Outline

- Brief Introduction of mdaccAutoPlan system
  - What is, why, how to use?
- Very brief introduction of “automation” algorithm of autoplan
  - Physics knowledge extraction, creation, and automation
  - Beam angle selection automation, physics parameters (minimum segment MUs/area, spot spacing for IMPT etc)
  - Dosimetrist knowledge extraction, and automation
  - Planning structure / Objective function automation
  - Optimization experts knowledge
  - Objective function parameter automation (OFPA)
- Results
  - Autoplan for advanced stage lung cancer (IMRT/VMAT)
  - Automatic treatment planning workflow for IMPT
- Automatic adaptive planning

What is mdaccAutoPlan?

- mdaccAutoPlan is the IMRT/VMAT/IMPT plan, which satisfies plan criteria used in MDACC for various disease sites, designed by the optimization algorithm without or with minimum human intervention.
Why AutoPlan?

• Current Treatment Planning
  – Manually select beam angles by trial and error
  – Manually adjust objective function parameters (OFPs) by trial and error
  – The quality of the plan was determined by the expertise of the “artist”/dosimetrist.
  – Manually contour the structures
  – Long learning curve to ramp up the new technologies: VMAT, Proton Plan, IMPT plans ...

• MDACC Automatic Planning
  – Automatic select beam angles by “expert system” or “beam angle optimizer”: no trial and error
  – Optimize OFPs by MDACC objective function parameter optimizer: no trial and error
  – The quality of the plan across the institution, dosimetrists is consistent.
  – Auto-segmentation will be implemented.
  – TPS vendors not only provide the TPS software but also provide the “solution.”

How autoplan works: “one button click” planning

- In Pinnacle, one button click, “AutoPlan_Lung” => high quality IMRT/VMAT plan.
- For IMPT, in-house developed system will generate robustly optimized IMPT plans without human intervention in super computer hosted in Texas Advanced Computing Center (TACC)

Currently, mdaccAutoPlan system is used by our research dosimetrist to create IMRT plans for the NCI sponsored trial to compare outcome of IMRT and proton therapy.

Special thanks Peter Balter, Lei Dong, Jaque Bleutt, Z. Liao and R. Mohan
Automation in mdaccAutoPlan
- Beam angle selection automation (BASA)
  - Data mining the expert beam angles to achieve Beam Angles Selection Automation (BASA)
  - For IMPT, using beam angle optimization algorithm to create the "expert" beam angles (collaborate with CH, Rice, IBM optimization experts)
  - For VMAT plan, use two arcs for all plans (one arc from 182º to 178º and the other from 178º to 182º, continuous delivery)
- Objective function parameters automation
  - The planning structures do not vary from patient to patient/data mining the expert knowledge
  - Predict the "DVH" before optimization based on previous expert plans
  - Establishing the "benchmark" IMPT plan database using most advanced optimizer (collaborating with IBM, Rice and UH)

Knowledge based beam angle optimization?

The non-coplanar beam angles were selected by matching a group of patients not by only one patient. The coplanar angle were selected by the patient position and by expert experiences.

The frequency distribution of beam angles used by MDACC dosimetrists in lung cancer IMRT plans, categorized by tumor position (left, center, and right).

14 coplanar angles will be selected and 5 additional non-coplanar angles will be selected based on the non-coplanar angles of closest matched patients.

Knowledge based objective function for lung cancer
- Those planning structures and initial values are being used for every lung patients

Many credits to our dosimetrists:
Knowledge based plan stopping criteria: Data mining the “expert” plans to predict the DVH data

A work is to have better way to predict 3D dose distribution based on machine learning is undergoing.

Roadmap of database driven prediction tool: (plan atlas)

- Predict 1D data: mean dose etc. (WUSTL, MDACC …)
- Predict 2D data: DVH (JHU, Duke etc.)
- Predict 3D data: full 3D dose distribution (???)

Predict Dmean based on overlap information: Moore et al. Int J Radiat Oncol Biol Phys, 81 p545, 2011

Validation of autoplan
- Automated VMAT treatment planning for stage III lung cancer: how does it compare with IMRT?
**Plan quality comparison between manually designed best effort plan with autoplan**

- Group I patients/best effort manual plan: dosimetrists and mdaccAutoPlan system designed IMRT plan simultaneously. The better plan was used for patient treatment. (in a trial comparing proton and photon, PI Z Liao)
- Group II patients/conventional plan, mdaccAutoPlan system retrospectively re-designed clinical plans.
- mdaccAutoPlan system designed auto-VMAT plans for both group patients
- “unbiased” plan evaluation
  - Five radiation oncologists blind-reviewed and ranked the three plans of each patient independently.
  - Drs. Chang, Liao (MDACC), Dr. T. Xia (301 Hospital, China), Dr. Z. Yuan, (Tianjin Cancer Institute, China), Dr. H. Liu (Zhong Shang Hospital, China) reviewed and ranked plan

**Blind review results**

- A lower rank value indicates a better plan quality and vice versa.
- Group I, dosimetric compete with mdaccAutoPlan system
- Group II, mdaccAutoPlan system replan the previous accepted plan

![Graph showing plan quality comparison]

Dosimetrically, difference is small for clinical plan with best effort, IMRT autoplan and VMAT autoplan.
Dosimetrically, the difference is small for IMPT autoplan and VMAT autoplan. However, both autoplans are significantly better than clinical plan designed conventionally.

**IMPT autoplan**

IMPT plan should be beam angle, spot arrangement, objective function parameter and robustly optimized without trial and error. IMPT autoplan is implemented as part of mdaccAutoPlan system with in-house developed dose calculation algorithms and optimization engine and most time running on the supercomputer hosted at Texas Advance Computing Center.

**IMPT AutoPlan workflow**

- Beam angle selection automation
  - First perform beam angle optimization (BAO) to create knowledge
  - Class solution of beam angles for various disease sites is obtained by analyzing BAO results
- Spot arrangement optimization
  - Incorporating deliverable monitor unit constraints into IMPT treatment planning
  - Automatic spot arrangements
- Objective function parameter optimization
  - Autoplan algorithm which was validated in IMRT/VMAT plan design into IMPT plan design
- Optimization model
  - Robust optimization algorithm
- Final results
  - Plan can be sent to TPS and dose can be recalculated in commercial TPS.
Beam angle: Three-beam angle class solution for prostate patients by analyzing beam angle optimized plans

<table>
<thead>
<tr>
<th></th>
<th>Two angles</th>
<th>Three angles</th>
<th>Four angles</th>
<th>Three angles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Optimized</td>
<td>Optimized</td>
<td>Optimized</td>
<td>Class</td>
</tr>
<tr>
<td></td>
<td>Conventional</td>
<td>Two angles</td>
<td>Three angles</td>
<td>Four angles</td>
</tr>
<tr>
<td>Rectum V30</td>
<td>20.9</td>
<td>17.4</td>
<td>16.9</td>
<td>14.9</td>
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<tr>
<td>V40%</td>
<td>21.2</td>
<td>17.4</td>
<td>14.2</td>
<td>13.9</td>
</tr>
<tr>
<td>V60%</td>
<td>17</td>
<td>14.4</td>
<td>11.6</td>
<td>11.3</td>
</tr>
<tr>
<td>V70%</td>
<td>13</td>
<td>11.4</td>
<td>9.5</td>
<td>8.8</td>
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<tr>
<td>Bladder V30%</td>
<td>20.8</td>
<td>23.7</td>
<td>24.8</td>
<td>25.5</td>
</tr>
<tr>
<td>V40%</td>
<td>17.6</td>
<td>19.7</td>
<td>20.2</td>
<td>20.7</td>
</tr>
<tr>
<td>V50%</td>
<td>15</td>
<td>16.2</td>
<td>16.6</td>
<td>17</td>
</tr>
<tr>
<td>V60%</td>
<td>12.2</td>
<td>13</td>
<td>13.3</td>
<td>13.6</td>
</tr>
<tr>
<td>V70%</td>
<td>9</td>
<td>9.4</td>
<td>9.6</td>
<td>9.7</td>
</tr>
<tr>
<td>PTV V70%</td>
<td>98.6</td>
<td>97.9</td>
<td>97.7</td>
<td>98.1</td>
</tr>
</tbody>
</table>

Impact of BAO: Improved plan quality for prostate case by BAO

Spot arrangement optimization

- Incorporating deliverable monitor unit constraints into IMPT treatment planning leads to automatic spot arrangements
- Optimized spot arrangement is the final spot arrangement using very dense initial spot spacing
### Impact of Spot Spacing Optimization

<table>
<thead>
<tr>
<th>Spot Spacing</th>
<th>STV V78</th>
<th>STV V70</th>
<th>STV V40</th>
<th>D_{\text{max}}</th>
<th>Rectum V70</th>
<th>Rectum V40</th>
<th>Bladder V70</th>
<th>Bladder V40</th>
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<tr>
<td>7 mm</td>
<td>100.0 (100.0-100.0)</td>
<td>100.0 (100.0-100.0)</td>
<td>100.0 (100.0-100.0)</td>
<td>79.7 (79.6-79.7)</td>
<td>4.6 (2.3-6.9)</td>
<td>16.9 (14.0-20.9)</td>
<td>6.4 (2.3-9.1)</td>
<td>12.4 (5.1-17.6)</td>
</tr>
<tr>
<td>6 mm</td>
<td>100.0 (100.0-100.0)</td>
<td>100.0 (100.0-100.0)</td>
<td>100.0 (100.0-100.0)</td>
<td>79.7 (79.6-79.7)</td>
<td>4.5 (2.3-6.8)</td>
<td>16.3 (14.0-20.0)</td>
<td>6.3 (2.3-8.8)</td>
<td>12.4 (5.1-17.2)</td>
</tr>
<tr>
<td>5 mm</td>
<td>100.0 (100.0-100.0)</td>
<td>100.0 (100.0-100.0)</td>
<td>100.0 (100.0-100.0)</td>
<td>79.6 (79.6-79.6)</td>
<td>4.4 (2.2-6.8)</td>
<td>16.2 (14.0-20.4)</td>
<td>6.2 (2.2-8.7)</td>
<td>12.1 (5.1-17.1)</td>
</tr>
<tr>
<td>4 mm</td>
<td>100.0 (100.0-100.0)</td>
<td>100.0 (100.0-100.0)</td>
<td>100.0 (100.0-100.0)</td>
<td>79.6 (79.6-79.6)</td>
<td>4.3 (2.2-6.7)</td>
<td>15.1 (13.0-17.5)</td>
<td>6.1 (2.3-8.6)</td>
<td>12.0 (5.2-17.0)</td>
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<tr>
<td>3 mm</td>
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<td>100.0 (100.0-100.0)</td>
<td>100.0 (100.0-100.0)</td>
<td>79.6 (79.6-79.6)</td>
<td>4.3 (2.2-6.7)</td>
<td>15.0 (13.0-17.1)</td>
<td>6.0 (2.3-8.5)</td>
<td>11.9 (5.2-16.9)</td>
</tr>
</tbody>
</table>


Number of scanning spots

Delivery efficiency was not sacrificed with 3mm initial spot spacing.

Optimization model: robust optimization

Nominal position

3.5% range overshoot

Nominal Green color wash: ITV

Robustly optimized plan

IMPT auto-robust plan for lung

Automatic adaptive planning

- It is possible to perform real-time on-line adaptive planning based on autoplan and super computing/GPU.
- If autoplan is adopted in the routine planning and clinicians accept the autoplan without modification, it is possible to perform the autoplan for each daily CT.
  - It is possible that clinicians do not need to approve plans for each daily CT.
- We proposed the AAP method: fully automated adaptive re-planning method:
  - Automatic contour propagation
  - Autoplan

Automatic contour propagation

Contour in simulation CT
Automatically propagated contour using deformable image registration
AAP plan compared with the iso-center shifted plan: dose distribution

Summary

We demonstrated that mdaccAutoPlan system can design the high quality IMRT/VMAT/IMPT plan without with minimum human intervention.

It is desired to validate and extend this system into more centers.

A sister institution network fund by MDACC to test the use of this system in two China sister institutions of MDACC (TMUCIH and CAMS) was funded recently.

Acknowledgements

Team
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- Hang Li
- Run X, Zhu
- Sahoo Narayan
- Jaime Yang
- Lei Ding
- Andrew Lee
- Dabria Kuban
- Joe Y Chang
- Zhongxing Liao
- M Gillin
Real clinical example: balance between robustness and normal tissue sparing

- 17 yr old female
- Stage IV metastatic adenocarcinoma with extensive involvement of the nodular right pleural
- Treated with multiple cycles of chemotherapy
- Eventually underwent extrapleural pneumonectomy
- Large and complex CTV ~ 2215 cc

Robustness v.s. Normal tissue sparing?

DVHs for normal tissue at worst scenario
Question?

- In what way does MCO help clinicians to make the decision?
- Once the clinical decisions were made for a cohort of patients, can we say that clinical decisions on “compromise” will be predicted by data mining using the machine learning tool?
- MCO can also be bypassed by the “one button click” approach.

**IMPT autoplan vs. IMRT Plans**
9 cases average

**IMPT autoplan vs. PSPT Plans**
9 cases average
Automatic planning for SBRT lung patients

- Hard cases: 11 patients’ tumors were centrally/superiorly located
  - within 2 cm of the bronchial tree, esophagus, heart, major vessels, trachea, or bronchial pleums and only 1 cm away from the spinal cord
- Currently, in MDACC, 3D-CRT plans used 6-12 non-coplanar beams
  - not efficient for the delivery and good treatment plan needs experience
- Can coplanar automatically generated VMAT or IMRT plans achieve similar or better plan quality than non-coplanar 3D or IMRT plan do?
  - All auto-VMAT plans for those patients were designed using two arcs (one arc from -182º to 178º and the other from -178º to 182º)
  - Efficient to deliver
  - Plan quality is consistent (automatically generated)

VMAT autopln v.s. 3DCRT v.s. IMRT

VMAT plan does not necessary lead to increased low dose in lung

<table>
<thead>
<tr>
<th>Table 2 Target Conformity Index and mean minimal lung volumes received with:</th>
<th>AIP/VMAT, 3D-CRT and IMRT (BAO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical structure</td>
<td>AIP VMAT</td>
</tr>
<tr>
<td>GTV</td>
<td>C_{TPV}</td>
</tr>
<tr>
<td></td>
<td>C_{PM}</td>
</tr>
<tr>
<td></td>
<td>C_{PM}</td>
</tr>
<tr>
<td>V&lt;5 Gy (%)</td>
<td>15.9</td>
</tr>
<tr>
<td>V&lt;10 Gy (%)</td>
<td>12.5</td>
</tr>
<tr>
<td>V&lt;20 Gy (%)</td>
<td>7.4</td>
</tr>
<tr>
<td>MLD (Gy)</td>
<td>4.5</td>
</tr>
</tbody>
</table>
VMAT autoplan led to better critical structure sparing

<table>
<thead>
<tr>
<th>Critical structure</th>
<th>Delivered D2Gy (%)</th>
<th>VMAT autoplan</th>
<th>BAO 2D</th>
<th>VMAT autoplan</th>
<th>BAO 2D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acute</td>
<td>19.3</td>
<td>21.7</td>
<td>0.01</td>
<td>17.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Bladder</td>
<td>15.94</td>
<td>25</td>
<td>0.07</td>
<td>11.2</td>
<td>0.49</td>
</tr>
<tr>
<td>Bowel</td>
<td>10.4</td>
<td>12.4</td>
<td>0.04</td>
<td>10.2</td>
<td>0.7</td>
</tr>
<tr>
<td>Bronchus</td>
<td>11.7</td>
<td>18.5</td>
<td>0.899</td>
<td>19.5</td>
<td>0.26</td>
</tr>
<tr>
<td>Heart</td>
<td>11.2</td>
<td>16.3</td>
<td>0.25</td>
<td>10</td>
<td>0.28</td>
</tr>
<tr>
<td>Pulmonary Vein</td>
<td>10.7</td>
<td>14.8</td>
<td>0.02</td>
<td>11</td>
<td>0.35</td>
</tr>
<tr>
<td>Spinal Cord</td>
<td>8.6</td>
<td>13.5</td>
<td>0.04</td>
<td>8.4</td>
<td>0.57</td>
</tr>
<tr>
<td>Testes</td>
<td>9.1</td>
<td>6.1</td>
<td>0.07</td>
<td>3.9</td>
<td>0.26</td>
</tr>
</tbody>
</table>

With more than 12 beams, coplanar IMRT plan converges to VMAT plan

Delivery Efficiency/Implication

<table>
<thead>
<tr>
<th></th>
<th>Non-coplanar SDOPT</th>
<th>Coplanar VMAT autoplan</th>
<th>Non-coplanar BAO IMRT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delivery time/Setup (minutes)</td>
<td>30:45</td>
<td>5:7</td>
<td>30:45</td>
</tr>
<tr>
<td>MU</td>
<td>2409</td>
<td>3243</td>
<td>2317</td>
</tr>
</tbody>
</table>

- Small segments help coplanar VMAT to achieve the better normal tissue sparing
- Non-coplanar BAO helps to find the better angle with large segments
- Non-coplanar angle does not lead to improved plan quality
- The VMAT/Rapid Arc is preferred in terms of delivery time and plan quality
- Only drawback is the risk of secondary cancer.
AutoPlan for H&N: status

- Work in progress. A preliminary version was implemented.
The radiation oncologist considered the VMAT plan to have superior dose distribution compared to the two IMRT plans. VMAT by AutoPlan: 78 Gy; IMRT by CMD: 74 Gy; IMRT by AutoPlan: 65 Gy.

GTV
CTV
PTV
Spinal cord
Esophagus

The auto-IMRT, auto-VMAT plans for selected cases were reviewed by Dr. Lee and were considered to be applicable for patient treatment.

AutoPlan for prostate

- Implemented for prostate sites for both fixed beam IMRT and VMAT plans.
- More beam angles, better IMRT plan?
- VMAT vs. many-angle-IMRT?

- The auto-IMRT, auto-VMAT plans for selected cases were reviewed by Dr. Lee and were considered to be applicable for patient treatment.
Example #2: **24-beam IMRT ~ VMAT**

- **PTV**
- **rectum**
- **bladder**
- **femoral heads**

Simultaneously beam angle and Objective function parameter automation algorithm

### Table 4  Inverse planning parameters for VMAT and IMRT

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum segment area (cm²)</td>
<td>2</td>
</tr>
<tr>
<td>Minimum segment MUs</td>
<td>1</td>
</tr>
<tr>
<td>Minimum number of leaf pairs</td>
<td>2</td>
</tr>
<tr>
<td>Minimum leaf end separation (cm)</td>
<td>1.5</td>
</tr>
<tr>
<td>Maximum number of iterations</td>
<td>25</td>
</tr>
<tr>
<td>Convolution dose iteration</td>
<td>5</td>
</tr>
<tr>
<td>Maximum number of segments (IMRT)</td>
<td>100</td>
</tr>
<tr>
<td>Maximum delivery time (second) (VMAT)</td>
<td>100</td>
</tr>
<tr>
<td>Dose engine</td>
<td>CC Convolution</td>
</tr>
</tbody>
</table>

*Abbreviations: IMRT = intensity-modulated radiotherapy; MU = Monitor unit; VMAT = volumetric-modulated arc therapy.*
Optimized beam direction

70 Gy
60 Gy
50 Gy
20 Gy
10 Gy
5 Gy

(a) clinical plan
(b) Autoplan-5B

Are there any differences among different radiation oncologists?

- p-values calculated from two-sided paired t-test of the blind ranking results between pairs of oncologists. All p-values are $> 0.05$, indicating insignificant difference in the rankings.
Lung plan: autoplan v.s. clinical plan: objective function parameters

- The same planning structures are used for all the patients: one reason why automation is possible.
- EUD-based objective function was adopted to optimize the whole, EUD curve rather than several dose volume values in a DVH curve.
- Constrained optimization