Cardiac CT Principles and Radiation Dose

Mahadevappa Mahesh, MS, PhD, FAAPM, FACR, FACMP, FSCCT.
Professor of Radiology and Cardiology
Johns Hopkins University School of Medicine
Chief Physicist – Johns Hopkins Hospital
Joint Appointment - Johns Hopkins School of Public Health
Baltimore, Maryland, USA
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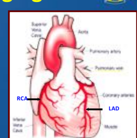
Contact Info: email - mmahesh@jhmi.edu Phone: 410-955-5115 (O)

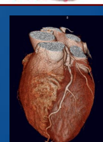
Introduction

- Cardiac CT studies were deemed high dose CT procedures in the beginning
- However, from past few years, radiation doses have decreased considerably
- Technological and operational factors are aiding in lowering the dose

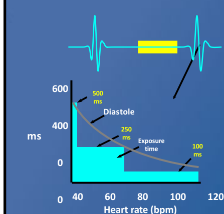
Essentials for Cardiac Imaging

- **High Temporal Resolution:** to image coronary segments proximal to heart
- **High Spatial Resolution:** to image proximal coronary segments (RCA, LAD, CX) of sub-millimeter size
- **High Contrast-to-noise ratio:** to resolve small structures such as plaques
- **High Low-contrast resolution** with limited **radiation exposure** with shorter exposure time is key



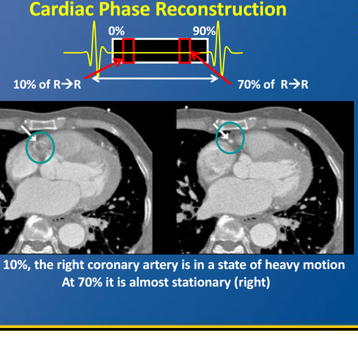


Diastolic Phase versus Heart Rate



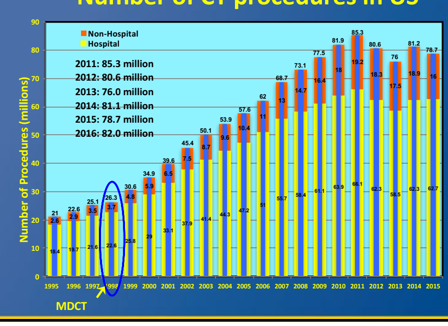
- Least cardiac motion is observed during diastolic phase
- Diastole phase narrows with increasing heart rate
- Desired temporal resolution for motion free cardiac imaging
  - ~ 250 ms for heart rates ~ 70 bpm
  - ~ 150 ms for heart rates ~ 100 bpm
- Motion-free imaging needs temporal resolution ~ 50 ms

Cardiac Phase Reconstruction



At 10%, the right coronary artery is in a state of heavy motion
At 70% it is almost stationary (right)

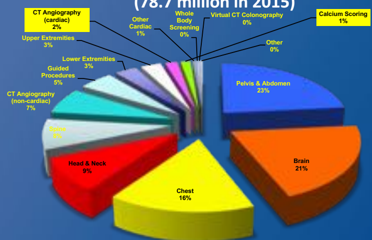
Number of CT procedures in US



IMV Benchmark 2016

Categories of CT procedures

(78.7 million in 2015)



HCAP: ~76% of all CT procedures

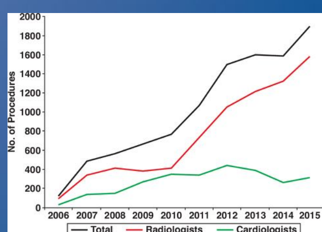
IMV 2015

Cardiac CT usage in US

CT Procedure Categories	Total 2016 CT Procedures (M)	% of All CT Procedures	% of CT Sites Performing
Head & Neck	22.5	27%	>90%
Chest, Abdomen & Pelvis	38.3	47%	>95%
Calcium Scoring	1.2	1%	30%
CT Angiography	2.2	3%	26%
Total 2015 CT Procedures	82.0	100%	

IMV 2016

Coronary CT Angiography volumes in Emergency Departments (Medicare programs, 2006-2015)



AJR 2018

Scan Parameters that impacts Dose and Image Quality in CT

Primary Factors
- Tube Current (mA)
- Tube Voltage (kV)
- Scan Time
- Pitch
- Scan Acquisition Type

Secondary Factors
- Scan Field of View (SFOV)
- Display Field of View (DFOV)
- Beam Collimation
- Reconstructed Slice Width
- Reconstruction Interval
- Reconstruction Algorithms

Other Factors
- Patient Size
- Patient Motion
- Geometry and Detector Efficiency
- Training and experience

Mahesh M., MDCT Physics: The Basics..., Lippincott, 2009

Tube Current (mA)

- Amount of x-rays produced in x-ray tube
- Indicate 'Quantity of x-rays'
- Radiation dose varies linearly with mA
- Decreasing tube current by 50%
  - Decreases radiation dose by ½
  - Increases image noise by √2

Tube Current (vary with clinical indications)

Calcium Score Image
Range: 25 to 200 mA

CTA Image
Range: 200 to 800 mA

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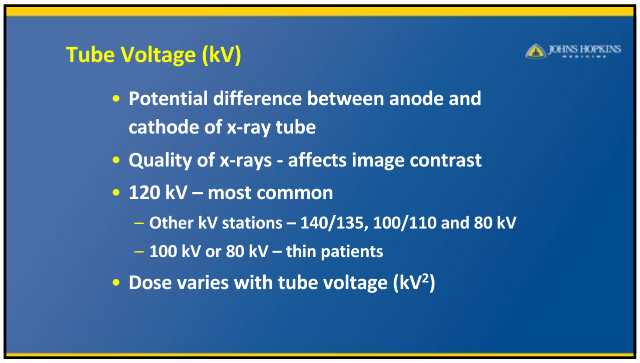

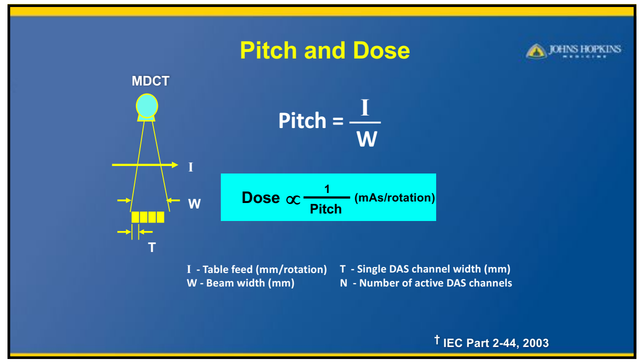

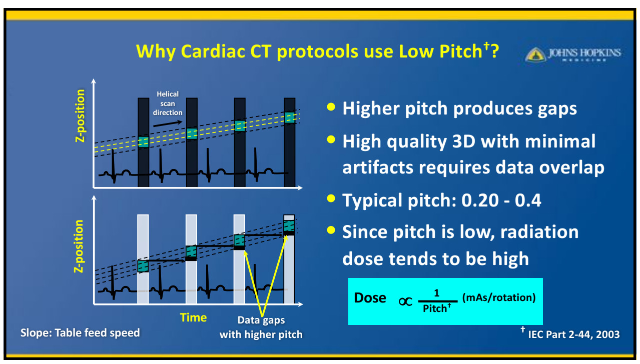

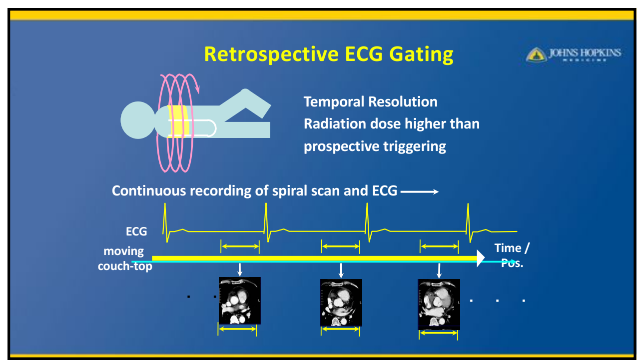

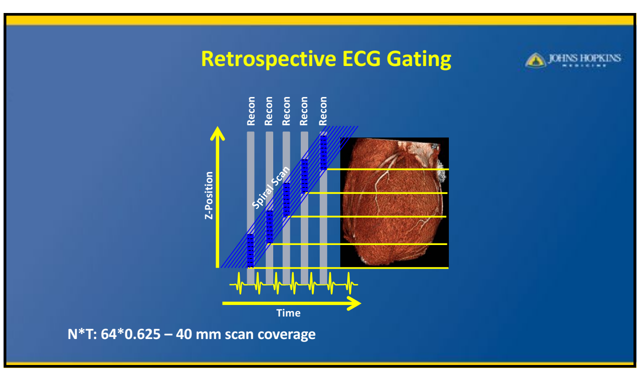

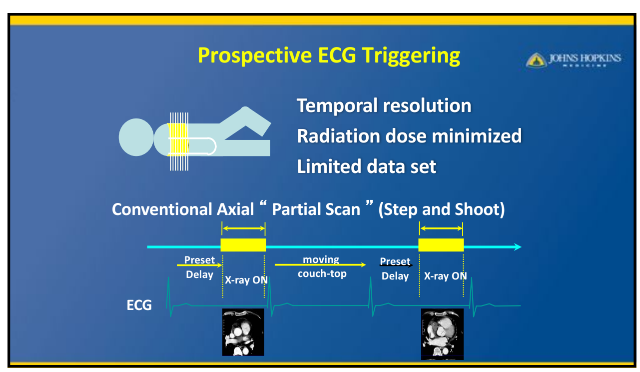

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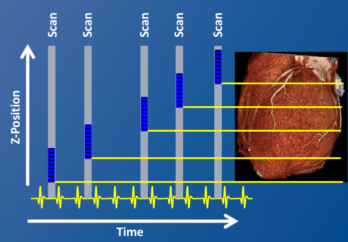
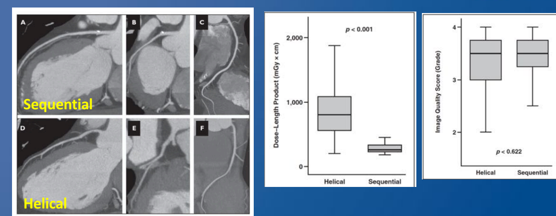
Prospective ECG Triggering



N*T: 64*0.625 – 40 mm scan coverage

CTA Dose: Prospective vs Retrospective



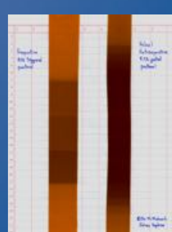
Helical mode: 11.2 mSv
Sequential mode: 3.6 mSv

PROTECTION I study, AJR, 2010

Coronary CT Angiography:
Prospective Triggered vs Helical Retrospective gated

Effective dose for CTA portion:

4-6 mSv



Effective dose for CTA portion:

12-15 mSv

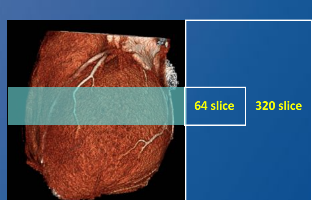
Javadi M, Mahesh M, et al., J Nucl Cardiol 2008

Motivation for advancement in CT technology

Goal

- To image entire heart in single CT gantry rotation
  - Achieved by wide-detector CT systems
- To image entire heart in a single heart beat
  - Achieved with high-pitch scan using dual source CT

Scan coverage - 320 vs 64 slice MDCT



Toshiba
Aquillion 64 - 32 mm beam width
Aquillion One - 320 slice MDCT - 160 mm beam width

MDCT Physics: The Basics..., Lippincott, 2009

Advantages of wide detector CT

- Wide detector CT systems have large scan regions
  - Scan ranges up to 160 mm
- Minimizes patient motion
- Requires less contrast
- Reduces overall exam time
- Step-and-shoot scanning with minimal overlap

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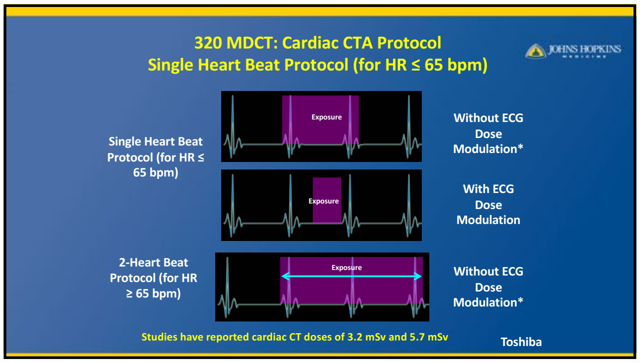

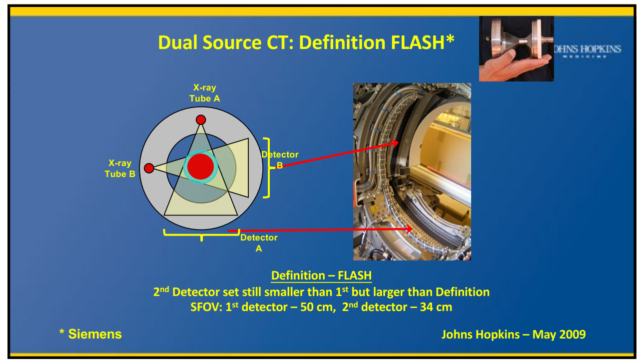

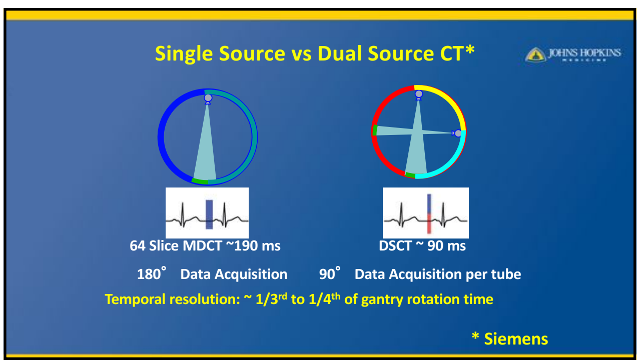

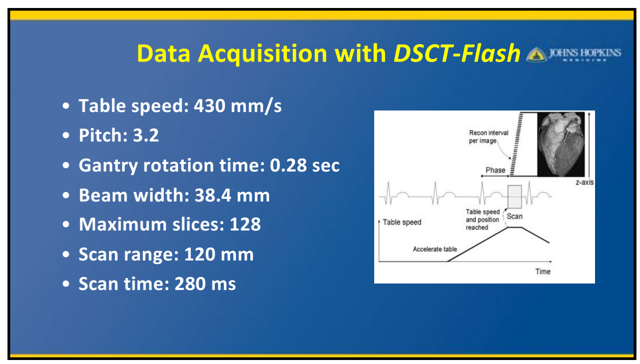

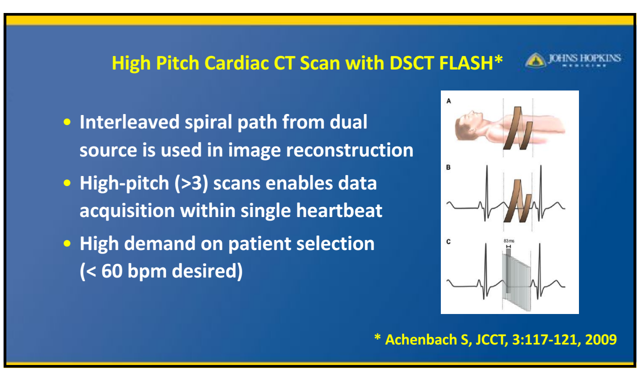

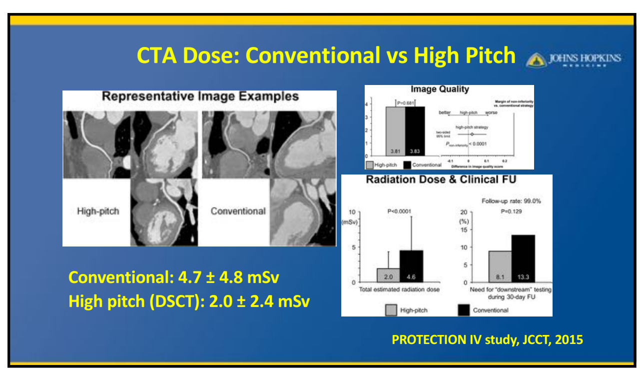

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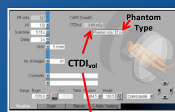
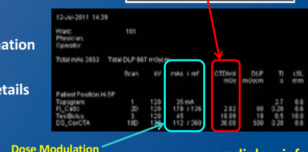
Understanding CT dose display

- Pre-scan display
  - Allows verification of set parameters are not too off the chart
- Post-scan display
  - Details on scan series
  - Scan parameters
  - DLP for effective dose estimation
  - No standard formats
  - DICOM headers for more details available

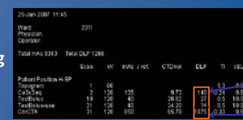




www.radiologyinfo.org

Radiation Dose Report – CT Angiography Exam

In the Beginning (2007)



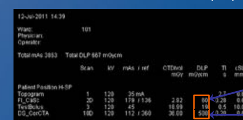
Effective dose (mSv)

2.7 mSv

15.0 mSv

Total effective dose (mSv) 17.7 mSv

Around 2011



1.1 mSv

8.2 mSv

k = 0.014 mSv/mGy-cm

Total effective dose (mSv) 9.3 mSv

Radiation Dose Optimization Strategies

- Minimize scan range
- Heart rate reduction
- ECG gated tube current modulation
- Reduced tube voltage in suitable patients
- Perform calcium scoring only if needed
- Sequential Scanning – Prospective triggering methods
- Iterative reconstruction methods

Guidelines

SCCT guidelines on radiation dose and dose-optimization strategies in cardiovascular CT

Sandra S. Halliburton, PhD[a,*], Suhny Abbara, MD[b], Marcus Y. Chen, MD[c], Ralph Gentry, RT(R) (MR) (CT)[d], Mahadevappa Mahesh, MS, PhD[e], Gilbert L. Raff, MD[d], Leslee J. Shaw, PhD[f], Jörg Hausleiter, MD[g]

[a]Imaging Institute, Heart and Vascular Institute, Cleveland Clinic, 9500 Euclid Avenue, J1-4, Cleveland, OH 44195, USA; [b]Massachusetts General Hospital, Boston, MA, USA; [c]National Institutes of Health, Bethesda, MD, USA; [d]William Beaumont Hospital, Royal Oak, MI, USA; [e]Johns Hopkins University, Baltimore, MD, USA; [f]Emory University, Atlanta, GA, USA; and [g]Deutsches Herzzentrum München, Munich, Germany

J Cardiovasc Comput Tomogr. 2011, 5(4):198-224

CT Dose Modulation

Spatial Dose Modulation

Temporal Dose Modulation

Automatic Tube Current Modulation (ATCM)

- Spatial modulation: Based on modulating tube current (mA) at different spatial projections
- Utilized in most routine body CT protocols
- Temporal modulation: Based on modulating tube current (mA) at specified time points of an electrocardiographically gated (ECG) signal
- Utilized in cardiac CT protocols

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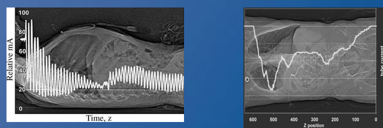
Spatial Dose Modulation

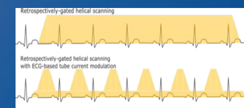


McCollough, C. H. et al. Radiographics 2006

- Body protocols
- Tube current variations based on spatial variations (patient thickness)

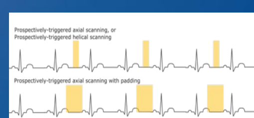
Temporal Dose Modulation with Retrospective-Gated Acquisition

- Constant tube current through entire R-R cycle can be modulated
- Tube current is lowered outside diastolic region enabling dose reduction during cardiac CT

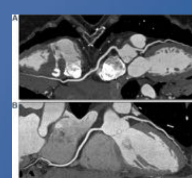


Temporal Dose Modulation with Prospectively Trigerred acquisition

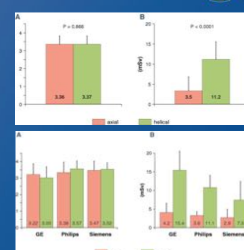
- Constant tube current through entire R-R cycle can be modulated
- Tube current is lowered outside diastolic region enabling dose reduction during cardiac CT



CTA Dose: Axial versus Helical



A - Axial: 3.5 ± 2.1 mSv
B - Helical: 11.2 ± 5.9 mSv



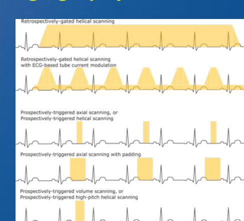
PROTECTION III study, JACC, 2012

Temporal Dose Modulation with Single beat or Single Gantry Rotation Acquisition

- Constant tube current through entire R-R cycle can be modulated
- Tube current is lowered outside diastolic region enabling dose reduction during cardiac CT

Temporal Dose Modulation for coronary CT Angiography

- Constant tube current through entire R-R cycle can be modulated
- Tube current is lowered outside diastolic region enabling dose reduction during cardiac CT



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Scan Modes

JOHNS HOPKINS MEDICINE

Recommendation

Retrospective ECG-gated helical techniques may be used in patients who do not qualify for prospective ECG-triggered scanning because of irregular heart rhythm or high heart rates (specific value depends on specific scanner characteristics and cardiovascular indication) or both.

Recommendations

Prospective ECG-triggered axial techniques should be used in patients who have stable sinus rhythm and low heart rates (typically <60–65 beats/min, but specific values depend on specific scanner characteristics and cardiovascular indication).

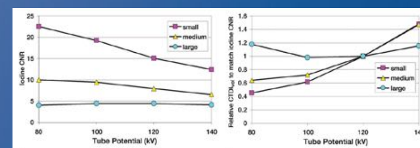
For prospective ECG-triggered axial techniques, the width of the data acquisition window should be kept at a minimum.

JCCT, 2011

Tube Voltage Modulation

JOHNS HOPKINS MEDICINE

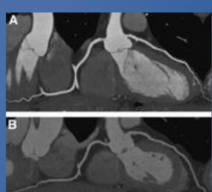
- Lower tube voltage improves image contrast and reduce dose
- As tube voltage decreases, tube current may have to be increased to maintain image noise

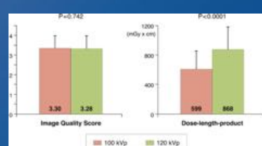


Radiology 2012; 264(2): :567-580

Influence of Tube Voltage on CTA Dose

JOHNS HOPKINS MEDICINE





Effective Dose Estimation

A - 100 kV: 8.4 ± 3.6 mSv

B - 120 kV: 12.2 ± 4.4 mSv

PROTECTION II study, JACC, 2010

Tube Potential

JOHNS HOPKINS MEDICINE

Recommendation

A tube potential of 100 kV could be considered for patients weighing ≤90 kg or with a BMI ≤ 30 kg/m^2; a tube potential of 120 kV is usually indicated for patients weighing >90 kg and with a BMI > 30 kg/m^2. Higher tube potential may be indicated for severely obese patients.

JCCT, 2011

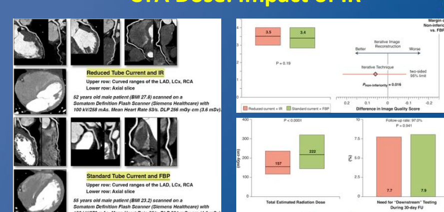
Iterative Reconstruction

JOHNS HOPKINS MEDICINE

- Objective is to enable user to acquire CT data at low dose and improve image quality with iterative process
- Most iterative reconstruction algorithms act as 'BLACK BOX' due to manufacturer proprietaries

CTA Dose: Impact of IR

JOHNS HOPKINS MEDICINE



Reduced mA + IR: 2.2 (1.6 – 3.3) mSv

Standard mA + FBP: 3.1 (2.0 – 4.5) mSv

PROTECTION V study, JACC, 2015

Estimating Effective Dose

- Computer software
  - Based on Monte Carlo simulations
  - IMPACT dose calculator
- k-factors based on DLP
  - E = DLP * k
  - where k in mSv/mGy-cm

Effective Dose = k * DLP

where, 'k'– standard conversion factors of head, neck, chest, abdomen and pelvis CT

Region of body	k (mSv × mGy^{-1} × cm^{-1})
Head	0.0021
Neck	0.0059
Chest	0.014
Abdomen	0.015
Pelvis	0.015

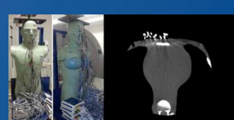
Quick estimation of effective dose for most cardiac CT protocols: ~ 1.4% of DLP

Ex: DLP = 1000 mGy * cm, E = 14 mSv
DLP = 500 mGy * cm, E = 7 mSv

AAPM Task Group Report No. 96, 2008

New k-factor for cardiac CT

- Current k-factor
  - 0.014 - 0.017 mSv/mGy-cm
- New conversion factors
- Accounts for ICRP 103 weighting factors and current CT technology
- Proposed new k-factor
  - 0.026 mSv/mGy-cm (0.020 to 0.035)



JACC Cardiovasc Imaging. 2018, 11(1): 64-74

CT Dose Check

CT Dose Alert

- US FDA has suggested CT alert value for $CTDI_{vol}$ of 1 Gy (1000 mGy)

CT Notification Values*

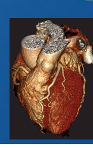
CT Scan Region (of each individual scan in an examination)	$CTDI_{vol}$ Notification Value (mGy)
Adult head	80
Adult torso	50
<2 years old	50
2-5 years old	60
Pediatric torso	
<10 years old(16-cm phantom)*	25
<10 years old (32-cm phantom)†	10
Brain Perfusion‡	600
Cardiac	
Retrospectively gated (spiral)	150
Prospectively gated (sequential)	50

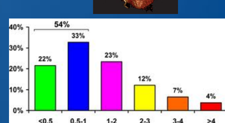
* NEMA XR 25-2010
**AAPM Dose Check Guidelines, 2011

* Mahesh M, JACR 2015

Cardiac CTA – submSv studies

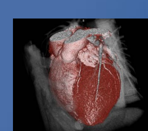
- 107 patients
  - 27.3 BMI
  - 100 kV for 97 patients
- Wide volume coverage (320 * 0.5 mm - Toshiba 320)
- Iterative Reconstruction
- Automatic exposure control
- Radiation dose: 0.93 mSv (0.58 – 1.74 mSv)

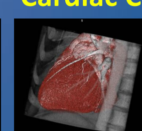


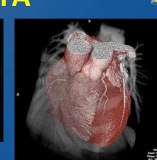


Chen MY, et al., Radiology 2013

Cardiac CTA







1.Coronary CTA for HR < 66 bpm

No.	Protocol	# of scan(s)	kVp	CTDIvol (mGy)	DLP (mGy.cm)	Exposure Time (sec)	Range (mm)	Body Size AP/LA
1	DualScano	1	120			3.31	***	***
2	DualScano	1	120			3.30	***	***
3	S&V	1	120	3.90 (Body)	0.80 (Body)	0.28	2.0	34.9/ 37.59
4	SURE Start	1	100	22.90 (Body)	9.10 (Body)	7.25	***	29.05/ 31.33
5	Volume	1	100	6.60 (Body)	92.40 (Body)	0.28	140.0	23.0/ 25.89

SURE Exposure

100 kV
6.6 mGy
92.40 mGy-cm
1.3 mSv

Johns Hopkins on Toshiba 320 CT

Johns Hopkins University mmahesh@jhmi.edu

Dose Optimization in Clinical Practice

Recommendation
Individual sites should consider developing site-specific algorithms for radiation dose optimization, which should be reviewed and revised if needed at least annually.

Recommendation
Use of breast shields is not recommended for cardiovascular CT.

JCCT, 2011

Dose Monitoring

Recommendation
$CTDI_{vol}$ (expressed in mGy) and DLP (expressed in mGy-cm) should be recorded for each patient.

Recommendation
Review of sites' radiation levels and adherence to institutional algorithms for radiation dose optimization should be performed at least twice per year.

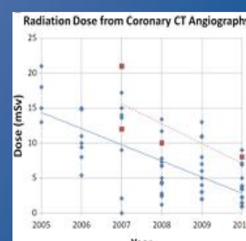
JCCT, 2011

Cardiac CTA - Unsteady HR and Ultra Low Dose

HR 41-96 bpm
1.1 mSv

HR 47 bpm
0.27 mSv

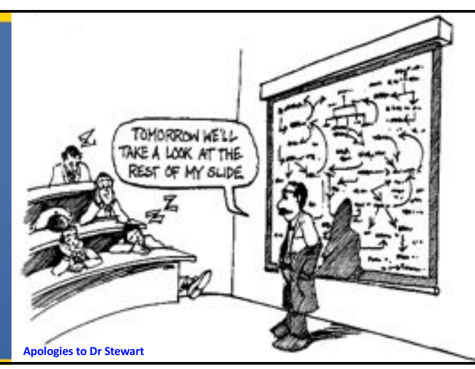
Courtesy - Toshiba



Raff GL, JCCT, 2010

Conclusions

- Cardiac CT imaging has been the driving force behind many technical advances in MDCT
- Novel technological advances have aided in lowering cardiac CT dose
- Radiation doses in Cardiac CT has been decreasing
- Important to understand and utilize techniques to lower cardiac CT dose in routine practice

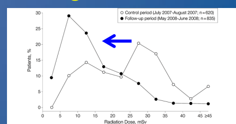


Apologies to Dr Stewart

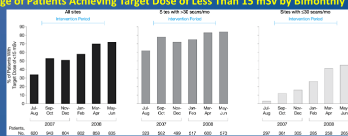
Johns Hopkins University mmahesh@jhmi.edu

Impact after implementing radiation reduction techniques

Distribution of Patients by Estimated Radiation Dose



Percentage of Patients Achieving Target Dose of Less Than 15 mSv by Bimonthly Intervals



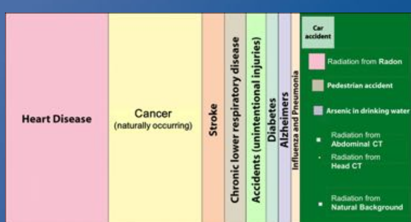
Raff, G. L. et al. JAMA 2009;301:2340-2348.

Cardiac CT: Radiation Dose Status

Imaging	Philips iCT	GE HD750	Toshiba one	Siemens FLASH
Tubes/sources	1	1	1	2
Slices/rot (detectors)	256 (128)	64	320	256 (128)
Total slice/rot (spiral mode)	256	64	320	256
Slice collimation (mm)	0.625	0.625	0.5	0.6
Tube voltage (kV, range)	80–140	80–140	80–135	80–140
Rotation time (ms)	270	350	350	285
Temporal resolution (ms)	135	175	175	75
Spatial resolution (mm^3)	0.3	0.3	0.3	0.3
X-ray dose (mSv)				
Spiral (full dose)	10–25	10–25	10–25	5–20
Spiral (ECG modulation)	3–8	3–8	3–8	3–8
Prospective (minimum)	1–2	1–2	1–2	1–2
High-pitch spiral	–	–	–	<1

Cademartiri F, Eur Radiol, 2013

Radiation Risks versus other causer



Fletcher JG, et al., Abdominal Imaging, 2012

Johns Hopkins University mmahesh@jhmi.edu