CT Image Quality, Radiation Dose and Clinical Applications

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Lerner College of Medicine
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Learning Objectives

- CT Image Quality Metrics
- CT Dose and Reduction Techniques
- CT Clinical Applications
CT Image Quality Metrics
CT Spatial Resolution

- Spatial resolution is the ability to resolve small but “high contrast” objects, such as bones, stent, small vessels with IV contrast.
  - In-plane (X-Y) by bar patterns or Modulation Transfer Function
  - Cross plane (Z) by Slice Sensitivity Profile or slice thickness

ACR Phantom

Modulation Transfer Function
MTF vs. Point Spread Function (PSF)

Wire Phantom

MTF

PSF

High Res

Low Res
Acquisition and Recon Parameters vs. Spatial Resolution

- Tube focal spot size
- Detector width
- Post-patient collimation
- Recon kernel
- Recon Field of View (FOV)

High Resolution CT Image of IAC
Siemens Ultra High Res Kernels

U30  U40  U80  U90
Display Image Matrix

• Defines number of voxels into which cross-section of the body is divided

• Typically square with number of elements in x and y equal to a power of 2 (e.g., 512 x 512, 1024 x 1024)
Reconstructed Field of View

• Defines in-plane (x and y) dimensions of an image
• $5\text{cm} \times 5\text{cm} \leq \text{Recon FOV} \leq 50\text{cm} \times 50\text{cm}$
• Smaller FOV improves visual resolution
CT Image Noise

Image noise = 31.6

Image noise = 10.3
CT Image Noise

- As a rule of thumb, CT image noise is a function of:

\[
noise \sim \frac{1}{\sqrt{mAs} \times \sqrt{slice\_thickness} \times \sqrt{(kVp)^n}}
\]

\[n = 2.5 \sim 3.0\]
Image noise increases significantly with high res kernels
Same Noise Mag but Different Texture

120 kV, 1000 eff mAs, B70
Noise = 16

120 kV, 10 eff mAs, B10
Noise = 16
Noise Power Spectrum (NPS)

- Noise (standard deviation) only measures the magnitude.
- Noise power spectrum measures not only the magnitude but also the spatial correlation of noise properties ("texture").
Images w/ Same noise Magnitude
Different Noise Texture

NPS for B30 and B70 Kernels

Spatial Frequency (1/mm)

NPS (μV²/mm²) / SNR

B30

B70
NPS Contains More Info

- Area under NPS curve is equal to the square of noise (magnitude)
- Mean and peak frequencies are related to the noise texture ("noise grain size").
- Fine texture usually indicates NPS has higher mean and peak frequencies

Mean freq: 3.2 lp/cm
Peak freq: 2.5 lp/cm

Mean freq: 5.4 lp/cm
Peak freq: 6.3 lp/cm
Low Contrast Resolution

- Ability to resolve low contrast objects, such as liver lesions
- mAs $\uparrow$, low contrast resolution $\uparrow$
Low Contrast Resolution

- Image thickness $\uparrow$, low contrast resolution $\uparrow$
- Smooth recon kernel -> better low contrast resolution
Slice Sensitivity Profile (SSP)

- SSP or Slice thickness is related to cross-plane resolution (or Z-axis resolution)
- Sharpness of reformat images
- Partial volume effect

SSP Phantom and SSP profile with FWHM and FWTM
Slice thickness vs. Reformat Resolution

0.625mm  
2mm  
4mm
Image thickness vs. Partial volume

0.6mm

6mm
CT Dosimetry
Computed Tomography Dose Index” (CTDI) is a standardized dose metric for CT.

- Common unit for CTDI is mGy

- CTDI is measured on 2 PMMA (Acrylic) phantoms
  - 16cm diameter “head” phantom
  - 32cm diameter “body” phantom
$\text{CTDI}_{100}$

- Using pencil ionization probe
- In axial scan mode without table movement
- Active probe length is 100mm -> $\text{CTDI}_{100}$
Weighted CTDI (CTDI\textsubscript{w})

\[ \text{CTDI}_{\text{w}} = \frac{1}{3} \text{CTDI}_{100, \text{center}} + \frac{2}{3} \text{CTDI}_{100, \text{periphery}} \]

- CTDI\textsubscript{w} represents the average dose over the entire cross-sectional area (i.e., the average dose across the field-of-view (FOV)) in the central plane of the scanned volume.
- The weighting factors of 1/3 and 2/3 approximate to the relative areas represented by the central and peripheral CTDI\textsubscript{100}. 
Volume CTDI (CTDI$_{vol}$)

- To account for the fact that, in helical CT, dose is inversely related to pitch

- CTDI$_w$ represents the average dose across the field-of-view (FOV) in the mid-plane of the scanned volume – for axial scans

- CTDI$_{vol}$ represents the average dose across the field-of-view (FOV) in the mid-plane of the scanned volume – for helical scans
Size-Specific Dose Estimate (SSDE)

\[ SSDE = CTDI_{vol} \times f(d) \]

water cylinder

for-your-child.blogspot.com

halftimefit.com

Courtesy of Dr. Xiang Li, Cleveland Clinic
Patients have equivalent SSDE
Dose Length Product (DLP)

$$\text{DLP} = \text{exposure length} \times \text{CTDIvol}$$

- DLP approximates the integrated dose along the scan range, therefore, clinically DLP is often used to indicate “total energy deposited.”
Organ Dose ($D_T$)

- A CT scan is usually a partial body exposure with dose to certain organs in the scan range. Organs may be entirely or partially irradiated.

Organs irradiated: lung, breast, heart, bones, vessels and skins
Effective Dose $E(\text{mSv})$

- Converts organ doses to an effective whole body dose
- Use tissue weighting factors from ICRP Report. 103

\[ E(\text{mSv}) = \sum_{T} W_T \times D_T \]

From ICRP Report 103 (2007)
Estimating Effective Dose

• Effective dose can be estimated using anatomic region specific conversion factors (k-factor):

\[ E(\text{mSv}) = DLP \times k \]

Table 3. Normalized effective dose per dose-length product (DLP) for adults (standard physique) and pediatric patients of various ages over various body regions. Conversion factor for adult head and neck and pediatric patients assume use of the head CT dose phantom (16 cm). All other conversion factors assume use of the 32-cm diameter CT body phantom.\(^{78,79}\)

<table>
<thead>
<tr>
<th>Region of Body</th>
<th>0 year old</th>
<th>1 year old</th>
<th>5 year old</th>
<th>10 year old</th>
<th>Adult</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head and neck</td>
<td>0.013</td>
<td>0.0085</td>
<td>0.0057</td>
<td>0.0042</td>
<td>0.0031</td>
</tr>
<tr>
<td>Head</td>
<td>0.011</td>
<td>0.0067</td>
<td>0.0040</td>
<td>0.0032</td>
<td>0.0021</td>
</tr>
<tr>
<td>Neck</td>
<td>0.017</td>
<td>0.012</td>
<td>0.011</td>
<td>0.0079</td>
<td>0.0059</td>
</tr>
<tr>
<td>Chest</td>
<td>0.039</td>
<td>0.026</td>
<td>0.018</td>
<td>0.013</td>
<td>0.014</td>
</tr>
<tr>
<td>Abdomen &amp; pelvis</td>
<td>0.049</td>
<td>0.030</td>
<td>0.020</td>
<td>0.015</td>
<td>0.015</td>
</tr>
<tr>
<td>Trunk</td>
<td>0.044</td>
<td>0.028</td>
<td>0.019</td>
<td>0.014</td>
<td>0.015</td>
</tr>
</tbody>
</table>

AAPM Report No. 96, “The measurement, Reporting, and Management of Radiation Dose in CT”
Dose Reduction Techniques

- Automatic tube current modulation (ATCM)
- Organ specific dose modulation
- Iterative Reconstruction
- Adaptive beam collimation
Conventional Beam Collimation

[Image of a diagram showing conventional beam collimation with labels for Pre-Spiral Dose, Post-Spiral Dose, Image area, and Conventional tube collimation.]

Courtesy of Siemens Healthcare, USA
Adaptive Beam Collimation

Collimator with Adaptive Dose Shield

No Pre-Spiral Dose

Image area

No Post-Spiral Dose

Adaptive Dose Shield

Courtesy of Siemens Healthcare, USA
CT Clinical Applications

- Dual Energy Imaging
- CT Lung Cancer Screening
- One heart beat Cardiac CT
- Mobile CT Stroke Unit
Dual Energy CT
Dual Energy CT

- Acquire signals containing low and high energy photons separately,
  - FastkV switching (GE)
  - Dual source (Siemens)
  - TwinBeam dual energy (Siemens)
  - Dual layer detector (Philips)

- Combining low and high energy signals using a pre-calibrated coefficients to generate material specific images and/or monochromatic images
Virtual Non-contrast (VNC) Image

140kVp w/ contrast

Water-only (renal calculi visible)

Iodine-only

Courtesy of GE Healthcare
Bone Removal

Plaque ON

Plaque ON
Monochromatic Brain Images w/ Contrast

100keV
80keV
70keV
60keV
50keV
poly

Courtesy of GE Healthcare
CT Low Dose Lung Cancer Screening (LCS)
Chest X-ray vs. CT

Chest X-ray

Chest CT

Nodule

Nodule
CT Lung Cancer Screening Scan Parameters

- **Scanner**
  - Gantry rotation period: ≤0.5s
  - Recon Slice thickness: ≤2.5mm (≤1.0mm is recommended)
  - No. of physical detector rows: ≥16 rows are preferred

- **Low Radiation Dose**
  - CTDIvol <3mGy for a standard sized patient (5’7” and 155lbs)
  - CTDIvol for smaller patients and for larger patients
  - Use Automatic Exposure Control system if available
  - Manual technique charts to adjust mA and/or kVp based on patient size
# AAPM CT Lung Screening Protocols (GE Protocols)

<table>
<thead>
<tr>
<th></th>
<th>LightSpeed 16 BrightSpeed 16</th>
<th>Optima 680</th>
<th>LightSpeed VCT</th>
<th>Discovery CT750 HD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scan Type</strong></td>
<td>Helical</td>
<td>Helical</td>
<td>Helical</td>
<td>Helical</td>
</tr>
<tr>
<td><strong>Rotation Time (s)</strong></td>
<td>0.5</td>
<td>0.6</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Beam Collimation (mm)</strong></td>
<td>10/20</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td><strong>Detector Configuration</strong></td>
<td>16x0.625/16x1.25</td>
<td>64x0.625</td>
<td>64x0.625</td>
<td>64x0.625</td>
</tr>
<tr>
<td><strong>Pitch</strong></td>
<td>1.375</td>
<td>1.375</td>
<td>0.969</td>
<td>0.969</td>
</tr>
<tr>
<td><strong>Speed (mm/rot)</strong></td>
<td>13.75/27.50</td>
<td>55.0</td>
<td>19.375</td>
<td>39.37</td>
</tr>
<tr>
<td><strong>kV</strong></td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td><strong>mA</strong></td>
<td>60</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td><strong>SFOV</strong></td>
<td>Large Body</td>
<td>Large Body</td>
<td>Large Body</td>
<td>Large Body</td>
</tr>
<tr>
<td><strong>CTDvol</strong></td>
<td>2.3/2.0 mGy</td>
<td>1.8 mGy</td>
<td>1.9 mGy</td>
<td>1.9 mGy</td>
</tr>
</tbody>
</table>

## RECON 1

<table>
<thead>
<tr>
<th>Plane</th>
<th>Axial</th>
<th>Axial</th>
<th>Axial</th>
<th>Axial</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Algorithm</strong></td>
<td>Bone or Lung</td>
<td>Bone or Lung</td>
<td>Bone or Lung</td>
<td>Bone or Lung</td>
</tr>
<tr>
<td><strong>Recon Mode</strong></td>
<td>Full</td>
<td>Full</td>
<td>Full</td>
<td>Full</td>
</tr>
<tr>
<td><strong>Thickness (mm)</strong></td>
<td>1.25</td>
<td>1.25</td>
<td>1.25</td>
<td>1.25</td>
</tr>
<tr>
<td><strong>Interval (mm)</strong></td>
<td>1.25</td>
<td>1.25</td>
<td>1.25</td>
<td>1.25</td>
</tr>
<tr>
<td><strong>ASIR (if used)</strong></td>
<td>SS50</td>
<td>SS50</td>
<td>SS50</td>
<td>SS50</td>
</tr>
</tbody>
</table>

## RECON 2

<table>
<thead>
<tr>
<th>Plane</th>
<th><strong>Axial DMPR-create Sag/Cor reformats</strong></th>
<th><strong>Axial DMPR-create Sag/Cor reformats</strong></th>
<th><strong>Axial DMPR-create Sag/Cor reformats</strong></th>
<th><strong>Axial DMPR-create Sag/Cor reformats</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Algorithm</strong></td>
<td>Bone or Lung</td>
<td>Bone or Lung</td>
<td>Bone or Lung</td>
<td>Bone or Lung</td>
</tr>
<tr>
<td><strong>Recon Mode</strong></td>
<td>Full</td>
<td>Full</td>
<td>Full</td>
<td>Full</td>
</tr>
<tr>
<td><strong>Thickness (mm)</strong></td>
<td>0.625</td>
<td>0.625</td>
<td>0.625</td>
<td>0.625</td>
</tr>
<tr>
<td><strong>Interval (mm)</strong></td>
<td>0.625</td>
<td>0.625</td>
<td>0.625</td>
<td>0.625</td>
</tr>
<tr>
<td><strong>ASIR (if used)</strong></td>
<td>SS50</td>
<td>SS50</td>
<td>SS50</td>
<td>SS50</td>
</tr>
</tbody>
</table>

Cardiac Imaging within A Single Heartbeat
Single Heartbeat Cardiac Imaging

- Wide area CT detector
- Dual source CT for exceptional temporal resolution
- High pitch spiral/helical scan mode
Single Heartbeat cardiac CT w/o Beta Blocker

12cm
Dual Source Recon

Temporal Resolution: \[
\frac{0.25 \text{s}}{\sim 4} = 63 \text{ ms}
\]

Courtesy of Siemens Healthcare, USA
High Pitch Flash Mode

- Single source CT spiral pitch <1.5
- Dual source CT spiral pitch ~3.2!
- Table speed up to 737 mm/s (Siemens Force).

Data gap from one tube is filled in by the data from 2nd tube.
Mobile Stroke CT Unit: Treatment on the Road
Stroke is the 5th leading cause of death in the U.S.

It is the No. 1 cause of disability in the U.S.

1 in 5 women and 1 in 6 men will have a stroke in their lifetime.

Courtesy of Stacey Winners, Cleveland Clinic
**Time is Brain!**

<table>
<thead>
<tr>
<th></th>
<th>Neurons Lost</th>
<th>Synapses Lost</th>
<th>Accelerated Aging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Per Stroke</td>
<td>1.2 billion</td>
<td>8.3 trillion</td>
<td>36 yrs</td>
</tr>
<tr>
<td>Per Hour</td>
<td>120 million</td>
<td>830 billion</td>
<td>3.6 yrs</td>
</tr>
<tr>
<td>Per Minute</td>
<td>1.9 million</td>
<td>14 billion</td>
<td>3.1 weeks</td>
</tr>
<tr>
<td>Per Second</td>
<td>32,000</td>
<td>230 million</td>
<td>8.7 hrs</td>
</tr>
</tbody>
</table>

(Total number of neurons in the average human brain is 130 billion)

*Stroke 2006;37:263-266*
TIME GOALS

Door to physician
10 minutes
Door to neurologist
15 minutes
Door to CT complete
25 minutes
Door to CT read
45 minutes
Door to needle
60 minutes

Stroke 2013;44:870-987
## Cleveland Clinic Stroke System (Pre-Mobile Stroke)

### Devastating Problem
- **Yearly Discharge Volume**
  - Cuyahoga County: 5,600

<table>
<thead>
<tr>
<th>Hospital Type</th>
<th>Discharge Volume</th>
<th>Vol inc past 6 yrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC Main</td>
<td>1,600</td>
<td>+10%</td>
</tr>
<tr>
<td>Rest of CCHS</td>
<td>1,400</td>
<td></td>
</tr>
<tr>
<td>UH main</td>
<td>1,200</td>
<td></td>
</tr>
</tbody>
</table>

### CC Slow to Improve

<table>
<thead>
<tr>
<th>Hospital</th>
<th>IVtPA delivery rate</th>
<th>Door to Drug in 60 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hosp A</td>
<td>17%</td>
<td>56</td>
</tr>
<tr>
<td>Hosp B</td>
<td>10%</td>
<td>67</td>
</tr>
<tr>
<td>Hosp C</td>
<td>11%</td>
<td>109</td>
</tr>
<tr>
<td>Hosp D</td>
<td>4%</td>
<td>107</td>
</tr>
<tr>
<td>Hosp E</td>
<td>7%</td>
<td>74</td>
</tr>
<tr>
<td>Hosp F</td>
<td>6%</td>
<td>-</td>
</tr>
<tr>
<td>Hosp G</td>
<td>18%</td>
<td>78</td>
</tr>
<tr>
<td>Hosp H</td>
<td>10%</td>
<td>88</td>
</tr>
<tr>
<td>Hosp I</td>
<td>0%</td>
<td>-</td>
</tr>
</tbody>
</table>
**Mobile Stroke Unit: Diagnosis and Emergency Care**

- Don’t wait for the patient to go to ER
- Bring the ER to the patient (CT and stroke expertise)
- Initiate treatment at the scene
  - Onboard Staff: EMT, Paramedic, CT Technologist, Critical Care RN and Virtual Stroke Neurologist enablement
- Dramatically cut time-to-treatment decisions
Mobile Stroke Unit Operation

Courtesy of Stacey Winners, Cleveland Clinic
Cleveland Clinic Telestroke (First 100 patients treated)

<table>
<thead>
<tr>
<th>Variable</th>
<th>MSTU (n = 100)</th>
<th>Controls (n = 56)</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, median (IQR), y</td>
<td>62 (53-76)</td>
<td>64 (57-79)</td>
<td>.22</td>
</tr>
<tr>
<td>Female sex, No. (%)</td>
<td>54 (54.0)</td>
<td>32 (57.1)</td>
<td>.70</td>
</tr>
<tr>
<td>Race/ethnicity, No. (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>African American</td>
<td>63 (63.0)</td>
<td>38 (67.9)</td>
<td>.12</td>
</tr>
<tr>
<td>Non-Hispanic white</td>
<td>29 (29.0)</td>
<td>9 (16.1)</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>8 (8.0)</td>
<td>7 (12.5)</td>
<td></td>
</tr>
<tr>
<td>Initial National Institutes of Health Stroke Scale score, median (IQR)</td>
<td>6.0 (2-12)</td>
<td>6.5 (2-13)</td>
<td>.70</td>
</tr>
<tr>
<td>IV-tPA, No. (%)</td>
<td>16 (16.0)</td>
<td>13 (23.2)</td>
<td>.30</td>
</tr>
<tr>
<td>Process time, median (IQR), min</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MSTU activation to scene arrival</td>
<td>12 (8-14)</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>On-scene time until entry into the MSTU</td>
<td>8 (5-11)</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Door to CT completion</td>
<td>13 (9-21)</td>
<td>18 (12-26)</td>
<td>.003</td>
</tr>
<tr>
<td>Door to CT read</td>
<td>25 (20-29)</td>
<td>25 (19-35)</td>
<td>.59</td>
</tr>
<tr>
<td>Door to international normalized ratio result</td>
<td>13 (7-18)</td>
<td>44 (36-61)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Door to IV-tPA</td>
<td>32 (24-47)</td>
<td>58 (53-68)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Door to video log-in</td>
<td>11 (7-17)</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Video duration</td>
<td>20 (14-27)</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Total MSTU use from activation until arrival at destination hospital per episode</td>
<td>86 (78-93)</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>