Current state of multi-criteria treatment planning

June 11, 2010
Fall River NE-AAPM meeting

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Talk outline

- Overview of optimization
- Multi-criteria optimization (MCO)
- MCO for radiation therapy
With IMRT comes the need for optimization

**IMRT = intensity modulated radiation therapy**

**Figure 1.** Illustrating the key differences between (a) conventional radiotherapy, (b) conformal radiotherapy (CFRT) without intensity-modulation and (c) CFRT with intensity modulation (IMRT). For almost a century radiotherapy could only be delivered using rectangularly-shaped fields with additional blocks and wedges (conventional radiotherapy). With the advent of the multileaf collimator (MLC) more convenient geometric field shaping could be engineered (CFRT). The most advanced form of CFRT is now IMRT whereby not only is the field geometrically shaped but the intensity is varied pixel-by-pixel within the shaped field. This is especially useful when the target volume has a concavity in its surface and/or closely juxtaposes organs-at-risk, e.g., as shown here in the head-and-neck, where tumours may be adjacent to spine, orbits, optic nerves and parotid glands.

(from Webb 2003 review)
A simple optimization problem: choose $x$ to minimize $f(x)$

Here $x$ is a single variable. Optimization theory deals with how to minimize functions of thousands (even millions) of variables:

A classic, difficult optimization problem (Traveling salesman)

minimize route length
subject to
visit each city exactly once.
The hardware behind IMRT

- High energy x-ray source
- Multi-leaf collimator with sliding leaves

By moving leaves while beam is on, non uniform intensity maps are created
Discrete optimization

Variables: where do I go next (discrete choice)

Continuous optimization

Variables: how much fluence at each beamlet (continuous)
Optimization setting for radiotherapy

Control variables
- Modality (protons, photons, etc)
- Beam angles
- Beamlet weights

System
- The patient being treated

Goals
- Get prescribed dose to target, minimize collateral damage

Output
- Some measures of the quality of the treatment plan. E.g. Target dose homogeneity, normal tissues within dose tolerance.

Each is fraught with challenges/uncertainties!
The current state of treatment planning

Treatment planner using standard treatment planning software
Goals
Get prescribed dose to target, minimize collateral damage to nearby healthy organs

Each patient will have her own best plan.

Very hard (impossible?) to specify a one-size-fits-all optimization formulation that will produce that plan.
Pancreas example

Minimize

- Mean liver dose
- Mean stomach dose
- Mean kidney dose
- Tumor underdosage
- Hotspots
Multi-objective optimization:

minimize $F_1$ and $F_2$

For example, $F_1$ might be mean dose to the left parotid gland and $F_2$ might be maximum dose to the brainstem.

(Each black dot represents a feasible treatment plan)

Which plans are “the best”?

ENTER Pareto Surface based MCO (aka “MCO”)
ANSWER: Pareto optimal plans

Each black dot represents a feasible treatment plan.

The dots along the red boundary are Pareto optimal since for each of them, there does not exist a plan better in both objectives.

Multi-objective optimization: minimize $F_1$ and $F_2$
2D Illustration if the idea of MCO treatment planning

Pre-calculate plans on the Pareto surface, then let physician coast along it to find the best trade-off
How to populate the Pareto surface as the number of objectives increases?

EUD_lung

EUD_heart

e.g. target coverage constrained
How to populate the Pareto surface as the number of objectives increases?
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Number of necessary plans for the database is modest, and grows linearly with number of objectives.
As you generate additional database plans, how additionally helpful are they? (diminishing returns)

**Figure 4.** Panel for the 6D prostate case. See the caption of figure 3 for an explanation of these figures. Abbreviations: r. fem. = right femoral head, l. fem. = left femoral head, a. rec. = anterior rectum, p. rec. = posterior rectum, blad. = bladder, u.t. = unclassified tissue.
Convex optimization

For an optimization problem to be convex, it must satisfy these two properties:

1) The constraint set is a convex set (the average of any two feasible solutions is also feasible)

2) The function to optimize is convex. (i.e. The level sets \( \{x \mid f(x) \leq c\} \) are convex sets)
What objectives to use? Does not matter so much in MCO.

Exploration of tradeoffs in intensity-modulated radiotherapy
D Craft, T Halabi, T Bortfeld - Physics in Medicine and Biology, 2005
Fast database generation requires a fast solver

Optimization $\approx$

finding a point that satisfies a set of constraints
Feasible for constraint 1

Feasible for constraint 2

Feasible for both constraints

Starting point

SLOW CONVERGENCE for non-orthogonal (“opposing”) constraints

FAST CONVERGENCE for nearly orthogonal constraints
Speeding convergence by projecting *into* the constraints

Feasible for constraint 1

Feasible for constraint 2

Feasible for both constraints

Starting point
Most voxel dose constraints are orthogonal (independent) since, with high precision therapy tools (IMPT, IMRT), the beamlets that affect one voxel are different from those that affect another voxel.

So, correcting one voxel dose that is violating its constraint does not affect the majority of other voxel doses.
From a fast constraint solver to an optimizer

\[
\begin{align*}
\text{Min } c'x \\
\text{s.t. } Ax & \leq b
\end{align*}
\]

\[
\begin{align*}
\text{solve } \\
Ax & \leq b \\
\text{Iterate on value of } r
\end{align*}
\]
Treatment planners, or physicians directly, can interactively explore full range of plan possibilities.
Treatment planners, or physicians directly, can interactively explore full range of plan possibilities. But how to navigate through these options?
Navigating a Pareto surface

Like in Pareto surface construction, in the 2D world, things are easy.

(Why is navigation easy in 2D? Only one way to go downhill!)
In dimensions above 2, many ways to go downhill.
Simultaneous navigation of multiple Pareto surfaces, with an application to multicriteria IMRT planning with multiple beam angle configurations
D Craft, M Monz - Medical Physics, 2010

Pareto navigation—algorithmic foundation of interactive multi-criteria IMRT planning, PMB, 2008, Monz, Küfer, Bortfeld, and Thieke
Fast (and clinically useful) database generation

Navigation

MCO treatment planning system
RayStation – produced by RaySearch Laboratories, Sweden. MCO module developed in collaboration with MGH. First commercially available (September 2010) Pareto-surface based IMRT MCO planning system
Astroid – produced by MGH (Madden, Kooy, Chen, Craft, Zhang)
IMPT (intensity modulated proton therapy) MCO planning system
Clamping helps the user to go anywhere on the Pareto surface.
Is MCO actually a superior approach?

**Treatment planning comparison study:**

Standard IMRT planning (XiO) versus MCO (RayStation)

**Study Design:**

- 5 GBMs
- 5 LAPCs
Patients chosen for this treatment planning study by the physicians at the time of contouring.

All patients planned with XiO and treated as in normal workflow.

Planning time logged by treatment planners.

In parallel, MCO databases were generated for patients using templates. This process was also logged.
Patient selected for inclusion. Contours drawn by physician.

Beam selection and optimization done by staff treatment planner using XiO.

Physician plan review.

Patient treated with XiO plan.

Template beam arrangement and optimization formulation input into RayStation.

Database generated.

Physician navigates to desired plan and accepts it.

Weeks later, DVHs (and dose statistics for LAPC cases) are blindly reviewed by physician and one of the plans is chosen as the better plan.
Study Results

Treatment planning time for individual cases

Brain cases

Pancreas cases
Study Results

<table>
<thead>
<tr>
<th>XiO</th>
<th>Planner time</th>
<th>MCO</th>
<th>Planner time</th>
</tr>
</thead>
<tbody>
<tr>
<td>156 ± 96 minutes</td>
<td>114 ± 33 minutes</td>
<td>12.4 ± 1.8 minutes</td>
<td>11.6 ± 0.6 minutes</td>
</tr>
<tr>
<td>Brain (GBM)</td>
<td>Pancreas</td>
<td>Brain (GBM)</td>
<td>Pancreas</td>
</tr>
</tbody>
</table>

About 2 hours  
About 10 minutes
### Study Results

<table>
<thead>
<tr>
<th>XiO</th>
<th>MCO</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Physician time</strong></td>
<td><strong>Physician time</strong></td>
</tr>
<tr>
<td>5.0 ± 2.5 minutes</td>
<td>8.2 ± 2.8 minutes</td>
</tr>
<tr>
<td>Brain (GBM)</td>
<td>Brain (GBM)</td>
</tr>
<tr>
<td>4.5 ± 2.7 minutes</td>
<td>9.0 ± 2.2 minutes</td>
</tr>
<tr>
<td>Pancreas</td>
<td>Pancreas</td>
</tr>
</tbody>
</table>

Physicians spend a few minutes longer for the MCO system.
For all cases, the physicians preferred the MCO plan to the XiO plan in a blind DVH review weeks after initial assessments.
Conclusions

• MCO is a good choice for radiotherapy optimization problems.

• Clinical MCO systems will be appearing soon.

• Moving MCO into more applications and into the clinic should improve planning process efficiency and treatment quality greatly.
Thanks!

Collaborators
Thomas Bortfeld, Hanne Kooy, Wei Chen, Tom Madden, Ted Hong, Helen Shih, Tarek Halabi, Tobias Spalke, Michael Monz, Phil Suess, Karl-Heinz Kueffer, Alexander Scherrer, Kevin Zhang, Jan Unkelbach, Dualta McQuaid.