Radiosurgical Planning

Minimally invasive procedure that uses an intense, focused beam of radiation as an ablative surgical instrument to destroy tumors.

Dose from multiple beams is additive.

The Radiosurgery Problem

Treatment Planning for Radiosurgery

- Determine a set of beam configurations that will destroy a tumor by cross-firing at it.
- Constraints:
  - Desired dose distribution
  - Physical properties of the radiation beam
  - Constraints of the device delivering the radiation
  - Duration/fractionation of treatment

Conventional Radiosurgical Systems

- Isocenter-based treatments
- Stereotactic frame required
Isocenter-Based Treatments

- All beams converge at the isocenter
- The resulting region of high dose is spherical

Nonspherically shaped tumors are approximated by multiple spheres
  - "Hot Spots" where coverage is poor
  - "Cold Spots" where the spheres overlap
  - Over-irradiation of healthy tissue

Stereotactic Frame for Localization

- Painful
- Fractionation of treatments is difficult
- Treatment of extracranial tumors is impossible

The CyberKnife

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- Fractionation of treatments is difficult
- Treatment of extracranial tumors is impossible

The CyberKnife (Accuray)

http://accuray.com/

Treatment Planning Becomes More Difficult

- Much larger solution space
  - Beam configuration space has greater dimensionality
  - Number of beams can be much larger
  - More complex interactions between beams
- Path planning
  - Avoid collisions
  - Do not obstruct X-ray cameras
- Automatic planning required (CARABEAMER)

Inputs to CARABEAMER

(1) Regions of Interest:

Surgeon delineates the regions of interest
CARABEAMER creates 3D regions
Inputs to CARABEAMER

(2) Dose Constraints:
- Tumor dose
- Falloff of dose around tumor
- Dose to critical structure
- Falloff of dose in critical structure

(3) Maximum number of beams

Basic Problem Solved by CARABEAMER

• Given:
  - Spatial arrangement of regions of interest
  - Dose constraints for each region: \( a \leq D \leq b \)
  - Max number of beams allowed: \( N (~100-400) \)
• Find:
  - \( N \) beam configurations (or less) that generate dose distribution that meets the constraints.

Beam Configuration

• Position and orientation of the radiation beam
• Amount of radiation or beam weight
• Collimator diameter

\( \Rightarrow \) Find 6N parameters that satisfy the constraints

CARABEAMER's Approach

1. Initial Sampling:
   Generate many (> \( N \)) beams at random, with each beam having a reasonable probability of being part of the solution.
2. Weighting:
   Use linear programming to test whether the beams can produce a dose distribution that satisfies the input constraints.
3. Iterative Re-Sampling:
   Eliminate beams with small weights and re-sample more beams around promising beams.
4. Iterative Beam Reduction:
   Progressively reduce the number of beams in the solution.

Initial Beam Sampling

• Generate even distribution of target points on the surface of the tumor
• Define beams at random orientations through these points

Deterministic Beam Selection is Less Robust
Curvature Bias

- Place more target points in regions of high curvature.

Dose Distribution Before Beam Weighting

CARABEAMER's Approach

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2. Weighting: Use linear programming to test whether the beams can produce a dose distribution that satisfies the input constraints.

3. Iterative Re-Sampling: Eliminate beams with small weights and re-sample more beams around promising beams.

4. Iterative Beam Reduction: Progressively reduce the number of beams in the solution.

Beam Weighting

- Construct geometric arrangement of regions formed by the beams and the tissue structures.

- Assign constraints to each cell of the arrangement:
  - Tumor constraints
  - Critical constraints

Linear Programming Problem

- \( 2000 \leq \text{Tumor} \leq 2200 \)
- \( 2000 \leq B_2 + B_4 \leq 2200 \)
- \( 2000 \leq B_3 + B_4 \leq 2200 \)
- \( 2000 \leq B_1 + B_3 + B_4 \leq 2200 \)
- \( 2000 \leq B_1 + B_4 \leq 2200 \)
- \( 2000 \leq B_3 + B_4 \leq 2200 \)
- \( 2000 \leq B_1 + B_2 + B_4 \leq 2200 \)
- \( 2000 \leq B_1 + B_2 \leq 2200 \)

- \( 0 \leq \text{Critical} \leq 500 \)
- \( 0 \leq B_2 \leq 500 \)

Results of Beam Weighting

- Before Weighting
- After Weighting
**CARABEAMER’s Approach**

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**Plan Review**

- Calculate resulting dose distribution
- Radiation oncologist reviews
- If satisfactory, treatment can be delivered
- If not...
  - Add new constraints
  - Adjust existing constraints

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**Treatment Planning: Extensions**

- Simple path planning and collision avoidance
- Automatic collimator selection

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**Evaluation on Sample Case**

- Linac plan: 80% Isodose surface
- CARABEAMER’s plan: 80% Isodose surface

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**Another Sample Case**

- LINAC plan
- CARABEAMER’s plan

- 50% Isodose Surface
- 80% Isodose Surface
Indications: Brain, spine, lung, prostate, liver, pancreas (most common)

Since January 1999, more than 335 patients have been treated at Stanford with the CyberKnife. 

May 2010

Number of CK installations: 182

Installation locations: 24 countries

http://www.cyberknife.com/CyberKnifeCenters/index.aspx

Patients treated to date: Over 100,000? (40,000 in May 2008)

Indications: Brain, spine, lung, prostate, liver, pancreas (most common)
Meningioma affecting vision

208 beam positions. The patient was treated with 5 fractions over 5 days at 40 minutes per fraction.

http://accuray.com/