Options for Automatic Exposure Control

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Motivation & Outline

- Automatic exposure control (AEC) aims at setting the CT acquisition parameters automatically to reduce radiation dose while simplifying the workflow for radiologists.

- AEC covers:
  - Angular and longitudinal tube current modulation (TCM)
  - Automatic tube current selection
  - Automatic tube voltage selection

- Review of the basic principles of AEC and vendor specific implementations.

- Future applications: tube current modulation that minimizes the radiation risk, i.e. the effective dose.
Tube Current Modulation

Basic principle

Good statistics
\[ N_0 = 1\,000\,000 \]

Bad statistics
\[ N_0 = 1\,000\,000 \]
\[ \sigma = 60 \text{ HU} \]

Constant tube current: High, inhomogeneous noise.

\[ N = 400 \]
\[ \frac{1}{N\alpha} \int k(\alpha) d\alpha = 1 \]

Tube Current Modulation

Basic principle

Good statistics

$N_0 = 250\,000$

$\sigma = 44\,\text{HU}$

Bad statistics

$N_0 = 3\,500\,000$

$N = 1\,400$

$N = 6\,250$

Modulated tube current: Lower, more homogeneous noise.

Tube Current Modulation
From a mathematical perspective

• The tube current modulation curve $J(\alpha)$ is chosen such that the variance in the CT reconstruction is minimal

$N_0(\alpha) = c \cdot J(\alpha)$

$N(\alpha) = c \cdot J(\alpha) \cdot e^{-p(\alpha)}$

- X-rays reaching the detector follow Poisson statistics:
  \[ \sigma_N^2(\alpha) = N(\alpha) = c \cdot J(\alpha) \cdot e^{-p(\alpha)} \]

- Variance propagation to projection domain yields:
  \[ \sigma_p^2(\alpha) = \frac{1}{c \cdot J(\alpha) \cdot e^{-p(\alpha)}} \]

- Variance propagation to image domain yields:
  \[ \sigma_f^2 = \sum_{\alpha} \frac{1}{c \cdot J(\alpha) \cdot e^{-p(\alpha)}} \]

• Cost function:
  \[ C = \sum_{\alpha} \frac{1}{c \cdot J(\alpha) \cdot e^{-p(\alpha)}} + \lambda \left( \sum_{\alpha} J(\alpha) - \text{const} \right) \]

• Minimization yields:
  \[ J(\alpha) \propto e^{\frac{1}{2}p(\alpha)} \]
Tube Current Modulation

Interpretation

- Tube current: \( J(\alpha) \propto e^{\frac{1}{2} \cdot p(\alpha)} \)
- Photon numbers: \( N(\alpha) = c \cdot J(\alpha) \cdot e^{-p(\alpha)} \)

Rule of thumb:
The number of quanta reaching the center of the patient should be constant for all view angles.
34% mAs reduction with AEC at constant image quality for that specific case
Dose Reduction by Tube Current Modulation

Conventional scan: 327 mAs

Online current modulation: 166 mAs

Average dose reduction of 35% - 60% has been reported\(^1\). 49% dose reduction in this case\(^2\).

## Features of AEC Systems

<table>
<thead>
<tr>
<th></th>
<th>Canon SURE Exposure 3D</th>
<th>GE AutomA 3D&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Philips DoseRight ACS</th>
<th>Siemens CARE Dose 4D</th>
</tr>
</thead>
<tbody>
<tr>
<td>mA adaptation for patient size</td>
<td>SURE Exposure</td>
<td>AutomA</td>
<td>automatic current selection (ACS)</td>
<td>yes</td>
</tr>
<tr>
<td>mA adaption for z-dimension</td>
<td>SURE Exposure</td>
<td>AutomA</td>
<td>Z-DOM, DOM</td>
<td>yes</td>
</tr>
<tr>
<td>mA adaption for α-angle</td>
<td>SURE Exposure 3D</td>
<td>SmartmA</td>
<td>D-DOM</td>
<td>yes</td>
</tr>
<tr>
<td>Simultaneous application</td>
<td>xy-AEC can be chosen separately</td>
<td>AutomA + SmartmA = AutomA 3D</td>
<td>ACS+Z-DOM or ACS+D-DOM, but not ACS+Z-DOM+D-DOM</td>
<td>always on</td>
</tr>
<tr>
<td>Method to determine the exposure level</td>
<td>standard deviation</td>
<td>noise index</td>
<td>reference image</td>
<td>reference mAs</td>
</tr>
<tr>
<td>Basis for AEC for z-position / α-angle</td>
<td>a.p. and lateral topogram / sinusoidal modulation</td>
<td>single topogram / sinusoidal modulation</td>
<td>a.p. and lateral topogram / previously acquired 180° data</td>
<td>a.p. and lateral topogram / previously acquired 180° data</td>
</tr>
</tbody>
</table>

DOM = dose modulation = TCM = tube current modulation

<sup>1</sup>Feature is disabled when in fast tube voltage switching DECT mode
Determination of the Patient Attenuation

From topogram / scout scan

Lateral topogram

A.p. topogram

From previously acquired data

Data of the previous 180°

→ Predictive calculations or sinusoidal interpolation between a.p. and lateral views

→ Online feedback loop that makes use of the previously acquired 180° data
ECG-Based Tube Current Modulation

**Phase of interest**

**Tube current**

**ECG**

<table>
<thead>
<tr>
<th>Modulation for cardiac CT - retrospective</th>
<th>Canon SURE Exposure 3D</th>
<th>GE Automa 3D</th>
<th>Philips DoseRight ACS</th>
<th>Siemens CARE Dose 4D</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;ECG Modulation&quot;</td>
<td>&quot;ECG Modulated mA&quot;</td>
<td>DoseRight Cardiac &quot;Step and Shoot&quot;</td>
<td>&quot;Adaptive ECG-Pulsing&quot;</td>
<td></td>
</tr>
<tr>
<td>&quot;SURE Cardio Prospective&quot;</td>
<td>&quot;Prospective Gating&quot;</td>
<td>DoseRight Cardiac ECG triggered dose modulation</td>
<td>Prospective sequence scan = “Adaptive Cardio” + “Pulsing”, prospective spiral scan = “Flash mode&quot;</td>
<td></td>
</tr>
</tbody>
</table>
Organ-Specific Tube Current Modulation

- Limit the radiation exposure of sensitive organs at the anterior body surface (breast, thyroid glands, eyes).
- Tube current is lowered in a 120° to 180° interval in front of the organ.
- Tube current may be increased for posterior-anterior views to maintain image quality.

<table>
<thead>
<tr>
<th>Organ-Specific AEC/TCM</th>
<th>Canon SURE Exposure 3D</th>
<th>GE AutomA 3D</th>
<th>Philips DoseRight ACS</th>
<th>Siemens CARE Dose 4D</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OEM, Decrease anterior tube current</td>
<td>ODM, Decrease anterior tube current</td>
<td>Liver DRI, Different image quality setting for the liver</td>
<td>X Care, Decrease anterior tube current, increase posterior tube current</td>
</tr>
</tbody>
</table>
## Automatic Tube Voltage Selection

<table>
<thead>
<tr>
<th>Tube Voltage</th>
<th>Iodine CNR</th>
<th>Soft tissue CNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>80 kV</td>
<td>19.1</td>
<td>3.1</td>
</tr>
<tr>
<td>100 kV</td>
<td>16.7</td>
<td>3.2</td>
</tr>
<tr>
<td>120 kV</td>
<td>14.7</td>
<td>3.3</td>
</tr>
</tbody>
</table>

All CT images are simulated with the same dose:

- C = 100 HU, W = 600 HU

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Tube Voltage Assist</th>
<th>Dose Assay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canon (SURE)</td>
<td>Sure kV</td>
<td>Exposure 3D</td>
</tr>
<tr>
<td>GE (AutomA)</td>
<td>kV Assist</td>
<td>3D</td>
</tr>
<tr>
<td>Philips (DoseRight)</td>
<td>-</td>
<td>ACS</td>
</tr>
<tr>
<td>Siemens (CARE)</td>
<td>CARE kV</td>
<td>4D</td>
</tr>
</tbody>
</table>

Automatic Tube Voltage Selection
Can we get any better?
TCM Minimizing the Radiation Risk

Motivation

- Conventional tube current modulation approaches can only account for a few organs.
- Conventional tube current modulation approaches do not have access to the actual dose distribution, but are based on minimizing the mAs product.

Additional prior knowledge may enable more sophisticated approaches.

- Here: Use deep learning-based prior knowledge to perform a tube current modulation that minimizes the radiation risk, i.e. the effective dose.
TCM Minimizing the Radiation Risk

Basic workflow

1. Coarse reconstruction from two scout views

2. Segmentation of radiation-sensitive organs

3. Calculation of the effective dose per view using the deep dose estimation (DDE)

4. Determination of the tube current modulation curve that minimizes the radiation risk
TCM Minimizing the Radiation Risk

Basic workflow

1. **Coarse reconstruction from two scout views**
   X. Ying, et al., "X2CT-GAN: Reconstructing CT From Biplanar X-Rays With Generative Adversarial Networks," *CVPR 2019*

2. **Segmentation of radiation-sensitive organs**

3. **Calculation of the effective dose per view using the deep dose estimation (DDE)**

4. **Determination of the tube current modulation curve that minimizes the radiation risk**

View angle
Deep Dose Estimation (DDE)

Basic principle

- Monte Carlo (MC) simulation is the gold standard for patient-specific dose estimation, but too slow to be applied routinely.

Training of a deep convolution to reproduce MC simulations given only the CT image and a 1\textsuperscript{st} order dose estimate as input.

Number of features of the convolutional layer:
- 16
- 32
- 64
- 128
- 256
- 128
- 64
- 32
- 16

\(3 \times 3 \times 3\) Convolution (stride = 1), ReLU
\(3 \times 3 \times 3\) Convolution (stride = 2), ReLU
Depth concatenate
\(1 \times 1\) Convolution (stride = 1), ReLU
\(2 \times 2 \times 2\) Upsampling

Deep Dose Estimation (DDE)
First order dose estimate

Monte Carlo:
Calculation of the complete photon trajectory through different tissues including scatter interactions.
→ Slow

First order dose:
Only direct rays are considered. Only a single material (water with the patient's density distribution) is considered.
→ Fast
Deep Dose Estimation (DDE)

Training data

- 35 full body scans were used to generate training data for the deep dose estimation.
- Different patients were used for training and testing.
- CT scans were simulated using the following parameters:
  - Anatomies: Head, thorax, abdomen, pelvis
  - Tube voltages: 70 kV – 150 kV
  - Scan trajectories: circular, spiral
  - Shaped filters: with and without bowtie
  - Angular coverage: 10°, 360°
- The DDE network was trained for 100 epochs on an Nvidia Quadro P6000 GPU using the mean absolute percentage error as loss function.
Deep Dose Estimation (DDE)
Dose predictions, 360° scans

CT image                              1st order dose

Monte Carlo                           DDE

Relative Error

<table>
<thead>
<tr>
<th></th>
<th>MC</th>
<th>DDE</th>
</tr>
</thead>
<tbody>
<tr>
<td>48 slices</td>
<td>1 h</td>
<td>0.25 s</td>
</tr>
<tr>
<td>whole body</td>
<td>20 h</td>
<td>5 s</td>
</tr>
</tbody>
</table>

MC uses 16 CPU kernels
DDE uses one Nvidia Quadro P6000 GPU

Mean relative error on the testing data set: 5 %
Deep Dose Estimation (DDE)
Dose predictions, 10° scans

Mean relative error on the testing data set: 5 %
TCM Minimizing the Radiation Risk

Determination of the modulation curve

- Calculation of dose estimates for 10° segments using the deep dose estimation
- Calculation of the effective dose according to the ICRP weighting factors for every 10° segment:

\[ D_{\text{eff}}(\alpha) = \sum_{T} w_{T} \cdot D_{T}(\alpha) \]

- New cost function:

\[ C = \sum_{\alpha} \frac{1}{c \cdot J(\alpha) \cdot e^{-p(\alpha)}} + \lambda \left( \sum_{\alpha} J(\alpha) \cdot D_{\text{eff}}(\alpha) \right) \]

Minimization:

\[ J(\alpha) \propto \frac{e^{\frac{1}{2} p(\alpha)}}{\sqrt{D_{\text{eff}}(\alpha)}} \]
Simulation Study

- Simulation of CT scans covering different anatomies at 70 kV, 120 kV, and 150 kV (6 mm Al prefiltration).
- Simulation of consecutive circle scans (38.4 mm apart), each with a z-collimation of 38.4 mm.

Axial view  
Coronal view

$$nz = 1$$  
$$z\text{-coverage of dose estimate at } nz = 10$$
Modulation Curves 70 kV
Angular modulation, nz = 6

CT image

Segmentation

<table>
<thead>
<tr>
<th>Organ / weight</th>
<th>Weight</th>
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<tbody>
<tr>
<td>Remainder</td>
<td>0.12</td>
</tr>
<tr>
<td>Bone surface</td>
<td>0.01</td>
</tr>
<tr>
<td>Brain</td>
<td>0.01</td>
</tr>
<tr>
<td>Breast</td>
<td>0.12</td>
</tr>
<tr>
<td>Colon</td>
<td>0.12</td>
</tr>
<tr>
<td>Esophagus</td>
<td>0.04</td>
</tr>
<tr>
<td>Liver</td>
<td>0.04</td>
</tr>
<tr>
<td>Lung</td>
<td>0.12</td>
</tr>
<tr>
<td>Skin</td>
<td>0.01</td>
</tr>
<tr>
<td>Stomach</td>
<td>0.12</td>
</tr>
<tr>
<td>Thyroid</td>
<td>0.04</td>
</tr>
<tr>
<td>Bladder</td>
<td>0.04</td>
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</table>

Future: TCM minimizing the patient risk
Current: TCM minimizing the mAs product

Relative modulation vs. View angle

0°, 90°, 180°, 270°, 360°
Modulation Curves 120 kV

Angular modulation, \( nz = 6 \)

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</tr>
<tr>
<td>Bladder</td>
<td>0.04</td>
</tr>
</tbody>
</table>

CT image

Segmentation

Relative modulation vs. View angle

Future: TCM minimizing the patient risk
Current: TCM minimizing the mAs product
Modulation Curves 150 kV
Angular modulation, nz = 6

CT image

Segmentation

Organ / weight
- Remainder 0.12
- Bone surface 0.01
- Brain 0.01
- Breast 0.12
- Colon 0.12
- Esophagus 0.04
- Liver 0.04
- Lung 0.12
- Skin 0.01
- Stomach 0.12
- Thyroid 0.04
- Bladder 0.04

Future: TCM minimizing the patient risk
Current: TCM minimizing the mAs product
Modulation Curves 70 kV
Angular modulation, nz = 10

CT image

Segmentation

Organ / weight
- Remainder 0.12
- Bone surface 0.01
- Brain 0.01
- Breast 0.12
- Colon 0.12
- Esophagus 0.04
- Liver 0.04
- Lung 0.12
- Skin 0.01
- Stomach 0.12
- Thyroid 0.04
- Bladder 0.04

Relative modulation

View angle

Future: TCM minimizing the patient risk
Current: TCM minimizing the mAs product
Modulation Curves 120 kV
Angular modulation, nz = 10

CT image

Segmentation

Organ / weight

Remainder 0.12
Bone surface 0.01
Brain 0.01
Breast 0.12
Colon 0.12
Esophagus 0.04
Liver 0.04
Lung 0.12
Skin 0.01
Stomach 0.12
Thyroid 0.04
Bladder 0.04

Relative modulation

View angle

0° 90° 180° 270° 360°

Future: TCM minimizing the patient risk
Current: TCM minimizing the mAs product
Modulation Curves 150 kV
Angular modulation, nz = 10

CT image
Segmentation

Organ / weight
- Remainder: 0.12
- Bone surface: 0.01
- Brain: 0.01
- Breast: 0.12
- Colon: 0.12
- Esophagus: 0.04
- Liver: 0.04
- Lung: 0.12
- Skin: 0.01
- Stomach: 0.12
- Thyroid: 0.04
- Bladder: 0.04

Relative modulation vs. View angle

Future: TCM minimizing the patient risk
Current: TCM minimizing the mAs product
Modulation Curves 70 kV

Angular modulation, nz = 18

CT image

Segmentation

Organ / weight

- Remainder 0.12
- Bone surface 0.01
- Brain 0.01
- Breast 0.12
- Colon 0.12
- Esophagus 0.04
- Liver 0.04
- Lung 0.12
- Skin 0.01
- Stomach 0.12
- Thyroid 0.04
- Bladder 0.04

Relative modulation vs View angle

Future: TCM minimizing the patient risk
Current: TCM minimizing the mAs product
Modulation Curves 120 kV
Angular modulation, nz = 18

Organ / weight
- Remainder 0.12
- Bone surface 0.01
- Brain 0.01
- Breast 0.12
- Colon 0.12
- Esophagus 0.04
- Liver 0.04
- Lung 0.12
- Skin 0.01
- Stomach 0.12
- Thyroid 0.04
- Bladder 0.04

CT image

Segmentation

Future: TCM minimizing the patient risk
Current: TCM minimizing the mAs product
Modulation Curves 150 kV
Angular modulation, nz = 18

Organ / weight
- Remainder 0.12
- Bone surface 0.01
- Brain 0.01
- Breast 0.12
- Colon 0.12
- Esophagus 0.04
- Liver 0.04
- Lung 0.12
- Skin 0.01
- Stomach 0.12
- Thyroid 0.04
- Bladder 0.04

Future: TCM minimizing the patient risk
Current: TCM minimizing the mAs product

CT image
Segmentation
Reduction of Effective Dose 70 kV

Reduction of the effective dose for the complete scan: 11.5 %
Reduction of Effective Dose 120 kV

Reduction of the effective dose for the complete scan: 7.5 %
Reduction of Effective Dose 150 kV

Reduction of the effective dose for the complete scan: 6.6 %
Conclusions

• Current AEC systems can reduce the dose by 35 % - 60 % while maintaining image quality\(^1\).
• Deep learning-based approaches may open new options for AEC.
• Here, the potential of a tube current modulation that minimizes the radiation risk instead of the mAs product was investigated.
• Compared to a conventional tube current modulation, the effective dose could be further reduced by about 11.5 %, 7.5 %, and 6.6 % for 70 kV, 120 kV and 150 kV, respectively.

Thank You!

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