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Dosimetry For Air Travelers

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Timeline for the Development of X-Ray Backscatter Standards – Whole Body Imaging in Aviation Security

**Radiation Safety:**
ANSI/HPS N43.17-2009
Radiation Safety for Personnel Security Screening Systems Using X-Ray or Gamma Radiation

2006
5/11/06 Kickoff

2008
12/9/08 (PINS) Work Item

2010
8/19/09 (Approved) Published

**Technical Performance (Image Quality):**
ANSI-IEEE N42.47-2010

2006
5/10/06 Kickoff

2008
7/7/06 (PINS) Work Item

2010
7/26/10 Published

ANSI-IEEE N42.47 test article
Then, on 12/25/09, someone did what?!
TSA investment has been half & half to date: mm-wave vs x-ray backscatter
Bodyscreening in Aviation Security

- privacy
- effectiveness
- cost-benefit
- metrology
- dose & rates
pencil beam
(apertured, not focused)

FIG. 5a

FIG. 5b

FIG. 11

+ wide-angle detectors
Typical Source Parameters:

W target, filtration 1 mm Al equivalent, 50 kV potential
1 mm focal spot, 5 mA
Beamsize $\approx$ 5 mm x 5 mm
Horizontal sweep $\approx$ 5.5 ms
Beam velocity $\approx$ 180 m/s, passby $\approx$ 35 μs
Total scan dimensions $\approx$ 2 m height x 1 m width

How does one measure a flying spot of x rays?
National and International X-Ray Standards for Security Screening of Persons

<table>
<thead>
<tr>
<th>Venue</th>
<th>Technical Performance</th>
<th>Radiation Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole Body Imaging for aviation security</td>
<td>ANSI N42.47 – 2010</td>
<td>ANSI/HPS N43.17 – 2009</td>
</tr>
<tr>
<td></td>
<td>IEC 62709 – CDV</td>
<td>IEC 62463 – 2010</td>
</tr>
</tbody>
</table>

**guidance:**

- air filled Ionization Chamber (IC)
- integrating mode
- entire volume “painted”
- large volume (sensitivity)
- low-E spectra → thin walls → not pressurized → T&P corrections
- absolutely calibrated & traceable
In this work, the following detectors were calibrated at NIST to air kerma:

(a) Radcal 10X5-1800, cylindrical IC

&

(b) RTI R100B solid-state detector, sensitive area 1 cm²

Also used:

- RTI CTDI100 CT Dose Profiler used for time structure investigation]

- Imaging plates for high-resolution spatial mapping
Components of a single-pose system

(1) master scanner; (2) slave scanner; (3) operator console; (4) front panel of the slave scanner; (5) floor mat; (6) wings of the slave scanner.
Characterizing the spectrum

- **master unit**: HVL (mm of Al) = 1.09
- **slave unit**: HVL (mm of Al) = 1.08
NIST M50: absolute air kerma rate

Normalized Fluence Spectra [rel. u.]

- Blue line: IPEM Report 78 spectrum generator & vendor B measured high-voltage & HVL
- Red line: NIST M50 beam (HVL = 1.04 mm Al)

X-Ray Energy

Detectors calibrated fully-illuminated, CW
Exposure uniformity as function of distance

at beam exit surface

at 41 cm from beam-exit surface

“background signal” level

Pixel Column Average [arb. u.]

Pixel Column # (vertical extent of 8.5 cm)
Lateral and vertical field mapping with solid-state detector

upscan = red
downscan = black
Location, location, location (IC)

fit functions:

- $\alpha \frac{1}{r}$
- $\alpha \frac{1}{r_1 \times r_2}$ where $r_2 = r_1 + 76$ cm

Vendor A, data & fit [1 scan, 1 source]
Vendor B, data & fit [1 scan, 1 source]
NIST M50 beam & fit [0.18 mA·s]
Dose rates...

NIST M50 beam (normalized to 5 mA)

Reference distance (Vendor B)

Radcal 10X5-1800 IC

Max kerma rate = 160 μGy/s
Source time structure:

RTI CTDI100 CT Dose Profiler

5.5 ms (avg of 20 measurements)
X-RAY OF CYLINDRICAL IONIZATION CHAMBER (IC)

The IC sees a pulsed x-ray source with Interpulse Interval $\approx 5.5$ ms

$T = \text{transit time for positive ions} = \frac{(a - b) K_{cyl}}{V \cdot k}$

$= \frac{(4.5 \text{ cm})(1.05)}{(300 \text{ V})(1.36 \text{ cm}^2 \text{s}^{-1} \text{V}^{-1})}$

$\approx 55$ ms

Interpulse interval * $T \approx 10$ overlapping ion pulses during most of the scan

In this regime, the electronic recombination is effectively what would be observed with a continuous beam with the same mean dose rate.
Recombination: spatial

(1) Vendor dose limit is for a fully-illuminated IC

(2) Flying spot illuminates < 1% of IC

Finally, *in situ* measurements showed recombination to be immeasurable
# Comparison of air kerma measurements from air-filled IC and solid-state detectors

<table>
<thead>
<tr>
<th>Detector</th>
<th>Average air kerma&lt;sup&gt;1&lt;/sup&gt; (front + back scans)&lt;sup&gt;2&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ionization Chamber</td>
<td>64.2 nGy ± 1 nGy</td>
</tr>
<tr>
<td>Solid State Detector</td>
<td>65.6 nGy ± 2 nGy</td>
</tr>
</tbody>
</table>

1) After two calibrations, separated by four months  
2) At 1 m height, 30 cm from master source beam-emitting surface

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**Now, to estimation of doses to persons...**
Organ and effective dose estimates

- Spectrum + Air kerma $\rightarrow$ Dose
- Three methods were used
  - Reference effective dose (ANSI N43.17-2009)
  - PCXMC 2.0 Monte Carlo package
  - ICRP116 tables based on voxel phantom results
ANSI N43.17 ref. eff. dose

• Simple formula (no modelling)
• Based on air kerma at hottest spot
• Some problems
• 13.0 nSv (1.3 μrem)

6.1.3 Determination of the Reference Effective Dose The reference effective dose for Class A full-body scanners shall be determined from measurements of the half-value layer (HVL) and air kerma (or exposure) according to Sections 6.1.3.1 and 6.1.3.2, respectively. One of the equations (1) or (1a) below shall be used.

\[ E_{\text{REF}} = K_a \times C \quad (\text{eq.1}) \]

where

- \( E_{\text{REF}} \) is the reference effective dose in Sv,
- \( K_a \) is the measured air kerma in Gy, and
- \( C \) in Sv/Gy is given by
  
  \[ C = 0.125 \times \text{HVL in mm of Al} \quad \text{or} \quad C = 1.14, \text{whichever is smaller} \]

Or, when using traditional units the equivalent equation is

\[ E_{\text{REF}} = X \times C_R \quad (\text{eq. 1a}) \]

where

- \( E_{\text{REF}} \) is the reference effective dose in rem,
- \( X = 0.625 \times \text{HVL in mm of Al} \quad \text{or} \quad X = 1.4, \text{whichever is smaller} \)
• Monte Carlo
• Gives organ and effective doses
• age-specific hermaphrodite phantoms of Cristy and Eckerman
### Table 3: Absorbed doses in organs per screening (AP + PA) calculated using PCXMC 2.0 Monte Carlo software

<table>
<thead>
<tr>
<th>Organ</th>
<th>Adult, 30 cm from front panel of master unit (nGy)</th>
<th>Adult, 10 cm from front panel of master unit (nGy)</th>
<th>Adult, 10 cm from front panel of slave unit (nGy)</th>
<th>Child, age 5, 30 cm from front panel of master unit (nGy)</th>
<th>Infant, 30 cm from front panel of master unit (nGy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active bone marrow</td>
<td>8.4</td>
<td>10.4</td>
<td>14.1</td>
<td>12.4</td>
<td>25.6</td>
</tr>
<tr>
<td>Adrenals</td>
<td>6.7</td>
<td>6.1</td>
<td>16.2</td>
<td>8.8</td>
<td>15.4</td>
</tr>
<tr>
<td>Brain</td>
<td>4.6</td>
<td>5.3</td>
<td>6.2</td>
<td>16.5</td>
<td></td>
</tr>
<tr>
<td>Breasts</td>
<td>31.2</td>
<td>52.4</td>
<td>15.5</td>
<td>49.4</td>
<td>46.3</td>
</tr>
<tr>
<td>(Upper large intestine)</td>
<td>9.2</td>
<td>15.1</td>
<td>6.4</td>
<td>13.4</td>
<td>21.9</td>
</tr>
<tr>
<td>(Lower large intestine)</td>
<td>6.9</td>
<td>10.8</td>
<td>10.8</td>
<td>18.9</td>
<td></td>
</tr>
<tr>
<td>Extrathoracic airways</td>
<td>10.5</td>
<td>17.6</td>
<td>6.2</td>
<td>13.3</td>
<td>28.8</td>
</tr>
<tr>
<td>Gall bladder</td>
<td>8.9</td>
<td>14.5</td>
<td>6.2</td>
<td>12.9</td>
<td>19.6</td>
</tr>
<tr>
<td>Heart</td>
<td>11.3</td>
<td>18.7</td>
<td>7.2</td>
<td>17.1</td>
<td>26.4</td>
</tr>
<tr>
<td>Kidneys</td>
<td>10.8</td>
<td>9.0</td>
<td>28.7</td>
<td>14.3</td>
<td>21.1</td>
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<tr>
<td>Liver</td>
<td>11.3</td>
<td>17.2</td>
<td>10.6</td>
<td>16.8</td>
<td>26.3</td>
</tr>
<tr>
<td>Lungs</td>
<td>12.5</td>
<td>16.7</td>
<td>17.6</td>
<td>19.6</td>
<td>29.0</td>
</tr>
<tr>
<td>Lymph nodes</td>
<td>10.4</td>
<td>16.0</td>
<td>9.5</td>
<td>15.2</td>
<td>24.3</td>
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<tr>
<td>Muscle</td>
<td>17.3</td>
<td>24.2</td>
<td>21.6</td>
<td>22.5</td>
<td>29.8</td>
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<tr>
<td>Oesophagus</td>
<td>3.2</td>
<td>4.4</td>
<td>4.1</td>
<td>6.5</td>
<td>12.8</td>
</tr>
<tr>
<td>Oral mucosa</td>
<td>11.5</td>
<td>18.4</td>
<td>8.7</td>
<td>17.1</td>
<td>30.3</td>
</tr>
<tr>
<td>Ovaries</td>
<td>5.6</td>
<td>8.5</td>
<td>5.3</td>
<td>9.7</td>
<td>19.0</td>
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<tr>
<td>Pancreas</td>
<td>5.2</td>
<td>7.5</td>
<td>6.0</td>
<td>9.1</td>
<td>16.7</td>
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<tr>
<td>Prostate</td>
<td>9.0</td>
<td>14.5</td>
<td>6.5</td>
<td>12.9</td>
<td>21.2</td>
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<tr>
<td>Salivary glands</td>
<td>16.4</td>
<td>22.2</td>
<td>23.3</td>
<td>21.1</td>
<td>34.2</td>
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<tr>
<td>Skeleton</td>
<td>28.9</td>
<td>38.3</td>
<td>41.5</td>
<td>48.8</td>
<td>76.2</td>
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<tr>
<td>(Skelet)</td>
<td>27.5</td>
<td>39.3</td>
<td>32.6</td>
<td>46.7</td>
<td>76.0</td>
</tr>
<tr>
<td>(Upper Spine)</td>
<td>16.8</td>
<td>19.7</td>
<td>30.4</td>
<td>27.4</td>
<td>44.7</td>
</tr>
<tr>
<td>(Middle Spine)</td>
<td>11.5</td>
<td>10.2</td>
<td>28.8</td>
<td>20.1</td>
<td>36.4</td>
</tr>
<tr>
<td>(Lower Spine)</td>
<td>13.7</td>
<td>11.9</td>
<td>34.7</td>
<td>22.0</td>
<td>38.7</td>
</tr>
<tr>
<td>(Scapula)</td>
<td>44.3</td>
<td>35.7</td>
<td>120.5</td>
<td>38.2</td>
<td>74.7</td>
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<tr>
<td>(Rib)</td>
<td>71.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Middle arm bones)</td>
<td>33.3</td>
<td>46.5</td>
<td>42.3</td>
<td>48.2</td>
<td>75.3</td>
</tr>
<tr>
<td>(Lower arm bones)</td>
<td>40.3</td>
<td>56.2</td>
<td>51.4</td>
<td>56.3</td>
<td>83.0</td>
</tr>
<tr>
<td>(Pelvis)</td>
<td>21.1</td>
<td>21.9</td>
<td>45.2</td>
<td>32.1</td>
<td>50.0</td>
</tr>
<tr>
<td>(Upper leg bones)</td>
<td>9.8</td>
<td>13.5</td>
<td>12.5</td>
<td>26.6</td>
<td>56.2</td>
</tr>
<tr>
<td>(Middle leg bones)</td>
<td>13.6</td>
<td>19.0</td>
<td>17.3</td>
<td>33.6</td>
<td>67.3</td>
</tr>
<tr>
<td>(Lower leg bones)</td>
<td>13.9</td>
<td>39.1</td>
<td>35.7</td>
<td>53.8</td>
<td>95.2</td>
</tr>
<tr>
<td>Skin</td>
<td>43.7</td>
<td>61.1</td>
<td>54.9</td>
<td>46.6</td>
<td>52.5</td>
</tr>
<tr>
<td>Small intestine</td>
<td>7.5</td>
<td>7.8</td>
<td>16.1</td>
<td>11.4</td>
<td>19.2</td>
</tr>
<tr>
<td>Spleen</td>
<td>13.6</td>
<td>22.7</td>
<td>8.1</td>
<td>19.5</td>
<td>26.8</td>
</tr>
<tr>
<td>Stomach</td>
<td>34.8</td>
<td>59.6</td>
<td>17.0</td>
<td>47.2</td>
<td>55.4</td>
</tr>
<tr>
<td>Thymus</td>
<td>20.2</td>
<td>34.7</td>
<td>9.6</td>
<td>25.9</td>
<td>35.3</td>
</tr>
<tr>
<td>Thyroid</td>
<td>21.2</td>
<td>36.3</td>
<td>10.6</td>
<td>32.8</td>
<td>43.8</td>
</tr>
<tr>
<td>Urinary bladder</td>
<td>14.5</td>
<td>24.4</td>
<td>8.1</td>
<td>19.3</td>
<td>27.2</td>
</tr>
</tbody>
</table>

**Effective dose**

- **Effective dose ICRP103 (nSv)**: 14.7 nSv
- 23.1 nSv
- 12.3 nSv
- 21.9 nSv
- 29.8 nSv
ICRP116

- Voxel phantom based on real CT data (ICRP110)
- Kerma to dose tables
- Calculated using EGSnrc, MCNPX, PHITS, FLUKA and GEANT4
- Irradiation geometry
- 16.0 nSv (1.6 μrem)
Hoppe and Schmidt

- Estimated organ and effective dose from a body scan
- June 2012
- Used measurements made by Johns Hopkins
- MC simulation

Figure 3. The Virtual Family: Duke, Ella, Billie, Thelochus (from left to right).

Figure 4. Thelochus: skin, muscle, inner organs, blood vessels, skeleton.
Hoppe and Schmidt

• Used an excellent model of the beam geometry
• After correcting problems with air kerma normalisation and phantom position
• Estimated effective dose
  – Adult male: 14.4 nSv
  – Adult female: 15.9 nSv
Effective dose from Rapiscan Secure 1000 SP ATR

- 13.0 nSv  ANSI/HSP N43.17-2009 reference effective dose
- 14.7 nSv  PCXMC 2.0
- 16.0 nSv  ICRP voxel phantom, ICRP116 conversion coefficients and SRS-78 spectrum generator
- 15.2 nSv  Hoppe and Schmidt
Radiation Dose Comparisons (effective dose)

One day of natural background
1,000 microrem

Flight from New York to LA
4,000 microrem

Chest X Ray
10,000 microrem

One backscatter scan
5 microrem

Each tiny box represents 1 microrem

(ANSI N43.17 requires < 25 µrem / scan)