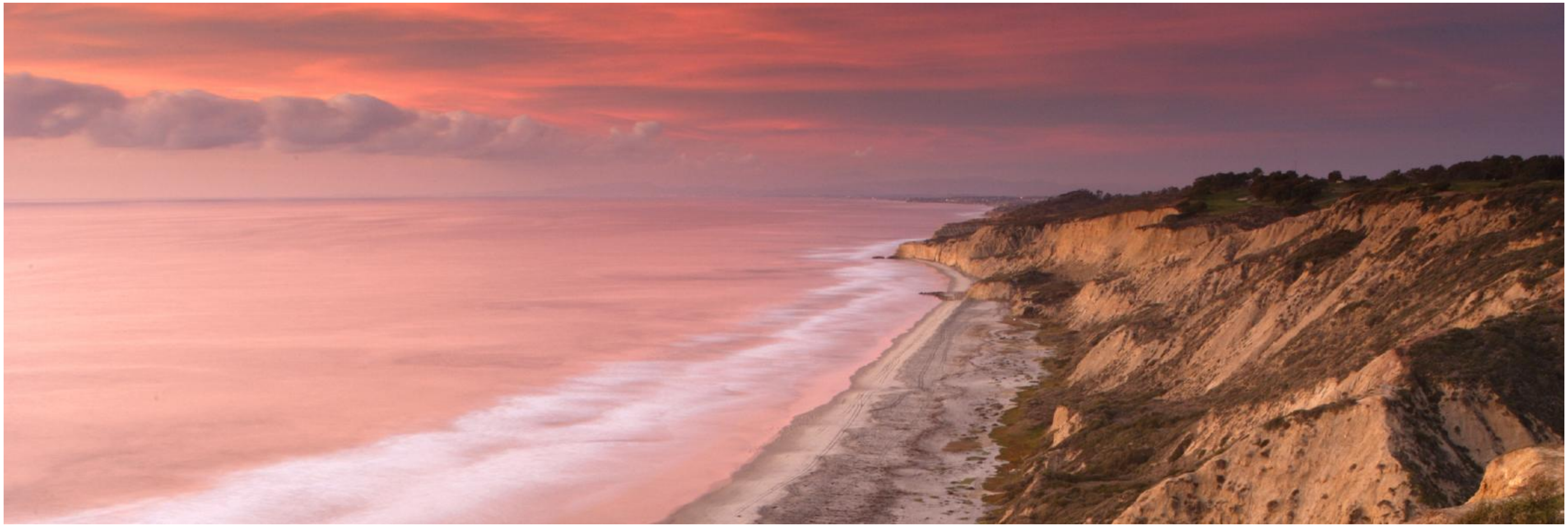

Knowledge-Based Planning for SRS: From Quality Control to Full Automation

Kevin L. Moore, PhD DABR

July 16, 2015

Disclosure Statement

- 2012 and 2014 patent filings
- Varian Medical Systems
  - Licensing Agreement
  - Master Research Agreement
  - Consulting
  - Honoraria

Outline

- Treatment plan quality control
- What is knowledge-based planning (KBP)?
- Case study: KBP for SRS at UCSD
- The future of treatment planning for SBRT/SRS (and everything else)

Do IMRT planning goals ensure “safe” plans?

		Bilateral Neck Treatment	Ipsilateral Neck Treatment
H&N	**PTV**	95% of PTV > 95% of Rx; Max dose < 110% of Rx	95% of PTV > 95% of Rx; Max dose < 110% of Rx
	Spinal Cord	Max dose 40 Gy	Max dose 40 Gy
	Spinal Cord + Margin	Max dose 52 Gy; < 1% (or 1 cc) exceeds 50 Gy	Max dose 52 Gy; < 1% (or 1 cc) exceeds 50 Gy
	Optic Nerves, Optic Chiasm	Max dose 54 Gy	Max dose 54 Gy
	Brainstem	Max dose 54 Gy; < 1% exceeds 60 Gy	Max dose 54 Gy; < 1% exceeds 60 Gy
	Brain	Max dose 60 Gy; < 1% exceeds 65 Gy	Max dose 60 Gy; < 1% exceeds 65 Gy
	Retina	Max dose 50 Gy; < 5% exceeds 45 Gy	Max dose 50 Gy; < 5% exceeds 45 Gy
	Larynx	As low as possible; mean dose < 45 Gy	As low as possible; mean Dose <25 Gy
	Upper Esophagus	As low as possible; mean dose < 45 Gy	As low as possible; mean dose < 25 Gy
	Parotid	As low as possible; mean dose ≤ 26 Gy	As low as possible; mean dose ≤ 10 Gy (contralateral)
	Pharyngeal Constrictors	As low as possible; V60 < 60 Gy	As low as possible; V60 < 45 Gy
	Submandibular	As low as possible; mean dose < 39 Gy	As low as possible; mean dose < 24 Gy (contralateral)
	Oral Cavity	As low as possible; mean dose < 35 Gy	As low as possible; mean dose < 20 Gy
	Mandible	Max 70 Gy; < 5% exceeds PTV Rx	Max 70 Gy; < 5% exceeds PTV Rx
	Unspecified Tissue	Less than PTV Rx; < 5% exceeds PTV Rx	Less than PTV Rx; < 5% exceeds PTV Rx

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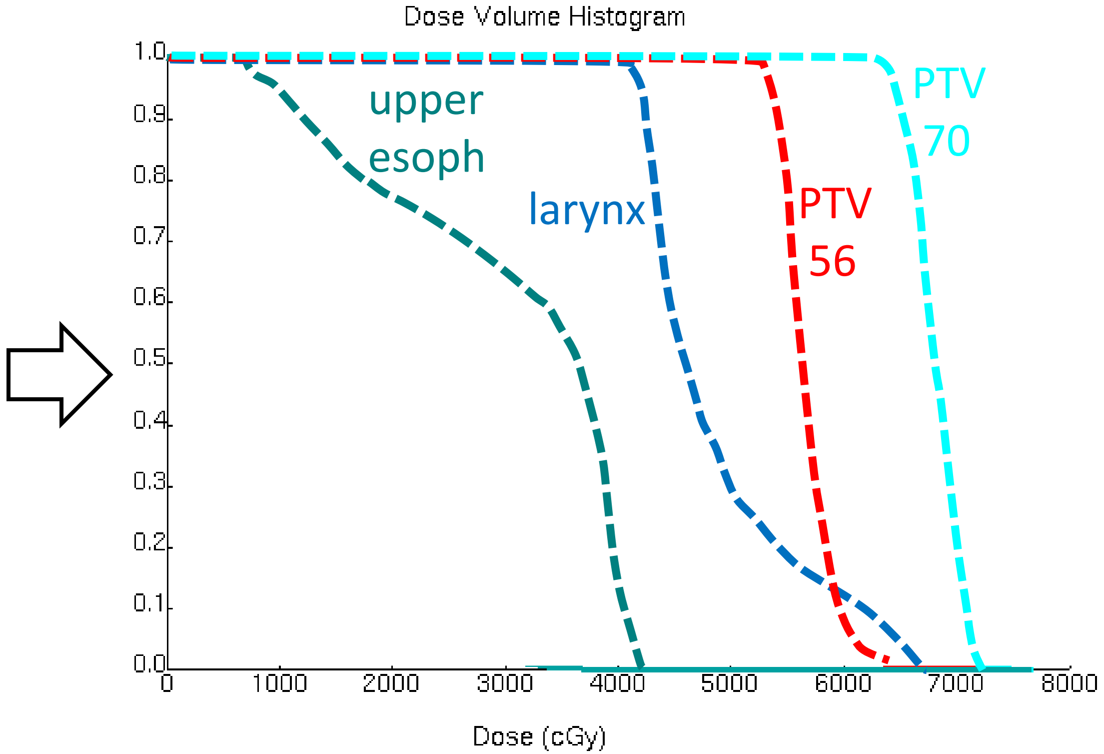

- This plan was QA’d at the treatment machine, passed all standard criteria.

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Do IMRT planning goals ensure "safe" plans?

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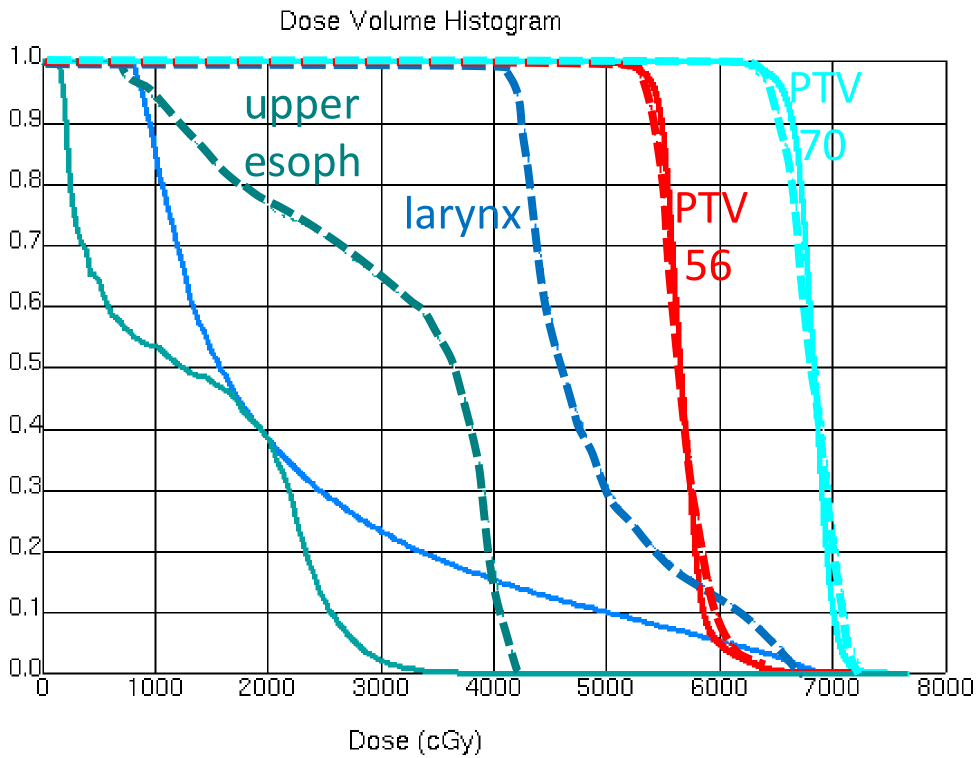

- (Dotted line plan was approved but not treated)
- Treatment plan was *safe* with respect to PTV coverage (TCP), but decidedly *unsafe* with respect to critical OARs (NTCP)

Do IMRT planning goals ensure "safe" plans?

		Bilateral Neck Treatment
H&N	**PTV**	95% of PTV > 95% of Rx; Max dose < 110% of Rx
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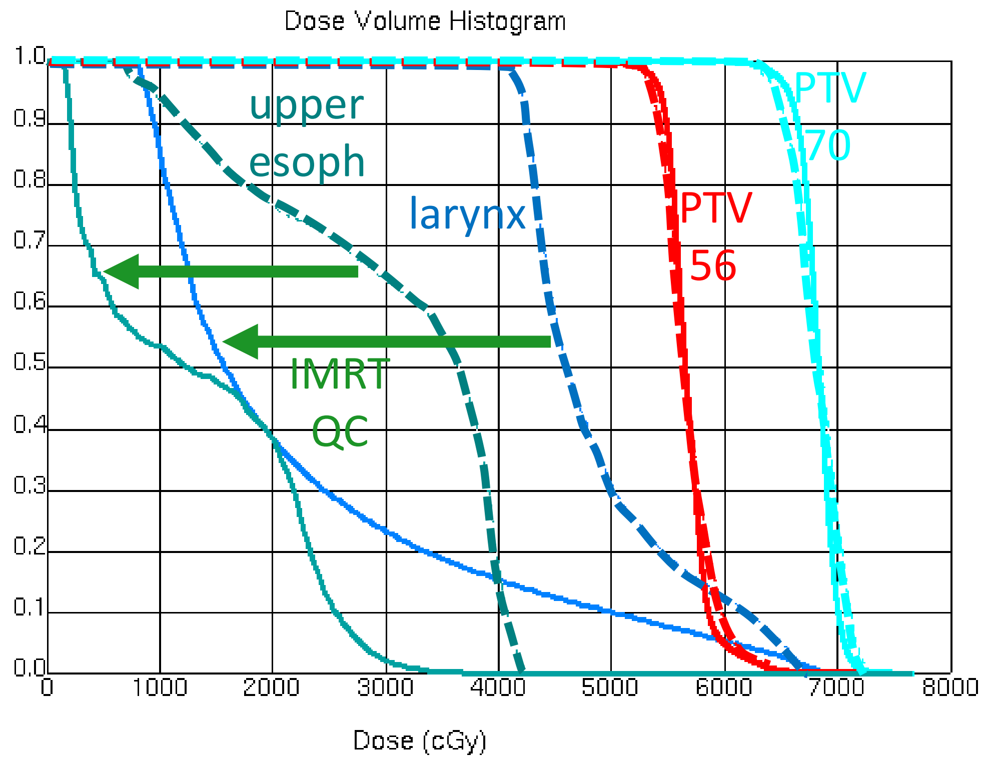
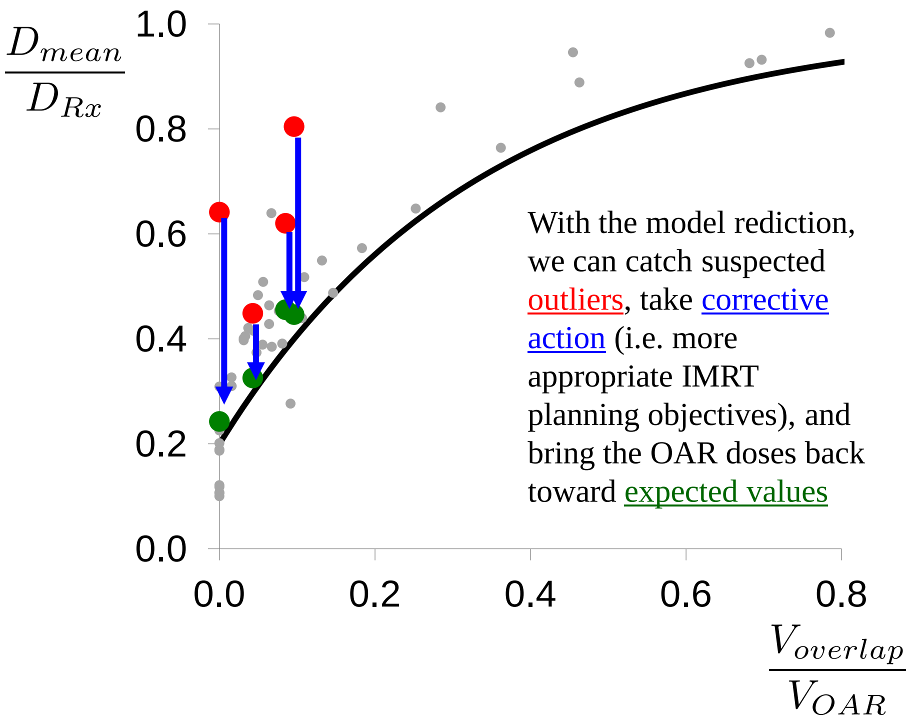
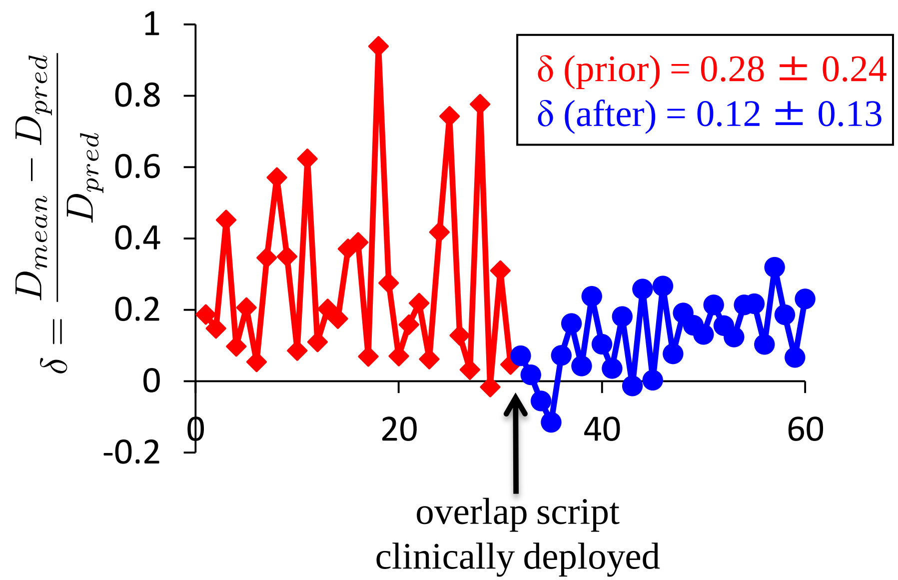


- Unless planning systems make trade-offs explicit, ignorance of what's possible can result in unsafe plan
- IMRT QC can addresses this problem on both input and output

The need for IMRT quality control

Goal is a system that can identify sub-optimal plans (most typically manifested as insufficient OAR sparing)





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KL Moore *et al*, IJROBP **81**, 545-551 (2011)

Salvageable parotids: 3 mos. before QC vs 3 mos. after

clinical plans prior to feedback

D_{mean} (Gy)	D_{pred} (Gy)
18.9	11.6
16.1	12.3
16.9	13.3
14.9	15.2
24.7	18.0
26.6	18.8
26.4	19.6
36.6	21.0
27.4	23.6
46.8	24.2
43.4	27.7
40.5	29.1
52.3	29.4

Avg D_{mean}	**Avg D_{pred}**
33.6 Gy	**22.4 Gy**

clinical plans after feedback

D_{mean} (Gy)	D_{pred} (Gy)
12.8	10.8
11.8	11.5
14.6	11.6
15.6	11.8
14.7	12.3
16.3	14.2
17.1	14.4
15.0	15.0
17.3	15.4
27.3	23.6
25.2	24.7
30.4	29.1
26.1	29.5

Avg D_{mean}	**Avg D_{pred}**
20.3 Gy	**18.8 Gy**

KL Moore *et al*, IJROBP **81**, 545-551 (2011)

The need for treatment plan quality control

1. Need system that can identify sub-optimal plans (most typically manifested as insufficient OAR sparing)

2. Requirement is quantitative knowledge of what trade-offs must be made on the Pareto optimal frontier.

3. Absence of such a "system" will inevitably rely on subjective quality assessments and user experience/alertness... <u>classic safety hazard</u>!

Treatment Plan Quality Control:

2% 1. eliminates plans that will fail IMRT QA at the treatment machine

2% 2. highlights dose calculation errors due to inhomogeneities

11% 3. guarantees that patients will not receive dose to critical structures that exceeds tolerance levels

1% 4. ensures no prescription dose penetrates into PTV-OAR overlap regions

84% 5. can flag clinically significant excess dose to critical structures

Correct Answer: 5

Can flag clinically significant excess dose to critical structures

Experience-Based Quality Control of Clinical IMRT Planning Moore, Kevin L.; Brame, R. Scott; Low, Daniel A.; Mutic, S.; INTERNATIONAL JOURNAL OF RADIATION ONCOLOGY * BIOLOGY * PHYSICS Volume: 81 Issue: 2 Pages: 545-551

Radiotherapy Dose-Volume Effects on Salivary Gland Function Deasy, Joseph O.; Moiseenko, Vitali; Marks, Lawrence; Chao, K.S. Clifford; Nam, Jiho; Eisbruch, Avraham; INTERNATIONAL JOURNAL OF RADIATION ONCOLOGY * BIOLOGY * PHYSICS Volume: 76 Issue: 3 Pages: S58-S63

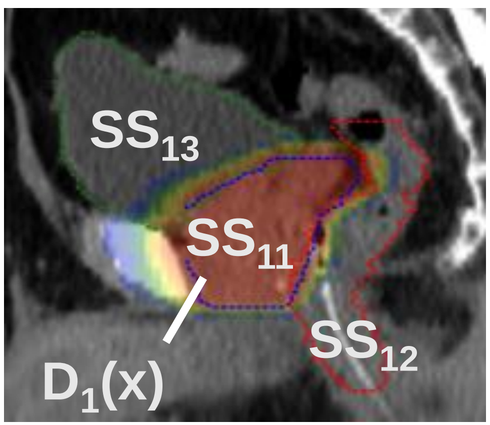
0D knowledge-based (single-variable) dose prediction

Step 1
- Identify a set of site similar training patients

Step 2
- Correlate mean dose with input geometry

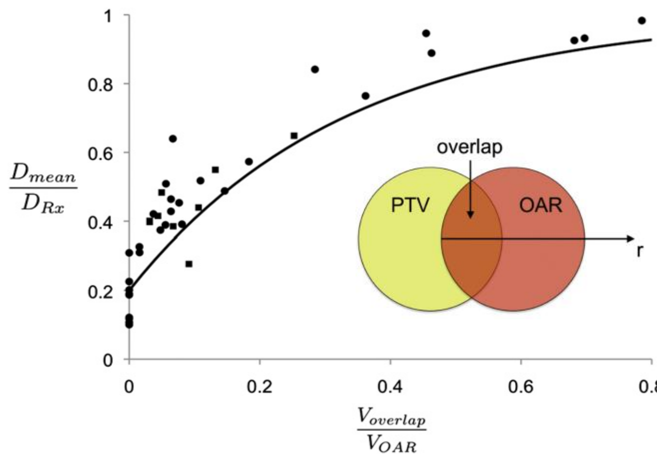
Step 3
- Utilize prediction to obtain mean dose estimation for new patients

Patient 1



⋮

Patient N



LT PAROTID Overlap

Volume = 13.5454 cc

- PTV 5400 overlap volume = 0.967021 cc
  Suggested Mean Dose = 1912.86 cGy
  Current Mean Dose = 2038.5 cGy

Moore KL *et al*, IJROBP **81**, 545-551 (2010)

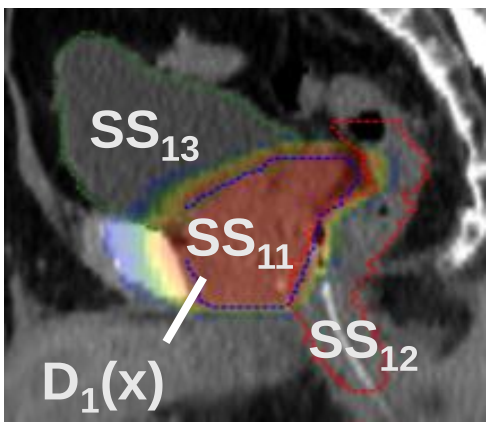
0D → 1D (DVH) knowledge-based dose prediction

Step 1
- Identify a set of site similar training patients

Step 2
- Generate pDVH model from training cohort

Step 3
- Utilize pDVH model to obtain DVH prediction for new patient

Patient 1



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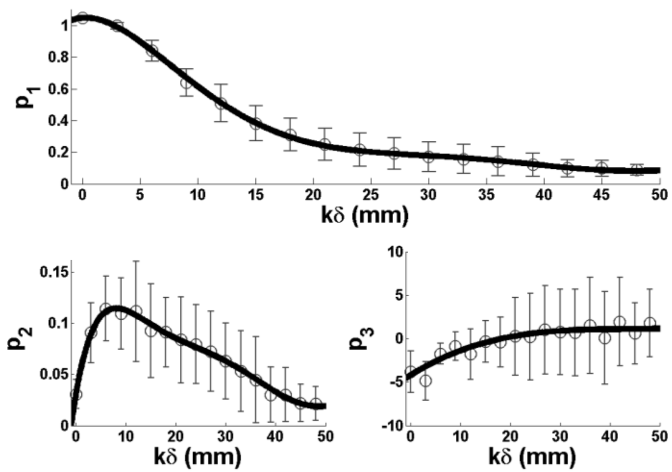
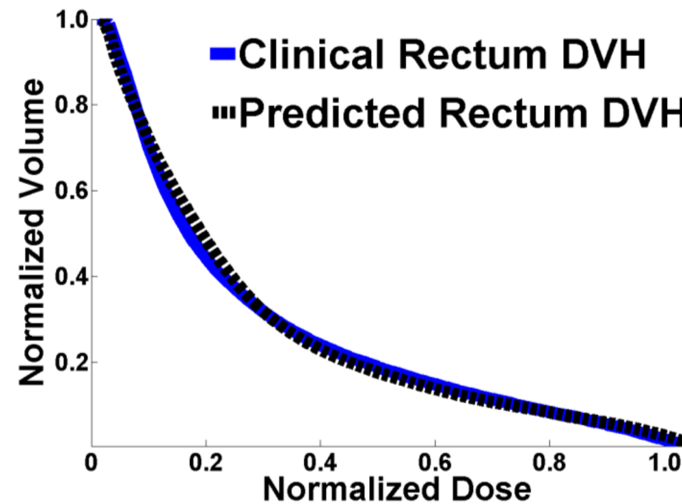
Patient N





Appenzoller *et al*, Med Phys **39**, 7446 (2012)

0D → 1D → 3D knowledge-based dose prediction

Step 1

- Identify a set of site similar training patients

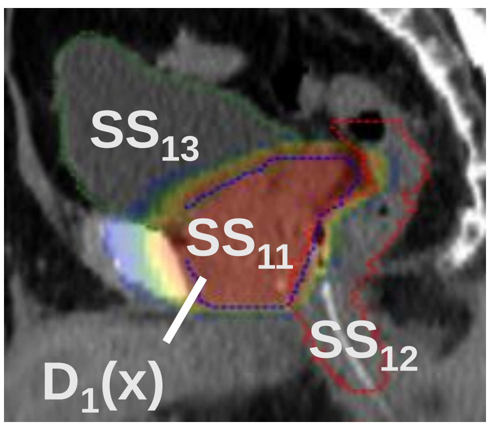
Step 2

- Generate 3D prediction model

Step 3

- Utilize model to obtain 3D dose prediction

Patient 1



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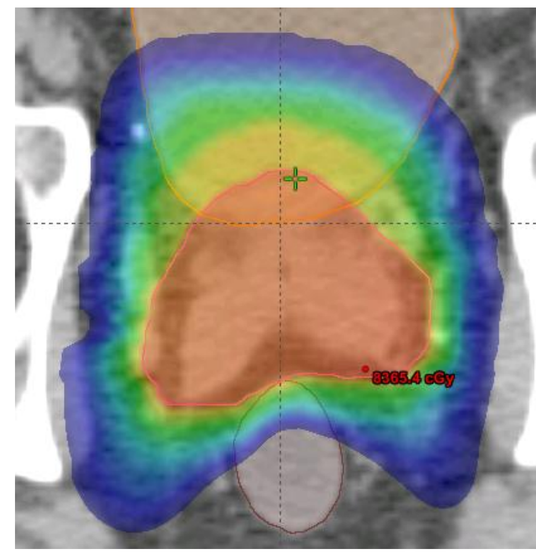
Patient N

?



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Medical Center Moores Cancer Center

Shiraishi and Moore, MO-FG-303-03, Manuscript under review

IMRT QC = knowledge-based plan assessment

Key features of a “knowledge base”:

1. Must be quantitative

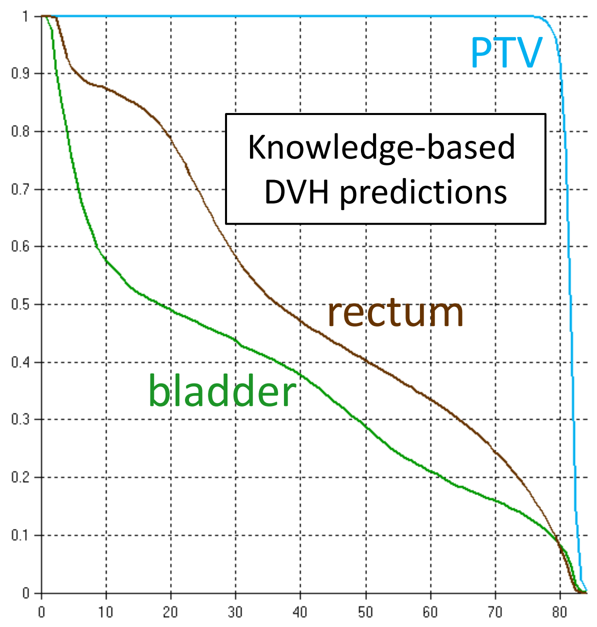
1. Must have discernable *correlations*
    - e.g. larger bladder = lower bladder DVH

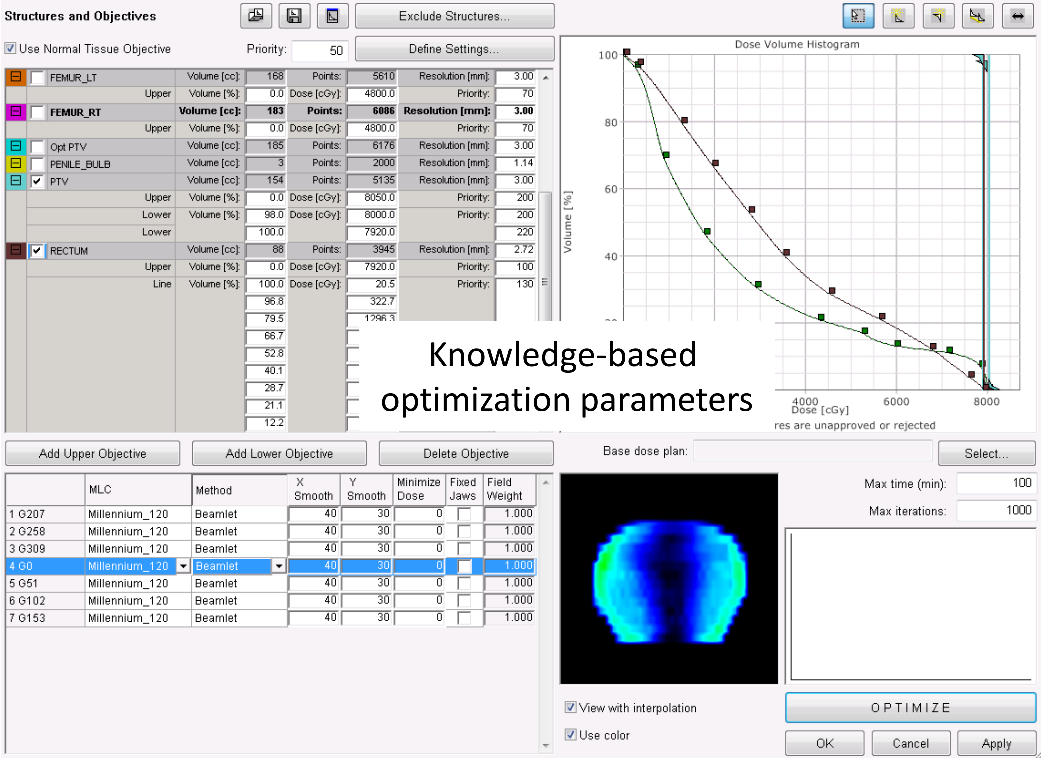
3. Must provide a sufficient range of previous experience

With these ingredients, one has everything needed to make *<u>patient-specific predictions</u>*

Knowledge-based planning "by hand"

- Knowledge-based planning involves nothing more than incorporating the dose-volume predictions directly into the optimization loop





Treatment plan quality:

0% 1. cannot be predicted using previously treated patient plans

5% 2. cannot be improved by retrospective and objective plan review

94% 3. metrics can be developed using previous plans to alert the user that their current plan is suboptimal

1% 4. is already standardized throughout the industry and needs no improvement

0% 5. is always guaranteed when using modern treatment planning systems

Correct Answer: 3

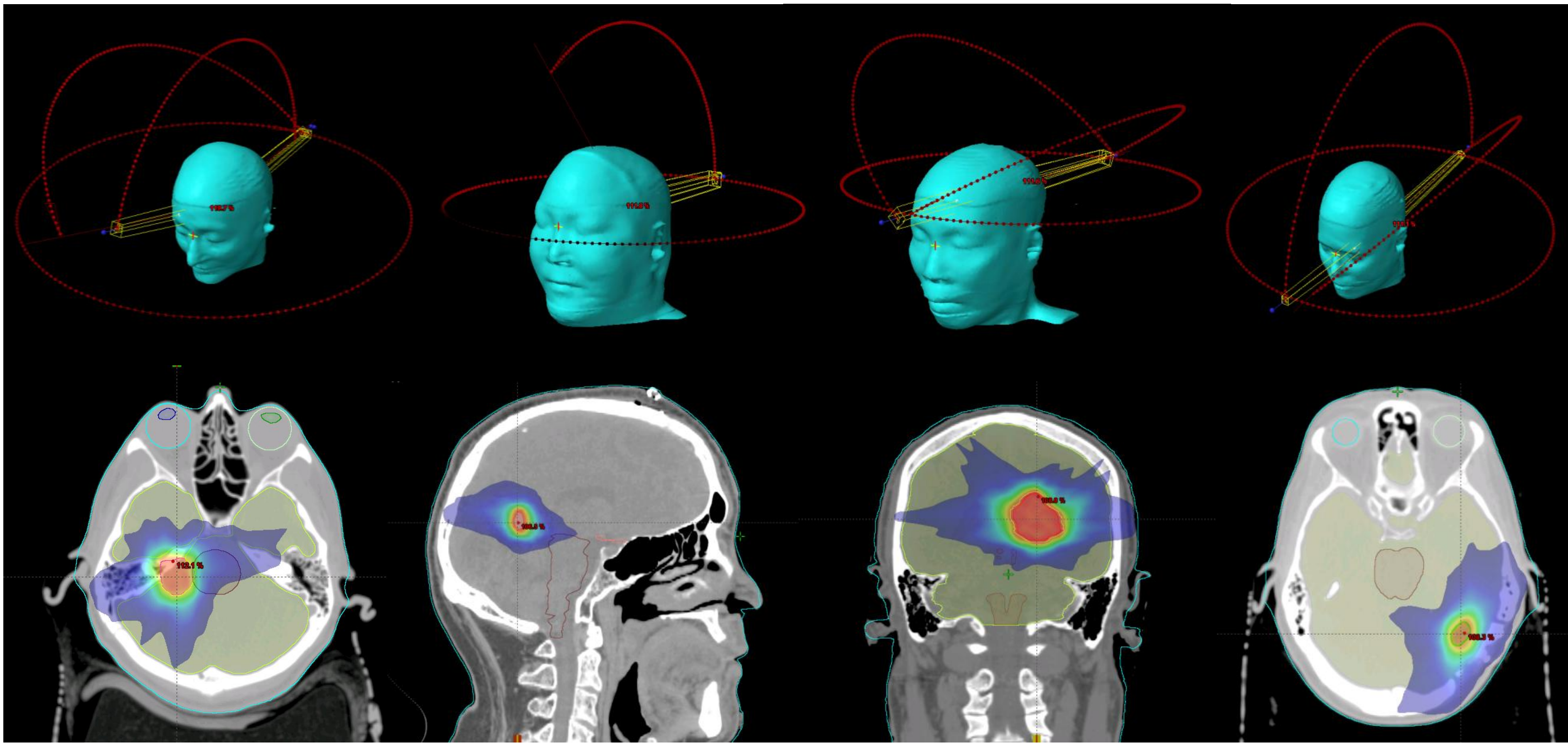
Metrics can be developed using previous plans to alert the user that their current plan is suboptimal

Quantitative Metrics for Assessing Plan Quality
Moore, Kevin L.; Brame, R. Scott; Low, Daniel A.; et al. SEMINARS IN RADIATION ONCOLOGY Volume: 22 Issue: 1 Pages: 62-69

Predicting dose-volume histograms for organs-at-risk in IMRT planning, Appenzoller, Lindsey M.; Michalski, Jeff M.; Thorstad, Wade L.; et al. MEDICAL PHYSICS Volume: 39 Issue: 12 Pages: 7446-7461

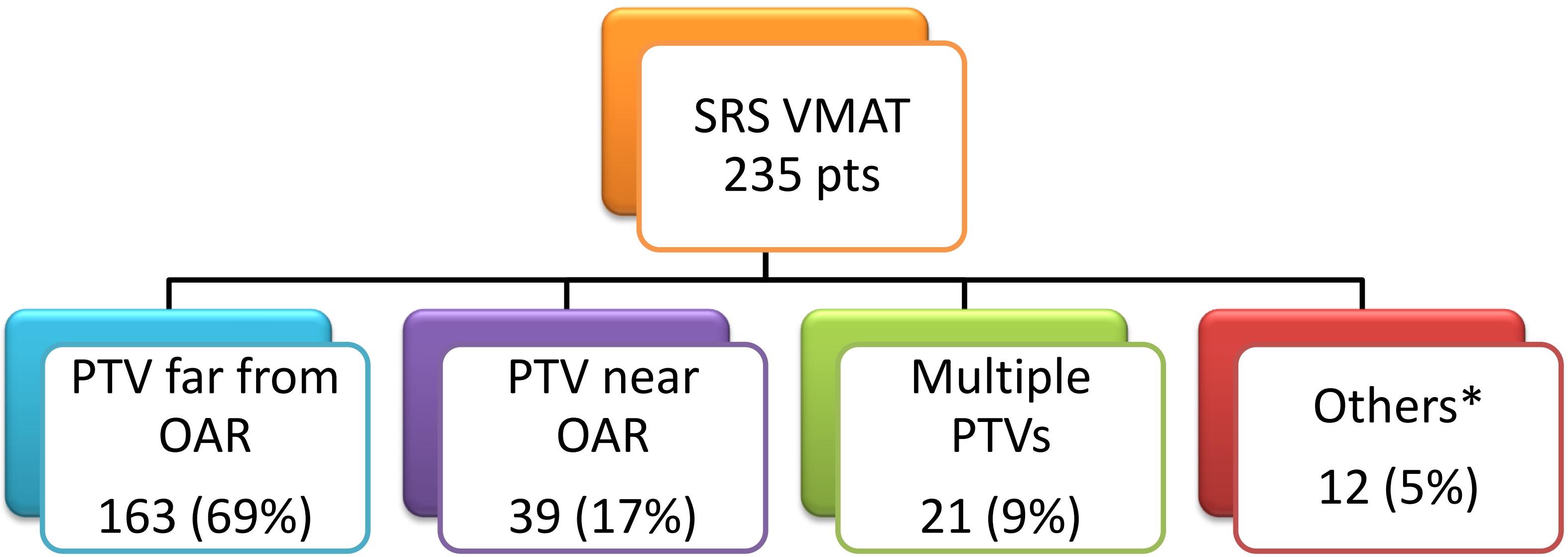
KBP in SRS: The UCSD experience

- For several years, standard treatment for SRS/SRT at UCSD has been multi-arc non-coplanar RapidArc



UCSD SRS experience

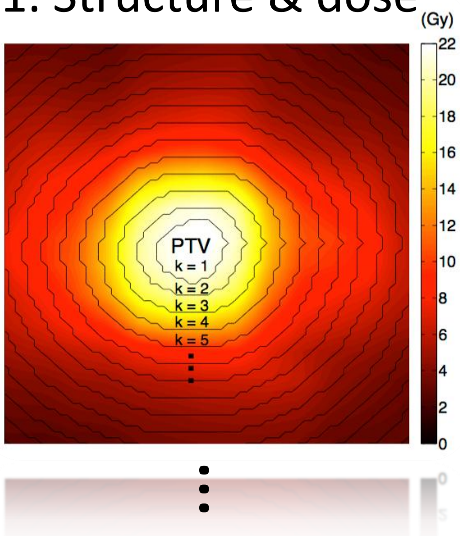
- SRS: Target size, shape, and location show enormous variation
  - PTV volume (0.1 cc - 60 cc)
  - Malignant vs. benign disease
  - Fractionation schedule and clinical priorities
  - Proximity to OARs (brainstem, optic nerves, cochlea) highly variable (0-10cm)
  - Multiple PTVs



* Overlapping retreatment, staged approach for AVM

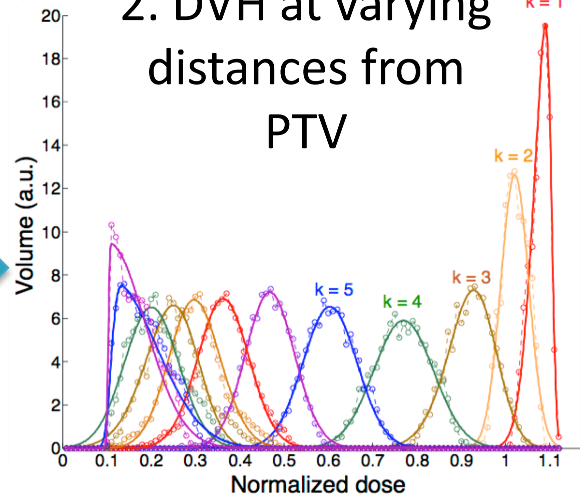
KBP in SRS

1. Structure & dose



N training plans

2. DVH at varying distances from PTV

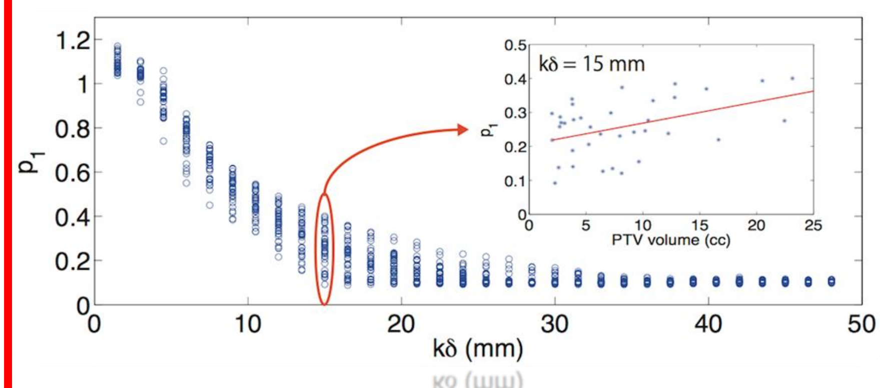


3. Fit with skew-normal PDF

$$f(p_1,p_2,p_3;\, D) = \frac{1}{\pi p_2}\exp\left(-\frac{(D-p_1)^2}{2p_2^2}\right) \times \int_{-\infty}^{p_3(D-p_1)/p_2} \exp(-t^2/2)\, dt,$$

Three fit parameters: location, scale, shape

4. Parameterize fit parameters

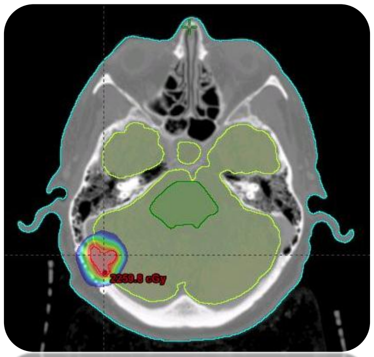


Fits include:
Distance from PTV
PTV volume

L. M. Appenzoller *et al.*, Med. Phys. **39**, 7446 (2012)
S. Shiraishi *et al.*, Med. Phys. **42**, 908 (2015)

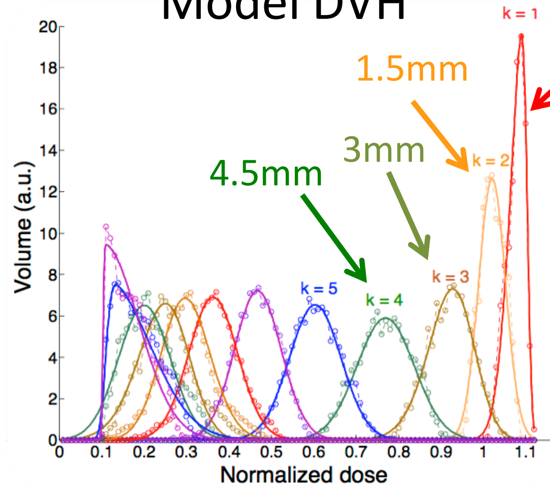
KBP in SRS

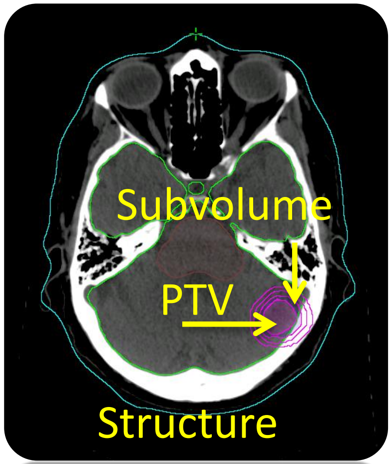
N training plans



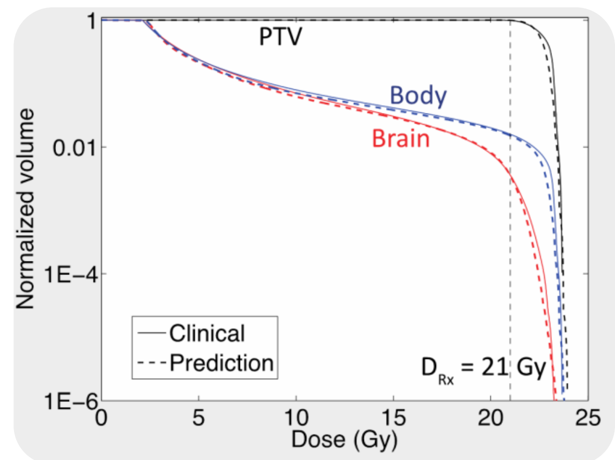
Structure & dose

Model DVH



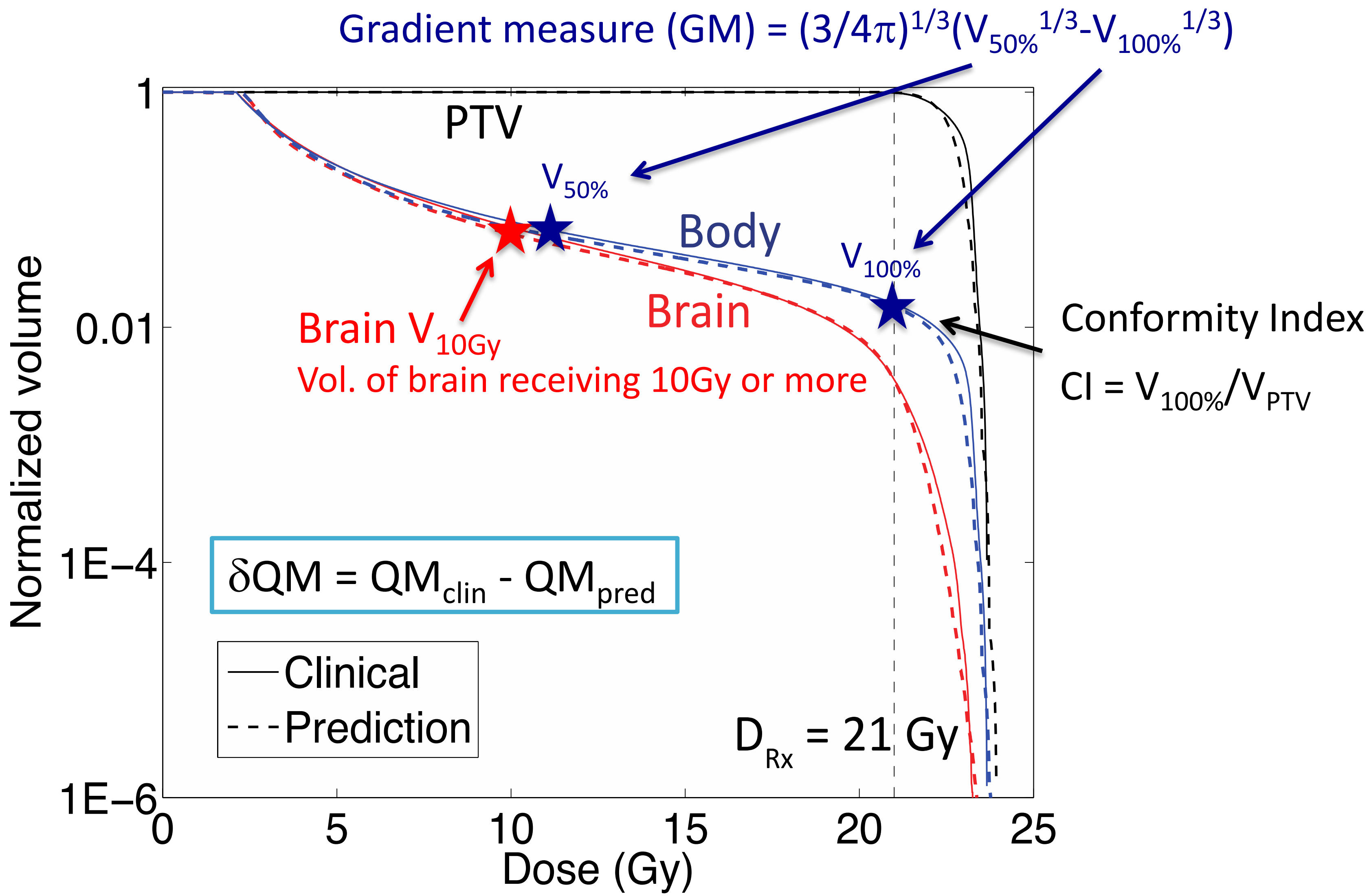


Predict DVH



L. M. Appenzoller *et al.*, Med. Phys. **39**, 7446 (2012)
S. Shiraishi *et al.*, Med. Phys. **42**, 908 (2015)

SRS plan quality metrics are DVH-based



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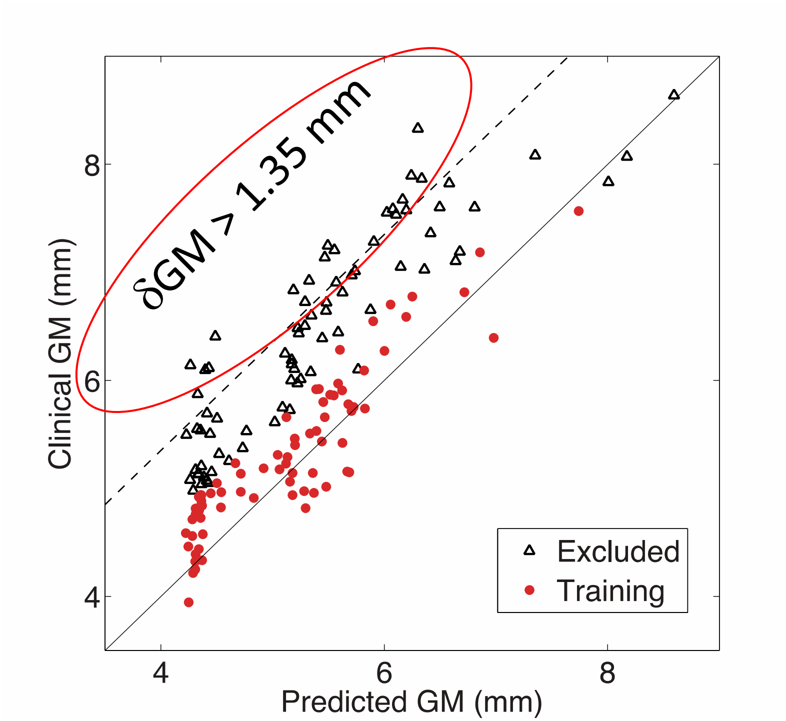
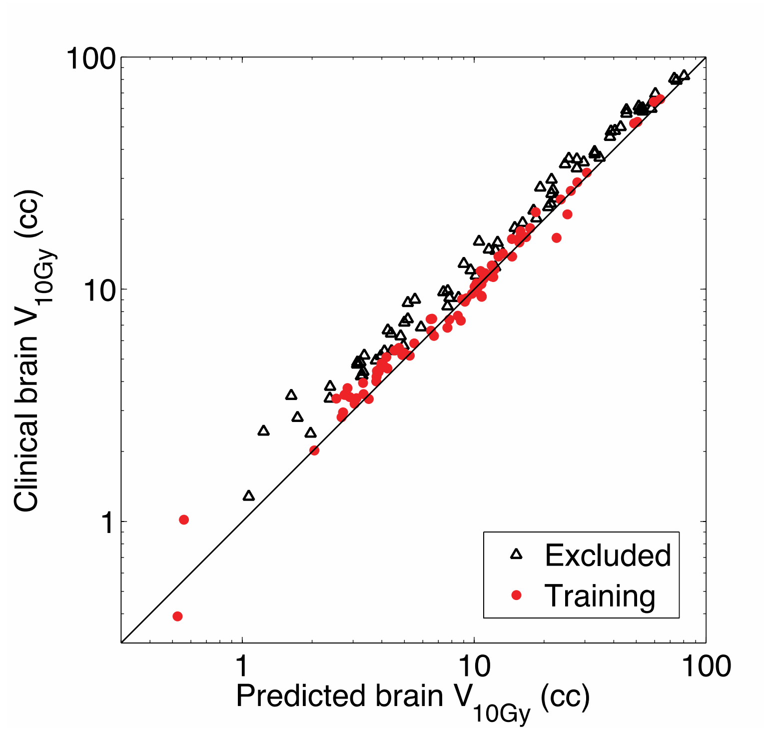
S. Shiraishi *et al.*, Med. Phys. **42**, 908 (2015)

Accurate QM predictions and outlier identification

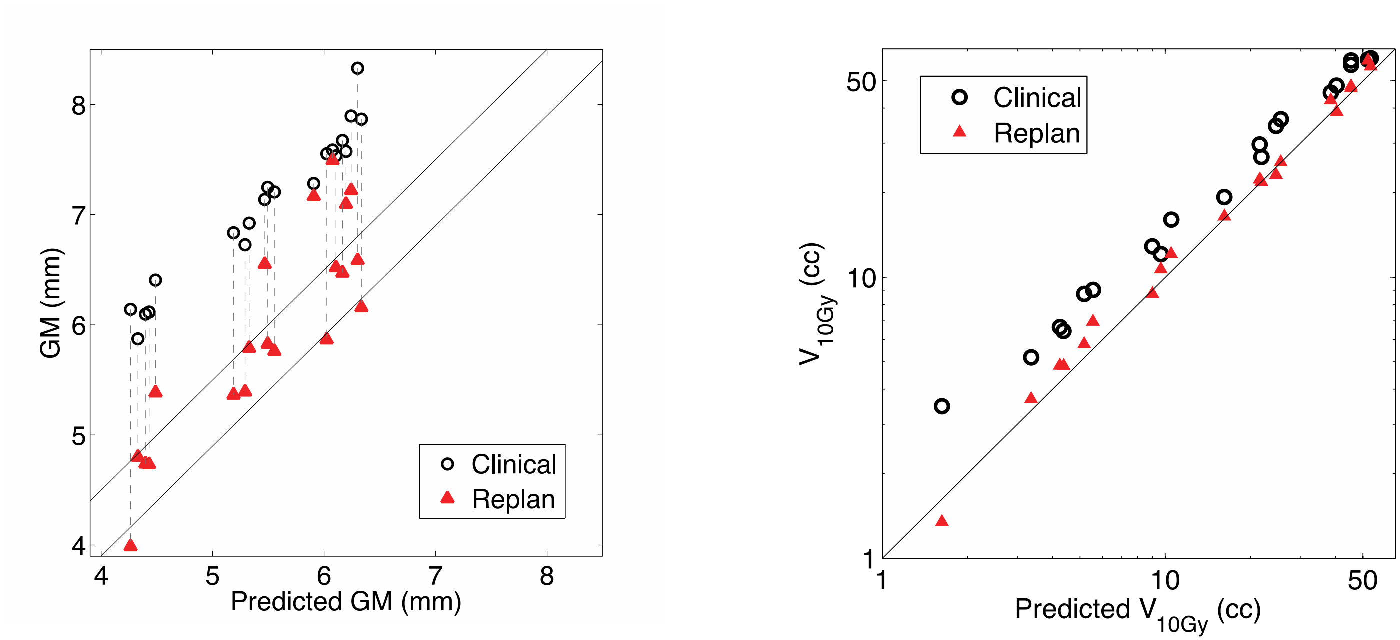




δQM	Training	Excluded	p-value
δGM (mm)	0.2 ± 0.3	1.1 ± 0.5	<0.001
$\delta V_{10Gy}/V_{10Gy}$	0.04 ± 0.12	0.20 ± 0.11	<0.001
δCI	-0.02 ± 0.12	-0.03 ± 0.10	0.19

S. Shiraishi *et al.*, Med. Phys. **42**, 908 (2015)

KBP replanning confirms predicted clinical gains



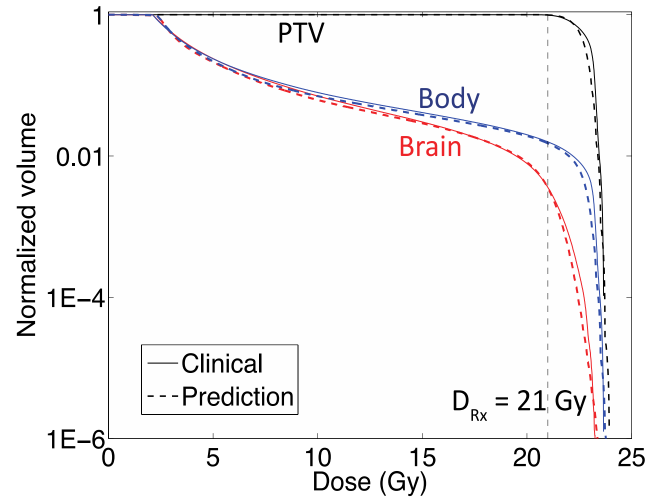
δQM	Clinical	Replan
δGM (mm)	1.6 ± 0.2	0.5 ± 0.5
$\delta V_{10Gy}/V_{10Gy}$	0.27 ± 0.11	0.04 ± 0.06
δCI	1.12 ± 0.09	1.08 ± 0.11
Max dose	1.10 ± 0.03	1.18 ± 0.04

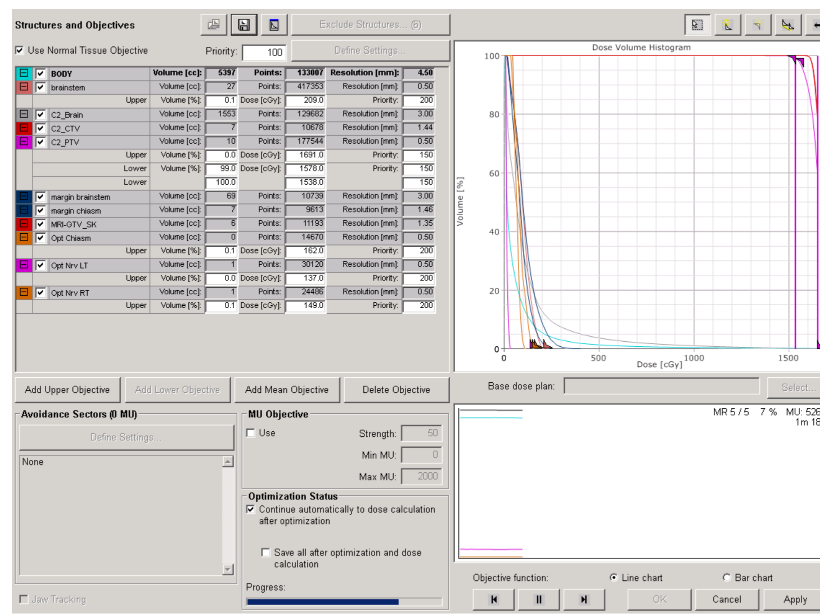
Improved QMs,
Higher max dose

S. Shiraishi *et al.*, Med. Phys. **42**, 908 (2015)

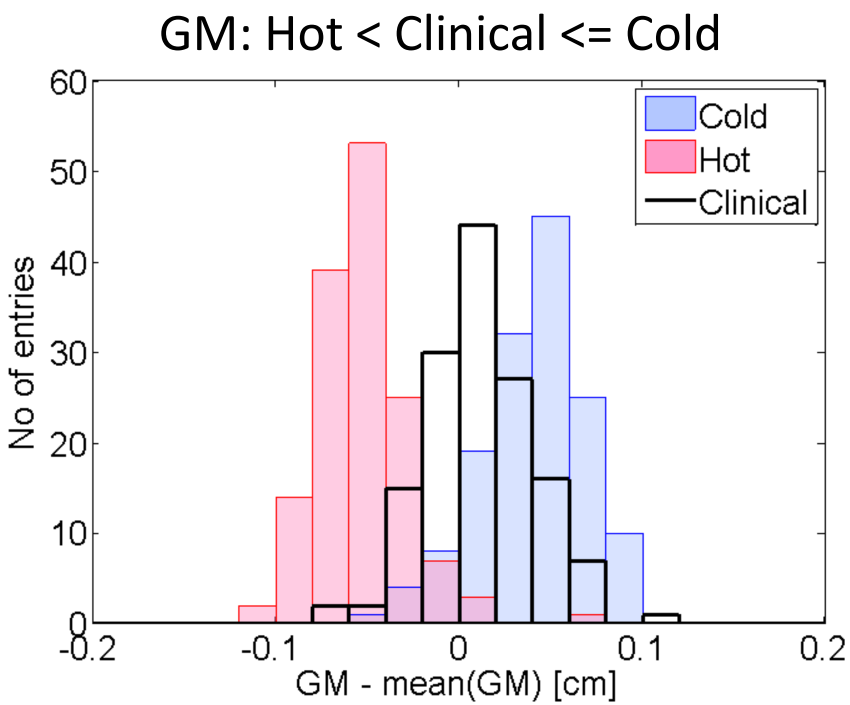
KBP SRS in Eclipse

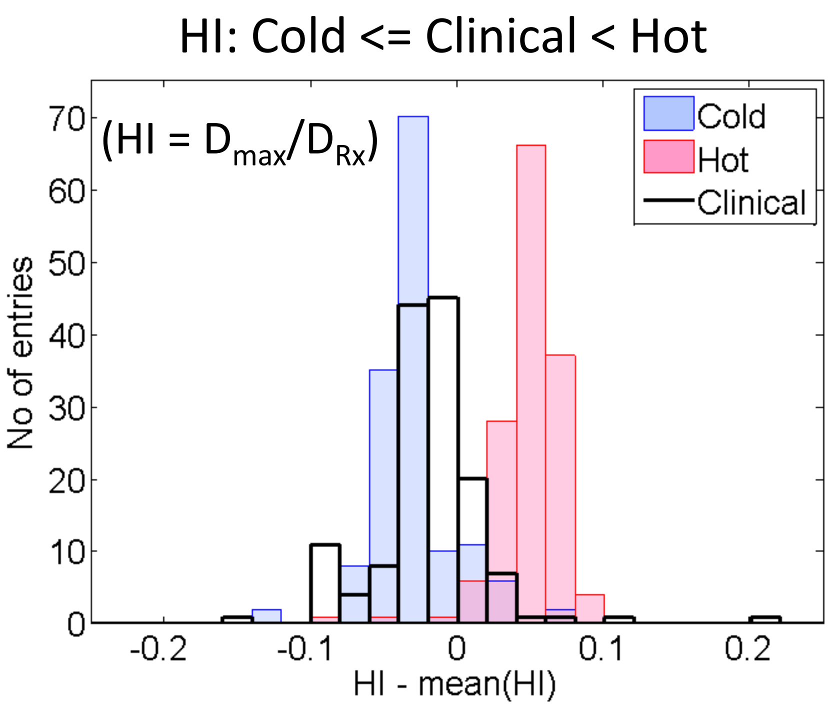
- Use original plan's arc arrangement
- DVH predictions feed two different optimization routines, coded as patient-specific templates
  - HOT: for brain metastases, reduces penalty for hot spots and prioritizes GM
  - COLD: for use in benign disease and retreatments where hot spot is clinically important
- All plans are normalized to the same PTV coverage (V100%=98% typically)





Tuning up autoplanning routines





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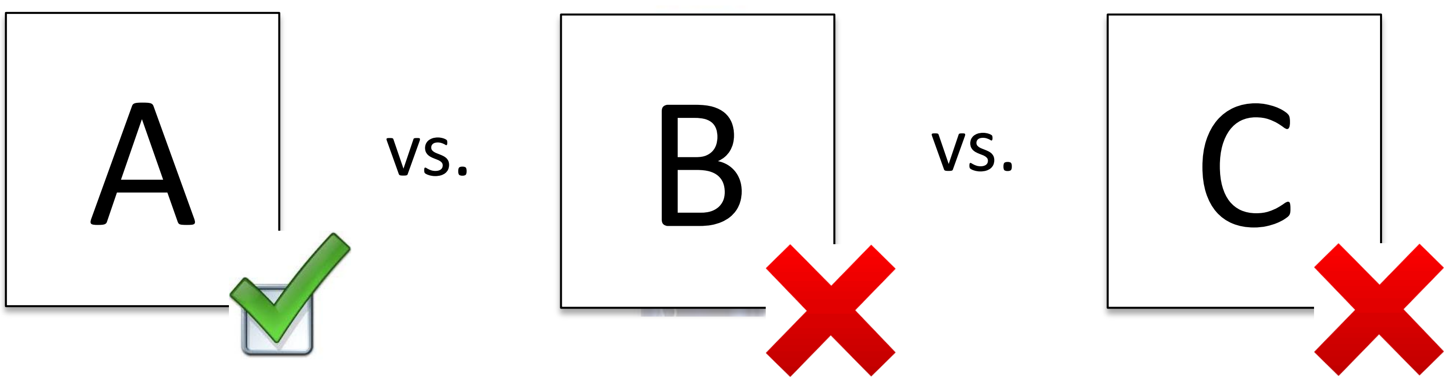
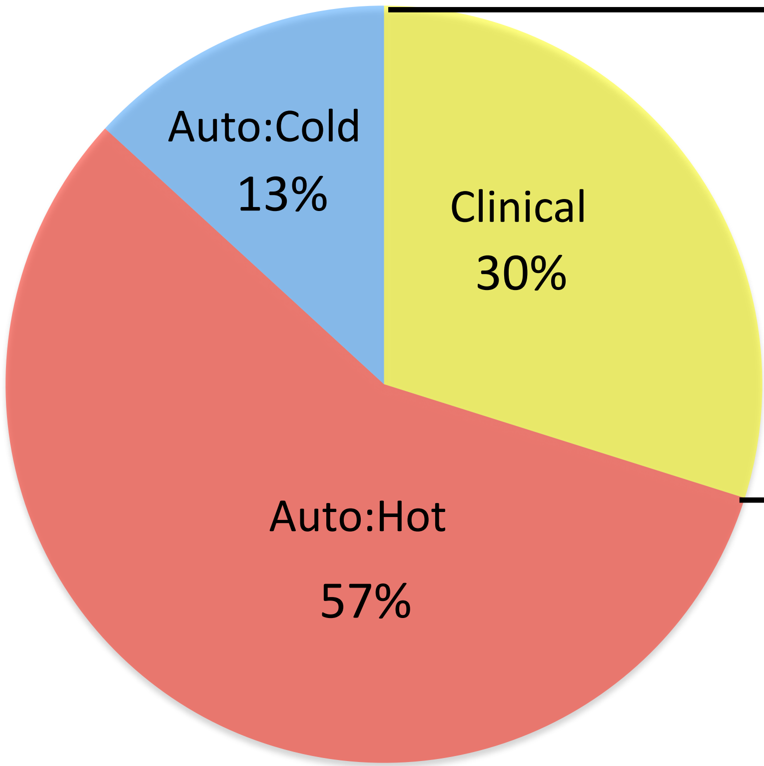
Single-blind study of autoplans vs. manual plans

Study schema:

1. Automatically replan 200+ SRS cases with *HOT* and *COLD* routines
2. Clinically approved plan and autoplans are de-identified (A, B, C randomly)
3. SRS physicians review plans with relevant clinical information and selects the preferred plan



Preliminary results

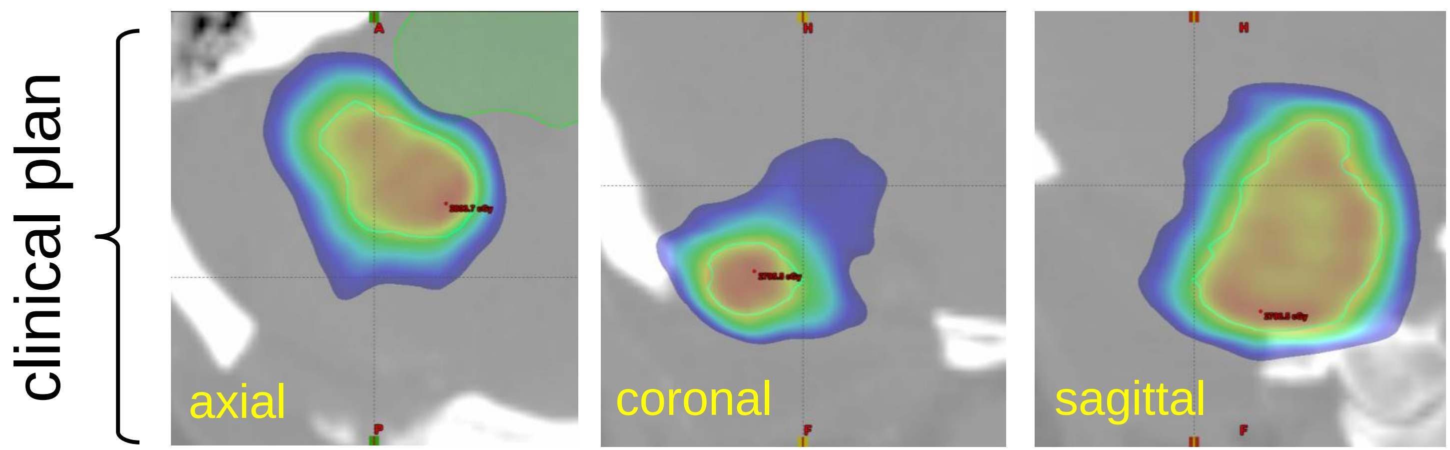


13%: Clinical and auto plans even
15%: Relatively close to OAR
2%: Near previous treatment site

	Clinical	Auto: Hot	Auto: Cold	Total
Dr. Sanghvi	18 (26%)	43 (61%)	9 (13%)	70
Dr. Hattangadi	25 (34%)	39 (53%)	10 (14%)	74
TOTAL	43 (30%)	82 (57%)	19 (13%)	144

Preliminary results

- Autoplan sequences took ~15 minutes on average
- In the (17%) 24/144 cases where the manually-planned treatments were preferred
  - 21 plans were selected because of more aggressive OAR sparing (brainstem, cochlea, or optic nerve) at ***max dose level***
  - 3 plans were selected because the manual plans better spared a nearby volume that received prior radiotherapy



Summary of current KBP system in SRS

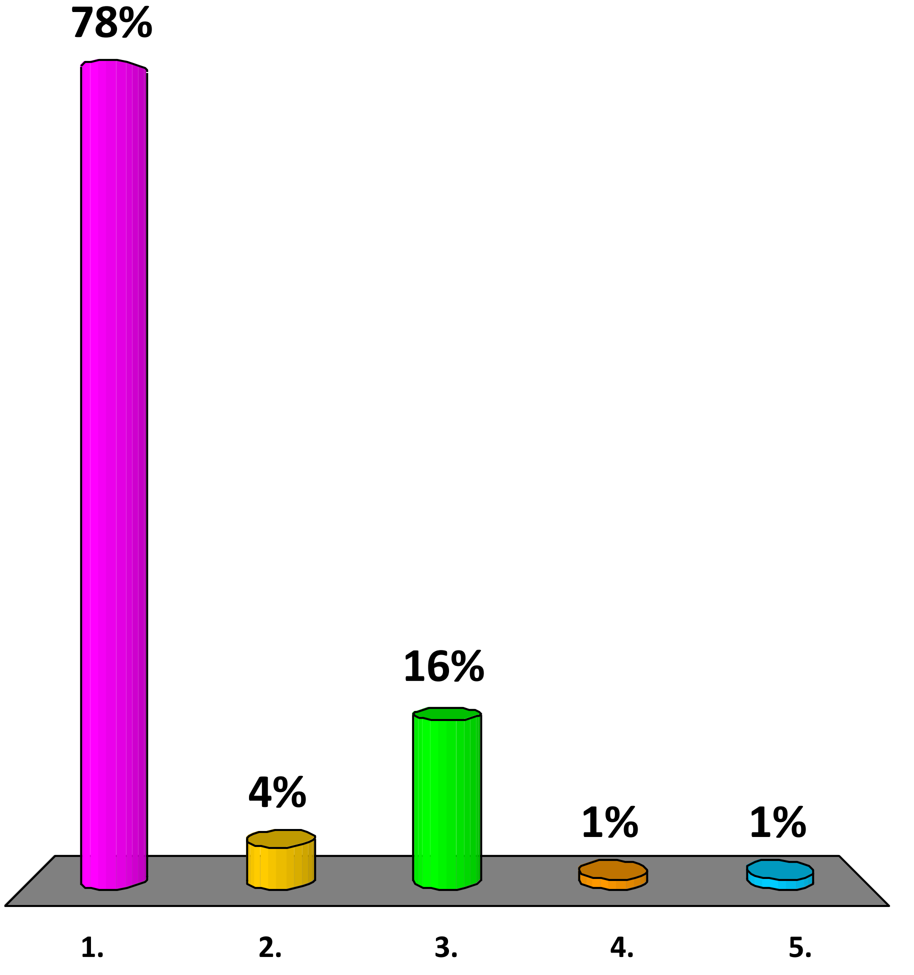
- Already have solution that yields superior or equivalent results for 83% of SRS cases

- Focusing on that remaining 17%...
  - Robust multi-met solution (forthcoming)
  - Robust neighboring OAR solution (underway)
  - Prior tx solution (underway)
  - Clinical “go live” after completion of blind study

- When possible, such a benchmarking study should be used before clinical implementation of automated planning

Knowledge-based planning in SRS:

1. can predict plan quality metrics and automate the planning process based on accurate dose-volume predictions
2. automatically loads standard planning templates for patients
3. guides the planning process by continually adjusting dose objectives during optimization
4. can only be used for inverse optimized planning
5. saves time but likely at the expense of plan quality



Correct Answer: 1

1. Can predict plan quality metrics and automate the planning process based on accurate dose-volume predictions

Knowledge-based prediction of plan quality metrics in intracranial stereotactic radiosurgery
S Shiraishi, J Tan, LA Olsen, KL Moore
Medical physics 42 (2), 908-917

Conclusion

- SRS and SBRT* are extremely well suited to knowledge-based techniques
- Knowledge-based quality metric prediction is useful for both quality control and planning automation
- Clinical KBP is still in its infancy, but in some form these techniques <u>will</u> be part of the treatment planning process
- KBP can also help inform clinical decision making (when to fractionate, benefits of different treatment techniques, e.g. 4π vs. static field vs. coplanar VMAT vs. protons)

** Abstracts at AAPM 2015:*

- *Foy et al SU-ET-97*
- *Snyder et al MO-F-CAMPUS-T-04*