A Dosimetry Summary of CT Participants in the National Lung Screening Trial (NLST)

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Anaheim, CA
Choonsik Lee
Background
National Lung Screening Trial

• Overview
  – Compares two ways of detecting lung cancer: CT vs. chest x-ray
  – 53,454 current or former heavy smokers (ages 55 – 74)
  – Found that CT screening will reduce lung cancer mortality 15-20% more than chest X-rays*

• However, potential risks from CT radiation need to be considered for risk-benefit profile, which requires individualized organ dose assessment.

*National Lung Screening Trial Research Team, New England Journal of Medicine 2011
Dose descriptors from CT scan

- **Computed Tomography Dose Index (CTDI)\textsubscript{100}**
  - 100-mm long ion chamber measurement for a single axial rotation
- **CTDI\textsubscript{w} = \frac{1}{3} \text{CTDI}\textsubscript{100,center} + \frac{2}{3} \text{CTDI}\textsubscript{100,peripheral}**
<table>
<thead>
<tr>
<th>Series</th>
<th>Type</th>
<th>Scan Range (mm)</th>
<th>CTDIvol (mGy)</th>
<th>DLP (mGy·cm)</th>
<th>Phantom cm</th>
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<tbody>
<tr>
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<td>Scout</td>
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<td>94.69</td>
<td>946.93</td>
<td>Head 16</td>
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<td>161.650–1101.650</td>
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<td>Cine</td>
<td>12.490–12.510</td>
<td>121.14</td>
<td>242.29</td>
<td>Head 16</td>
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<td>121.14</td>
<td>242.29</td>
<td>Head 16</td>
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<td></td>
<td><strong>Total Exam DLP:</strong></td>
<td><strong>3122.36</strong></td>
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</table>
Dose descriptors from CT scan

\[ E (mSv) = DLP (mGycm) \times k \left( \frac{mSv}{mGycm} \right) \]

Table 3. Normalized values of effective dose per dose-length product (DLP) over various body regions and (standard) patient ages [33]

<table>
<thead>
<tr>
<th>Region of body</th>
<th>Effective dose per DLP (mSv (mGy cm(^{-1})) by age</th>
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<tr>
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<td>0 year old(^a)</td>
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<td>Head and neck</td>
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<td>Chest</td>
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<td>Abdomen and pelvis</td>
<td>0.049</td>
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<tr>
<td>Trunk</td>
<td>0.044</td>
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</table>

CTDIm vs. organ dose

Organ dose per CTDIm 32 cm (AP scan of adult male)*

* Lee et al. Medical Physics (2011)
Two approaches to **organ dose** estimation in CT

**MEASUREMENT**
- Reliable
- Expensive
- Substantial man-hour
- Not flexible

**CALCULATION**
- Validation required
- Cost-effective
- Fewer man-hour
- More flexible
CT Dosimetry Programs

Existing CT dose calculators are limited to fixed-size stylistic phantom and not designed for a large scale dosimetry.

ImPACT CT Dosimetry Calculator (NRPB)
More recent developments:

**WAZA-ARI** (Japan)

- Under beta testing
- Japanese adult male/female
- Web-interface
More recent developments:
*VirtualDose™CT* (Virtual Phantoms™ Inc)

- Commercial solution
- Pediatric/adult phantoms
More recent developments:

**eXposure™ (Radimetrics™ Inc)**

- Commercial solution
- Advanced interface between dosimetry tool and PACS
- Adopted by a large number of clinical centers worldwide
- Based on pediatric and adult stylized phantoms
More recent developments: **GPU-based** on-site dose calculation

- Calculate dose distribution right after CT images are reconstructed.
  - Kalender et al. (Germany)
  - Xu et al. (RPI, USA)

- Not appropriate for epidemiologic study
  - Only provide 3D dose distribution
  - Organ segmentation is required for organ dose calculation
ICRP Reference Pediatric and Adult Phantoms

ICRP Publication in progress

Newborn 1-year 5-year 10-year 15-year Female 15-year Male

Adult Female Adult Male

ICRP Publication 110
Scanner-independent organ dose

Scanner Model 1  Scanner Model 2  Scanner Model 3

\[
\frac{\text{Organ Dose 1}}{CTD_{vol1}} \cong \frac{\text{Organ Dose 2}}{CTD_{vol2}} \cong \frac{\text{Organ Dose 3}}{CTD_{vol3}}
\]

*COV less than 5% (Turner et al. MP 2010)
Algorithm for organ dose calculations

Machine Output

\[
CTD\text{I}_\text{vol}(m\text{Gy}) = \frac{nCTD\text{I}_\text{w}(m\text{Gy/mAs})}{\text{Pitch}} \times \text{mAs}
\]

CTDI Library (from measurements)

Patient Dose

Organ Dose (mGy) = \text{Dose Coefficients (mGy/mGy)} \times CTD\text{I}_\text{vol}(m\text{Gy})

Organ Dose Library (from calculations)
National Cancer Institute dosimetry system for Computed Tomography (NCICT)*

ICRP Reference Phantoms

Reference CT Scanner Model (Siemens Sensation 16)

Organ Dose Library

Organ dose normalized to CTDI_{vol} (mGy/mGy)

CTDI Library

CTDI_{w} normalized to mAs (mGy/mAs)

Experimental Validation

• UK Survey
• German Survey
• NEXT Survey (US FDA)
• NLST measurement

*Lee et al. Medical Physics (in review)
CT scanner modeling

Monte Carlo dose calculations

– Phantoms were coupled with a CT scanner simulation model* within a Monte Carlo transport code, MCNPX2.7.
– Organ dose normalized to CTDI$_{vol}$ (mGy/mGy) were calculated using a computing server (Mac Pro)

Dose conversion coefficients

- Dose coefficients calculated for a series of axial scans.
- Organ doses for a given scan range were approximated as the sum of doses from multiple axial slices included in the scan range of interest.
Objectives

Method Development

• To extend the NCICT program to body size-specific computational phantoms

Application

• To calculate individualized organ doses in CT screening for a subset of the total NLST cohort

• To compare organ doses based on reference size phantoms vs. size-specific phantoms
Materials and Methods
CT scan data collection from the NLST

- 23,773 CT scans (body size available) identified.
- Patient ID, gender, **height**, **weight**, scan length, kVp, and CTDI$_{vol}$ were collected from DICOM data.

- 9,406 females and 14,367 males
- Mean height: 173 cm (125 – 231 cm)
- Mean weight: 84 kg (39 – 202 kg)
ICRP Reference Adult Phantoms

Adult Female
163 cm
60 kg

Adult Male
176 cm
73 kg
Body size-dependent computational phantoms*

Body size-dependent computational phantoms*

100 male and 93 female phantoms were used to calculate organ dose conversion coefficients (mGy/mGy)

Body size-specific dose conversion coefficients

- Organ dose conversion coefficients (mGy/mGy) were calculated for 100 male and 93 female adult phantoms.
Organ dose calculations

- **Thyroid, heart, and lung doses** calculated for 23,773 NLST CT scans using:
  - Reference size phantoms ignoring patient body size
  - Body size-specific phantoms using patient body size
Batch Module in NCICT-X
(with or without CTDI<sub>vol</sub>)

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Results
NCICT-eXtended

Dose (organ, slice, *6 ages, 2 genders*, spectra)

Dose (organ, slice, *pediatric/adult, height, weight*, spectra)

- Full calculation of dose coefficients took 7 months and incorporated into NCICT-eXtended program.
Organ dose conversion factors

- We established a comprehensive library of organ doses normalized to CTDI_{vol} (mGy/mGy) for reference and size-specific adult phantoms.

<table>
<thead>
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<th>Reference Library</th>
<th>Extended Library</th>
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<tr>
<td>31 organs</td>
<td>31 organs</td>
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<tr>
<td>176 slices max</td>
<td>190 slices max</td>
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<tr>
<td>2 genders</td>
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<tr>
<td>6 X-ray spectra</td>
<td>6 X-ray spectra</td>
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<tr>
<td></td>
<td>7 height bins</td>
</tr>
<tr>
<td></td>
<td>19 weight bins</td>
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</tbody>
</table>
Results: Size-specific organ doses for NLST

Thyroid dose distribution

Mean: 1.8 mGy (SD=0.6)
Results: Size-specific organ doses for NLST

Heart dose distribution

Mean: 4.8 mGy (SD=1.6)
Results: Size-specific organ doses for NLST

Lung dose distribution

Mean: 4.6 mGy (SD=1.5)
Previous study based on CT- Expo

Unrealistic thyroid location

Visible Human Project Anatomy

ORNL Stylized Phantom

*C Lee and J Lee Medical Physics (2004)*
Results: Lung dose comparison

Ratio of lung doses from reference phantoms to those from size-specific phantoms

Reference phantom is **overestimating** lung dose based on size-specific phantoms
Results: Lung dose comparison

Ratio of lung doses from reference phantoms to those from size-specific phantoms

Reference phantom is underestimating lung dose based on size-specific phantoms

Underweight: BMI 16-18.5
Obese: BMI > 30
Overweight: BMI 25-30
Severely underweight: BMI < 16
Underweight: BMI 16-18.5
Normal: BMI 18.5-25

Percent of scans (%)
Conclusion

• We developed a method to estimate patient size-specific organ doses.

• We calculated individualized organ doses for 23,773 CT scans involved in the NLST.

• The established dose conversion factors can be also used for other studies including patient dose monitoring and epidemiological studies of cancer risk.
Future work

• Include additional organs
  – Ovaries and uterus in adult female patients
  – Fetus dose in pregnant female patients in different pregnancy stages

*Maynard et al. PMB (2014)
Which of the following information from the patient records was most useful in organ dose assessment for the chest CT arm of the trial?

1. Tube current-time product (mAs)
2. Tube potential (kVp)
3. $\text{CTDI}_{\text{vol}}$ (mGy)
4. Scanner model
5. Scan length (cm)
Answer: 3. CTDI\textsubscript{vol}

Mean lung dose of the NLST low dose CT patients was about:

- **5%** 1. 0.1 mGy
- **58%** 2. 2 mGy
- **36%** 3. 5 mGy
- **1%** 4. 10 mGy
- **0%** 5. 20 mGy
Answer: 3.5 mGy

Dose calculation methods based on the reference size phantoms lung doses of obese (BMI >30) CT patients in the trial.

1. Accurately estimated
2. Overestimated up to 60%
3. Overestimated up to 200%
4. Underestimated up to 60%
5. Underestimated up to 200%
Answer: 2. Overestimated up to 60%