Patient Dosimetry in CT: what to measure and estimate; why and how?
Disclosures

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15 Sept 2013
Patient Dosimetry in CT: what to measure and estimate; why and how?

Why

What

How: conventional CT systems

How: cone beam CDT systems

IEC methods

Other approaches

Measure versus Estimate

Summary
EMI Mark 1: 1972

water bag for bolus
4 minute scan (120 sec/image)
overnight reconstruction

80 x 80 matrix
8 grey scale (3 bit images)

Images courtesy ImPact Website (UK)
Modern helical multi-slice CT
high resolution three dimensional imaging

axial
coronal
sagittal
Nobel Prize for Medicine 1979

Allan M. Cormack

Godfrey N. Hounsfield
technology advancements have led to greater CT use
CT x-ray tube output

GE VCT 120 kV
32.3 mGy/100 mAs @ IC
600 mAs
1/6 rotation
432 mGy @ isocenter
ISL = 2.57
1.1 Gy @ skin

~60°
Radiation-induced temporary hair loss as a radiation damage only occurring in patients who had the combination of MDCT and DSA


Radiation Overdoses Point Up Dangers of CT Scans

Written by Humboldt Online Editor on 16 October 2009

New York Times
Raven Knickebocker, then an X-ray technologist at Mad River Community Hospital in Arcata, Calif., activated a CT scan 151 times on the same area of the head of 2-year-old Jacoby Roth, investigators concluded.
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Summary
A brief history of the...

Evolution of CT Scanners and Dosimetry

- First Brain CT
- First Whole Body CT
- First 4th Generation CDT
- Spiral CT
- Dual Slice CT (again)
- mA Modulation
- Mega HU x-ray tubes
- Four Slice CT
- 8 to 40 slice CT
- 64 slice CT
- Dual Source CT
- Flying focal spot
- Adaptive Dose Collimation
- Epilation caused by CT

CTDI
CTDI\textsubscript{W}
CTDI\textsubscript{VOL}
CTDI\textsubscript{FDA}

SB-1237
TG-233
TG-220
TG-200
TG-111
TG-204

Years:
- 1972
- 1974
- 1989
- 1992
- 1994
- 1995
- 1997
- 2000
- 2004
- 2006
- 2007
- 2009
- 2010
- 2013
CTDI:
Computed Tomography Dose Index

A method for describing the doses delivered by transmission x-ray computed tomography\textsuperscript{a)}

Thomas B. Shope, Robert M. Gagne, and Gordon C. Johnson

*Bureau of Radiological Health, Food and Drug Administration, 5600 Fishers Lane, Rockville, Maryland 20857*

(Received 23 September 1980; accepted for publication 3 October 1980)

II. SUGGESTED DOSE DESCRIPTOR FOR COMPUTED TOMOGRAPHY

The dose descriptor we propose is the computed tomography dose index (CTDI) denoted as $C$ and defined by

$$C = (1/T) \int_{-\infty}^{\infty} D_1(z)dz,$$  \hspace{1cm} (1)
The solid state CT detector

\[ n=16 \times 0.625 \text{ mm} = 10 \text{ mm} \]
$nT$ is the width of the x-ray beam at IC

Multiple Detector CT

Many detector arrays along $z$

fan angle

cone angle

$z$-axis
\[ CTDI_\infty = \frac{1}{nT} \int_{-\infty}^{+\infty} D(z) \, dz \]
$$CTDI_\infty = \frac{1}{nT} \int_{-\infty}^{+\infty} D(z) \, dz$$
$$CTDI_{100} = \frac{1}{nT} \int_{-50mm}^{+50mm} D(z) \, dz$$
$$\text{CTDI}_{100} = \frac{1}{nT} \int_{-50\text{mm}}^{+50\text{mm}} D(z) \, dz$$
\[ CTDI_{100} = \frac{1}{nT} \int_{-50\text{mm}}^{+50\text{mm}} D(z) \, dz \]

This equation requires table movement, either axial or helical CT scans which traverse 100 mm. It is not valid for a stationary table scan such as with CT perfusion or CT fluoroscopy.
$$C_{TDI_{100}} = \frac{1}{nT} \int_{-50\text{mm}}^{+50\text{mm}} D(z) \, dz$$
CTDI - based Dose Metrics

Adult Body Phantom
- 32 cm diameter PMMA

Head Phantom
- 16 cm diameter PMMA

Peds Body Phantom
- 100 mm pencil chamber

The Tools.......
CTDI - based Dose Metrics

The Methods........
Measuring $\text{CTDI}_{100}$ in the real world
The CTDI “Head” Phantom in position for CTDI\textsubscript{100} measurement

The CTDI “Body” Phantom in position for CTDI\textsubscript{100} measurement
CTDI - based Dose Metrics

\[
\frac{2}{3} \times \text{CTDI}_{100} \text{ peripheral }
\]

\[
+ \frac{1}{3} \times \text{CTDI}_{100} \text{ center }
\]

weighted CTDI, \( \text{CTDI}_w \)

\[
dose = \frac{1}{\text{pitch}}
\]

Volume CTDI, \( \text{CTDI}_{vol} = \frac{\text{CTDI}_w}{\text{pitch}} \)

The Mechanics

CTDI-based Dose Metrics

The CTDI$_w$ is the planar average dose to the central slice of the phantom in a series of slices spanning 100 mm.
Which scan has more “dose”?

...to first order, the dose is the same
Dose Length Product (DLP):

\[ \text{DLP} = \text{CTDI}_{\text{vol}} \times L \quad (\text{mGy} \times \text{cm}) \]

- \( \text{dose} = \frac{\text{energy}}{\text{mass}} \)
- \( \text{energy} = \text{dose} \times \text{mass} \)

\[ \text{energy imparted} = \text{dose} \cdot \rho(L \times \pi r^2) \]

DLP is related to the total energy deposited in the patient.
**Effective Dose per DLP (AAPM TG-96)**

<table>
<thead>
<tr>
<th>Region of Body</th>
<th>k (mSv/[mGy·cm])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head and neck</td>
<td>0.0031</td>
</tr>
<tr>
<td>Head</td>
<td>0.0021</td>
</tr>
<tr>
<td>Neck</td>
<td>0.0059</td>
</tr>
<tr>
<td>Chest</td>
<td>0.014</td>
</tr>
<tr>
<td>Abdomen / pelvis</td>
<td>0.015</td>
</tr>
<tr>
<td>trunk</td>
<td>0.015</td>
</tr>
</tbody>
</table>

**Effective Dose ≈ DLP × k**
The CT scanners now have a dose report that state the DLP. One can use these values with the conversion factors above to estimate the effective dose for the patient.
CTDI - based Dose Metrics
Free-in-air measurement (no phantom)

CTDIfree-in-air or CTDI_{air}
CTDI - based Dose Metrics

The Tools

The Methods

CTDI\textsubscript{100} (center & peripheral)

CTDI\textsubscript{w}

CTDI\textsubscript{vol}

CTDI\textsubscript{air}

DLP
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Summary
CTDI - based Dose Metrics

average peripheral measurement

effect of table attenuation
\[ CTDI_{100} = \frac{1}{nT} \int_{-50mm}^{+50mm} D(z) \, dz \]

\[ \chi \text{ mGy} \times 100 \text{ mm} = 100 \chi \text{ mGy.mm} \]

For a chamber reading out in air kerma:

\[ CTDI_{100} = \frac{K \times L_c}{n \times T} \]
1. exposure to kerma correction
   \[ \frac{1507.3 \text{ mR}}{114.5 \text{ mR/mGy}} = 13.16 \text{ mGy} \]

2. chamber reading air kerma
   \[ 13.16 \text{ mGy} \times 100 \text{ mm} = 1316 \text{ mGy.mm} \]

3. correction for nT
   \[ \frac{1316 \text{ mGy.mm}}{20} = 65.8 \text{ mGy (CTDI}_{100}) \]
CTDI-based Dose Metrics

Dependency on collimated beam width (nT)

\[ \varepsilon = \frac{\text{detected}}{\text{beam}} \]

Data are approximated.

Graph showing dependency on the number of detector arrays.
CTDI - based Dose Metrics

Dependency on collimated beam width (nT)

(but MDCT has reduced use of this)
GE-16 CT Scanner
UC Davis Medical Center

Scanner 2
June 8, 2006
Reference LogBook 1 page 121

Measurements made by John M. Boone, Ph.D. and Alex LC Kwan, Ph.D.

<table>
<thead>
<tr>
<th>BODY (32 cm PMMA)</th>
<th>20 mm collimation, 100 mAs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RAW DATA (mR)</strong></td>
<td><strong>0.043668 Corrected mGy / 100 mAs</strong></td>
</tr>
<tr>
<td>kVp</td>
<td>in air</td>
</tr>
<tr>
<td>80</td>
<td>180.2</td>
</tr>
<tr>
<td>100</td>
<td>328.9</td>
</tr>
<tr>
<td>120</td>
<td>507.2</td>
</tr>
<tr>
<td>140</td>
<td>718.0</td>
</tr>
</tbody>
</table>

| -6.8% Differences from IMPACT (%) | IMPACT RESULTS* mGy/100 mAs |
| kVp | in air | center | edge | kVp | in air | center | edge |
| 80  | -14.9%| -1.2%  | 13.2% | 80  | 9.2   | 1.5    | 3.3   |
| 100 | -16.0%| -11.8% | 1.9%  | 100 | 17.1  | 3.6    | 7.0   |
| 120 | -12.2%| -12.6% | -5.6% | 120 | 25.2  | 6.2    | 11.8  |
| 140 | -8.9% | -13.0% | -0.5% | 140 | 34.4  | 9.3    | 16.0  |

*Impact results are reported for 10 mm collimation, but were corrected to 20 mm by a factor 0.86

**correction of raw data includes multiplication by 100mm/20mm and division by 114.5 (cell E11)

<table>
<thead>
<tr>
<th>HEAD (16 cm PMMA)</th>
<th>20 mm collimation, 100 mAs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RAW DATA (mR)</strong></td>
<td><strong>0.043668 Corrected mGy / 100 mAs</strong></td>
</tr>
<tr>
<td>kVp</td>
<td>in air</td>
</tr>
<tr>
<td>80</td>
<td>230.6</td>
</tr>
<tr>
<td>100</td>
<td>393.9</td>
</tr>
<tr>
<td>120</td>
<td>585.9</td>
</tr>
<tr>
<td>140</td>
<td>804.8</td>
</tr>
</tbody>
</table>

| -5.6% Differences from IMPACT (%) | IMPACT RESULTS* mGy/100 mAs |
| kVp | in air | center | edge | kVp | in air | center | edge |
| 80  | -10.1%| -3.4%  | -5.0% | 80  | 11.2  | 6.1    | 6.5   |
| 100 | -8.8% | -3.7%  | -5.4% | 100 | 18.9  | 11.6   | 11.7  |
| 120 | -7.5% | -4.1%  | -4.5% | 120 | 27.7  | 18.1   | 17.9  |
| 140 | -6.8% | -4.3%  | -3.5% | 140 | 37.7  | 25.5   | 24.9  |

*Impact results are reported for 10 mm collimation, but were corrected to 20 mm by a factor 0.86

**correction of raw data includes multiplication by 100mm/20mm and division by 114.5 (cell E11)
<table>
<thead>
<tr>
<th>Scanner Group</th>
<th>KVP</th>
<th>Sub-group</th>
<th>Scanner</th>
<th>CTDI (Head, mGy/100mAs) Air</th>
<th>CTDI (Body, mGy/100mAs) Air</th>
<th>mPACT Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>GE</td>
<td>120</td>
<td>GE</td>
<td>LightSpeed Ultra</td>
<td>35.0</td>
<td>22.5</td>
<td>10.7</td>
</tr>
<tr>
<td>GE</td>
<td>140</td>
<td>GE</td>
<td>LightSpeed Ultra</td>
<td>47.4</td>
<td>31.6</td>
<td>20.5</td>
</tr>
<tr>
<td>GE</td>
<td>160</td>
<td>GE</td>
<td>LightSpeed Ultra</td>
<td>60.7</td>
<td>42.0</td>
<td>30.7</td>
</tr>
<tr>
<td>GE</td>
<td>180</td>
<td>GE</td>
<td>LightSpeed Ultra</td>
<td>74.0</td>
<td>51.7</td>
<td>40.7</td>
</tr>
<tr>
<td>GE</td>
<td>200</td>
<td>GE</td>
<td>LightSpeed Ultra</td>
<td>87.3</td>
<td>60.1</td>
<td>50.7</td>
</tr>
<tr>
<td>GE</td>
<td>220</td>
<td>GE</td>
<td>LightSpeed Ultra</td>
<td>100.7</td>
<td>73.9</td>
<td>61.7</td>
</tr>
<tr>
<td>GE</td>
<td>240</td>
<td>GE</td>
<td>LightSpeed Ultra</td>
<td>114.0</td>
<td>87.7</td>
<td>71.7</td>
</tr>
<tr>
<td>GE</td>
<td>260</td>
<td>GE</td>
<td>LightSpeed Ultra</td>
<td>127.3</td>
<td>101.9</td>
<td>81.7</td>
</tr>
<tr>
<td>GE</td>
<td>280</td>
<td>GE</td>
<td>LightSpeed Ultra</td>
<td>140.7</td>
<td>116.7</td>
<td>91.7</td>
</tr>
<tr>
<td>GE</td>
<td>300</td>
<td>GE</td>
<td>LightSpeed Ultra</td>
<td>154.0</td>
<td>131.9</td>
<td>101.7</td>
</tr>
<tr>
<td>GE</td>
<td>320</td>
<td>GE</td>
<td>LightSpeed Ultra</td>
<td>167.3</td>
<td>147.7</td>
<td>111.7</td>
</tr>
<tr>
<td>GE</td>
<td>340</td>
<td>GE</td>
<td>LightSpeed Ultra</td>
<td>180.7</td>
<td>163.9</td>
<td>121.7</td>
</tr>
</tbody>
</table>

Impactscan.org (UK)

Sue Edyvean
Patient Dosimetry in CT: what to measure and estimate; why and how?

- Why
- What
- How: conventional CT systems
- How: cone beam CDT systems (stationary table)
  - IEC methods
  - Other approaches
- Measure versus Estimate
- Summary
Toshiba Aquillion 1: 320 x 0.5 mm = 160 mm
\[ CTDI_{\infty} = \frac{1}{nT} \int_{-\infty}^{+\infty} D(z) \, dz \]

\[ \varepsilon = \frac{CTDI_{100}}{CTDI_{\infty}} \]

\[ CTDI_{100} = \frac{1}{nT} \int_{-50\text{mm}}^{50\text{mm}} D(z) \, dz \]
CTDI - based Dose Metrics

cone beam CT

100 mm

nT > 100 mm

1507.3 mR
The trouble with $\text{CTDI}_{100}$

John M. Boone$^{a)}$

Departments of Radiology and Biomedical Engineering, University of California Davis Medical Center, Ellison Building, 4860 Y Street, Suite 3100, Sacramento, California 95817

(Received 1 September 2005; revised 26 October 2006; accepted for publication 6 November 2006; published 20 March 2007)

\[ \varepsilon = \frac{\text{CTDI}_{100}}{\text{CTDI}_\infty} \]
\[ \varepsilon = \frac{CTDI_{100}}{CTDI_{\infty}} \]
\[ CTDI_{\text{free-in-air},(n\times T)} = \frac{L_c}{n \times T} \sum_{i=1}^{m} D_i \]
\[ CTDI_{\text{free-in-air,REF (eg 20mm)}} = \frac{K \times L_c}{n \times T} \]
\[ CTDI_{100,} = \frac{1}{(n \times T)_{REF}} \times \left( \int_{-50\,mm}^{+50\,mm} D_{REF}(z) \, dz \right) \times \frac{CTDI_{\text{free-in-air},n \times T}}{CTDI_{\text{free-in-air},REF}} \]
Patient Dosimetry in CT: what to measure and estimate; why and how?

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Summary
dose

position

-\text{Z} \quad \text{Z}=0 \quad +\text{Z}

100 \text{ mm ion chamber}

18 \text{ mm thimble chamber}
CT perfusion
(stationary table)

- Actual beam width
- 30–50 CT scans at the same location

- Perfusion
- Time to peak enhancement
- Blood volume
Stationary table perfusion CT ($j$ rotations)

$$\text{dose} = \text{peak dose} \times j \text{ rotations}$$

CTDI$_w$

peak dose

100 mm
Patient Dosimetry in CT: what to measure and estimate; why and how?

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Summary
In general, it is best to say that doses are estimated, and not calculated or measured. This conveys the proper notion that CT dosimetry is an imprecise science, which it is.
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Summary
The phantom is either a 16 cm diameter acrylic (head) or a 32 cm diameter (body) phantom.
CTDI is a good measure of CT dose to a large plastic phantom, but is not a stand-alone metric for patient dose

A new look at CT dose measurement: Beyond CTDI

Robert L. Dixon
Med Phys 2003

The trouble with CTDI_{100}

John M. Boone

Departments of Radiology and Biomedical Engineering, University of California Davis Medical Center, Ellison Building, 4860 Y Street, Suite 3100, Sacramento, California 95817

(Received 1 September 2005; revised 26 October 2006; accepted for publication 6 November 2006; published 20 March 2007)

Restructuring CT dosimetry—A realistic strategy for the future
Requiem for the pencil chamber

Robert L. Dixon

CT Dose Index and Patient Dose:
They Are Not the Same Thing

Experimental validation of a versatile system of CT dosimetry using a conventional ion chamber: Beyond CTDI100

Robert L. Dixon and Adam C. Ballard
Comprehensive Methodology for the Evaluation of Radiation Dose in X-Ray Computed Tomography

A New Measurement Paradigm Based on a Unified Theory for Axial, Helical, Fan-Beam, and Cone-Beam Scanning With or Without Longitudinal Translation of the Patient Table
Size Specific Dose Estimates (SSDE) in Pediatric and Adult CT Examinations
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