Cardiac CT Principles and Radiation Dose

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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

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**Categories of CT procedures (78.7 million in 2015)**

- **Head & Neck**: 22.5% of all CT procedures
- **Chest, Abdomen & Pelvis**: 38.3% of all CT procedures
- **Calcium Scoring**: 1.2% of all CT procedures
- **CT Angiography**: 2.2% of all CT procedures
- **Total 2015 CT Procedures**: 82.0%

**IMV 2015**

**Cardiac CT usage in US**

<table>
<thead>
<tr>
<th>CT Procedure Categories</th>
<th>Total 2016 CT Procedures (M)</th>
<th>% of All CT Procedures (%)</th>
<th>% of CT Sites Performing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head &amp; Neck</td>
<td>22.5</td>
<td>27%</td>
<td>&gt;90%</td>
</tr>
<tr>
<td>Chest, Abdomen &amp; Pelvis</td>
<td>38.3</td>
<td>47%</td>
<td>&gt;95%</td>
</tr>
<tr>
<td>Calcium Scoring</td>
<td>1.2</td>
<td>1%</td>
<td>30%</td>
</tr>
<tr>
<td>CT Angiography</td>
<td>2.2</td>
<td>3%</td>
<td>26%</td>
</tr>
<tr>
<td>Total 2015 CT Procedures</td>
<td>82.0</td>
<td>100%</td>
<td></td>
</tr>
</tbody>
</table>

**IMV 2016**

**Coronary CT Angiography volumes in Emergency Departments**

(Medicare programs, 2006-2015)

- **CTA Image Range**: 200 to 800 mA

**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 (DOFOV)
  - 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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**Tube Voltage (kV)**

- Potential difference between anode and cathode of x-ray tube
- Quality of x-rays - affects image contrast
- 120 kV – most common
  - Other kV stations – 140/135, 100/110 and 80 kV
  - 100 kV or 80 kV – thin patients
- Dose varies with tube voltage (kV^2)

**Pitch and Dose**

\[ \text{Pitch} = \frac{I}{W} \]

\[ \text{Dose} \propto \frac{1}{\text{Pitch}} \]

\( I \) - Table feed (mm/rotation) \( W \) - Beam width (mm) \( T \) - Single DAS channel width (mm) \( N \) - Number of active DAS channels

IEC Part 2-44, 2003

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**Why Cardiac CT protocols use Low Pitch?**

- Higher pitch produces gaps
- High quality 3D with minimal artifacts requires data overlap
- Typical pitch: 0.20 - 0.4
- Since pitch is low, radiation dose tends to be high

\[ \text{Dose} \propto \frac{1}{\text{Pitch}} \]

IEC Part 2-44, 2003

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**Retrospective ECG Gating**

- Temporal Resolution
- Radiation dose higher than prospective triggering

Continuous recording of spiral scan and ECG

**Prospective ECG Triggering**

- Temporal resolution
- Radiation dose minimized
- Limited data set

Conventional Axial "Partial Scan" (Step and Shoot)
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

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

Scan coverage - 320 vs 64 slice MDCT

Coronary CT Angiography:
Prospective Triggered vs Helical Retrospective gated

Effective dose for CTA portion:
- Prospective: 4-6 mSv
- Helical: 12-15 mSv

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

Aquilion 64 - 32 mm beam width
Aquilion One - 160 mm beam width

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

Without ECG Dose Modulation

With ECG Dose Modulation

Studies have reported cardiac CT doses of 3.2 mSv and 5.7 mSv

Dual Source CT: Definition FLASH*

Definition – FLASH
2nd Detector set still smaller than 1st but larger than Definition SFOV: 1st detector – 50 cm, 2nd detector – 34 cm

Data Acquisition with DSCT-Flash

- Table speed: 430 mm/s
- Pitch: 3.2
- Gantry rotation time: 0.28 sec
- Beam width: 38.4 mm
- Maximum slices: 128
- Scan range: 120 mm
- Scan time: 280 ms

High Pitch Cardiac CT Scan with DSCT FLASH*

- Interleaved spiral path from dual source is used in image reconstruction
- High-pitch (>3) scans enables data acquisition within single heartbeat
- High demand on patient selection (< 60 bpm desired)

CTA Dose: Conventional vs High Pitch

Conventional: 4.7 ± 4.8 mSv
High pitch (DSCT): 2.0 ± 2.4 mSv

* Achenbach S, JCCT, 3:117-121, 2009

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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

Radiation Dose Report – CT Angiography Exam

In the Beginning (2007)
- Effective dose (mSv)
  - 2.7 mSv
- Total effective dose (mSv)
  - 15.0 mSv
- Around 2011
  - 1.1 mSv
  - 8.2 mSv
  - 9.3 mSv

Effective dose:
- k = 0.014 mSv/mGy - cm

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

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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Radiation Dose Report – CT Angiography Exam


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Spatial Dose Modulation

- 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 Triggered 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
Scan Modes

Recommendations
Retrospective ECG-gated helical techniques may be used in patients who do not qualify for prospective ECG-gated scanning because of irregular heart rhythms or high heart rates (specific values depend on specific scanner characteristics and cardiovascular findings) or AoA.

Tube Voltage Modulation

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

Influence of Tube Voltage on CTA Dose

Effective Dose Estimation
A - 100 kV: 8.4 ± 3.6 mSv
B - 120 kV: 12.2 ± 4.4 mSv

Tube Potential

Recommendation
A tube potential of 100 kV could be considered for patients weighing ≤50 kg or with a BMI ≤ 20 kg/m²; a tube potential of 120 kV is usually indicated for patients weighing >50 kg and with a BMI > 30 kg/m². Higher tube potential may be indicated for severely obese patients.

Iterative Reconstruction

- 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 proprieties.

CTA Dose: Impact of IR

Reduced mA + IR: 2.2 (1.6 – 3.3) mSv
Standard mA + FBP: 3.1 (2.0 – 4.5) mSv

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Estimating Effective Dose

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

Effective Dose = k \times DLP

where, $k$—standard conversion factors of head, neck, chest, abdomen and pelvis CT

<table>
<thead>
<tr>
<th>Region of Body</th>
<th>$k$ (mSv/mGy-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>0.0021</td>
</tr>
<tr>
<td>Neck</td>
<td>0.0499</td>
</tr>
<tr>
<td>Chest</td>
<td>0.043</td>
</tr>
<tr>
<td>Abdomen</td>
<td>0.045</td>
</tr>
<tr>
<td>Pelvis</td>
<td>0.045</td>
</tr>
</tbody>
</table>

Quick estimation of effective dose for most cardiac CT protocols: $1 \times 4\%$ of DLP

Ex: $DLP = 1000 \text{ mGy}, E = 14 \text{ mSv}$

Cardiac CTA – submSv studies

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

Cardiac CTA

- 100 kV
- 6.6 mGy
- 92.40 mGy/cm
- 1.3 mSv

Johns Hopkins on Toshiba 320 CT

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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.

Dose Monitoring

Recommendation
CTDIvol (expressed in mGy) and DLP (expressed in mGy-cm) should be recorded for each patient.

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

Cardiac CTA - Unsteady HR and Ultra Low Dose

HR 41-96 bpm 1.1 mSv
HR 47 bpm 0.27 mSv

Courtesy - Toshiba

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
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

Cardiac CT: Radiation Dose Status

<table>
<thead>
<tr>
<th>Imaging</th>
<th>Philips CT</th>
<th>GE 64/320</th>
<th>Toshiba 64/320</th>
<th>Siemens 64/320</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task/technique</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total effective dose</td>
<td>178</td>
<td>44</td>
<td>250</td>
<td>296</td>
</tr>
<tr>
<td>Tissue effective dose</td>
<td>178</td>
<td>44</td>
<td>300</td>
<td>356</td>
</tr>
<tr>
<td>Skin estimated dose</td>
<td>0.02</td>
<td>0.02</td>
<td>0.1</td>
<td>0.4</td>
</tr>
<tr>
<td>Total dose (mSv, range)</td>
<td>30-40</td>
<td>60-90</td>
<td>100-150</td>
<td>120-140</td>
</tr>
<tr>
<td>Effective dose (mSv)</td>
<td>1.0</td>
<td>1.5</td>
<td>1.7</td>
<td>7.0</td>
</tr>
<tr>
<td>Skin dose (mSv)</td>
<td>0.2</td>
<td>0.1</td>
<td>5.1</td>
<td>4.3</td>
</tr>
</tbody>
</table>

Cademartiri F, Eur Radiol, 2013

Radiation Risks versus other causes

Fletcher JG, et al., Abdominal Imaging, 2012