Quantum Annealing Applied to Optimization Problems in Radiation Medicine

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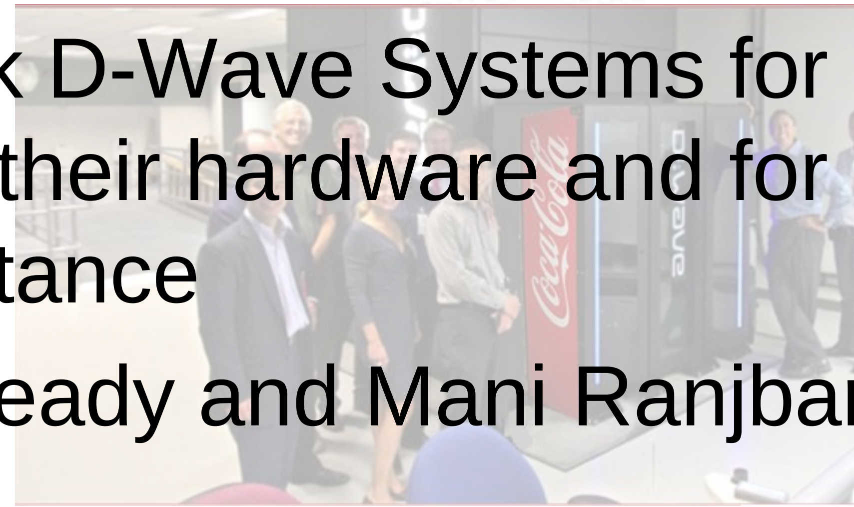


Introduction

- Cancer is one of the leading causes of morbidity and mortality worldwide
- In 2012 there were 14 million new cases of cancer
- There were 8.2 million cancer-related deaths
- Number of new cases expected to rise by 70% over next 2 decades (WHO)

Introduction

Cancer in the European Union:

In 2012 there were 1.3 million cancer-related deaths

This represented 25.8% of all deaths

29.2% of male deaths, 22.5% of female deaths due to cancer

Introduction

Cancer in Germany:

In 2012 there were 222,000 cancer-related deaths

This represented 25.4% of all deaths

28.8% of male deaths, 22.4% of female deaths due to cancer

Most common types: breast, lung, prostate, colon, bladder

Introduction

Cancer is treated using three methods:

- Surgery

Introduction

Cancer is treated using three methods:

Chemotherapy

Introduction

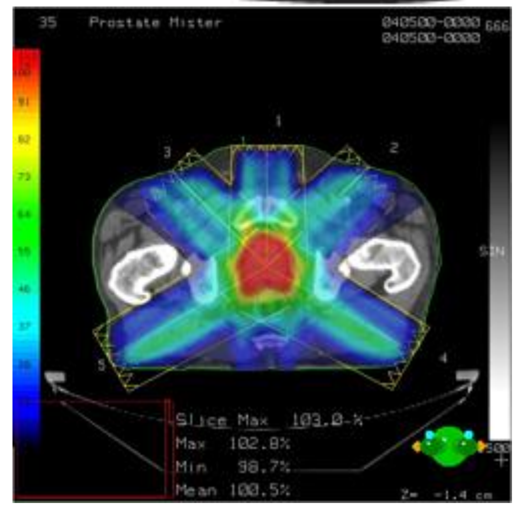
Cancer is treated using three methods:

Radiation Therapy

This is the subject of our work

Dose Calculation

Radiation dose distribution



Absorbed dose measured in Gy (J/kg)

Calculated from well-known physics principles

Clinical calculations use FDA-approved software

CT Simulation

- CT scan determines electron density of each voxel of patient anatomy
- Allows dose calculation and anatomic structure identification (contouring)

Medical Linear Accelerator

[Linear Accelerator Part 1]

Radiation Production

[Linear Accelerator Part 2]

Energy ~ 6 MeV

Beam Shaping

[Linear Accelerator Part 3]

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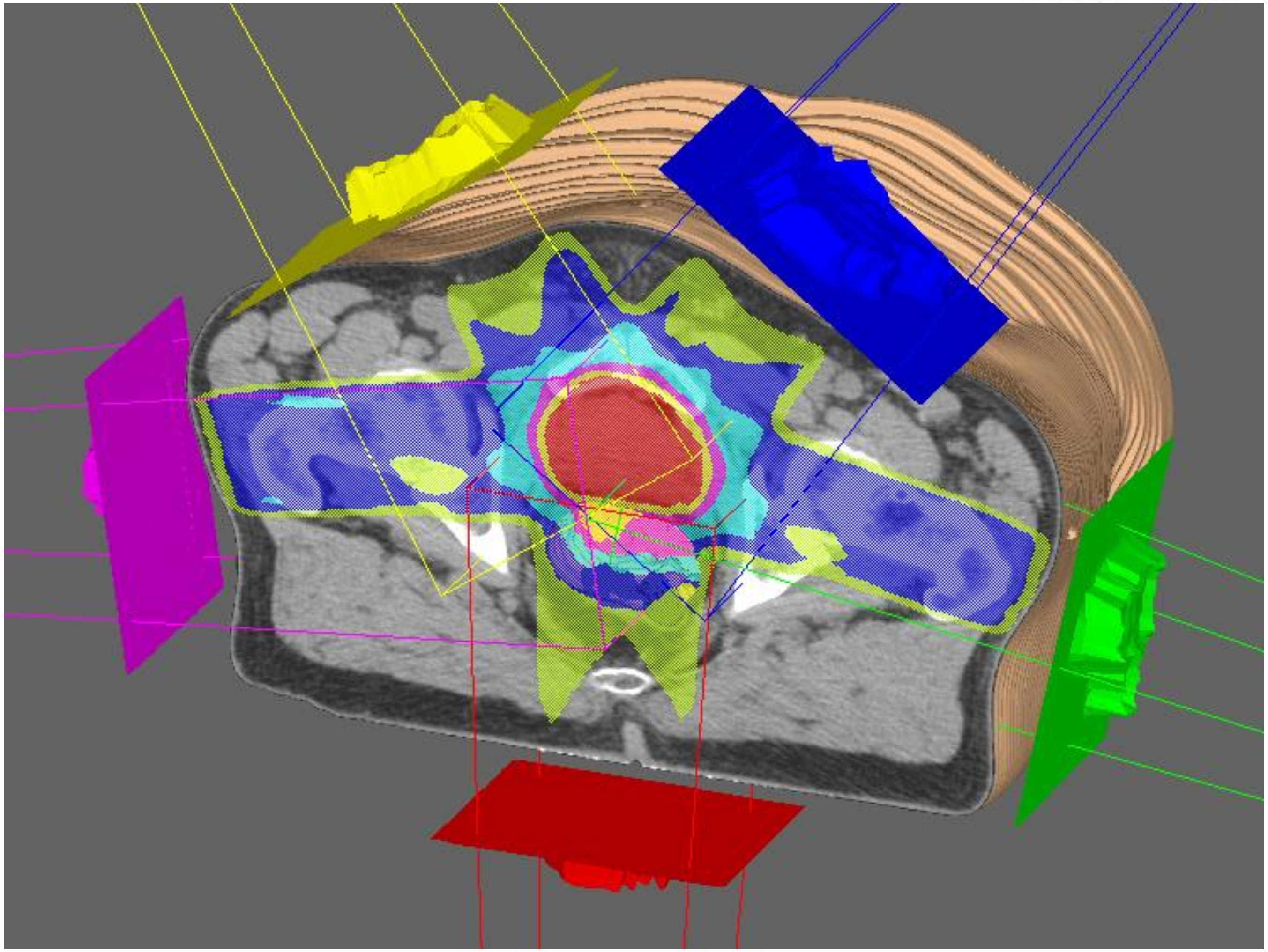
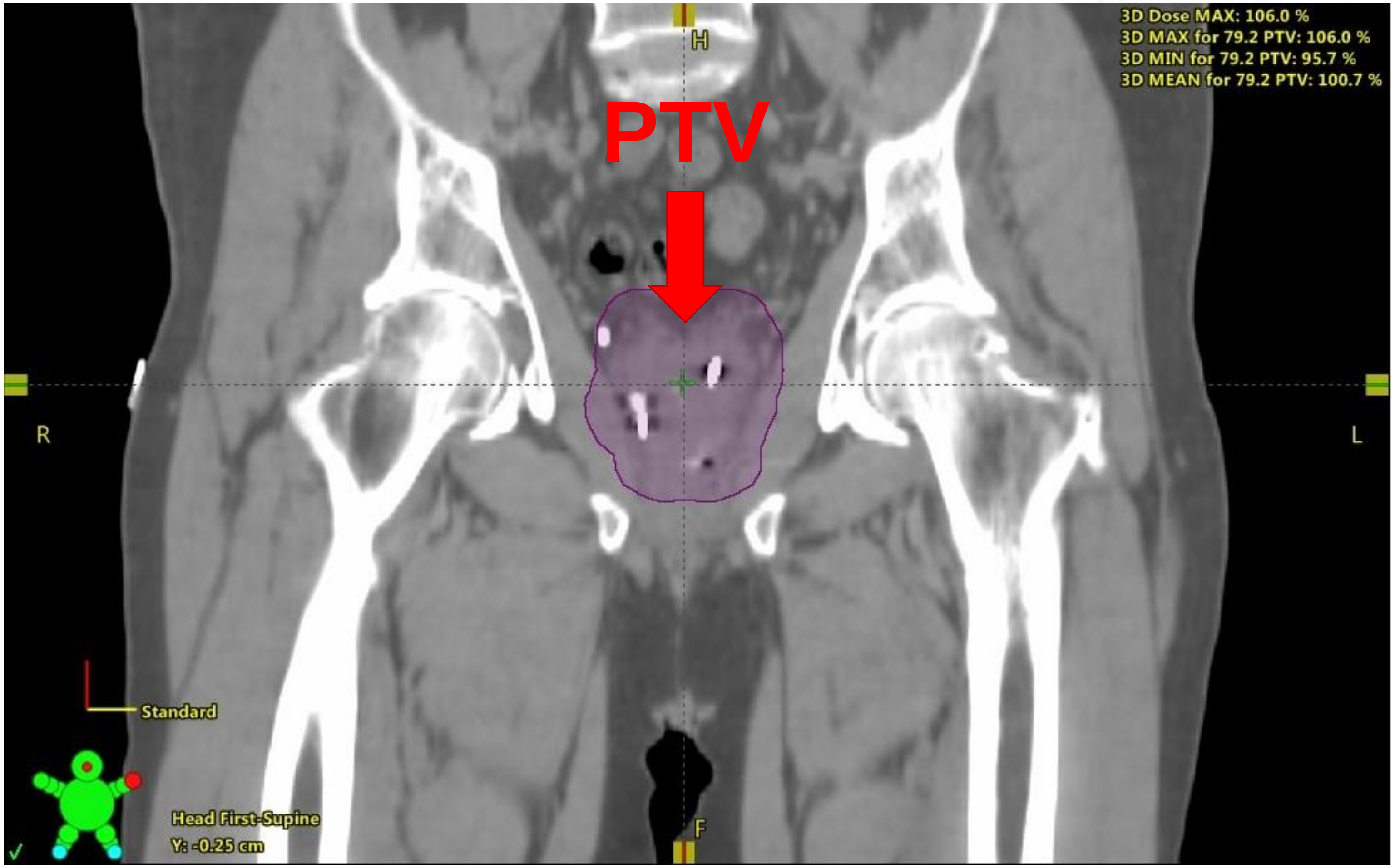
IMRT

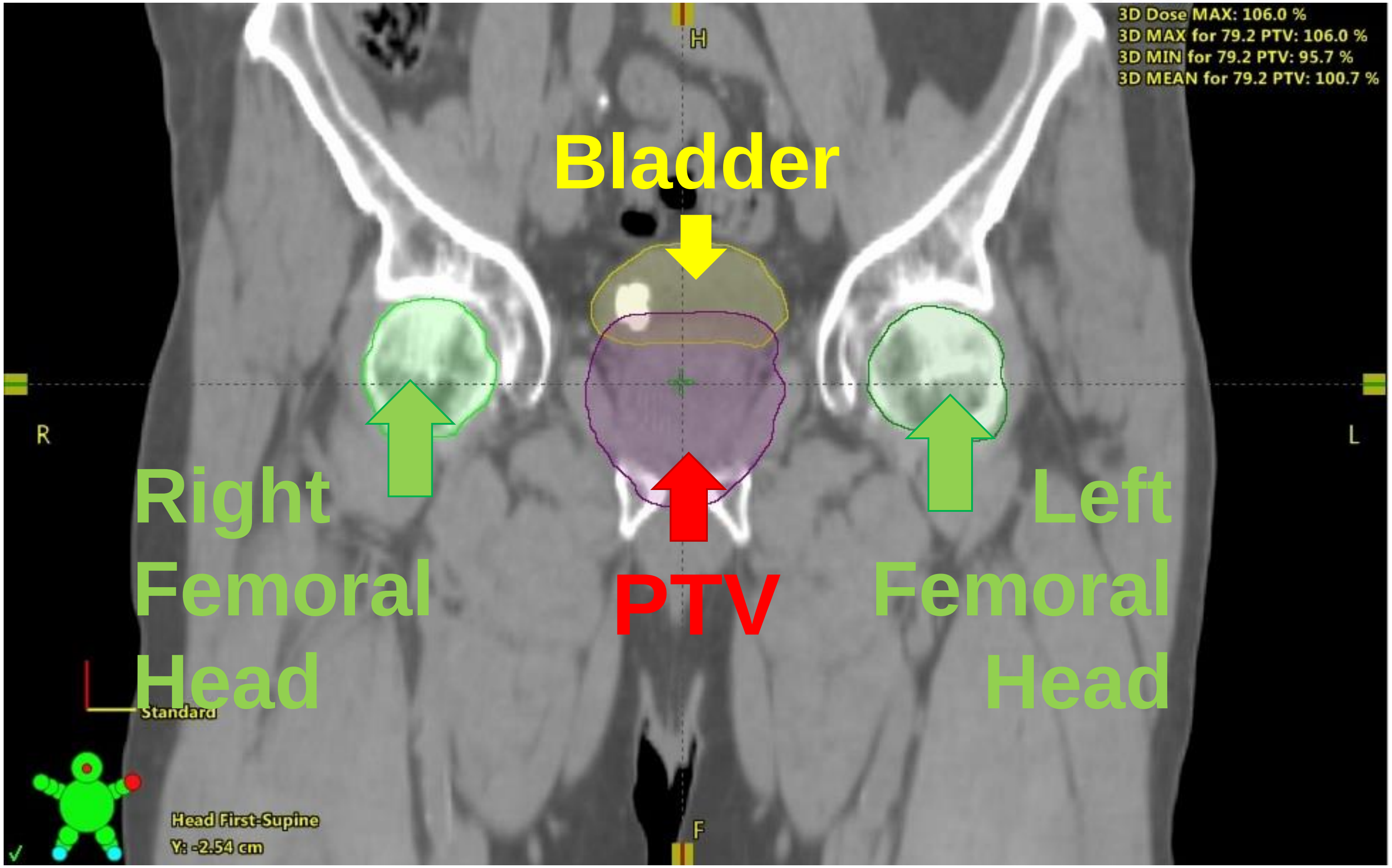


[IMRT Treatment]

The PTV

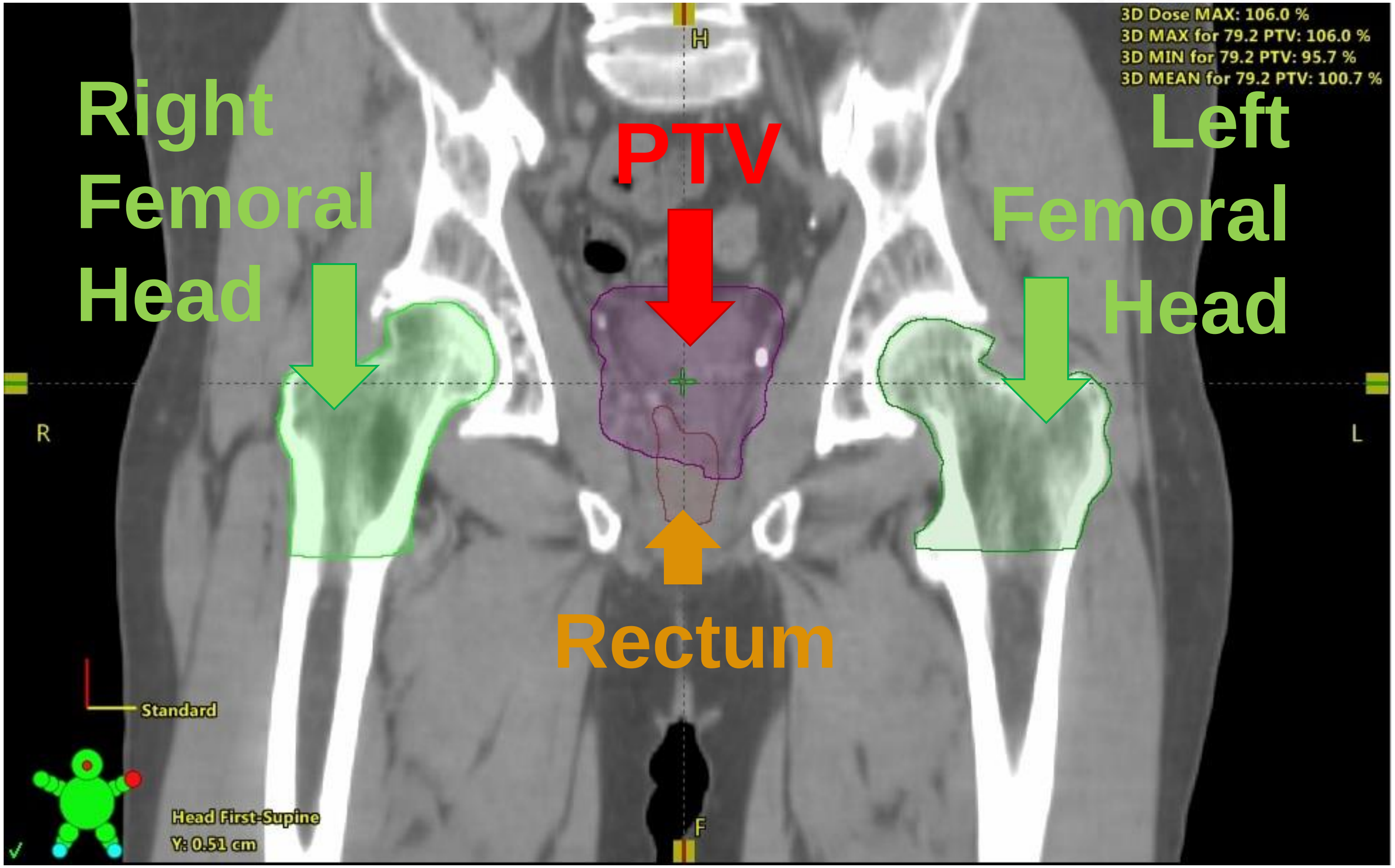

3D Dose MAX: 106.0 %
3D MAX for 79.2 PTV: 106.0 %
3D MIN for 79.2 PTV: 95.7 %
3D MEAN for 79.2 PTV: 100.7 %
PTV
H
R
L
F
Standard
Head First-Supine
Y: -0.25 cm

OARs Slice 1



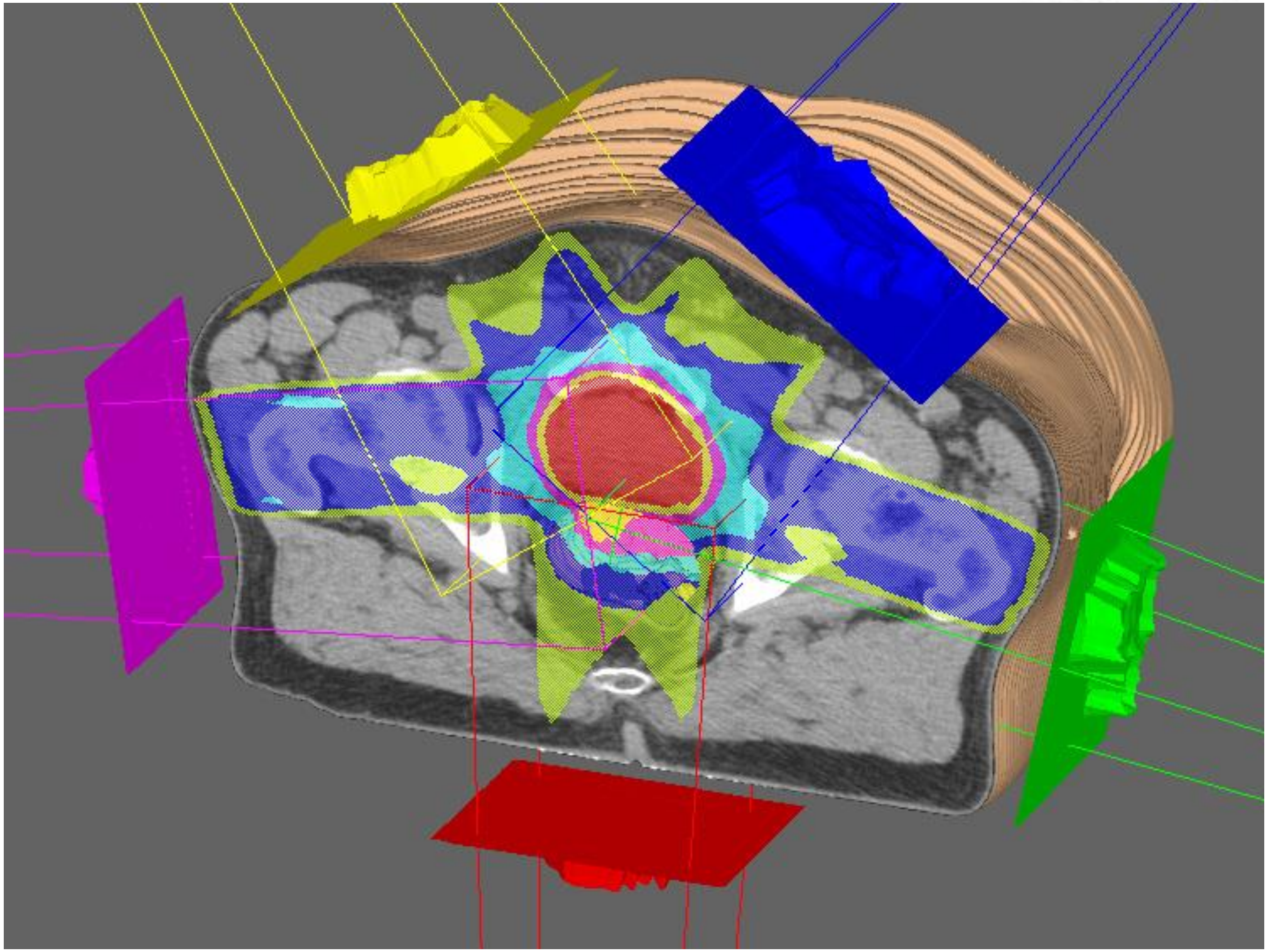
3D Dose MAX: 106.0 %
3D MAX for 79.2 PTV: 106.0 %
3D MIN for 79.2 PTV: 95.7 %
3D MEAN for 79.2 PTV: 100.7 %
H
Bladder
R
L
Right Femoral Head
PTV
Left Femoral Head
Standard
Head First-Supine
Y: -2.54 cm
F

OARs Slice 2

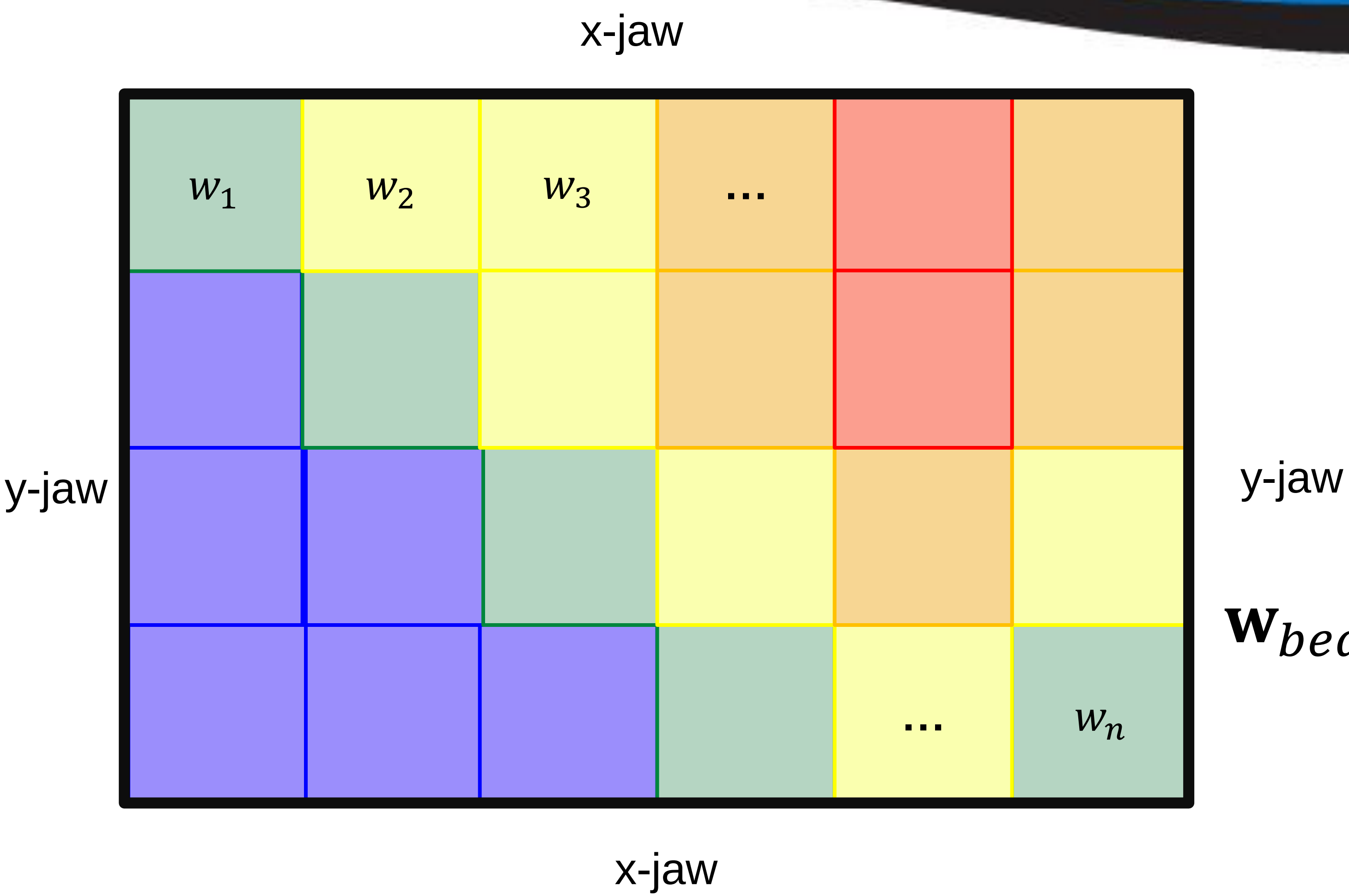


H
3D Dose MAX: 106.0 %
3D MAX for 79.2 PTV: 106.0 %
3D MIN for 79.2 PTV: 95.7 %
3D MEAN for 79.2 PTV: 100.7 %
Right Femoral Head
PTV
Left Femoral Head
R
L
Rectum
Standard
Head First-Supine
Y: 0.51 cm
F

IMRT

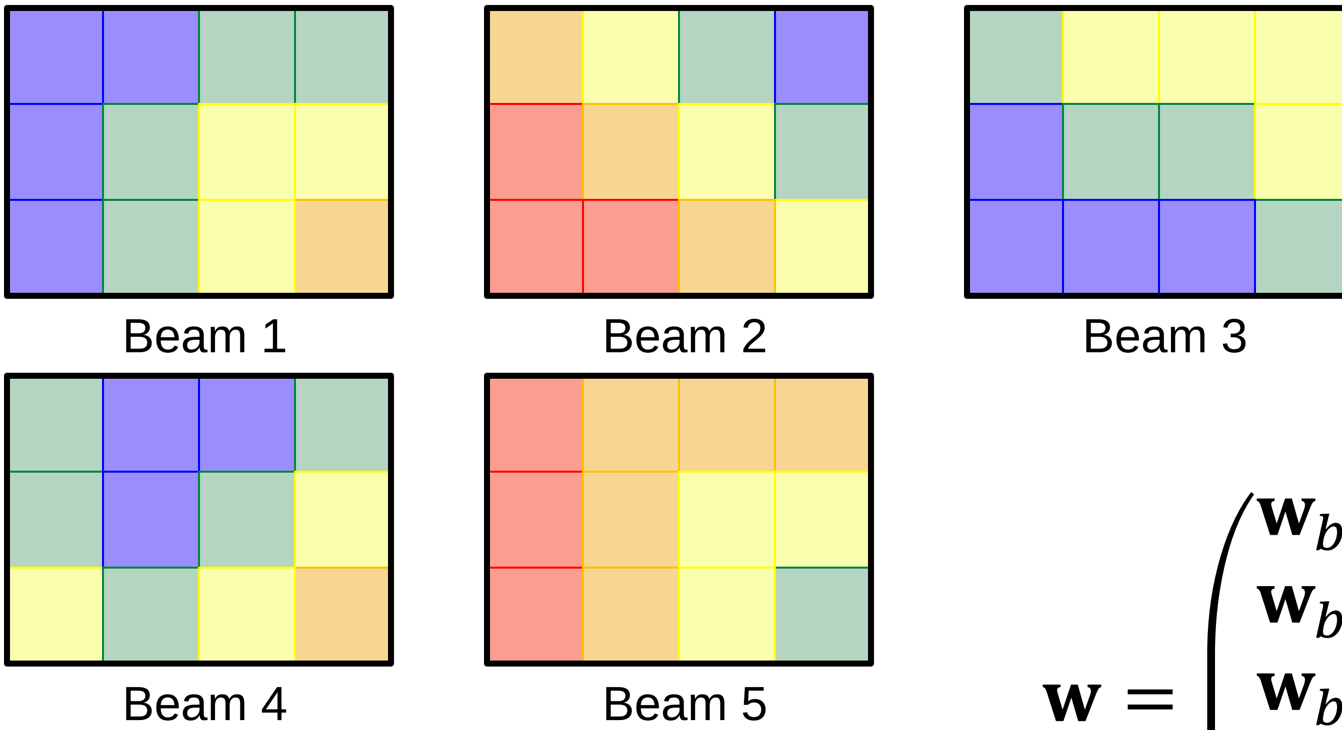


Beamlets



$$\mathbf{w}_{beam} = \begin{pmatrix} w_1 \\ w_2 \\ w_3 \\ . \\ . \\ . \\ w_n \end{pmatrix}$$

Beams

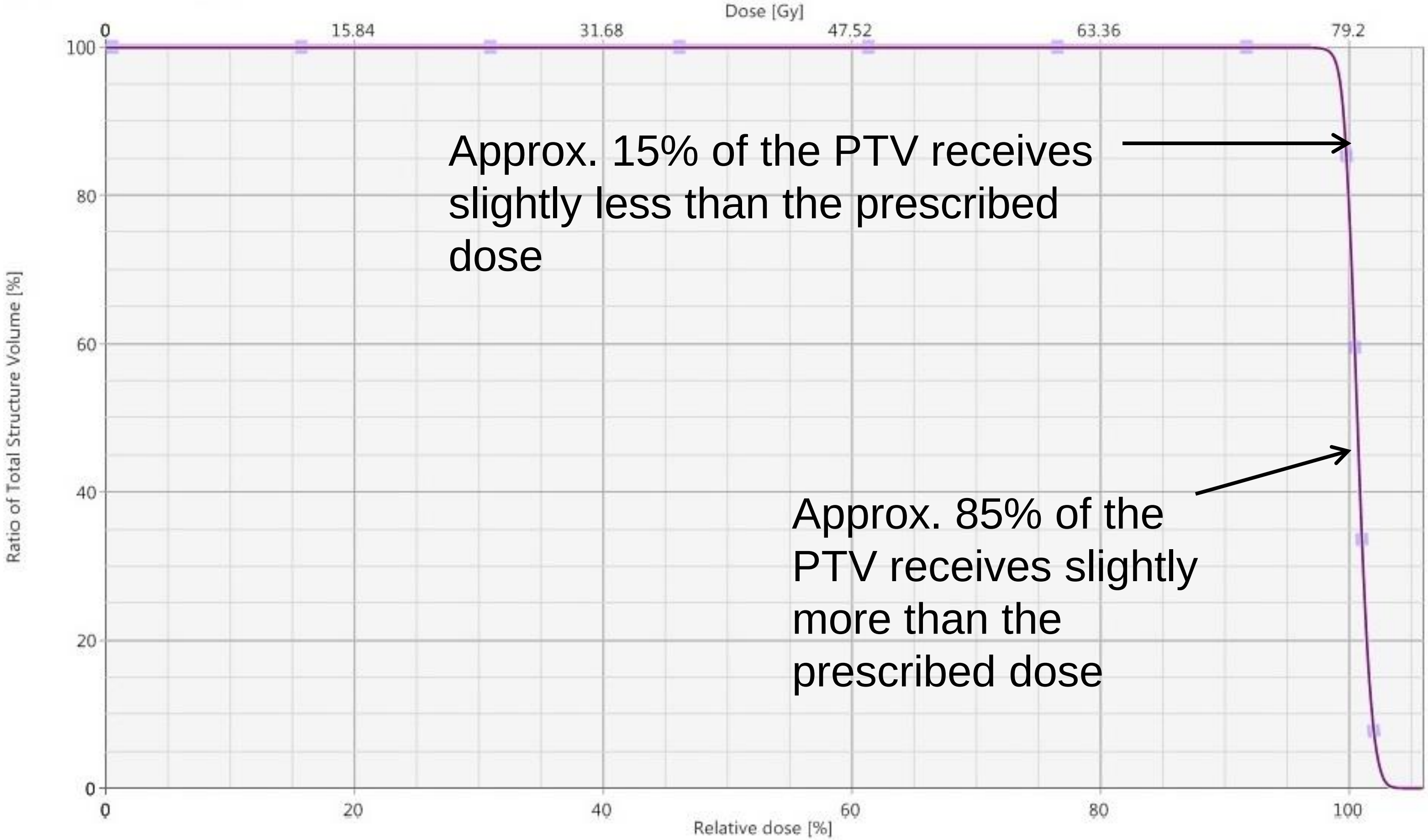


$$\mathbf{w} = \begin{pmatrix} \mathbf{w}_{beam\ 1} \\ \mathbf{w}_{beam\ 2} \\ \mathbf{w}_{beam\ 3} \\ \mathbf{w}_{beam\ 4} \\ \mathbf{w}_{beam\ 5} \end{pmatrix}$$

The DVH

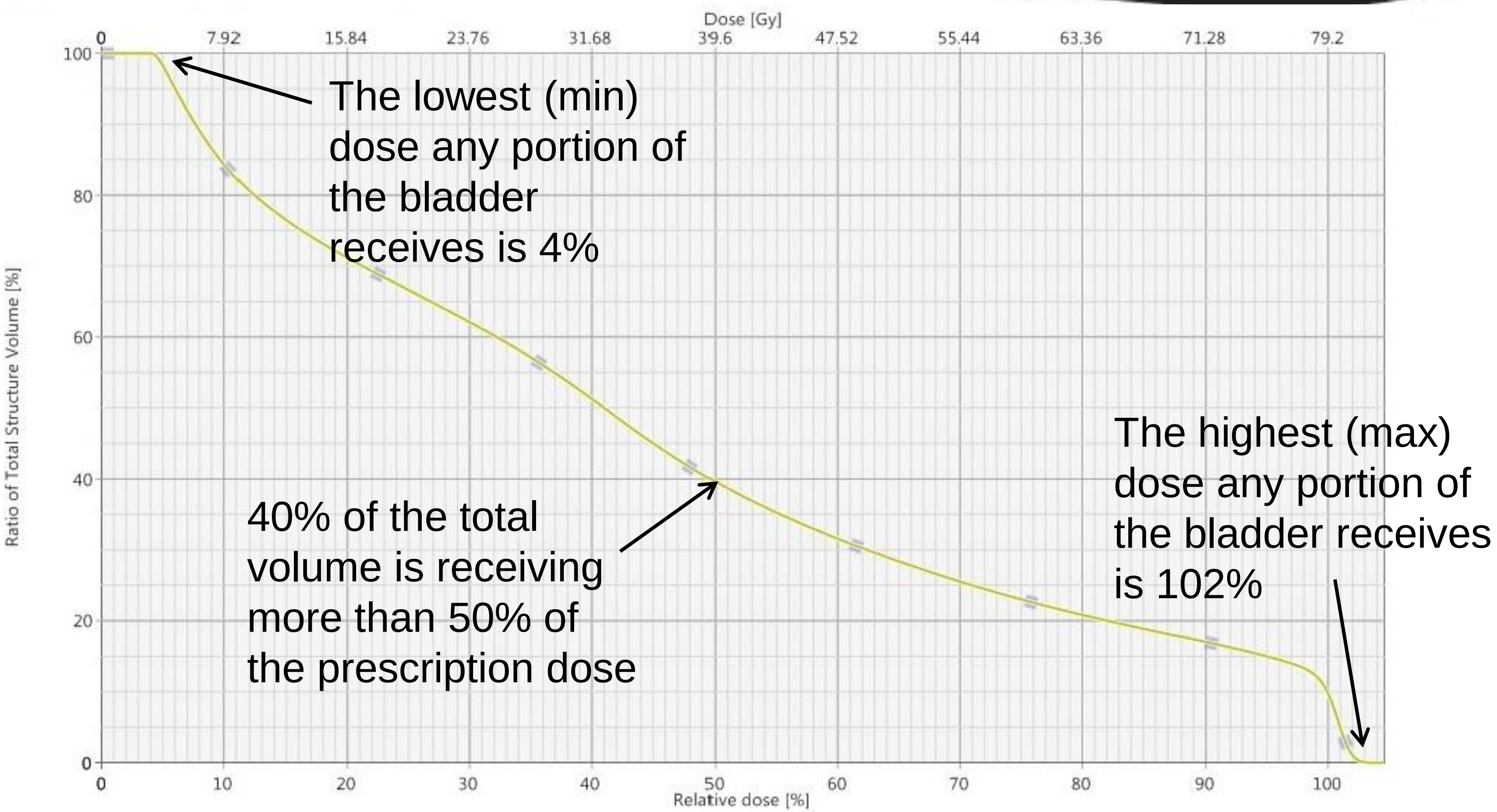
- A Dose-Volume Histogram (DVH) is a graphical representation of the percentage of dose received by a portion of the volume
- For a given treatment plan, the PTV and each organ has an associated DVH
- Is critical to defining the objective function

PTV DVH



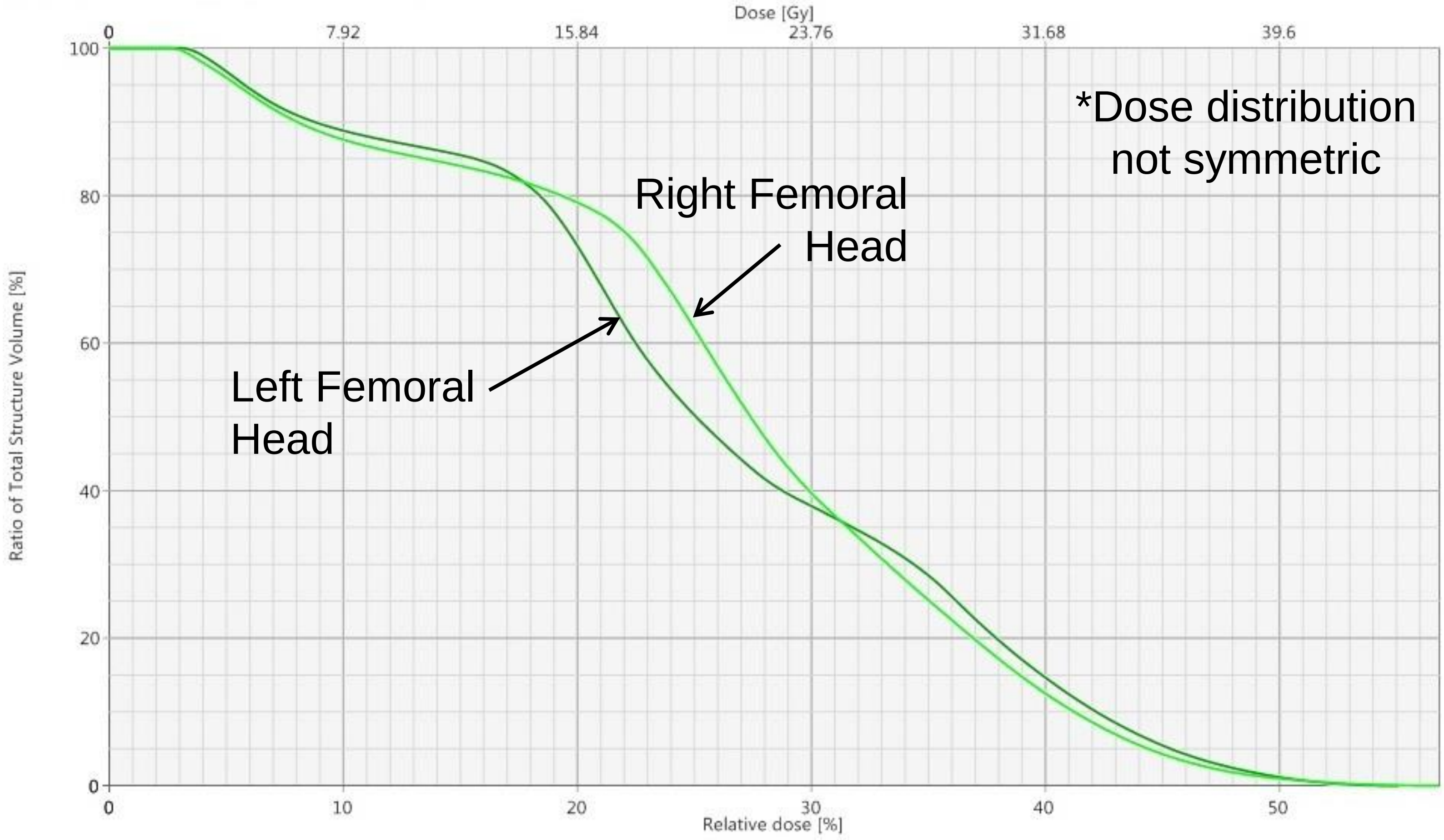
Dose [Gy]
0
15.84
31.68
47.52
63.36
79.2
100
80
60
40
20
0
Ratio of Total Structure Volume [%]
0
20
40
60
80
100
Relative dose [%]
Approx. 15% of the PTV receives slightly less than the prescribed dose
Approx. 85% of the PTV receives slightly more than the prescribed dose

Bladder DVH



Dose [Gy]
0
7.92
15.84
23.76
31.68
39.6
47.52
55.44
63.36
71.28
79.2
Ratio of Total Structure Volume [%]
100
80
60
40
20
0
10
30
50
70
90
Relative dose [%]
The lowest (min) dose any portion of the bladder receives is 4%
40% of the total volume is receiving more than 50% of the prescription dose
The highest (max) dose any portion of the bladder receives is 102%

Fem. Heads DVH



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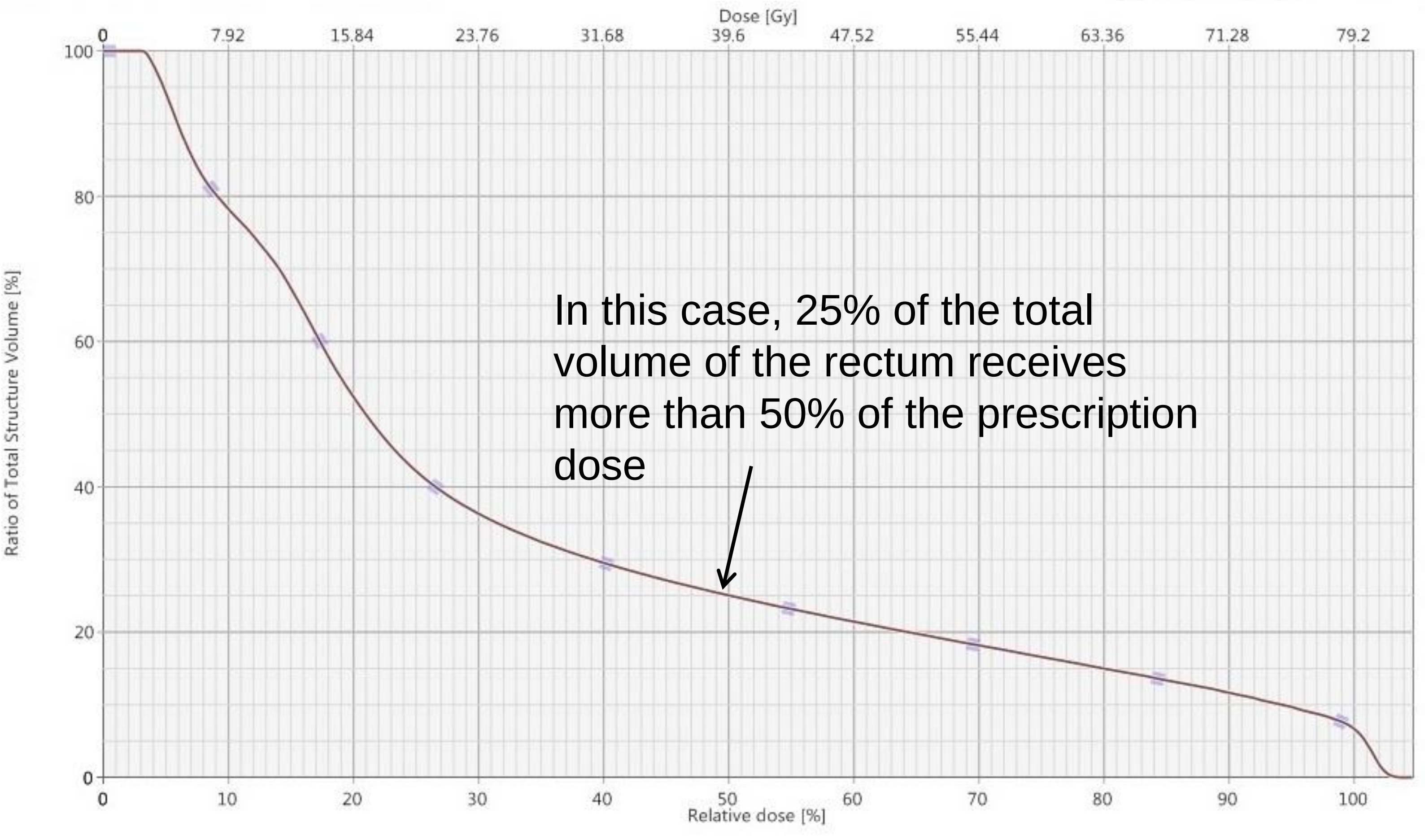
Rectum DVH



The Objective Function

$$F(\mathbf{w}) = \alpha(P_v - D_v(\mathbf{w}))^2 + \sum_i \sum_j \beta_i(\max[0, D_{ij}(\mathbf{w}) - C_{ij}])^2$$

w is a vector of beamlet weights or intensities

Minimizing $F(\mathbf{w})$ results in optimal IMRT treatment plan

The Target

$$F(\mathbf{w}) = \alpha(P_v - D_v(\mathbf{w}))^2 + \sum_i \sum_j \beta_i \left(\max\left[0, D_{ij}(\mathbf{w}) - C_{ij}\right]\right)^2$$

α=Priority of target dose (How important is it that this dose is fully administered?)

P_v=Dose prescribed to a given volume, v, of the target

$D_v(\mathbf{w})$=Dose actually received by volume v for weight vector $\mathbf{w}$

The Target

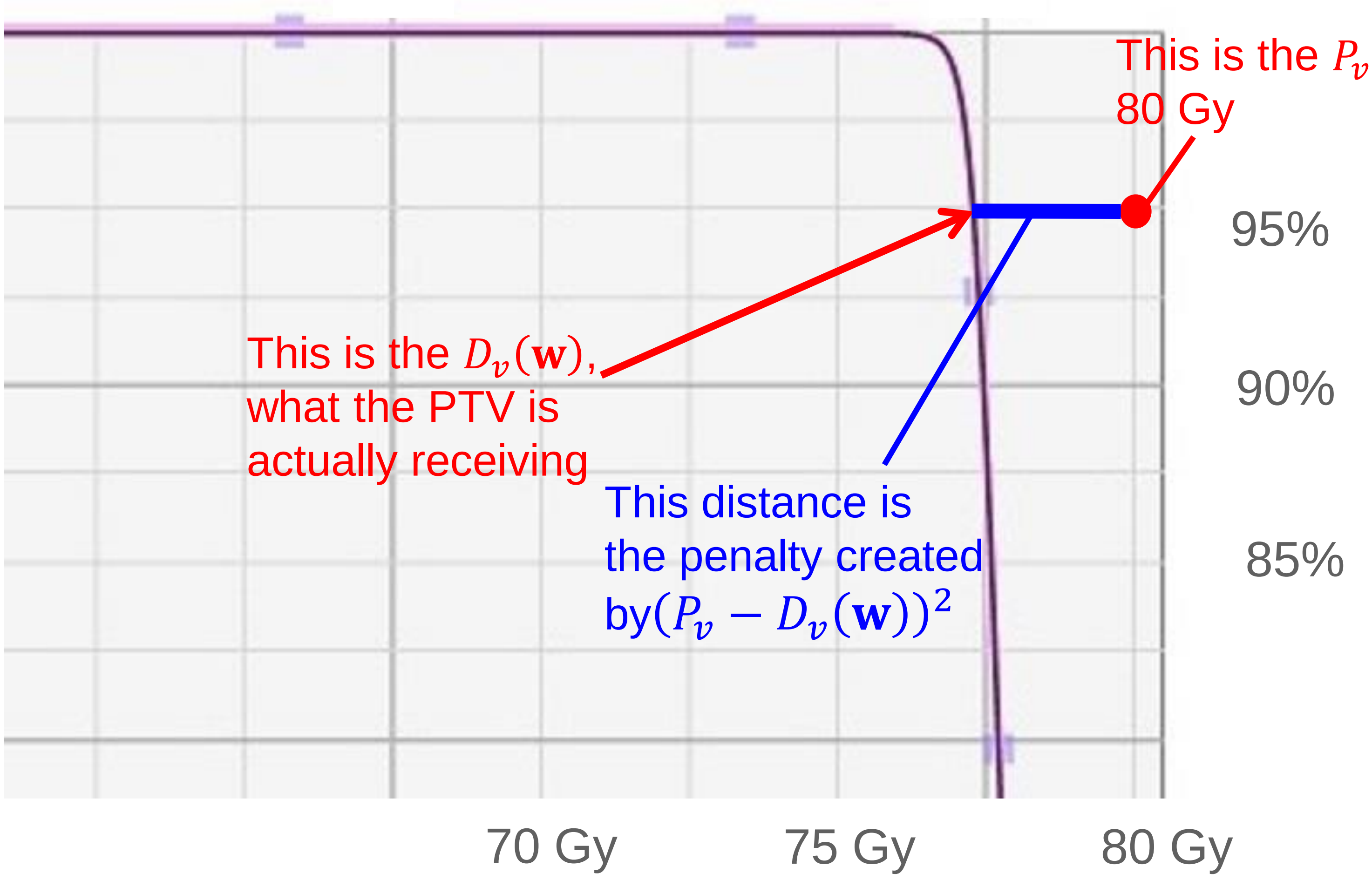
$\alpha(P_v - D_v(\mathbf{w}))^2$

In this case, if we want 95% of the volume to receive 80 Gy, $P_v = 80$

Let's take a closer look

The Target

$$\alpha(P_v - D_v(\mathbf{w}))^2$$



Penalties

$$\alpha(P_v - D_v(\mathbf{w}))^2$$

- In clinical terms, this ensures that the dose received by the target is as close as possible to the dose prescribed

Organs at Risk (OARs)

$$F(\mathbf{w}) = \alpha(P_v - D_v(\mathbf{w}))^2 + \sum_i \sum_j \beta_i (\max[0, D_{ij}(\mathbf{w}) - C_{ij}])^2$$

$\sum_i$ =Sum over each OAR, eg. bladder = 1

$\sum_j$ =Sum over multiple objectives for a given OAR

β_i =Priority of OAR

C_{ij} =Objective dose

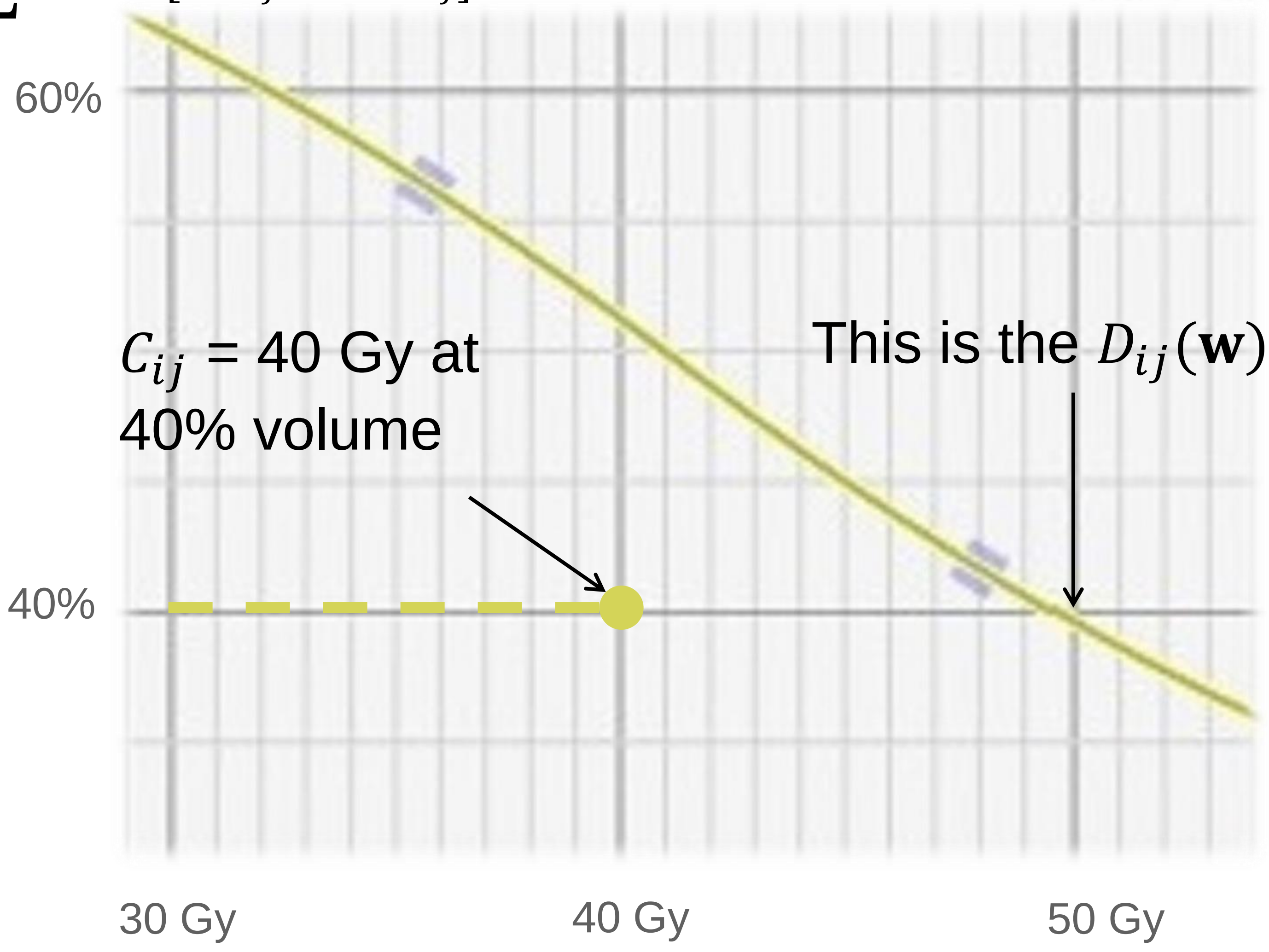
D_{ij} =Actual dose received by OAR

Organs at Risk (OARs)

$$\sum_i \sum_j \beta_i (\max[0, D_{ij}(\mathbf{w}) - C_{ij}])^2$$

Organs at Risk (OARs)

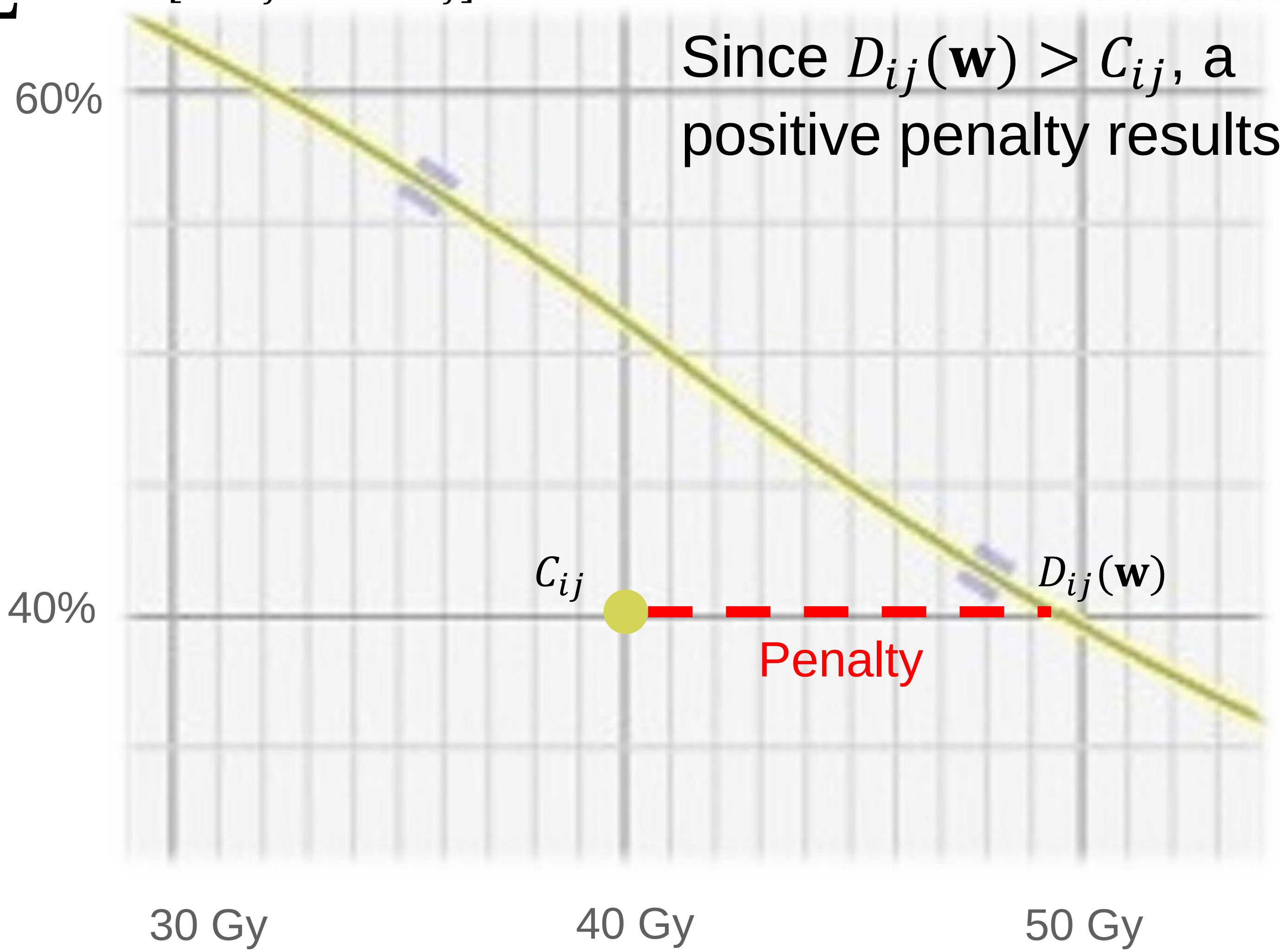
$$\sum_i \sum_j \beta_i (\max[0, D_{ij}(\mathbf{w}) - C_{ij}])^2$$



Organs at Risk (OARs)

$$\sum_i \sum_j \beta_i (\max[0, D_{ij}(\mathbf{w}) - C_{ij}])^2$$

Since $D_{ij}(\mathbf{w}) > C_{ij}$, a positive penalty results



Penalties

$$\sum_{i}\sum_{j}\beta_i(\max[0, D_{ij}(\mathbf{w}) - C_{ij}])^2$$

- There is no reward for $D_{ij}(\mathbf{w}) < C_{ij}$ because there is negligible clinical benefit to administering less than the objective dose to the OAR

The Process

Initial beamlet weight vector $\mathbf{w}$ is chosen

$$\mathbf{w}_n = \begin{pmatrix} d_1 \\ \vdots \\ d_n \end{pmatrix}$$

Beamlet results in dose for each voxel

$$\mathbf{w}_{beam} = \begin{pmatrix} \mathbf{w}_1 \\ \vdots \\ \mathbf{w}_n \end{pmatrix}$$

Beamlet dose matrices are added to create a beam dose matrix

Beam dose matrices are added to create total dose matrix

$$\mathbf{w}_{total} = \begin{pmatrix} \mathbf{w}_{beam\ 1} \\ \vdots \\ \mathbf{w}_{beam\ n} \end{pmatrix}$$

DVHs are created and F(w) calculated

$\mathbf{w}$ is modified using optimization algorithm

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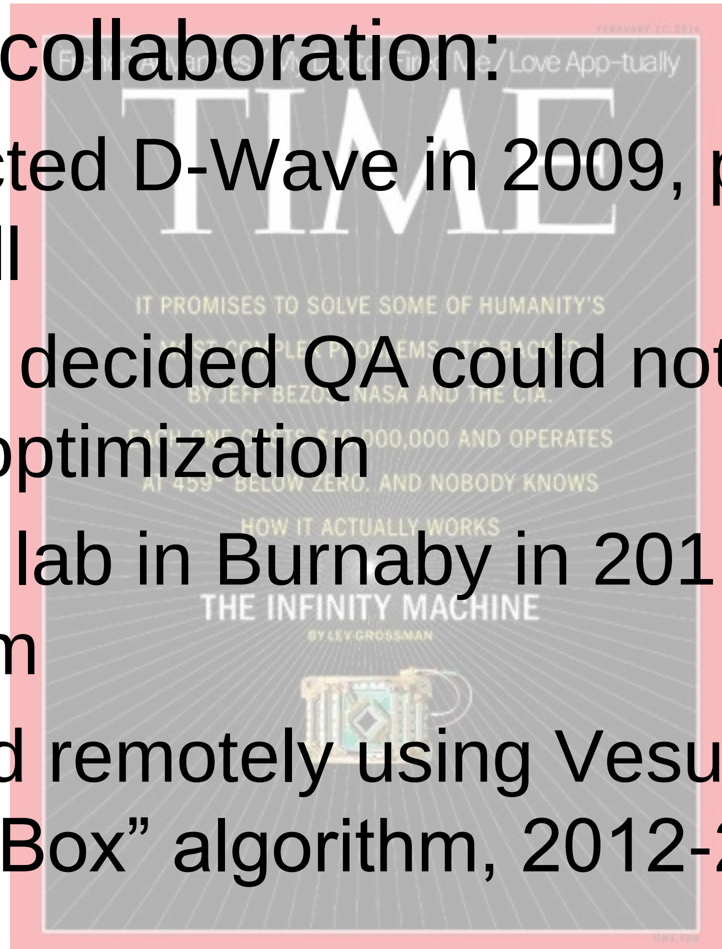
D-Wave Systems

History of collaboration:

- Contacted D-Wave in 2009, put in touch with Bill
- Initially decided QA could not support IMRT optimization
- Visited lab in Burnaby in 2011 and revisited problem
- Worked remotely using Vesuvius chip and “Black Box” algorithm, 2012-2014



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First application of quantum annealing to IMRT beamlet intensity optimization

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Abstract

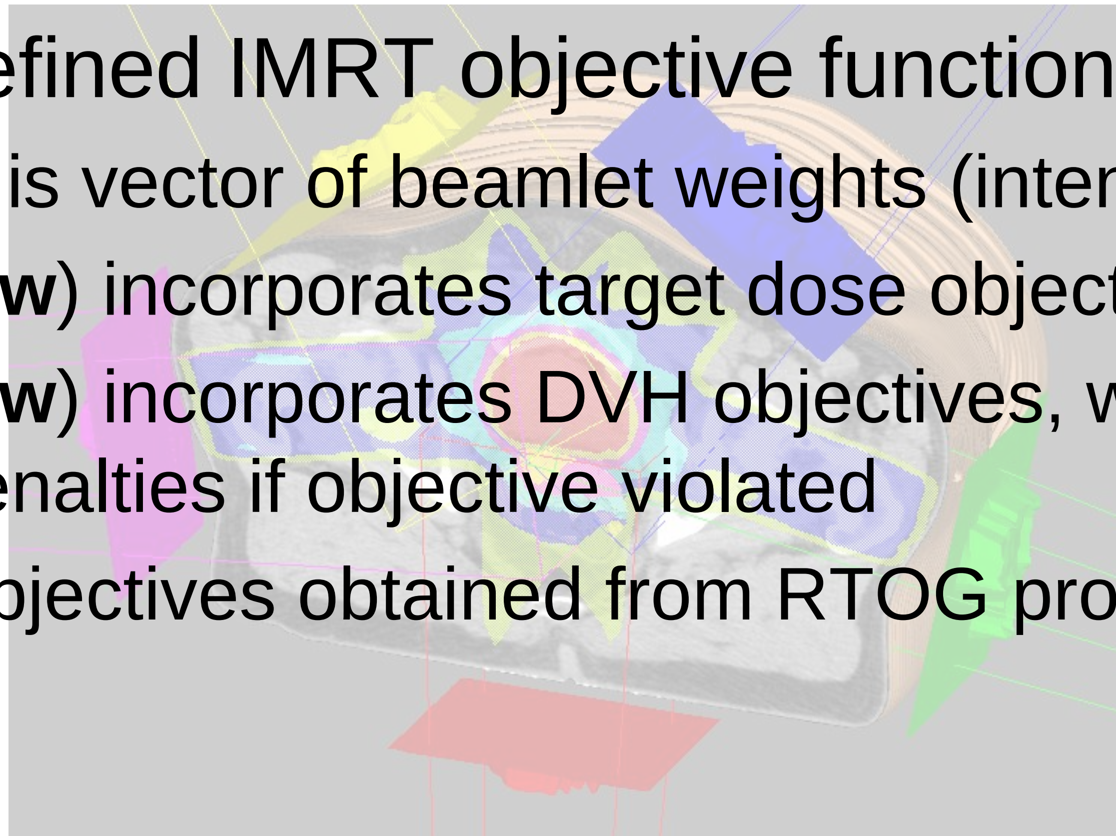
Optimization methods are critical to radiation therapy. A new technology, quantum annealing (QA), employs novel hardware and software techniques to address various discrete optimization problems in many fields. We report on the first application of quantum annealing to the process of beamlet intensity optimization for IMRT.

We apply recently-developed hardware which natively exploits quantum mechanical effects for improved optimization. The new algorithm, called

RT Optimization

We defined IMRT objective function: *F*(**w**)

- **w** is vector of beamlet weights (intensities)
- *F*(**w**) incorporates target dose objective
- *F*(**w**) incorporates DVH objectives, with penalties if objective violated
- Objectives obtained from RTOG protocols



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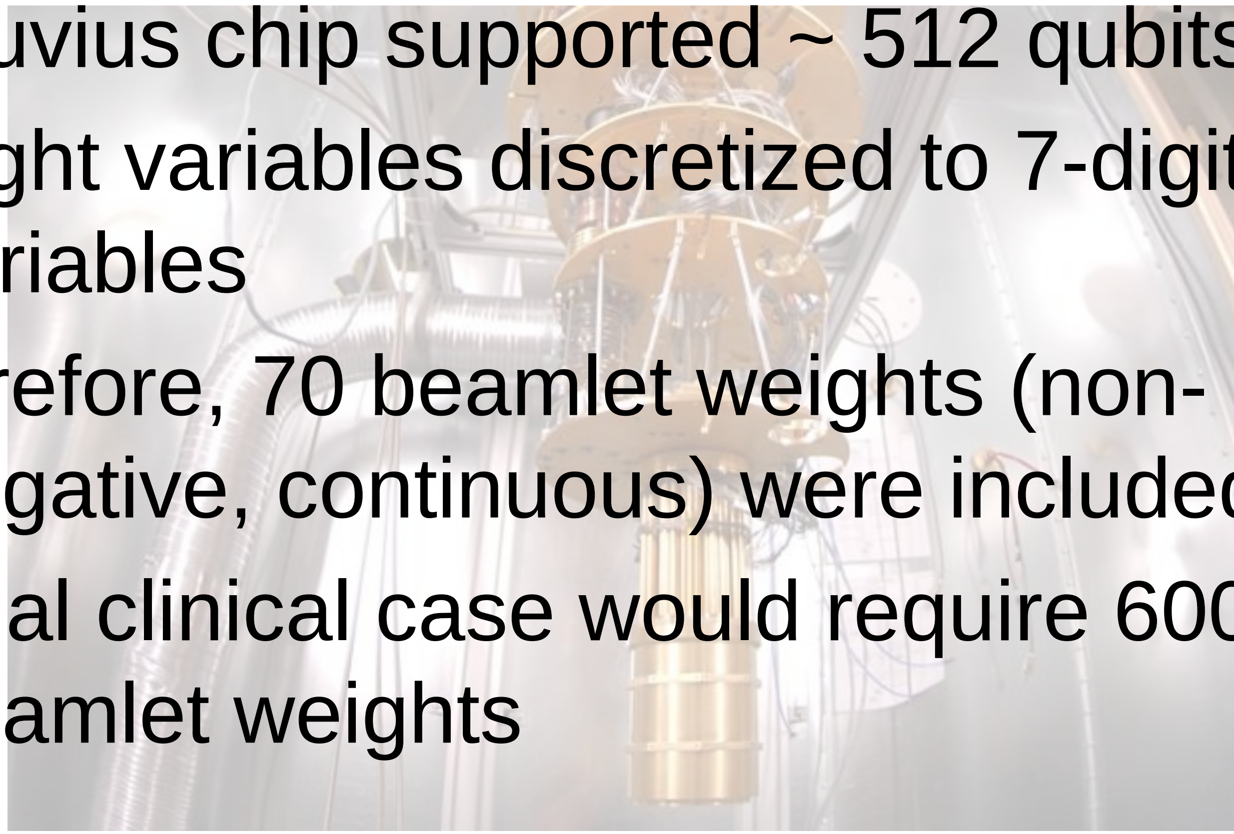
Applying QA



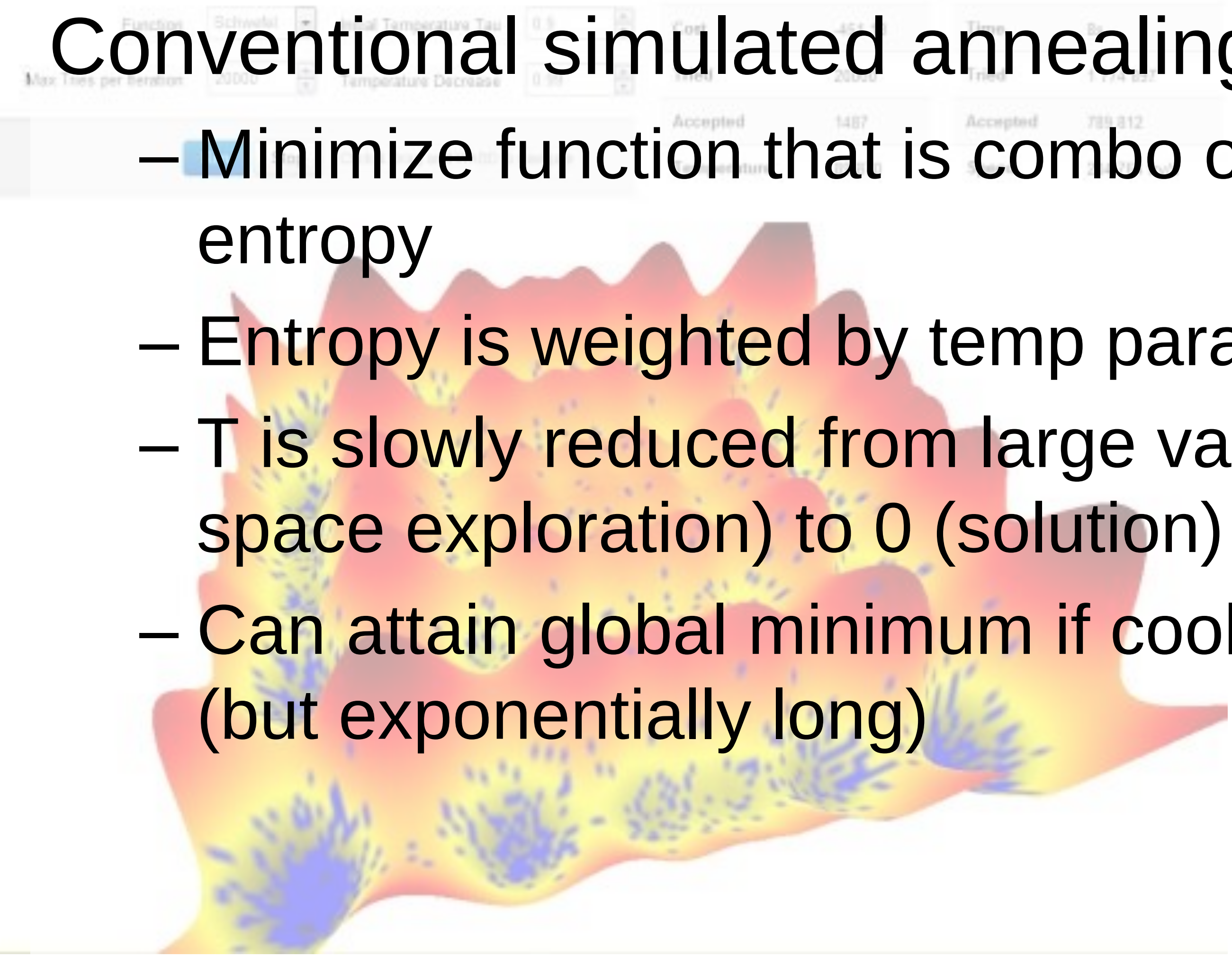
Vesuvius chip supported ~ 512 qubits

Weight variables discretized to 7-digit binary variables

Therefore, 70 beamlet weights (non-negative, continuous) were included

Actual clinical case would require 600-1000 beamlet weights

SA Algorithm



Conventional simulated annealing (SA) features:

- Minimize function that is combo of original plus entropy
- Entropy is weighted by temp parameter T
- T is slowly reduced from large values (search space exploration) to 0 (solution)
- Can attain global minimum if cooling slow enough (but exponentially long)

Evaluations

Three methods compared:

- Quantum annealing
- Simulated annealing
- Tabu search: popular heuristic used in combinatorial optimization

Methods were used to determine beamlet weights for two prostate bed cases

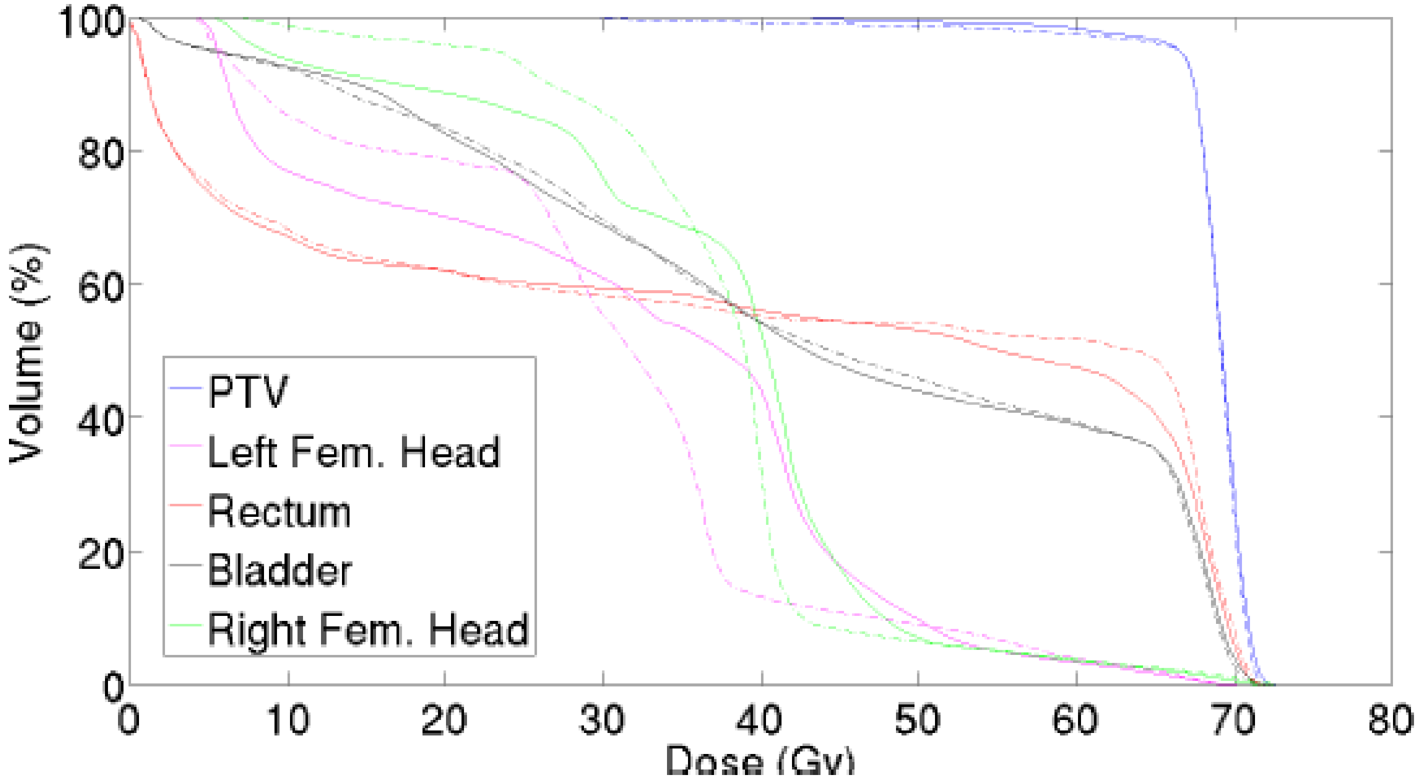
Each was run for 10^7 function evaluations and compared for speed and score

Results

Patient	Method	Evals/sec /core	Final Score
1	QA	9.3	16.9
1	SA	9.6	6.7
1	Tabu	4.3	10.0

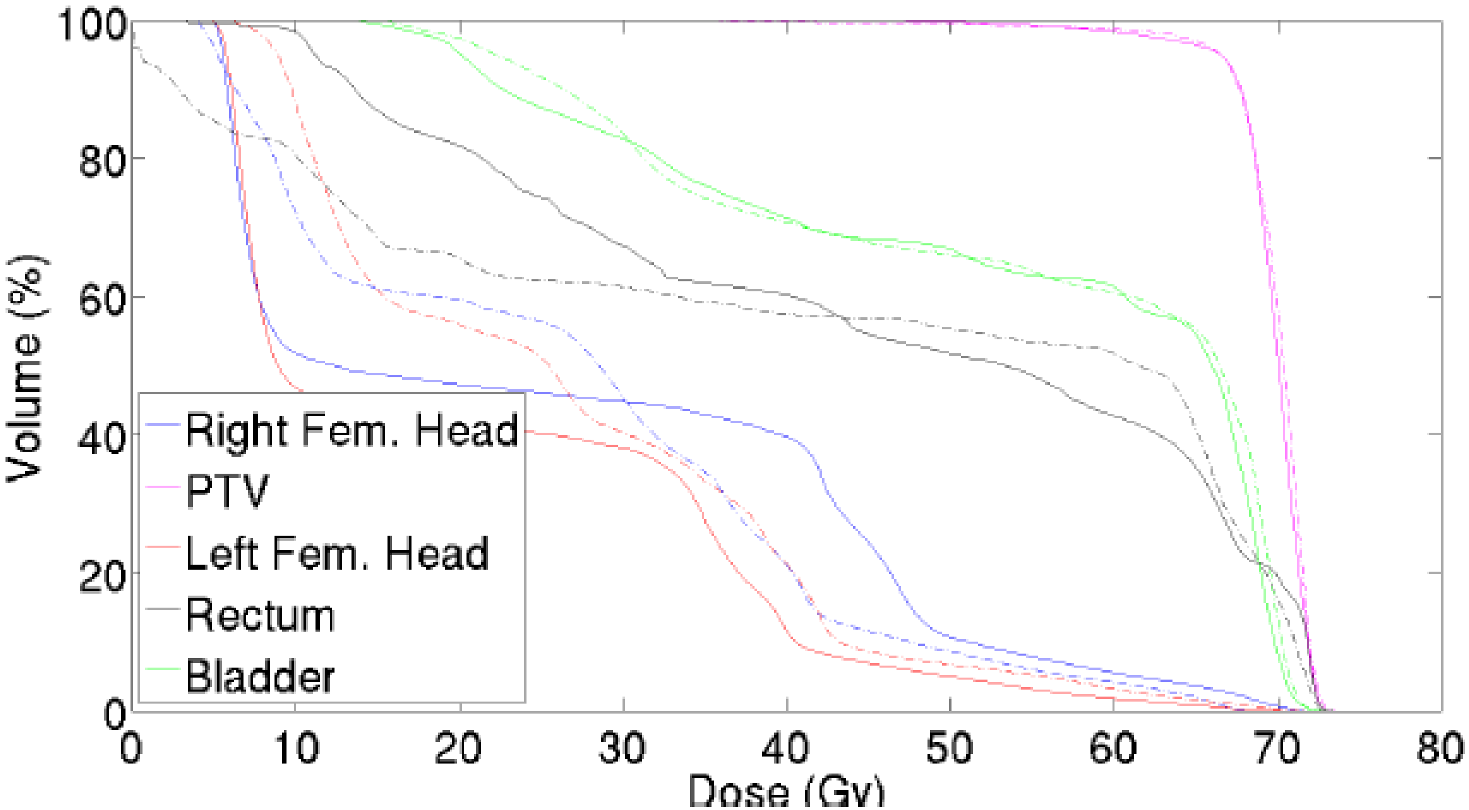
2	QA	15.4	70.7
2	SA	17.4	22.9
2	Tabu	6.3	120.0

DVHs



QA (solid) and SA (dashed) for Patient 1

DVHs



QA (solid) and Tabu (dashed) for Patient 2

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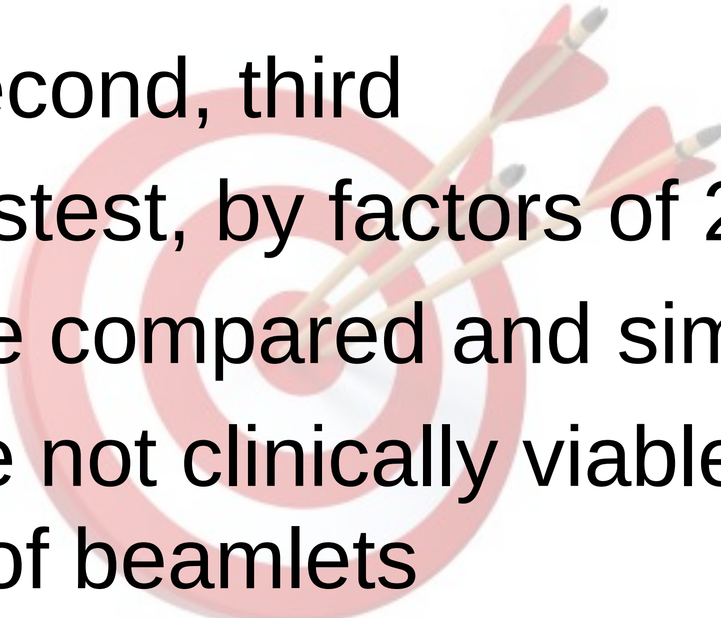
Wall Clock Time

Patient	Method	Time
1	QA	1.00
1	SA	2.89
1	Tabu	3.23
2	QA	1.00
2	SA	2.67
2	Tabu	3.67

Results Summary



- SA produced best score for both patients
- QA was second, third
- QA was fastest, by factors of 2.7 – 3.7
- DVHs were compared and similar
- Plans were not clinically viable due to small number of beamlets

Future Work – VMAT

VMAT

VMAT

VMAT Treatment

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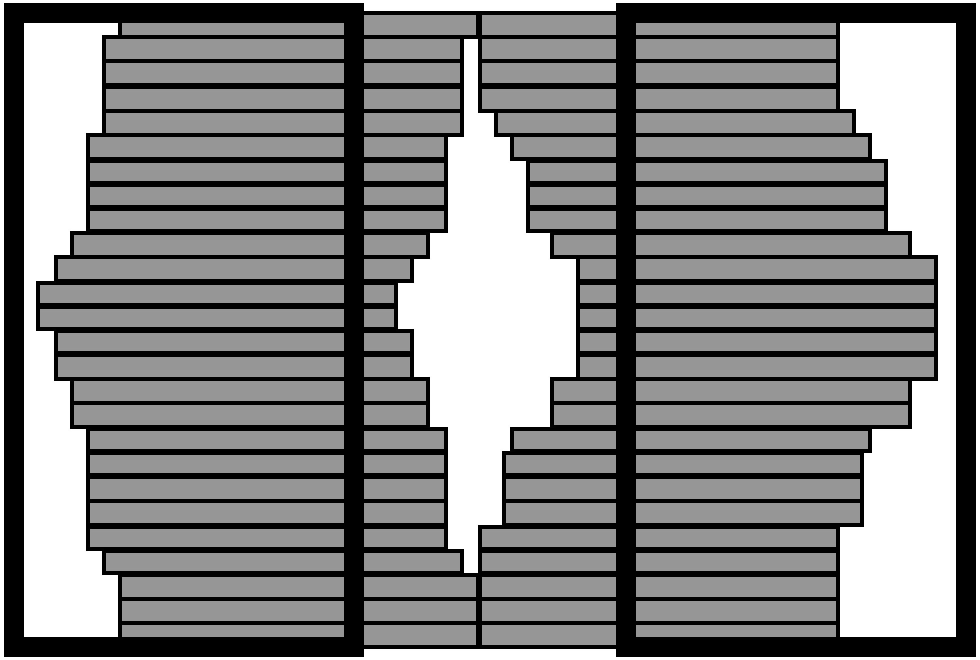
VMAT Optimization



Conclusions

- This is first application of QA to IMRT optimization
- Compared QA to SA and Tabu
- Evaluated using clinical DVH-based objective functions
- QA hardware will rapidly scale in size
- Further research on application of QA to VMAT may offer promising returns

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Thank You!

YouTube Embeds

Linear Accelerator

IMRT Treatment

VMAT Treatment