Slide 1

Serial Tomotherapy

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Slide 2

Outline

• Description of Tomotherapy
• Clinical Implementation
  – Commissioning
  – Clinical Setup and Treatment
  – Patient-Specific QA
• Clinical Issues
  – Abutment-region Dosimetry
  – Superficial Doses
  – Whole-Body Doses
  – Room Shielding

Slide 3

Commercial Application

• NOMOS Corporation
  – Multileaf collimator (MIMiC)
  – “Indexing” hardware
  – Treatment planning software
  – QA tools
• >40 users worldwide
Serial Tomotherapy

Slide 4

MIMiC

- 20 pairs of leaves = 20 cm diameter cylinder
- Binary operation (pneumatic)
- Leaves subtend 0.84 (1 cm) or 1.7 cm (2 cm) width
  - Longer targets treated in successive abutted slices (indexes)
- Fluence modulated during arc
- Arcs subdivided into 5 degree bins
- Fluence nearly arbitrary each bin
- Up to 72 independent coplanar beams
- Patient indexed between slices

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Slide 5

Crane

- Couch repositioning and immobilization
- Attaches to couch rail
- Position read out using linear digital encoders

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Slide 6

Treatment Planning System

- Trade-name Corvus
- Structure delineation/import
- DVH-based optimization user interface
- Simulated annealing algorithm
- Multiple 2-D cross-section views
- DVHs
- Also supports DMLC
Slide 7

Clinical Implementation

- Commissioning
  - Traditional
  - Dosimetric
- Patient setup and treatment
  - Immobilization
  - CT scan acquisition
  - Contour delineation and dose optimization
  - Treatment
- Patient-based QA
  - Dosimetric pre-treatment
  - Positioning verification

Slide 8

Commissioning

- Traditional, e.g.
  - TG 53
  - Patient information
  - Printout accuracy
  - Data transfer
- IMRT
  - Dose distributions
  - Monitor unit determinations

Slide 9

IMRT Dosimetry

- Dosimeters
  - Accuracy and dimensionality conflict
  - Point
    - Ionization chambers
    - TLD chips
    - Others
    - Poor spatial coverage
  - Size vs. dose heterogeneity
  - Response as function of incident fluence angle
Slide 10

IMRT Dosimetry

• Dosimeters (cont’d)
  – Planar
    • Radiographic Film
      – Poor energy response
    • Radiographic Film
  – Radiochromic Film
    – Still difficult to use quantitatively
    – Possible to get 2% precision with 0.1 x 0.1 mm² resolution
    – Excellent for benchmarking

Slide 11

IMRT Dosimetry

• Dosimeters (cont’d)
  – Volumetric
    • Polymerizing gel (Trade name BANG)
    • MRI or optical readout
    • Reasonable sensitivity (1-20 Gy)
    • MRI readout shown to be excellent as relative dosimeter (single experiment yields nearly 1,000,000 1 x 1 x 3 mm³ data points)
    • MRI readout still requires benchmarking for absolute IMRT dose measurements
    • Optical readout requires benchmarking for large volumes

Slide 12

IMRT Dosimetry

• Phantoms
  – Anthropomorphic
    • Geometrically irregular
    • Patient-like structures including heterogeneities
    • Heterogeneities may yield unnecessary dosimetric uncertainties
    • Highly accurate spatial film registration difficult
Slide 13

**IMRT Dosimetry**

- Phantoms (cont’d)
  - Geometrically regular
  - Easily aligned and registered
  - Precise internal construction
  - Homogeneous internal construction
  - Multiple dosimeters measuring in same dose distribution environment

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Slide 14

**Patient Setup and Treatment**

- Immobilization
  - Dose delivered in sequential slices
  - If patient moves perpendicular to arc during or between slice delivery, large dose heterogeneity results in abutment region
  - Immobilization system should concentrate on longitudinal direction
  - Don’t forget localization to enable smallest possible margins

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Slide 15

**Patient Setup and Treatment**

- Volumetric anatomy measurement
  - Usually done with CT
  - Targets and critical structures delineated

- Optimization
  - Commercial system uses DVH-based system
  - Target and critical structure dose limits entered as 3-point DVHs
  - Pre-filtering of gantry angles
  - Simulated annealing determines individual beam fluences
  - Patient treatment plan written on a floppy disk which monitors number of delivered fractions
### Slide 16

**Patient Setup and Treatment**
- Laser alignment marks placed similar to conventional CT
- Intersection of alignment marks determines coordinate system “Origin”
- Gantry rotation axis usually passes through isocenter, but tool is provided to move axis if necessary
- Patient is aligned to marks, CRANE readouts zeroed
- Patient moved as required by treatment plan

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### Slide 17

**Patient Setup and Treatment**
- Accelerator uses normal arc mode
- MIMiC leaves open and close as function of gantry angle (inclinometers)
- MIMiC controlling computer monitors gantry rotation rate and angles to determine of treatment proceeding correctly
- Monitor units or dose are not monitored by MIMiC controlling computer

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### Slide 18

**Patient-Based QA**
- Treatment plan yields monitor units
- For same dose, MUs can vary by 40%
- How do we know the MUs are correct?
- MEASUREMENT!
- Patient fluence distribution transferred to QA phantom and dose measured at select points
- Ionization chambers for MU normalization
- Film used for spatial localization
Patient-Based QA

- **Patient Localization QA**
  - How do we know the patient is in the correct location?
  - **PORTAL FILMS**
  - Compared against DRRs from commercial virtual simulation software using same CT dataset and radiopaque markers as treatment plan
  - Use double exposures when possible (with and without MIMiC)

Clinical Issues

- **Abutment-Region Dosimetry**
  - **CRANE indexing precision**
  - Dosimetric consequences of indexing error
  - Intrinsic abutment dose distribution heterogeneity

CRANE Indexing Precision

- Readout precision = 0.01 mm
- Readout made at rack and pinion gears, not at accelerator isocenter
- Couch bearing friction limits precision
- **Measurement:**
  - Radiographs using sequence of open MIMiC field images
  - Purposely change index amount from overlap to underlap
  - Scan film and correlate hot and cold spots to intended couch index movement
  - Fabricate high precision system to provide baseline for relationship between referenced and cold spots and couch index distance (“gold standard”)
  - Also evaluate optical based system: miniCRANE
Slide 22

16.8 mm 16.3 mm 17.2 mm

Slide 23

Index offset (mm)

Dose Error (%)

Gold Standard CRANE

Square = gold standard
Triangle = miniCRANE
Circle = CRANE

Indexing Precision Results

• Standard deviation
  - CRANE = 0.10 mm
  - miniCRANE = 0.08 mm
  - gold standard = 0.02 mm
Consequences of Incorrect Indexing

- Either incorrect indexing or patient movement yields undesired overlap or underlap between successive abutments
- Carol determined dose error 10% mm$^{-1}$
- Measurement
  - 8 cm diameter target
  - Radiographic film (coronal)
  - Purposeful index error 0, ±1, ±2 mm

Dose Error vs Index Error

Slope = 25% mm$^{-1}$
Slide 28

Intrinsic Abutment Dosimetry

- Narrow but divergent beams
  - Unequal matching at abutments
  - Hot and cold spots created
  - Only narrow width
  - Dose heterogeneities are function of gantry angle rotation, off-axis distance, width of leaves ("1 cm" vs "2 cm" modes)
  - Random daily setup error may redistribute and reduce dose heterogeneity magnitude

Slide 29

Intrinsic Dose Heterogeneity Measurement

- Treatment Plans
  - 8 cm cylindrical targets (head phantom)
  - Position relative to isocenter
  - 180°, 240°, 300° arcs
  - "1" and "2" cm modes
- Measurement
  - Radiographic film (coronal)
  - Precise indexing of phantom
  - Densitometry - 0.25 mm laser digitizer

Slide 30

Experimental Layout
Experimental Method

- Determine heterogeneity throughout 20 cm diameter volume
  - Apply smooth fit in x and y
- Position of abutment region in patient
  - Longitudinal position has random error
  - Smooths (distributes) abutment region
  - Model as Gaussian distribution
  - Convolve with abutment hot/cold spots

Measured Overlap Profiles
Slide 34

180°, 1 cm Example

Slide 35

Result Presentation

- 2D contour plot difficult to interpret
- Largest variation in “y” direction
- Show 1-D plots of smoothed dose heterogeneity in “y” direction with superimposed measured data points

Slide 36

180° arc, 1 cm mode

- Plot of dose heterogeneity vs. y (mm) for different σ values (σ = 0 mm, σ = 1 mm, σ = 2 mm, σ = 3 mm)
- Graph showing decreasing dose heterogeneity as y increases
Slide 37

180° arc, 2cm mode

Slide 38

240° arc, 1cm mode

Slide 39

300° arc, 1cm mode
Slide 40

Intrinsic Abutment Summary

Target off-axis distance along y axis required to achieve 90% dose homogeneity

<table>
<thead>
<tr>
<th>Mode</th>
<th>σ=0mm</th>
<th>σ=2mm</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>ant post</td>
<td>ant post</td>
</tr>
<tr>
<td>1 cm</td>
<td>5 10</td>
<td>8 10</td>
</tr>
<tr>
<td>2 cm</td>
<td>3 3</td>
<td>5 6</td>
</tr>
</tbody>
</table>

Recommendations

• 2 cm mode yields approx 70% greater heterogeneities than 1 cm, use 1 cm whenever practical
• Keep targets near isocenter
• Use as large a gantry angle as possible
• Periodically monitor couch indexing precision
Future Implementation

- Spiral tomotherapy unit - Mackie
- Abutment region heterogeneities distributed throughout patient
- Improved patient throughput
- On-line images acquired during irradiation may yield tomographic information

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