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Greater Omaha Radiation Oncology Conference
October 19, 2019

• Omaha area native
• UNL Physics
• Nebraska Medicine internship: intro to Med Phys

About John

• Mayo Clinic, Rochester, MN
• Biomedical Engineering PhD
  • Medical Imaging and Rad Onc
• Clinical Therapy Physics Residency
About John

• Clinical Physicist, Nebraska Methodist, 3 years

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• Varian Transition

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Outline

- Intro/Refresher to CT number
- Role of CT number in dose planning
- Other modalities (MR, PET)
  - what they provide, what they lack
- CT dose planning with metals
- CT dose planning for protons*
- Future directions in CT
What’s in a CT?

• Projection

What’s in a CT?

• Sinogram
What’s in a CT?

• Reconstruction

![Reconstructed Image](image1)

![Filtered Projection](image2)

CT Number

\[ HU = 1000 \times \frac{P - P_{\text{water}}}{P_{\text{water}} - P_{\text{oxygen}}} \]

• Hounsfield Units (HU)
  • Measurement of photon attenuation
  • Map of Relative Electron Density (RED)

![Map of RED](image3)

Relative Electron Density

• Compton interactions proportional to RED

![Graph of Relative Electron Density](image4)

![Map of RED](image5)
Relative Electron Density

- Compton interactions proportional to RED

Map of RED

Accurate dose calculation depends on this!

CT-RED Calibration

- Tissue surrogate phantom
  - Special formulated density & chemical composition

CT-RED Calibration

- Plot HU vs. RED for Treatment Planning System
CT-RED Calibration

• Plot HU vs. RED for Treatment Planning System

Other Imaging Modalities

• MRI
  • Proton spin characteristics
  • Soft tissue resolution
  • Flexibility to highlight special features
Other Imaging Modalities

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Other Imaging Modalities

- PET
  - Radiotracer uptake
  - Functional Imaging
    - [cell activity [FDG], division, hypoxia, more]

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CT Dose Planning

• Additional challenges?

![CT Dose Planning Diagram]

Metal Implants

• Metals saturate CT number (< 3000 HU)
  • Standard practice:
    • Contour metal
    • Must be accurate
    • Manually assign CT number
  • Extended CT scale
    • No manual metal identification
    • No manual contouring/geometric concern

Extended CT Scale

• 12 vs. 16 bit images (Philips)
  • 12 bit historical standard
  • $2^{12} = 4096$ (1000 HU to +3000 HU range)
  • $2^{16} = 65536$ (1000 HU to 64k HU)
    • Practically no upper limit on metals
  • DICOM Slope/Intercept (Siemens)
Extended CT Scale

Treatment planning for metals using extended CT number scale
Mullins J, Grams M, Herman M, Brinkmann D, Antolak J (Mayo Clinic)
Journal of Applied Clinical Medical Physics, 2015

Hypothesis

• Extended scale CT dose calculations are
  • Of comparable accuracy to manual CT number assignment
  • Dosimetrically similar to manual CT number assignment

• If so, use extended scale directly
  • Improve workflow efficiency
  • Remove potential source of systematic error

Study

• Create extended calibration curve
• Phantom study
  – Variety of metals / geometries
  – Dosimetric verification
• Patient plan study
  – Relative dosimetric comparison
  – Clinical relevance
Phantom Study

- Solid water
- Metal sample in Superlab
- Film at 2 positions posterior
- Scatter artifacts contoured
  - Assigned water HU
- Metal
  - Contoured and assigned
  - Extended CT scale
- AP/PA, 10x10, 135 MU each

Phantom Study

- Metals
  - Rods ~ 6 mm diam.
    - CoCr, Steel, Al
  - Sheets ~ 1-2 mm thick
    - Cu, Steel, Stainless Steel
  - Mesh
    - Brass bolus
- Line profiles through measured / Eclipse dose
  - Quantify difference
Phantom Study Results

• Film Dosimetry
• Control: No metal sample

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Phantom Study Results

• CoCr rod

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Phantom Study Results

- Brass Mesh "Bolus"
  - 0.5 cm posterior
  - 2.5 cm posterior

Patient Planning Study

- 4 examples
  - 2 hip implants; Ti, Ti/SS
  - Breast expander; neodymium
  - Femur rod; Ti
- Standard (assigned HU) DVH
- Extended scale DVH

Hip 1 – 2 Arc VMAT
Conclusions

• Extended scale CT is accurate for dose calculation with metals
• Dosimetric difference of extended CT vs. manually assigned metal in clinical plans is typically minor
• Manual contouring and HU assignment can introduce errors
• Direct use of extended CT viable for dose calculation
  • efficient
  • reduces source of potential systematic error

Implementation

• Create extended CT to RED calibration
  • Measure actual metal samples
  • Use clinical protocols
• Update calibration in TPS
• DO contour scatter artifacts
  • Assign HU of water or local tissue
  • Avoid contouring over the metal implant
• DO NOT need to contour implant or manually assign metal HU

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Proton Dose

• Finite range
  • Advantage, also a challenge

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Pencil Beam Scanning

Energy per spot calculated in TPS by radiological depth

Impact of small range error creates large dose % error
Proton Therapy Margins

• Proximal and distal margins
  • Standard: 3.5% CTV radiological depth + 1 mm
• Asymmetric / beam angle dependent

CTV: Clinical Target Volume
PTV: Planning Target Volume

5 mm, from positioning uncertainty
3.5% + 1 mm, from beam range uncertainty

CT for Dose Calculation

• Measure of photon attenuation
  • Photon therapy: directly physically relevant
  • Proton therapy: less physically relevant
    • Careful, intricate method for CT calibration

Proton Stopping Power

\[
\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \left( \frac{1}{\beta^2} \right) \left( 4\alpha m_e \left( \frac{2m_e c^2 \beta^2}{\beta^2 - (1 - \beta^2)} \right) \right)
\]

Tissue specific variables
Proton Stopping Power

\[ S = \frac{\Delta E}{E} = \frac{4\pi}{m_e c^2} \beta^2 \left( \frac{\beta^2}{2} \right) \left[ \frac{2\Delta E c^2 \beta^2}{\beta^2 (1 - \beta^2)} \right] \]

Stoichiometric Conversion Method (Schneider '96)

1. Scan materials of known composition
\[ HU = \rho^C \alpha(Z_{m}^n \beta + \beta Z_{m}^n - \rho) \]
2. Calculate HU and Sp for ICRP/ICRU reference tissues
3. Plot and fit reference tissue data points

Known Scan specific Stoichiometric Conversion Method (Schneider '96)

1. Scan materials of known composition
2. Calculate HU and Sp for ICRP/ICRU reference tissues
3. Plot and fit reference tissue data points

Inorganic, Sparse
Organic, Broad

~3.5%
1. Scan materials of known composition
   • Varies by position in bore, phantom size, scan protocol, between scanners
2. Calculate relative Sp and HU for ICRP/ICRU reference tissues
   • Some tissues outliers (thyroid, fat)
   • Variability between patients (unknown)
3. Plot and fit reference tissue data points
   • Discontinuities, multiple line segments

CT Scanning Methods

• Each sample individually
• Center of phantom
• Head and Torso phantom
• All CT techniques, 4 Siemens scanners
• ~500 scans

Multiple Calibrations
Multiple Calibrations

- Multiple calibrations: most precise
- Must always select correct one
- Eclipse only stores 1 per scanner
- Average calibrations: most universal

Average Two Calibrations

- Pelvis and Head protocols, 120 kVp
“Final” Result

Validation

Organic Samples

• Femur, kidney, liver, brain, muscle, adipose, shank, foot...(sheep head)
Organic Sample Scans

Experimental Setup

Organic Results

<table>
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<tr>
<th>Sample</th>
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<td>4.74</td>
</tr>
<tr>
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### Correction for Fat Region

- Systematic shift, slope
- Extension based on patient data
Cadaver Measurements

Cadaver Results

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<td>163.52</td>
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<tr>
<td>Thigh</td>
<td>82.03</td>
<td>83.00</td>
<td>1.17%</td>
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Conclusions

- Head / pelvis size discrepancies small enough to average
- Scan protocol-specific and scanner-specific discrepancies small enough to average
- Final calibration falls within standard range uncertainty margins
Alternatives and Future Work

• Proton CT
  • Currently resource-limited
• Megavoltage CT (MVCT)
  • More direct RED measurement
• Dual-energy CT (DECT)
  • Extract more tissue information
  • Methods to measure RED and <I>
• Standard of Care: Stoichiometric calibration
  • Modern refinements

Final Recap

• CT Number
  • Provides measured radiation attenuation for dose calculation
• Other imaging modalities
  • Provide extra imaging/spatial/physiology info
  • Do not provide necessary dose calc info
• CT Calibration
  • Required for CT dose calc to be accurate
• Extended CT Scale
  • Accurate for heterogeneity corrections of metal implants
  • More efficient, reduced error

Questions