State of the art CT dose reduction and protocol optimization approaches for children

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COI

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  – CONNECT
  – Clarity Pharmaceuticals
Purpose

• Innovation in diagnostic CT technology and protocol development has led to significantly reduced pediatric patient dose levels

• This talk will discuss:
  – the key technologies that provide dose reduction
  – use of figure of merits (FOM) for image quality optimization
  – the effect of new, deep learning, CT reconstruction algorithms on image quality and patient dose reduction
Historical Perspective

- Pediatric sensitivity to radiation
  - It has been 20 years since Hall’s paper

Lessons we have learned from our children: cancer risks from diagnostic radiology

- Pediatric protocols have evolved
- Dose reduction has been significant
Appropriateness

• #1 best dose reduction method:
  – Only scan when medically indicated!

• ACR appropriateness criteria
  – Physician/physics committee
  – Indication specific
    • Rank imaging modalities
    • Provides a dose estimate

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Variation 2:
Left lower quadrant pain. Suspected complications of diverticulitis.

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Appropriateness Category</th>
<th>Relative Radiation Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT abdomen and pelvis with IV contrast</td>
<td>Usually Appropriate</td>
<td>★★★</td>
</tr>
<tr>
<td>CT abdomen and pelvis without IV contrast</td>
<td>May Be Appropriate</td>
<td>★★</td>
</tr>
<tr>
<td>CT pelvis with bladder contrast (CT cystography)</td>
<td>May Be Appropriate</td>
<td>★★★★</td>
</tr>
<tr>
<td>MRI abdomen and pelvis with and without IV contrast</td>
<td>May Be Appropriate</td>
<td>★★</td>
</tr>
<tr>
<td>Fluoroscopy contrast enema</td>
<td>May Be Appropriate</td>
<td>★★★★</td>
</tr>
<tr>
<td>Fluoroscopy cystography</td>
<td>May Be Appropriate</td>
<td>★★★</td>
</tr>
<tr>
<td>US abdomen transabdominal</td>
<td>May Be Appropriate</td>
<td>★★</td>
</tr>
<tr>
<td>MRI abdomen and pelvis without IV contrast</td>
<td>May Be Appropriate</td>
<td>★★</td>
</tr>
<tr>
<td>CT abdomen and pelvis without and with IV contrast</td>
<td>Usually Not Appropriate</td>
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</tr>
<tr>
<td>Radiography abdomen and pelvis</td>
<td>Usually Not Appropriate</td>
<td>★★★</td>
</tr>
<tr>
<td>US pelvis transvaginal</td>
<td>Usually Not Appropriate</td>
<td>★★</td>
</tr>
</tbody>
</table>

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www.acr.org/Clinical-Resources/ACR-Appropriateness-Criteria
Appropriateness

• How is this applicable in RT?
  – It is not a question of if a patient needs a CT but how many

  – Do it right the first time: set the right dose!
    • Too low of dose usually equals non diagnostic exams which lead to repeat exams
    • Carefully position and double check settings
Appropriateness

• How is this applicable in RT?
  – Follow up CTs
    • Is surveillance necessary?
    • How often should these occur?
    • Can follow up be reasonably be performed w/ MRI?

90% cured
Most relapses are salvaged
All relapsed patients were symptomatic and didn’t require CT surveillance for detection
Appropriateness

– Follow up CTs

Relapsed patients only have a 10% salvage rate
Patients' w/o thoracic disease at diagnosis were otherwise symptomatic

– Reduction or removal of chest CT for surveillance leads to 35-40% dose reduction
Tube Current Modulation

• The #2 best dose reduction methodology in CT
Organ Dose Modulation

- Organ dose modulation reduces mA over anterior portion of the body
  - Used to reduce eye lens, thyroid, and breast dose
  - Used along with TCM for additional dose reduction NO IQ PENALTY

mA reduced
Centering Patient

- Affects patient dose when using TCM
  - Patients lower in the gantry lead to beam hardening and photon starvation artifacts

Images belong to Timothy Szczykutowicz, PhD
Barreto et al. JACMP 2019 20(6); 141-151
Centering Patient

• How is this applicable in RT?
  – May be difficult to find a patient’s actual center
    • Due to immobilization devices
    • OR nontypical supine positions

Centering Patient

- Patient centering verification based on attenuation map
  - Some CT vendors will allow a single click move to center
  - Others require technologists' manual intervention
Centering Patient

• AI algorithms + camera
  – Visual light based cameras identify anatomical landmarks
  – Provide centering & position guidance
  – Consistent scan coverage
    • Appropriate scan coverage helps reduce unnecessary patient dose
Patient Size

- Same age patients vary dramatically in size
  - Abdomen of smallest 17-yr-old and largest 3-year-old are same size
  - Use patient cross sectional size not age or even weight when setting protocols
Patient Size

• Use of scan projection radiograph (SPR) to set protocols
  – Measure patient attenuation or “size”
  – Protocol selected based on measured size

• Use of SSDE to better approximate patient dose
  – SSDE is calculated for body (TG 204 & 220) and the head (TG 293)

\[
SSDE = CTDI_{\text{vol}} \cdot f_{\text{size}}
\]

  – Where \( f_{\text{size}} \) can be found by measuring patient attenuation or effective dia.
Low kV Imaging

- Why do we use low kV imaging in Radiology?
  - Lower radiation dose to the patient
  - Better tissue contrast differentiation
  - Why does the dose go down?
    - Dose increases/decreases linearly with mA, but quadratically with kV
    - If we reduced kV by 40: \( \left( \frac{80 \text{ kV}}{120 \text{ kV}} \right)^2 \) we get 56% dose reduction
    - If we reduce mA by 40: \( \left( \frac{80 \text{ mA}}{120 \text{ mA}} \right) \) we get 33% dose reduction

Remember:
Changing mA affects dose/noise
Changing kV affects dose/noise, image contrast, AND CT #
Low kV Imaging

- Lower kV requires high mAs capacity
- Modern scanners use high tube current (e.g., 1200 mA) w/ low kV
- Deliver lower dose for all patient sizes
Low kV Imaging

• Lower kV requires more mAs for similar exposure/noise
  – What is the correct mAs/eff mAs

• Don’t match noise, match CNR!
  – CNR improves with lower kV even though noise increases
  – Noise may be higher at lower kV than at 120 kV

120 kV
31% dose reduction
Fletcher, AAPM 2010
Yu et al. Med Phys 57(1) 2010: 234-43
Low kV Imaging

- **Rule of thumb**
  - **Routine body imaging @ 70 kV**
    - < 30 cm AP+LAT (CCHMC)
    - Typically, neonates (< 15 kg)

  - **Routine body imaging @ 80 kV**
    - 30-60 cm AP+LAT (CCHMC)
    - Typically, toddlers to large teenagers

  - **Routine body imaging @ 100 kV**
    - > 60 cm AP+LAT (CCHMC)
    - Typically, large teenagers young adults

- **Rule of thumb**
  - **Routine imaging @ 100 kV**
    - Heads < 5 years old

  - **Routine imaging @ 120 kV**
    - Heads > 5 years old
Low kV Imaging

• Lower kV protocols may lead to lower IV contrast
  – This is largely true for all pediatric patients
  – Limited for adults
Low kV Imaging

• How is this applicable in RT?
  – When changing kV, CT number changes for high attenuating material
    • Bone & contrast infused tissues
  – Less change for soft tissue
    • Water and Air CT #s stay the same for all kV’s

  – Minimize CT # changes to keep changes in Tx dose by <1%*
    • Changes in soft tissue #s are more detrimental to Tx doses than to bone
    • Suggest that CT # changes be kept to:
      – ± 20 HU for soft tissue &
      – ± 50 HU for the lung and bone

*Davis et al. BJR 2017 90(1076):20160406
Low kV Imaging

– Suggest that CT # changes be kept to:
  • ± 20 HU for soft tissue &
  • ± 50 HU for the lung and bone

*Davis et al. BJR 2017 90(1076):20160406
CT Reconstruction Timeline

1971
First Clinical CT


1971 ART

FBP

Key
- Statistical Iterative recon (IR)
- Hybrid: Statistical/Model-based IR
- Model-based IR
- Deep Learning IR

2008
GE ASiR

2009
GE VEO

2010
Canon ADIR

2012
Canon ADIR3D

2014
Siemens ADMIRE

2016
Canon FIRST

2009
Siemens IRIS

2010
Siemens SAFIRE

2013
Philips iDose^4

2019
Canon AiCE

2017
AlgoMedica PixelShine

Image Reconstruction - Options

FBP

SBIR

MBIR

DLIR

CT DLIR-CCHMC Experience

• How is this applicable in RT?
  – No measurable difference in CT # between DLIR and IR
  – Noise reduction, CNR improvement do not affect dose planning accuracy
  – Additionally: shown to improve organ segmentation time/accuracy

Deep learning–based image quality improvement for low-dose computed tomography simulation in radiation therapy

Deep Learning: A Review for the Radiation Oncologist
CT DLIR-CCHMC Experience

• Two vendors, two installs, two years apart
  – Canon’s AiCE installed on Aquilion One Genesis
  – GE’s TrueFidelity installed on Revolution Apex

• Two different approaches to implement DLIR
  – AiCE install occurred first (2019)
  – We needed to sort through all the reconstruction options
    • Learn radiologist preference(s)
    • Test for diagnostic confidence
Canon’s AiCE

AIDR3D

Body Sharp Mild
Body Sharp Standard
Body Sharp Strong

Body Mild
Body Standard
Body Strong
GE’s TrueFidelity

FBP

ASiR-V 50%

Low

Medium

High
GE’s TrueFidelity

FBP

ASiR-V 50%

Low

Medium

High
Objective Observer Preference

• To learn radiologist preference(s) & test for diagnostic confidence

  – We selected a variety of patient ages/sizes for reconstruction
    • Total was ~130 exams
     – Each patient was reconstructed using clinical SBIR + 6 DLIR options

  – Each exam was evaluated
    1. Mathematical observer/rater [using a non-prewhitening-matched mathematical-observer model with eye filter (d’_{NPWE})]
    2. Human observer/rater
    3. Took all data and did an ROC analysis
Objective Observer Preference

- Objective model: non-prewhitening matched detection index observer model ($d'_{NPWE}$):

\[
d'_{NPWEi} = \frac{2\pi \cdot \int_{0}^{Nyquist} |W(f)|^2 \cdot TTF(f)^2 \cdot E(f)^2 \cdot df}{2\pi \cdot \int_{0}^{Nyquist} [\|W(f)\|^2 \cdot TTF(f)^2 \cdot E(f)^4 \cdot NPS(f) + \|N(f)\| \cdot NPS(f)] df}
\]

- Eye Function: models the eye response to spatial freq

\[
E(f) = \rho^{1.5} \cdot e^{-C \cdot \rho^2}; \quad \rho = f \cdot \frac{\pi}{180} \cdot \frac{d_v \cdot SFOV}{DFOV(cm)}
\]

- $d_v = 50 \text{ cm}$ & $C = 3.22^*$


Objective Observer Preference

- Objective model: non-prewhitening matched detection index observer model ($d'_{NPWE}$):

$$d'_{NPWEi} = \frac{\left[2\pi \cdot \int_0^{\text{Nyquist}} |W(f)|^2 \cdot TTF(f)^2 \cdot E(f)^2 \cdot df\right]^2}{2\pi \cdot \int_0^{\text{Nyquist}} \left[|W(f)|^2 \cdot TTF(f)^2 \cdot E(f)^4 \cdot NPS(f) + N(f) \cdot NPS(f)\right] df}$$

- $W(f)$ is the task function, i.e., the Fourier transform of the signal to be detected
  - Circular objects ranging from 0.5 to 10 mm
Objective Observer Preference

- Noise Power Spectrum \([\text{NPS}(f)]\)
  - Patient images imported into IMQUEST, Duke University

\[
d'_{\text{NPWEi}} = \frac{\left[ 2\pi \cdot \int_{0}^{\text{Nyquist}} |W(f)|^2 \cdot TTF(f)^2 \cdot E(f)^2 \cdot df \right]^2}{2\pi \cdot \int_{0}^{\text{Nyquist}} \left[ |W(f)|^2 \cdot TTF(f)^2 \cdot E(f)^4 \cdot \text{NPS}(f) + N(f) \cdot \text{NPS}(f) \right] df}
\]
Objective Observer Preference

- Objective model: non-prewhitening matched detection index observer model ($d'_{NPWE}$):

$$d'_{NPWEi} = \frac{\left[2\pi \cdot \int_0^{Nyquist} |W(f)|^2 \cdot TTF(f)^2 \cdot E(f)^2 \cdot df\right]^2}{2\pi \cdot \int_0^{Nyquist} [|W(f)|^2 \cdot TTF(f)^2 \cdot E(f)^4 \cdot NPS(f) + N(f) \cdot NPS(f)] \cdot df}$$

- $N(f)$ is a scalar to model the human inefficiency caused by cognitive inconsistency
  - Defined as 60% of NPS based on prior studies*

Objective Observer Preference

- Task Transfer Function \([\text{TTF}(f)]\)
  - CatPhan 600 Phantom imported into IMQUEST, Duke University

\[
d'_{\text{NPWEi}} = \frac{2\pi \cdot \int_{0}^{\text{Nyquist}} |W(f)|^2 \cdot \text{TTF}(f)^2 \cdot E(f)^2 \cdot df}{2\pi \cdot \int_{0}^{\text{Nyquist}} [\|W(f)\|^2 \cdot \text{TTF}(f)^2 \cdot E(f)^4 \cdot \text{NPS}(f) + N(f) \cdot \text{NPS}(f)] df}
\]
Objective Observer Preference

- Non-prewhitening matched detection index observer model ($d'_{NPWE}$)
  - Used as a metric of SNR
- Use $d'_{NPWE}$ to calculate an area under the curve ($A_z$) score

$$A_z = \frac{1}{2} \cdot \left[ 1 + \frac{2}{\sqrt{\pi}} \cdot \int_0^{d'_{NPWEi}/2} e^{-x^2} \, dx \right]$$

- Used as a metric for detection accuracy
  - Calculated at each object size (0.5 to 10 mm)
  - Calculated at each contrast difference level (50 to 350 HU; increments of 100 HU)
Mathematical Evaluation

• Mathematical observer study
  – AUC scores normalized to AIDR3D (SBIR)
    • 5mm thick images
  – AUC scores averaged over all patients
  – Results:
    • DLIR > MBIR > SBIR
    • DLIR(0.5 mm) > SBIR(5 mm)

Brady et al. Radiology 2020 298(1); doi.org/10.1148/radiol.2020202317
22-year-old woman with flank pain. Axial and coronal reformatted images reconstructed with iterative reconstruction (a and b) and deep learning reconstruction (c and d) show multiple calculi in both kidneys. One of the two stones in the upper pole of the left kidney is not visible in the axial image reconstructed using iterative reconstruction (a) and is visible on the deep learning reconstruction image (white arrow in c). All stones are visible on both reconstructions in the coronal plane. Note the decreased image noise in the deep learning reconstruction image.
Observer Preference

- Is there a preference for the use of DLIR by patient size/weight?

- When considering all aspects of the image, in a blinded observer study, the participants demonstrated DLIR preference by patient weight.
Conclusions

• Use tube current modulation!
  – Use organ dose modulation if available

• Center your patients

• Create size-based protocol

• Reduce kV where possible (be careful of CT # change)
  – Dose reduction & CNR improvement
  – Potential reduction of IV/oral contrast concentration

• Adopt DLIR when possible