Limits of Dose Reduction in CT: How low is too low?

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Why do we need to reduce radiation dose?

380 mA

70 mA
18% of dose
AJR January 2008: 190

130 mAs
40 mAs*
20 mAs*
Karmazyn, B et al. AJR January 2009
Qualitative preference ≠ performance

Image quality changes monotonically with dose
Lower dose produces lower IQ
How much IQ is good enough?
How can we objectively measure IQ?

Outlook

- Imaging provides a clinical benefit:
  - Image quality
  - Universally-appreciated
  - Illusive to define and measure
- Imaging involves a level of “cost”
  - Radiation dose:
    - Universally-depreciated
    - Unclear what to reduce and by how much

Outlook

- We cannot optimize what we cannot define or measure
- We cannot optimize dose in isolation from image quality
How can we determine the appropriate dose level?

1. Reasonable measures of radiation burden—estimated probability of harm
2. Reasonable measures of image quality—needed information for effective clinical management
3. Justified balance btw the two by targeted adjustment of system settings
4. Standardization and consistent implementation of the process

What is image quality?

- Diagnostic accuracy
  - Expensive
  - Impractical given the extent and variability of technologies
- Image esthetics
  - Subjective and qualitative
  - Not necessarily reflective of diagnostic performance

1. The “risk”
2. The “benefit”
3. The “balance”
4. Implementation
What is image quality?

- Physical metrics
  - Convenient and practical
  - Limited in scope, but
  - Effective if related to diagnostic performance under qualified conditions

 1. CNR
2. Model observer metrics
3. Quantitative metrics

CNR

- Related to detectability for constant resolution and noise texture (Rose, 1948)
- 1st order approximation of image quality
- Task-generic

\[ CNR = \frac{O_t - O_B}{\sigma_B} \]

Why CNR is not enough

<table>
<thead>
<tr>
<th>Parameters that affect detectability</th>
<th>Parameters that CNR considers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Contrast</td>
<td>1. Contrast</td>
</tr>
<tr>
<td>2. Lesion size</td>
<td>2. Noise magnitude</td>
</tr>
<tr>
<td>3. Lesion shape</td>
<td></td>
</tr>
<tr>
<td>4. Lesion edge profile</td>
<td></td>
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<tr>
<td>5. Noise magnitude</td>
<td></td>
</tr>
<tr>
<td>6. Noise texture</td>
<td></td>
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<tr>
<td>7. Resolution</td>
<td></td>
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<tr>
<td>8. Viewing distance</td>
<td></td>
</tr>
<tr>
<td>9. Display size</td>
<td></td>
</tr>
</tbody>
</table>
Why CNR is not enough

Noise texture vs kernel

Texture similarity
Methods to measure detectability

Parameters that affect detectability

1. Contrast
2. Lesion size
3. Lesion shape
4. Lesion edge profile
5. Noise magnitude
6. Noise texture
7. Resolution
8. Viewing distance
9. Display size

Model observers

Resolution and contrast transfer \times Attributes of image feature of interest

Image noise magnitude and texture
Model observers

Fisher-Hotelling observer (FH)
\[
(d_{FH})^2 = \int \int \frac{MTF^2(u,v)W_u^2(u,v)NPS(u,v)}{NPS(u,v)} dudv
\]

Non-prewhitening observer (NPW)
\[
(d_{NPW})^2 = \int \int MTF^2(u,v)W_u^2(u,v)NPS(u,v)dudv
\]

NPW observer with eye filter (NPWE)
\[
(d_{NPWE})^2 = \int \int \frac{MTF^2(u,v)W_u^2(u,v)E^2(u,v)\delta(u,v)\delta(v,v)}{MTF^2(u,v)W_u^2(u,v)NPS(u,v)dudv}
\]

Task functions

- Small feature with iodine
- Large feature with iodine
- Small feature no iodine
- Large feature no iodine

Task function plots for different spatial frequencies and kVp values.
Validation of model observers

NPWE best matched observer performance — for FBP, across different doses and tasks

Richard, Li, Samei, SPIE 2011

Duke-UMD-NIST study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>GE Discovery CT 750 HD</th>
<th>Siemens Flash</th>
<th>Philips ICT</th>
</tr>
</thead>
<tbody>
<tr>
<td>kVp</td>
<td>120</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Rotation time</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>SFOV</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>DFOV</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Recon Algorithm</td>
<td>FBP Standard / ASIR(_a) / B31f / 120f Safire 3</td>
<td>B / iDose5</td>
<td></td>
</tr>
<tr>
<td>Recon Mode</td>
<td>Helical</td>
<td>Helical</td>
<td>Helical</td>
</tr>
<tr>
<td>Collimation</td>
<td>0.625</td>
<td>0.6</td>
<td>0.625</td>
</tr>
<tr>
<td>Pitch</td>
<td>0.984</td>
<td>1</td>
<td>0.93</td>
</tr>
<tr>
<td>Slice Thickness</td>
<td>1.25</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Dose levels: 20, 12, 7.2, 4.3, 1.6, 0.9 mGy
For anonymity will be referred to as vendor A, B, and C

Observer study design
Observer study design

- 3 scanner models
- 3 dose levels (out of 7)
- 2 reconstruction algorithms
- 10 slices
- x 5 repeated exams
- Total of 900 images

12 expert observers from two institutions
2AFC with 10,800 images
AUC converted to d’
Performance vs image noise, eg 1

- IR gives lower performance (AUC) for a given noise level

![Graph 1](chart1)

Performance vs image noise, eg 2

- IR gives lower performance (AUC) for a given noise level

![Graph 2](chart2)

Model observer qualifications

- Task-based
  - Requires task definition
  - Requires generalization for optimizing task-generic systems
- Non-linear systems require prescribed evaluation conditions
  - eg, using contrast and noise relevant to the targeted task
Resolution and noise, eg 1

Comparable resolution

Lower noise but different texture

Resolution and noise, eg 2

Higher resolution

Lower noise but different texture

Mercury Phantom

Duke University
Mercury Phantom

- Three tapered, four cylindrical regions of polyethylene (Diameters: 16, 23, 30, 37 cm)
- Cylindrical inserts
  - air, polystyrene, acrylic, teflon
  - different concentration of iodinated targets

imQuest
(image quality evaluation software)

HU, Contrast, Noise, CNR, MTF, NPS, and d' per patient size, mA modulation profile

IQ vs dose
How much can IR reduce dose?

**Vendor A**
- Default clinical protocol at 12 mGy
- 23% dose reduction

**Vendor B**
- Default clinical protocol at 12 mGy
- 6% dose reduction

**Vendor C**
- Default clinical protocol at 12 mGy
- 33% dose reduction
Task function ($W_{task}$):
Virtual model, task characteristics

- "Designer nodule*"
  
  \[ C(r) = C_{max} (1 - \left( \frac{r}{R} \right)^2) \]

- Noise free background

Task function ($W_{task}$):
Virtual model, task characteristics

<table>
<thead>
<tr>
<th>Size</th>
<th>Lesion diameter (mm)</th>
<th>Task function ($W_{task}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lesion concentration</td>
<td>(5, 7.5, 10, 12.5, 15 mm)</td>
<td>(100, 150, 200, 250, 300 HU)</td>
</tr>
</tbody>
</table>

$d'$ for FBP and IRs

SAFIRE5 > SAFIRE3 > IRIS > FBP
AUC vs. dose

Dose reduction w/ IR vs task

AUC threshold = 0.9 : Dose reduction potential (relative value with respect to FBP) for a medium size patient

Quantitative IQ
Conclusions

- Quality is paramount
- Dose reduction
  - Is possible BUT requires science
  - Requires surrogates of image quality
    - Task- and indication-specific
    - Protocol-specific
    - Patient-specific
  - Requires surrogates of dose
    - Individualized
    - Scalar
    - Cross-modality

Conclusions

- Quality-dose gradient may be used as a basis for dose setting and reduction
- Dose operating point is a more important target to aim than percent dose reduction
  - Iso-gradient operating points for targeted indications

Conclusions

- Iterative recons and post-processing
  - Significant dose reduction
  - Different noise texture than FBP
  - Resolution dependent on contrast, noise
  - Highly implementation-dependent
  - Effective use requires 2nd-order image quality metrology