Dose-calculation Algorithms Used in Radiation Treatment Planning

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Purpose

• To familiarize radiation oncology residents with the most common algorithms used to compute photon-beam dose distributions

Types of Dose-Calculation Algorithms

• Data-driven algorithms
• Model-driven algorithms
Data-driven algorithms
- Data-driven algorithms are based on measured data
  - Simplest form is look-up table
- For conditions identical to those of measurement, the method provides the most accurate reproduction of acquired beam data

Beam commissioning procedure is very simple
- No adjustable parameters
- Discrepancies may be due to grid size or errors
- May not accurately reproduce beams for which measurements have not been taken

Model-Driven Algorithms
- Based on beam model which may or may not have adjustable parameters
  - Approximation to reality
- May not reproduce beams from which data was acquired to same accuracy as data-driven algorithm
  - Inadequacies of model
Model-Driven Algorithms

- Beam-commissioning procedure may be complex
- More flexibility in reproducing beam configurations for which measurements have not been taken
- Algorithms in current treatment planning systems are primarily model-driven

Criteria for Algorithm Assessment

- Capability of modeling the beam
- Capability of modeling the patient
- Ease of beam commissioning
- Accuracy of dose calculation
- Speed of dose calculation

Criteria for Algorithm Assessment

- The dose calculation algorithm must accurately model all beam configurations normally used in the clinic
  - Treatment machine, beam energy
  - Beam geometry
  - Treatment portal definition: symmetric, asymmetric collimation, MLC, customized blocks, electron applicators, skin collimation
  - Beam modifiers: physical wedge, dynamic wedge, compensators, bolus
Criteria for Algorithm Assessment

• No system models all configurations
  – Ingenuity required to develop suitable work-arounds

Criteria for Algorithm Assessment

• The dose calculation algorithm must accurately model the patient
  – External surface anatomy
  – Heterogeneous internal anatomy
    • Based on high-resolution, pixel-based CT data

Criteria for Algorithm Assessment

• The dose calculation algorithm must make it easy to commission beams
  – May be difficult for model-based algorithm
  – Need software tools to aid in commissioning beam data
Criteria for Algorithm Assessment

• Caveat in commissioning beam data:
  Make sure the physics is in the beam model and not in the empirical parameters

Criteria for Algorithm Assessment

• The dose calculation algorithm must be accurate
  – Verification responsibility of vendor via type test
  – Supporting documentation should be provided
  – No general agreement on desirable accuracy
  • See Van Dyk paper or AAPM TG 53 report
  • Cited figures based on experience and expectations, not on what is desirable

Criteria for Algorithm Assessment

• The dose calculation algorithm must be accurate
  – Need verification data
    • AAPM TG 23 - photons
    • ECWG - electrons
Criteria for Algorithm Assessment

• The dose calculation must be fast
  – Goal: real-time calculation and display
  – Reality: more sophisticated dose model
  – Work-arounds
    • Background calculation
    • Fast calculation option

Specific Dose-Calculation Algorithms

• Bentley-Milan
• Scatter-Summation
• Convolution
• Monte Carlo

Bentley-Milan Algorithm

• Data-driven algorithm
• Acquired measured central-axis depth doses and off-axis profiles
• Central-axis depth doses acquired at small depth intervals (0.5 cm - 1.0 cm)
• Off-axis profiles acquired at few depth intervals (around 5) and many off-axis intervals (40 or more)
Bentley-Milan Algorithm

- Beam model
  - Product of central-axis depth dose and off-axis profile
- Which central-axis depth dose?
  - Equivalent square based on collimators
  - Equivalent square based on irregular-field calculation
  - Equivalent square based on convolution calculation at reference depth

Bentley-Milan Algorithm

- Model effect of blocks: Multiply off-axis ratio by block transmission
  - Does not account for scatter near block boundary
  - Block transmission not necessary true transmission

Bentley-Milan Algorithm

- Resolution of problem
  - Convolve dose with penumbra model, e.g. Gaussian function
  - Use effective block transmission factor that includes effects of scatter
Bentley-Milan Algorithm

- Model conventional wedge
  - Use measured central-axis depth dose and off-axis ratio for specific wedge field
  - Explicitly accounts for beam hardening due to wedge

Bentley-Milan Algorithm

- Model dynamic wedge
  - Scale off-axis ratios by STT values
  - If algorithm does not explicitly support dynamic wedge, need to enter separate beam data for wedge

Bentley-Milan Algorithm

- Model compensating filter analogous to block
  - Multiply off-axis ratio by filter transmission
  - Explicitly measure off-axis profile for compensated field
    - This may be tedious
**Bentley-Milan Algorithm**

- Model heterogeneities
  - Calculate dose in homogeneous medium
  - Multiply by correction factor
    - Effective depth correction
    - Batho power law method
    - Equivalent TAR method

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**Bentley-Milan Algorithm**

- Commissioning beam relatively straightforward
  - Discrepancies due to errors in input data or approximations due to grid size

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**Bentley-Milan Algorithm**

- Problem may exist for calculating beams for which calculation conditions are significantly different from data acquisition conditions, e.g., extended SSD
  - Accuracy should be verified for these conditions
Scatter-Summation Algorithm

- Based on Clarkson irregular-field calculation

\[ D(r, fs) = D(d_{eff}, fs)ISF(r)[P(r)TPR(d) + \frac{S(0)}{S(fs)}] \]

Scatter-Summation Algorithm

- \( P(r) \) accounts for beam modifiers and penumbra

\[ P(r) = W(x)B(x,y)P_0(x)P_0(y) \]

- \( W(x) \): wedge transmission
- \( B(x,y) \): block transmission
- \( P_0(x), P_0(y) \): model profile of unmodified beams

Scatter-Summation Algorithm

- Input data:
  - Tissue-phantom ratios
  - Large-field off-axis profile
    - Models off-axis corrections due to spectral changes
  - Parameters model penumbra and collimator transmission
    - Need to be fit to measured dose distributions
Scatter-Summation Algorithm

- Model effect of blocks
  - Multiply zero-area TPR by block transmission
  - Explicitly accounts for effect of block on scatter

Scatter-Summation Algorithm

- Model conventional wedge
  - Multiply zero-area TPR by wedge transmission along fan line
  - Does not account for beam hardening due to wedge unless wedge-specific TPR tables used
  - Does not account for effect of wedge transmission on scattered radiation
  - May use fan-line wedge transmission as fitting parameter

Scatter-Summation Algorithm

- Model dynamic wedge
  - Scale zero-area TPR by STT values along fan lines
  - Does not account for effect of modified primary on scattered radiation
Scatter-Summation Algorithm

• Model compensating filter
  – Multiply zero-area TPR by filter transmission along fan lines
  – Beam hardening probably not an issue
  – Does not account for effect of filter transmission on scattered radiation

Scatter-Summation Algorithm

• Model heterogeneities
  – Calculate dose in homogeneous medium
  – Multiply by correction factor

Scatter-Summation Algorithm

• Advantages
  – More model-driven than Bentley-Milan
    • More accurately reproduces beam configurations not explicitly entered
  – Point-dose calculation
    • Rapid calculation of doses to displayed plane or points of interest
Scatter-Summation Algorithm

- Disadvantages
  - Need to fit parameters
  - Penumbra modeling parameters
  - Wedge transmission
  - More time consuming calculation

Convolution Algorithm

- Model beam – convolve primary fluence with dose-spread kernel
  \[ D(r) = \int dE \int d'r' \Phi(r', E) K(r - r', E) \]

- Primary fluence
  - In-air fluence exiting from treatment head
  - Attenuated through blocks, wedges, filters, etc
  - Attenuated through patient
- Primary fluence modeled as spectrum
  - Accounts for beam hardening
**Convolution Algorithm**

- Dose-spread kernel is spatially invariant
  - Caveat 1: calculation points must be equally spaced
  - Caveat 2: heterogeneities must be small

**Convolution Algorithm**

- Boyer: speed up calculations by assuming spatial invariance and transforming into Fourier space
  - FFT Convolution
    \[ D(r) = \text{FT}^{-1} \left( \sum_{i=1}^{N} W_i \times \text{FT} \left[ \Phi(E_i) \right] \times \text{FT} \left[ K(E_i) \right] \right) \]

**Convolution Algorithm**

- Mackie: Speed up calculations by taking energy averages of dose-spread kernel
  - Convolution/Superposition
    \[ D(r) = \int d^3r' \overline{\Phi(r')} K(r, r') \]
Convolution Algorithm

- Electron contamination
  - Empirical modeling
  - Results in additional parameters to fit during commissioning process
- Contribution from electron contamination should be kept small

Convolution Algorithm

- Model beam modifiers
  - Attenuation of incident fluence through beam modifier
  - Does not explicitly handle scatter from modifier
    - Scatter may be accounted for empirically

Convolution Algorithm

- Model heterogeneities
  - Calculate primary fluence in heterogeneous medium
  - Include heterogeneity corrections in dose-spread kernel
Convolution Algorithm

- Advantages of convolution algorithms:
  - Large amount of physics reflected in algorithm
- Disadvantages of convolution algorithms:
  - Calculation time
  - Difficulty of commissioning
    - Technique requires significant development

Monte Carlo

- Model beam by simulating photon and electron transport
- Separate into two parts
  - Simulate machine head (BEAM)
    - Calculate for each configuration and store
  - Simulate patient (DOSXYZ or Peregrine)

Monte Carlo

- Large number of computations
  - Not clinically practical at present
  - Parallel processors
- Issues remain with beam commissioning
Conclusions

- Radiation oncologist needs to be familiar with dose-calculation algorithms to make intelligent decisions
  - Evaluate treatment planning systems
  - Assess validity of clinical treatment plans