Summary and Outlook of “How Low Can CT Dose Go”? 

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Total Dose Reduction
Additionally Possible Compared to Today’s CTs

- **Risk-specific AEC (Joscha Maier)**
  - about 10%, depending on the tube voltage

- **Optimized spectra (Michael McNitt-Gray)**
  - 20% to 50% with Sn prefilters for unenhanced depending on object size
  - ??? for enhanced scans

- **Dynamic bowtie (Grace Gang)**
  - 27% to 50%

- **Photon counting:**
  - ???

- **Deep learning instead of iterative recon**
  - ???
Dose Reduction by Patient-Specific Tin or Copper Prefilters\textsuperscript{1,2}

<table>
<thead>
<tr>
<th></th>
<th>Child (15 cm × 10 cm)</th>
<th>Adult (30 cm × 20 cm)</th>
<th>Obese (50 cm × 40 cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basis (no filter)</td>
<td>30 mAs</td>
<td>100 mAs</td>
<td>600 mAs</td>
</tr>
<tr>
<td>Soft tissue, Sn</td>
<td>0.8 mm / 5000 mAs / 15% → 17%</td>
<td>1.6 mm / 5000 mAs / 33% → 34%</td>
<td>1.5 mm / 5000 mAs / 48% → 57%</td>
</tr>
<tr>
<td>Soft tissue, Cu</td>
<td>1.7 mm / 5000 mAs / 16% → 17%</td>
<td>4.5 mm / 5000 mAs / 33% → 34%</td>
<td>4.5 mm / 5000 mAs / 47% → 57%</td>
</tr>
<tr>
<td>Iodine, Sn</td>
<td>0 / 30 mAs / 0%</td>
<td>0.2 mm / 1300 mAs / 14%</td>
<td>0.3 mm / 5000 mAs / 29% → 33%</td>
</tr>
<tr>
<td>Iodine, Cu</td>
<td>0.6 mm / 5000 mAs / 39% → 42%</td>
<td>1.2 mm / 5000 mAs / 37% → 42%</td>
<td>0.5 mm / 5000 mAs / 30% → 52%</td>
</tr>
</tbody>
</table>

- **Soft tissue CNRD in single energy CT:**
  - Can be maximized by choosing the Sn or Cu prefilter as thick as the tube power allows to.

- **Iodine CNRD in single energy CT:**
  - Cu prefiltration allows for significantly higher iodine CNRD than Sn.
  - Can be maximized by choosing the Cu prefilter as thick as the tube power allows to.
  - Sn prefilter thickness should be adapted to the patient size (zero for children, small for adults, as thick as tube power allows for obese).

- Deviating from the optimal Sn filter thickness by 0.1 mm results in a dose increase of up to 4%.

\textsuperscript{1}Steidel, Maier, Sawall, Kachelrieß. Tin or Copper Prefilters for Dose Reduction in Diagnostic Single Energy CT? RSNA 2020.
\textsuperscript{2}Steidel, Maier, Sawall, Kachelrieß. Dose Reduction through Patient-Specific Prefilters in Diagnostic Single Energy CT. RSNA 2020.

This confirms the dose reduction values reported by Michael McNitt-Gray for unenhanced scans also for enhanced scans (but with Cu instead of Sn).
Dose Reduction by Photon Counting

• Numerous publications (next slides)
Willemink et al. (Review Paper)

- Dose reduction values of 32%, 34%, 36%, 60% for various scenarios, also including patients.

Radiation Dose

During the past decade, the number of CT examinations increased yearly, with a 6.5% increase in the United States, resulting in a total of approximately 80 million CT scans per year (56,57). Despite the introduction of several dose-reducing techniques such as iterative reconstruction, automatic exposure control, and electrocardiography-triggered imaging, radiation exposure remains a concern (58–60).

Image noise levels with photon-counting CT will be lower at the same level of x-ray exposure compared with conventional CT scanners because FCDs minimize electronic noise and enable optimal x-ray photon energy weighting (Fig 14). This can be used to reduce radiation doses. Kaplan and colleagues (61) evaluated contrast and image noise by using water phantoms. They found increased iodine contrast with similar image noise compared with EID, resulting in a radiation dose reduction of up to 32%. Recent in vivo human experiments confirmed a dose reduction of up to 34% in photon-counting CT scans of the chest and brain (21,26).

Giersch et al (41) assessed the possibilities of energy weighting by simulating an ideal system. They found that images could be acquired with the same image quality using fewer photons, resulting in a radiation dose reduction by a factor of 2.5 (60% reduction). Photon-counting CT has the potential to improve CNR, which could be clinically used to reduce either the amount of contrast agent or the radiation dose (46,22). Compared with conventional CT, the smaller detector element size in photon-counting CT can be used for two different types of improvement, either increasing spatial resolution at a similar radiation dose and noise level or lowering radiation dose at a similar spatial resolution and noise level. This is because decreasing the detector element size means acquiring more data points. Even though this gives more noise in each individual detector element, the net result is that more high spatial resolution information is obtained, which the reconstruction algorithm can translate to lower noise in the final images (38). A recent in vivo human study has shown that additional dose reduction of up to 36% is achievable with high-spatial-resolution photon-counting CT (39). Thus, it is likely that photon-counting CT will reduce radiation levels by approximately 30%–60%, depending on the imaging task.
To demonstrate the functionality of the hybrid prototype scanner and its underlying conceptual methods, we have recorded axial CT images of an anatomical phantom. To quantify the clinical benefits of counting detectors with small pixels, we have investigated contrasts, noise and dual-energy capability in 20cm water phantoms. At low counter thresholds, we could verify that iodine contrast is increased by up to 20% (at 140kVp) while image noise is basically unaffected, all relative to the energy-integrating system. Merging the data from counters at 25keV and 55keV can further improve the iodine CNR². This allows to reduce patient dose by up to 32% (at 140kVp). Dual-energy capability was demonstrated in a first quick study, confirming predictions from earlier CT image simulations. Continuative studies of the material separation properties of the quantum-counting detector including studies with up to four energy bins are planned in the near future.
Brain imaging: dose reduction of approx. 40% possible (iterative reconstruction).

• Radiation dose reduction up to 34% (due to small pixels effect), B70f kernel
Zhou et al.

Comparison of a Photon-Counting-Detector CT with an Energy-Integrating-Detector CT for Temporal Bone Imaging: A Cadaveric Study


ABSTRACT

BACKGROUND AND PURPOSE: Evaluating abnormalities of the temporal bone requires high-spatial-resolution CT imaging. Our aim was to assess the performance of photon-counting-detector ultra-high-resolution acquisitions for temporal bone imaging and compare the results with those of energy-integrating-detector ultra-high-resolution acquisitions.

MATERIALS AND METHODS: Phantom studies were conducted to quantify spatial resolution of the ultra-high-resolution mode on a prototype photon-counting-detector CT scanner and an energy-integrating-detector CT scanner that uses a comb filter. Ten cadaveric temporal bones were scanned on both systems with the radiation dose matched to that of the clinical examinations. Images were reconstructed using a sharp kernel, 0.6-mm (minimum) thickness for energy-integrating thicknesses for photon-counting-detector CT. Image noise was measured and compared with noise levels obtained by 3 neuroradiologists to assess the incus/malleus joint, stapes footplate, and 2 temporal bone structures. A moderate interobserver agreement was observed with the Hounsfield unit. photon-counting-detector CT image sets were ranked significantly higher than the PC-UHR (Statistical Analysis System: SAS Institute).

RESULTS: Photon-counting-detector CT showed an increase in in-plane resolution to the same thickness (0.6 mm) images from photon-counting-detector CT had significantly higher energy-integrating-detector CT. Results differed in the photon-counting-detector CT for all 3 temporal bone structures. A moderate interobserver agreement was observed with the Hounsfield unit. photon-counting-detector CT image sets were ranked significantly higher than the PC-UHR (Statistical Analysis System: SAS Institute).

CONCLUSIONS: This study demonstrated substantially better delineation of fine and ultra-high-resolution mode of photon-counting-detector CT compared with the ultra-high-resolution mode of photon-counting-detector CT with the EID-CT system. In this present work, with multiple cadaveric temporal bone specimens, we strated that with a clinical temporal bone reconstruction (U70), the PCD-CT UHR mode could achieve a higher level of resolution compared with an EID-CT system when the same dose level and reconstruction levels are similar. The more aggressive noise reduction used in this study compared with the previous report is more than double the potential difference (U70 is sharper than S80). Our n the potential of a 64% reduction in dose using PCI temporal bone imaging to achieve the same imaging with the EID-CT. This finding confirmed the previous conclusion that...
Comparison between PC-UHR+Sn 100 kV (CounT) and EI 120 kV (Flash)

- A UHR mode with comb filter was used (only) for the temporal bone cadaver scan on the EID-CT.
- Phantom: Dose reduction of up to 56.5% (H70 kernel)
- Cadaver:
  - Sinus protocol: dose reduction of 67% (H70)
  - Temporal bone protocol (EI with comb filter): dose reduction of 83% (U70)
Dose reduction due to small pixels: 31% for B70f.

Dose reduction due to small pixels + iodine: up to 43% for D40f and up to 63% for B70f.
Dose Reduction by Photon Counting

• Reasons for less dose
  – Better iodine contrast
  – Energy bin weighting
  – UHR without comb
  – Smaller pixels
  – ...

In general, it seems realistic that a dose reduction of 30% or more can be achieved in clinical routine.
Dose Reduction by Deep Learning

- Not many clinical studies exist
  - Canon’s AiCE shown 20% noise reduction (36% less dose) compared to AIDR 3D in coronary CTA\(^1\)
  - Canon’s AiCE outperforms AIDR 3D which outperforms FIRST in lesion detection\(^2\). It further outperforms FIRST which outperforms AIDR 3D noise-wise\(^2\): Average dose reduction (taken from noise reduction) compared to FIRST is 38%.

\(^1\)Tatsugami et al. Deep learning–based image restoration algorithm for coronary CT angiography. EuRad 29:5322-5329, 2019
\(^2\)Singh et al., Image Quality and Lesion Detection on Deep Learning Reconstruction and Iterative Reconstruction of Submillisievert Chest and Abdominal CT. AJR 214:566-573, March 2020
## Dose Reduction by Deep Learning

<table>
<thead>
<tr>
<th>Region</th>
<th>Noise DL</th>
<th>Noise Iterative</th>
<th>Dose Reduction DL to Iterative</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liver</td>
<td>11.4 HU</td>
<td>16.2 HU</td>
<td>51%</td>
<td>[1]</td>
</tr>
<tr>
<td>Subcutaneous fat</td>
<td>9.9 HU</td>
<td>13.2 HU</td>
<td>44%</td>
<td>[1]</td>
</tr>
<tr>
<td>Paraspinal muscle</td>
<td>9.9 HU</td>
<td>14.5 HU</td>
<td>54%</td>
<td>[1]</td>
</tr>
<tr>
<td>Abdominal aorta</td>
<td>11.11 HU</td>
<td>15.5 HU</td>
<td>48%</td>
<td>[1]</td>
</tr>
<tr>
<td>Abdomen SNR</td>
<td>SNR = 5.08</td>
<td>SNR = 2.93</td>
<td>69%</td>
<td>[2]</td>
</tr>
<tr>
<td>Phantom</td>
<td>9% to 17% DLR-L, 46 to 56% DLR-H compared to AV50 (IR with 50% dose level)</td>
<td>[3]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coronary Artery</td>
<td>42%</td>
<td>100% (ASiR70)</td>
<td>66% compared to ASiR70</td>
<td>[4]</td>
</tr>
<tr>
<td>Abdomen</td>
<td></td>
<td></td>
<td>61% compared to MBIR</td>
<td>[5]</td>
</tr>
<tr>
<td>Full body</td>
<td></td>
<td></td>
<td>50% compared to FBP</td>
<td>[6]</td>
</tr>
</tbody>
</table>

10% or significantly more dose reduction can be seen.
Total Dose Reduction
Additionally Possible Compared to Today’s CTs

- Risk-specific AEC (Joscha Maier)
  - about 10%, depending on the tube voltage
- Optimized spectra (Michael McNitt-Gray and)
  - 20% to 50% depending on object size
- Dynamic bowtie (Grace Gang)
  - 27% to 50%
- Photon counting (literature):
  - 30%
- Deep learning replacing iterative recon
  - 10% to 30%
- The additional future dose reduction potential is conservatively estimated to be round about 70%.
  - \[1 - (1 - 10\%) \cdot (1 - 20\%) \cdot (1 - 27\%) \cdot (1 - 30\%) \cdot (1 - 10\%) = 67\%\]
Outlook

• Vendors:
  – Implement those measures and bring them into clinical routine

• Medical physicists and radiologists:
  – Use the new technology to reduce patient dose
  – Or use it to improve image quality
Thank You!

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Conference Chair: Marc Kachelriß, German Cancer Research Center (DKFZ), Heidelberg, Germany

This presentation is available at www.dkfz.de/ct.
Job opportunities through DKFZ’s international Fellowship programs (marc.kachelriess@dkfz.de).
Parts of the reconstruction software were provided by RayConStruct® GmbH, Nürnberg, Germany.