - Adjust W/L settings
  - Reorient data acquisition (e.g. gantry tilt)
  - Metallic artifact reduction (MAR) software

Examples of Metallic Artifacts

Dental Fillings

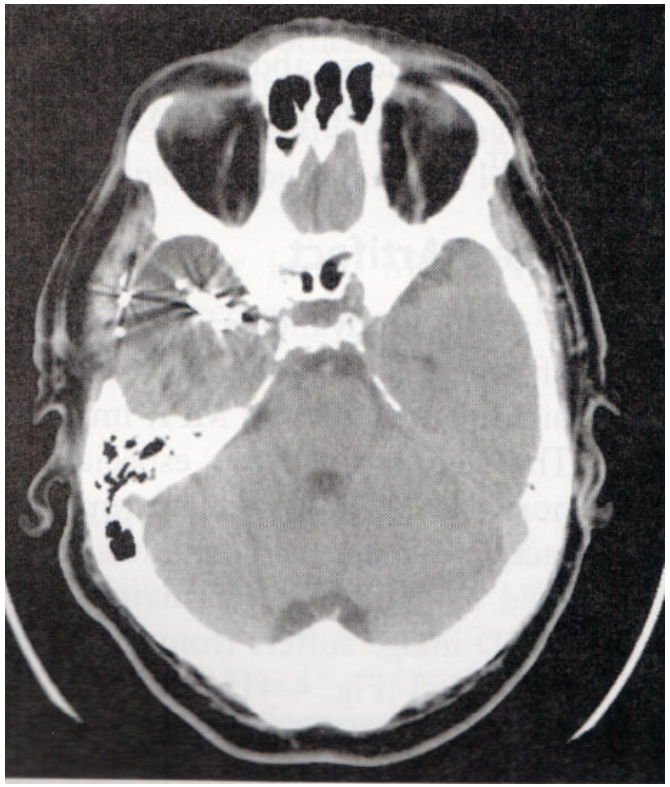


Portacath Device



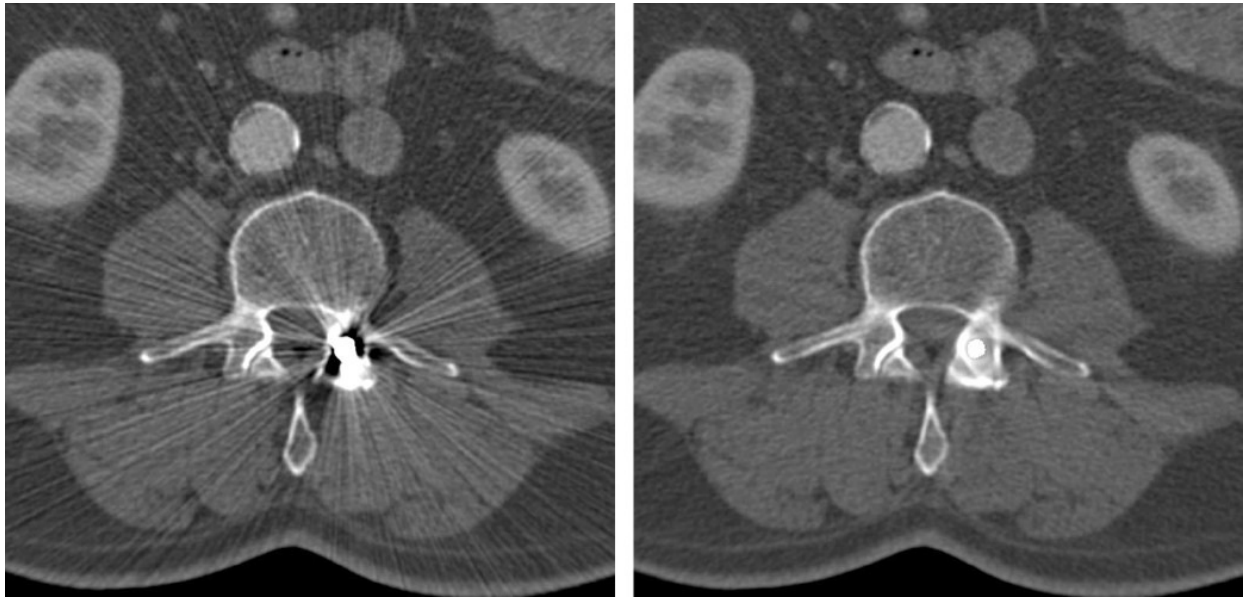
W/L Adjustments

Aneurism Clip in Soft Tissue Window



Aneurism Clip in Bone Window

MAR Software

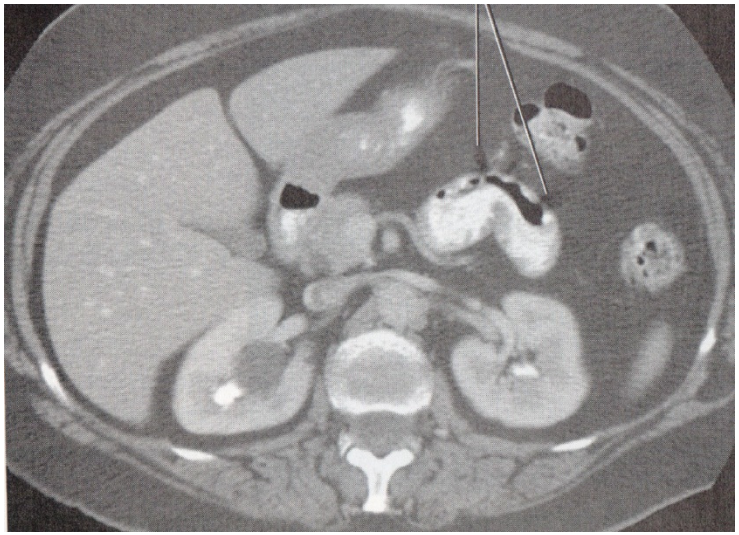


Software uses interpolation techniques to substitute over range values in attenuation profiles

Still have loss of detail around metal-tissue interface

Edge Gradients

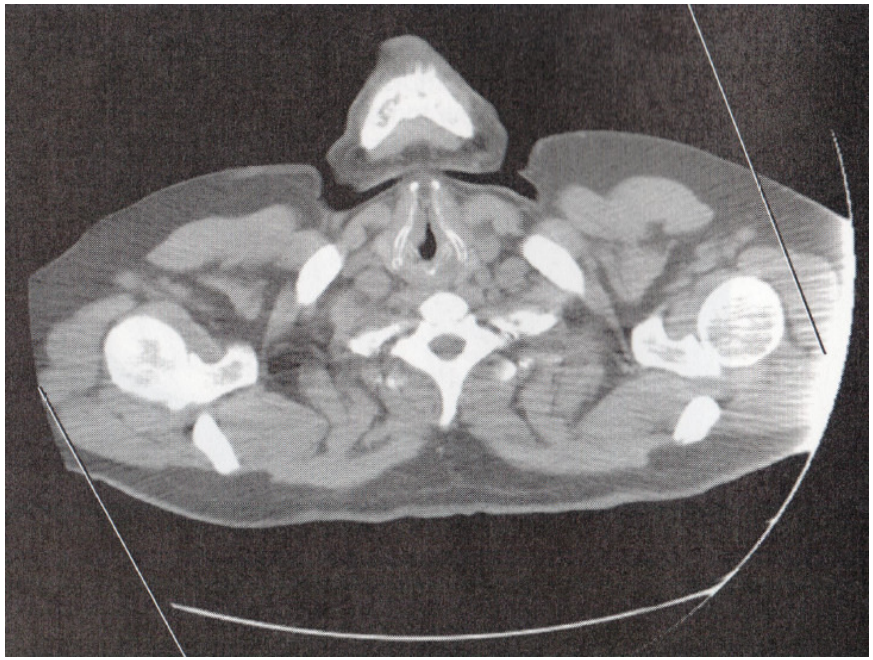
- Streak artifacts at interface between high-density material surrounded by low-density material
- System unable to process high spatial frequency signal required for sharp edges
- Common sites:
  - Dense bone and surrounding tissue
  - Bowel loops with contrast
  - Blood vessels with IV contrast
  - Areas around biopsy needles



Patient Positioning

- Out of field artifacts occur when portion of patient is outside of the scan field of view (SFOV)
- Results in hyperdense streaking
- Common problem areas include shoulders, abdomen and lower pelvis
- Solution:
  - Adjust patient position (L/R, table height)
  - Expand SFOV if possible

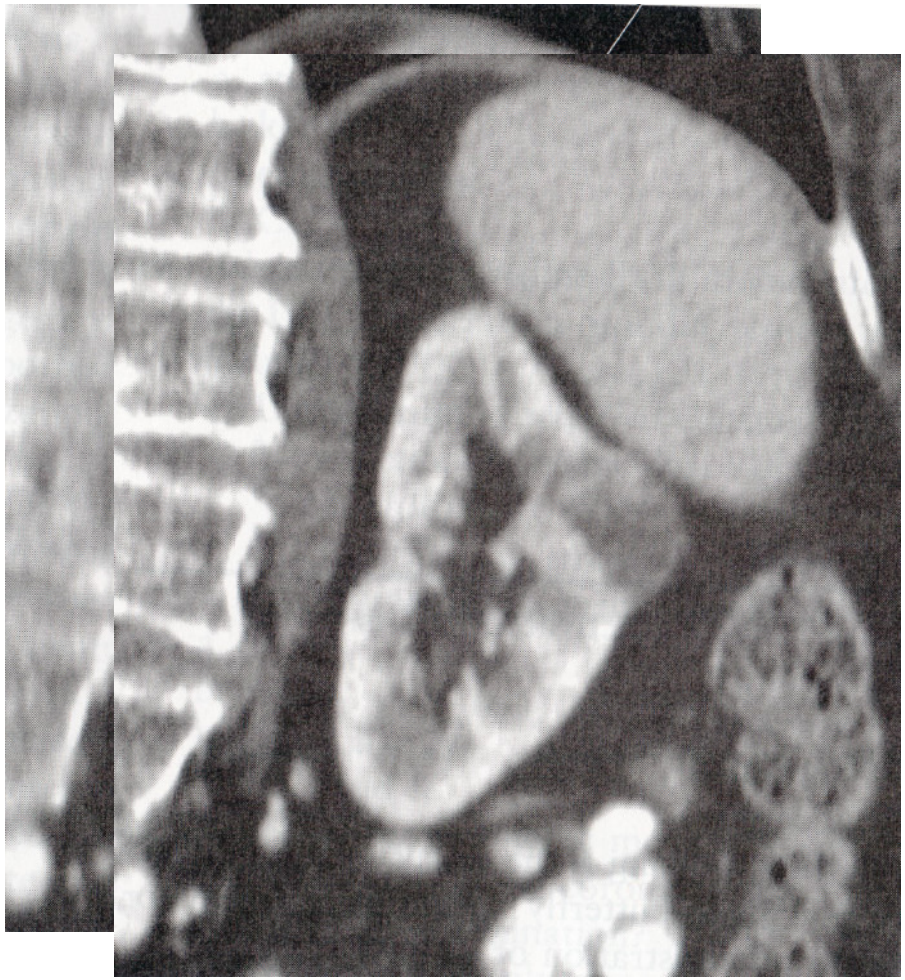
Outside SFOV



Outside Display FOV, but inside SFOV

Step Artifact

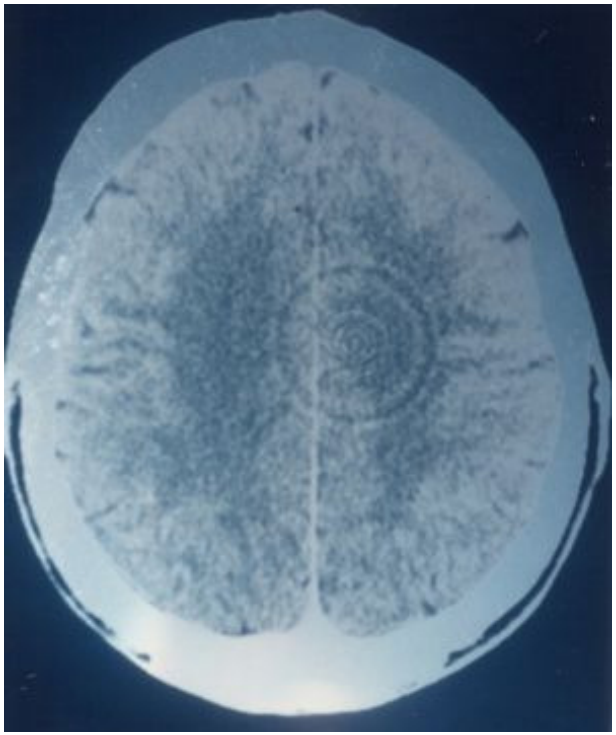
- 3D and MPR imaging when original scanning was axial in nature
- Best avoidance when section width (z-axis) is same dimension as x- and y- pixel dimensions
- Can still occur in MSCT system unless thin, overlapping sections are used



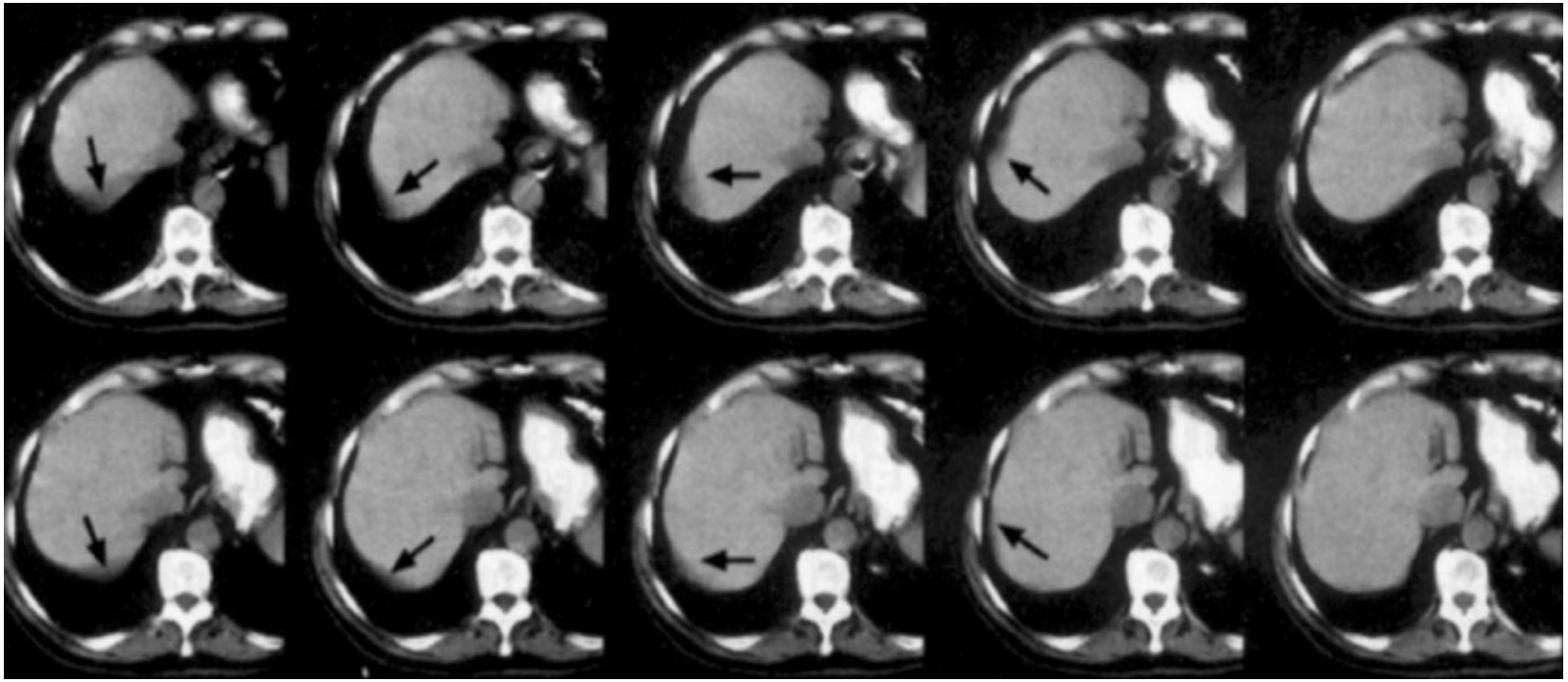
Equipment-Induced Artifacts

- Numerous artifacts possible b/c of improper system performance
- Including:
  - Rings, e.g. faulty detectors
  - Streaks, e.g. detector malfunction or misalignment
  - Tube arcing
  - Windmill, i.e. z-spacing or interpolation artifacts, from increased pitch values

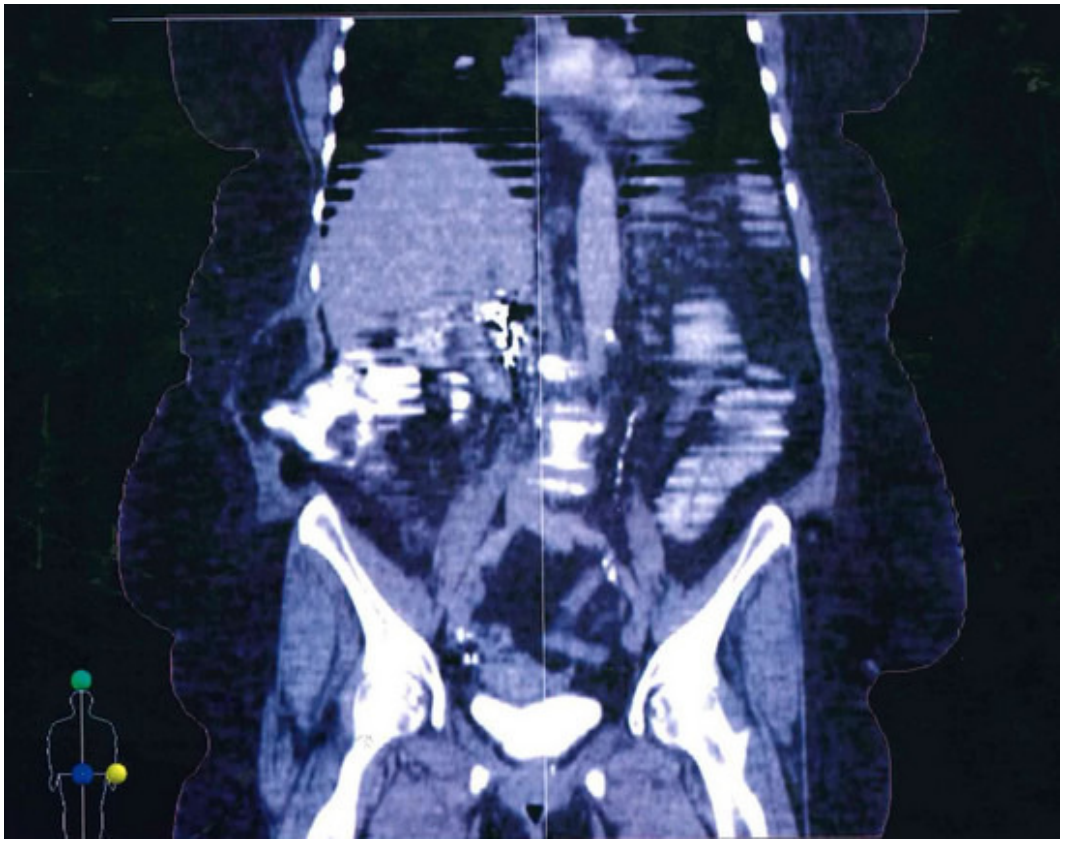
Examples



Examples



Examples



Summary

- CT dose has increased dramatically in the recent past, both from # of procedures and ability of CT machines to irradiate patients
- Dose reduction procedures ARE available and NEED to be implemented by facilities providing this service
  - Automated and user-driven
  - Control your protocols!
- Dose management options exist and NEED to be in place
- Artifacts can arise from multiple causes
  - Patient based
  - Technologist based
  - Scanner based
- Together, the imaging community can and must reduce exposure and produce diagnostic information

Integrated Science Support, Inc.

Integrated Science Support, Inc.

- Shirley Bartley (sbartley@issphysics.com)
- Jon Erickson (jerickson@issphysics.com)
- Steve Hale (shale@issphysics.com)
- Greg Sackett (gsackett@issphysics.com)

- www.issphysics.org
- (816) 390-9011