Advanced Imaging Techniques

Photon Counting CT

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Learning Goals

- introduction to advanced imaging techniques in MR, CT and CBCT
  - basic MRI principles -> Physics of Imaging Techniques

- Goals:
  1. How does the technique work?
  2. What kind of images do we receive?
  3. Where is this applied to?

- Literature is given in the respective lectures
- Slides of the lectures at https://www.umm.uni-heidelberg.de/inst/cbtm/ckm/lehre/index.html
Readings


History

- 8.11.1895 Discovery of X-rays by Wilhelm Conrad Röntgen
- 1901 Nobel Price Physics
- 1972 Development of computed tomography (CT) by Allan M. Cormack and Godfrey N. Hounsfield
- 1979 Nobel Price Medicine and Physiology
- 1996 Cone Beam CT by Tacconi et al.
Computertomography today

- wide distribution of diagnostic and therapeutic applications
  - high scanning speed,
  - high spatial resolution
  - availability
- US >80 million CT examinations / year
- approx. 7 million CT examinations / year
- CT is one of the most important and widely used imaging techniques in patient care

Leng et al., Radiographics 2019
https://www.bfs.de/DE/themen/ion/anwendung-medizin/diagnostik/roentgen/haeufigkeit-exposition.html

Quelle: University Hospital of Munich – Grosshadern, Munich

- Räumliche Auflösung: 0.33 mm
- 42 s für 1889 mm
- Rotation: 0.5 sec
- 120 kV, 120 mAs/Rotation
Computertomography today

- Length of 63 cm with
- Total dose of 1.9 mSv
- Recording time 1.2 s

- The image quality is very good, although the patient's left arm had to remain in the scan area

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Computertomography today

Key figures*:
- Table feed up to 737 mm/s
- Gantry rotation 0.25 s
- 70 - 150 kV, Dual Energy

Thorax scan < 1 s, full body scan in 5 s

40 Years of CT Technology
The end of development?

Sudanski et al. Sci Rep 2018
*Siemens Somatom Force
Photon Counting CT

Limitations:
- Radiation exposure of the patient
- Artifacts through noise, metal, beam hardening, blooming
- Normalization to so-called Hounsfield Units (signal intensity of water -> 0, air -> -1000)

https://www.flickr.com/photos/nihgov/25209682566

Leng et al., Radiographics 2019
Photon Counting CT - Technique

- X-ray tube produces X-rays
- Bremstrahl spectrum
  - depending on the tube voltage
- different energies of X-rays
- Image information in X-rays is generated by attenuation the X-rays during fluoroscopy
  - attenuation depending on the initial energy of the rays

Willemink et al., Radiology 2018

Photon Counting CT - Technique

- Current detector technology (EID) adds up signals
  - incident X-ray photon is converted into visible light in a scintillator.
  - meets a light sensor, where it generates positive and negative electrical charges.
  - Integration of the charges as an overall signal
Photon Counting CT - Technique

- Photo Counting Detector Technology (PCD)
  - X-ray photon is absorbed in a semiconductor material where it generates positive and negative charges
  - each photon can therefore be counted

Willemink et al., Radiology 2018

Photon Counting CT - Technique

Energy Integrating Detector  Dual Layer Detector  Direct Conversion Detector

X-Ray Photons

- Scintillator
- Photo Diode
- Integrating ASIC
- Integrated Energy (white light intensity)

- Low density Scintillator
- High density Scintillator
- Integrating ASIC
- Integrated Two Energies (low and high energy intensities)

- Direct Conversion Material
- Counting ASIC
- Spectral Profile (Discrimination and count)
Photon Counting CT - Prototyps

<table>
<thead>
<tr>
<th>Project</th>
<th>Detector Material*</th>
<th>Detector Element Size (mm)$^2$</th>
<th>Current Status</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>GE Healthcare (Chicago, Ill/Stanford University (Stanford, Calif)/Rensselaer Polytechnic Institute (Troy, NY) high-dose efficiency CT)</td>
<td>CZT, planned integration with dynamic bowtie</td>
<td>0.5 × 0.5</td>
<td>Table-top system under construction at Rensselaer Polytechnic Institute</td>
<td>29</td>
</tr>
<tr>
<td>Medipin All Resolution System (MARS Biostimulation, Christchurch, New Zealand)</td>
<td>CZT</td>
<td>0.11 × 0.11</td>
<td>Imaging of specimens and small animals. Human-size scanner under construction.</td>
<td>30</td>
</tr>
<tr>
<td>Philips Healthcare (Best, the Netherlands) spectral photon-counting CT</td>
<td>CZT</td>
<td>0.5 × 0.5</td>
<td>Imaging of specimens and small animals. Prototype system with small detector installed in human-sized gantry in Lyon, France.</td>
<td>31,32</td>
</tr>
<tr>
<td>KTH Royal Institute of Technology (Stockholm, Sweden)/Prismatic Sensor (Stockholm, Sweden) silicon strip</td>
<td>Silicon</td>
<td>0.5 × 0.4</td>
<td>Table-top measurements at KTH Royal Institute of Technology</td>
<td>5</td>
</tr>
<tr>
<td>Siemens (Forchheim, Germany) dual detector</td>
<td>Dual-source CT with one CsI:Tl photon-counting detector</td>
<td>0.225 × 0.225, detector elements binned into macro mode (0.9 × 0.9) and sharp mode (0.45 × 0.45)</td>
<td>Prototype human-size systems installed at Mayo Clinic (Rochester, Minn.), at National Institutes of Health (Bethesda, Md), and in Forchheim, Germany. Research imaging of human volunteers</td>
<td>33</td>
</tr>
</tbody>
</table>

Photon Counting CT

- besides counting also the corresponding energies can be differentiated
- Classification of the distribution of photons according to energies
- allows weighting of these energies
  - Improvement of the CNR
- Material Decomposition
  - Representation of images of post-determined substances

Willemink et al., Radiology 2018
Photon Counting CT - Applications

Dose reduction
- Simulation, factor 2.5 (60% reduction)
- in vivo, up to 36%.

Giersch et al, Nucl Instrum Methods Phys Res A 2004
Pourmorteza et al., Proc. RSNA, 2017

Resolution
- PCD elements smaller (up to 50%)

ex-vivo heart, A: Standard resolution,
B: high resolution

Willemink et al, Radiology 2018
Photon Counting CT - Applications

Material Decomposition & Mono energetic Images

Photon Counting CT - Limitations

Why is this technique not yet clinically available?

- Cross-talk of detector elements
  - no unambiguous allocation and counting possible

- Time sampling rate of the detector
  - Pile-up of photons at short time intervals
Summary

- Electron integrating detectors sum all photon energies
  - No differentiation of single energies/photons
- Photon counting detectors direct conversion of the energies
  - Allows for counting each incident photon
  - Detection of multiple energies from the Bremsstrahl spectrum

- Limitations are detector materials (cross talk, pile up)

- Applications are material decomposition, higher resolution, monoenergetic images in a single acquisition
  - Further dose reduction