Tissue Density Correction in Radiotherapy Dose Calculation

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Outline

• Joke of the day
• Audience questions
• What are tissue densities?
• Why perform tissue density corrections?
• Some Physics speak.
• Some of my experiments.
• Other smarter people’s experiments.
What are tissue density corrected dose calculations?

• Energy from radiotherapy x-rays is absorbed as it travels through a material.
• Historically, the dose was calculated assuming the patient is entirely water.
• This was a reasonable approximation for most tissues (muscle, fat).
• X-ray and electron interactions vary with tissue density.
• Dose calculations can be modified to account for those tissue differences.
What are tissue densities?

- $\rho_m$, Mass density
- $\rho_e$, Relative electron Density per unit volume (ReD) (relative to water)
- These parameter is used to characterize a tissue and how a particular x-ray beam will interact with it.

  – *More on this later*
Relative electron Density

\[ \rho_e = Na \times Z \times \rho_m/A \approx 6.02 \times 10^{23} \times 1/2 \times \rho_m \]

ReD = \( \rho_{e,tissue}/\rho_{e,water} \)

Air = 0.001
Lung \approx 0.3
Water = 1
Bone \approx 1.8
ReD curve in eclipse
Hounsfield Units

$\text{HU} = \frac{\mu_{\text{tissue}} - \mu_{\text{water}}}{\mu_{\text{water}}} \times 1000$

Air = -1000
Lung ≈ -800
Water = 0
Bone ≈ 1500
Why do Tissue Density corrections? TCP and NTCP

• The therapeutic ratio can be significantly affected by small changes in dose
AAPM Task Group 65

• The slope of dose-effect curves. TCP/NTCP
• The level of dose differences that can be detected clinically.
• Statistical estimates of the level of accuracy needed for clinical studies.
• The level of dose accuracy that will be practically achievable.

• AAPM report 85 (TG 65)
Why do tissue density corrections?

• Without tissue density correction, the true dose to tumors and normal tissues is not known therefore future TCP and NTCP will not be known.
• e.g. RTOG protocol 0236 lung has no density correction
• But what about normal tissues?
• Some geometries would have 1 Gy = 1 Gy other geometries passing through lung or air cavity would not.
• With density corrections, dose would be true and consistent independent of lung size, geometry, modality etc.
RTOG 0236 Lung recalculation

• 60 Gy in 3 fractions, no inhomogeneity corrections
SBRT lung recalculated

With:
- prescription isodose is contracted and
- the 50% line extended

Unit density
Tissue density

60 Gy, 30 Gy
Change in PTV DVH when heterogeneity correction is off

Heterogeneity correction evaluation for RTOG 0236 – Y. Xiao et al.
RTOG 0236 SBRT Lung 60 Gy/3 fractions, no tissue density corrections

<table>
<thead>
<tr>
<th></th>
<th>Dose (Gy)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>No correction</td>
</tr>
<tr>
<td>Min PTV D95</td>
<td>57.0</td>
</tr>
<tr>
<td>Max PTV D95</td>
<td>63.5</td>
</tr>
<tr>
<td>Mean PTV D95</td>
<td>60.6</td>
</tr>
<tr>
<td>Standard error PTV D95</td>
<td>0.3</td>
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</tbody>
</table>

N = 20 patients

DOSIMETRIC EVALUATION OF HETEROGENEITY CORRECTIONS FOR RTOG 0236: STEREOTACTIC BODY RADIOTHERAPY OF INOPERABLE STAGE I-II NON–SMALLCELL LUNG CANCER

YING XIAO, PH.D.,* LECH PAPIEZ, PH.D.,REBECCA PAULUS, B.S.,ROBERT TIMMERMAN, M.D., WILLIAM L. STRAUBE, M.S.,WALTER R. BOSCH, D.SC., JEFF MICHALSKI, M.D., AND JAMES M. GALVIN, D.SC.*
Dose to isocenter with and without heterogeneity corrections
PTV Volume coverage

Fig. 6. Percentage of volume that received prescription dose of $\geq 60$ Gy (V60) compared against protocol required value of 95%, without and with heterogeneity (Hetero) correction.
Factors affecting a inhomogeneity corrected plan

Because of the attenuation and scatter the difference between a corrected and uncorrected plan varies by

- Location
- Tissue
- Energy
- Field size
- Number of fields
When comparing density corrected plans to homogenous density plans for solid lung tumors

1. Corrected tumor periphery dose will be lower than uncorrected dose.
2. Corrected dose to the center of the tumor may higher than uncorrected dose.
3. Corrected lung dose will be lower than uncorrected dose.
4. All of the above
Why is inhomogeneity correction important? Normal tissue tolerance!

- Single beam, 10x, much lung, cord dose

\[ D_{\text{water}} = 30 \text{ Gy} \quad \text{D}_{\text{corr}} = 40 \text{ Gy} \]
Small fields

- Small fields are more largely affected by tissue densities and scatter.
Small fields

Percentage of dose reduction in lung region relative to homogenous phantom for 6 MV photon beam were 44.6%, 39%, 13%, and 7%.

How do Megavoltage photons interact with different density materials?

- Attenuation (photon interacts) (TERMA)
- Absorption (energy absorbed) (KERMA$_c$)
- Scatter
  - Local dose deposition
  - Penumbra
  - Surface dose/ dose build up
Attenuation

• Exponential function
  – $e^{-\mu x}$
  – $\mu$ is the linear attenuation coefficient in units of (distance)$^{-1}$
  – Describes the fraction of photons interacting per unit length
  – E.g. $\mu$ for water at 2 MeV is 0.04942 cm$^{-1}$ which indicates that about 4.942% of 2 MeV photons will interact within 1 cm of water travel.
Primary photon interactions

• Yellow line = photon path
• Red dot = point of interaction

Shahid Naqvi, Radiation Oncology, St. Agnes Hospital
Photon interactions in water
Mass attenuation coefficient

![Graph showing mass attenuation coefficient vs. energy (MeV). The graph includes lines for Bone, Cortical (ICRU-44), Air, Dry (Near Sea Level), and Water, Liquid.](image)

- **Bone, Cortical (ICRU-44)**
- **Air, Dry (Near Sea Level)**
- **Water, Liquid**

Mass attenuation coefficient (cm\(^2\)/g) vs. Energy (MeV)
Linear attenuation coefficient

Energy (MeV)

attenuation coefficient (cm⁻¹)

- Bone, Cortical (ICRU-44)
- Air, Dry (Near Sea Level)
- Water, Liquid
# Attenuation coefficients for 2 MeV x-rays

<table>
<thead>
<tr>
<th></th>
<th>Air</th>
<th>Water</th>
<th>Bone</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\frac{\mu}{\rho}) (cm²/g)</td>
<td>0.04447</td>
<td>0.04942</td>
<td>0.04607</td>
</tr>
<tr>
<td>(\rho) (g/cm³)</td>
<td>0.001205</td>
<td>1</td>
<td>1.85</td>
</tr>
<tr>
<td>(\mu) (cm⁻¹)</td>
<td>5.35864E-05</td>
<td>0.04942</td>
<td>0.08523</td>
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</tbody>
</table>
Photon interactions in different tissues

• Attenuation (scatter)
  
  – The amount of attenuation and the directional distribution of scatter will be dependent upon electron density, mass density, atomic number
Primary photon interactions

Shahid Naqvi, Radiation Oncology, St. Agnes Hospital
Interaction -> KERMa$_c$ -> Dose

- Interaction density (proportional to fluence) peaks at surface
- Collision kerma (proportional to interaction density)
- Dose does not peak at the surface

Shahid Naqvi, Chief Physicist, Radiation Oncology at St. Agnes Hospital
Photon interactions in different tissues

• Secondary electron fluence
  – The secondary electron fluence is affected by the physical properties of the material
  – changes in tissue density (i.e. lung/chest wall interface) results in electronic disequilibrium which significantly affects absorbed dose.
<table>
<thead>
<tr>
<th>Location of inhomogeneity</th>
<th>In front of inhomogeneity: not much affect in MV beams (little backscatter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lung</td>
<td>Within inhomogeneity: Changes in secondary electron fluence is primary influence on dose difference (attenuation is secondary)</td>
</tr>
<tr>
<td>Water</td>
<td>Beyond Inhomogeneity: Change in attenuation is the primary influence on dose difference (secondary electron fluence is secondary)</td>
</tr>
</tbody>
</table>
Photon and electron interactions in lung

- Both photons and electrons travel further in lung.
- Electron energy loss per unit path length is less in lung.
Origin of electrons that contribute to dose

Figure 5. Isolation of electron contributions launched in different density regions. In such a case (high energy, small field, low density), lung inhomogeneity corrections based solely on photon fluence or attenuation would be inadequate.
Electron origin

Tracks due to primary interactions in 1

Tracks due to primary interactions in 2

Tracks due to primary interactions in 3
Electron origin
Lateral electronic disequilibrium

- In most photon algorithms, electrons set-in-motion by primary photons are assumed to be absorbed “on the spot.” This assumption weakens for higher energy x-rays which launch electrons that travel several centimeters, especially in lower density tissue.
Increase of penumbra in lung

Illustrates how spreading of isodose lines in lung correlates with spreading of electron tracks.

Physical penumbra increases in lung.
Small field versus big field

- Small fields are more affected by lateral scatter loss
Dose changes beyond the heterogeneity are primarily due to?

1. Secondary electron energy deposition
2. Attenuation
3. Backscatter
Dose Calculation Algorithms

- Data based
- Model based
- Monte Carlo
Data based dose calculations

Far: $CF = \frac{TAR(d_3)}{TAR(d)}$ same as RTAR
Near: $CF = \frac{TAR(d_3)}{TAR(d_3+d_2)}$

$CF = \frac{[TAR(d_3) \times \exp(-\mu(d-d_2-d_3))] }{[TAR(d_3+d_2) \times \exp(-\mu(d-d_2-d_3))] }$
$= \frac{TAR(d_3)}{TAR(d_3+d_2)}$
Figure 8.8
Single photon history. Each primary photon interaction releases a shower of secondary electrons and photons. The energy deposited by charged particles (e^-, e^+) is scored in voxels. [Adapted with permission from reference [8].]
Model based algorithms

5MeV photons interacting at red dot

These e- and e+ tracks make the primary kernel

These e- and e+ tracks make the scatter kernel
Model based dose calculations

Convolution in 2D

Convolution is efficiently solved by Fast Fourier Transform techniques.
PBC and AAA algorithm in cork

10 cm Cork/2 cm S.W./10 cm Cork

SSD = 100 cm
PBC and AAA algorithm in cork

10 cm Cork/2 cm SW/10 cm Cork

Ratio of AAA to PBC vs Depth (cm)

- 10 x 10
- 6 x 6
- 5 x 5
- 4 x 4
- 3 x 3
Monte Carlo does calculations are considered more accurate than

1. Hand calculations
2. Data based calculation
3. Model based calculation
4. All of the above
CT HU phantoms
HU/Red variation with kVp

**Figure 2.5:** The CT energy specific calibration curves generated.
Dose variation with single (kVp) ReD curve 5 cm slab at 5 cm depth
Depth dose through prosthesis
Dose variation in single field through metal prosthesis

**Figure 4.15**: Prosthesis: 30 × 30 field of view, 23X photon beam.
HU/ReD calibration variation with phantom manufacturer

Multi Institution and Multi Vendor Comparison of CT # to RED Curves for Gammex 467 and Catphan Model 500

CT Number to Relative electron density curves for the Catphan and Gammex phantoms diverge in the high relative electron density region.

The correct order of factors affecting the measurement of HU is

1. Phantom > kVp > scanner manufacturer
2. kVp > Phantom > scanner manufacturer
3. scanner manufacturer > Phantom > kVp
4. scanner manufacturer > kVp > Phantom
What about metals

• Most CT scanners saturate around 3071 HU
• This implies that any materials with saturated HU will have the same x-ray interaction parameters (i.e. titanium, stainless steel, lead etc.)
• Need to expand density curves
• Assign fake HU to metals such that it corresponds to the correct ReD
• (AcurosXB, assign appropriate mass density)
Type of metals

• Prostheses – hip, titanium, cobalt, stainless steel
• Dental fillings – small in size, difficult/tedious to define
Solution

- Extend the CT calibration curves using numbers to incorporate higher density materials
- Collect several samples of various metals
- Expose each sample and combinations of samples to radiation
- Create a plan to calculate the dose measured for each experimental setup
- Compare doses and determine best HU value for each metal

Extended calibration curves
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<th>Dose</th>
<th>HU</th>
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<td>54.46</td>
<td>54.40</td>
<td>8750</td>
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</tr>
</tbody>
</table>
Error if you were to use saturated HU number

- The percent error between the measured and calculated doses using the saturated and composite value for each metal to demonstrate the accuracy of the new composite value

<table>
<thead>
<tr>
<th>Material</th>
<th>% Error @ Saturation</th>
<th>% Error @ Composite HU</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead</td>
<td>78.31</td>
<td>-2.36</td>
<td>75.96</td>
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<tr>
<td>Copper</td>
<td>15.98</td>
<td>-0.30</td>
<td>15.68</td>
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<td>Bronze</td>
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<tr>
<td>Stainless Steel</td>
<td>71.35</td>
<td>0.88</td>
<td>70.47</td>
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<td>Iron</td>
<td>51.73</td>
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<tr>
<td>Tin</td>
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<tr>
<td>Titanium</td>
<td>8.78</td>
<td>0.93</td>
<td>7.86</td>
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<tr>
<td>Aluminum</td>
<td>-4.66</td>
<td>0.05</td>
<td>4.61</td>
</tr>
</tbody>
</table>
Hip Prosthesis

- 6 MV energy
- Pass Rate = 97.8% — (3%/3mm)
- Pass = 435
- Fail = 10

The absolute dose compared for 6 MV energy, showing the failed diodes.
Hip Prosthesis

- 10 MV energy
- Pass Rate = 94.8%
  - (3%/3mm)
- Pass = 422
- Fail = 23

The absolute dose compared for 10 MV energy, showing the failed diodes
Hip Prosthesis

- 23 MV energy
- Pass Rate = 97.8%
  - (3%/3mm)
- Pass = 435
- Fail = 10

The absolute dose compared for the 23 MV energy, showing the failed diodes
All metals with equal HU will attenuate a radiotherapy beam the same.

1. True
2. False
4 fields, square phantom, in lung

Lasse Rye Aarup, Alan E. Nahum, Christina Zacharatou, Trine Juhler-Nøttrup, Tommy Knöös, Håkan Nyström, Lena Specht, Elinore Wieslander, Stine S. Korreman

The effect of different lung densities on the accuracy of various radiotherapy dose calculation methods: Implications for tumour coverage, PMB (91) p.405-414
Dose algorithm calculations comparison for lung tumor
Which factors will reduce the dose deficit in the periphery of solid lung tumors?

1. A plan utilizing 6 MV rather than 18 MV
2. A lung of higher density
3. Increasing the number of treatment fields
4. Larger treatment fields
5. All of the above
To achieve adequate dose coverage for a lung tumor, an 18 MV field requires a larger field than a 6 MV field.

1. True
2. False
CT artifact reduction

• The GE scanner can be equipped with an **Smart Metal Artifact Reduction (MAR)**

• MAR is designed to reveal anatomic details obscured by metal artifacts, helping clinicians utilize CT scans, diagnose disease and contour targets with greater confidence.

http://www3.gehealthcare.com/en/Products/Categories/Computed_Tomography/Radiation_Therapy_Planing/Metal_Artifact_Reduction
Questions?