Patient doses in paediatric radiology

K. Smans\(^{(1)}\)^{(2)}, F. Vanhavere\(^{(1)}\), M. Smet\(^{(2)}\), H. Bosmans\(^{(2)}\)

(1) SCK-CEN, Mol, Belgium
(2) University Hospital, Leuven, Belgium

ALARA in the medical world

http://www.sck.be
Patient dose in paediatric radiology

- Why is it important?
  - Significant radiation detriment
    - 2-3 times higher than average population
    - 6-9 times higher than a 60-year old person
  - Medical Exposure Directive (97/43/Euratom)
Patient dose in paediatric radiology

- Why is it important?
  - Long life expectancy
  - Exposed to a large number of X-ray examinations
    - Neonatal Intensive Care Unit (NICU)
Paediatric Radiology

Simple examinations

Dynamic examinations

< 1 year

Low dose

> 1 year

High dose (CT)
Examinations at the neonatal unit

- < 1 year
- Neonatal Intensive Care Unit
  - Newborn infants with pathology/disease
  - Premature newborn infants
- Chest radiograph and abdominal radiograph
Examinations at the neonatal unit

Up to 78 X-ray examinations
Examinations at the neonatal unit
Paediatric radiology department

- > 1 year
- Simple examinations
  - Chest, abdomen, pelvis
- Dynamic examinations
  - Lower GI-tract, Upper GI-tract, Voiding Cystourethrogram
Radiation exposure

- Dose
- Image Quality
Radiation exposure

How high is the dose?

Dose

Image Quality
Radiation exposure

- Radiation risks
  - Based on doses in various organs and tissues in the body

- Effective dose

\[
E = \sum w_T \cdot \sum w_R \cdot D_T
\]

\(W_T\): Developed for reference populations of equal number of both sexes and a wide range of ages
Radiation exposure

- Radiation risks
  - Based on doses in various organs and tissues in the body
    - Direct measurements of organ doses are not possible
  
- What can we measure? What do we know?
  - Protocols
  - Entrance Surface Dose (ESD)
  - Dose Area Product (DAP)
Radiation exposure

- Leuven
  - University Hospitals Leuven

- Europe
  - Sentinel project
    - European survey on patient doses in paediatric radiology
    - 13 Countries
    - http://www.dimond3.org/

- European Guidelines
Radiation exposure

I. Measurements
Radiation exposure

- What can we measure? What do we know?
  - Protocols
  - Entrance Surface Dose (ESD)
  - Dose Area Product (DAP)
Protocols and equipment (NICU)

- Equipment
  - Mobile X-ray unit
  - Computed Radiography plates
Protocols and equipment (NICU)

- Equipment
  - Mobile X-ray unit
  - Computed Radiography plates
  - Old, secondhand
Protocols and equipment (NICU)

- Protocols
  - Where are they coming from?
  - Are they optimized for Computed Radiology?
Protocols in Leuven (NICU)

- Procedure map is available:
  - No Automatic Exposure Control
  - Exposure parameters have to be selected based on patient weight.

<table>
<thead>
<tr>
<th>Gewicht (g)</th>
<th>kV</th>
<th>mAs</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>60</td>
<td>0.56</td>
</tr>
<tr>
<td>800</td>
<td>60</td>
<td>0.63</td>
</tr>
<tr>
<td>1100</td>
<td>60</td>
<td>0.63</td>
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<tr>
<td>1300</td>
<td>61.5</td>
<td>0.8</td>
</tr>
<tr>
<td>1700</td>
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<tr>
<td>2000</td>
<td>66</td>
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<tr>
<td>2500</td>
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<tr>
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<tr>
<td>3000</td>
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<td>4000</td>
<td>70</td>
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## Protocols in Europe (NICU)

<table>
<thead>
<tr>
<th>Centre</th>
<th>Distance [cm]</th>
<th>kVp</th>
<th>mAs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre 1</td>
<td>100</td>
<td>60-70</td>
<td>0.56-1.0</td>
</tr>
<tr>
<td>Centre 2</td>
<td>80-100</td>
<td>50-70</td>
<td>1.0-2.0</td>
</tr>
<tr>
<td>Centre 3</td>
<td>50-70</td>
<td>60-65</td>
<td>2.0-2.5</td>
</tr>
<tr>
<td>Centre 4</td>
<td></td>
<td>55</td>
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</tr>
<tr>
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<td>80-100</td>
<td>60-65</td>
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### Protocols in Europe (NICU)

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<td>2.0-2.5</td>
</tr>
<tr>
<td>Centre 4</td>
<td>55</td>
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<td>80-100</td>
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<td></td>
</tr>
</tbody>
</table>

Proportional with the length of the radiographer!

Equipment (Paediatric department)

- Equipment
  - Fixed X-ray unit
  - CR (computed radiography) or DR (digital radiography)
Protocols in Europe (Paediatric department)

<table>
<thead>
<tr>
<th>Distance [cm]</th>
<th>kVp</th>
<th>mAs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre 1</td>
<td>110-150</td>
<td>70-110</td>
</tr>
<tr>
<td>Centre 2</td>
<td>78-146</td>
<td>37-54</td>
</tr>
<tr>
<td>Centre 11</td>
<td>100-200</td>
<td>38-73</td>
</tr>
<tr>
<td>European Guidelines</td>
<td>100-150</td>
<td>60-80</td>
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</tbody>
</table>

Radiation exposure

- What can we measure? What do we know?
  - Protocols
  - Entrance Surface Dose (ESD)
  - Dose Area Product (DAP)
Entrance surface dose

- Entrance Surface Dose (ESD)
  - Measurement: TLD (ThermoLuminescent Dosimeter)
  - TLDs wrapped in plastic bag
  - Attached to patients skin
  - Time consuming
Entrance Surface Dose (ESD)

- Measurement: TLD (ThermoLuminescent Dosimeter)
- TLDs wrapped in plastic bag
- Attached to patients skin
- Time consuming
Entrance Surface Dose Study in Leuven (< 1y)

Chest radiograph

ESD [µGy] vs Weight [kg]

- Weight range: 0 to 5 kg
- ESD range: 0 to 180 µGy

The scatter plot shows the relationship between chest radiograph exposure (ESD) in µGy and weight in kg for children under 1 year old.
**Entrance Surface Dose Study in Leuven (< 1y)**

<table>
<thead>
<tr>
<th></th>
<th>Median ESD (µGy)</th>
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<tbody>
<tr>
<td>Chest Radiograph</td>
<td>62 [5-142]</td>
</tr>
<tr>
<td>Abdomen Radiograph</td>
<td>89 [67-102]</td>
</tr>
<tr>
<td>Combined Radiograph</td>
<td>81 [30-151]</td>
</tr>
</tbody>
</table>
Entrance surface dose European study (<1y)

Entrance surface dose

European study (3y-8y)

Chest radiograph

ESD [µGy]

Centre 2 Centre 4 Centre 7 Centre 8 Centre 9 Centre 11 Centre 12

European Guidelines (100 µGy)

DRL (176 µGy)
Radiation exposure

- What can we measure? What do we know?
  - Protocols
  - Entrance Surface Dose (ESD)
  - Dose Area Product (DAP)
Dose area product

- Dose Area Product (DAP)
  - DAP-meter = plan parallel ionization chamber
  - DAP = Dose x irradiated area
  - Attached to diaphragm RX-tube
  - ‘easy’ measurement
Dose area product

- **DAP-measurements**
  - DAP = Dose Area Product
- **“Dose”**
  - Depends on exposure parameters
- **“Area”**
  - Depends on collimation

<table>
<thead>
<tr>
<th>Fieldsize</th>
<th>Patient 1</th>
<th>Patient 2</th>
<th>Patient 3</th>
<th>Patient 4</th>
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</thead>
<tbody>
<tr>
<td>Day 1</td>
<td>56 cm²</td>
<td>90 cm²</td>
<td>190 cm²</td>
<td>90 cm²</td>
</tr>
<tr>
<td>Day 2</td>
<td>91 cm²</td>
<td>140 cm²</td>
<td>112 cm²</td>
<td>108 cm²</td>
</tr>
<tr>
<td>Day 3</td>
<td>84 cm²</td>
<td>122 cm²</td>
<td>109 cm²</td>
<td>-</td>
</tr>
</tbody>
</table>
Dose Area Product

Bad collimation

Good collimation
Dose Area Product

No radiation protection

Good radiation protection
Dose area product study in Leuven (< 1y)

Chest radiograph

DAP [cGy.cm²] vs. Weight [kg]

Data points indicate a trend where DAP increases with weight.
Dose area product
European study (1 y)

Dose area product
European study (3y-8y)

Chest radiograph

DAP [cGy.cm²]

Centre 1  Centre 4  Centre 9  Centre 9bis  Centre 10  Centre 11

DRL (24 cGy.cm²)
Dose area product European study

Voiding Cystourethrogram

DAP [cGy.cm²]

Centre 1
Centre 2
Centre 3
Centre 4
Centre 5

< 1 year  1y – 2y  2y – 3y  3y – 8y  8y –  > 12y
Dose and risk Overview

- Protocols
- ESD
- DAP

Step 1: Measurements

- Organ dose
Dose and risk Overview

- Protocols
- ESD
- DAP

Step 2: Conversion factors

- Conversion factors
  - NRPB
  - PCXMC
  - Simulations with Monte Carlo software

- Organ dose
Radiation exposure

II. Conversion coefficients
Conversion coefficients

- NRPB
- PCXMC
- Simulations with Monte Carlo
Conversion coefficients

NRPB

NRPB-R279: “Coefficients for estimating effective dose from pediatric X-ray examinations”

- $D_{\text{organ}} = CC_{\text{ESD}} \times \text{ESD}$
- $D_{\text{organ}} = CC_{\text{DAP}} \times \text{DAP}$

Fixed radiographic views – 26 organs

Phantom: 0, 1, 5, 10 and 15 years old
NRPB

NRPB-R279: “Coefficients for estimating effective dose from pediatric X-ray examinations”

- \( D_{\text{organ}} = \text{CC}_{\text{ESD}} \times \text{ESD} \)
- \( D_{\text{organ}} = \text{CC}_{\text{DAP}} \times \text{DAP} \)

- Fixed radiographic views – 26 organs
- Phantom: 0, 1, 5, 10 and 15 years old

- Discrete ages?
- Appropriate to represent premature babies?
Conversion coefficients

- NRPB
- PCXMC
- Simulations with Monte Carlo
Conversion coefficients

PCXMC

Adjustable size

Adjustable radiographic views
Conversion coefficients

**Mathematical Phantom**
- Modify phantom based on patient weight (m) and height (h)
- Linear scaling

Conversion coefficients

PCXMC

- Mathematical Phantom
  - Modify phantom based on patient weight (m) and height (h)
  - Linear scaling

Not validated
Conversion coefficients PCXMC

- **Input Dose**
  - Entrance Skin Dose (ESD), Dose Area Product (DAP), Current Time Product (mAs)
  - Spectra (kVp + filtration)

- **Output Dose Calculation**
  - Dose to tissues/organs
Conversion coefficients

- NRPB
- PCXMC
- Simulations with Monte Carlo
Conversion coefficients

MCNP

- **Mathematical models (Adam, Eva)**
  - Planes, spheres and cylinders are used to represent the model
  - Model resembles human anatomy only vaguely

- **Voxel models**
  - High resolution cross-sectional digital images of internal anatomy are used to create a 3D representation of the shape, volume and composition of the human organs.
  - Realistic representation of anatomical structures
### Currently published models

- [www.virtualphantoms.org](http://www.virtualphantoms.org)

<table>
<thead>
<tr>
<th>Model</th>
<th>Number</th>
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</thead>
<tbody>
<tr>
<td>Adults</td>
<td>30</td>
</tr>
<tr>
<td>Children</td>
<td>6</td>
</tr>
<tr>
<td>Babies</td>
<td>7</td>
</tr>
</tbody>
</table>
Voxel models

- Currently published pediatric models
  - Voxel models > 1y

<table>
<thead>
<tr>
<th>Model</th>
<th>Gender</th>
<th>Age</th>
<th>Modality</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADELAIDE</td>
<td>F</td>
<td>14 years</td>
<td>CT</td>
<td>Caon et al</td>
</tr>
<tr>
<td>CHILD</td>
<td>F</td>
<td>7 years</td>
<td>CT</td>
<td>Zankl et al</td>
</tr>
<tr>
<td>UF 4-y</td>
<td>F</td>
<td>4 years</td>
<td>CT</td>
<td>Lee et al</td>
</tr>
<tr>
<td>UF 8-y</td>
<td>F</td>
<td>8 years</td>
<td>CT</td>
<td>Lee et al</td>
</tr>
<tr>
<td>UF 11-y</td>
<td>F</td>
<td>11 years</td>
<td>CT</td>
<td>Lee et al</td>
</tr>
<tr>
<td>UF 14-y</td>
<td>F</td>
<td>14 years</td>
<td>CT</td>
<td>Lee et al</td>
</tr>
</tbody>
</table>
## Voxel models

### Currently published pediatric models

#### Voxel models < 1y

<table>
<thead>
<tr>
<th>Model</th>
<th>Gender</th>
<th>Weight [kg]</th>
<th>Age</th>
<th>Voxel volume [mm³]</th>
<th>Modality</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>BABY</td>
<td>F</td>
<td>4,2</td>
<td>2 months</td>
<td>2,9</td>
<td>CT</td>
<td>Zankl et al</td>
</tr>
<tr>
<td>UF-newborn (original)</td>
<td>F</td>
<td>3,8</td>
<td>6 days</td>
<td>0,35</td>
<td>CT</td>
<td>Nipper et al</td>
</tr>
<tr>
<td>UF 2 month</td>
<td>M</td>
<td>5,4</td>
<td>2 months</td>
<td>0,30</td>
<td>CT</td>
<td>Nipper et al</td>
</tr>
<tr>
<td>UF 9 month</td>
<td>M</td>
<td>6,9</td>
<td>9 months</td>
<td>0,56</td>
<td>CT</td>
<td>Lee et al</td>
</tr>
<tr>
<td>UFH-NURBS</td>
<td>M/F</td>
<td>3,5</td>
<td>6 days</td>
<td>surfaces</td>
<td>CT</td>
<td>Lee et al</td>
</tr>
<tr>
<td>Phantom 1</td>
<td>M</td>
<td>1,9</td>
<td>0 days</td>
<td>0,922</td>
<td>CT/MRI</td>
<td>Smans et al</td>
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<tr>
<td>Phantom 2</td>
<td>M</td>
<td>0,6</td>
<td>0 days</td>
<td>0,548</td>
<td>CT/MRI</td>
<td>Smans et al</td>
</tr>
</tbody>
</table>
Voxel models

- Voxel model¹: 32 weeks, 1910 g, male

Voxel models

- **Voxel model**: 22 weeks, 590 g, male

Dose and risk Overview

- Protocols
- ESD
- DAP

- Organ dose

- Conversion factors
  - NRPB
  - PCXMC
  - Simulations with Monte Carlo software

Step 3: Calculations
Radiation exposure

III. Organ doses
Different “models” give different organ doses

Example Baby 590 g
- Voxel phantom (MCNP)
- Scaled mathematical phantom (PCXMC)
Organ dose
Baby 590 g

<table>
<thead>
<tr>
<th>Dose (µGy)</th>
<th>PCXMC (scaled)</th>
<th>MCNP (voxel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lung</td>
<td>20.2</td>
<td>23.8</td>
</tr>
<tr>
<td>Heart</td>
<td>22.8</td>
<td>22.3</td>
</tr>
<tr>
<td>Thymus</td>
<td>26.6</td>
<td>23.3</td>
</tr>
<tr>
<td>Liver</td>
<td>4.8</td>
<td>7.0</td>
</tr>
<tr>
<td>Bone</td>
<td>12.3</td>
<td>12.5</td>
</tr>
<tr>
<td>RBM</td>
<td>2.2</td>
<td>3.3</td>
</tr>
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</table>

EAK: 25 µGy
<table>
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<td>2.2</td>
<td>3.3</td>
</tr>
</tbody>
</table>

**EAK: 25 µGy**

Within the field
### Organ dose

**Baby 590 g**

<table>
<thead>
<tr>
<th>Organ</th>
<th>Dose (µGy)</th>
<th>PCXMC (scaled)</th>
<th>MCNP (voxel)</th>
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<tbody>
<tr>
<td>Lung</td>
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<td></td>
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</table>

**EAK: 25 µGy**

- Partially within the field
- Same field size (7x5 cm)
### Organ dose

**Baby 590 g**

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<th>MCNP (voxel)</th>
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</thead>
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<tr>
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<td>3.3</td>
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**EAK: 25 µGy**

Widely distributed tissues
Conclusion

- It is important to investigate radiation exposures in the neonatal unit
  - Training to radiographers
  - There is room for optimization

- One has to be careful for:
  - Organ doses for organs partially in the radiation field
  - Dose to the bone/red bone marrow
Conclusion

- Image Quality
Patient doses in paediatric radiology

Thank you for your attention!