Intensity Modulated Radiation Therapy: Treatment Planning Techniques

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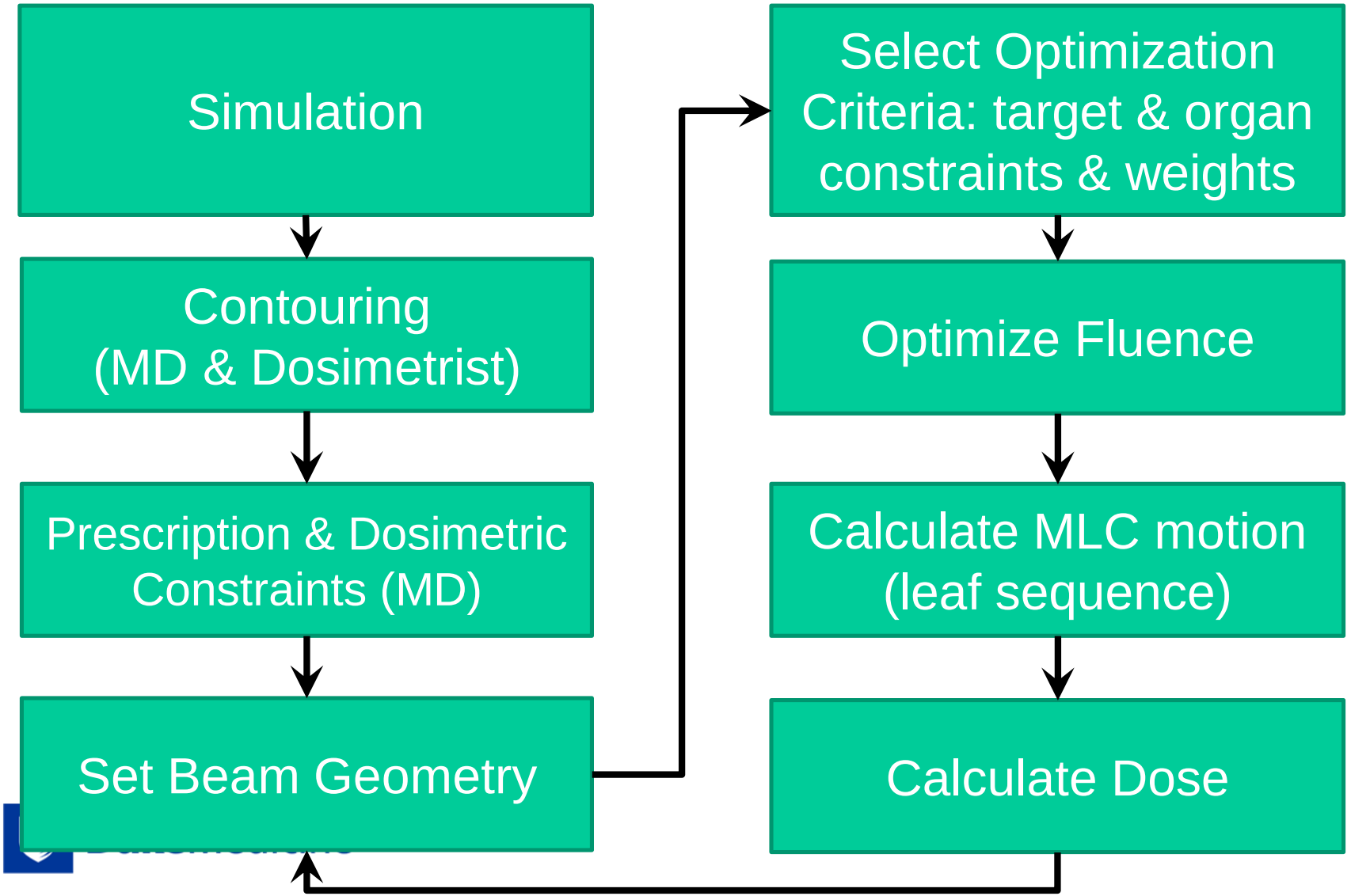
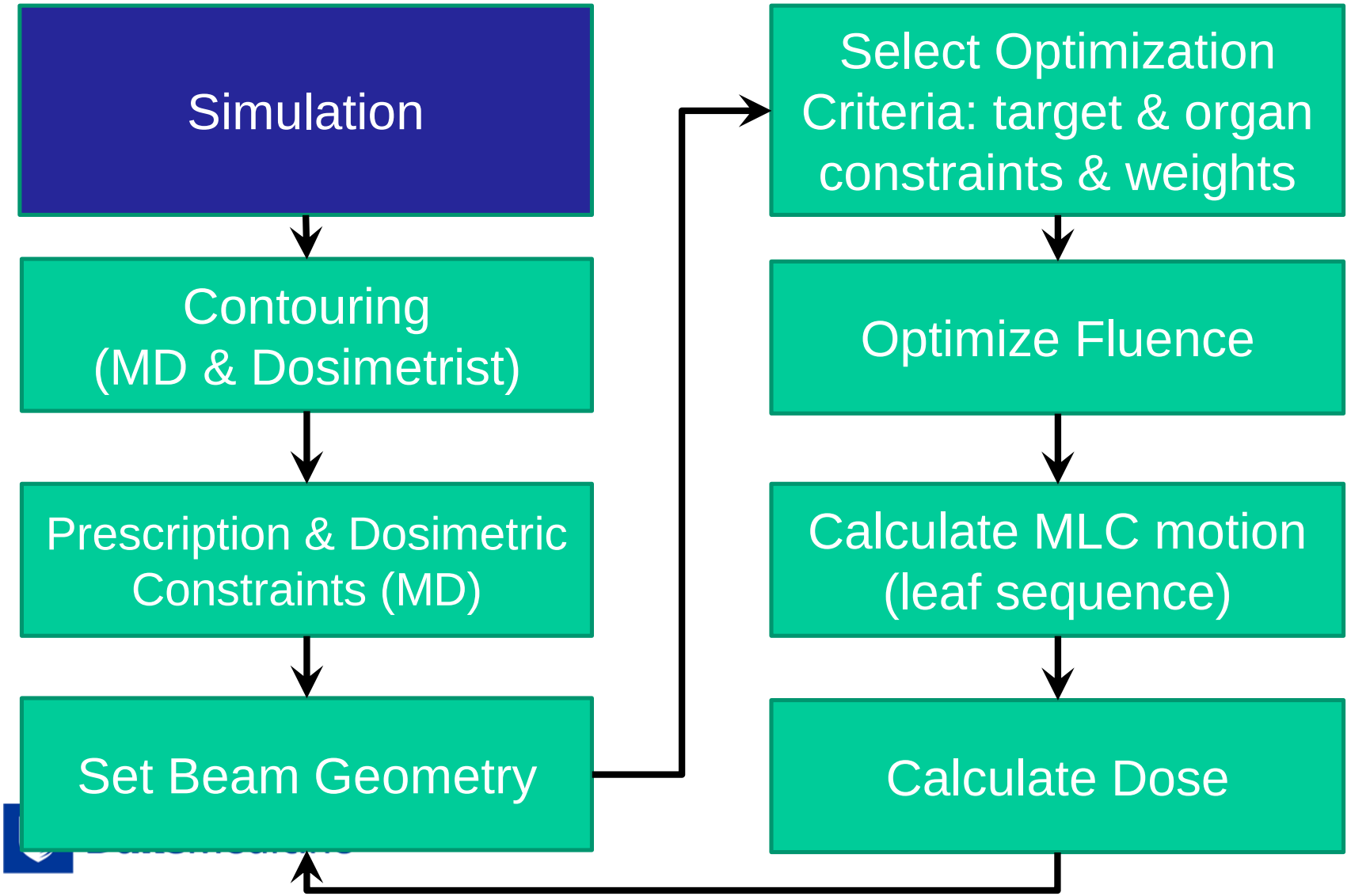
IMRT Treatment Planning Techniques: Today's Overview

- Treatment chain & implications for successful IMRT treatment planning
- Case study: Head and Neck
- Case study: Prostate

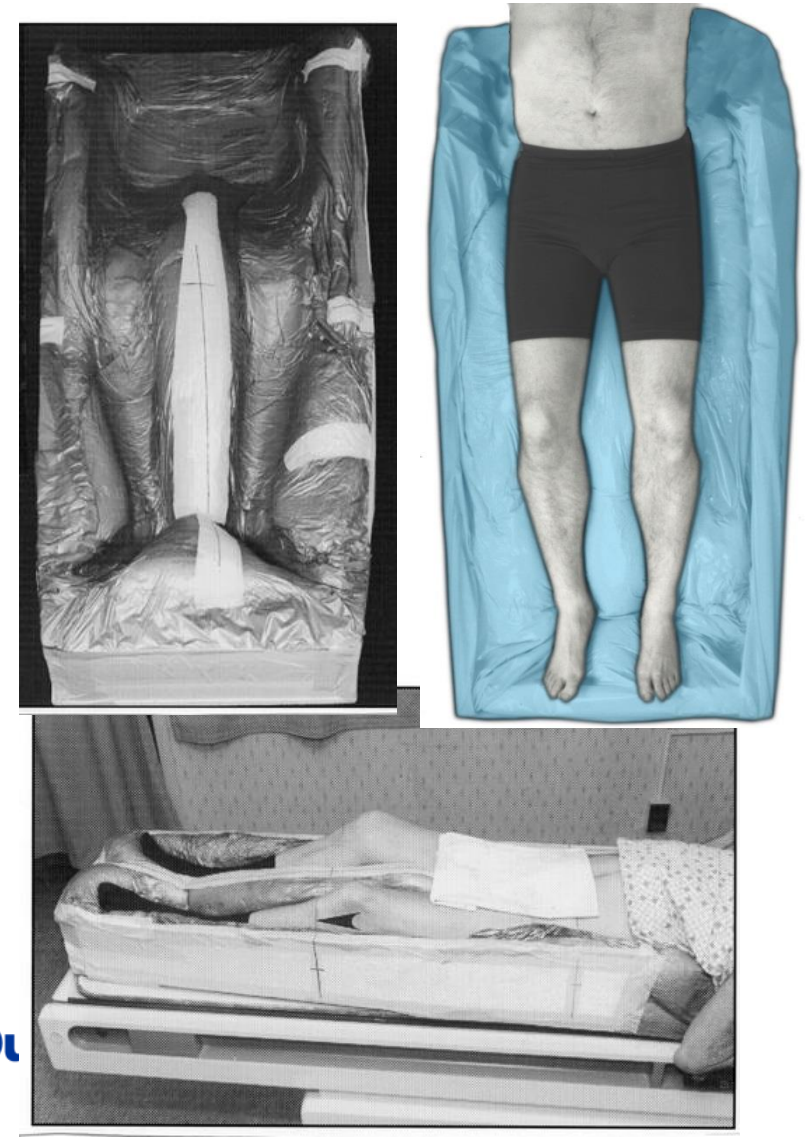
IMRT Treatment Planning Process



IMRT Treatment Planning Process

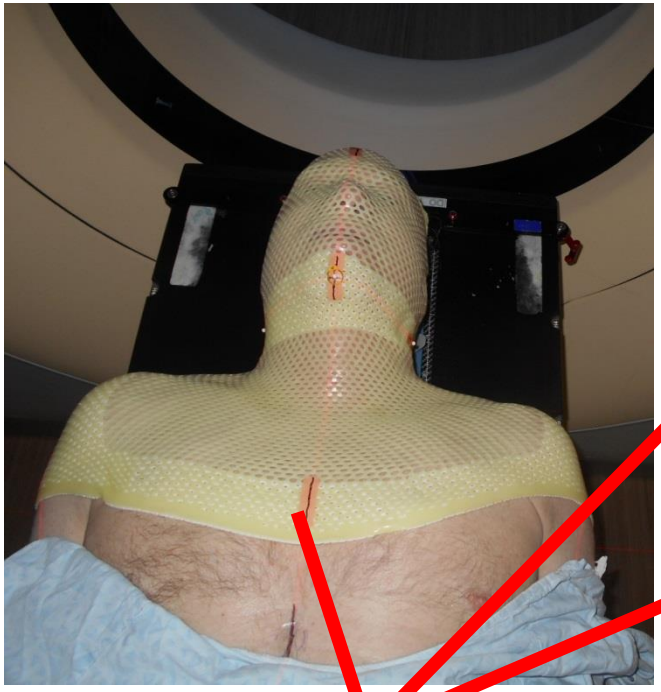


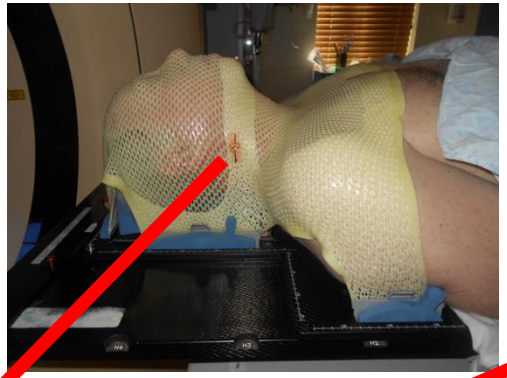
Implications for successful IMRT Treatment Planning: Simulation

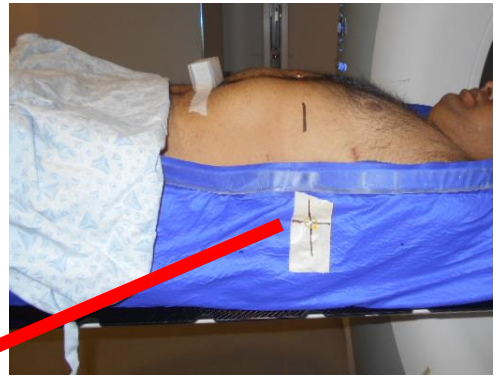


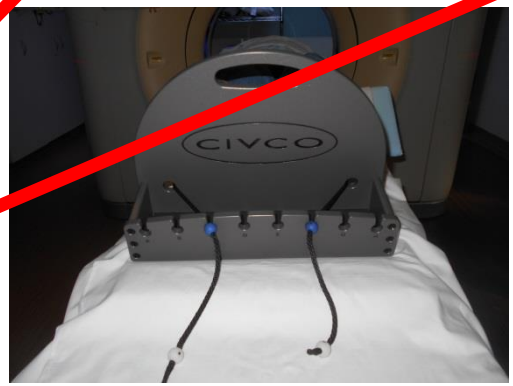
- Better immobilization = smaller CTV to PTV margins
- Poor immobilization = larger margins -> can negate conformality benefit of IMRT
- Patient comfort: longer treatment times for IMRT
  - Can the patient remain in this position for the full treatment?

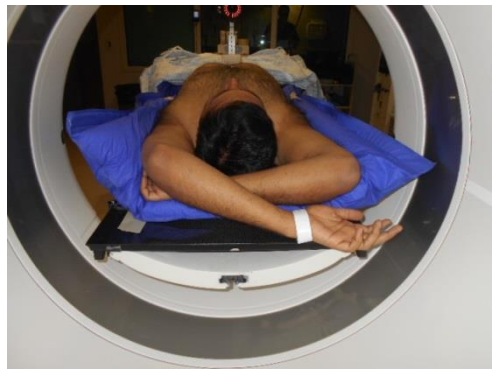
CT Simulation Setup Examples:





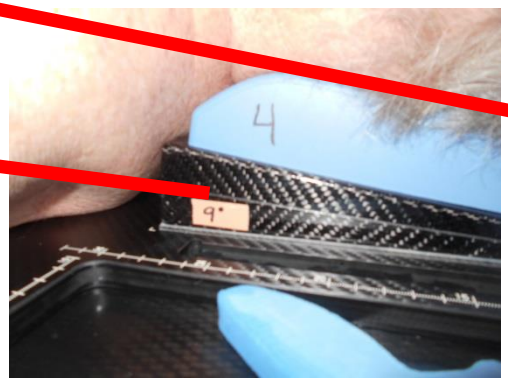


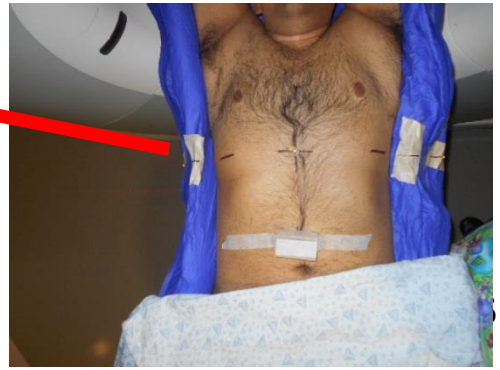




laser location
Marked
(often fiducials placed for CT)

Immobilization
details noted





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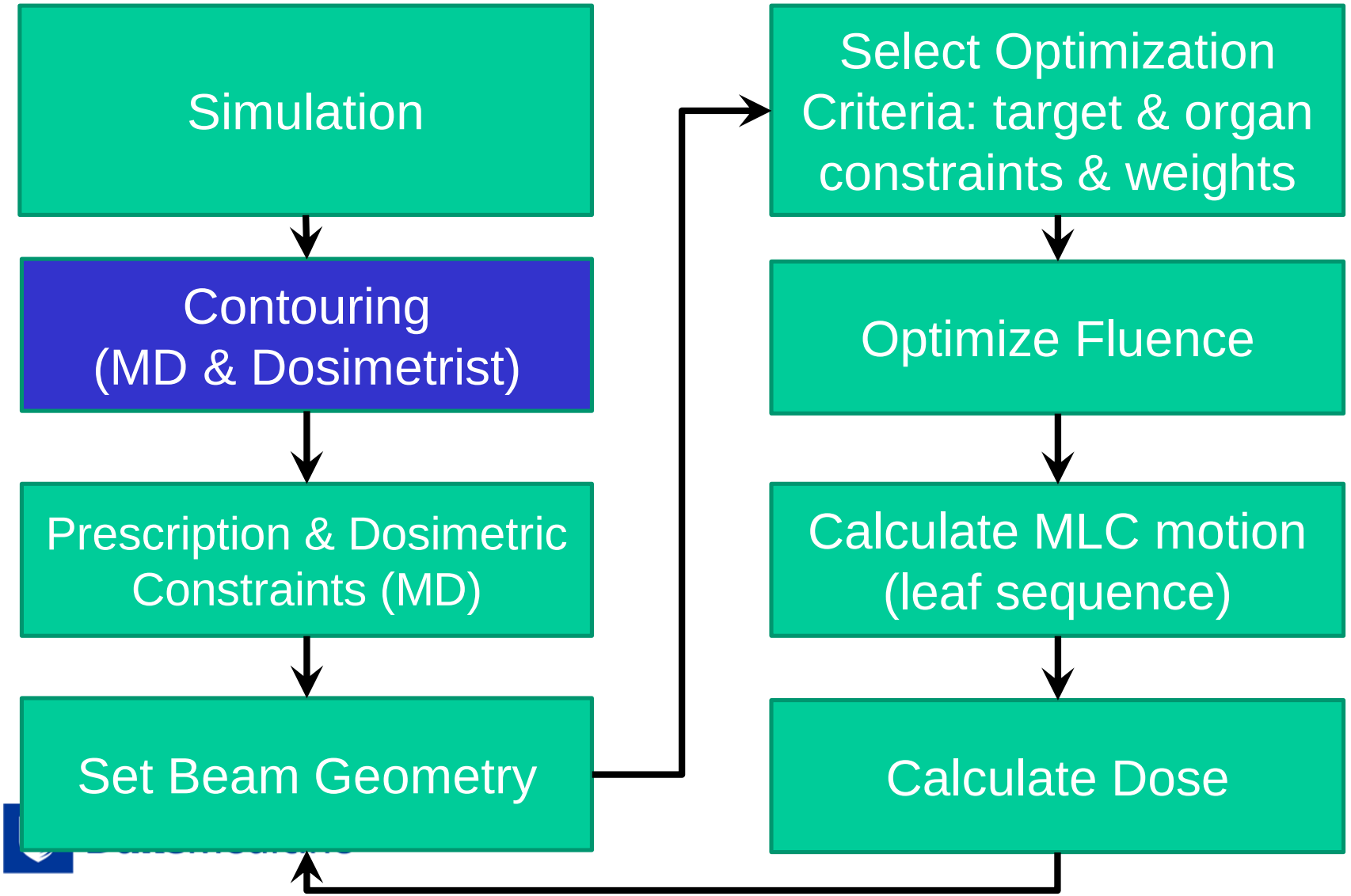
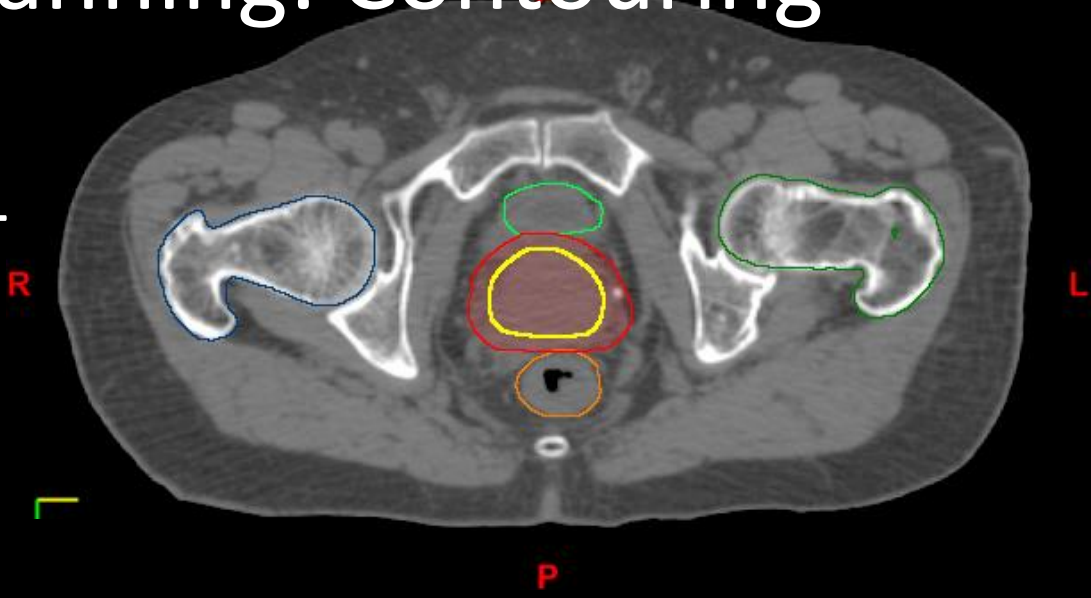
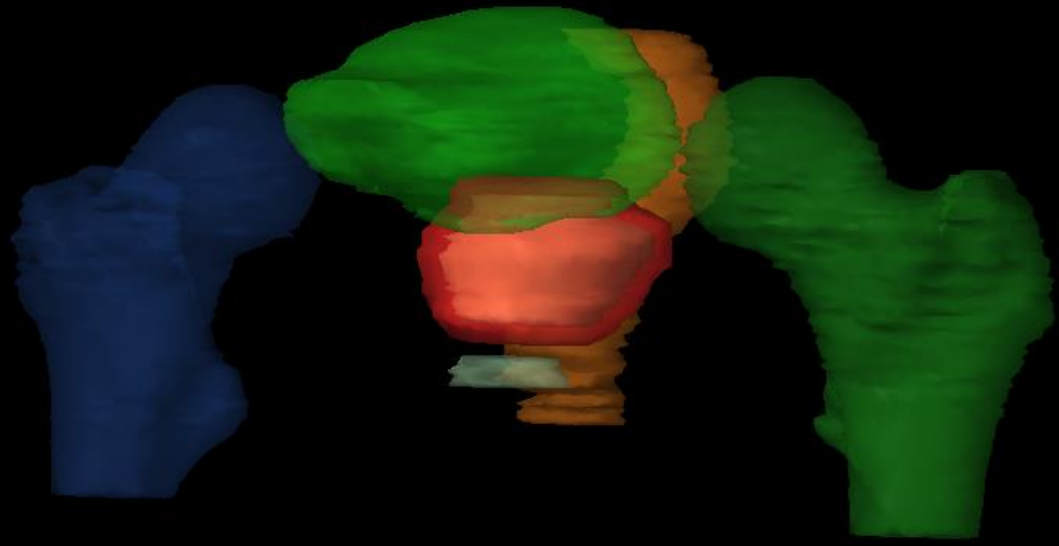
IMRT Treatment Planning Process



Implications for successful IMRT Treatment Planning: Contouring

Accurate contours are more important for IMRT than 3D because inverse optimization tailors the dose to them

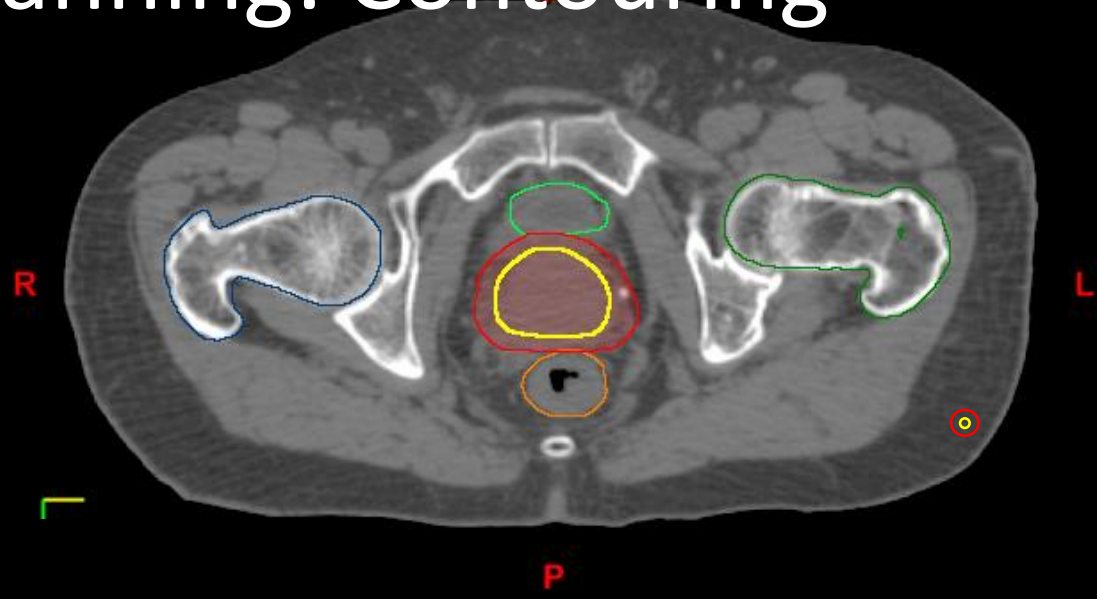


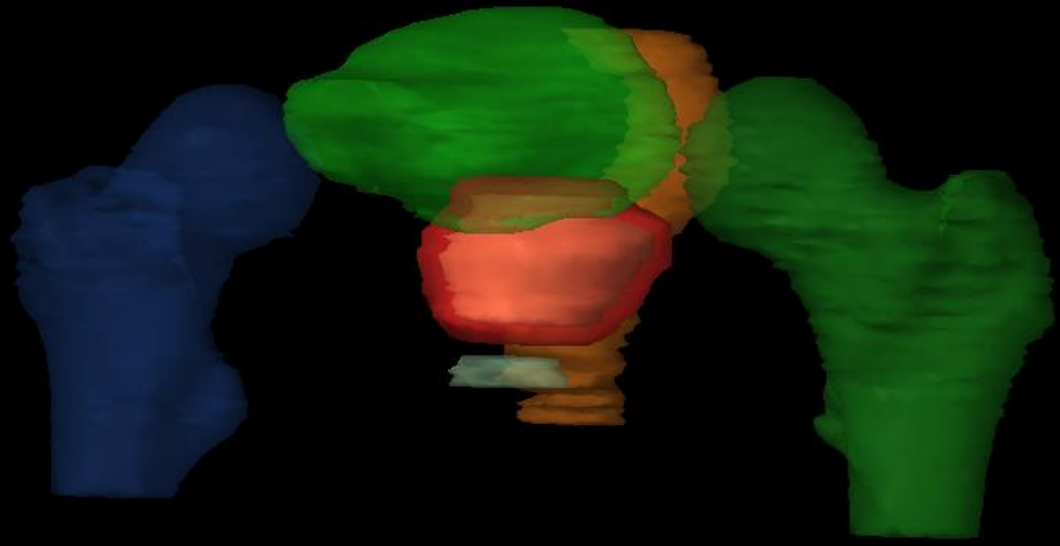


The IMRT plan is only as good as the contours!

Implications for successful IMRT Treatment Planning: Contouring

What effect will a small erroneous pixel in the PTV have?

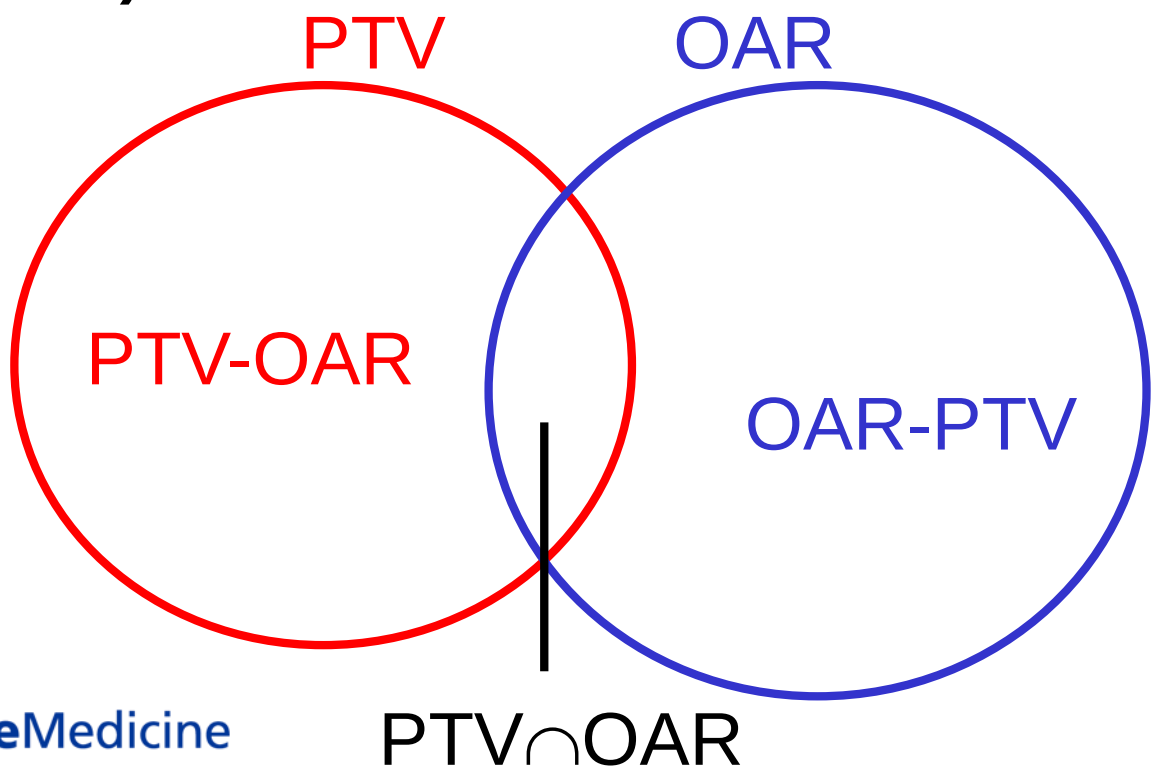




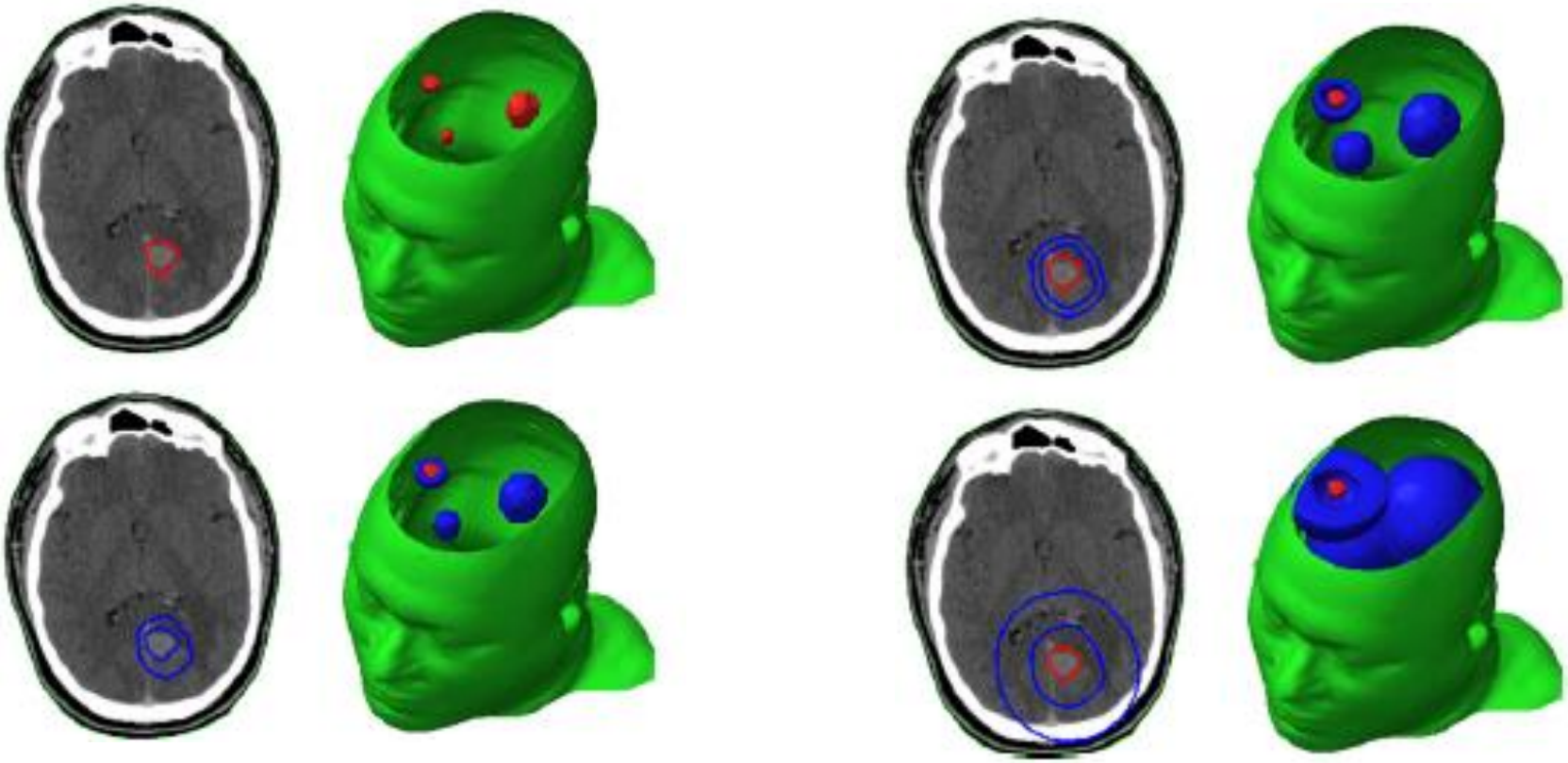
Verify contours especially in areas where PTV and OARs

Implications for successful IMRT Treatment Planning: Contouring

May be useful to create separate structures in overlap regions (PTV-OAR, OAR-PTV & OAR∩PTV)



Optimization Structures



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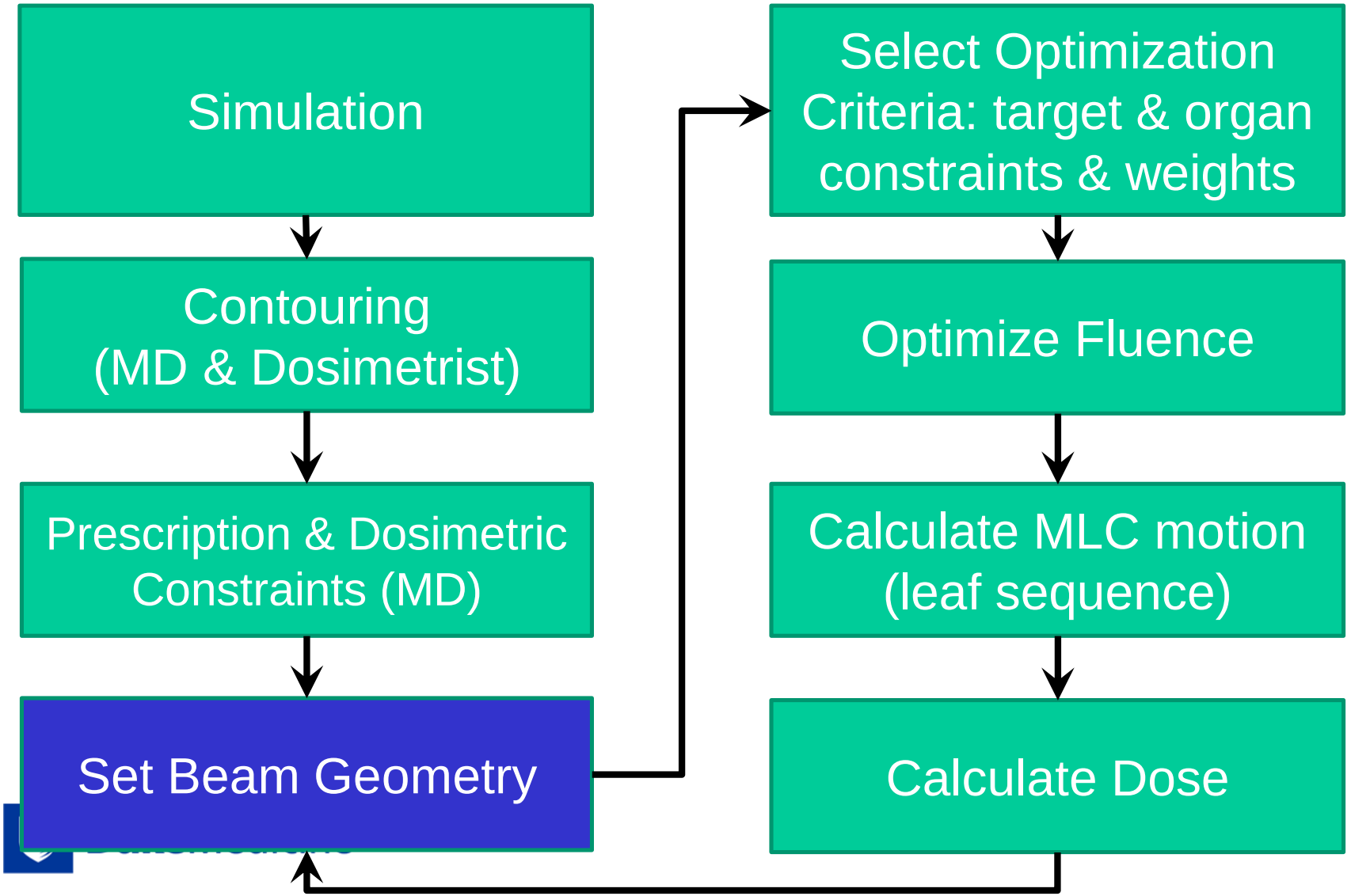
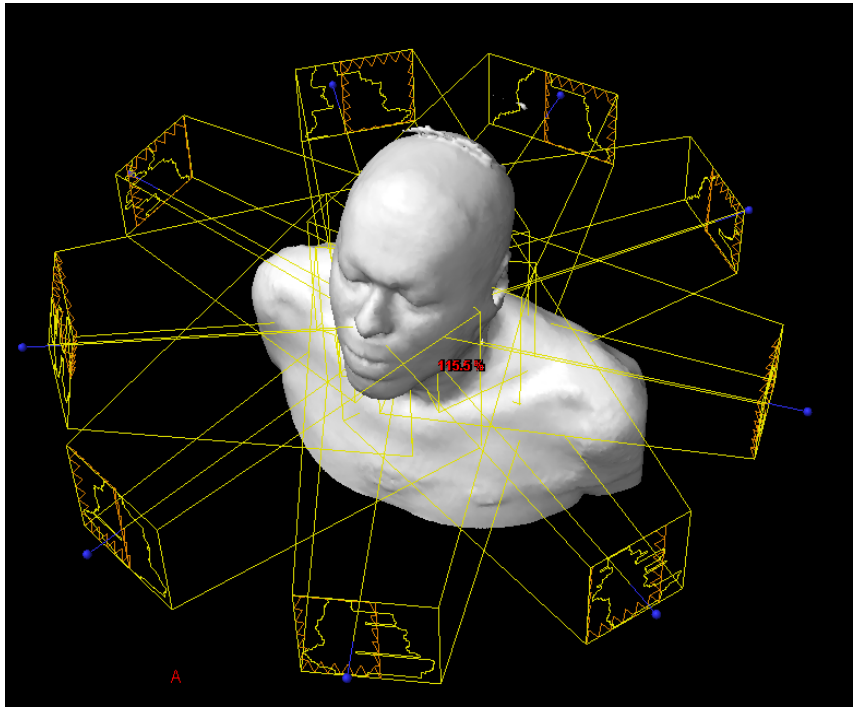
Practical Radiation Oncology (2012) 2, 306–313

IMRT Treatment Planning Process



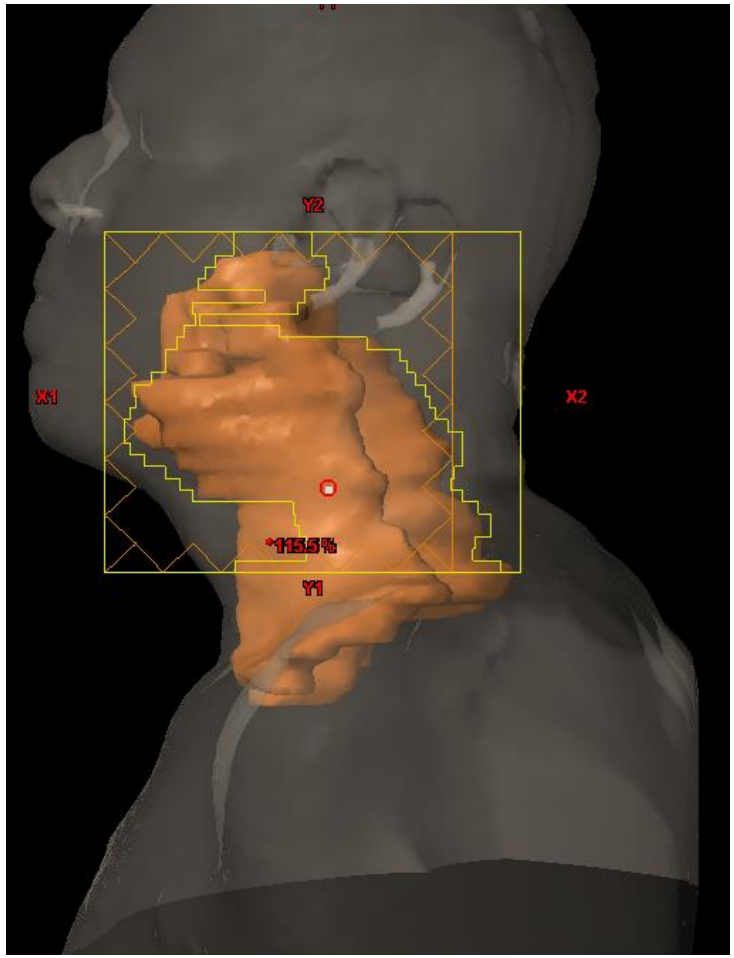
Implications for successful IMRT Treatment Planning: Beam Geometry

- Typically 5-12 equi-spaced beams
  - Provides degrees of freedom for the inverse optimization
- Isocenter placed near center of PTV



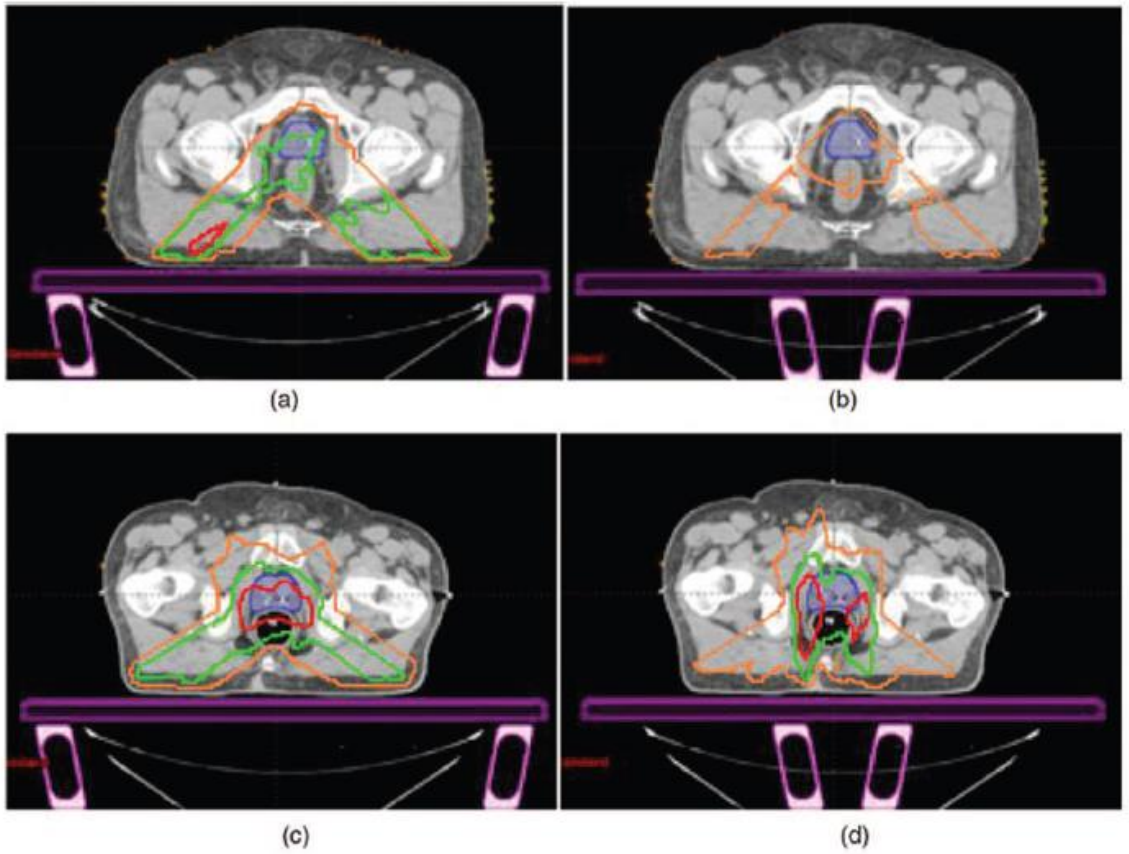
Implications for successful IMRT Treatment Planning: Beam Geometry

- Jaws can be set automatically or manually
- Examples when jaws should be manually fixed:
  - avoid going through shoulders
  - avoid OARs with very stringent dose criteria



Implications for successful IMRT Treatment Planning: Beam Geometry

- Some tables have adjustable support bars with high attenuation!
- Take care to make sure the beam doesn't enter through them
- Otherwise, the inverse optimization may force high fluence through them



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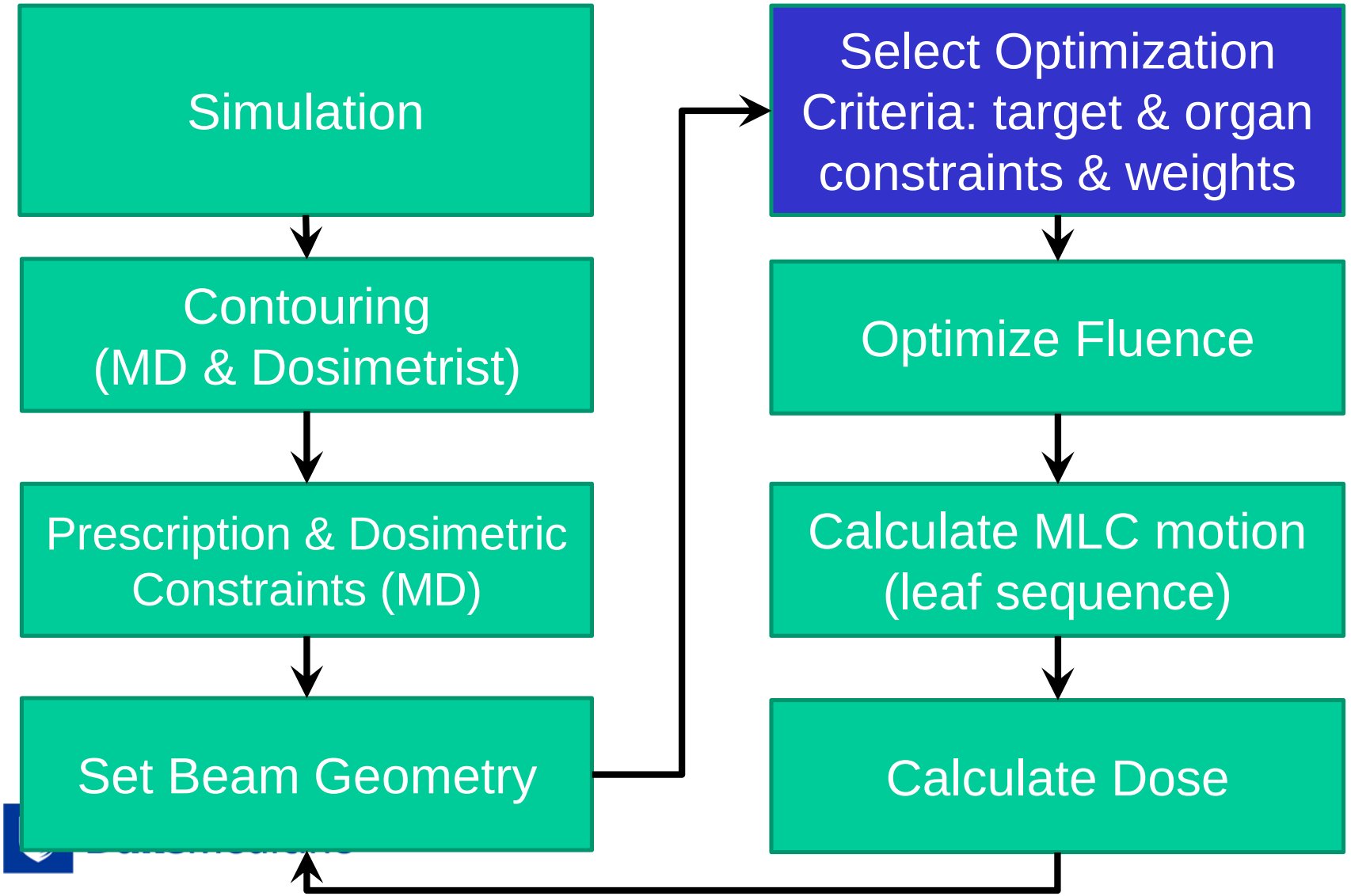
AAPM Task Group 176, "Dosimetric effects caused by couch tops and immobilization devices" (2014)

IMRT Treatment Planning Process

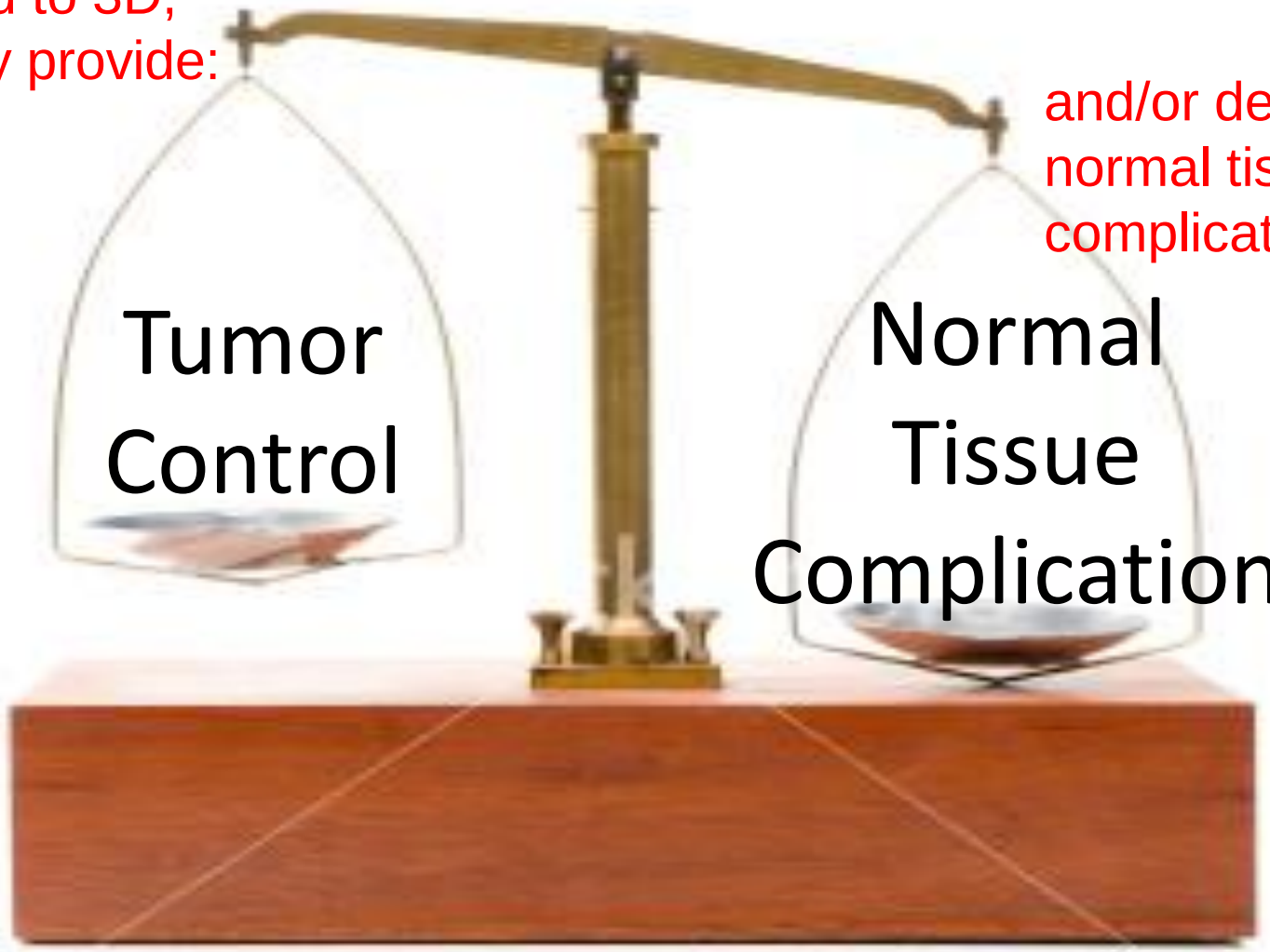


Implications for successful IMRT Treatment Planning: Setting Optimization Criteria

Compared to 3D, IMRT may provide:

dose escalation

and/or decreased normal tissue complications



Normal Tissue Tolerances

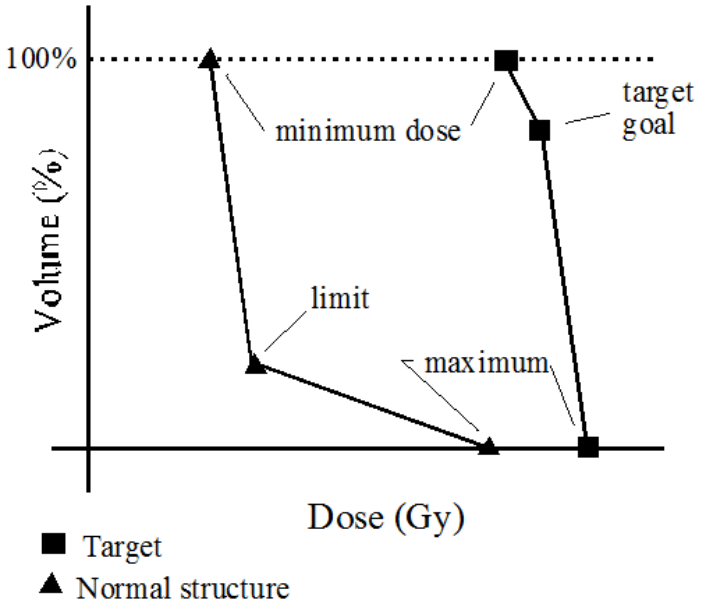
- Derived from various sources:
  - Animal irradiation experiments
  - Analysis of radiotherapy patients
- Quantitative Analyses of Normal Tissue Effects in the Clinic (QUANTEC)
  - Recent compilation of relationship between complication and dose / volume.

Optimization Criteria

- DVH based & mean dose criteria
- Normal tissue constraint(s)
- Fluence smoothing
- Biological optimization criteria

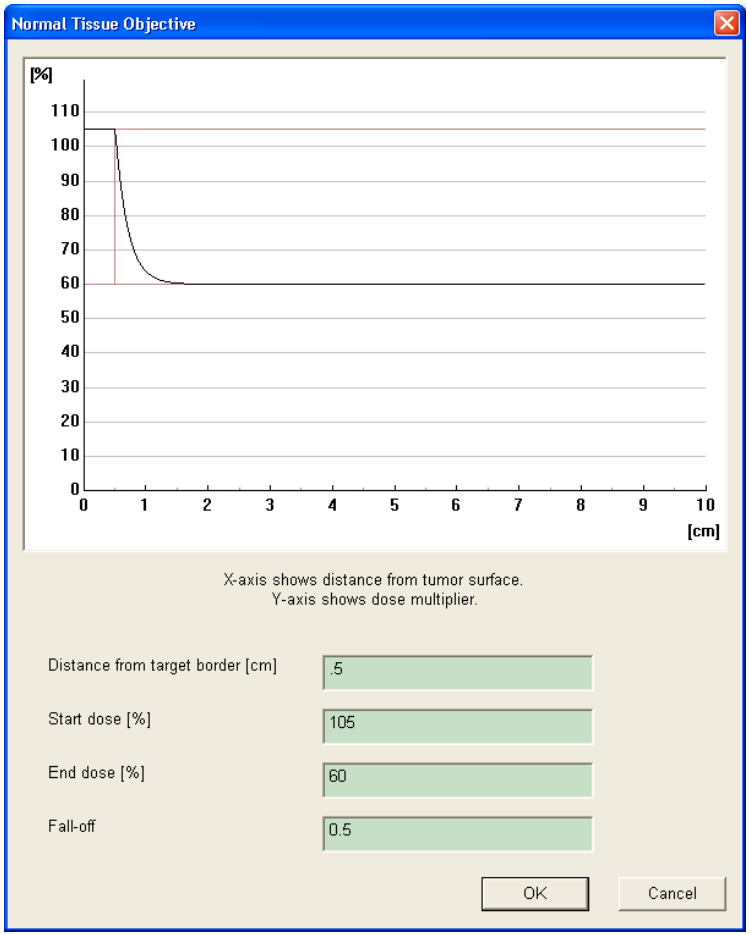
DVH based optimization criteria

- Most common criteria for inverse optimization
- Weightings are relative, no need to overstress



Normal tissue optimization criteria

- Penalize all volume outside the PTV
- Cost is defined as a function of distance from the PTV



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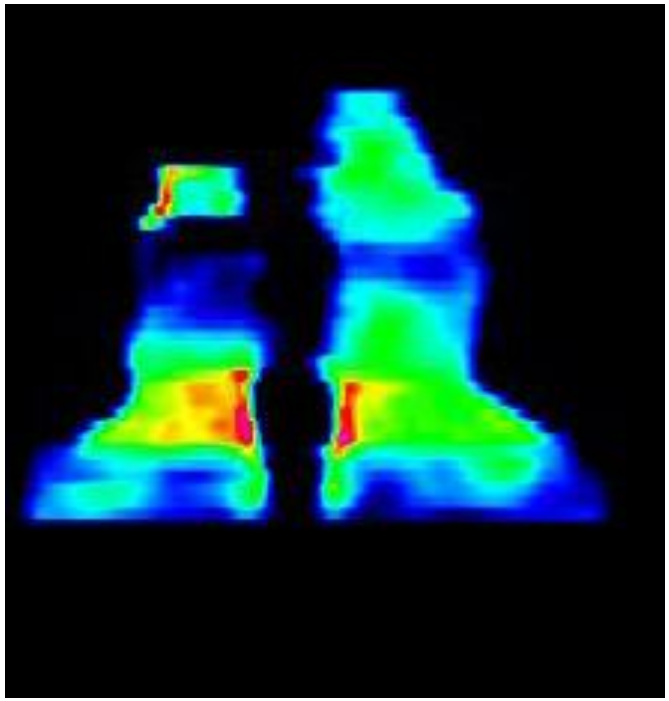
Fluence smoothing

- Smooth fluence =
  - <monitor units
  - <leakage
  - More robust dose distribution (less susceptible to motion)
- Some inverse planning systems allow for criteria to encourage smoother fluence



Biological Optimization Criteria

$$\mathrm{EUD} = \left(\sum_i v_i D_i^a \right)^{1/a}.$$

Phys. Med. Biol. **51** (2006) 2567–2583

Int. J. Radiation Oncology Biol. Phys., Vol. 49, No. 2, pp. 327–337, 2001

Medical Physics, Vol. 36, No. 5, May 2009

Medical Physics, Vol. 39, No. 3, March 2012

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Biological Optimization Criteria

Medical Physics, Vol. 36, No. 5, May 2009

TABLE I. Biological models used for treatment plan optimization in CMS MONACO.

Structure type	Name	Parameters	Objectives/constraints	Comments
Target	Poisson statistics cell kill model	Cell sensitivity ($0.1–1.0\,Gy^{-1}$)	Prescription (1–150 Gy)	Mandatory cost function for targets; no penalty for hot spots
OAR	Serial complication model	Power law exponent (1–20)	Equivalent uniform dose (1–150 Gy)	Effective for controlling maximum organ dose
OAR	Parallel complication model	Reference dose (1–100 Gy) Power law exponent (1–4)	Mean organ damage (1–100%)	Effective for controlling mean organ dose

TABLE II. Biological models used for treatment plan optimization in Philips PINNACLE.

Structure type	Name	Parameters	Objectives/constraints (Gy or cGy)	Comments
Target	Min EUD	Volume parameter ($a < 1$)	EUD	Penalizes for too low EUD
Target	Target EUD	Volume parameter ($a < 1$)	EUD	Penalizes for any deviation from the desired EUD
OAR	Max EUD	Volume parameter ($a \geq 1$)	EUD	Penalized for too high EUD; can be used with both serial and parallel structures

Tool	Structure type	Name/description	Parameters/inputs	Comments
NTCP/TCP editor	Target	Empirical TCP model	D_{50}, m	Sigmoid curve represented by the CDF of the normal distribution
	OAR	Lyman-Kutcher model	D_{50}, m, n	Database of model parameters is provided
Biological response panel	Target	Poisson/LQ-based TCP model	D_{50}, γ, α/β	Database of model parameters is provided
	OAR	Källman s-model	D_{50}, γ, α/β, seriality (s)	Database of model parameters is provided
	Multiple targets	Composite TCP	TCP for individual targets	$\mathrm{TCP} = \prod_i \mathrm{TCP}_i$
	Multiple OARs	Composite NTCP	NTCP for individual OARs	$\mathrm{NTCP} = 1 - \prod_i (1 - \mathrm{NTCP}_i)$
	Targets and OARs	Probability of complication-free tumor control	Composite TCP, composite NTCP	$P_+ = \max(\mathrm{TCP} - \mathrm{NTCP}, 0)$

Biological Optimization Criteria

Medical Physics, Vol. 36, No. 5, May 2009

TABLE IV. Biological models used for treatment plan optimization in Varian ECLIPSE.

Structure type	Name	Parameters	Objectives/constraints	Comments
Target	Min EUD	Volume parameter (a)	EUD (Gy or cGy)	Penalizes for too low values. Cannot be weighted. Listed under physical functions
Target or OAR	Max EUD	Volume parameter (a)	EUD (Gy or cGy)	Penalizes for high values. Cannot be weighted. Listed under physical functions
Target	TCP Poisson-LQ	D_{50}, γ, α/β, *seriality(s)*, $T_{1/2}$ *for short vs long repair time, % with long repair time, repopulation times: Tpot and Tstart*	TCP	Penalizes for small values. Can be weighted
OAR	NTCP Poisson-LQ	D_{50}, γ, α/β, *seriality(s)*, $T_{1/2}$ *for short vs long repair time, % with long repair time*	NTCP	Penalizes for large values. Can be weighted
OAR	NTCP Lyman	D_{50}, m, n,α/β, $T_{1/2}$ *for short vs long repair time, % with long repair time*	NTCP	Penalizes for large values of NTCP. Can be weighted

Tool	Structure type	Name	Parameters	Comments
Biological evaluation	Target	TCP Poisson-LQ	D_{50}, γ, α/β, *seriality(s)*, $T_{1/2}$ *for short vs long repair time, % with long repair time, repopulation times: Tpot and Tstart*	User selectable parameters or from database of model parameters
	OAR	NTCP Poisson-LQ	D_{50}, γ, α/β, *seriality(s)*, $T_{1/2}$ *for short vs long repair time, % with long repair time*	User selectable parameters or from database of model parameters
	OAR	NTCP Lyman	D_{50}, m, n,α/β, $T_{1/2}$ *for short vslong repair time, % with long repair time*	User selectable parameters or from database of model parameters

Biological Optimization Criteria

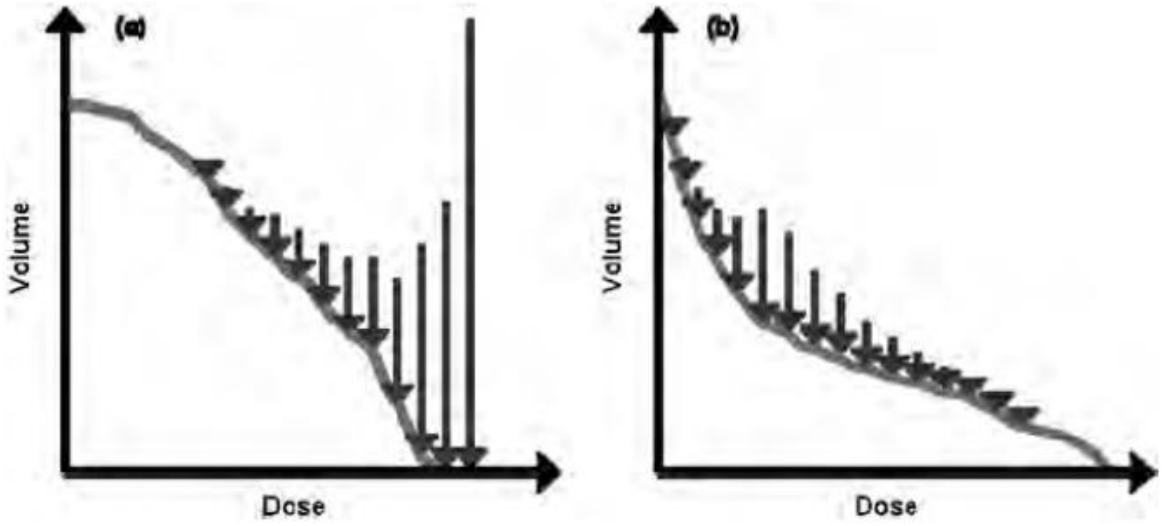
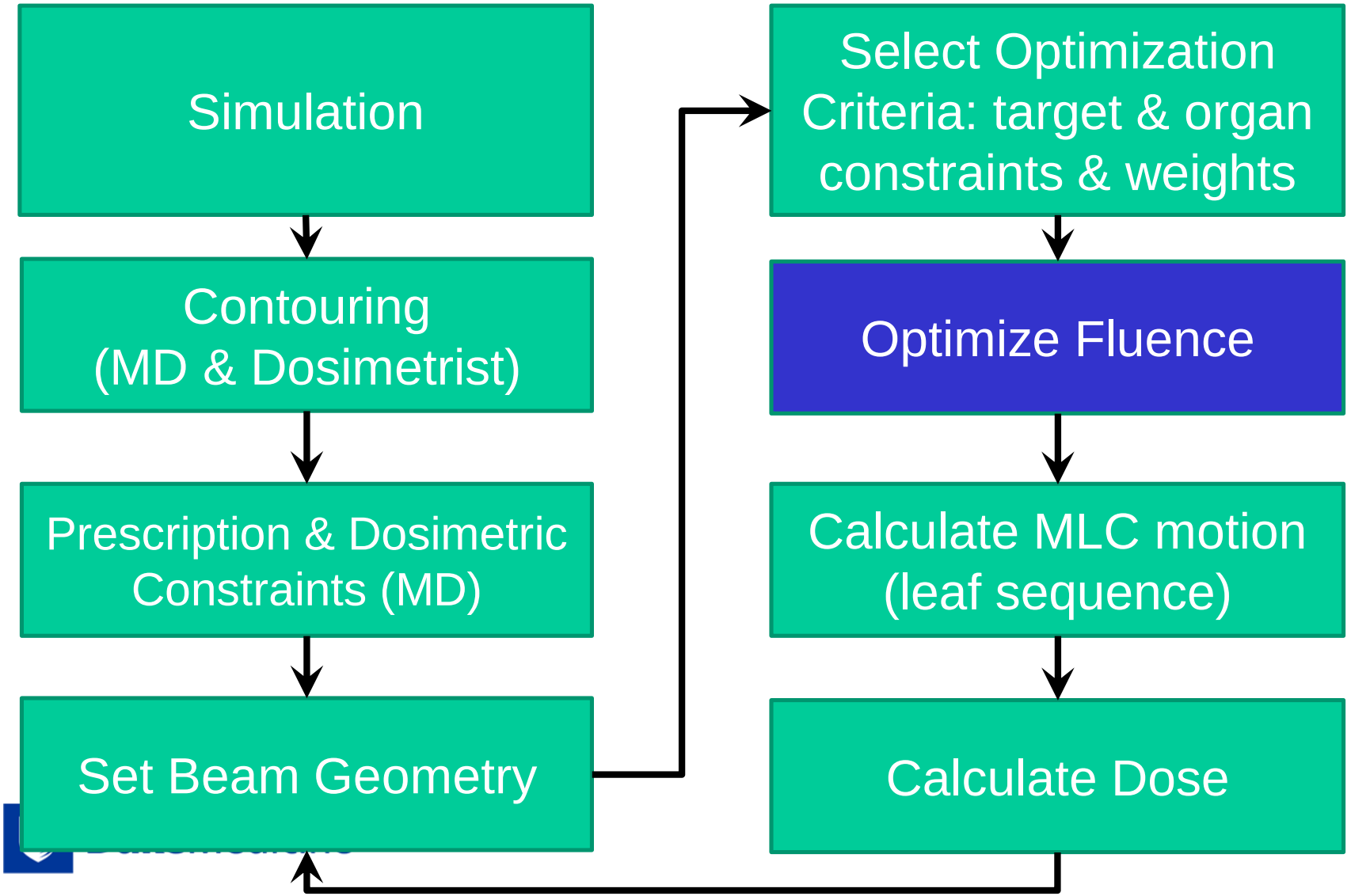


FIG. 1. Weights of "virtual" DV objectives representing the same volume effect as a serial-type cost function (a) or a parallel-type cost function (b).

Biological Constraints: Summary

- Controls entire DVH rather than a single point
  - Multiple OAR DV constraints may be replaced with a single EUD constraint with appropriate parameters
- Biological constraints for target control cold spots-> equivalent to DVH based minimum dose constraint
- Biological constraints do not control target maximum dose- large dose heterogeneities for standard IMRT have no track record (except SRS, brachy, & SIB) and should be avoided
- DVH & isodose lines should still be used for plan analysis
- EUD generic numbers:
  - Parallel organ: a=1
  - Serial organ: a=8

IMRT Treatment Planning Process

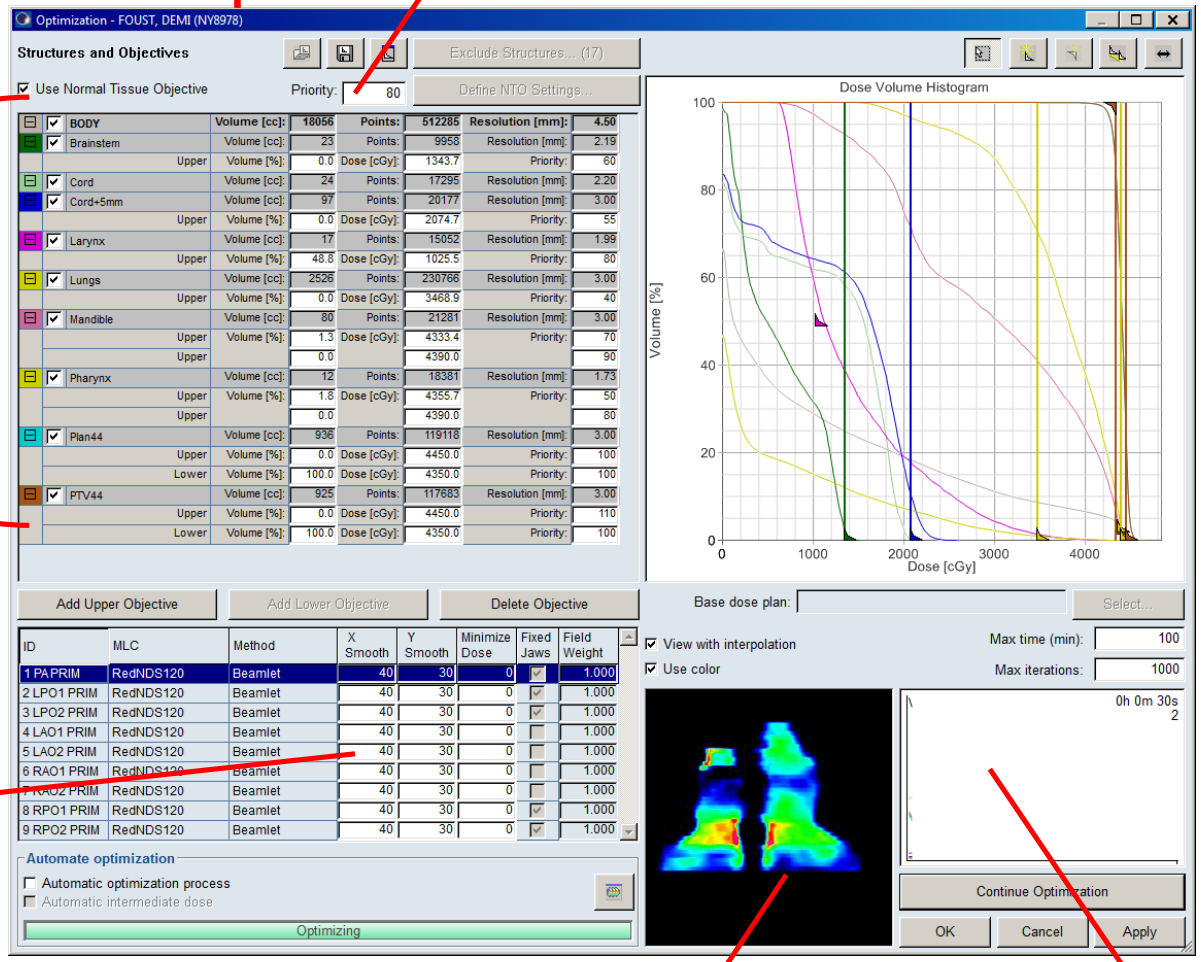


Inverse Planning: Optimization (Eclipse)

normal tissue

optimization constraint

dosimetric criteria



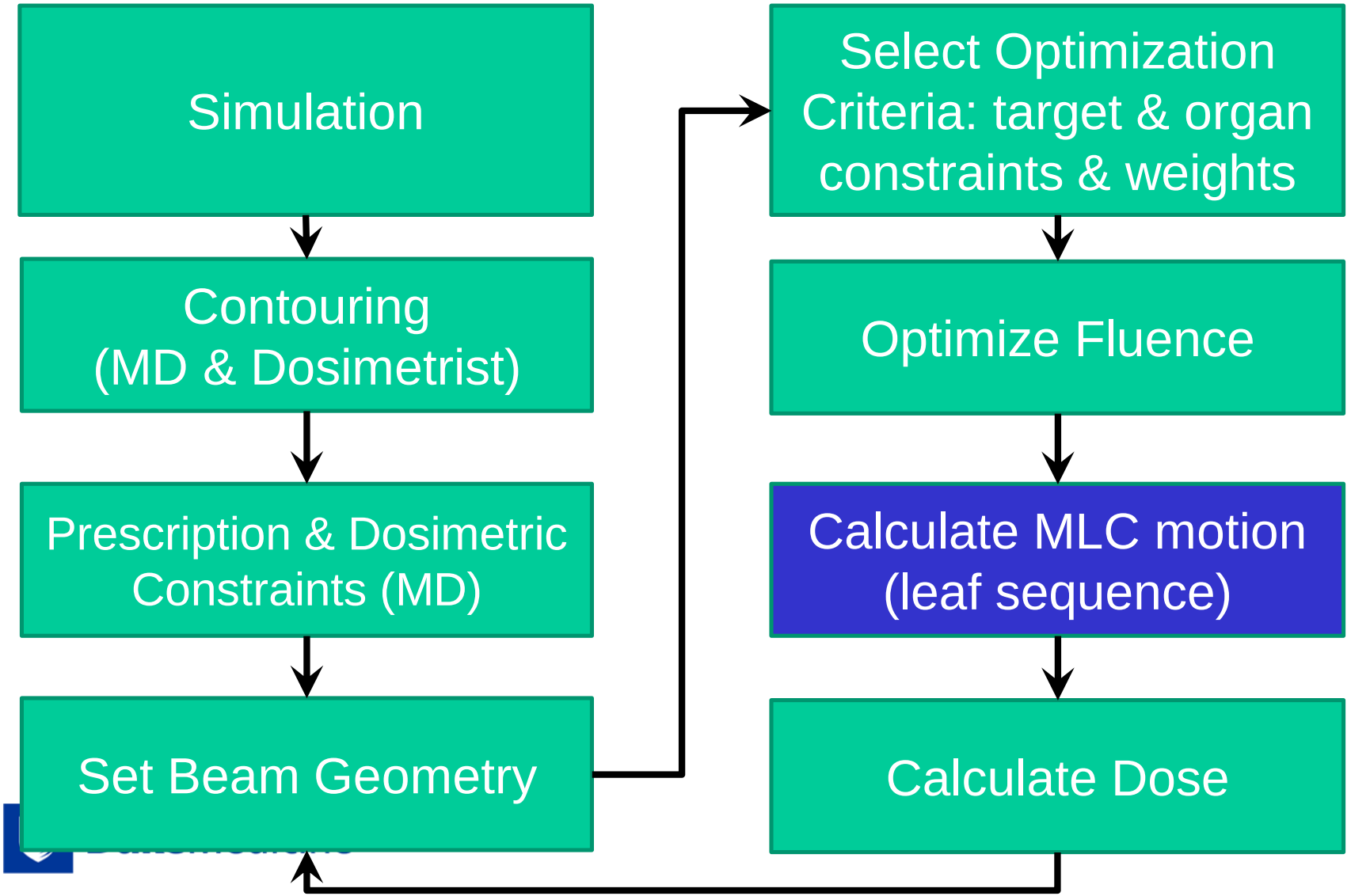
dosimetric criteria & dose volume histogram

penalty to smooth fluence

beam fluence

objective function

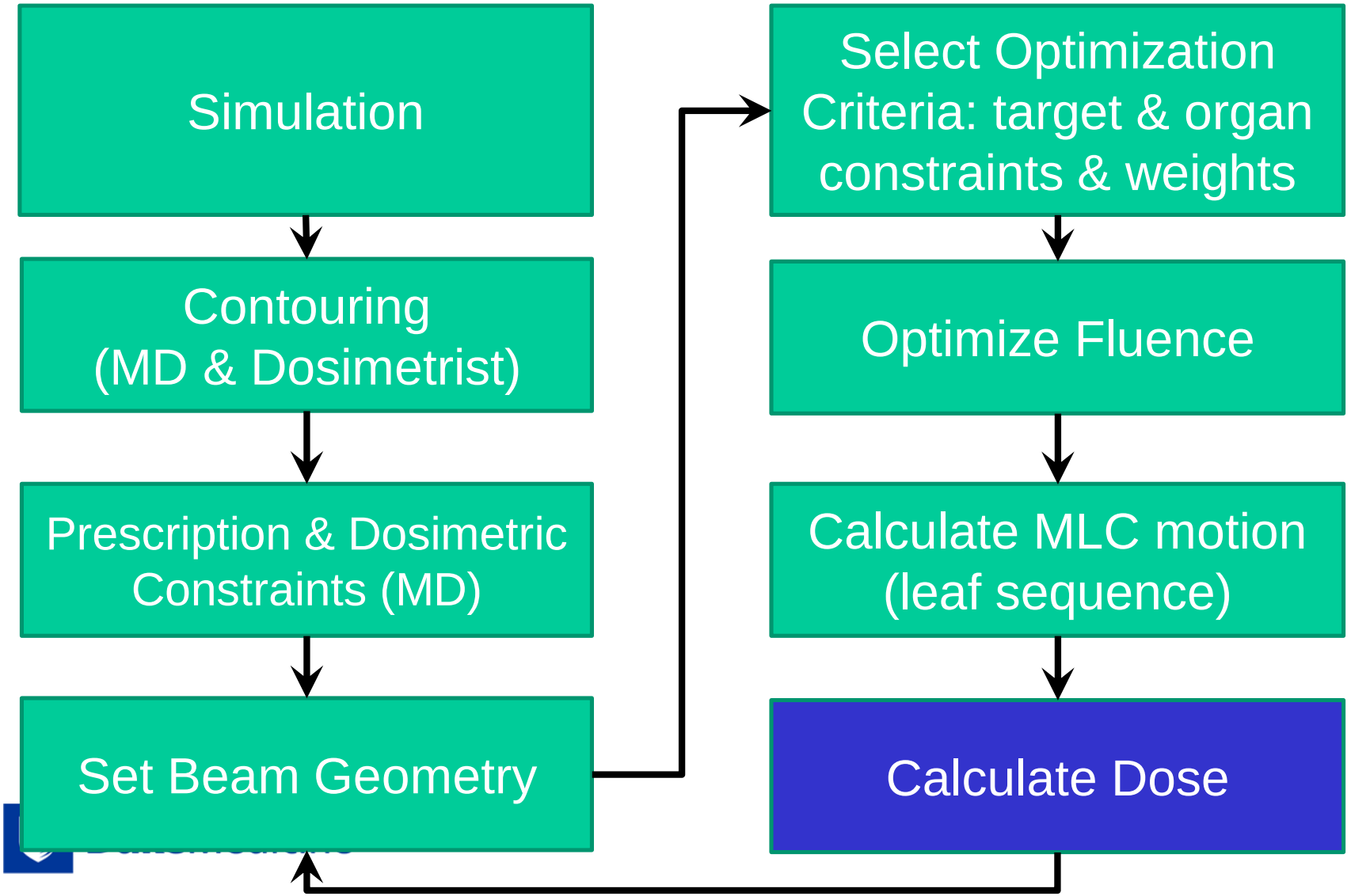
IMRT Treatment Planning Process



Implications for successful IMRT Treatment Planning: Calculating the leaf sequence

- When fluence is optimized, some differences may exist between ideal and actual fluence
- More segments-> better agreement between DVH during optimization & final dose calculation

IMRT Treatment Planning Process



Dose Calculation

- Dose can be modified further by:
  - Dose renormalization
  - Fluence painting
  - Re-optimization
- Make sure dose grid is appropriate for the amount of dose falloff that is expected

Example Case: Head and Neck

Planned Treatment Volume: Primary Volume vs. Nodal Extension

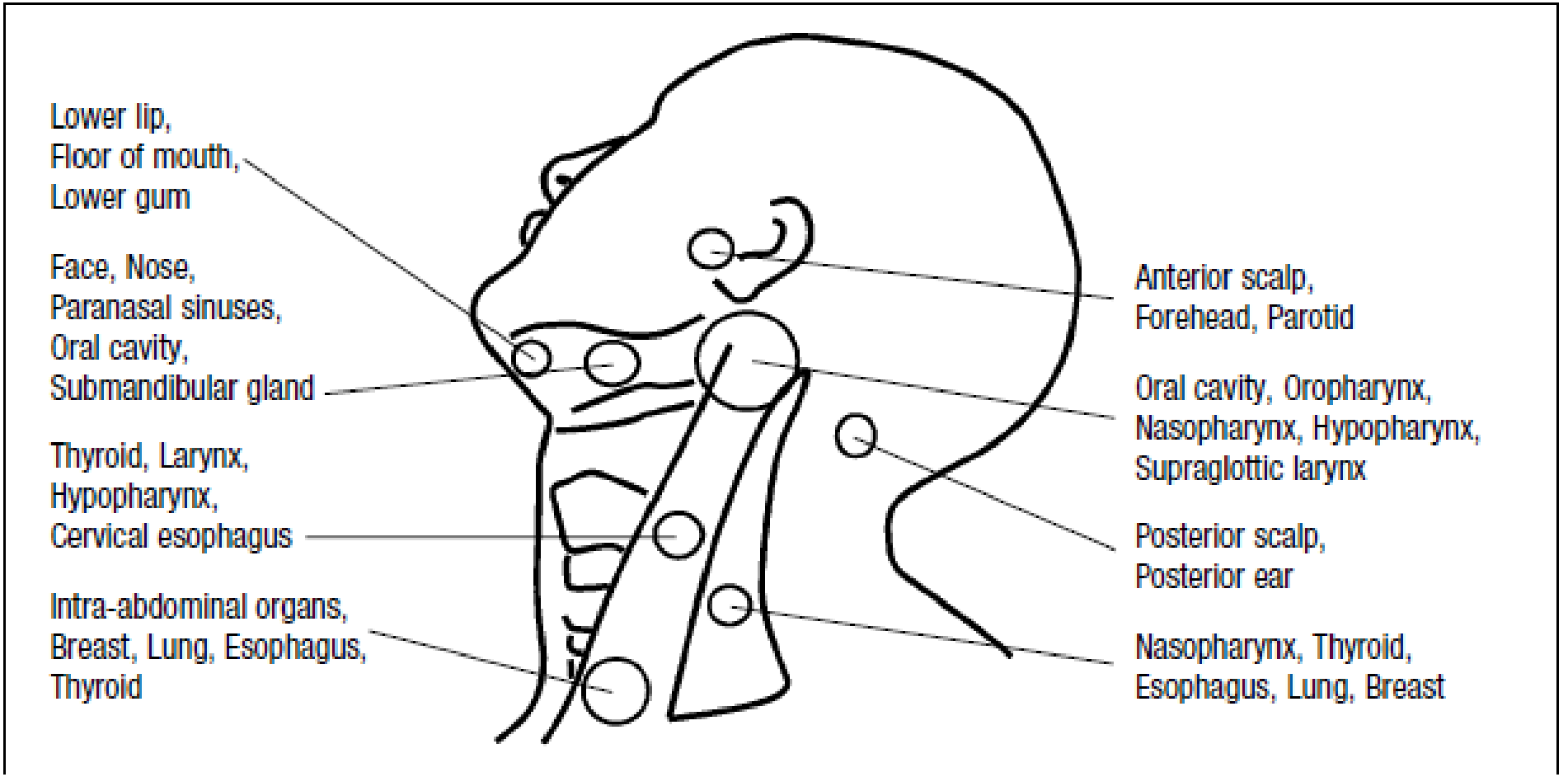
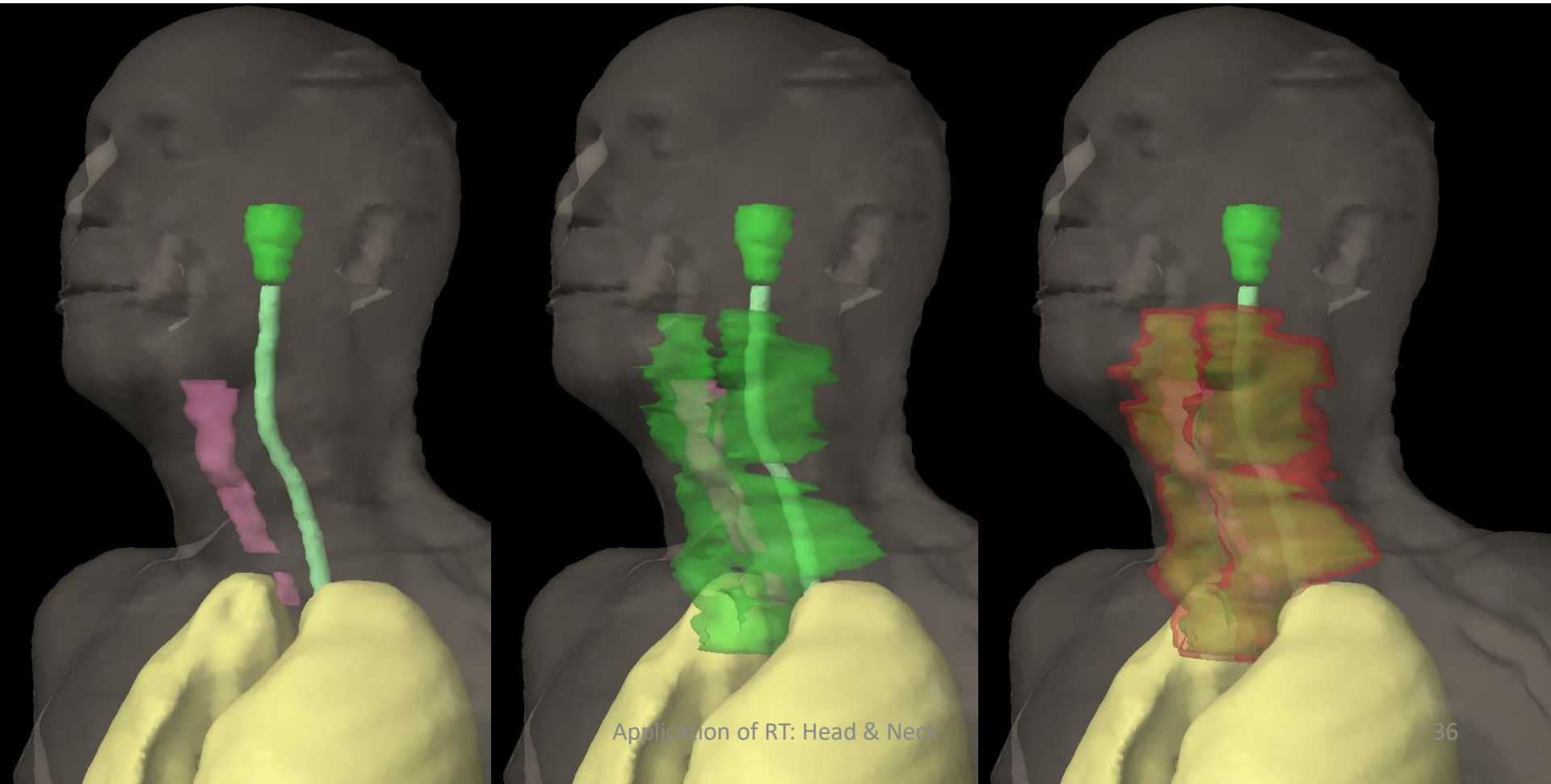
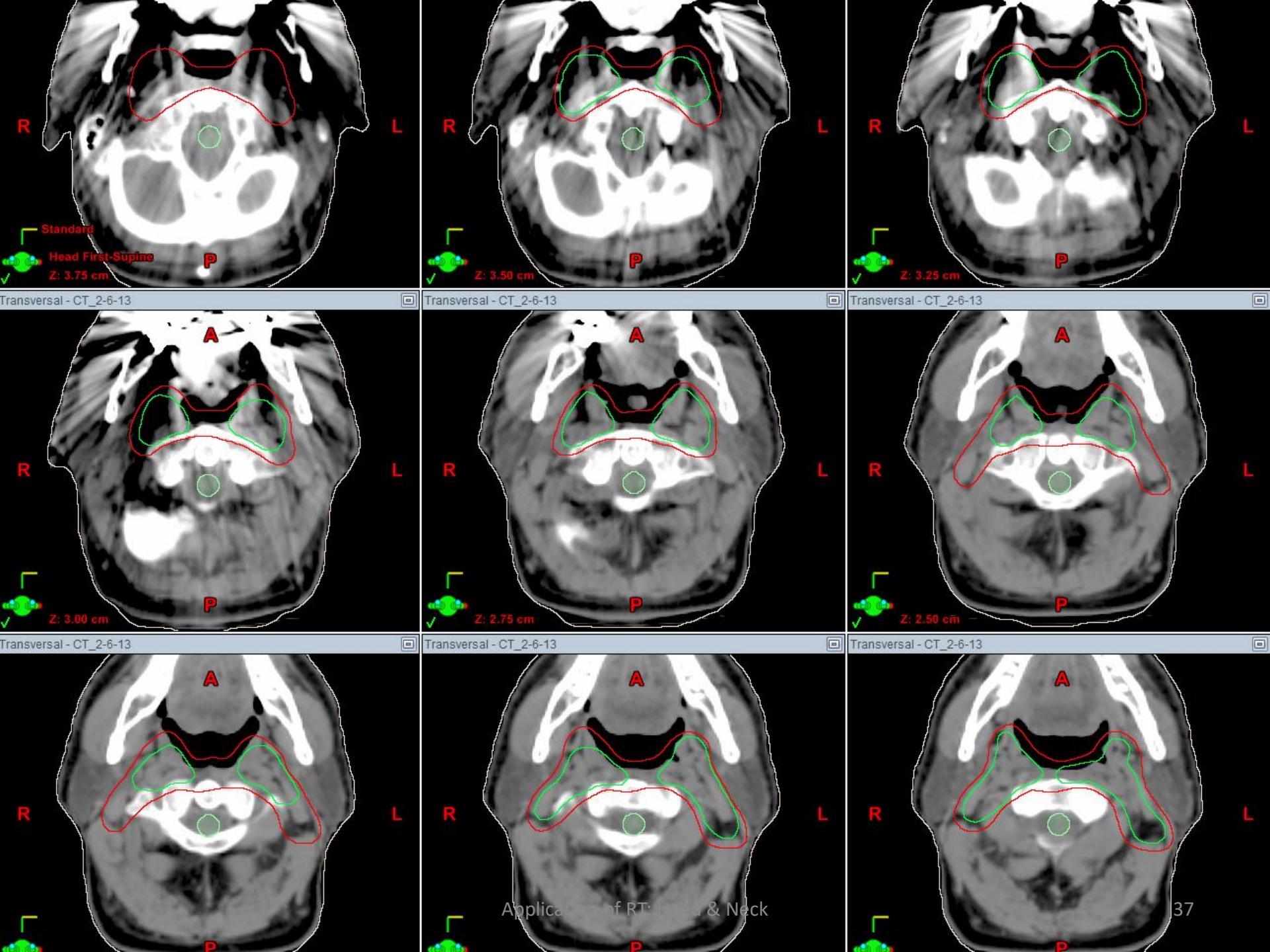
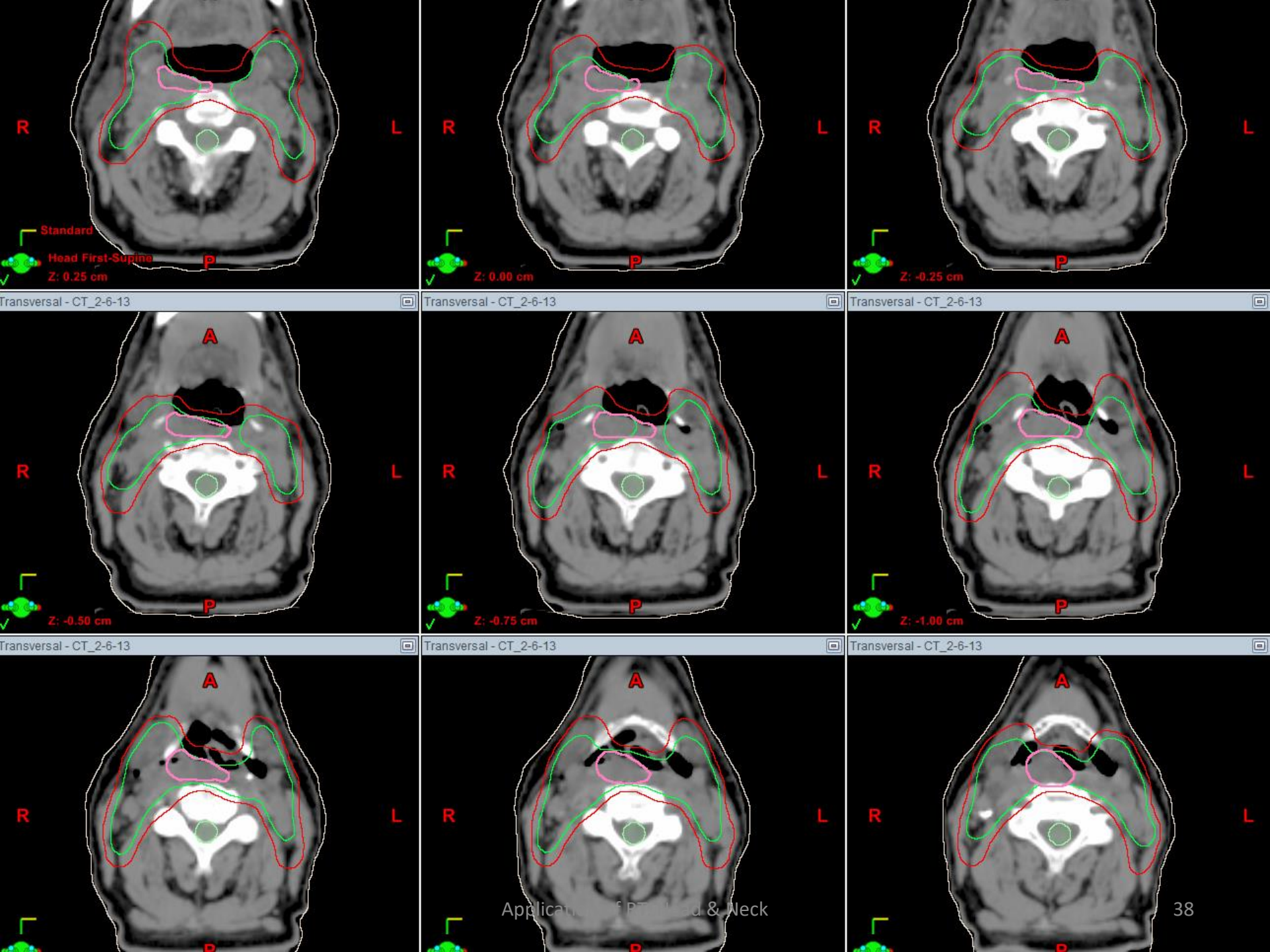


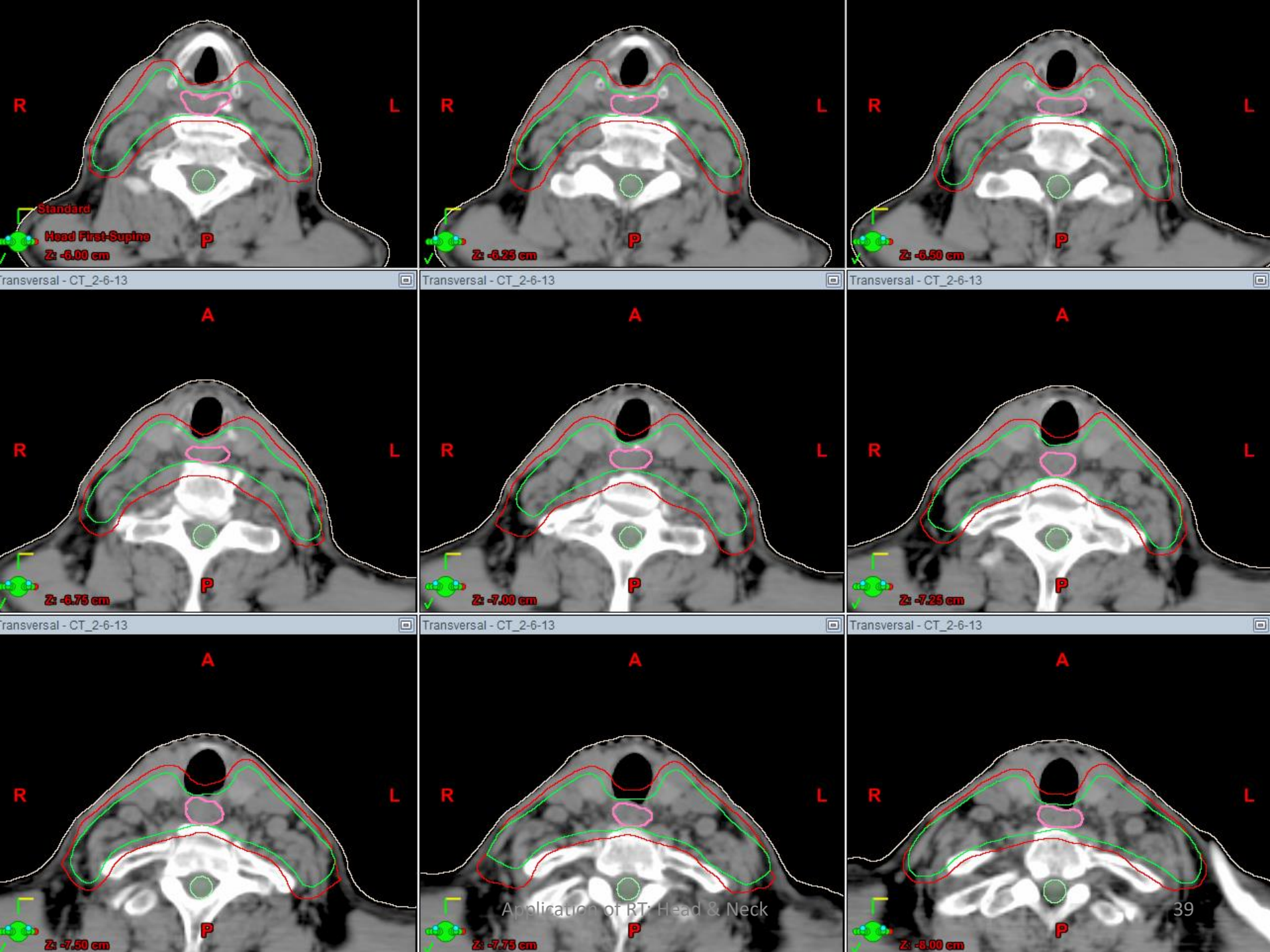
Fig. 6. Likely sites of metastasis from various sites of the head and neck.

Example 1: GTV-> CTV->PTV

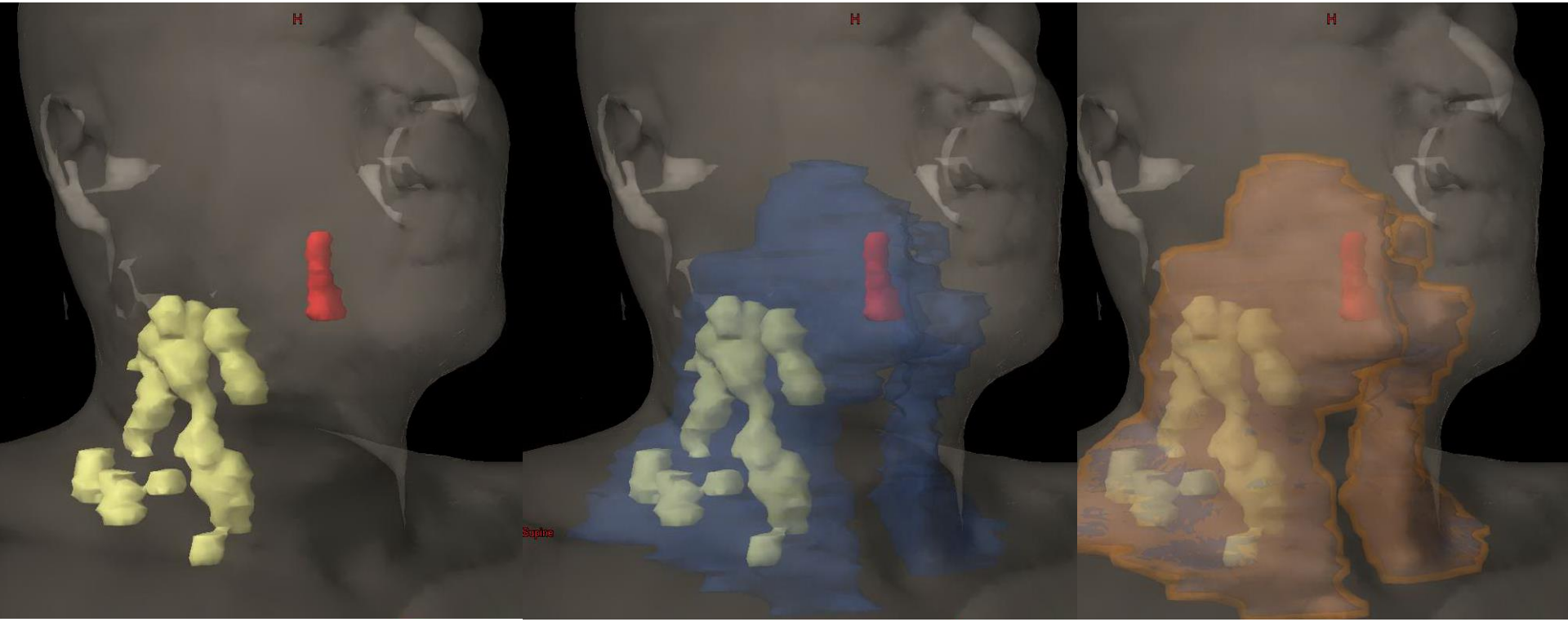


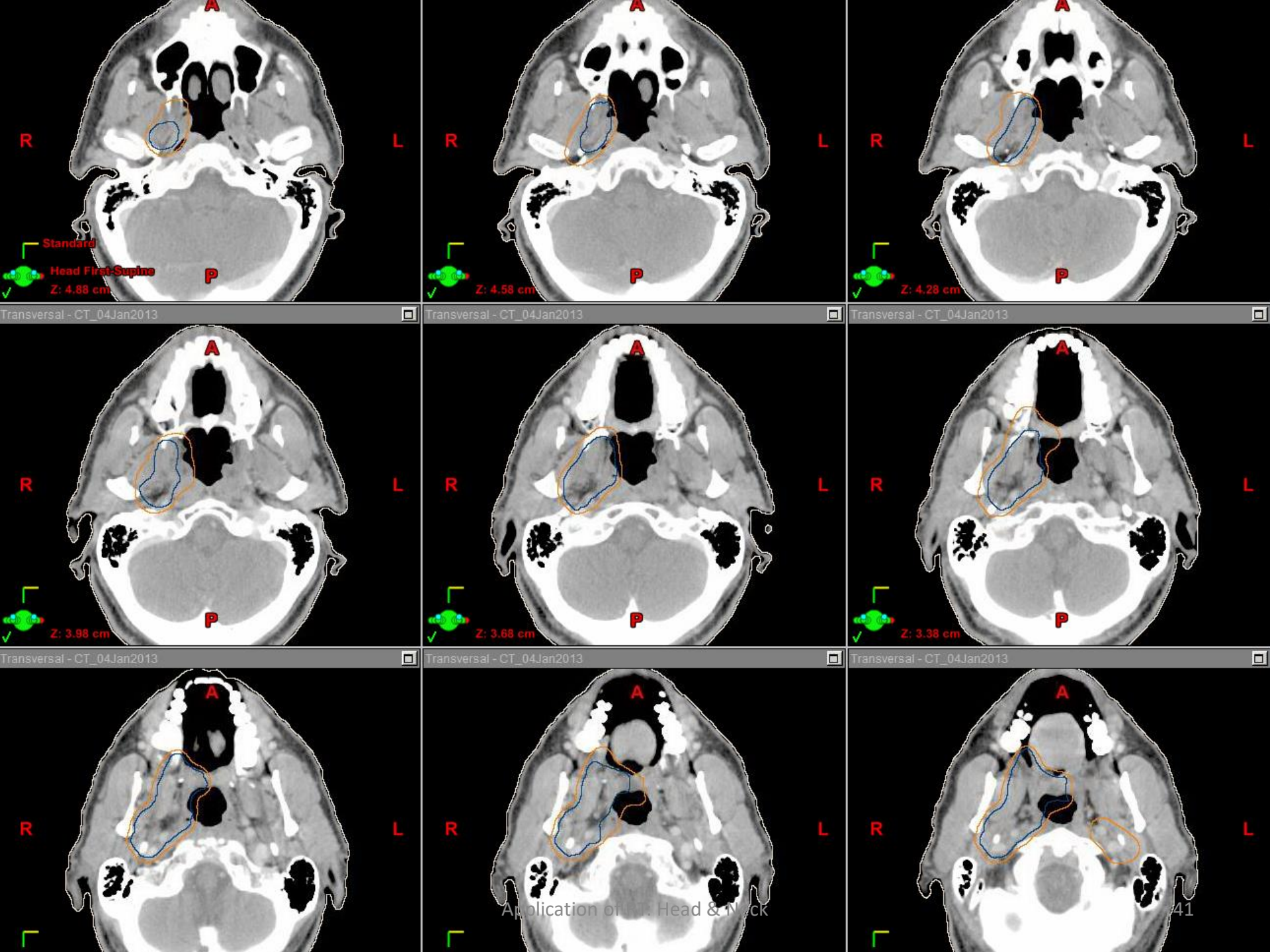

Standard
Head First-Supine
Z: 3.75 cm
Z: 3.50 cm
Z: 3.25 cm
Transversal - CT_2-6-13
Z: 3.00 cm
Z: 2.75 cm
Z: 2.50 cm
R
L
A
P

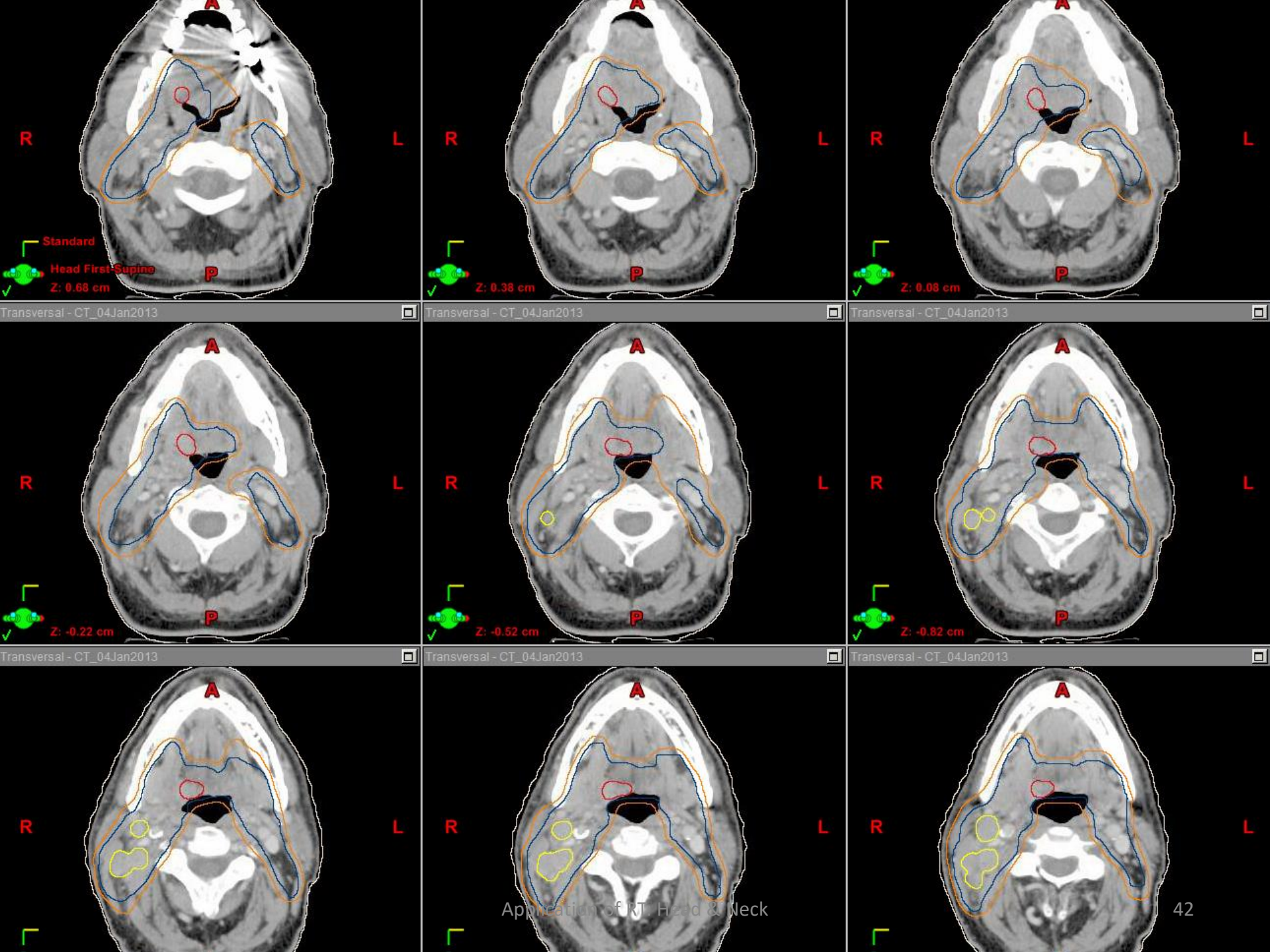

R
L
P
A
Standard
Head First-Supine
Z: 0.25 cm
Z: 0.00 cm
Z: -0.25 cm
Z: -0.50 cm
Z: -0.75 cm
Z: -1.00 cm
Transversal - CT_2-6-13

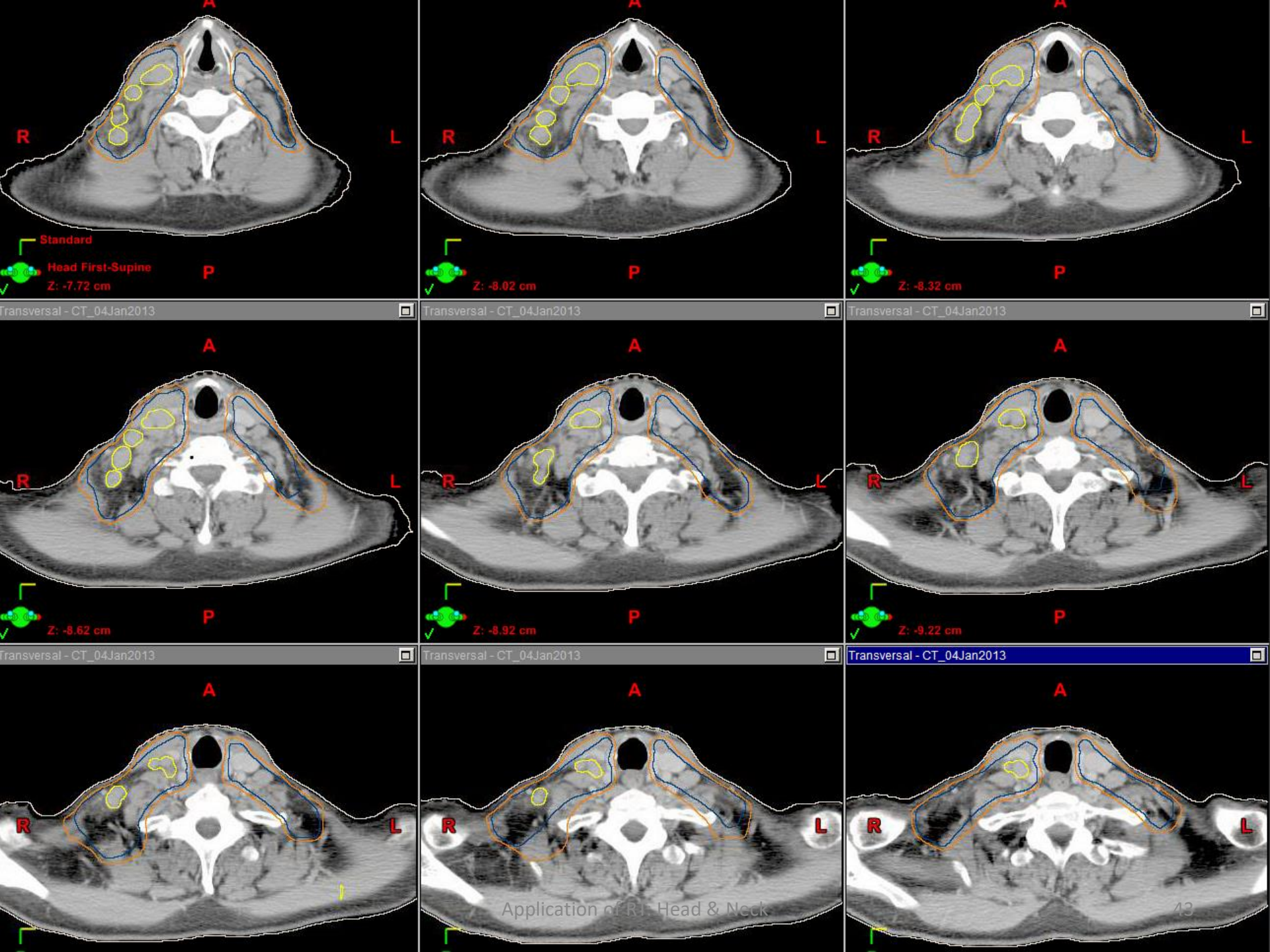

R
L
A
P
Standard
Head First-Supine
Z: -6.00 cm
Z: -6.25 cm
Z: -6.50 cm
Z: -6.75 cm
Z: -7.00 cm
Z: -7.25 cm
Z: -7.50 cm
Z: -7.75 cm
Z: -8.00 cm
Transversal - CT_2-6-13

Example: GTV (Primary & Nodes)->CTV->PTV

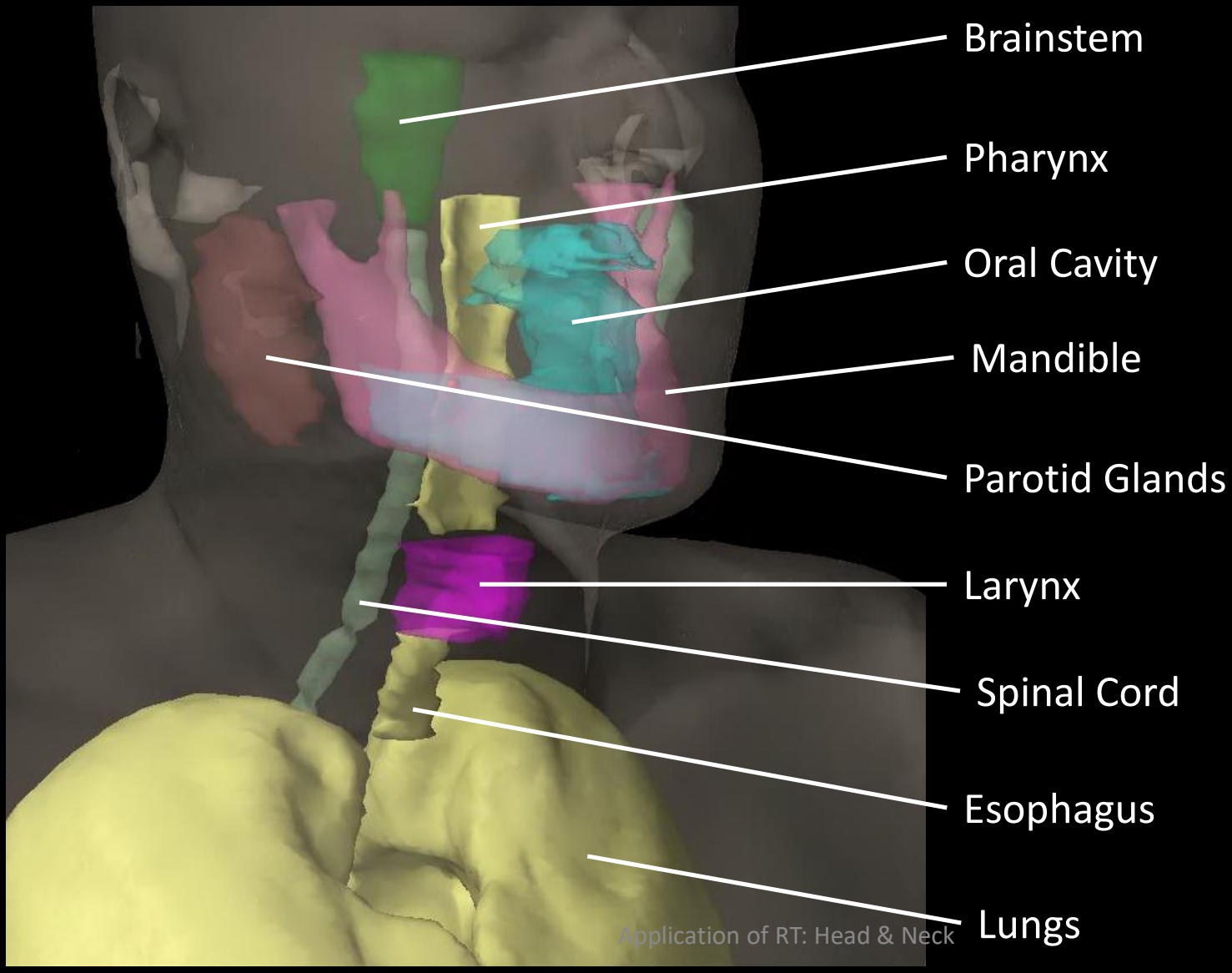



A
R
L
P
Standard
Head First-Supine
Z: 4.88 cm
Z: 4.58 cm
Z: 4.28 cm
Z: 3.98 cm
Z: 3.68 cm
Z: 3.38 cm
Transversal - CT_04Jan2013


A
R
L
P
Standard
Head First-Supine
Z: 0.68 cm
Z: 0.38 cm
Z: 0.08 cm
Transversal - CT_04Jan2013
Z: -0.22 cm
Z: -0.52 cm
Z: -0.82 cm


A
R
L
P
Standard
Head First-Supine
Z: -7.72 cm
Z: -8.02 cm
Z: -8.32 cm
Transversal - CT_04Jan2013
Z: -8.62 cm
Z: -8.92 cm
Z: -9.22 cm

Nearby Normal Tissues



Normal Tissue Tolerances

Larynx:

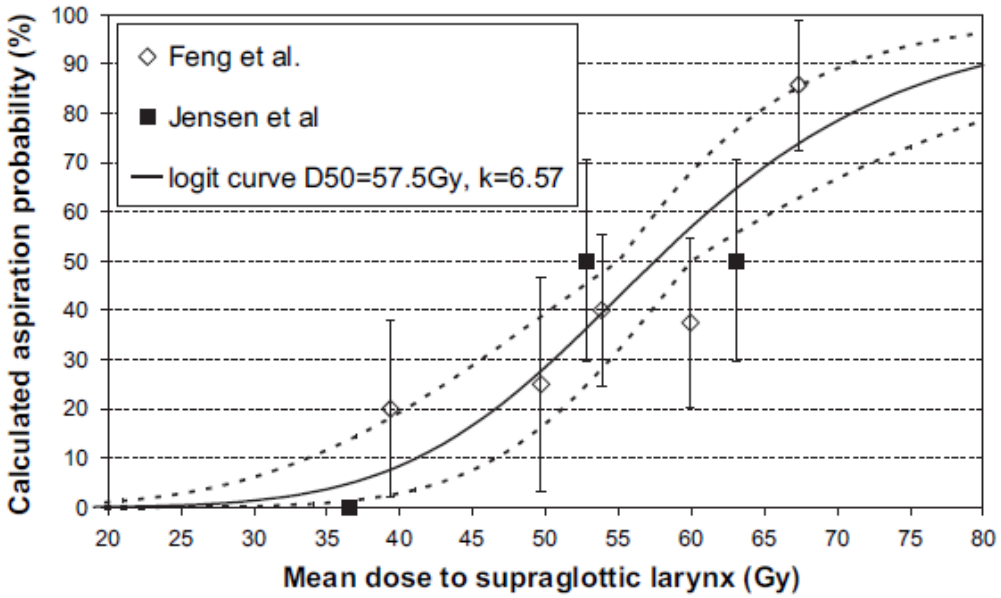


Fig. 1. Dose–effect relationship for dysphagia according to data from Feng *et al.* (14) and Jensen *et al.* (16). Solid line fit to combined data; dotted line fit to 68% confidence area for normal tissue complication probability-logit curve.

Parotids:

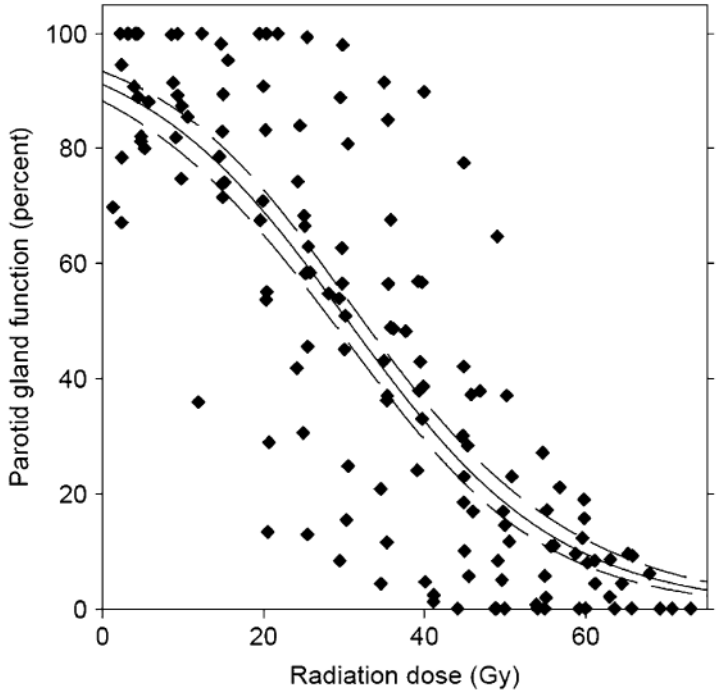
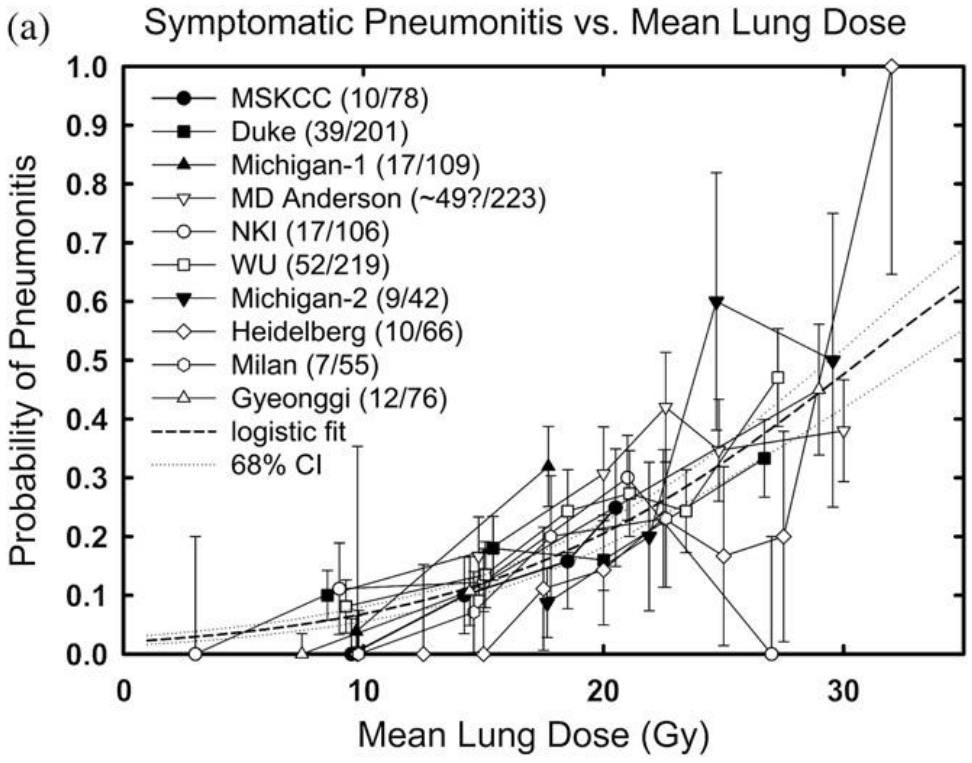


Fig. 4. Population-based dose vs. local function response (salivary function at rest) from imaging study by Buus *et al.* (2). Local functional decline in metabolic clearance of parotid salivary glands vs. local dose, according to voxel-by-voxel estimated time-activity curves of intravenously injected C11-methionine. Data points from 12 patients shown, along with best-fit curve and 95% confidence intervals of curve fit. Individual gland curves reported by Buus *et al.* (2) deviated significantly from this population average curve (reproduced from Buus *et al.* [2], used with permission.) This population curve demonstrated functional decline in salivary function even at low doses.

Normal Tissue Tolerances

Lung:



Spinal Cord:

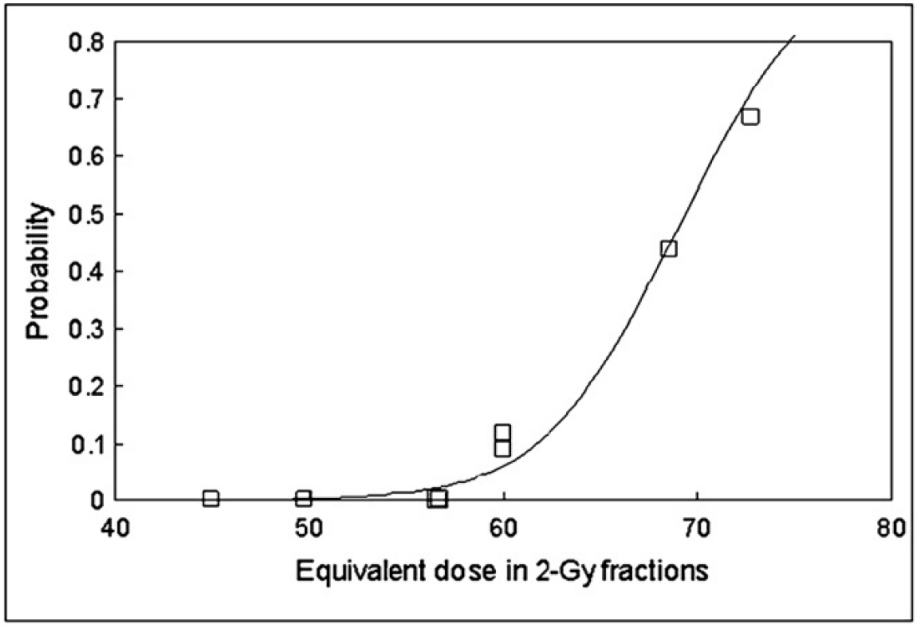
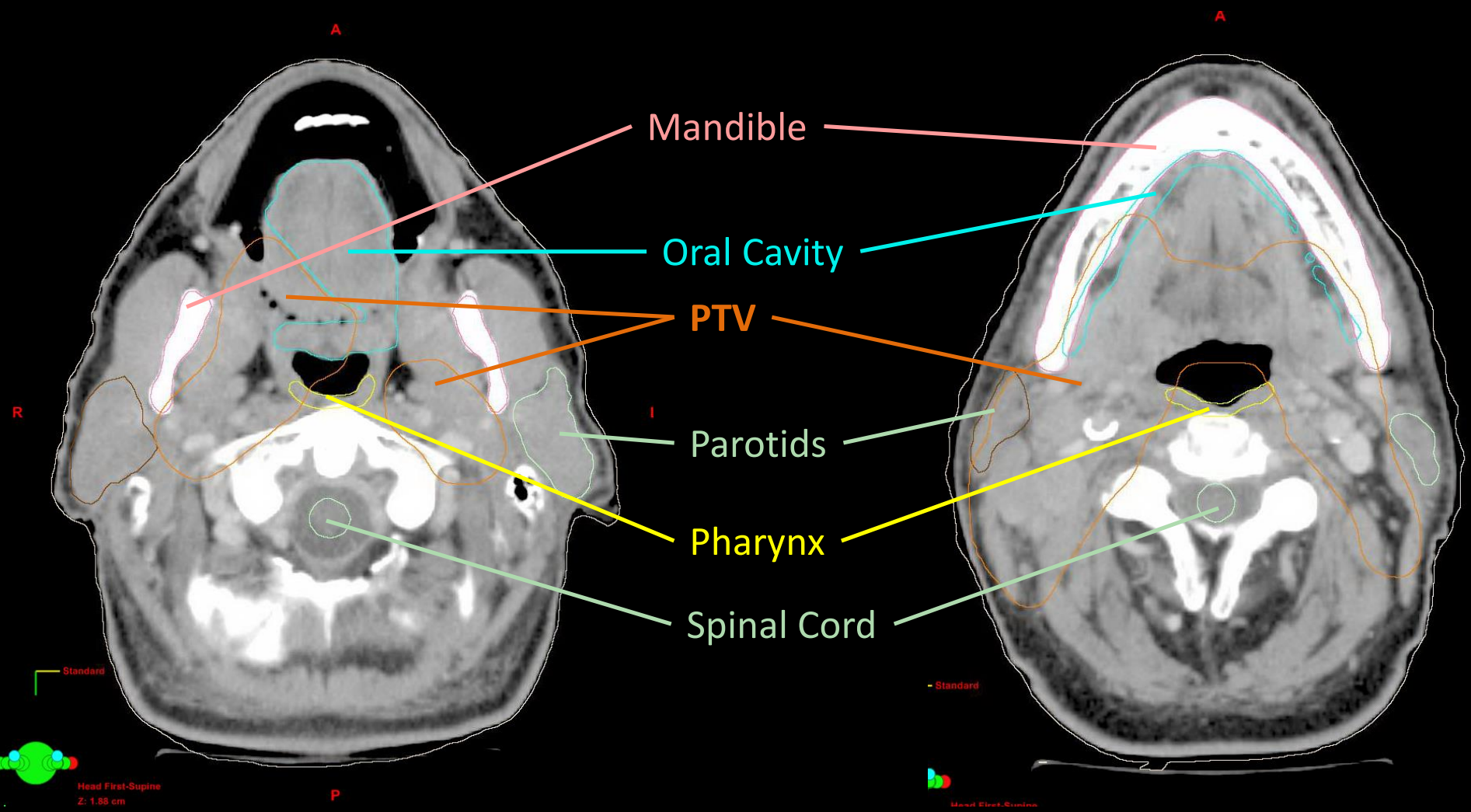
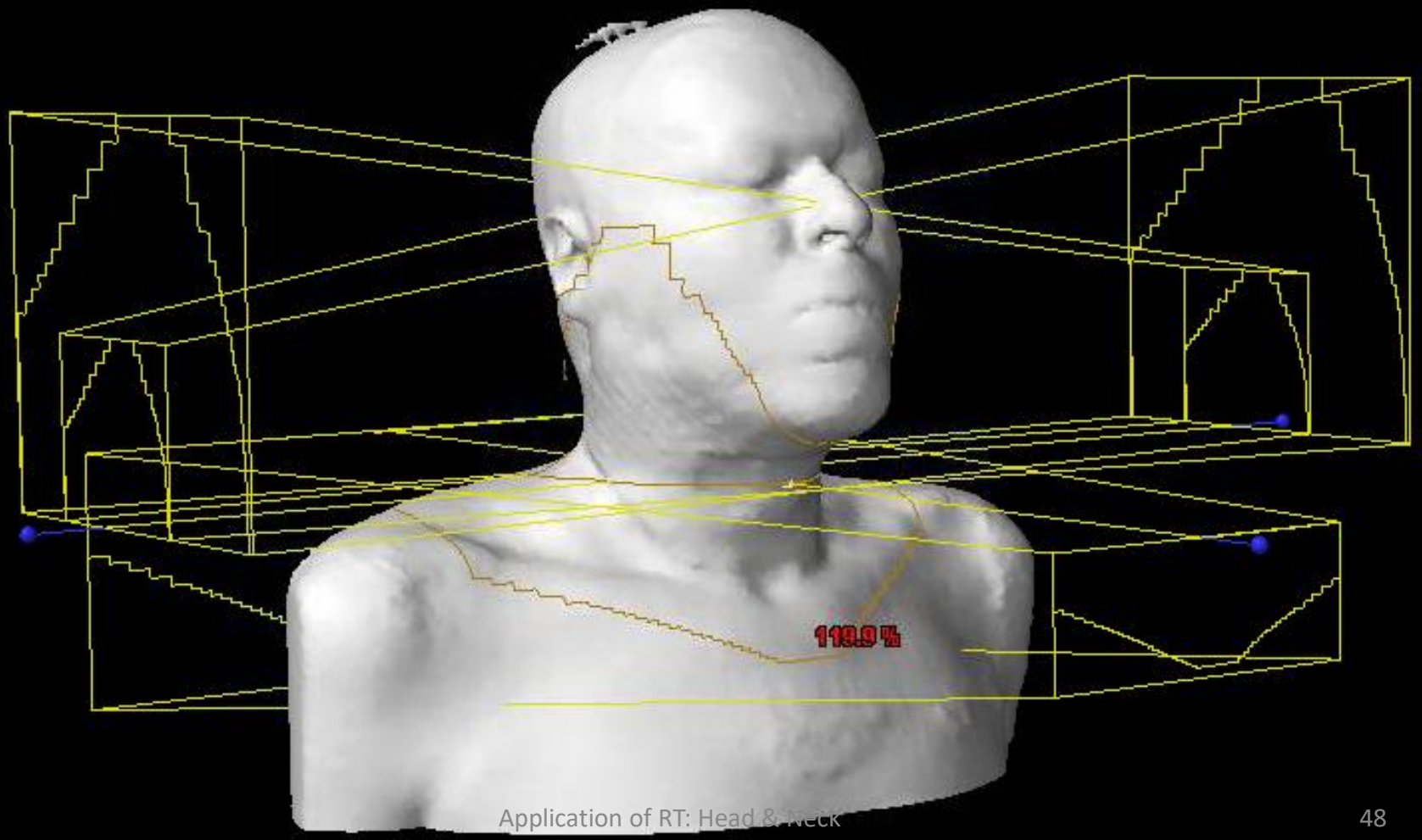


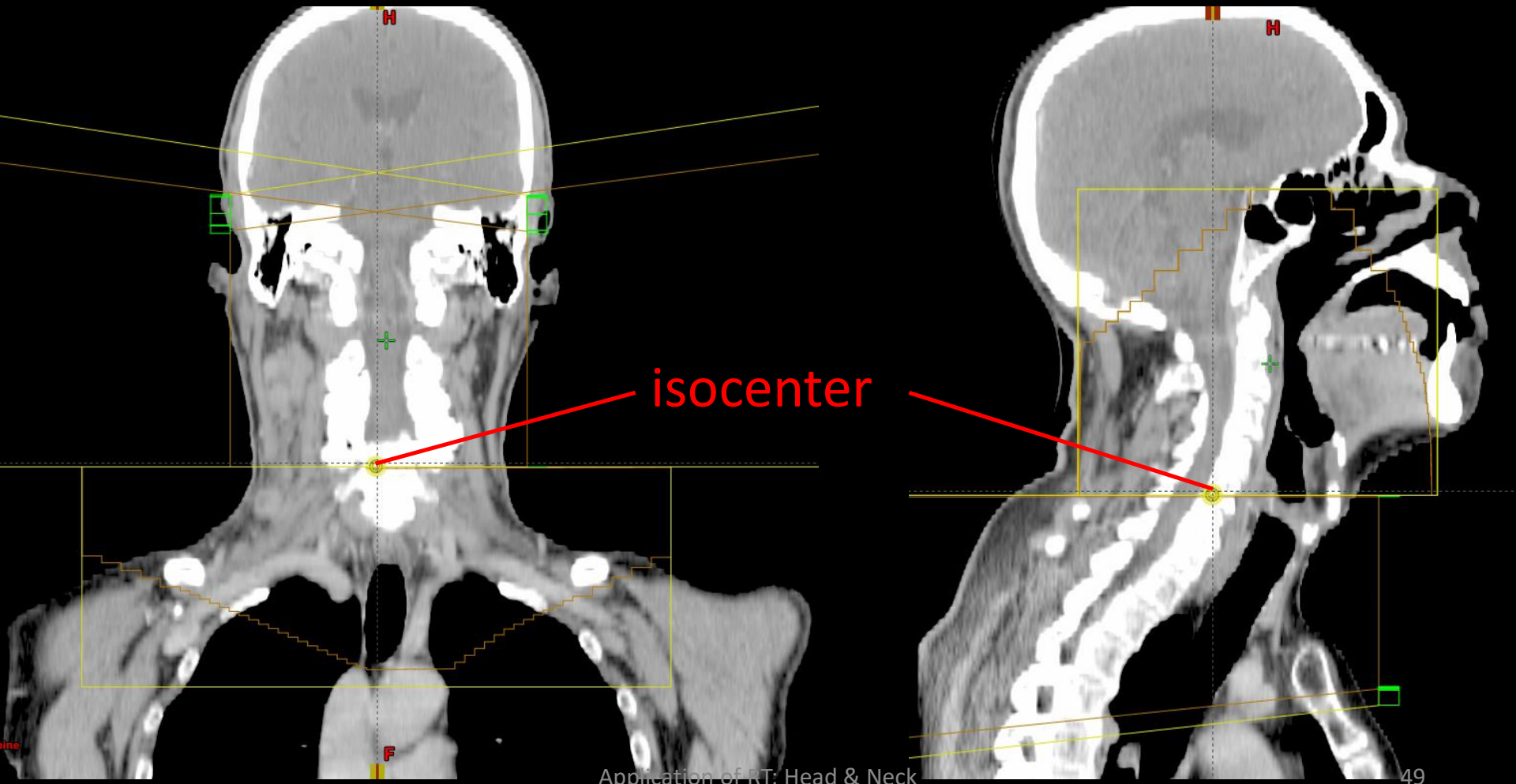
Fig. 1. The dose–response function for the myelopathy of the cervical spinal cord and data points (□) derived from Table 1. The probability of myelopathy was calculated from the data in Table 1, adjusted for estimated overall survival per (18).


Mandible
Oral Cavity
PTV
Parotids
Pharynx
Spinal Cord
A
R
I
P
Standard
Head First-Supine
Z: 1.88 cm
A
Standard

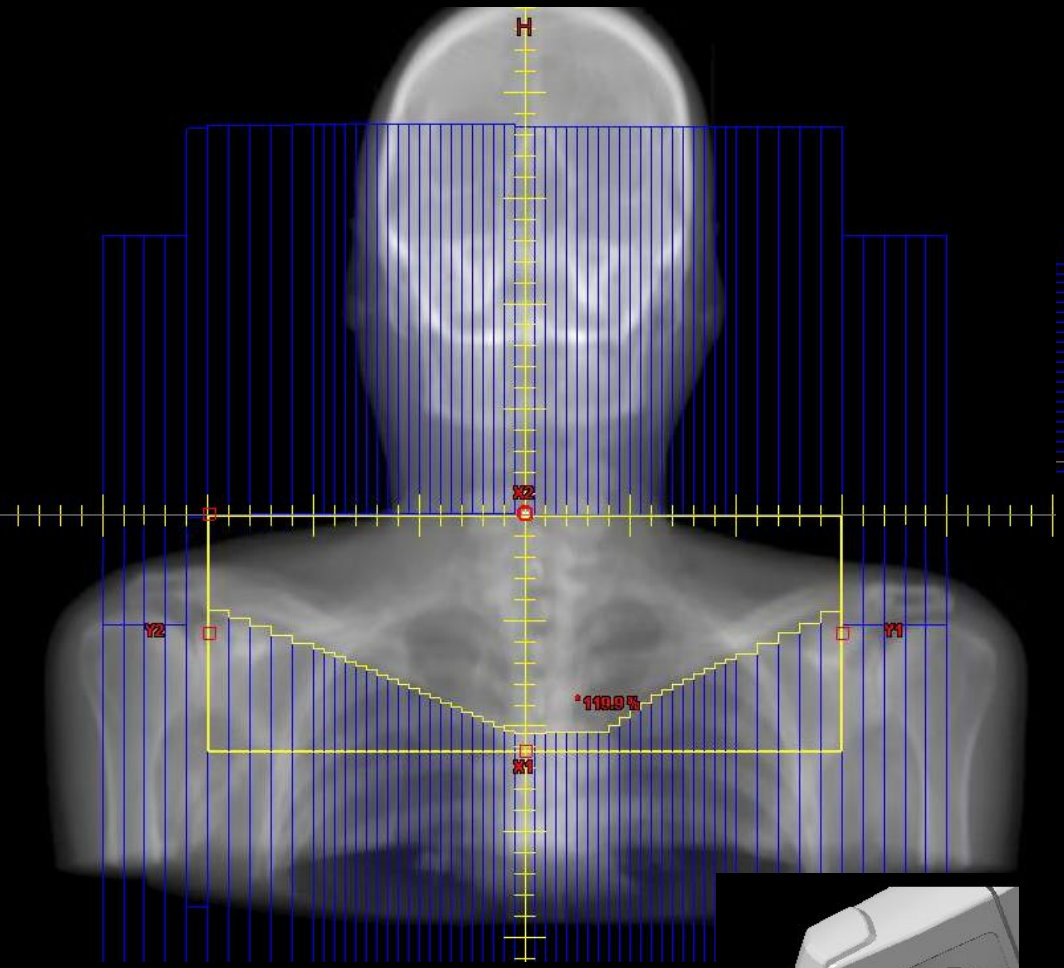
Historical (3D) Treatment Technique

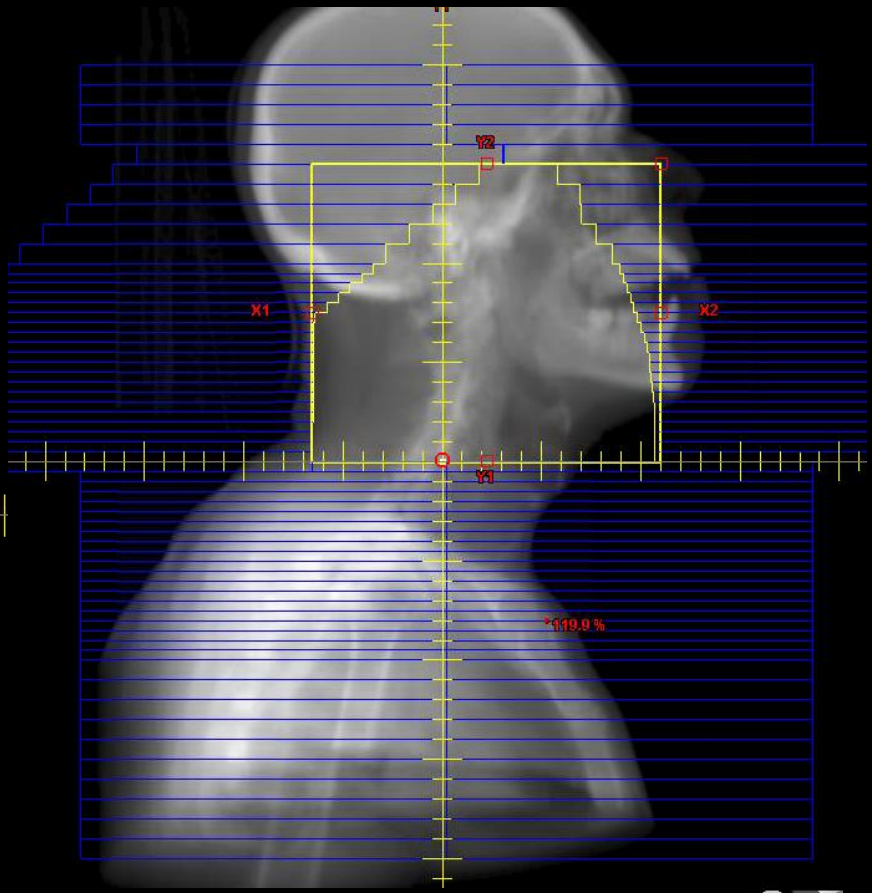


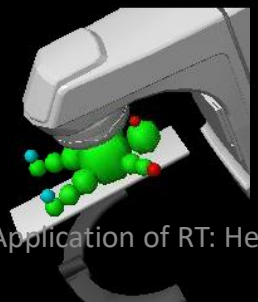
Historical (3D) Treatment Technique: Isocenter Placement

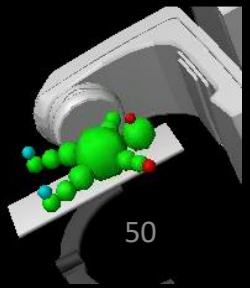


Historical (3D) Treatment Technique

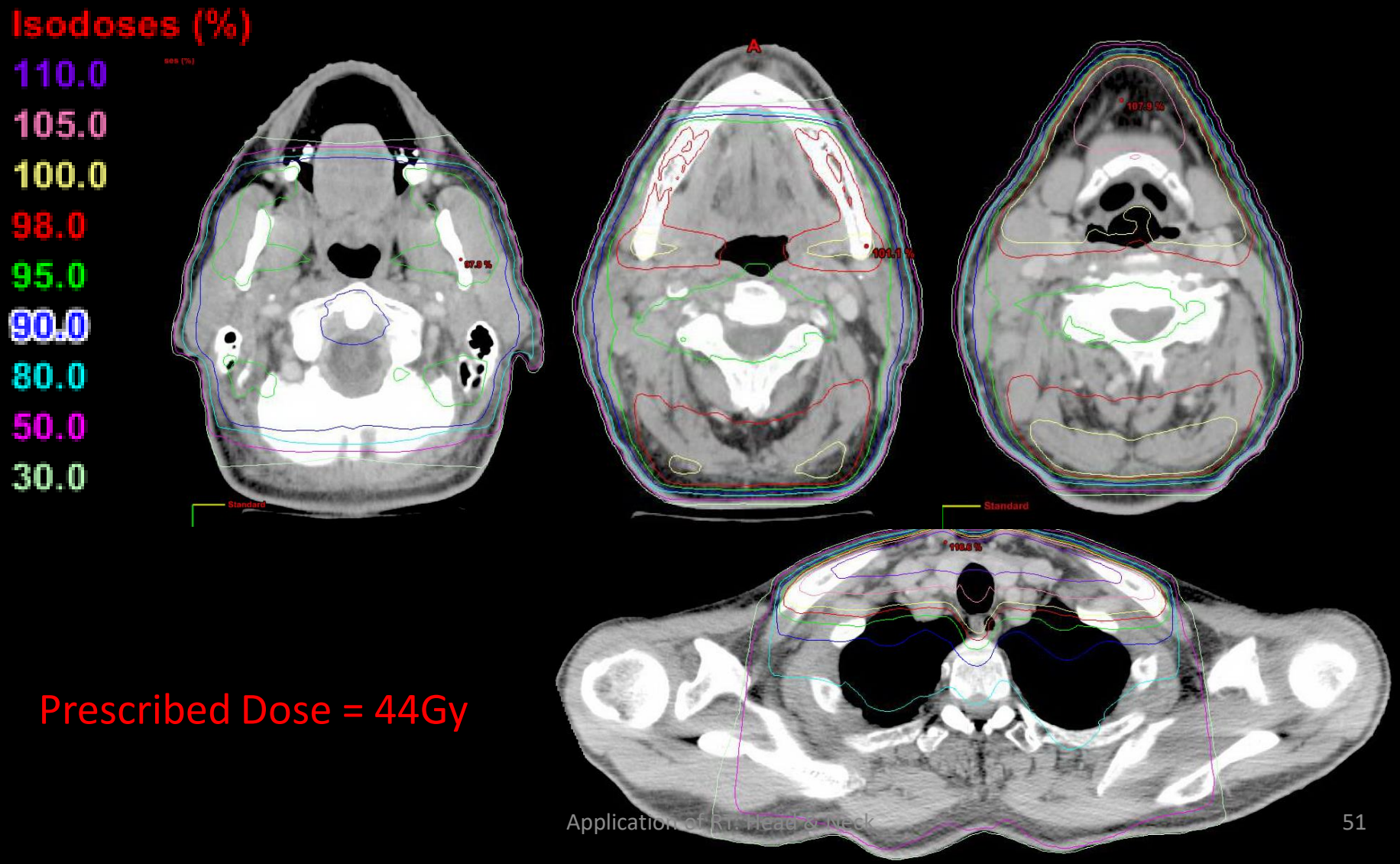






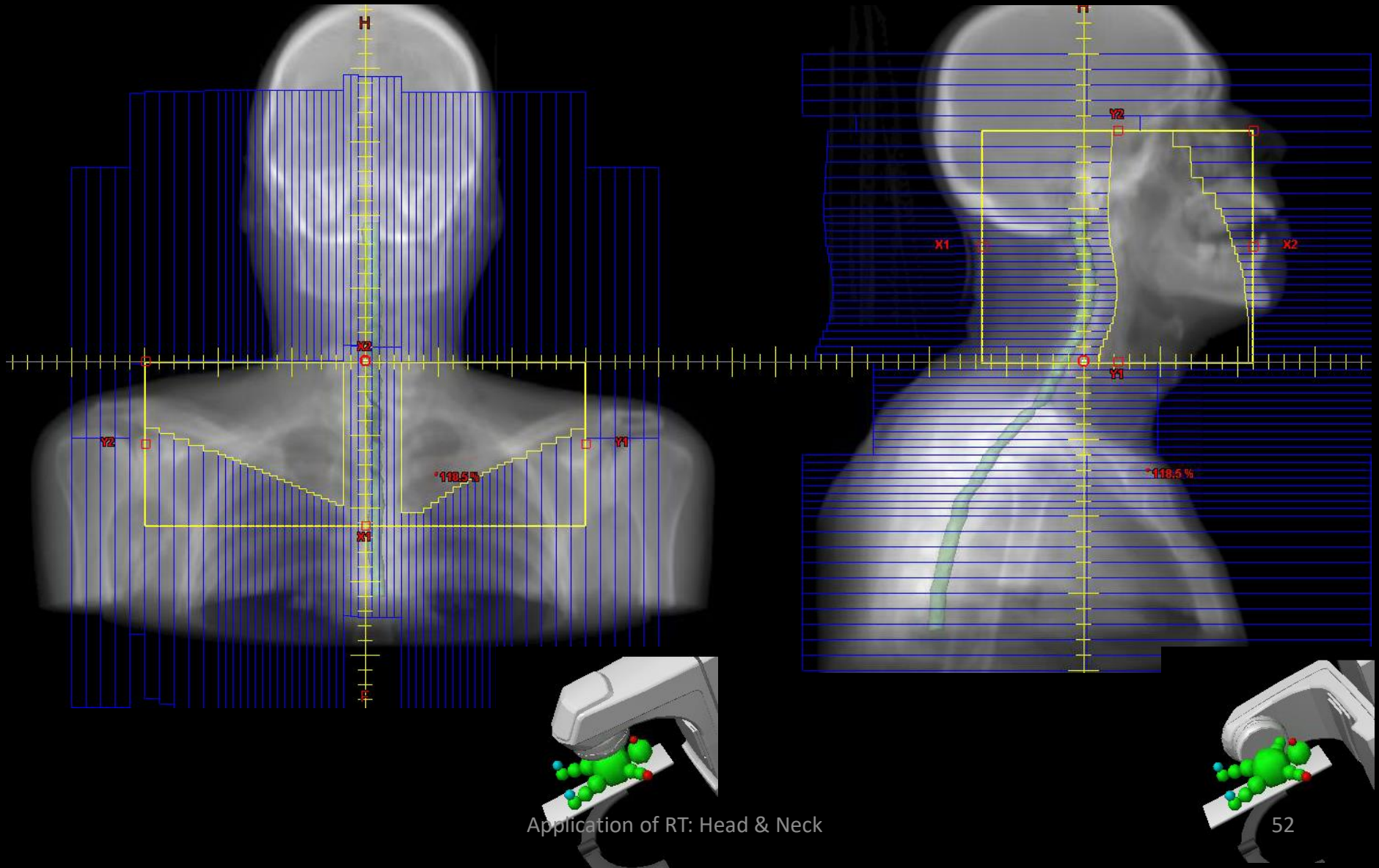


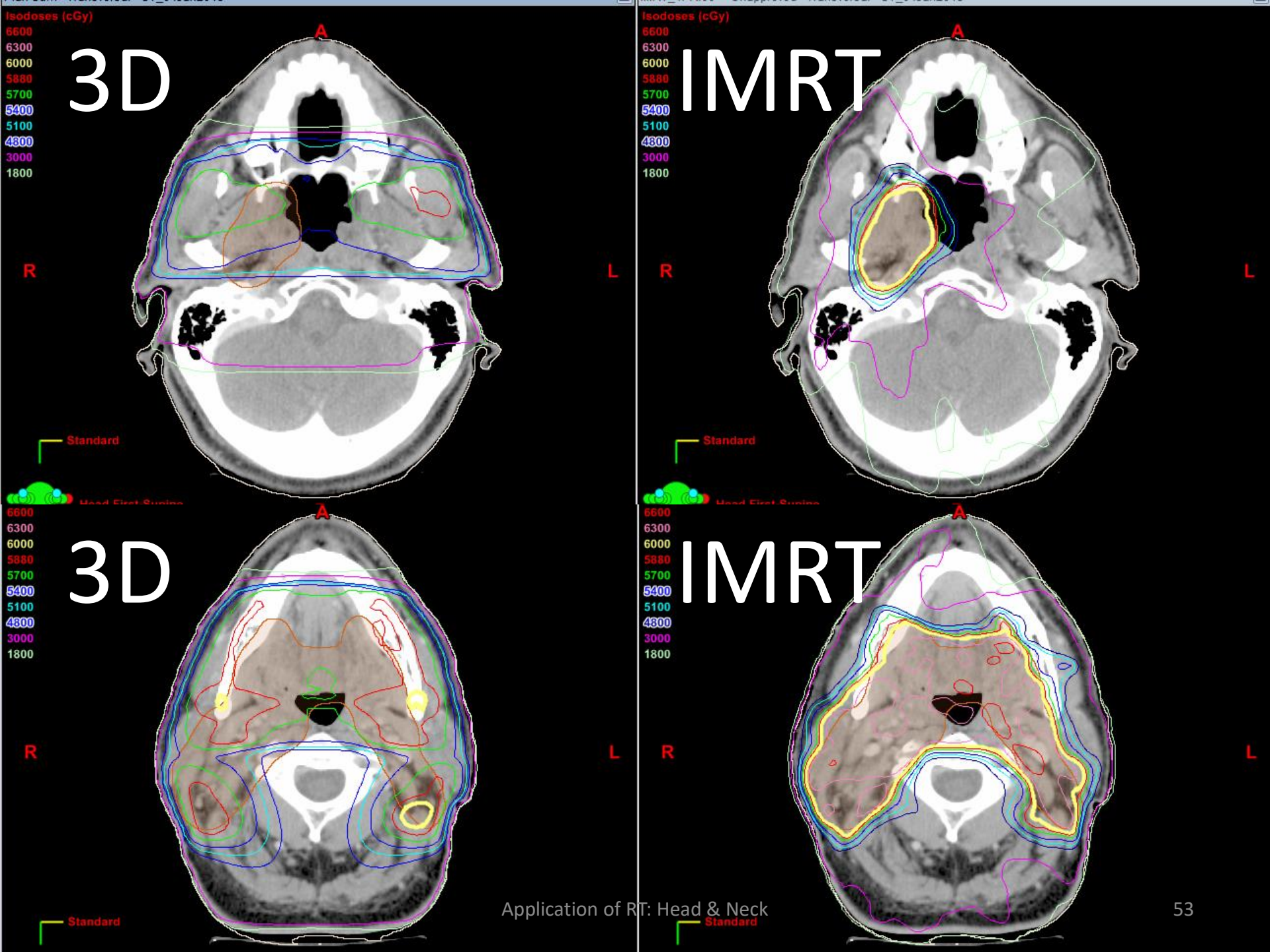
Historical (3D) Treatment Technique



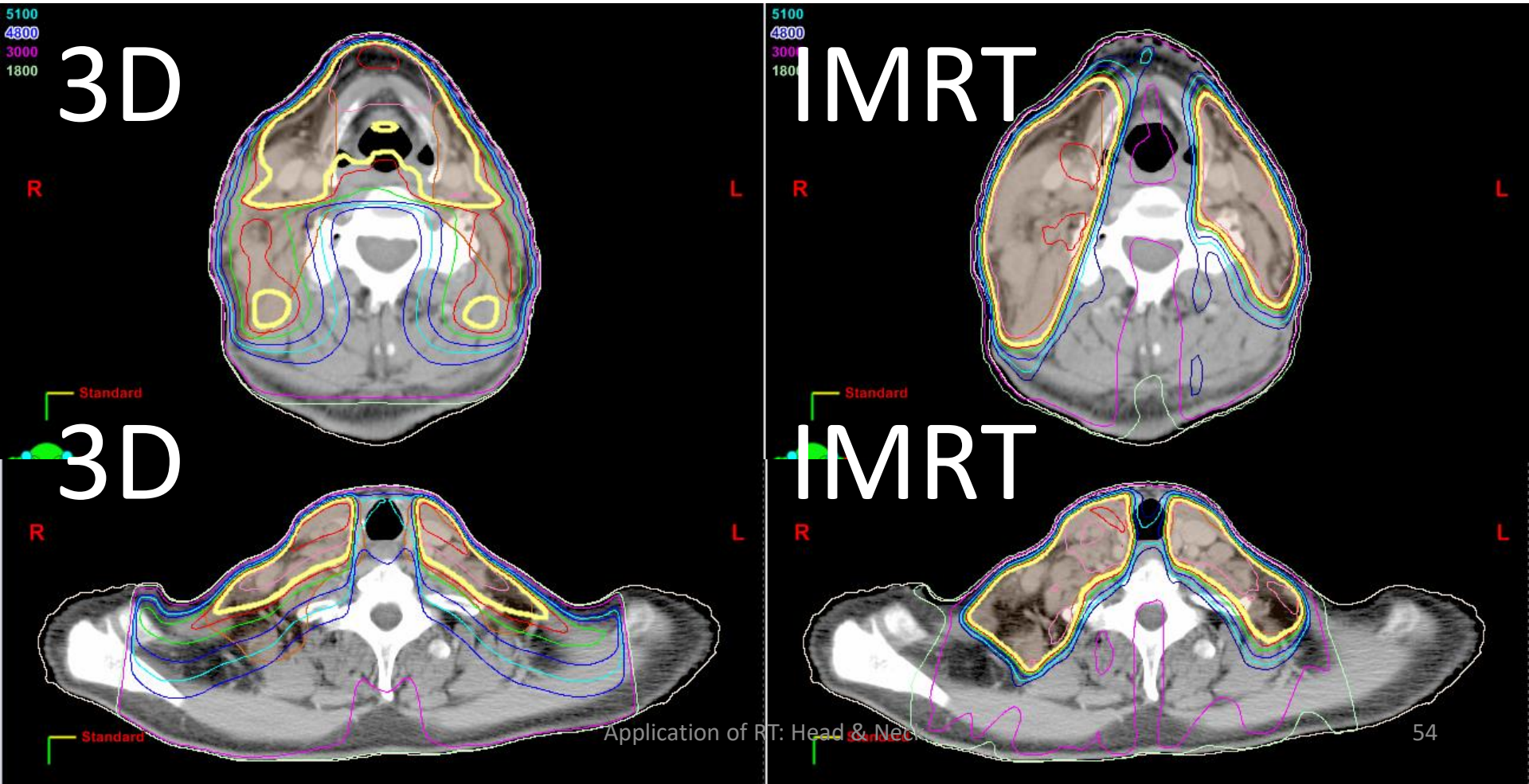
Prescribed Dose = 44Gy

3D Boost to 60Gy

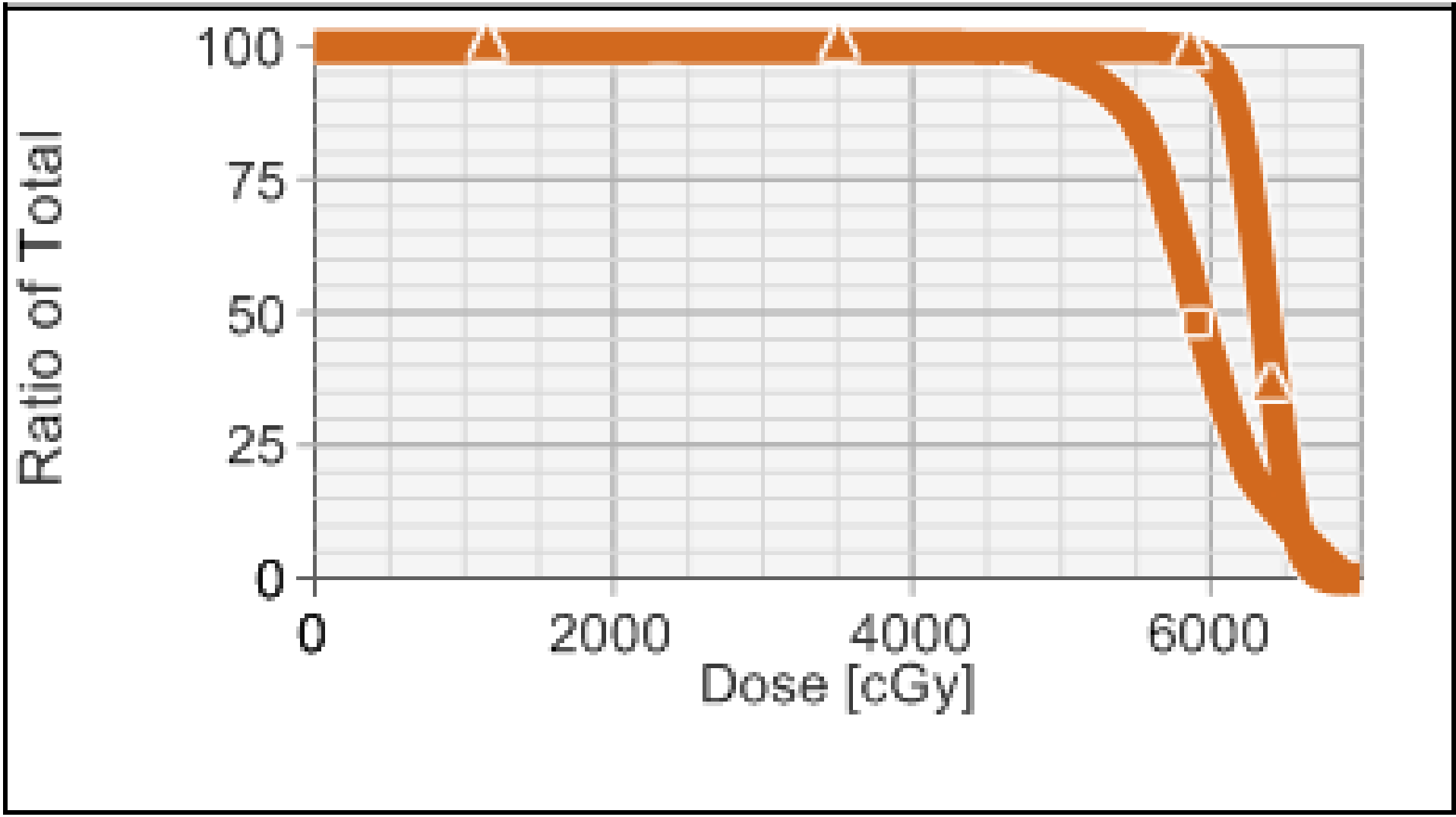



3D
IMRT
3D
IMRT
Isodoses (cGy)
6600
6300
6000
5880
5700
5400
5100
4800
3000
1800
A
R
L
Standard

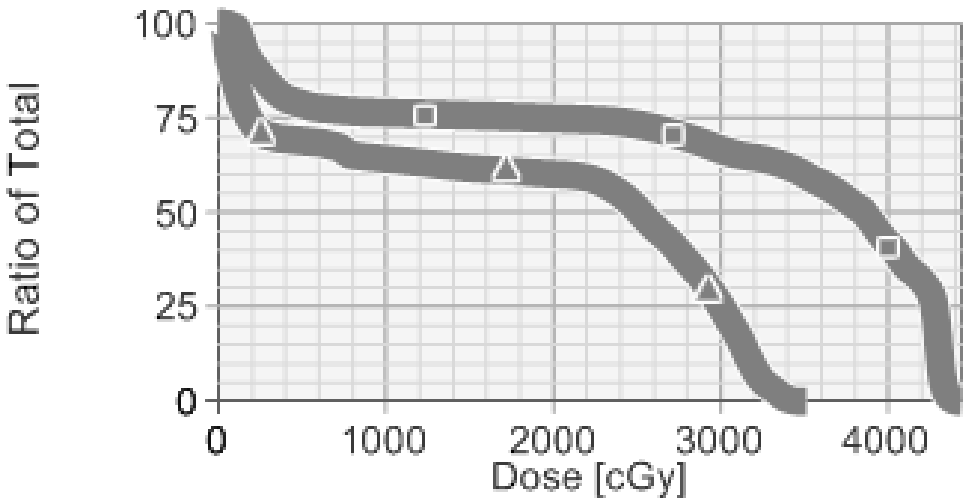
3D vs IMRT



PTV DVH: 3D vs IMRT



Spinal Cord DVH: 3D vs IMRT



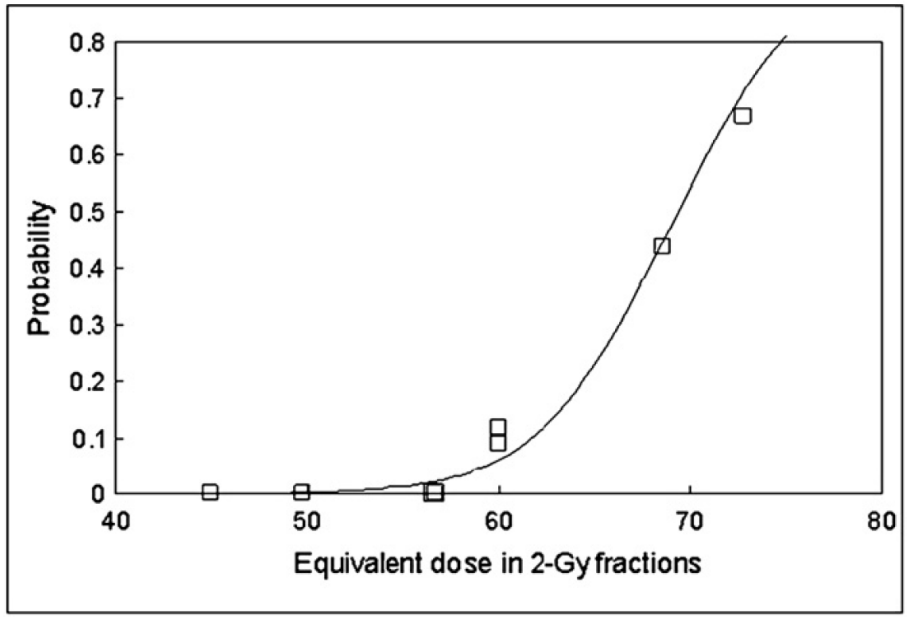
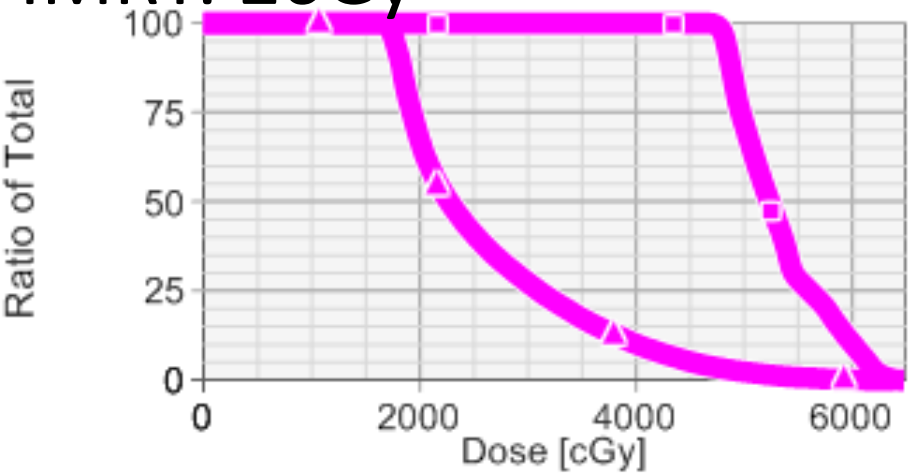


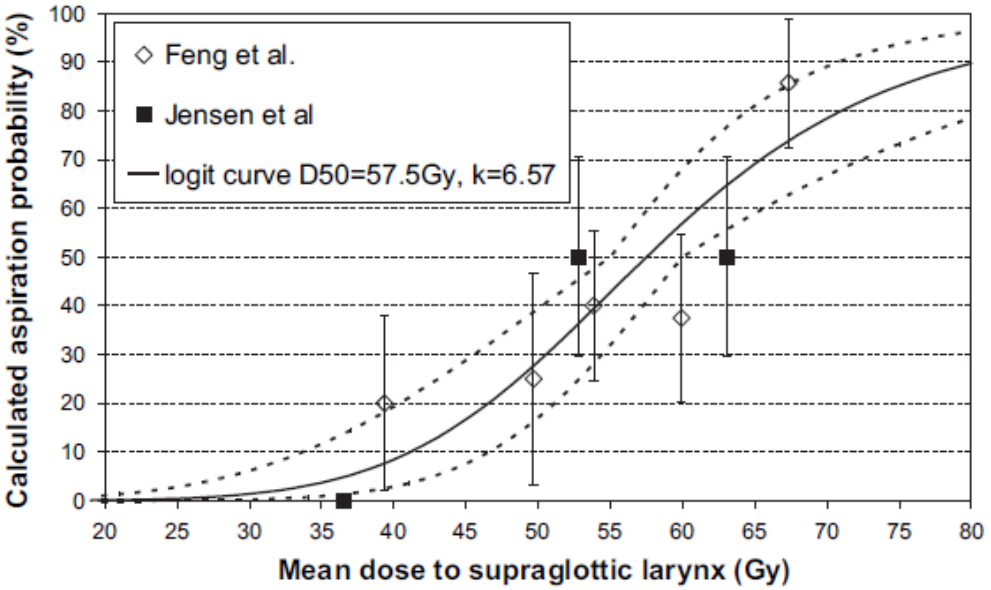
Fig. 1. The dose–response function for the myelopathy of the cervical spinal cord and data points (□) derived from Table 1. The probability of myelopathy was calculated from the data in Table 1, adjusted for estimated overall survival per (18).

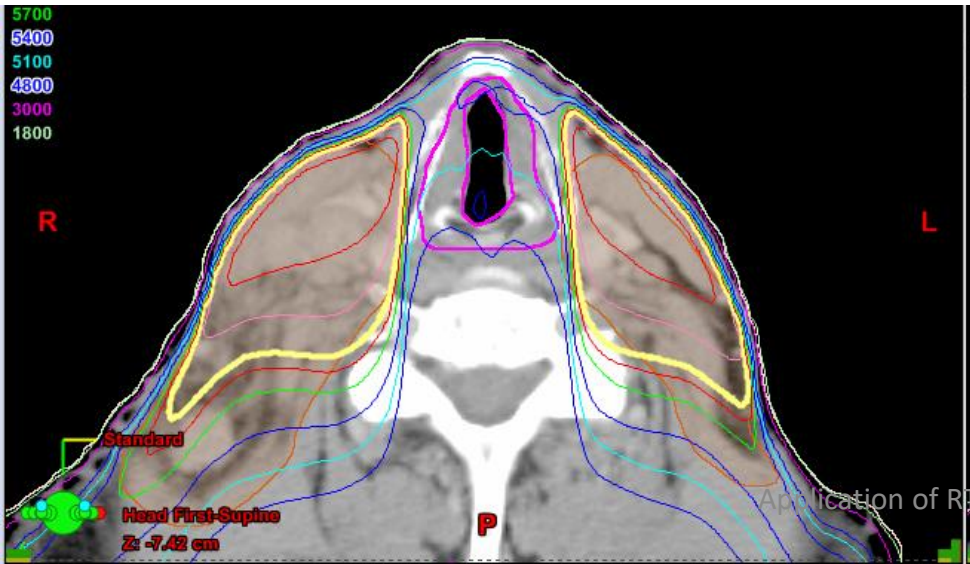
Larynx DVH: 3D vs IMRT

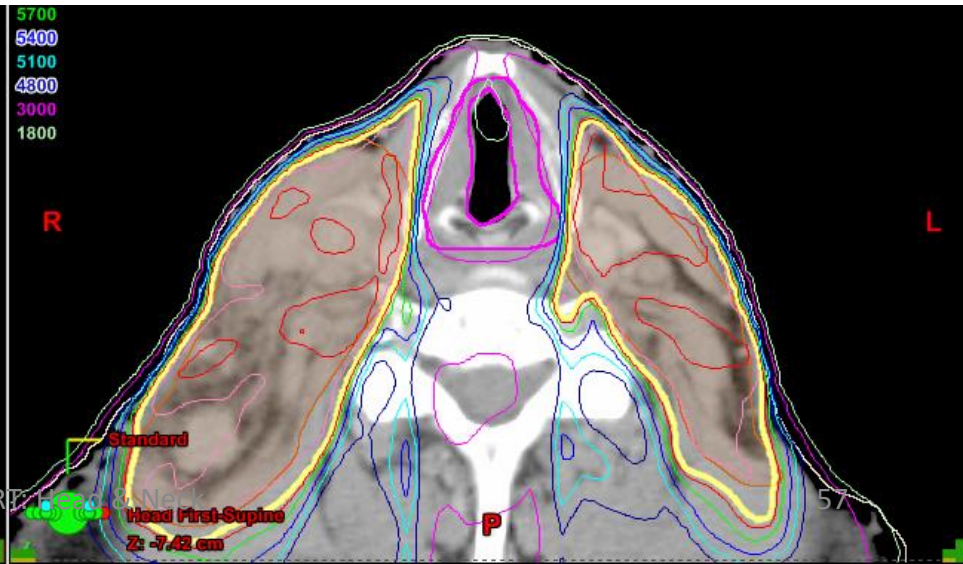
Mean dose: 3D: 53Gy

IMRT: 26Gy

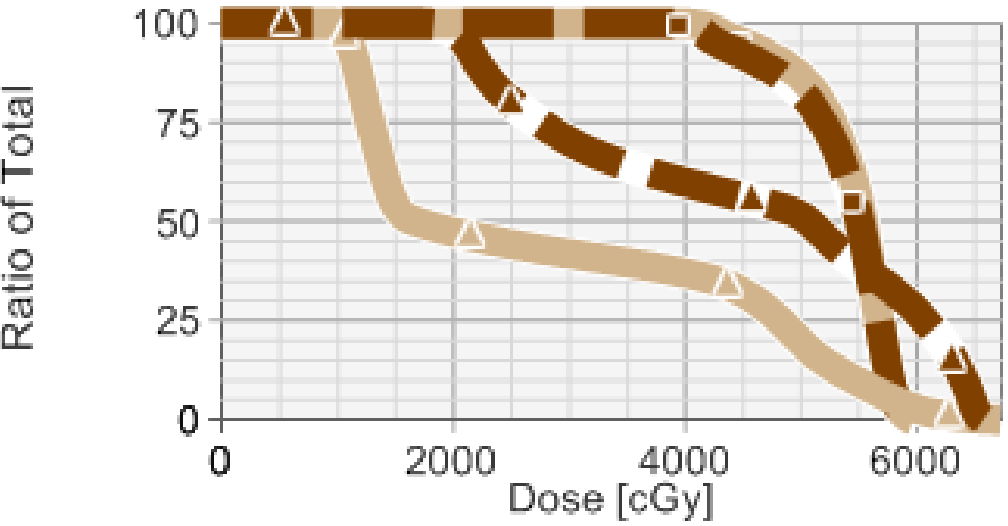


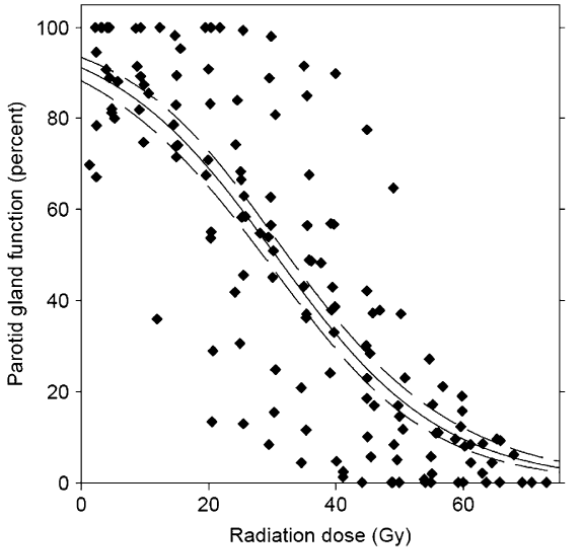


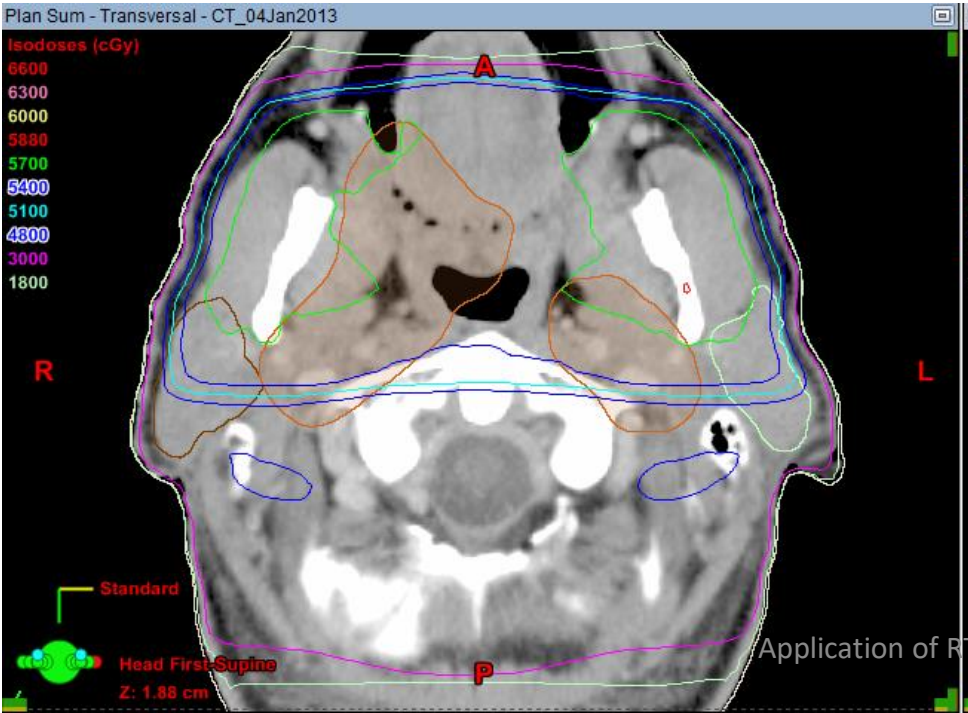


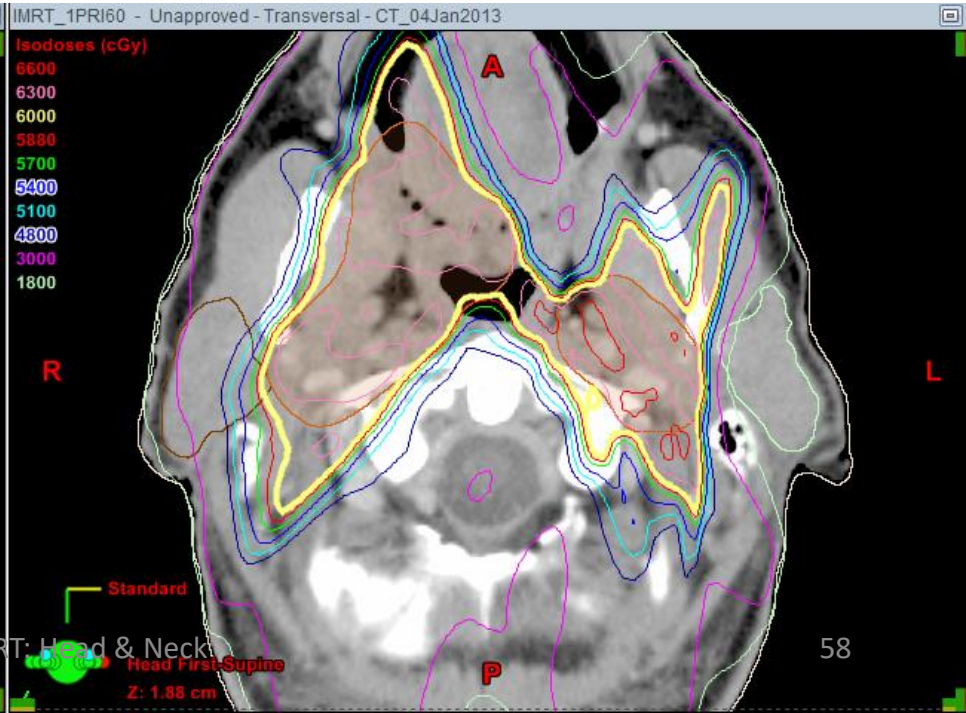


Parotid DVH: 3D vs IMRT









Some comments on IMRT

- Better conformity -> may be easier to miss the target ?!
  - Potentially a significant problem
  - First get the margins correct, then implement IMRT
- Beam selection can be non-intuitive
- Tendency to use more beams not less !
- Typical MUs for an IMRT plan are 3-5 times higher
  - Tendency to use lower energy (reduce neutron)
- Tendency to 'over-stress' IMRT planning
  - Give the optimization a consistent set of objectives
  - Avoid extreme weighting etc

Summary of IMRT

Advantages

- Ability to produce remarkably conformal dose distributions
- Dose escalation (improvement in local control)
- Decreased dose to surrounding tissues (reduction in complications)

Disadvantages

- Planning is labor intensive
- Extended delivery time (typically)
- Danger of being too conformal
- Generally more inhomogeneous dose distribution
- Increased MU→ increased whole body dose & increased room shielding

References

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- Optimized Planning Using Physical Objectives and Constraints, Thomas Bortfield, Seminars in Radiation Oncology, Vol 9, No 1 (January), 1999:pfl 20-34
- Image Guided Radiation Therapy (IGRT) Technologies for Radiation Therapy Localization and Delivery, Int J Radiation Oncol Biol Phys, Vol. 87, No. 1, pp. 33e45, 2013
- Image-guided radiotherapy: rationale, benefits, and limitations, *Lancet Oncol* 2006; 7: 848–58
- Planning in the IGRT Context: Closing the Loop, Semin Radiat Oncol 17:268-277

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- AAPM:
  - Report 82: Guidance document on delivery, treatment planning, and clinical implementation of IMRT: Report of the IMRT subcommittee of the AAPM radiation therapy committee (2003)
  - TG119: IMRT commissioning: Multiple institution planning and dosimetry comparisons (2009)
  - TG120: Dosimetry tools and techniques for IMRT (2011)

Thank you!