Automatic IMRT, VMAT, IMPT treatment planning

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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
- Summary

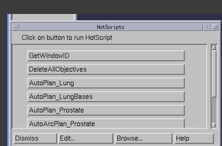
What is mdaccAutoPlan?

- 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.

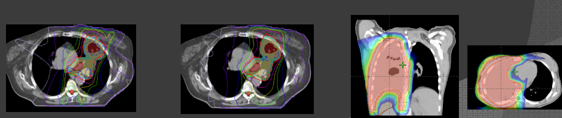
Why AutoPlan?

- 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 structure~~
  - 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" venders not only provide the TPS software but also provide the "solution.."

How autoplan works: "one button click" planning



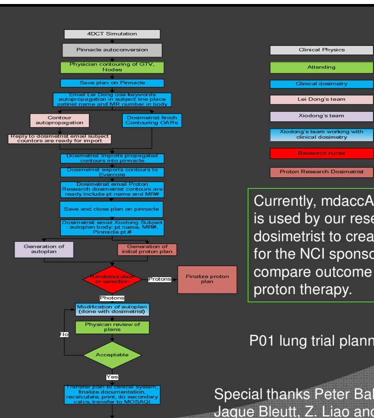
- In Pinnacle, one button click, "AutoPlan_Lung" => high quality IMRT/VMAT plan.
- For IMPT, in-house developed system will generate robustly optimized IMPT plans without human intervention in super computer hosted in Texas Advanced Computing Center (TACC)



IMRT autoplan

VMAT autoplan

IMPT autoplan



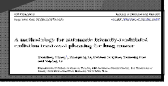
Currently, mdaccAutoPlan system is used by our research dosimetrist to create IMRT plans for the NCI sponsored trial to compare outcome of IMRT and proton therapy.

P01 lung trial planning process

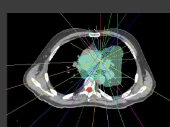
Special thanks Peter Balter, Lei Dong, Jaque Bleutt, Z. Liao and R. Mohan

Automation in mdaccAutoPlan

- Beam angle selection automation (BASA)
  - Data mining the exert beam angles to achieve Beam Angles Selection Automation (BASA)
  - For IMPT, using beam angle optimization algorithm to create the "expert" beam angles. [collaborate with UH, 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, continusly 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)

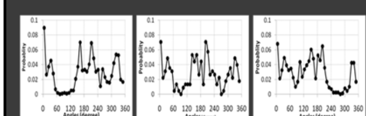


Knowledge based beam angle optimization?



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.



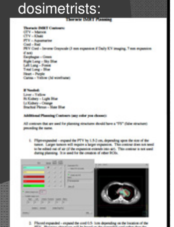
The frequency distribution of beam angles used by MDACC dosimetrists in lung cancer IMRT plans, categorized by tumor position (left, middle, and right).

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.

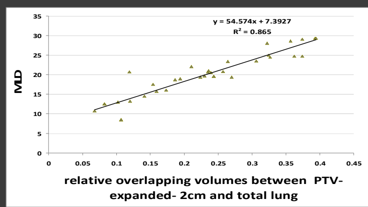
Knowledge based objective function for lung cancer

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

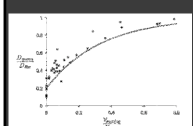
Used to predict whether MLD <22 Gy will be met or not. If not, three different plans will be automatically generated

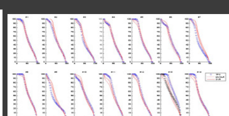
Roadmap of database driven prediction tool: (plan atlas)

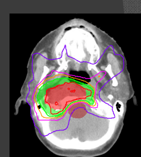
Predict 1D data: mean dose etc. (WUSTL, MDACC …)

Predict 2D data: DVH (JHU, Duke etc.)

Predict 3D data: full 3D dose distribution (???)







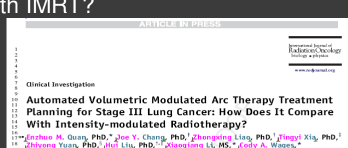
Predict Dmean based on overlap information: Moore et. al. IJROBP, 81,p545, 2011

Predict DVH based on OVH/DTH using SVM and machine learning tools. Zhu et. al. Med. Phys. ,38, p719,2011

MDACC?? 2012 or 2013

Validation of autoplan

- Automated VMAT treatment planning for stage III lung cancer: how does it compare with IMRT?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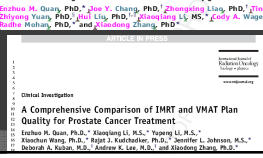
Clinical Investigation

Automated Volumetric Modulated Arc Therapy Treatment Planning for Stage III Lung Cancer: How Does It Compare With Intensity-modulated Radiotherapy?

Enzhuo M. Quan, PhD,* Joe Y. Chang, PhD,† Zhongxing Liao, PhD,† Tingyi Xia, PhD,‡ Zhiyong Yuan, PhD,§ Hui Liu, PhD,†,‖ Xiaoqiang Li, MS,* Cody A. Wages,* Radhe Mohan, PhD,* and Xiaodong Zhang, PhD*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Clinical Investigation

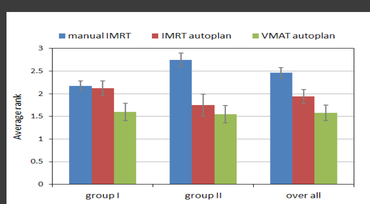
A Comprehensive Comparison of IMRT and VMAT Plan Quality for Prostate Cancer Treatment

Enzhuo M. Quan, Ph.D.,* Xiaoqiang Li, M.S.,* Yupeng Li, M.S.,* Xiaochun Wang, Ph.D.,* Rajat J. Kudchadker, Ph.D.,* Jennifer L. Johnson, M.S.,* Deborah A. Kuban, M.D.,† Andrew K. Lee, M.D.,† and Xiaodong Zhang, Ph.D.*

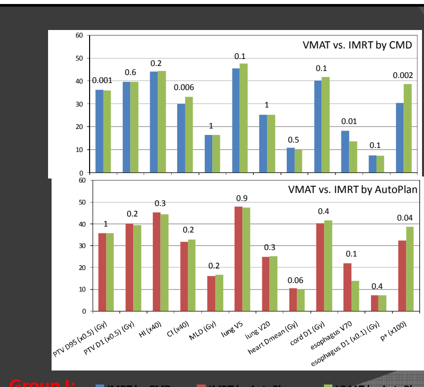
Plan quality comparison between manually designed best effort plan with autoplan

- 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

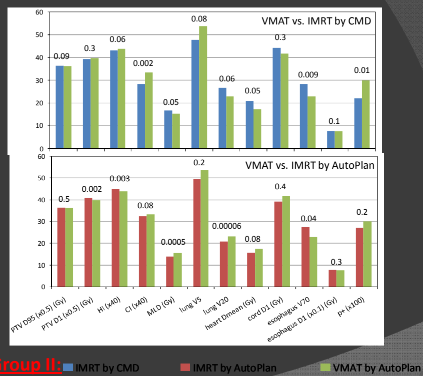
Blind review results



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



Dosimetrically, difference is small for clinical plan with best effort, IMRT autoplan and VMAT autoplan



Dosimetrically, difference is small for IMRT 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.

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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.

Li Y, Lii M, Li H, Taylor M, Li X, Zhu X, Sahoo N, Zhu R, “Independent Dose Verification System for Spot Scanning Proton Therapy”, 2012 AAPM poster presentaton
Zhang X, Liu W, Li Y, Li X, Quan E M, Mohan R, Anand A, Sahoo N, Gillin M, Zhu R. Parameterization of multiple Bragg curves for scanning proton beams using simultaneous fitting of multiple curves. Physics in Medicine and Biology 56:7725, 11/2011.
Li Y, Zhu Ron, Sahoo N, Anand A, Zhang X. Beyond Gaussians: a study of single spot modeling for scanning proton dose calculation. Physics in Medicine and Biology. 57:983, 2012

Beam angle: Three-beam angle class solution for prostate patients by analyzing beam angle optimized plans

	Two angles Conventional {90, 270}	Two angles Optimized	Three angles Optimized	Four angles Optimized	Three angles Class {10,140,270}
Rectum $V30_{Gy}$	25.7	20.9	17.4	16.9	18.3
$V40_{Gy}$	21.2	17.4	14.2	13.9	14.8
$V50_{Gy}$	17	14.4	11.6	11.3	11.9
$V60_{Gy}$	13	11.4	9.1	8.8	9.2
$V70_{Gy}$	8.4	7.9	6.5	6.1	6.4
Bladder $V30_{Gy}$	20.8	23.7	24.8	25.5	24.7
$V40_{Gy}$	17.8	19.7	20.2	20.7	20.1
$V50_{Gy}$	15	16.2	16.6	17	16.6
$V60_{Gy}$	12.2	13	13.3	13.6	13.3
$V70_{Gy}$	9	9.4	9.6	9.7	9.6
PTV $V76_{Gy}$	98.6	97.7	97.9	98.1	98.1

Cao W, Lim G, Lee A, Li Y, Liu W, Zhu X, Zhang X, "Uncertainty incorporated beam angle optimization for IMPT treatment planning", Medical Physics, 2002 (**tentatively accepted**)

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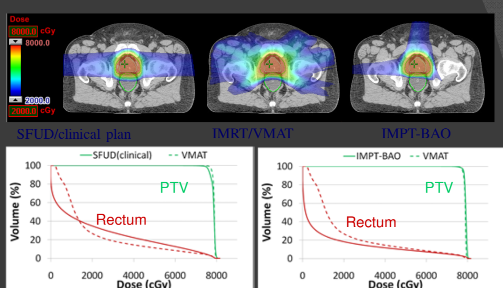
Impact of BAO: Improved plan quality for prostate case by BAO



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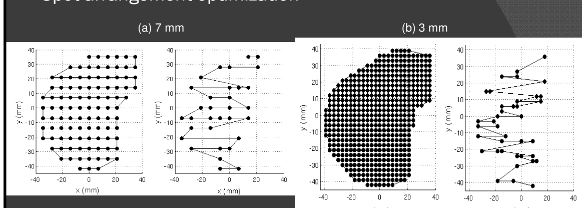
Spot arrangement optimization



Initial spot arrangement

Final spot arrangement

Initial spot arrangement

Final spot arrangement/optimal spot arrangement

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 spot spacing

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Impact of Spot Spacing Optimization

	7 mm	6 mm	5 mm	4 mm	3 mm
	Avg (min-max)	Avg (min-max)	Avg (min-max)	Avg (min-max)	Avg (min-max)
STV					
V_{78Gy} (%)	100.0 (100.0-100.0)	100.0 (100.0-100.0)	100.0 (100.0-100.0)	100.0 (100.0-100.0)	100.0 (100.0-100.0)
D_{max} (Gy)	79.7 (79.6-79.7)	79.7 (79.6-79.7)	79.6 (79.6-79.6)	79.6 (79.6-79.6)	79.6 (79.6-79.6)
Rectum					
V_{70Gy} (%)	4.6 (2.3-6.9)	4.5 (2.4-6.8)	4.4 (2.2-6.8)	4.3 (2.2-6.7)	4.3 (2.2-6.7)
V_{40Gy} (%)	**16.9 (14.0-20.9)**	16.3 (14.0-20.0)	16.2 (14.0-20.4)	15.1 (13.0-17.5)	**14.8 (11.8-17.3)**
D_{mean} (Gy)	**15.7 (12.9-18.7)**	15.4 (13.7-17.5)	15.1 (13.2-17.7)	14.8 (13.2-17.1)	**14.7 (12.8-16.9)**
Bladder					
V_{70Gy} (%)	6.4 (2.3-9.1)	6.3 (2.3-8.8)	6.2 (2.4-8.7)	6.2 (2.4-8.6)	6.2 (2.3-8.6)
V_{40Gy} (%)	12.4 (5.1-17.6)	12.4 (5.5-17.2)	12.1 (5.3-17.1)	12.0 (5.2-17.0)	11.9 (5.1-17.0)
D_{mean} (Gy)	11.4 (5.3-15.4)	11.3 (5.5-15.2)	11.1 (5.3-15.1)	11.0 (5.3-14.9)	10.9 (5.2-14.5)

Cao W, Li X, Lim G, Li Y, Zhu X, Zhang X, "An Investigation of the Impact of Spot Spacing On Plan Quality Using IMPT Optimization Incorporating Deliverable Monitor Unit Constraints", 2012 AAPM Annual Meeting, Oral Presentation, TH-A-213AB-9.

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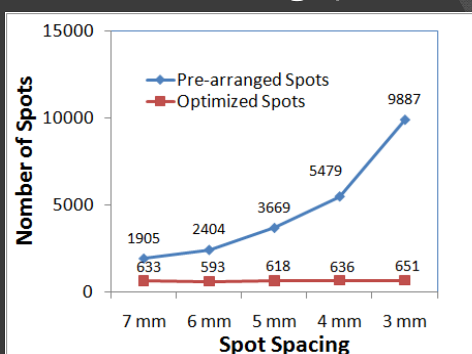
Number of scanning spots



Delivery efficiency was not sacrificed with 3mm initial spot spacing

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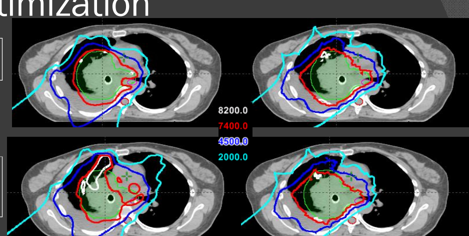
Optimization model: robust optimization

Nominal position

3.5% range overshoot



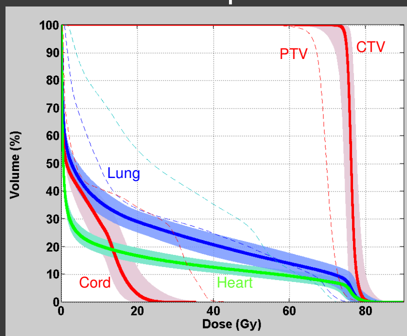
Nominal

Robustly optimized plan

Green color wash: ITV

Liu W, Zhang X, Li Y, Mohan R. Robust Optimization of Intensity Modulated Proton Therapy. Medical Physics 39:1079, 2/2012.
Liu W, Li Y, Cao W, Li X, Zhang X. Influence of robust optimization in intensity-modulated proton therapy with different dose delivery techniques. Medical Physics. In Press.

IMPT auto-robust plan for lung



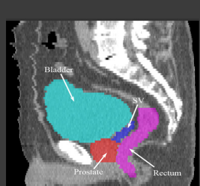
Dashed line: clinical nominal IMRT plan.

Automatic adaptive planning

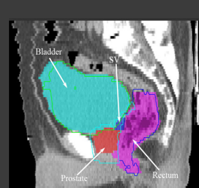
- It is possible to perform real time on-line adaptive planning based on autoplan and super computing/GPU.
- If autoplan is adopted in the routine planning and clinicians accepts the autoplan without modification, it is possible to perform the autoplan for each daily CT.
  - It is possible that clinician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

Li X et. al. IJROBP, under revision

Automatic contour propagation

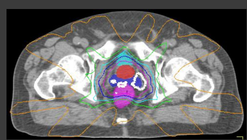


Contour in simulation CT

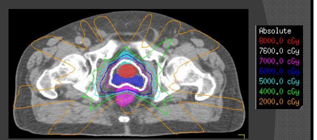


Automatically propagated contour using deformable image registration

AAP plan compared with the iso-center shifted plan: dose distribution



Original plan on day 4 CT using isocenter-shift



Automatically generated plan on day 4 CT using AAP method

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
  - Xiaoqiang Li
  - Michelle Quan
  - Yupeng Li
  - Wenhua Cao
  - Xiaoning Pan
  - Radhe Mohan
- Indispensable contribution
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  - Kudchadker R, Johnson J and GU physics team
  - Stephen Bilton and thoracic dosimetry team
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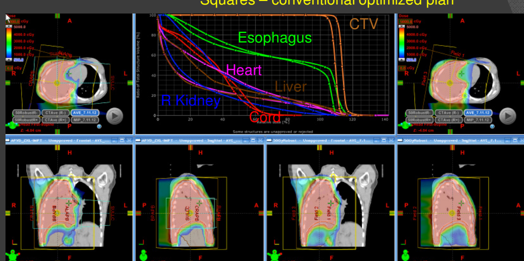
  - Heng Li
  - Ron X, Zhu
  - Sahoo Narayan
  - Jame Yang
  - Lei Dong
  - Andrew Lee
  - Debora Kuban
  - Joe Y Chang
  - Zhongxing Liao
  - M. Gillin

Real clinical example: balance between robustness and normal tissue sparing

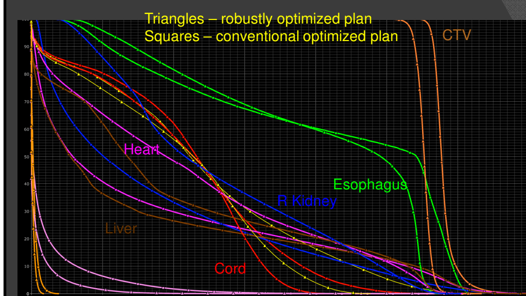
- 17 yr old female
- Stage IV metastatic adenocarcinoma with extensive involvement of the nodular right pleural
- Treated with multiple cycles of chemotherapy
- Eventually underwent extrapleural pneumonectomy
- Large and complex CTV ~ 2215 cc

Robustness v.s. Normal tissue sparing?

Triangles – robustly optimized plan
Squares – conventional optimized plan



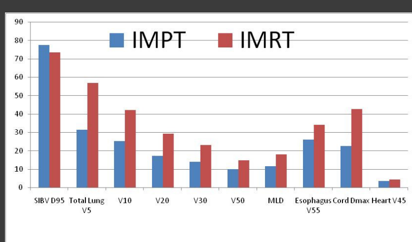
DVHs for normal tissue at worst scenario



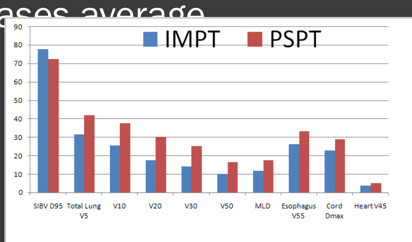
Question ?

- 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



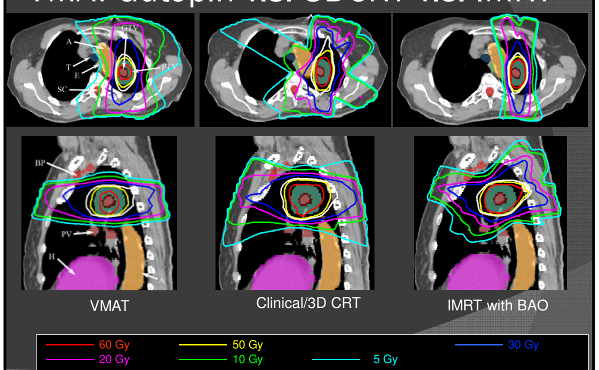
IMPT autoplan vs. PSPT Plans 9 cases average



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 brachial plexus 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

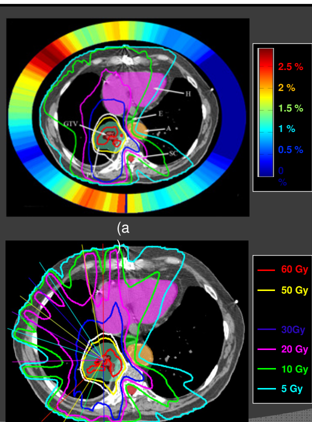
Table 2 Target Conformity Index and mean critical total lung volumes received with AIP-VMAT, 3D-CRT and BAO IMRT

Critical structures	Index	AIP-VMAT	3DCRT	p^*	BAO-IMRT	$p^\dagger$
PTV	$Cl_{100\%}$	1.08	1.47	0.006	1.27	0.001
	$Cl_{80\%}$	1.81	2.45	0.006	1.81	0.95
	$Cl_{50\%}$	4.88	6.31	0.009	4.52	0.35
Total lung	V_5 (%)	**17.9**	**22.1**	0.003	22.9	0.02
	V_{10} (%)	**13.3**	**14.7**	0.01	13.8	0.71
	V_{20} (%)	**7.4**	**8.7**	0.02	6.7	0.23
	MLD (Gy)	**4.5**	**5.4**	<0.001	4.8	0.17

VMAT autoplan led to better critical structure sparing

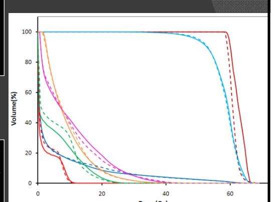
Table 3. Critical structures dosimetric index for the AIP-VMAT, 3DCRT and BAO IMRT

Critical structures	index	AIP-VMAT	3DCRT	p^*	BAO-IMRT	$p\dagger$
Aorta	$D_{1\%}$ (Gy)	19.3	23.7	0.01	17.3	0.3
Brachial plexus	Max (Gy)	13.84	23	0.07	11.2	0.49
Bronchial tree	$D_{1\%}$ (Gy)	9.3	12.4	0.04	10.2	0.7
Esophagus	$D_{1\%}$ (Gy)	11.7	16.3	0.003	10.5	0.36
Heart	$D_{1\%}$ (Gy)	11.3	14.1	0.21	10	0.31
Pulmonary Vessels	$D_{1\%}$ (Gy)	10.7	14.5	0.02	11	0.93
Spinal Cord	$D_{1\%}$ (Gy)	9.8	13.5	0.01	8.4	0.27
Trachea	$D_{1\%}$ (Gy)	5.1	6.1	0.47	3.2	0.25



(a

(b



(c)

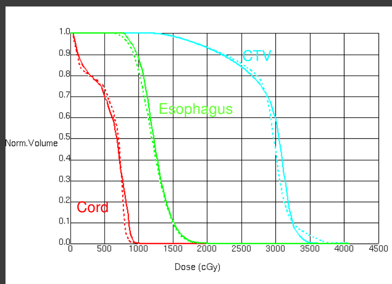
With more than 12 beams, coplanar IMRT plan converges to VMAT plan

Delivery Efficiency/Implication

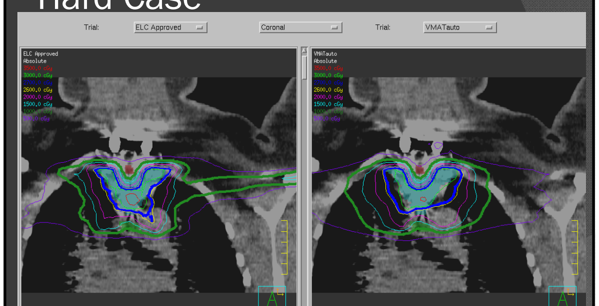
	Non-coplanar 3DCRT	Coplanar VMAT autoplan	Non-coplanar BAO IMRT
Delivery time/Setup (minutes)	30-45	5-7	30-45
MU	2409	3243	2317

- 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.

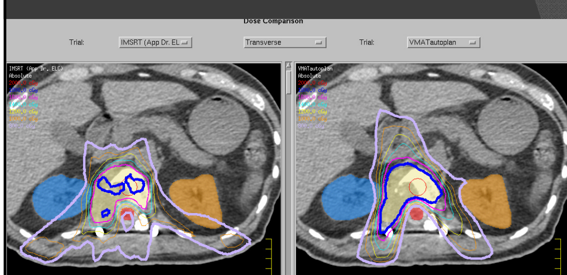
AutoPlan for Spine (IMSRT)



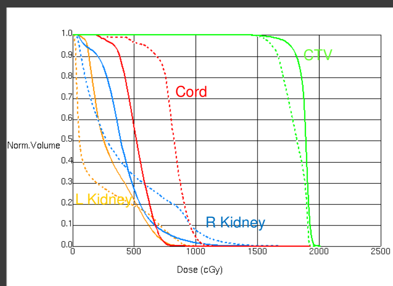
AutoPlan for Spine (IMSRT): Hard Case



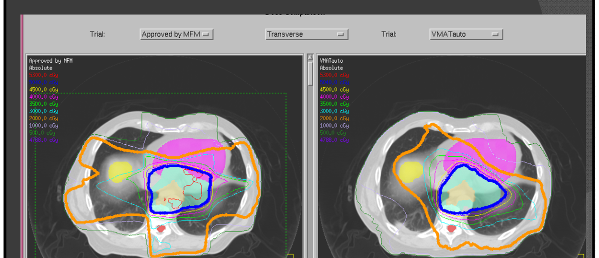
AutoPlan for Spine (IMSRT): Easy Case



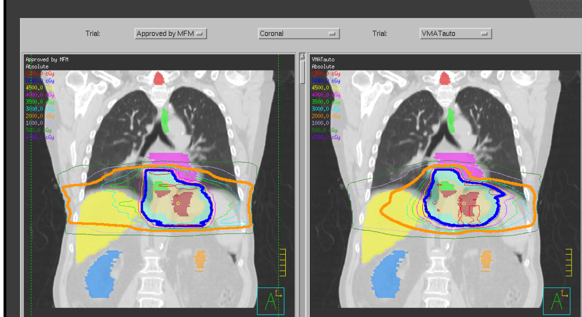
AutoPlan for Spine (IMSRT): Easy Case



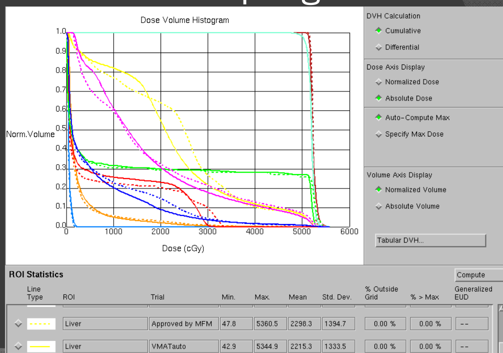
AutoPlan for Esophagus



AutoPlan for Esophagus



AutoPlan for Esophagus

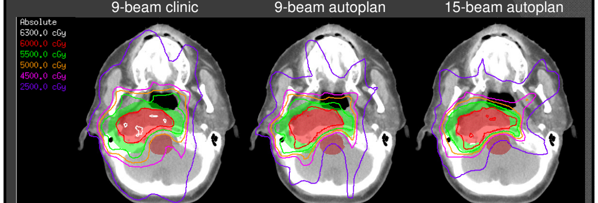


AutoPlan for H&N: status

- Work in progress. A preliminary version was implemented.

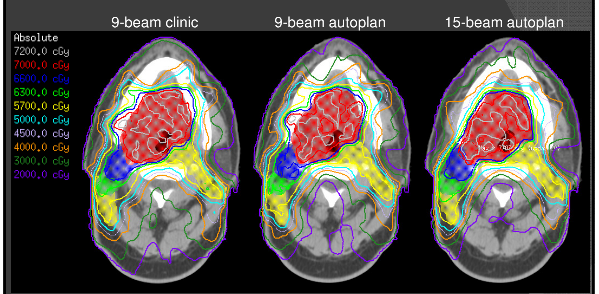
Head-and-Neck Patient 1

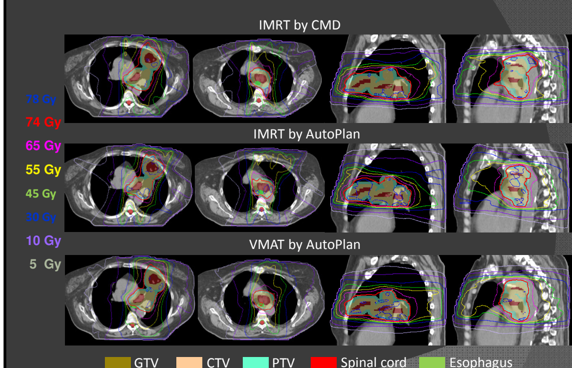
9-beam clinic | 9-beam autoplan | 15-beam autoplan



Dose distributions represented by isodose lines from the clinical plan and the 9- and 15-beam autoplan

Head-and-Neck Patient 2

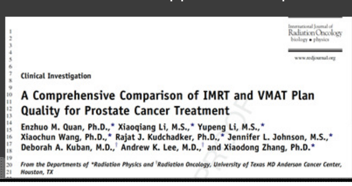




The radiation oncologist considered the VMAT plan to have superior dose distribution to the two IMRT plans.

AutoPlan for prostate

- Autoplan was implemented for prostate sites for both fixed beam IMRT and VMAT plan
  - 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.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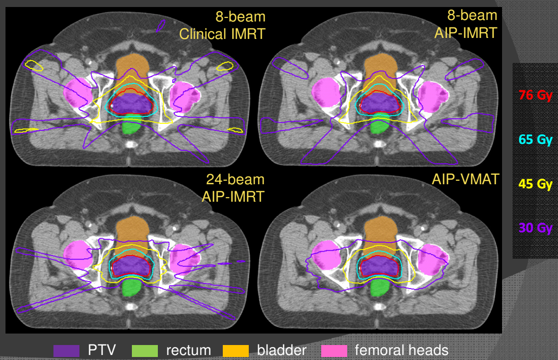
Clinical Investigation

A Comprehensive Comparison of IMRT and VMAT Plan Quality for Prostate Cancer Treatment

Enzhuo M. Quan, Ph.D.,* Xiaoqiang Li, M.S.,* Yupeng Li, M.S.,* Xiaochun Wang, Ph.D.,* Rajat J. Kudchadker, Ph.D.,* Jennifer L. Johnson, M.S.,* Deborah A. Kuban, M.D.,† Andrew K. Lee, M.D.,† and Xiaodong Zhang, Ph.D.*

*From the Departments of *Radiation Physics and †Radiation Oncology, University of Texas MD Anderson Cancer Center, Houston, TX*

Example #2: 24-beam IMRT ~ VMAT



Simultaneously beam angle and Objective function parameter automation algorithm

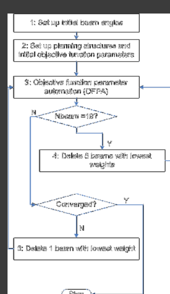
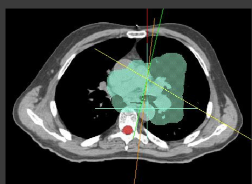


Table 4 Inverse planning parameters for VMAT and IMRT

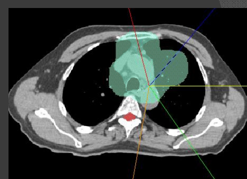
Minimum segment area (cm^2)	2
Minimum segment MUs	1
Minimum number of leaf pairs	2
Minimum leaf end separation (cm)	1.5
Maximum number of iterations	25
Convolution dose iteration	5
Maximum number of segments (IMRT)	100
Maximum delivery time (second) (VMAT)	100
Dose engine	CC Convolution

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

Optimized beam direction



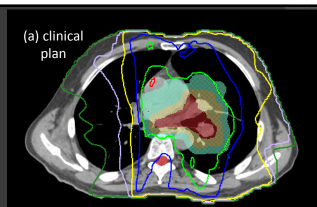
Autoplan-5B [0, 13, 120,187,(30,90)]

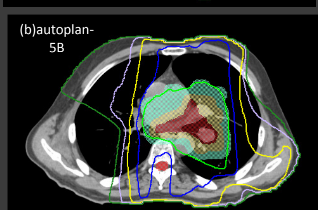


Clinical beam (345,40,90,145,190)

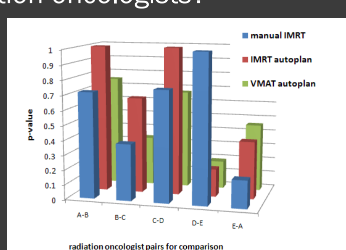
70 Gy
60 Gy
45 Gy
20 Gy
10 Gy
5 Gy

GTV
ITV
PTV
Spinal cord





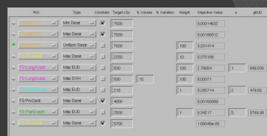
Are there any differences among different radiation oncologists?



- *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

Dosimetrist plan



autoplan

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