Applications of Advanced Phantoms for Radiation Dosimetry in CT, PET and Radiotherapy

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Acknowledgements

Rensselaer Radiation Measurements and Dosimetry Group (RRMDG): http://RRMDG.rpi.edu

Current Students/Research Staff

Alumni (Not including undergraduate)
Acknowledgements

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- H Paganetti, H Jiang, B Bednarz, H Suit, G Chen, B Liu, A Trofimov, Y Wang, MGH
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Conflict of Interest

Committees
- CIRMS, 1998 – present
- NCRP Council Member, 2008 – present
- ICRP DOCAL Committee, 2005 – present
- RADAR, 2005 – present
- AAPM TG-158, 2007 – present
- AAPM TG-180, 2008 – present

Companies
- Acetech
- Virtual Phantoms, Inc
Patient Phantoms  
(Full-Body vs. Partial-Body)

**Full Body Model**

**Visible Human**
- 0.33 X 0.33 X 1 mm$^3$
- Whole body
- More than 100 organs are segmented / labeled

**Partial Body Model**

**CT images**
- 5mm x 20 slices
- Only the PTV and OARs are outlined

Many applications rely on “full-body” phantoms
- Radiation protection of workers
- Imaging (PET for example)
- Out-of-field organ doses
Two Ways to Determine Organ Doses

**Measurements**

- Dosimeters
- Physical phantom

**Monte Carlo Simulations**

- Computational phantoms
- Monte Carlo codes

AP  PA  RLAT  LLAT
Organization of Slides

1. **Intro to Patient Phantoms**
2. MDCT, CBCT, PET/CT Dose
3. Electronic Brachytherapy Dose
4. External-Beam Dose (out-of-field)
5. Respiration in External Beam
Simplified MIRD-type Phantoms Used as ICRP “Reference Man” for 40 Years
(SNM’s MIRD Committee)

Stomach defined as concentric ellipsoids:

\[
\left(\frac{x - x_0}{a}\right)^2 + \left(\frac{y - y_0}{b}\right)^2 + \left(\frac{z - z_0}{c}\right)^2 \leq 1
\]

Head/brain model by Bouchet et al. J. NM (37)1226-1236; 1996.

Stylized adult by Cristry and Eckerman 1987 (MIRD report)
Simplified Models Used To Study Secondary Cancers of Patients for Years at MDACC

ICRP Paradigm Change in Phantom

ICRP 2002 Annual Report:

“An important issue for Committee 2 is the substitution of an anatomically realistic voxel phantom, obtained digitally in magnetic resonance tomography and/or computed tomography, for the MIRD phantom which is a mathematical representation of a human body.”
Work at RPI: VIP-Man Phantom
(Visible Human Project Visible Images)
(Courtesy of NLM)

Color Photography
(0.33mm x 0.33mm x 1mm)

Computed Tomography
(1mm x 1mm x 1mm)

Magnetic Resonance Imaging
(4mm x 4mm x 4mm)
VIP-Man Phantom Segmentation and Labeling

Original Color Photo

Segmented Slice

Labeled

3D Rendering
Challenges

**Computer Memory**
- Visible Man (0.33mm x 0.33mm x 1mm) is 3.7 GB data set
- The max. allowable RAM is < 2 GB

**Monte Carlo Codes**
- EGS4 and MCNP4b/MCNPX had to be enhanced for handling such huge voxel data

**Computer Timing**
- The smaller the voxel size, the longer to run (~several hours)
VIP-Man Phantom For Radiation Dosimetry


EGS4 Code

0.33 mm x 0.33 mm x 1 mm Resolution Photons / Electrons

MCNP5 Code

4 mm x 4mm x 4 mm Resolution Photons/Electrons/Neutrons

MCNPX Code

And

GEANT4 Code

Protons etc

Dr. T.C. (Ephraim) Chao,
Class 2001

Dr. Ahmet Bozkurt,
Class 2000
Earlier Pregnant Female Phantoms

Stylized models

Partial-body CT phantom (7-month)


Shi and Xu (2004)
A New Method of Morphing and Deforming

Weight-Dependent Percentile Phantoms

• Same height (e.g. 176cm Male), but different weights:

<table>
<thead>
<tr>
<th>Weight</th>
<th>58.5kg</th>
<th>66.3kg</th>
<th>73.1kg</th>
<th>86.4kg</th>
<th>103.8kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentile</td>
<td>5th</td>
<td>25th</td>
<td>50th</td>
<td>75th</td>
<td>95th</td>
</tr>
</tbody>
</table>

The skin meshes from an open source software, MakeHuman™ version 0.9.1 RC1 (http://www.makehuman.org/), were adopted.
Weight & Height-Dependent Percentile Phantoms

• Described the different sizes in both weight and height

**Male**
- Weight: 56.1kg, 73.0kg, 110.9kg
- Height: 165cm, 176cm, 188cm

**Female**
- Weight: 41.0kg, 60.0kg, 91.0kg
- Height: 152cm, 163cm, 173cm

**Percentile**
- 5th, 50th, 95th
The Latest RPI Adult Male and Female Phantoms

In 2005, the research group led by Xu et al. at RPI used the 3D VIP-Man phantom to simulate respiratory motions by adopting the gated respiratory motion data of the NCAT phantom. The 3D VIP-Man Chest phantom was used to study external-beam treatment planning for a lung cancer patient. The group decided to apply the BREP techniques to a more challenging problem and, in 2007, made a breakthrough in the development of a set of phantoms representing a pregnant woman and her fetus at the end of 3rd, 6th, and 9th months gestation.

These phantoms, referred to as RPI Pregnant Female, were defined in polygonal meshes that were derived from separate anatomic information of a non-pregnant female, a 28-month pregnant woman CT data set, and a mesh model of the fetus. The organ volumes were adjusted in the mesh format using a commercial software package. The paper by Xu et al. was rated one of the 10 best papers in 2007 by Physics in Medicine and Biology. Chapter 12 presents details on this set of phantoms. Continuing their triangular mesh approach, this group reported in 2008 the development of a pair of adult male and female phantoms, the so-called RPI Deformable Adult Male and Female. As described in Chapter 14, this pair of adult phantoms was carefully adjusted to match the ICRP-59 reference values for more than 70 organs and 45 bones (including cortical bone, spongiosa, and cartilage) as well as muscles. Several software algorithms were systematically developed to automate the deformation and organ overlay detection that were based entirely on about 126 sets of triangle meshes. The RPI Deformable Adult Male and Female phantoms are mesh-based BREP phantoms.
Posture-adjustable phantoms

- Raised Arms
- Sitting
- Walking
Founding members of The Consortium of Computational Human Phantoms (CCHP):

X. George Xu, Rensselaer Polytechnic Institute (Contact Person, xug2@rpi.edu), USA
Wesley E. Bolch, University of Florida, USA
Loic de Carlan, IRSN - Institute of Nuclear Safety and Radiation Protection, France
Martin Caon, Flinders University, Australia
Keith F. Eckerman, Oak Ridge National Laboratory, USA
Rickard Kramer, Federal University of Pernambuco, Brazil
Choonsik Lee, Hanyang University, Korea
Tomoaki Nagaoka, Kitasato University Graduate School of Medical Sciences, Japan
Lawrence S. Pinsky, University of Houston, USA
Kimiaki Saito, Japan Atomic Energy Research Institute, Japan
William Segars, Johns Hopkins University, USA
Michael G. Stabin, Vanderbilt University, USA
Maria Zankl, GSF - National Research Center for Environment and Health, Germany
George Zubal, Yale University, USA

www.virtualphantoms.org
Available since 2009

- 30 chapters
- 64 authors
- 13 countries (regions)
- 100+ phantoms
<<Handbook of Anatomical Models for Radiation Dosimetry>>
– courtesy sample images from various authors

REX & REGINA (ICRP)  NORMAN  MAX06  FAX06  Zubal  NCAT  VIP-Man, Pregnant, Adult M/F

Otoko Onago  JM  KF  KTMAN 1, 2  CNMAN  VCH  Vanderbilt Family  UF Family

www.virtualphantoms.org
Organization of Slides

1. Intro to Patient Phantoms
2. MDCT, CBCT, PET/CT Dose
3. Electronic Brachytherapy Dose
4. External-Beam Dose (out-of-field)
5. Respiration in External Beam
“Imaging dose” is NOT negligible.

The question is: “What can we do about it in radiation treatment?”
Imaging Dose from IGRT Too Great To Be Ignored - A Prostate IGRT “worst” Scenario

• Volume definition: (Courtesy of Y i Wang and Alex Trofimov, MGH)
  GTV: Prostate
  CTV: Prostate + SVs up to 1 cm superior to prostate
  PTV1: CTV + 5 mm margin
  PTV2: GTV + 5 mm margin

• Dose prescription:
  50 Gy in 25 fractions to PTV1
  Boost of 28 Gy in 14 fractions to PTV2

• Coverage: PTV2>97% at 78 Gy, PTV1>97% at 50 Gy

• Dose constraints to organs at risk (MGH criteria):
  Rectum: V_{75}<10\% and V_{70}<25\%
  Bladder: V_{80}<15\% and V_{75}<25\%, no hotspot over 105\%
  Femoral heads: No volume > 45 Gy

If CT scan is performed for each fraction, will dose from 40 CT scans affect constraints for OARs?
Prostate, Bladder and Rectum shown in CERR
Patient-Specific CT to Imaging Dose

- CT numbers converted to density and assigned composition
- Voxel phantom to MCNPX code
- GE LightSpeed 16 Scanner
- Dose to rectum, bladder, and prostate
Methods: MDCT Scanner Modeling

CT setup with CTDI phantom

GE LightSpeed 16 scanner model
(Gu et al, PMB 2009)
Treatment Plans for Prostate IMRT

What is “imaging dose” of 1 Gy is added?

Constraints: Rectum: V75 < 15%, V70 < 25%
### Basic Parameters

<table>
<thead>
<tr>
<th></th>
<th>kV CBCT</th>
<th>MV CBCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field of view (at isocenter)</td>
<td>17 cm x 25 cm</td>
<td>27.4 cm x 27.4 cm</td>
</tr>
<tr>
<td>Tube potential</td>
<td>125 kVp</td>
<td>6 MV</td>
</tr>
<tr>
<td>Tube current</td>
<td>25 mA /</td>
<td></td>
</tr>
<tr>
<td>Exposure time</td>
<td>320 ms /</td>
<td></td>
</tr>
<tr>
<td>Projection number</td>
<td>675 /</td>
<td>200</td>
</tr>
<tr>
<td>Total mAs for CBCT acquisition</td>
<td>5400 mAs</td>
<td>~ 2 MUs</td>
</tr>
<tr>
<td>Angular range of projection views</td>
<td>364</td>
<td>200 (rotation from 270-110)</td>
</tr>
</tbody>
</table>

### Effective Dose

<table>
<thead>
<tr>
<th></th>
<th>kV CBCT</th>
<th>MV CBCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head and Neck (mSv)</td>
<td>37.9</td>
<td>369.6</td>
</tr>
<tr>
<td>Prostate (mSv)</td>
<td>36.5</td>
<td>574.4</td>
</tr>
</tbody>
</table>

( The photon energy spectrum for 125 kVp, courtesy of Steve B. Jiang )

( The photon energy spectrum for 6 MV, courtesy of Bryan Bednarz )
Summing Imaging Doses

• For assessing “risk” and comparing procedures
  – Use “organ dose” and “effective dose”
  – Population phantoms OK

• For treatment planning
  – Use “voxel dose” to Organs at Risk (OARs)
  – Patient-specific CT phantoms (and TP software?)
Existing CT Software Packages Do Not Meet the Needs

(1) 40-year-old stylized patient phantoms
(2) No pregnant or pediatric patients
(3) Single average body morphometry
(4) Modern MDCT scanners and features not covered
(5) The Effective Dose algorithm based on ICRP-60, not ICRP-103
(6) Poor GUIs (for example, spreadsheet-based)
(7) Developed by people only from Europe
Work at RPI to develop a new software for CT Dose, *VirtualDose*

- A easy to use graphical user interface (GUI)
- Interactive 3D phantom rendering
- Scan parameters can be interactively specified on GUI
CT Organ Dose Using VirtualDose Software

Software Features

User input parameters

- CT Manufacturer
- Type of scanner
- kVp for the scanner
- Collimation for the scanner
- mAs and rotation time
- Phantom type
- Pitch
- Scan range on the 3D patient phantoms displayed on the GUI directly
- Standard scan protocols from a drop-down Combo box
PET/CT protocol (Discovery LS and ST, GE Healthcare): Topogram (A), or scout scan, is obtained for positioning. Spiral CT scan (B) is obtained, followed by a PET scan (C) over the same axial range as B. CT based attenuation-correction factors are generated (D), and attenuation-corrected PET emission data are reconstructed (E). Finally, fused CT and PET images are displayed (F).


Internal dose from PET + external dose from CT
Existing Nuclear Medicine Dose Software

• MIRDose replaced by OLINDA
• OLINDA/EXM 1.0 approved by FDA 2005 (distribution via Vanderbilt)
  – Only stylized phantoms and ICRP-60 are used
• NIH STTR grant (Stabin, Brill and Xu)
• OLINDA/EXM 2.0 will include voxel family phantoms and ICRP-103 algorithms

There is currently NO single software tool for PET/CT dose

Image courtesy of Mike Stabin
PET/CT Protocols (adults whole-body)

PET: 555 MBq (15 mCi) of F-18

<table>
<thead>
<tr>
<th>CT</th>
<th>Range</th>
<th>kVp</th>
<th>mAs</th>
<th>Beam Collimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>low dose non-contrast CT</td>
<td>Whole Body</td>
<td>140</td>
<td>25</td>
<td>20 mm</td>
</tr>
<tr>
<td>attenuation correction (CTAC)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard Diagnostic CT</td>
<td>Whole Body</td>
<td>140</td>
<td>200</td>
<td>20 mm</td>
</tr>
</tbody>
</table>

Adopted from Bob Liu, MGH
PET Dose Calculations using OLINDA/EXM 1.1 (Courtsey of Mike Stabin)

Main Menu

Nuclide Selection

Model Selection

Biokinetic Input (ICRP-106 Biokinetics Data)
 Radiation Risk Indicators

**Effective Dos (ED) defined in ICRP-60 (1991)**

1) Organ “Equivalent Dose”: \( H_T = \sum R_w R D_{T,R} \)
2) Total Body “Effective Dose” = \( \sum T w_T H_T \)

<table>
<thead>
<tr>
<th>Tissue or Organ</th>
<th>( w_T, ) ICRP 26</th>
<th>( w_T, ) ICRP 60</th>
<th>( w_T, ) ICRP 103</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gonads</td>
<td>0.25</td>
<td>0.20</td>
<td>0.08</td>
</tr>
<tr>
<td>Red Bone Marrow</td>
<td>0.12</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td>Colon</td>
<td>Not given</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td>Lung</td>
<td>0.12</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td>Stomach</td>
<td>Not given</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td>Bladder</td>
<td>Not given</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>Breast</td>
<td>0.15</td>
<td>0.05</td>
<td>0.12</td>
</tr>
<tr>
<td>Liver</td>
<td>Not given</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>Esophagus</td>
<td>Not given</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>Thyroid</td>
<td>0.03</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>Skin</td>
<td>Not given</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Bone surface</td>
<td>0.03</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Brain</td>
<td>Not given</td>
<td>Not given</td>
<td>0.01</td>
</tr>
<tr>
<td>Salivary glands</td>
<td>Not given</td>
<td>Not given</td>
<td>0.01</td>
</tr>
<tr>
<td>Remainder*</td>
<td>0.30</td>
<td>0.05</td>
<td>0.12</td>
</tr>
</tbody>
</table>

**Occupational dose limits:**
- 0.5 Sv per year for an organ
- 0.02 Sv per year total body
# PET Dose OLINDA Results

$^{18}$F-FDG PET emission scan using ICRP-106 Biokinetics

<table>
<thead>
<tr>
<th>Phantom</th>
<th>ICRP-60 ED (mSv/MBq)</th>
<th>Admin. Activity (MBq)</th>
<th>ED (mSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adult Male</td>
<td>$1.85 \times 10^{-2}$</td>
<td>555</td>
<td>10.3</td>
</tr>
<tr>
<td>Adult Female</td>
<td>$2.41 \times 10^{-2}$</td>
<td>555</td>
<td>13.4</td>
</tr>
</tbody>
</table>
CT Organ Dose Using *VirtualDose* Software

(Adult female)

- Organ dose from low dose CT
- Organ dose from diagnostic CT

<table>
<thead>
<tr>
<th>Organ</th>
<th>Organ Dose (mGy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gonads</td>
<td>23.0</td>
</tr>
<tr>
<td>Red Bone Marrow</td>
<td>19.0</td>
</tr>
<tr>
<td>Colon</td>
<td>24.0</td>
</tr>
<tr>
<td>Lung</td>
<td>26.0</td>
</tr>
<tr>
<td>Stomach</td>
<td>20.0</td>
</tr>
<tr>
<td>Bladder</td>
<td>18.0</td>
</tr>
<tr>
<td>Breast</td>
<td>16.0</td>
</tr>
<tr>
<td>Liver</td>
<td>25.0</td>
</tr>
<tr>
<td>Esophagus</td>
<td>6.0</td>
</tr>
<tr>
<td>Thyroid</td>
<td>12.0</td>
</tr>
<tr>
<td>Skin</td>
<td>14.0</td>
</tr>
<tr>
<td>Bone surface</td>
<td>10.0</td>
</tr>
<tr>
<td>Remainder*</td>
<td>3.0</td>
</tr>
</tbody>
</table>

*Note: Organ dose from diagnostic CT is shown in red, while organ dose from low dose CT is shown in blue.*
CT Organ Dose Using *VirtualDose* Software (adult male)

![Bar chart showing organ doses for different organs in low dose and diagnostic CT scans.](image_url)
## Combined PET/CT Doses

<table>
<thead>
<tr>
<th>Scan parameter</th>
<th>MDCT</th>
<th>PET/CT</th>
</tr>
</thead>
<tbody>
<tr>
<td>U (kVp)</td>
<td>120</td>
<td>140</td>
</tr>
<tr>
<td>mAs per rotation</td>
<td>100</td>
<td>25 (low dose), 200 (diagnostic)</td>
</tr>
<tr>
<td>Beam collimation (mm)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Pitch</td>
<td>1.375</td>
<td>1.375</td>
</tr>
<tr>
<td>E (mSv)</td>
<td>Female 10.5; male 8.1</td>
<td>Female 2.6, male 2.6 (low dose); Female 21.0, male 16.1 (diagnostic); Female 13.4, male 10.3 (PET)</td>
</tr>
</tbody>
</table>

**Total ~ 40 mSv**

(compare with ICRP limits for workers on next slide)
Uncertainty in Risk Assessment and Worrisome Trends about Patient Exposure

ICRP Occupational Limits:
- 500 mSv / year for an organ
- 20 mSv / year total body

These limits are for workers. However, the radiation risk for a given dose is the same. The risk for single PET/CT (40 mSv) is still small when compared with the clinical benefit. But the risk to the society as whole is not negligible and may continue to rise due to widespread uses
Organization of Slides

1. Intro to Patient Phantoms
2. MDCT, CBCT, PET/CT Dose
3. Electronic Brachytherapy Dose
4. External-Beam Dose (out-of-field)
5. Respiration in External Beam
• In 2005, the FDA approved S700 Axxent™ X-ray source for treatment of early-stage breast cancer

• Electronic brachytherapy has advantage:
  o lower energy (20 to 50 keV)
  o tunable energy
  o can instantly turn off radiation

• Patient-specific dosimetry needed to consider inhomogeneities and healthy organs away from target
Objectives

• Compare HDR Ir-192 and electronic balloon breast brachytherapy dosimetry in tissue using Monte Carlo methods and a whole-body phantom

• Examine healthy tissue dose distant from the treatment site

Mille M, Xu XG, Rivard MJ. Medical Physics, 37(2):662-671, 2010
Materials: Whole-body Female Phantom

- Deformable, mesh-based computational model
- ICRP reference woman characteristics
  - Height = 163 cm
  - Weight = 60 kg
- Over 140 organs and tissues
- Voxel Size 2.5 mm x 2.5 mm x 2.5 mm
  - ≈ 24 million voxels

(Na et al., Wednesday, 5:24 PM, Monte Carlo General I)
Methods: Monte Carlo Simulation of Treatment

Mille M, Xu XG, Rivard MJ. Medical Physics, 37(2):662-671, 2010

• Treatment assumptions:
  o 4.4 cm diameter MammoSite™ balloon with saline
  o Lumpectomy cavity in left breast
  o 34 Gy delivered in 10 fractions (5 min.) to PTV

• Use Monte Carlo to calculate dose to various organs for electronic and HDR Ir-192 source

• MCNPX results provided per photon, must convert to dose rate
Methods: Monte Carlo Source Modeling

**Electronic Source**
- Experiment measurement of 50 kVp photon spectrum
  (Rivard et al., Med. Phys., 2006)
  - $E_{\text{avg}} \approx 26.6$ keV

**HDR Ir-192 Seed**
- Discrete gamma spectrum
- 2.13 photons per disintegration
- Betas ignored
  - $E_{\text{avg}} \approx 372$ keV
Methods: Virtually Implanted Balloon

- Balloon
- Left Lung
- Right Lung
- Heart
Results: Radial Dose Rate In Water

![Graph showing the relationship between Dose Rate (Gy/min) and Radial Distance (cm) for PTV Outer Edge and Electronic. The graph indicates a decreasing trend as the radial distance increases.]
Results: Organ Doses

34 Gy treatment

- Electronic

Dose (cGy)

- Ovaries
- Thyroid
- Thymus
- Spleen
- Skin
- Salivary...
- Pancreas
- Esophagus
- Right Lung
- Left Lung
- Liver
- Kidneys
- Heart...
- Heart wall
- Large...
- Small...
- Stomach...
- Eye Lenses
- Brain
- Tongue
- Adrenal...
However Rib Dose Higher for eBx (volume% for each dose level)

<table>
<thead>
<tr>
<th>Dose (Gy)</th>
<th>Rib4 (ipsilateral)</th>
<th>Tissue</th>
<th>50 kVp eBx</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HDR $^{192}$Ir</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.1</td>
<td>22.4% ± 0.3%</td>
<td></td>
<td>20% ± 0.1%</td>
</tr>
<tr>
<td>6.8</td>
<td>18.5% ± 0.1%</td>
<td></td>
<td>18% ± 0%</td>
</tr>
<tr>
<td>10.2</td>
<td>13.5% ± 0.1%</td>
<td></td>
<td>15.5% ± 0%</td>
</tr>
<tr>
<td>13.6</td>
<td>10.2% ± 0.1%</td>
<td></td>
<td>13.6% ± 0.1%</td>
</tr>
<tr>
<td>17.0</td>
<td>7.6% ± 0.1%</td>
<td></td>
<td>11.9% ± 0%</td>
</tr>
</tbody>
</table>

Mille M, Xu XG, Rivard MJ. Medical Physics, 37(2):662-671, 2010
Summary and Future Direction

• Dickler et al. (*Brachytherapy* 2007) showed similar target dose for both modalities

• Healthy tissue dose may be critical in selection

• Rib dose disadvantage of eBx

• eBx dose distribution is complex, future studies should consider many factors using advanced MC-based treatment planning
  - distant healthy tissues, inhomogeneities, backscattering from different body sizes, imaging contrast, etc.
Organization of Slides

1. Intro to Patient Phantoms
2. MDCT, CBCT, PET/CT Dose
3. Electronic Brachytherapy Dose
4. External-Beam Dose (out-of-field)
5. Respiration in External Beam
Secondary Cancer from “Out-of-field” Doses from Radiation Therapy: A Price to Pay for Successful RT


- Cancer patients survive and live longer
- Patients younger
- IMRT requires greater MU (x3 3DCRT)
- Neutrons (18-MV x-rays and protons)
Monte Carlo Modeling of Medical Accelerators


- Include both accelerator model and computational phantom
- The Accelerator Details:
  - Varian blueprints of 2100C
  - Model by Kase et al. in HPJ
- The Patient Details:
  - RANDO Phantom
  - VIP-Man
  - Pregnant patients
  - RPI adult male and female
Organization of Slides

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Is Management of Respiratory Motion the “Next Big Thing?"

- Techniques:
  - Conventional 3D plan increases PTV size
  - Breath-hold techniques (ABC)
  - Respiratory gating
  - Others (couch synchronization etc.)

- 4D planning is essential

Courtesy of C Shi
Organ Motion is Best Modeled by Boundary Representation (BREP)

- Surfaces and volumes are built up from constituent parts
- Related with algebraic functions or complex functions or \textit{B-splines (advanced BREPS)}
- Used in most CAD and movie industries

\textbf{Non-Uniform Rational B-Splines (NURBS)}

- Xu and Shi 2005 at Monte Carlo 2005
- Shi and Xu at AAPM 2005

NCAT phantom courtesy of Paul Segars
Physics-Based Respiration Model - “Ground Truth”
- No Image Artifact
- Predictive

3D anatomy → Tissue mechanical modeling → Patient-specific data → 4D real time motion model → 4D Treatment planning and delivery → Prediction
Finite Element Modeling Using ABAQUS/standard
- linear and nonlinear material
- contact modeling with friction

Courtesy of J Eom
- 3 data sets are ready to use
- Additional 6 data set is under way

Courtesy of J Eom
Correlation between external marker and respiratory motion

Courtesy of J Eom
4D Geometry-Based Respiration Modeling

Two Treatment Plans Simulated in Monte Carlo Code

Treatment Planning #1 (gating TP)
- The center of ODM is aligned to the lesion in Phase 1 (early inhalation), i.e., 3D treatment planning

Treatment Planning #2 (4D TP)
- The “image-guided” 4D TP where PTV moves according to 8 phases
Results: Case #1

- The center of ODM is always kept conformal to the center of the lesion in Phase 1.
- The data show that dose distributions in phase 3 and phase 4 are under-dosed.
Different medical exposures and doses (Xu et al. PMB 2008)

<table>
<thead>
<tr>
<th>Radiation Type</th>
<th>Energy (MeV)</th>
<th>Approximate Dose (Gy)</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary target</td>
<td>Tissue outside the treatment volume</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Radiotherapy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. External Beam</td>
<td>X-ray photons, electrons, protons and neutrons</td>
<td>6-250</td>
<td>Low dose region: D&lt; 5 Gy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MeV</td>
<td>Intermediate dose region: 5 Gy &lt; D &lt; 45 Gy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>and neutrons</td>
<td>High dose region: D &gt; 45 Gy</td>
</tr>
<tr>
<td>b. Brachytherapy</td>
<td>Gamma-ray photons, electrons, and neutrons (Ra-226, Cs-137, Ir-192, I-125, etc)</td>
<td>&lt; 2</td>
<td>~ 1 Gy</td>
</tr>
<tr>
<td>c. Radioimmuno-therapy (RIT)</td>
<td>Photons, electrons, alphas (Y-90, Bi-214, etc)</td>
<td>&lt; 5</td>
<td>~ 10 Gy</td>
</tr>
</tbody>
</table>

2. Diagnostic Imaging

<table>
<thead>
<tr>
<th>Imaging</th>
<th>Energy (MeV)</th>
<th>Approximate Dose (Sv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Radiography</td>
<td>X-ray photons</td>
<td>&lt;150 kVp</td>
</tr>
<tr>
<td>a. Multi-slice CT (4D)</td>
<td>X-ray photons</td>
<td>&lt;140 kVp</td>
</tr>
<tr>
<td>c. Interventional Fluoroscopy</td>
<td>X-rays photons</td>
<td>&lt;140 kVp</td>
</tr>
<tr>
<td>d. Hybrid PET/CT</td>
<td>Photons/positrons</td>
<td>0.511 keV</td>
</tr>
<tr>
<td>e. Cone beam CT IGTR</td>
<td>X-ray photons</td>
<td>KV or MV</td>
</tr>
</tbody>
</table>

Adopted from Hall
Summary and Future Directions on Phantoms

• Both population (average) and patient-specific
• Ability to deform and morph
• Family of various ages and body sizes/shapes
• Physical and physiological details (vs geometry)
• Software based
• Easy to end-users
Summary and Future Directions on CT and PET/CT

• Integrated software for PET/CT dose assessment
• Dose reduction features such as “tube current modulation”
• Software
• Patient of various ages and body sizes/shapes
• Patient-specific CT to dose
• Multi-modality
• Be part of treatment planning (?)

Siemens Biograph Care Dose
http://www.medical.siemens.com/