Radiation Dose Reduction Strategies in Coronary CT Angiography

Noor Diyana Osman, PhD

noordiyana@usm.my
Contents:

• Introduction
• Radiation dosimetry in CT
• Radiation risk associated with coronary CT angiography
• Dose reduction strategies
• Coronary CTA for paediatric patients
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Introduction

Cardiac CT Imaging

**Cardiac CT** is a painless, non-invasive test that allows high-resolution, 3D visualization of the heart coronary arteries and other adjacent structures.

The two main types of cardiac CT imaging:
- Coronary artery calcium scoring (CASc)
- Coronary CT angiography (CTCA)
Coronary artery calcium scoring (CASc)

→ A CT scan to examine or measure the amount of calcified, or hardened, plaques in the arteries, which is usually explained as a calcium score of low, moderate or high. Unlike a CT angiogram, a calcium score doesn’t involve contrast.
Coronary CT Angiography (CCTA)

→ **Cardiac CTA** is an exam used to evaluate the structure and function of the heart, coronary arteries and large vessels of the chest.

→ **Coronary CTA** is a non-invasive method to image the coronary arteries with the use of contrast. Applications include the following:
  - Diagnosis of coronary artery disease (CAD)
  - Diagnosis of in-stent restenosis
  - Evaluation of coronary bypass graft patency
Coronary CT Angiography
Coronary CT angiography is currently regarded as the diagnostic imaging method of choice for evaluating coronary arteries.
Conventional vs. Modern Angiography

Conventional coronary angiography (conventional cardiac catheterization)

- Invasive methods (ICA)
- Expensive
- Superior spatial & temporal resolution

Coronary CT angiography (CTCA)

- Non – invasive
- Improved spatial & temporal resolution
- Higher dose to patients

Studies have shown that coronary CT angiography has a high diagnostic accuracy for the detection of significant CAD (≥ 50% lumen stenosis) when compared to ICA (Sun Z, et.al., 2011).
Coronary CT Angiography versus Conventional Cardiac Angiography for Therapeutic Decision Making in Patients with High Likelihood of Coronary Artery Disease

Table 2

Performance of Coronary CT Angiography in Determining the Appropriate Treatment Strategy

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Patients with CAD (n = 143)</th>
<th>All Patients (n = 185)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy (%)</td>
<td>95.1</td>
<td>96.2</td>
</tr>
<tr>
<td>Sensitivity (%)</td>
<td>100 (94.6, 100)</td>
<td>100 (95.7, 100)</td>
</tr>
<tr>
<td>Specificity (%)</td>
<td>90.1 (83.2, 97.0)</td>
<td>93.8 (89.3, 98.2)</td>
</tr>
<tr>
<td>Negative predictive value (%)</td>
<td>100 (93.9, 100)</td>
<td>100 (96.5, 100)</td>
</tr>
<tr>
<td>Positive predictive value (%)</td>
<td>91.1 (84.8, 97.4)</td>
<td>91.1 (84.8, 97.4)</td>
</tr>
<tr>
<td>No. of true-positive findings</td>
<td>72</td>
<td>72</td>
</tr>
<tr>
<td>No. of false-positive findings</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>No. of true-negative findings</td>
<td>64</td>
<td>106</td>
</tr>
<tr>
<td>No. of false-negative findings</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Note.—Numbers in parentheses are 95% confidence intervals. Conventional cardiac catheterization was used as the standard of reference.
With latest MSCT (≥ 64 slice CT), CTCA has been reported to have high diagnostic value & can be used as reliable alternative to invasive coronary angiography in selected patients.
Mean effective dose for MSCT coronary angiography was significantly higher than that for conventional angiography → MSCT angiography (14.7 mSv) vs. conventional angiography (5.6 mSv).

(Duncan R. et.al, 2006)
In AMDI, only 3 cardiac CT examinations were performed since Jan 2015 → CTA (1 patients) + CAScore (2 patients) – 0.7% of total studies performed in 2015.
Coronary CT Angiography

Study Protocols:

• Siemens SOMATOM Definition AS+ (128 slices/DECT)
• Tube voltage: 120 kVp
• Tube current: AEC for mAs
• Scan length: 15-20 cm (as reported in literature) – depends on patient’s height
• Pitch: 0.2
• Scan time: 0.33 s
Coronary computed tomography angiography in coronary artery disease

Zhonghua Sun, Kwan-Hoong Ng

(85%) of the studies. Figure 1 shows the distribution of different generations of MSCT scanners that were identified in the analysis. Despite rapid technological developments of MSCT scanners, such as the increased availability of 256- and 320-slice CT, single source 64-slice and dual-source CT (DSCT) still dominated 78% of the coronary CT angiography studies. Coronary CT angiography was compared with integrated single photon emission computed tomography/CT and positron emission tomography/CT in two studies to investigate the myocardial perfusion value of coronary CT angiography.

Figure 1 The number of studies performed with different generations of multislice computed tomography scanners. CT: Computed tomography; DSCT: Dual-source CT; MSCT: Multislice CT; PET: Positron emission tomography; SPECT: Single photon emission computed tomography.
A systematic review of radiation dose associated with different generations of multidetector CT coronary angiography

Akmal Sabarudin, Zhonghua Sun and Kwan-Hoong Ng

1 Discipline of Medical Imaging, Department of Imaging and Applied Physics, Curtin University, Perth, Western Australia, Australia; 2 Department of Biomedical Imaging, and 3 University of Malaya Research Imaging Centre, University of Malaya, Kuala Lumpur, Malaysia

<table>
<thead>
<tr>
<th>CT scanner</th>
<th>Scanning methods</th>
<th>Slice thickness / collimation (mm)</th>
<th>Pitch</th>
<th>Exposure settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 64 slices CTA (4/16/40- slices)</td>
<td>Retrospective/ Prospective/ High pitch/ ECG-controlled tube current modulation</td>
<td>0.625 – 2.5</td>
<td>0.18 – 0.75 (low pitch) 1.5 – 2.0 (high pitch)</td>
<td>100 – 140 kVp 100 – 800 mAs</td>
</tr>
<tr>
<td>64-slices CTA</td>
<td>Retrospective/ Prospective/ High pitch/ low kVp/AEC/ tube current modulation</td>
<td>0.6, 0.625</td>
<td>0.2 – 0.44 (low pitch) 3.2 – 3.4 (high pitch)</td>
<td>80 – 140 kVp 190 – 900 mAs</td>
</tr>
<tr>
<td>&gt; 64 slices CTA (128/256/320-slices)</td>
<td>Retrospective/ Prospective/ High pitch/ tube current modulation</td>
<td>0.5, 0.6, 0.625</td>
<td>0.18, 0.2 – 0.5 (low pitch)</td>
<td>100 – 140 kVp 180 – 950 mAs</td>
</tr>
</tbody>
</table>
Min requirements:
- A 64-detector row (or above) is required.
- The detector width must be 0.625 mm or less.
- Gantry rotation time should be <350 ms.
- The z-axis coverage (CC) must be at least 20 mm & 30 mm for DSCT. 30 – 40 mm for the best practice.
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Radiation dosimetry in CT

<table>
<thead>
<tr>
<th>Scan</th>
<th>kV</th>
<th>mAs / ref</th>
<th>CTDvol* (mGy)</th>
<th>DLP (mGycm)</th>
<th>TI</th>
<th>cSL</th>
<th>mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topogram</td>
<td>1</td>
<td>120</td>
<td>35 mAs</td>
<td>0.13 L</td>
<td>4</td>
<td>3.2</td>
<td>0.6</td>
</tr>
<tr>
<td>CaSc</td>
<td>2</td>
<td>120</td>
<td>19 / 40</td>
<td>4.44 L</td>
<td>67</td>
<td>0.33</td>
<td>0.6</td>
</tr>
<tr>
<td>Contrast</td>
<td>3</td>
<td>120</td>
<td>20</td>
<td>13.11 L</td>
<td>13</td>
<td>0.33</td>
<td>10.0</td>
</tr>
<tr>
<td>TestBolus</td>
<td>16</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Last scan no.</td>
<td>Contrast</td>
<td>17</td>
<td>120</td>
<td>20</td>
<td>6.56 L</td>
<td>7</td>
<td>0.33</td>
</tr>
<tr>
<td>TestBolus</td>
<td>23</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CorCTA</td>
<td>24</td>
<td>120</td>
<td>127 / 160</td>
<td>26.63 L</td>
<td>630</td>
<td>0.33</td>
<td>0.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Medium</th>
<th>Type</th>
<th>Iodine Conc. (mg/ml)</th>
<th>Volume (ml)</th>
<th>Flow (mL/s)</th>
<th>CM Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contrast</td>
<td>OMNIPAQUE</td>
<td>350</td>
<td>10</td>
<td>4.9</td>
<td>100%</td>
</tr>
<tr>
<td>Saline</td>
<td></td>
<td>20</td>
<td>20</td>
<td>4.9</td>
<td></td>
</tr>
</tbody>
</table>

1 of 2

*: L = 32cm, S = 16cm
• The dose display is created upon completion of a study $\rightarrow$ delivered CTDI$_{vol}$, DLP for each series, and phantom size used to calculate these values.

• It is useful to check CTDI$_{vol}$ after a study is performed to ensure that the output of the scanner was as expected.
Dose Display
(Post Study Data Page)

- \(\text{CTDI}_{\text{vol}}\) is calculated based on the technique factors used to acquire the data
- \(\text{DLP}\) is calculated based on the technique factors and scan length used
CT dose index (CTDI) is a standardized measure of radiation dose output of a CT scanner which allows the user to compare radiation output of different CT scanners.

\[
CTDI = \frac{1}{NT} \int_{-\infty}^{\infty} D(z)dz
\]

- \(D(z)\) = the radiation dose profile along the z-axis,
- \(N\) = the number of tomographic sections imaged in a single axial scan.
- \(T\) = scan width

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Radiation dosimetry in CT

- Measured in large (32 cm diameter) or small (16 cm or 10 cm diameter) PMMA cylindrical phantom.

- The CTDI measured in large phantom is for adult CT (chest, abdomen, and pelvis).

- The CTDI measured in small phantom (16 cm) is for adult head CT, and pediatric body CT and 10 cm phantom is for pediatric head.
Radiation dosimetry in CT

- **CTDI\textsubscript{100}** is a measure of radiation on a 100cm long pencil ionization chamber.

- **CTDI weighted, CTDI\textsubscript{w}**:

  \[
  CTDI_w = \frac{2}{3} CTDI_{\text{peripheral}} + \frac{1}{3} CTDI_{\text{center}}
  \]

  ‘Head’

  160 mm

  ‘Body’

  320 mm

AAPM Report 96
• **CTDI volume, CTDI\textsubscript{vol}** is the approximate average radiation dose over x, y, and z axis of the patient.

\[
CTDI_{vol} = \frac{NT}{I} CTDI_{w}
\]

\[
CTDI_{vol} = \frac{1}{pitch} CTDI_{w}
\]

• **CTDI\textsubscript{vol}** estimates the average radiation dose within the irradiated volume for an object of similar attenuation to the CTDI phantom.
CTDI<sub>vol</sub> \(\rightarrow\) estimation of patient dose (in mGy) – a standardized parameter to measure **Scanner Radiation Output**.

✓ **CTDI<sub>vol</sub>** is NOT patient dose!

✓ **CTDI<sub>vol</sub>** is slice-specific dose measurement

✓ **CTDI<sub>vol</sub>** is based on measurements made by the manufacturer in a factory setting.
$\text{CTDI}_{\text{vol}}$ does not represent the average dose for objects of substantially different size, shape, or attenuation!
# Summary of Acquisition Parameter Settings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Relationship to CTDI\textsubscript{vol}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scan Mode</td>
<td>Changes in the scan mode may affect CTDI\textsubscript{vol}</td>
</tr>
<tr>
<td>Table Feed/Increment</td>
<td>Table feed affects CTDI\textsubscript{vol} through its inclusion in pitch</td>
</tr>
<tr>
<td>Detector Configuration</td>
<td>Decreasing the beam collimation typically, but not always, increases the CTDI\textsubscript{vol}</td>
</tr>
<tr>
<td>Pitch</td>
<td>CTDI\textsubscript{vol} relationship to pitch is vendor dependent</td>
</tr>
<tr>
<td>Exposure Time Per Rotation</td>
<td>CTDI\textsubscript{vol} relationship to exposure time per rotation is vendor dependent</td>
</tr>
<tr>
<td>Tube Current</td>
<td>CTDI\textsubscript{vol} ( \mu ) tube current</td>
</tr>
<tr>
<td>Tube Potential</td>
<td>CTDI\textsubscript{vol} ( \mu ) ( \frac{(kVp_1/kVp_2)^n}{n} ) ( n \sim 2 \text{ to } 3 )</td>
</tr>
<tr>
<td>Tube Current Time Product</td>
<td>CTDI\textsubscript{vol} ( \mu ) tube current time product</td>
</tr>
<tr>
<td>Effective mAs</td>
<td>CTDI\textsubscript{vol} ( \mu ) effective tube current time product</td>
</tr>
<tr>
<td>Field of Measurement</td>
<td>Changes in the field of measurement may affect CTDI\textsubscript{vol}</td>
</tr>
<tr>
<td>Beam Shaping Filter</td>
<td>Changes in the beam shaping filter may affect CTDI\textsubscript{vol}</td>
</tr>
</tbody>
</table>
Radiation dosimetry in CT

- **Dose-length product (DLP)** → product of the length of the irradiated scan volume and the average CTDI$_{vol}$ over that distance

\[
DLP = CTDI_{vol} \times \text{scan length}
\]

- **Unit**: mGy.cm
CTDI vs. DLP
Radiation dosimetry in CT

- **Effective dose, E** is a measure of radiation and organ system specific damage in humans (in unit sievert, Sv)

- **E** is the **DLP multiplied by conversion factor, k** (takes into account organ size and radiosensitivity)
Effective Dose \( E = \sum T w_T H_T \)

- \( H_T \) are the tissue-specific equivalent doses in tissues \( T \)
- \( w_T \) are committee-defined dimensionless tissue-specific weighting factors
**Table shows tissue weighting factor (as published by ICRP)**

<table>
<thead>
<tr>
<th>Tissue or organ</th>
<th>Weighting Factor, $w_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone marrow (red)</td>
<td>0.12</td>
</tr>
<tr>
<td>Breast</td>
<td>0.15</td>
</tr>
<tr>
<td>Lung</td>
<td>0.12</td>
</tr>
<tr>
<td>Stomach</td>
<td>-</td>
</tr>
<tr>
<td>Colon</td>
<td>-</td>
</tr>
<tr>
<td>Gonads</td>
<td>0.25</td>
</tr>
<tr>
<td>Thyroid</td>
<td>0.03</td>
</tr>
<tr>
<td>Bladder</td>
<td>-</td>
</tr>
<tr>
<td>Liver</td>
<td>-</td>
</tr>
<tr>
<td>Oesophagus</td>
<td>-</td>
</tr>
<tr>
<td>Bone surface</td>
<td>0.03</td>
</tr>
<tr>
<td>Skin</td>
<td>-</td>
</tr>
<tr>
<td>Salivary glands</td>
<td>-</td>
</tr>
<tr>
<td>Brain</td>
<td>-</td>
</tr>
<tr>
<td>Remainder</td>
<td>0.30</td>
</tr>
</tbody>
</table>
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Cell Radiosensitivity

• **Radiosensitivity** → relative susceptibility of cells, tissues & organs to the injurious action of radiation.

• Cell radiosensitivity is **directly proportional** to cell division rate and **inversely proportional** to cell differentiation degree.

• The most radiosensitive (most at risk from radiation) cells are:
  
  ➢ actively dividing cells (high division rate)
  ➢ not fully mature or non-specialized type
  ➢ cells that have a high metabolic rate
  ➢ well nourished cells
Tissues radiosensitivity

**High Radiosensitivity**
Lymphoid organs, bone marrow, blood, testes, ovaries, intestines

**Fairly High Radiosensitivity**
Skin and other organs with epithelial cell lining (cornea, oral cavity, esophagus, rectum, bladder, vagina, uterine cervix, ureters)

**Moderate Radiosensitivity**
Optic lens, stomach, growing cartilage, fine vasculature, growing bone

**Fairly Low Radiosensitivity**
Mature cartilage or bones, salivary glands, respiratory organs, kidneys, liver, pancreas, thyroid, adrenal and pituitary glands

**Low Radiosensitivity**
Muscle, brain, spinal cord
Computed Tomography — An Increasing Source of Radiation Exposure


The advent of computed tomography (CT) has revolutionized diagnostic radiology. Since the inception of CT in the 1970s, its use has increased rapidly. It is estimated that more than 62 million CT scans per year are currently obtained in the United States, including at least 4 million for children.

By its nature, CT involves larger radiation doses than the more common, conventional x-ray imaging procedures (Table 1). We briefly review the nature of CT scanning and its main clinical applications, both in symptomatic patients and, in a more recent development, in the screening of asymptomatic patients. We focus on the increasing number of CT scans being obtained, the associated radiation doses, and the consequent cancer risks in adults and particularly in children. Although the risks for any one person are not large, the increasing exposure to radiation in the population may be a public health issue in the future.
CT scans deliver ~500 times the radiation of standard X-ray!!!
### Radiation dose from common imaging tests

<table>
<thead>
<tr>
<th>Test</th>
<th>Radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Echocardiogram</td>
<td>0 mSV</td>
</tr>
<tr>
<td>MRI</td>
<td>0 mSV</td>
</tr>
<tr>
<td>Chest x-ray</td>
<td>0.05 mSV</td>
</tr>
<tr>
<td>Mammogram</td>
<td>0.7 mSv</td>
</tr>
<tr>
<td>Calcium scoring test</td>
<td>1-2 mSv</td>
</tr>
<tr>
<td>Cardiac catheterization</td>
<td>7 mSv</td>
</tr>
<tr>
<td>Chest CT</td>
<td>10 mSv</td>
</tr>
<tr>
<td><strong>Coronary CT angiography</strong></td>
<td><strong>3-14 mSv</strong></td>
</tr>
<tr>
<td>Radionuclide sestamibi stress test</td>
<td>10-12 mSv</td>
</tr>
<tr>
<td>Radionuclide dual isotope myocardial perfusion imaging</td>
<td>25 mSv</td>
</tr>
</tbody>
</table>
Computed Tomography — An Increasing Source of Radiation Exposure


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Figure 4. Estimated Dependence of Lifetime Radiation-Induced Risk of Cancer on Age at Exposure for Two of the Most Common Radiogenic Cancers.

Cancer risks decrease with increasing age both because children have more years of life during which a potential cancer can be expressed (latency periods for solid tumors are typically decades) and because growing children are inherently more radiosensitive, since they have a larger proportion of dividing cells. These risk estimates, applicable to a Western population, are from a 2005 report by the National Academy of Sciences and are ultimately derived from studies of the survivors of the atomic bombings. The data have been averaged according to sex.
A systematic review of radiation dose associated with different generations of multidetector CT coronary angiography

Akmal Sabarudin,1 Zhonghua Sun1 and Kwan-Hoong Ng2,3

1Discipline of Medical Imaging, Department of Imaging and Applied Physics, Curtin University, Perth, Weste Biomedical Imaging, and 2University of Malaya Research Imaging Centre, University of Malaya, Kuala Lumpur

A Sabarudin MSc, Z Sun PhD; K-H Ng PhD.

Correspondence
Associate Professor Zhonghua Sun, Discipline of Medical Imaging, Department of Imaging and Applied Physics, Curtin University, GPO Box, U1987, Perth, WA 6845, Australia.
Email: z.sun@curtin.edu.au

Conflict of interest: None.

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Summary
The purpose of this paper is to perform a systematic review of radiation dose associated with different generations of multidetector CT coronary angiography using different generations of multidetector four-slice to 320-slice CTs, and have different exposure factors and scan parameters. The effective radiation dose reported in each generation of MDCT scanners was analysed in this systematic review.

Fig. 4. Distribution of mean effective dose between 4-, 16-, 64-, 128-, 256- and 320-slice multidetector CT scanners is displayed in the box plot. Radiation dose increases with the increase of number of slices; in particular, this is apparent when comparing 4-slice with 16- and 64-slice CT. With latest models such as 128-, 256- and 320-slice CT, radiation dose was reduced to some extent as prospective gating is commonly used. Horizontal line in each box shows median and top and bottom lines of boxes show interquartile range (IQR). Whiskers show lowest value still within 1.5 IQR of lower or upper quartile; however, the highest value for 16-slice CT studies is outside 1.5 IQR of upper quartile.
Although we only scan 15-20 cm of the chest for most cardiac CT exams, particularly CCTA, the doses are relatively higher because we’re looking at very fine structures with overlapping data acquisition and matching the data with the cardiac cycle or the motion of the heart.

Higher dose due to higher image quality → higher resolution and thinner slices is needed.

(Cristen C. B., 2008)
MDCT coronary angiography: does the benefit justify radiation burden?

September 2010  Br J Cardiol 2010;17:207–08  Leave a comment

Authors: Khaled Alfakih, Mathew Budoff

Recent technical developments in multi-detector computed tomography (MDCT), and particularly the introduction of 64-slice MDCT, have made the non-invasive imaging of coronary arteries a clinical reality. Beta blockers are used to decrease the heart rate to 65 bpm. Sublingual glyceryl trinitrate (GTN) can be used to dilate the coronary arteries, and the patient is only required to breath-hold for a few seconds. Fast or irregular heart rates, extensive calcium blooming artefacts and patients with high body mass index (BMI) are the only limiting factors. The temporal resolution is faster with dual-source MDCT, reducing the need for beta blockers, and the 320-slice MDCT can image the heart in one heart beat.

MDCT coronary angiography (CTCA) has been shown to be highly accurate at detecting coronary artery disease (CAD) with more than 30 studies and several meta-analyses confirming excellent sensitivity and negative predictive value (NPV), when compared with invasive X-ray coronary angiography. This was confirmed in three multi-centre trials: Assessment by Coronary Computed Tomographic Angiography of Individuals Undergoing Invasive Coronary
Estimated Radiation Dose Associated With Cardiac CT Angiography

Jörg Hausleiter, MD
Tanja Meyer, MD
Franziska Hermann, MD
Martin Hadamitzky, MD
Markus Krebs
Thomas C. Gerber, MD
Cynthia McCollough, PhD
Stefan Martinoff, MD
Adnan Kastrati, MD
Albert Schömig, MD
Stephan Achenbach, MD

Context Cardiac computed tomography (CT) angiography (CCTA) has emerged as a useful diagnostic imaging modality in the assessment of coronary artery disease. However, the potential risks due to exposure to ionizing radiation associated with CCTA have raised concerns.

Objectives To estimate the radiation dose of CCTA in routine clinical practice as well as the association of currently available strategies with dose reduction and to identify the independent factors contributing to radiation dose.

Design, Setting, and Patients A cross-sectional, international, multicenter, observational study (50 study sites: 21 university hospitals and 29 community hospitals) of estimated radiation dose in 1965 patients undergoing CCTA between February and December 2007. Linear regression analysis was used to identify independent predictors associated with dose.

Main Outcome Measure Dose-length product (DLP) of CCTA.

Results The median DLP of 1965 CCTA examinations performed at 50 study sites was 885 mGy × cm (interquartile range, 568-1259 mGy × cm), which corresponds to an estimated radiation dose of 12 mSv (or 1.2 × the dose of an abdominal CT study or 600 chest x-rays). A high variability in DLP was observed between study sites (range of median DLPs per site, 331-2146 mGy × cm). Independent factors associated with radiation dose were patient weight (relative effect on DLP, 5%; 95% confidence interval [CI], 4%-6%), absence of stable sinus rhythm (10%; 95% CI, 2%-19%), scan length (5%; 95% CI, 4%-6%), electrocardiographically controlled tube current modulation (−25%; 95% CI, −23% to −28%; applied in 73% of patients), 100-kV tube voltage (−46%; 95% CI, −42% to −51%; applied in 5% of patients), sequential scanning (−78%; 95% CI, −77% to −79%; applied in 6% of patients), experience in cardiac CT (−1%; 95% CI, −1% to 0%), number of CCTAs per month (0%; 95% CI, 0%-1%), and type of 64-slice CT system (for highest vs lowest dose system, 97%; 95% CI, 88%-106%). Algorithms for dose reduction were not associated with deteriorated diagnostic image quality in this observational study.

Conclusions Median doses of CCTA differ significantly between study sites and CT systems. Effective strategies to reduce radiation dose are available but some state...
Radiation risk associated with CCTA

Comparisons of effective radiation dose in adults for various CT procedures.

<table>
<thead>
<tr>
<th>Examination</th>
<th>Average Effective Dose (mSv)</th>
<th>Values Reported in Literature (mSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>2</td>
<td>0.9–4.0</td>
</tr>
<tr>
<td>Neck</td>
<td>3</td>
<td>...</td>
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<tr>
<td>Chest</td>
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<tr>
<td>Chest for pulmonary embolism</td>
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<td>Abdomen</td>
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<td>Pelvis</td>
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<td>Three-phase liver study</td>
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<td>Spine</td>
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<td>1.5–10</td>
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<tr>
<td><strong>Coronary angiography</strong></td>
<td><strong>16</strong></td>
<td><strong>5.0–32</strong></td>
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<td><strong>1.0–12</strong></td>
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<tr>
<td>Virtual colonoscopy</td>
<td><strong>10</strong></td>
<td><strong>4.0–13.2</strong></td>
</tr>
</tbody>
</table>

FA. Mettler et.al., Radiology: 2008
Estimating Risk of Cancer Associated With Radiation Exposure From 64-Slice Computed Tomography Coronary Angiography

Andrew J. Einstein, MD, PhD
Milena J. Henzlova, MD, PhD
Sanjay Rajagopalan, MD

Coronary artery disease (CAD) is the leading cause of death in men and women in the United States, accounting for 1 in 5 deaths, and a major cause of health care expenditures, with annual costs estimated at $142 billion. While the gold standard for CAD diagnosis remains conventional coronary angiography, its associated costs and morbidity, including a 1.7% rate of major complications, have led to the development of noninvasive modalities for CAD diagnosis. Since its approval in 2004, 64-slice computed tomography coronary angiography (CTCA) has generated particular interest due to its visualization of the coronary arteries with a spatial resolution as low as 0.4 mm, resulting in high diagnostic sensitivity and specificity and a per-patient negative predictive value greater than 95% in most series.

Context Computed tomography coronary angiography (CTCA) has become a common diagnostic test, yet there are little data on its associated cancer risk. The recent Biological Effects of Ionizing Radiation (BEIR) VII Phase 2 report provides a framework for estimating lifetime attributable risk (LAR) of cancer incidence associated with radiation exposure from a CTCA study, using the most current data available on health effects of radiation.

Objectives To determine the LAR of cancer incidence associated with radiation exposure from a 64-slice CTCA study and to evaluate the influence of age, sex, and scan protocol on cancer risk.

Design, Setting, and Patients Organ doses from 64-slice CTCA to standardized phantom (computational model) male and female patients were estimated using Monte Carlo simulation methods, using standard spiral CT protocols. Age- and sex-specific LARs of individual cancers were estimated using the approach of BEIR VII and summed to obtain whole-body LARs.

Main Outcome Measures Whole-body and organ LARs of cancer incidence.

Results Organ doses ranged from 42 to 91 mSv for the lungs and 50 to 80 mSv for the female breast. Lifetime cancer risk estimates for standard cardiac scans varied from 1 in 143 for a 20-year-old woman to 1 in 3261 for an 80-year-old man. Use of simulated electrocardiographically controlled tube current modulation (ECTCM) decreased these risk estimates to 1 in 219 and 1 in 5017, respectively. Estimated cancer risks using ECTCM for a 60-year-old woman and a 60-year-old man were 1 in 715 and 1 in 1911, respectively. A combined scan of the heart and aorta had higher LARs, up to 1 in 114 for a 20-year-old woman. The highest organ LARs were for lung cancer and, in younger women, breast cancer.

Conclusions These estimates derived from our simulation models suggest that use of 64-slice CTCA is associated with a nonnegligible LAR of cancer. This risk varies markedly and is considerably greater for women, younger patients, and for combined car-
Estimating Risk of Cancer Associated With Radiation Exposure From 64-Slice Computed Tomography Coronary Angiography

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<table>
<thead>
<tr>
<th>Sex</th>
<th>ECTCM</th>
<th>Aorta</th>
<th>Effective Dose, mSv</th>
<th>Organ Equivalent Doses, mSv a</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
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<td>19</td>
<td>74</td>
</tr>
<tr>
<td>Male</td>
<td>Yes</td>
<td>Yes</td>
<td>15</td>
<td>69</td>
</tr>
</tbody>
</table>

Abbreviation: ECTCM, electrocardiographically controlled tube current modulation.

aOrgan equivalent doses reported here only for organs with a dose >10 mSv for standard male or female patient; the doses are displayed here as integers, although more significant figures were retained for calculations.

bEffective dose determined using International Commission on Radiological Protection Publication 60 tissue weighting factors.13
Radiation risk associated with CCTA

One study estimated that one in every 270 women aged 40 years who undergo a CT coronary angiogram will develop cancer from the procedure.

(Smith-Bindman R, et al., 2009)
## Radiation risk associated with CCTA

Comparisons of effective radiation dose in adults with background radiation exposure for several radiological procedures.

<table>
<thead>
<tr>
<th>CT PROCEDURES</th>
<th>* An adult’s approximate effective radiation dose is:</th>
<th>Comparable to natural background radiation for:</th>
</tr>
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<tbody>
<tr>
<td>ABDOMINAL REGION:</td>
<td></td>
<td></td>
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<tr>
<td>CT Abdomen + Pelvis</td>
<td>10 mSv</td>
<td>3 years</td>
</tr>
<tr>
<td>CT Abdomen + Pelvis, repeated with and without contrast</td>
<td>20 mSv</td>
<td>7 years</td>
</tr>
<tr>
<td>CT Colonography</td>
<td>6 mSv</td>
<td>2 years</td>
</tr>
<tr>
<td>CENTRAL NERVOUS SYSTEM:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CT Head</td>
<td>2 mSv</td>
<td>8 months</td>
</tr>
<tr>
<td>CT Head, repeated with and without contrast</td>
<td>4 mSv</td>
<td>16 months</td>
</tr>
<tr>
<td>CT Spine</td>
<td>6 mSv</td>
<td>2 years</td>
</tr>
<tr>
<td>CHEST:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CT Chest</td>
<td>7 mSv</td>
<td>2 years</td>
</tr>
<tr>
<td>CT-Lung Cancer Screening</td>
<td>1.5 mSv</td>
<td>6 months</td>
</tr>
<tr>
<td>DENTAL:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intraoral X-ray</td>
<td>0.005 mSv</td>
<td>1 day</td>
</tr>
<tr>
<td>HEART:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coronary CTA</td>
<td>12 mSv</td>
<td>4 years</td>
</tr>
<tr>
<td>Cardiac CT for Calcium Scoring</td>
<td>3 mSv</td>
<td>1 year</td>
</tr>
</tbody>
</table>

**Note:** Paediatric patients vary in size. Doses given to paediatric patients will vary significantly from those given to adults.

* The effective doses are typical values for an average-sized adult. The actual dose can vary substantially, depending on a person's size as well as on differences in imaging practices.

Contents:

- Introduction
- Radiation dosimetry in CT
- Radiation risk associated with coronary CT angiography
- **Dose reduction strategies**
- Coronary CTA for paediatric patients
The big challenges!

Risks
(radiation dose)

Benefits
(image quality)
Principles of radiation protection

**JUSTIFICATION** → radiation exposures should not be performed unless it demonstrates significant benefit – benefit exceeds the risk

**OPTIMISATION** → the dose should be *As Low As Reasonably Practicable (ALARP)*

**LIMITATION** → dose limits apply to those who work with radiations and members of the public

(ICRP 1999)
3 immediate ways to reduce the radiation burden of CT:

- **Review your CT imaging protocols** → radiation dose per examination is optimized, and minimized where appropriate. Avoid delivering higher radiation dose than what is necessary for optimal image quality.

- **Ensure proper utilization of CT** → avoid inappropriate ordering of imaging procedures (variability between referring physicians). By using standards-based ordering decision support, referring clinicians can enter a patient’s symptoms and qualify the effectiveness of their exam choice (e.g. Nuance’s Radport is a decision support system for diagnostic image ordering).

- **There are always alternative to CT** → go for nonionizing radiation based modalities (e.g. MRI and ultrasound).

*(Cristen C. Bolan, 2008)*
What we already have?

- MDCT scanner
- Dual-energy CT
- Helical /Spiral CT
- Iterative image reconstruction
- Automatic exposure control (AEC)

http://rpop.iaea.org
Are we **FULLY UTILIZE** the technology advancements that we have?

Are these technologies **utilized appropriately** so that their benefits ultimately reach our patients?
CCTA dose reduction strategies

- Adapt to Clinical Indications
  - Implementing iterative reconstruction software
- Automatic exposure control (AEC)
- Limiting the scan length & scan phase
- Automatic pitch adaption
- ECG pulsing

(Cristen C. Bolan, 2008)
CCTA dose reduction strategies

**Patient Preparation**
- Appropriate imaging indications
- Shield non-imaged organs

**Scanner Technology**
- Iterative reconstruction
- Dual energy
- Tube current modulation software
- Cardiac ECG-gating

**Acquisition Parameters**
- Appropriate coverage
- Limit no. of acquisition
- Lowest possible kVp & mAs
- High pitch, fast gantry rotation time
- Thick detector width
- Iodine dose optimization
Figure 2: Box plot shows the mean effective dose associated with different dose-reduction techniques. Coronary computed tomography angiography with the use of high pitch and prospective electrocardiography-triggering leads to the lowest radiation dose. The boxes indicate the first to third quartiles, and each midline indicates the median (second quartile) and the whiskers represent the maximum and minimum values of effective dose.
CCTA dose reduction strategies

Effect of dose reduction on image quality and diagnostic performance in coronary computed tomography angiography

Noortje van der Bijl · Raoul M. S. Joemai · Bart J. A. Mertens · Albert de Roos · Wouter J. H. Veldkamp · Jeroen J. Bax · Joanne D. Schuijf · Jacob Geleijns · Lucia J. M. Kroft

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Abstract To evaluate the effect of radiation dose reduction on image quality and diagnostic accuracy of coronary computed tomography (CT) angiography. Coronary CT angiography studies of 40 patients with \((n = 20)\) and without \((n = 20)\) significant \((\geq 50\%)\) stenosis were included (26 male, 14 female, 57 ± 11 years). In addition 12.5\% of the original dose. Image quality and diagnostic performance in identifying significant stenosis were determined. Receiver–operator-characteristics analysis was used to assess diagnostic accuracy at different dose levels. The identification of patients with significant stenosis decreased consistently at doses of 50, 25 and 12.5 of the
1) ECG-Based Tube Current Modulation

- **Electrocardiogram (ECG) pulsing (or ECG controlled tube current modulation)** → for minimizing dose. If you are looking for coronary arteries and the heart is constantly moving, what we do is segment the heart in order to obtain a measure of the coronary arteries when they are least moving. We only want to acquire coronary arteries when the heart is relatively resting, which is the diastolic phase.

- The tube current is adjusted based on the ECG signal that we obtain. The tube current is increased when at resting phase or diastolic phase and then is reduced during the systolic phase, or when the heart is moving very rapidly.

- If the systolic phase is longer than the diastolic phase (occurs when patient’s heart rate is too high) → results in little dose reduction.
ECG-Based Tube Current Modulation

• AEC feature used with prospectively gated cardiac imaging that adjusts the tube current based on the phase within the cardiac cycle

• It is important for heart rate considerations when using prospective gating.
ECG-Based Tube Current Modulation (TCM)

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

Radiation On
The use of ECG-Based Tube Current Modulation with prospective gating will decrease $\text{CTDI}_{\text{vol}}$ compared to retrospective gating.
Traditional way → retrospective ECG-gating with tube modulation

Fig. 1 Normal retrospective electrocardiogram-gating without tube current modulation. The X-ray beam is turned on during the entire cardiac cycle without adjusting the tube current.

Fig. 2 Retrospective electrocardiogram-gating with tube current modulation. The normal tube current is applied only during the image reconstruction phase (late diastolic phase), while the tube current is reduced during the systolic phase.
More dose reduction through prospective ECG triggering → up to 80% of dose reduction.

What’s the difference between prospective ECG triggering and the ECG tube current modulation?

In prospective ECG triggering instead of dropping the tube current during the phase when the heart is rapidly moving, we turn off the tube current to obtain much higher dose reduction.

This technique is commonly employed for coronary CaScore and also coronary CTA, if the patient’s heart rate is stable and slow.

To avoid the tube to be off when the heart is relaxing.
Prospective electrocardiogram-triggering with X-ray beam turned on during a portion of the cardiac cycle, while in the remaining cardiac phase, the X-ray beam is turned off.
2) Automatic Pitch Adaptation

- Most scanners have this technique. When the heart is moving fast (higher heart rate), the scanner will go faster (higher pitch), less overlapping, and higher pitch during scanning → dose is reduced.

- For dual source MDCT - the extent to change the pitch is much greater. For SSCT (64-slice scanner), pitch change ranged from 0.2–0.35 but for DSCT pitch change ranged from 0.2 to 0.55.

- With dual source you don’t need the beta blockers because the scanner is faster, and the dose can be reduced using the pitch adaptation.
Pitch $< 1$ implies overlapping
Pitch $= 1$ same as contiguous axial scanning
Pitch $> 1$ implies extended imaging (preferable for dose reduction)
How pitch affect the average dose?

- Volume CTDI takes account of non-contiguous exposure along z-axis

\[
\text{CTDI}_{\text{vol}} = \frac{\text{CTDI}_{\text{w}}}{\text{Pitch}}
\]

- CTDI$\_vol = \text{CTDI}_w$
  - Pitch $= 1$
- CTDI$\_vol = \text{CTDI}_w/2$
  - Pitch $= 2$
- CTDI$\_vol = 2 \times \text{CTDI}_w$
  - Pitch $= 0.5$
The drawbacks:
Higher pitch gives lower dose, but poor image quality (less resolution)!
3) Automatic Exposure Control (AEC)

- This AEC technique, if used appropriately, will allow the radiologist/cardiologist to reduce doses in children by 30-50%. The clinician selects an appropriate level of image quality. The system then calculates the size of the patient (child/adult) and automatically uses the lowest possible dose to obtain the optimal image quality.

- AEC controls the **tube current to adapt to the patient’s size** based on what image quality the clinician has specified→ patient dose can be optimized.

- With AEC, the radiologists need to decide based on the clinical indications and level of comfort to assess low radiation dose images. Inappropriate selection of superior image quality can actually increase the dose with AEC technique.
Redesigning CT acquisition protocols

**Decreased kVp**
- Low kVp can reduce the radiation dose reduction, improve soft tissue contrast. However, mAs likely have to be increased to compensate the image quality.

**Auto mAs**
- mA can be adjusted automatically (automatic dose modulation by AEC) based on the patient’s size and shape (auto-mA). Decrease mA will reduce patient dose (but must maintain the diagnostic image quality).

**Pitch > 1**
- Dose inversely proportional to dose. Pitch < 1, beam overlapping, dose increased. Faster pitch (pitch > 1), will reduce radiation dose. But, reducing image quality.

* Nelson TR, 2014
  http://info.atlantisworldwide.com
Lower tube potential (kVp)

• The use of 100 kV instead of 120 kV (conventionally used) can reduces the dose by 30 - 35%. Reducing the dose, will increase the image contrast and therefore you need higher volumes of contrasts.

• **But it depends on the patient’s size!** 100 kV may produce optimal quality for average size but may produce inappropriate image quality for larger patient or else higher dose to smaller patients.

• So, the regional size of the body or large region of interest is very important and avoid doing lower kV with large size patients or patients with a large region of interest.

• Adapt the scanning protocol to the clinical indication and the size of the patient.

• Vendors don’t know about the specific clinical indications, and the radiation awareness is a major concern for radiologists and team.
Adjusting CT dose based on size

- Adjust exposure based on individual size and shape.
- Standard kVp for adult is 120, but adults vary in size.
- By using a patient’s BMI to determine patient size → kVp can be accurately adjusted and optimized for dose reduction.

<table>
<thead>
<tr>
<th>Size</th>
<th>Measured CTDI&lt;sub&gt;vol&lt;/sub&gt;</th>
<th>Displayed CTDI&lt;sub&gt;vol&lt;/sub&gt;</th>
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</thead>
<tbody>
<tr>
<td>10 cm</td>
<td>47 mGy</td>
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<tr>
<td>16 cm</td>
<td>37 mGy</td>
<td>37 mGy</td>
</tr>
<tr>
<td>32 cm</td>
<td>18 mGy</td>
<td>18 mGy</td>
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</table>

Adapted from: Nelson TR, 2014
Size-Specific Dose Estimates (SSDE) in Pediatric and Adult Body CT Examinations

Report of AAPM Task Group 204, developed in collaboration with the International Commission on Radiation Units and Measurements (ICRU) and the Image Gently campaign of the Alliance for Radiation Safety in Pediatric Imaging
• **Decreased length of scan coverage:** The scan length is directly proportional to CT dose. Limits the length (z-axis) so that only the anatomy of clinical interest is included in the scan.

• **Limitations on double scans & multi-phase studies:** Whenever possible, eliminates non-contrast scans → provide little additional diagnostic information and increase patient dose. Limits no. of phases (pre- & post-contrast monitoring) in multi-phase examinations.
Limiting the scan phase!

<table>
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<tr>
<th>Total mAs</th>
<th>Total DLP</th>
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<table>
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<th>mAs / ref</th>
<th>CTDvol* mGy</th>
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<th>cSL mm</th>
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<td>18 / 40</td>
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<td>13.11 L</td>
<td>13</td>
<td>0.33</td>
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<tr>
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<td>120</td>
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<td>6.56 L</td>
<td>7</td>
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<tr>
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<th>Type</th>
<th>Iodine Conc. mg/ml</th>
<th>Volume ml</th>
<th>Flow ml/s</th>
<th>CM Ratio</th>
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<tr>
<td>Saline</td>
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<td></td>
<td>20</td>
<td>4.9</td>
<td></td>
</tr>
</tbody>
</table>

1 of 2

*: L = 32cm, B = 18cm
By reducing the number of passes that you take of the same part of the body, you will reduce the dose. Reducing the number of phases in CT can help you reduce the dose.

How many times you scan the same body part?
How you position your patients?

It is also important to center the patient right in the center of the gantry. If you don’t center the patient right in the center of the gantry, you can increase the dose by 11-15%. This is a very common error.
Iterative reconstruction (IR) method

- **Iterative Reconstruction Software / SafeCT**: IR is the newest & effective method for CT image reconstruction.
- **Advantages** → reducing image noise, reduce patient dose by 40% to 50%.
- Faster technique, improves image quality & SNR.

*Nelson TR, 2014
http://info.atlantisworldwide.com*
Contents:

- Introduction
- Radiation dosimetry in CT
- Radiation risk associated with coronary CT angiography
- Dose reduction strategies
- Coronary CTA for paediatric patients
Paediatric patients → inherently more radiosensitive and because they have more remaining years of life during which a radiation-induced cancer could develop.

The Critical Group!
The Critical Group!

• There is a latent period following radiation exposure and the time it takes for the radiation effects to develop.

• The latent period for development of cancer following low level radiation dose is variable and can be as long as 10-30 years.

• If a person getting a CT scan at age 60, he is unlikely to develop cancer in his remaining lifetime, but children have much longer to live.

• Children’s cells are more susceptible to radiation and they are also likely to live longer than adults.
Estimated age-dependent CT doses to various organs

Estimated age-dependent doses to various organs for typical single CT scan of head (assuming the same exposure techniques for all ages)

Risk depends strongly on the age at the time of irradiation → the younger the child, the higher the potential risk

(Brenner DJ et.al., 2007)
Estimated risk of death by cancer attributable to a CT scan at different ages

Estimated lifetime CT-attributable cancer mortality risks as a function of age (for different gender)

(Brenner DJ et.al., 2007)
CCTA for Paediatric patient

Different imaging needs for paediatric patients!

Child’s cells dividing in different ways & more sensitive & susceptible to radiation risks!

(Nelson TR, 2014)
One size does not fit all...when imaging paediatric patients, radiation dose matters!
Dose reduction strategies for paediatric patient

- Children are more sensitive to radiation. So when we image, let's image gently.

- The right things to do:
  - Scan only the indicated area.
  - Selection of the kVp and mA → child size.
  - One scan (single phase) is often enough.
A well-known strategy for reducing radiation exposure for paediatric is to **decrease CT dose based on the patient’s weight** (Johnson et.al., 2012).

Appropriate radiation levels for their age and size!
Establishment of Local Diagnostic Reference Levels (DRLs)

Regularly analyse local CT dose values!
Monthly/Annual dose audit.
# National DRLs

<table>
<thead>
<tr>
<th>Examination Type</th>
<th>CTDI&lt;br&gt;\text{\textsubscript{w}}&lt;br&gt;(mGy)</th>
<th>DLP&lt;br&gt;(mGy·cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abdomen</td>
<td>12.8</td>
<td>450</td>
</tr>
<tr>
<td>Brain</td>
<td>46.8</td>
<td>1050</td>
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<tr>
<td><strong>Cardiac</strong></td>
<td><strong>11.8</strong></td>
<td><strong>870</strong></td>
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<tr>
<td>Chest</td>
<td>19.9</td>
<td>600</td>
</tr>
<tr>
<td>Pelvis</td>
<td>39.1</td>
<td>730</td>
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<tr>
<td>Spine/Musculo-skeletal</td>
<td>16.3</td>
<td>390</td>
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<tr>
<td>Thorax</td>
<td>21.3</td>
<td>420</td>
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<tr>
<td>Others</td>
<td>12.3</td>
<td>380</td>
</tr>
</tbody>
</table>

Recommended Malaysian DRLs for CT examination (MOH, 2013)
Establishment of Local Diagnostic Reference Levels (DRLs)

- **DRLs** are proposed to help manage radiation dose to patients so that the dose is commensurate with the clinical purpose (*ICRP Committee 3*).

- As recommended by MOH, the respective medical institutions are advised to obtain **individual local data** in their setup in order to compare with the national DRLs (*MOH, 2013*).
A single institution study of radiation dose received from CT imaging: A comparison to Malaysian NDRL

N D Osman¹, S B M Shamsuri¹,², Y W Tan³, M A S M Razali¹ and S M Isa¹

¹ Advanced Medical and Dental Institute, Universiti Sains Malaysia, Kepala Batas, Penang, 13200, Malaysia
² Faculty of Science, Technology, and Human Development, Universiti Tun Hussein Onn, Batu Pahat, Johor, 86400, Malaysia
³ School of Physics, Universiti Sains Malaysia, Minden, Penang, 11800, Malaysia

E-mail: noordiyana@usm.my

Abstract. Advancement of CT technology has led to an increase in CT scanning as it improves the diagnosis. However, it is important to assess health risk of patients associated with ionising radiation received from CT. This study evaluated current dose distributions at Advanced Medical and Dental Institute (AMDI), Malaysia and was used to establish Local Diagnostic Reference Level (LDRL). Dose indicators such as CT Dose Index (CTDIvol and CTDIw) and Dose-Length Product (DLP) were gathered for all routine CT examinations performed at the Imaging Unit, AMDI from January 2015 to June 2016. The first and third quartile values for each dose indicator were determined. A total of 364 CT studies were performed during that period with the highest number of cases being Thorax-Abdomen-Pelvis (TAP) study (57% of total study). The CTDIw ranged between 2.0 mGy to 23.4 mGy per procedure. DLP values were ranged between 94 mGy.cm to 1687 mGy.cm. The local dose data was compared with the national DRL to monitor the current CT practice at AMDI and LDRL will be established from the calculated third quartile values of dose distribution. From the results, some of the local dose values exceeded the Malaysian and further evaluation is important to ensure the dose optimisation for patients.
Table 2. Comparison of local CT dose data in AMDI with the reference values of NDRL.

<table>
<thead>
<tr>
<th>Examination types</th>
<th>CTDI&lt;sub&gt;w&lt;/sub&gt; (mGy)</th>
<th>% difference</th>
<th>DLP (mGy.cm)</th>
<th>% difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>This study&lt;sup&gt;a&lt;/sup&gt;</td>
<td>NDRL&lt;sup&gt;b&lt;/sup&gt;</td>
<td>This study&lt;sup&gt;a&lt;/sup&gt;</td>
<td>NDRL&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Abdomen</td>
<td>12.6</td>
<td>12.8</td>
<td>466</td>
<td>450</td>
</tr>
<tr>
<td>Brain / Head</td>
<td>49.5</td>
<td>46.8</td>
<td>995</td>
<td>1050</td>
</tr>
<tr>
<td>Cardiac</td>
<td>21.0</td>
<td>11.8</td>
<td>295</td>
<td>870</td>
</tr>
<tr>
<td>Pelvis</td>
<td>29.4</td>
<td>39.1</td>
<td>632</td>
<td>730</td>
</tr>
<tr>
<td>Spine</td>
<td>21.0</td>
<td>16.3</td>
<td>578</td>
<td>390</td>
</tr>
<tr>
<td>Thorax</td>
<td>33.8</td>
<td>21.3</td>
<td>642</td>
<td>420</td>
</tr>
</tbody>
</table>

<sup>a</sup> Local dose data in this study were set at the level of third quartile value for CTDI<sub>w</sub> and DLP.

<sup>b</sup> NDRL values are based on reference standard established by MOH Malaysia [3].

Figure 1. CTDI<sub>w</sub> (mGy) distribution.

Figure 2. Dose-length product (DLP) distribution for each CT procedure.
Take home notes!

Risks  
(radiation dose)

Benefits  
(image quality)
Thank you