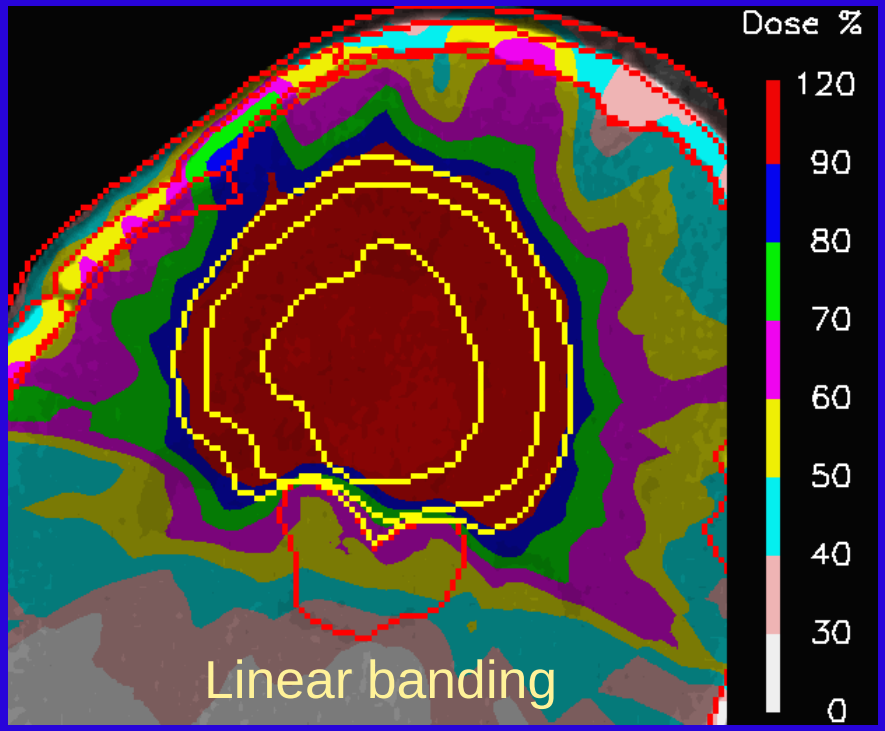
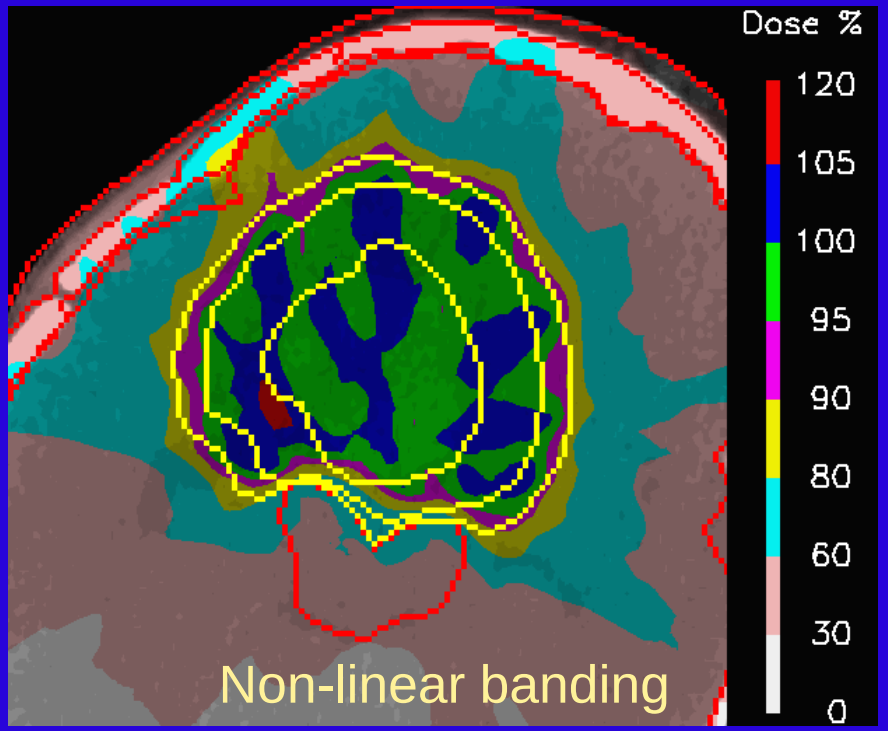
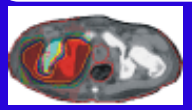
Treatment plan evaluation





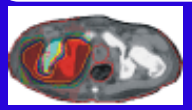
Tony Lomax

Centre for Proton Radiotherapy, Paul Scherrer Institute

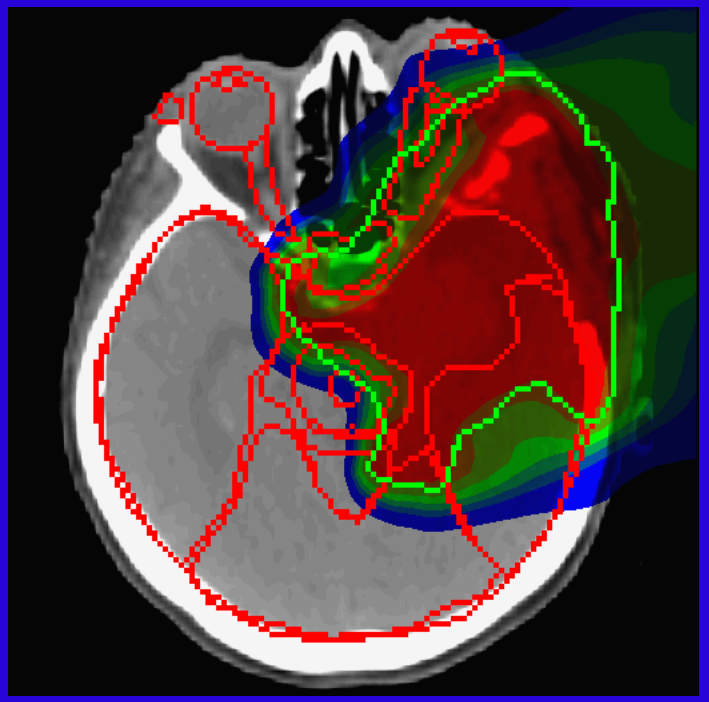


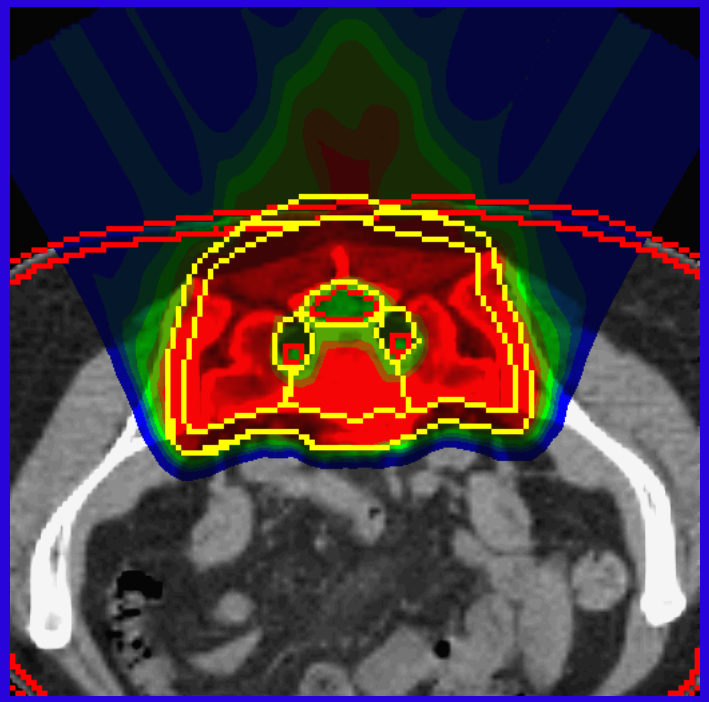
Overview

1. Displaying and interpreting dose distributions
2. Scoring and evaluating plans
3. Summary

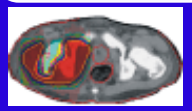


Example dose distributions



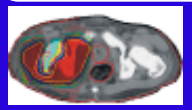


Are they acceptable? What are the risks to the patient? Will they 'cure' the patient?



The display and analysis of dose distributions

1. Displaying dose
2. Dose volume histograms
3. Characterising dose distributions and DVH's



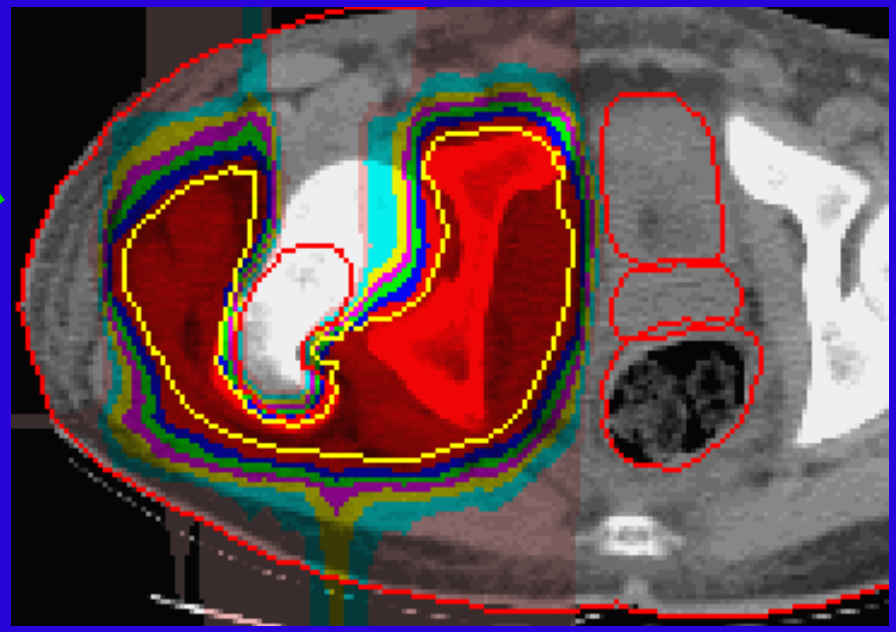
Displaying dose

The dose delivered during a radiation treatment…

…is a 3-d distribution of energy deposited within the patient

The result of a treatment plan….

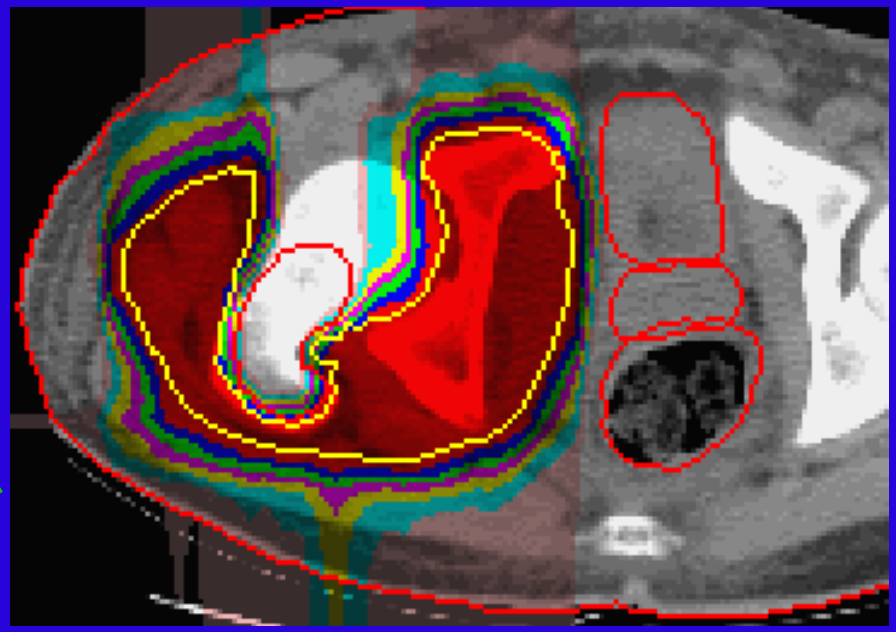
… is a (prediction of the) 3-d distribution of energy deposited within the patient

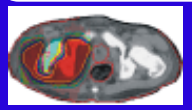


Displaying dose

The display of a 3-d dose distribution in relation to the target volume and normal structures is the most direct and informative method of assessing a treatment plan.

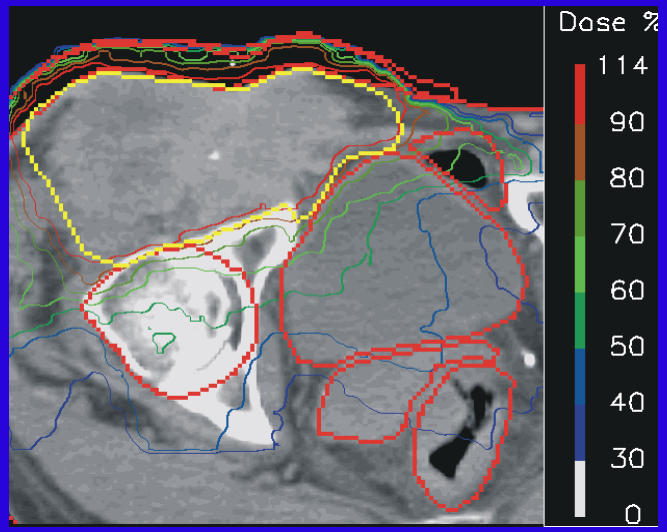
All other methods of analysing dose distributions are surrogates of this and involve (to a lesser or greater extent) a loss of information.



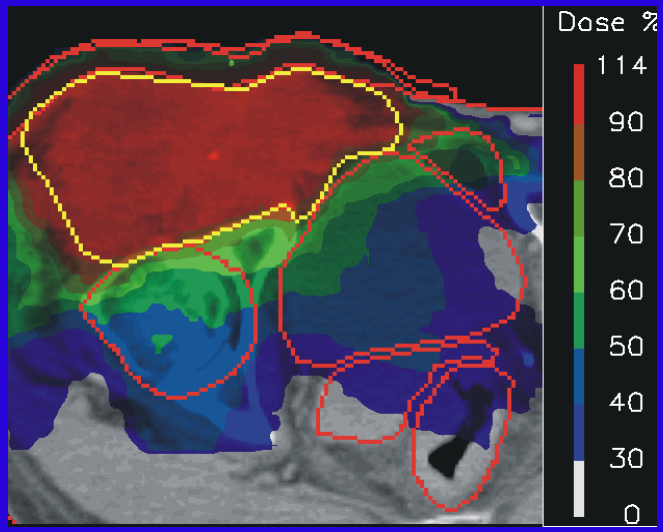


Methods of displaying dose

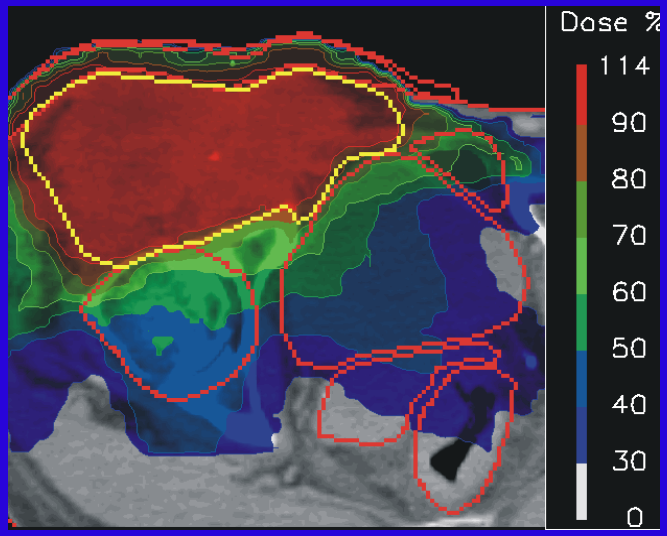
Iso-dose contours



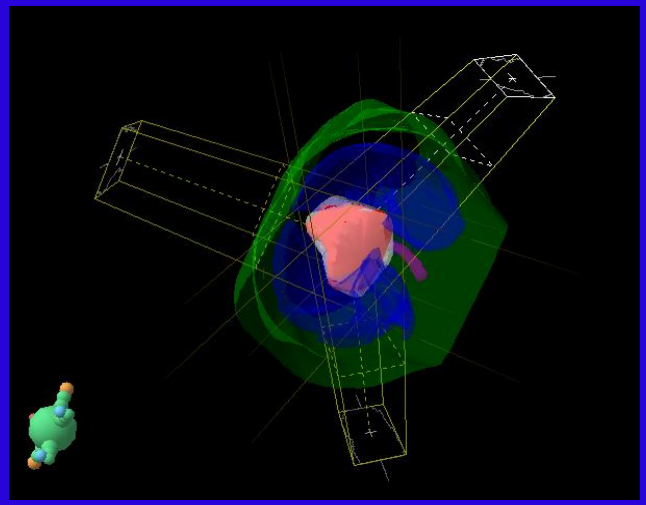
Colour wash

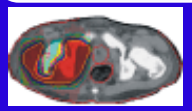


Iso-dose contours and colour wash



Iso-dose surface

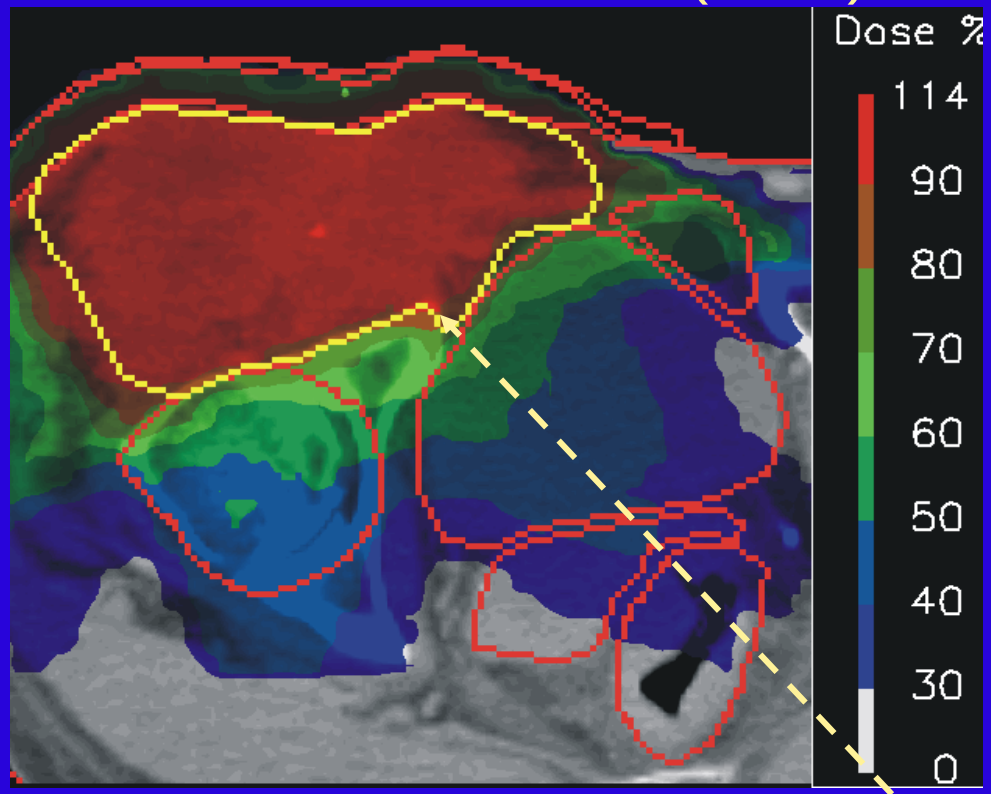




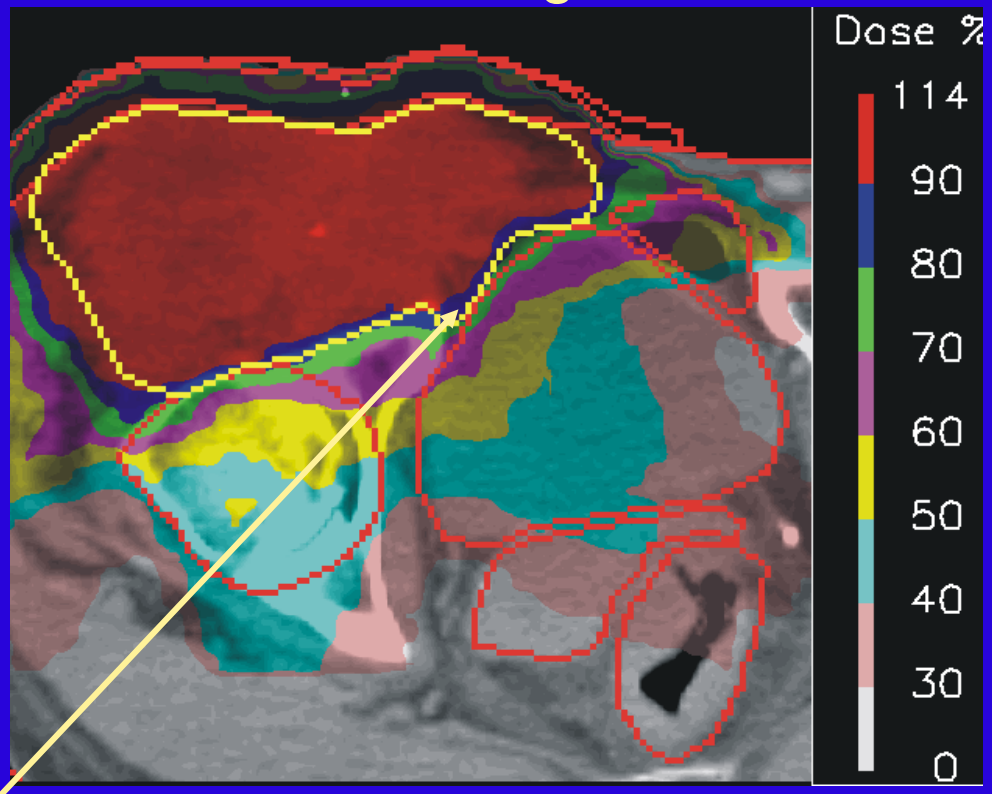
Colour scales

The gradation of colour as a function of dose value

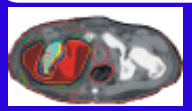
1. Continuous colour (BGR)



2. Contrasting colour



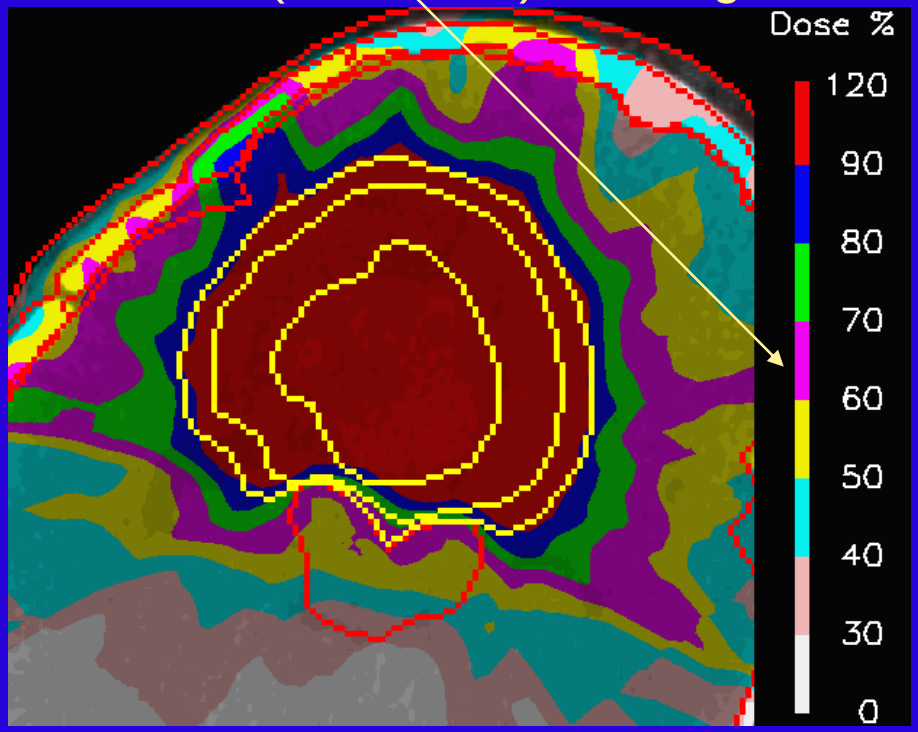
Clearer indication of ‘under-dosage’ within target volume



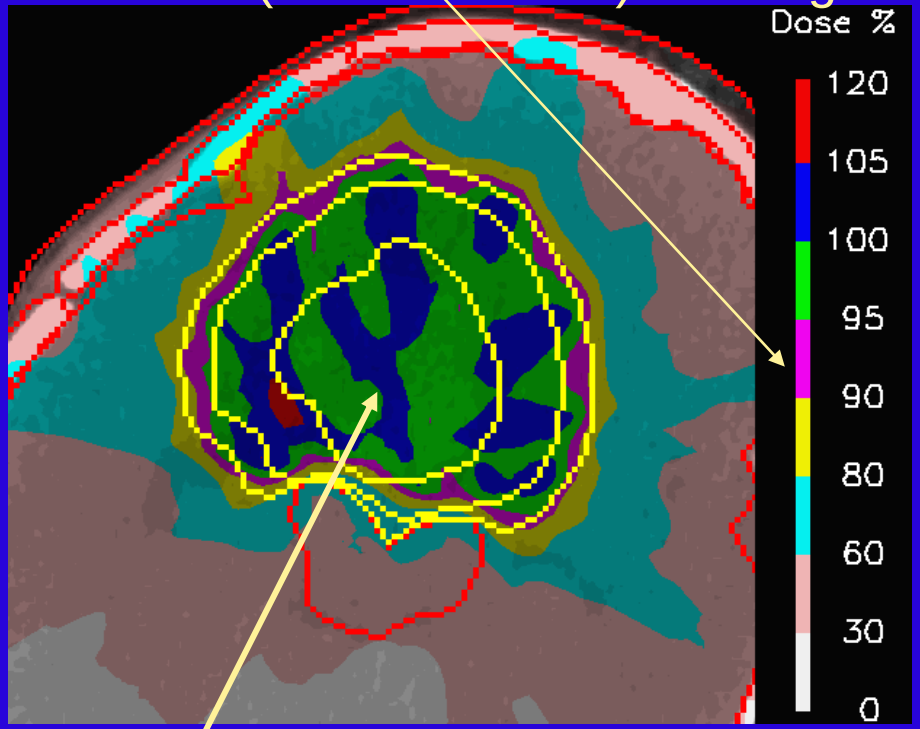
Dose banding

The mapping of dose to colours or contour levels

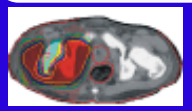
Wide (and linear) banding



Narrow (and non-linear) banding



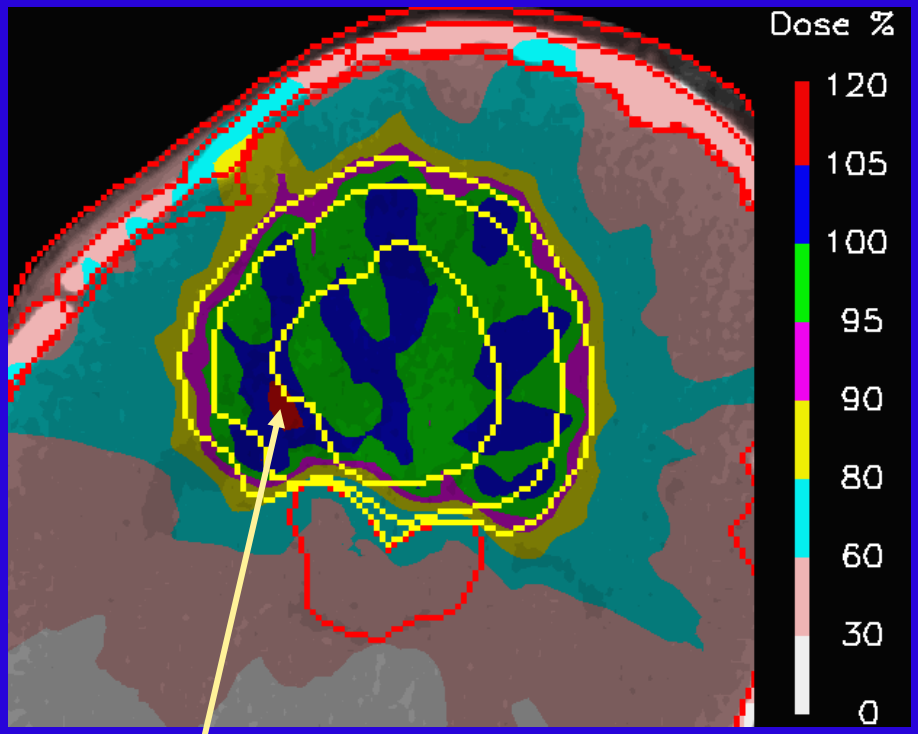
Improved visualisation of dose heterogeneity within PTV



Dose banding

Reasons to be cautious!

1. Accentuated structure due to banding

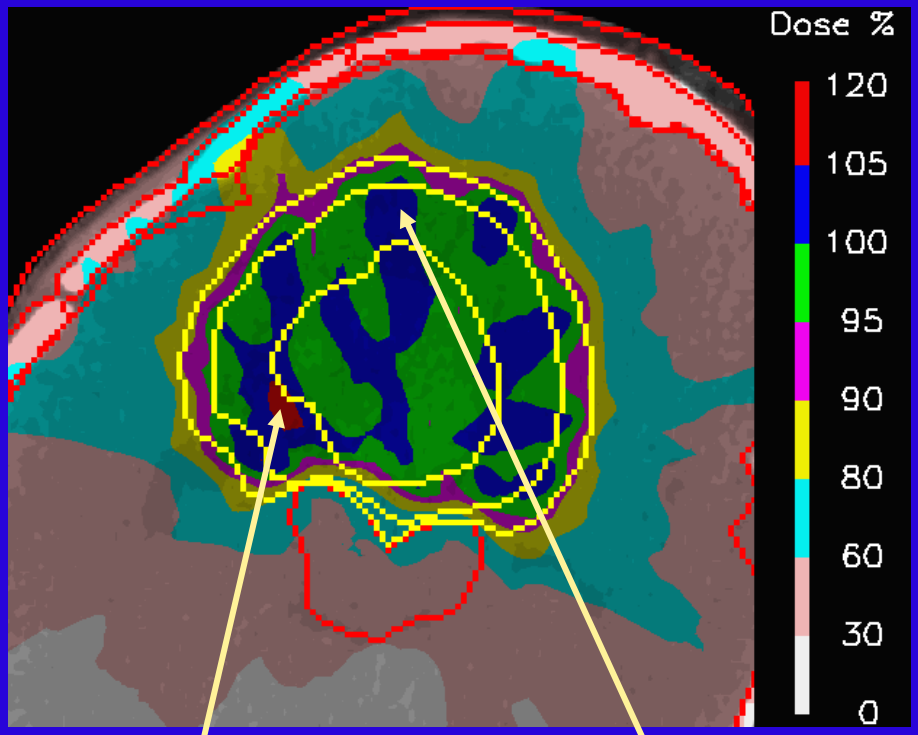


Hot spot?

Dose banding

Reasons to be cautious!

1. Accentuated structure due to banding



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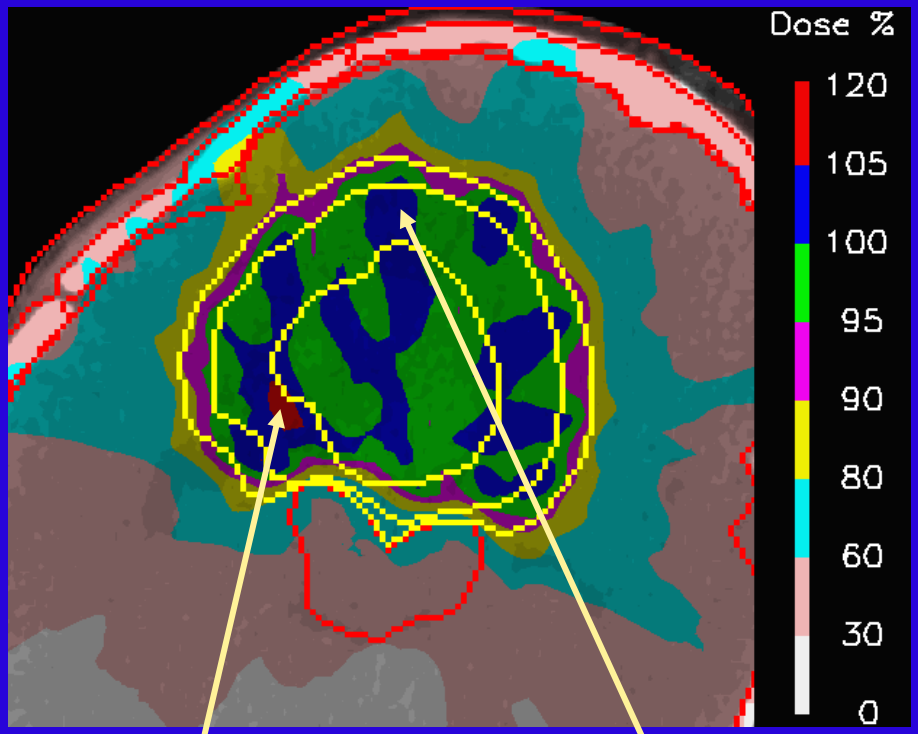
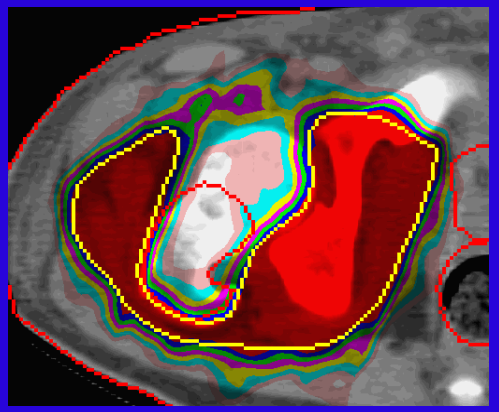
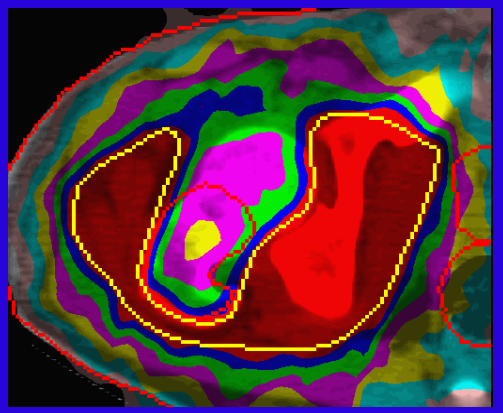


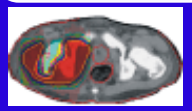
108% ⟵ 3% ⟶ 105%

2. 'Hidden' dose

Take two plans for comparison







Dose banding

Reasons to be cautious!

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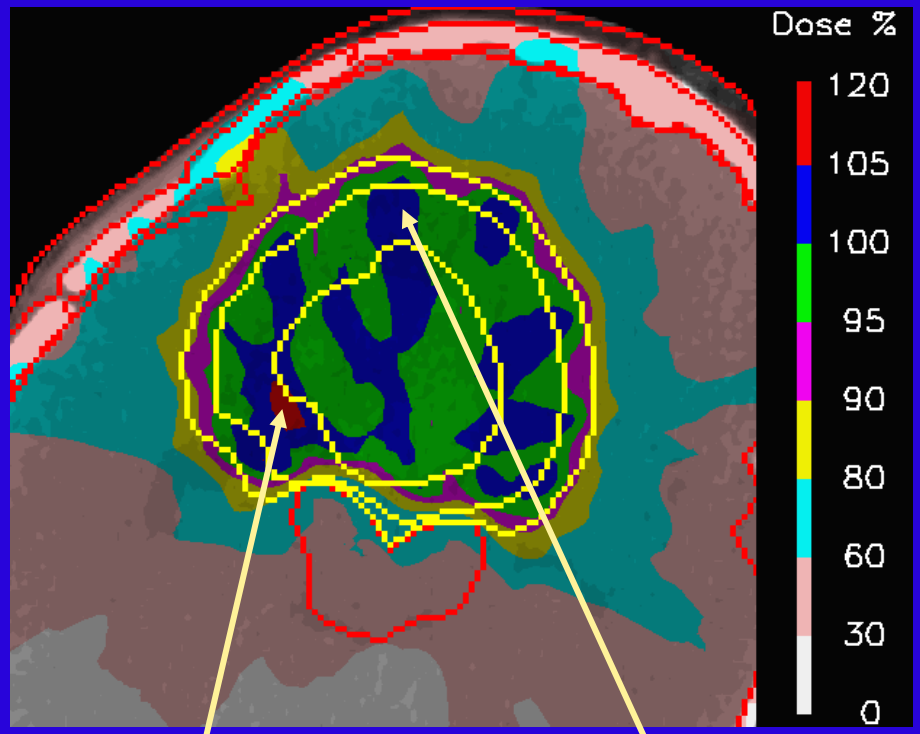
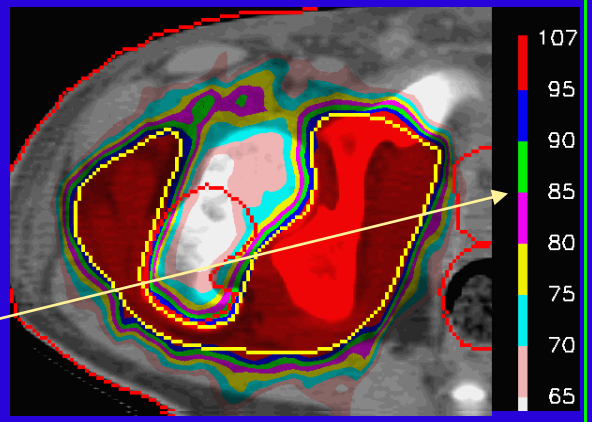
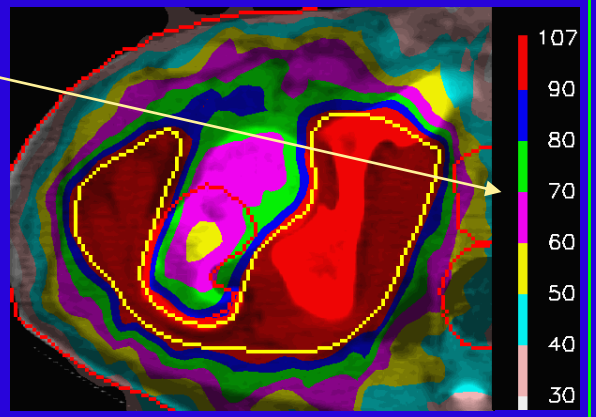


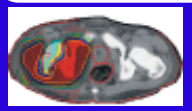
108% ⟵ 3% ⟶ 105%

2. 'Hidden' dose

But actually Identical dose distributions, just displayed with different dose bandings!

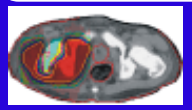






The display and analysis of dose distributions

1. Displaying dose
2. Dose volume histograms
3. Characterising dose distributions and DVH's



Dose volume histograms - Why?

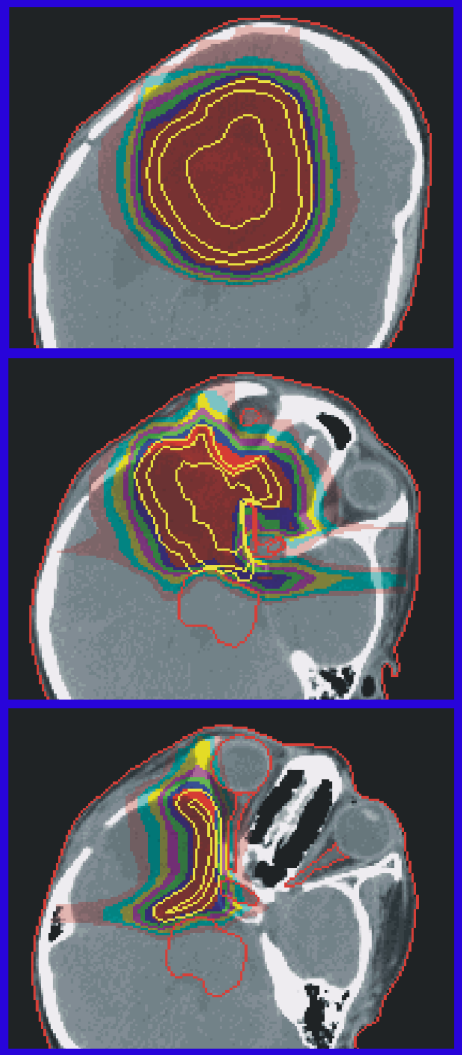
Disadvantages of 3-d dose distributions

1. Huge amount of information to assess

2. Difficult to quantify visually

3. Difficult to understand relationship between dose and anatomy in 3-d

4. Dose is itself only a surrogate for clinical outcome (Michael Goitein)

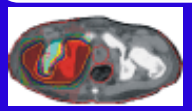


Example 3-d dose distribution

90 CT slices (>1.5M voxels within patient outline)

>500000 voxels with non-zero dose.

>60000 PTV voxels, >70000 critical structure voxels

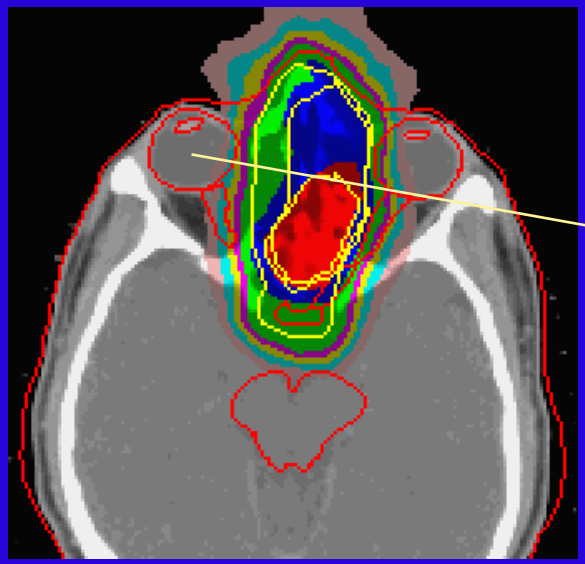


Dose volume histograms (DVH)

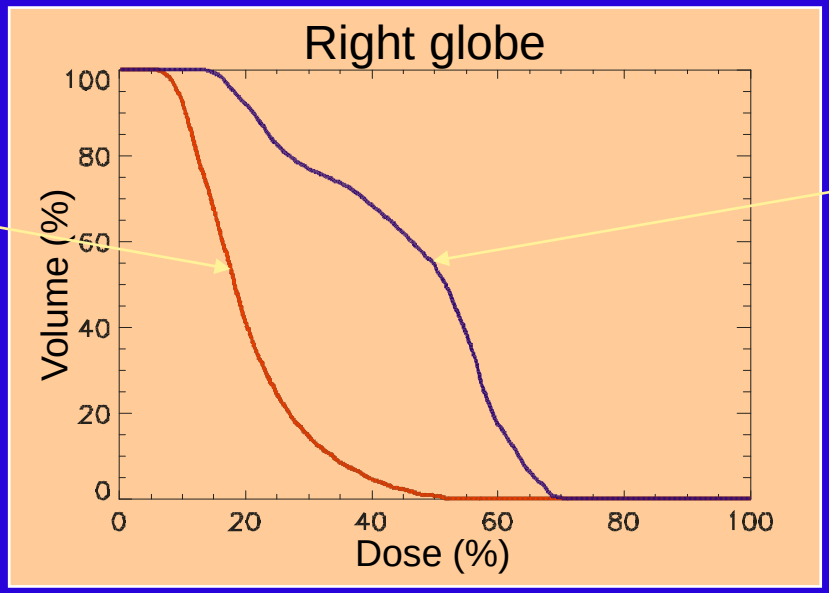
DVHs reduce 3-d dose distributions within a defined volume of interest to simple 1-d curves.

For example...

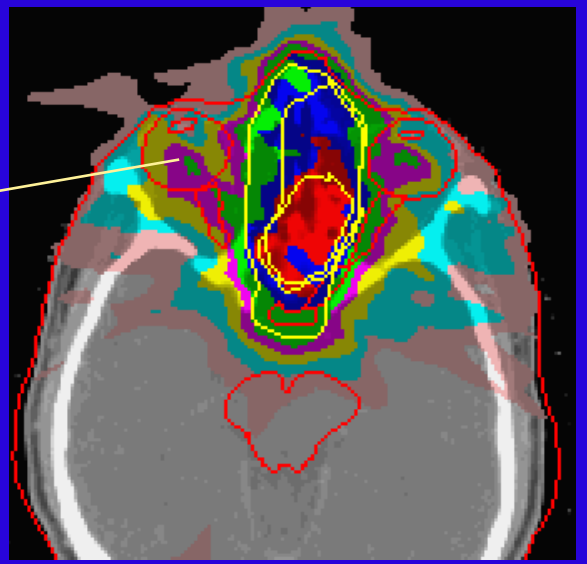
Plan 1



Comparative DVH's

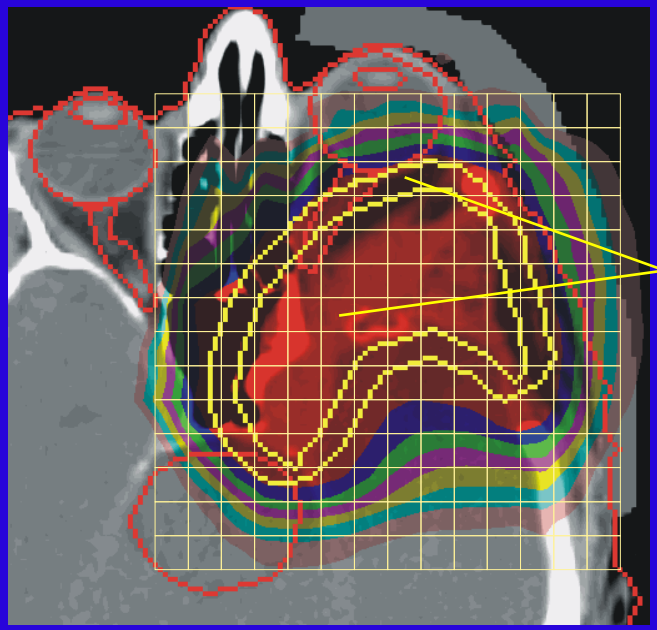


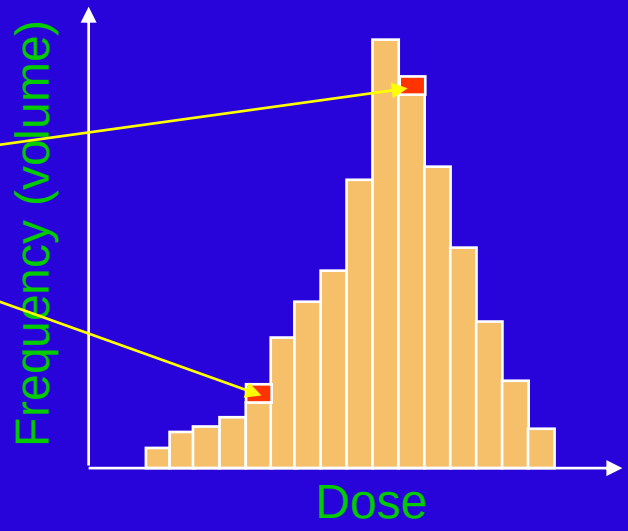
Plan 2



DVH's - Calculation and interpretation

The differential (true) histogram



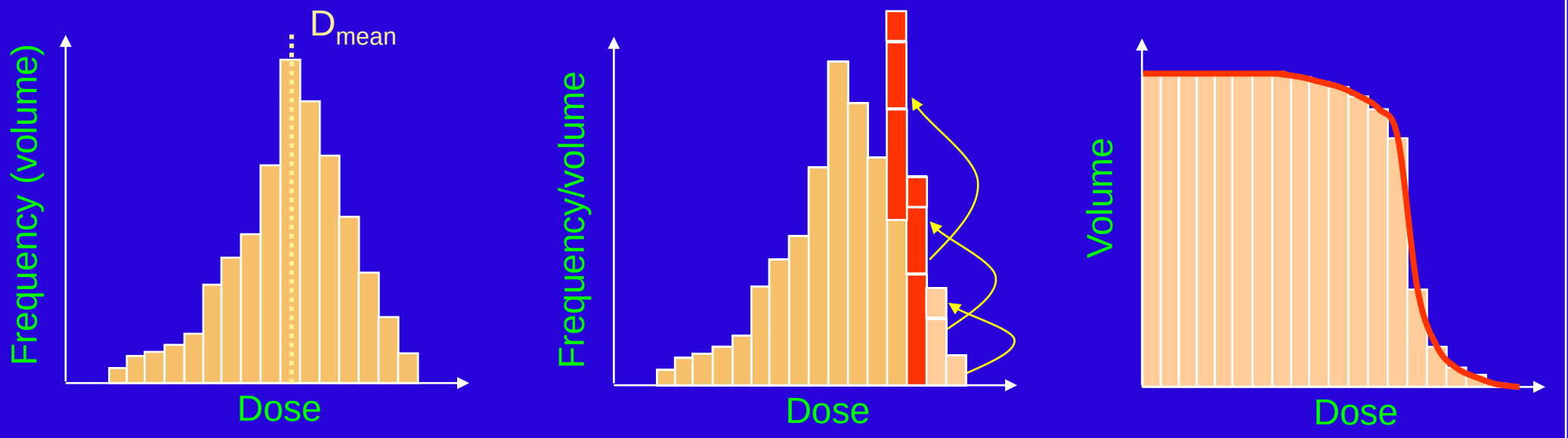


Dose distribution and defined VOI

Differential (true) histogram

DVH's - Calculation and interpretation

The cumulative dose volume 'histogram'

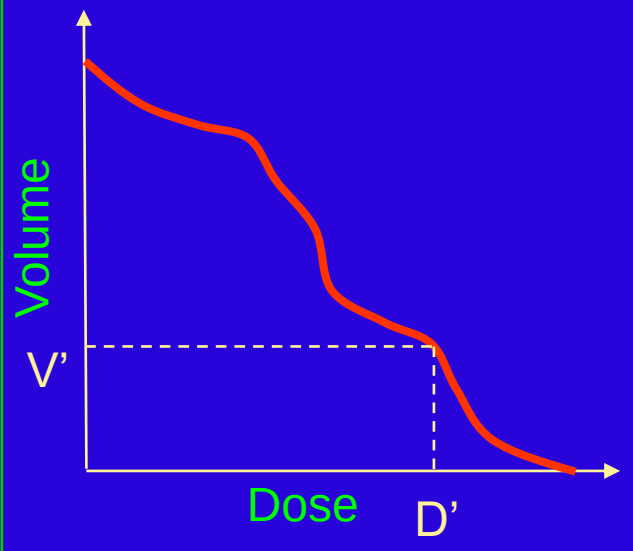


Differential DVH → Bin-by-bin integration → Cumulative DVH

DVH's - Calculation and interpretation

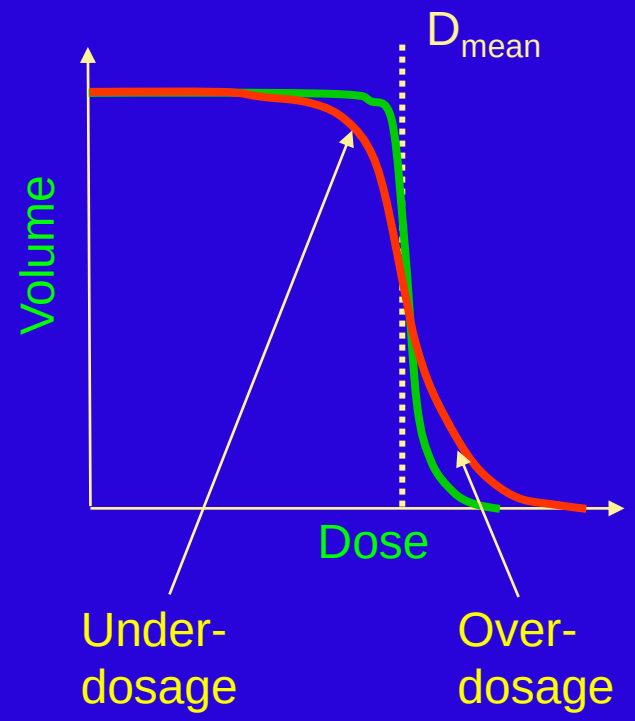
Interpreting cumulative DVHs

For all DVHs

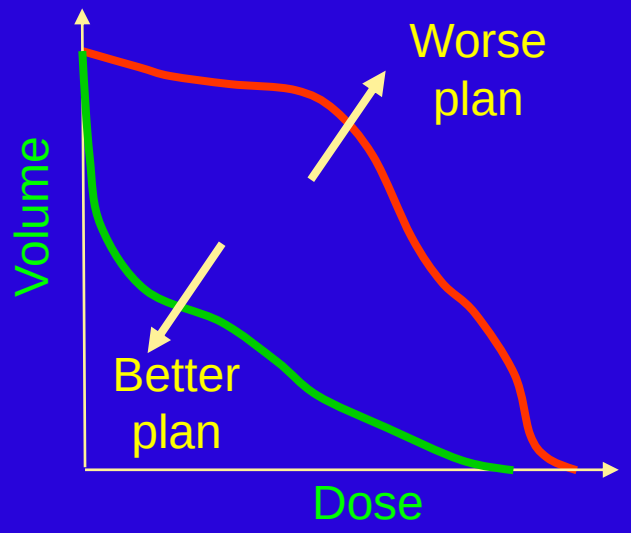


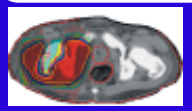
Volume V' that receives a dose >= D'

For target DVHs



For anatomy DVHs

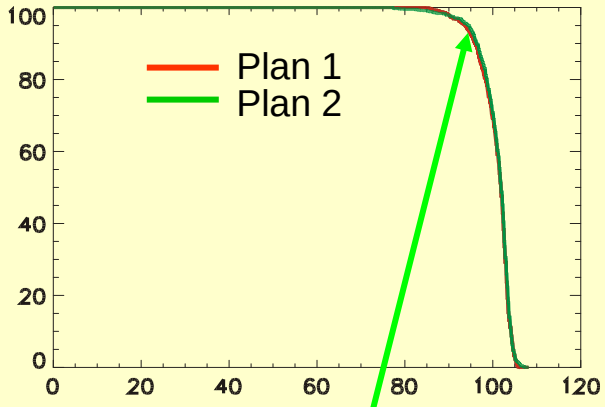




DVH's - Problems and pitfalls

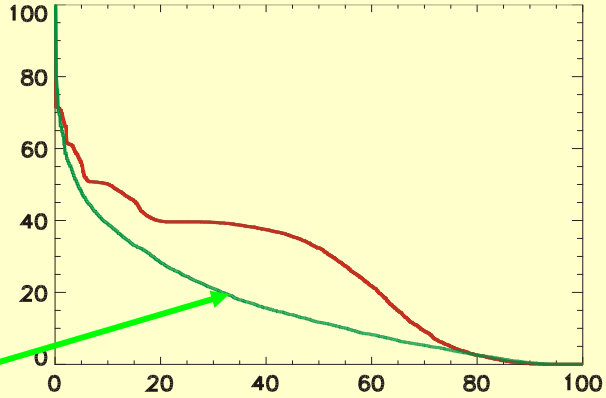
1. DVHs are insensitive to small 'hot' and 'cold' spots

Target volume



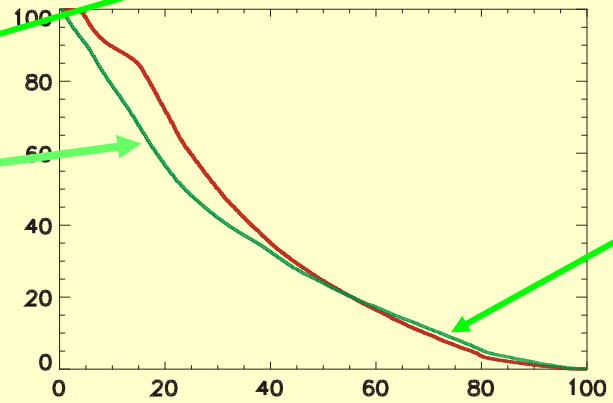
Consider comparative DVHs from two competing plans

Brain stem

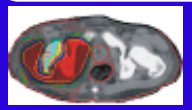


From DVHs, plan 2 appears to be the best….

Posterior fossa



…apart from apparently insignificant increase in high dose to posterior fossa



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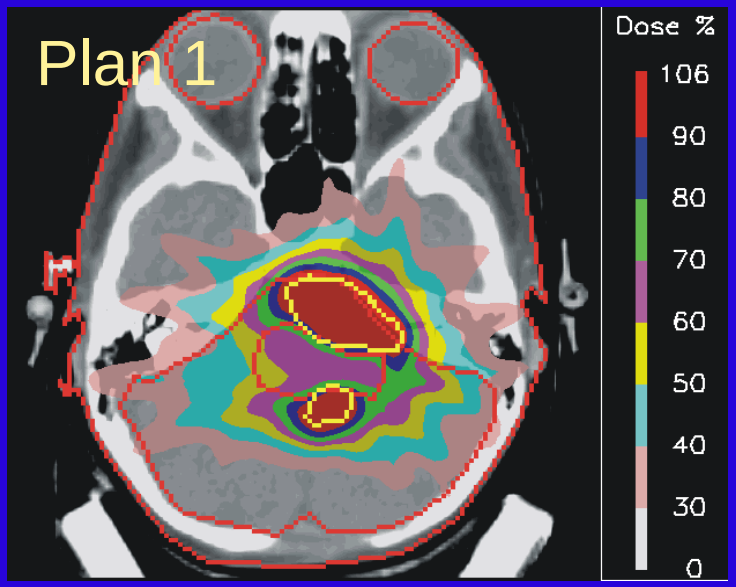
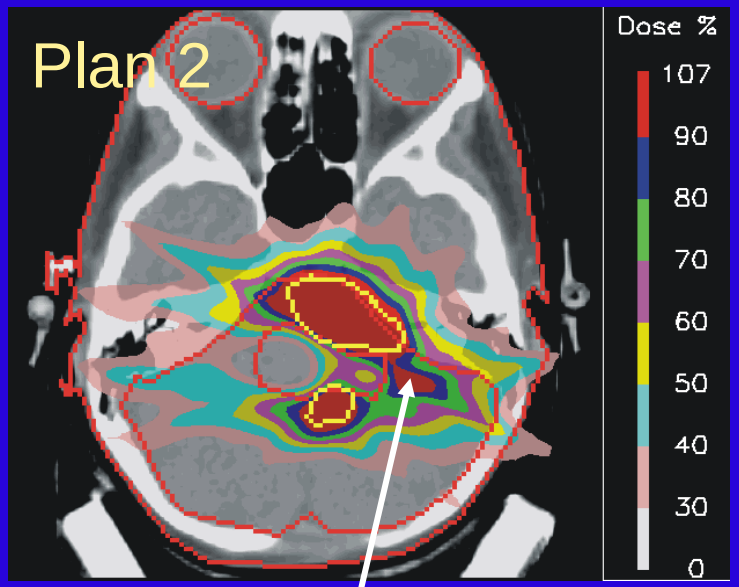
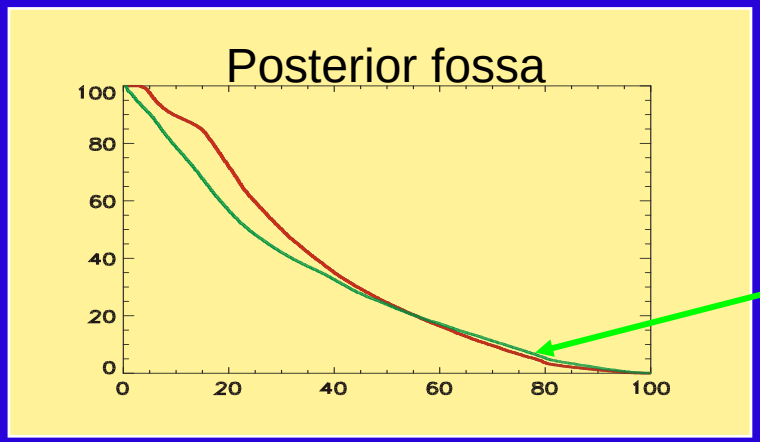
1. DVHs are insensitive to small 'hot' and 'cold' spots





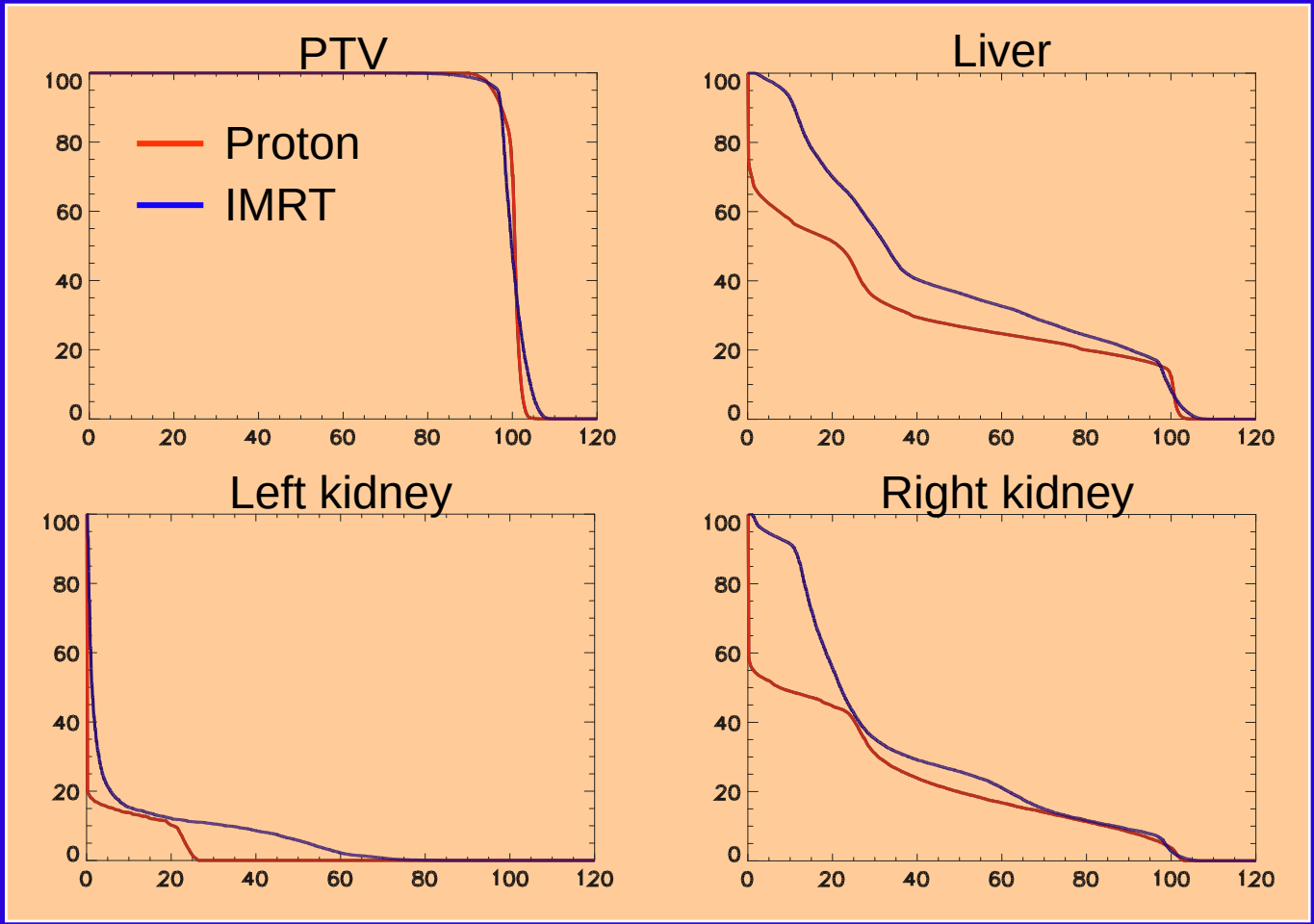


But this increase corresponds to a 105% hot spot in posterior fossa

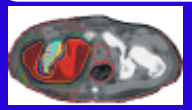
DVH's - Problems and pitfalls

2. DVHs can only be calculated for defined VOIs.

Consider comparative DVHs for proton/IMRT plans



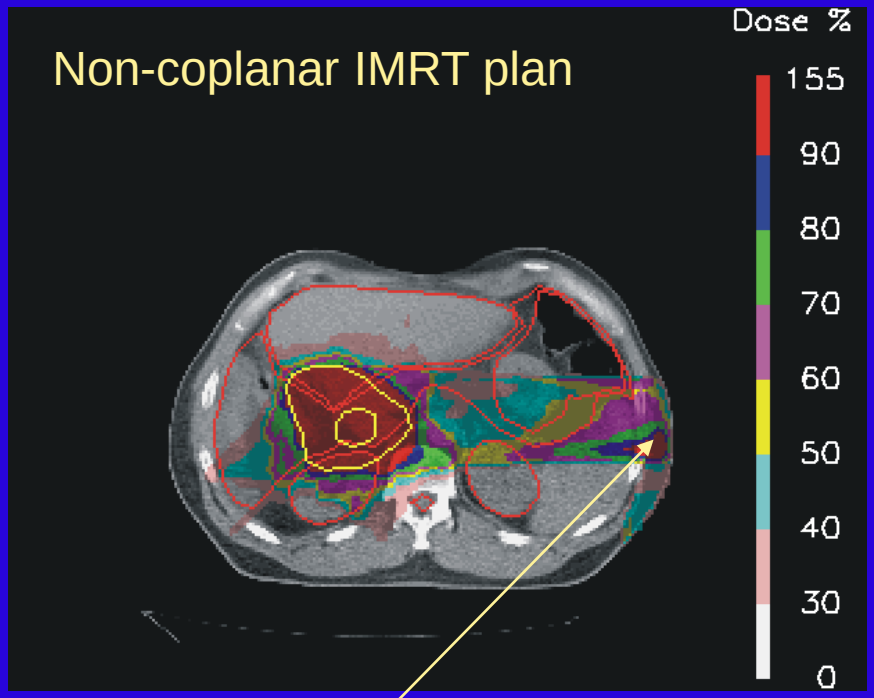
From DVHs alone, the IMRT plan looks reasonably favourable in comparison to the proton plan



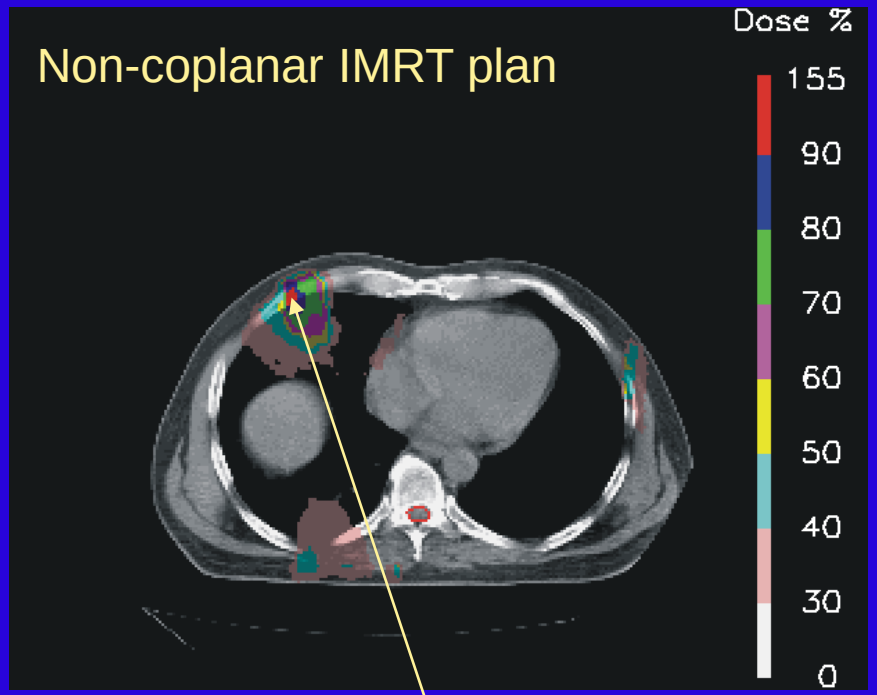
DVH's - Problems and pitfalls

2. DVHs can only be calculated for defined VOIs.

Visual inspection however shows the IMRT plan to be unacceptable



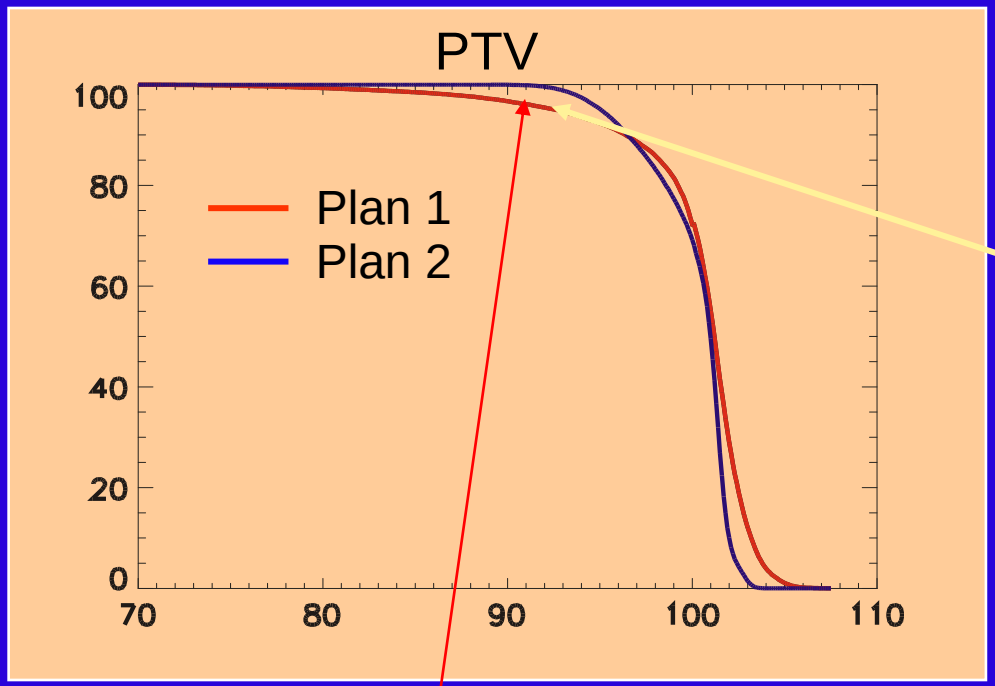
>120% hot spot in rib in target plane

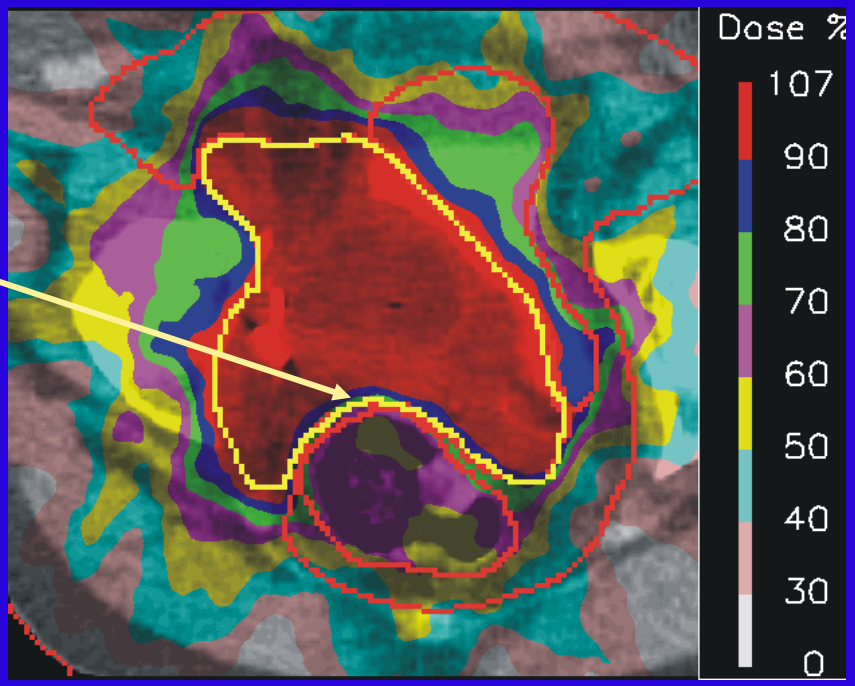


>90% hot spot in rib *out of* target plane

DVH's - Problems and pitfalls

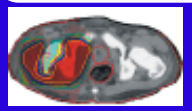
3. DVHs throw away all spatial information





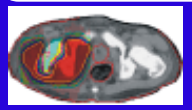
DVH analysis shows clear under-dosage for plan 1 vs plan 2, but...

… it needs analysis of the dose distribution to show where.



The display and analysis of dose distributions

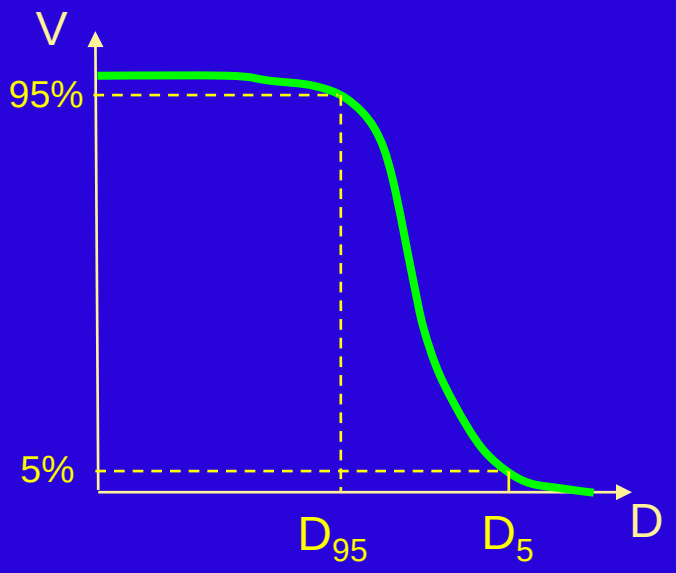
1. Displaying dose
2. Dose volume histograms
3. Characterising dose distributions and DVH's



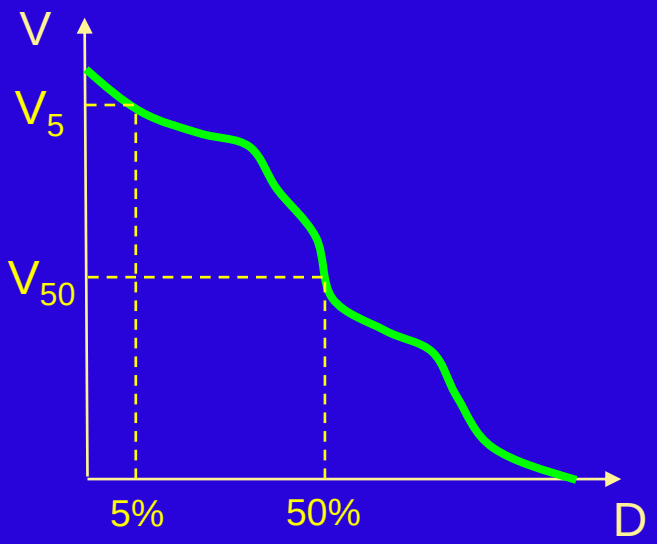
Characterising dose distributions

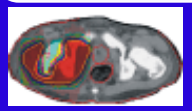
Common Dose-Volume parameters

D_v – The minimum dose (%/Gy) that volume v (%/ml) of a selected organ receives



V_d – The volume (%/ml) of a selected organ that receives at least dose d (%/Gy)





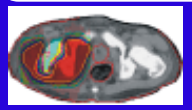
Characterising dose distributions
Common Dose-Volume parameters?

Table 1. Various normal tissue doses reported for IMRT breast plans in the literature compared with the results for plans X-E, IMXT1, IMXT2 and P from this work

	Authors and plans									
Dose parameter	Evans *et al.* (5)	Kestin *et al.* (7)	Van Asselen *et al.* (4)	Hong *et al.* (6)	Li *et al.* (8) (IMRT)	Li *et al.* (8) (IMXE)	Smitt *et al.* (3)	X-E	IMX1	IMX2	P
PTV (breast only)											
Max dose (%)		108.0		112.0	117.0	130		163.0	111.8	129.4	108.0
Min dose (%)					80.0	80.0	45.6	0.0	76.2	47.0	69.6
V95 (%)	95.2	98.0						86.6	96.2	88.1	97.1
V105 (%)	7.2							24.6	3.3	12.5	0.5
D05 (%)				107.0				108.0	105.0	108.0	104.0
D95-D05 (%)			7.6					36.0	10.0	16.0	8.0
Ipsilateral lung											
Mean dose (%)			8.0		25.6	14.3	23.8	33.3	36.3	29.7	25.0
V50 (%)				27.0				28.1	24.4	30.9	22.9
Contralateral lung											
Mean dose (%)				0.7	14.1	2.6	6.0	2.5	24.7	21.3	1.2
Heart											
Max dose (%)					74.6	75.6	73.4	101.0	101.1	99.9	107.6
Mean dose (%)					24.6	10.3	27.8	29.3	32.1	15.8	11.6
D05 (%)				32.0				77.0	76.0	66.0	78.0
Contralateral breast											
Max dose (%)				0.0	62.1	44.8	33.7	2.5	53.7	32.8	2.7
Mean dose (%)				0.0	10.5	2.4	6.0	0.4	11.8	4.1	0.1

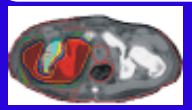
Abbreviations: V95 = the volume receiving >95% of the target dose; D05 = the maximum dose to which at least 5% of the volume is irradiated; IMRT = intensity-modulated radiation therapy; PTV = planning target volume.

Lomax et al, IJROBP, 55, 2003, 785-792



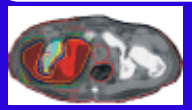
Overview

1. Displaying and interpreting dose distributions
2. Scoring and evaluating plans
3. Summary



Scoring and evaluating plans

1. What is an optimal plan?
2. Biological based scoring



What is an optimal plan?
An example

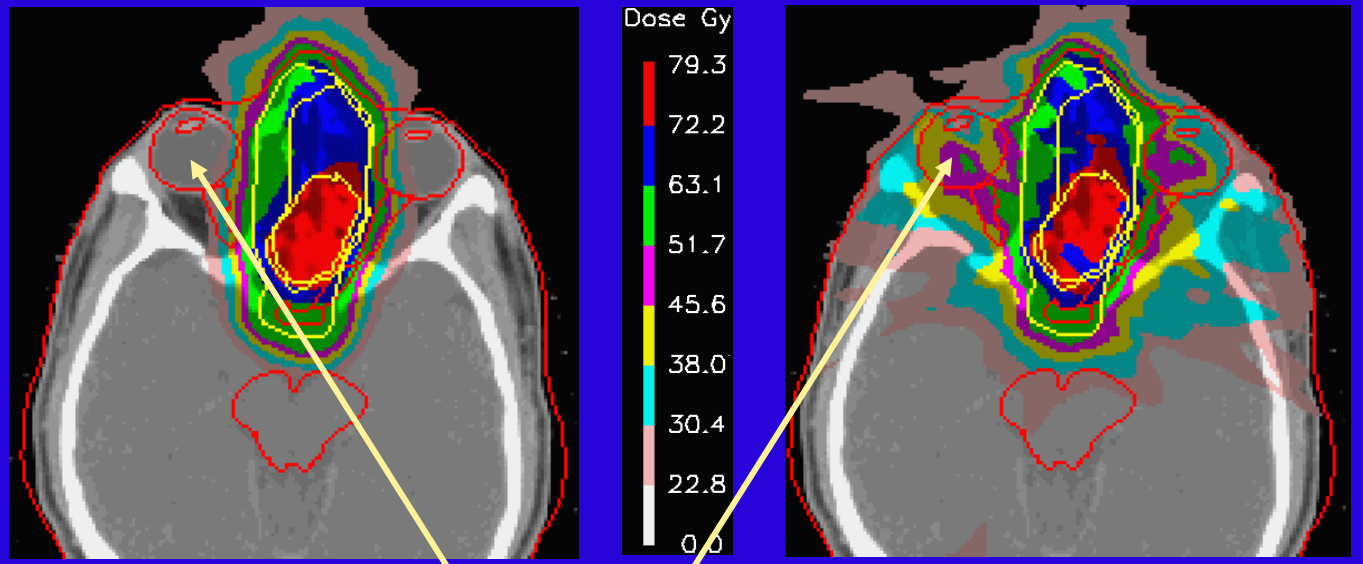
9 intensity-modulated beams, evenly spaced over 360^0

3 Target Volumes
Gross volume: 76Gy
Subclinical: 66Gy
Microscopic: 54Gy

Nominal constraints
Optic nerves < 56Gy
Brainstem < 53Gy
Eyes < 50Gy

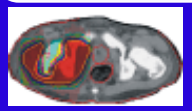
Consider a comparison of intensity modulated protons and IMRT photons...

Protons

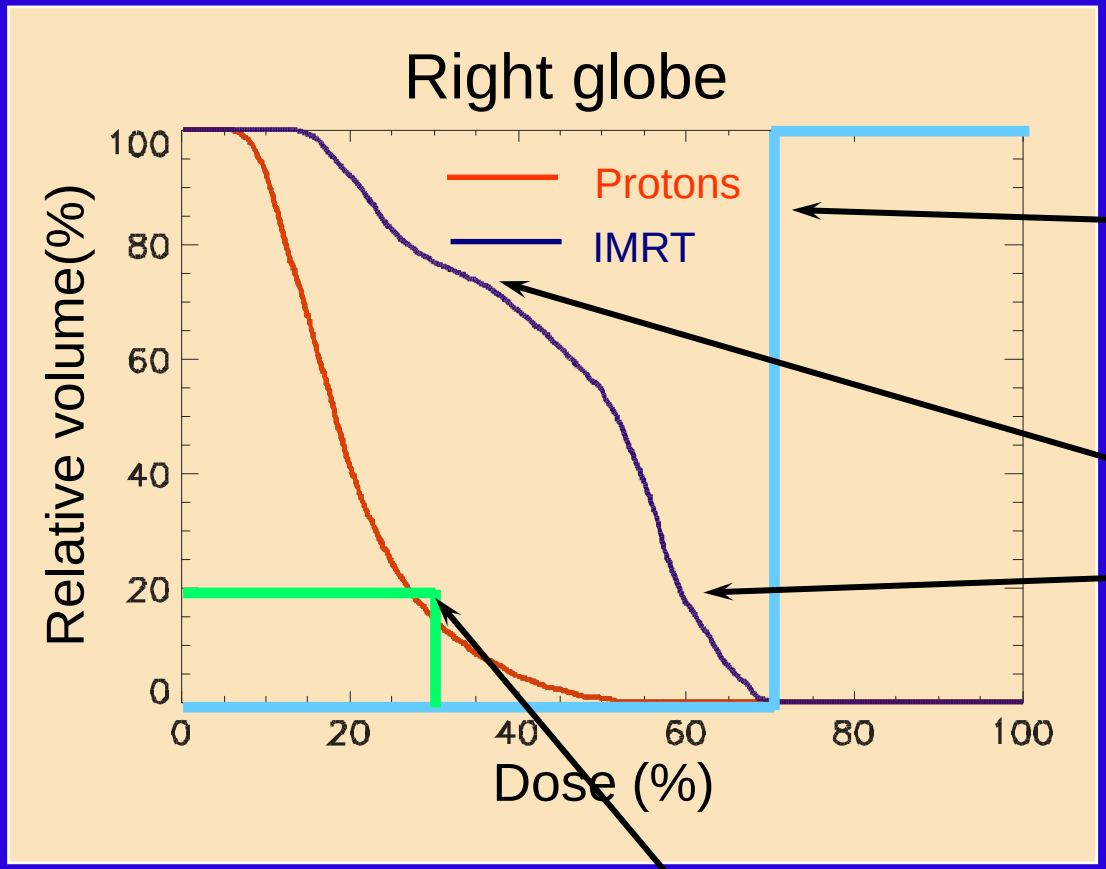


IMRT

Both plans calculated with exactly the same constraints, but clear differences in doses



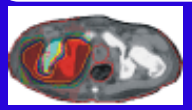
What is an optimal plan?
An example



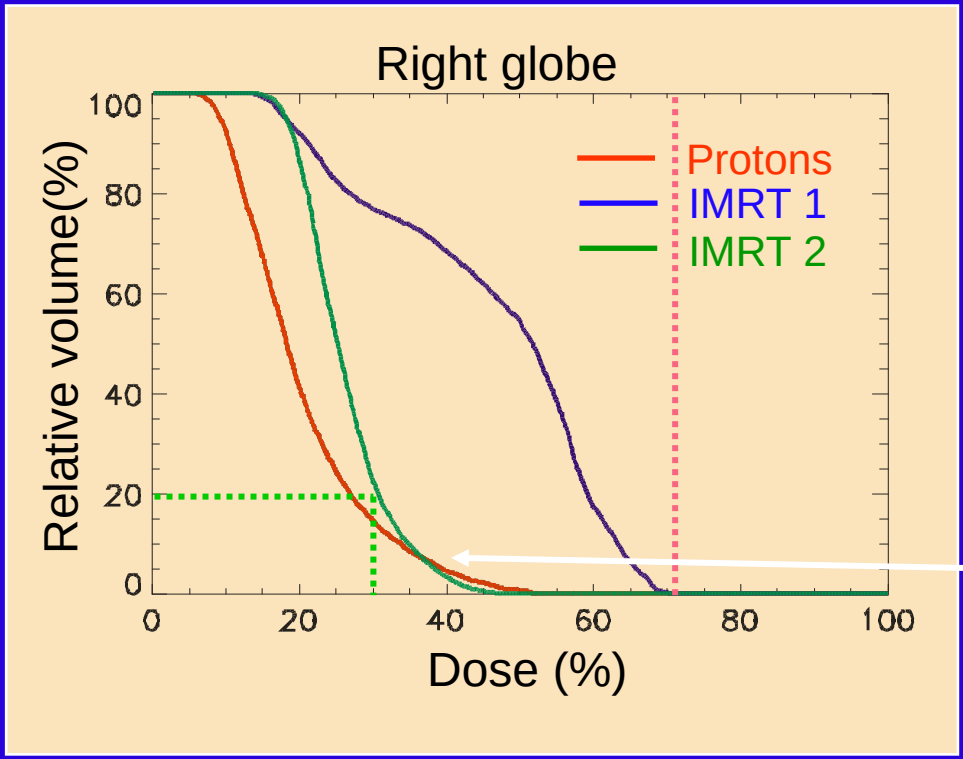
Single dose weighting function

Optimisation makes no attempt to reduce doses below constraint (zero weight)

What happens when we use a *dose-volume* constraint to attempt to match IMRT DVH to proton (nominal) DVH?

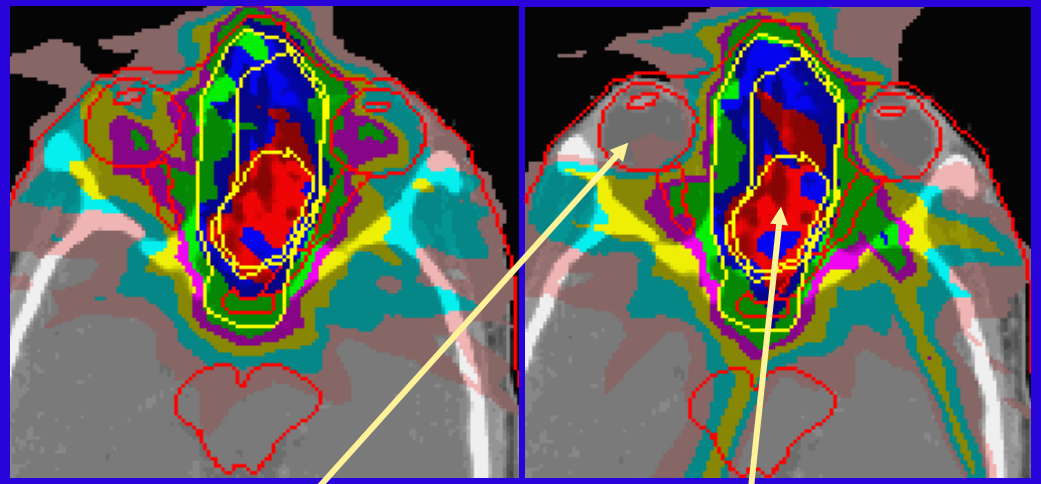


What is an optimal plan?
An example



IMRT plan 1

IMRT plan 2

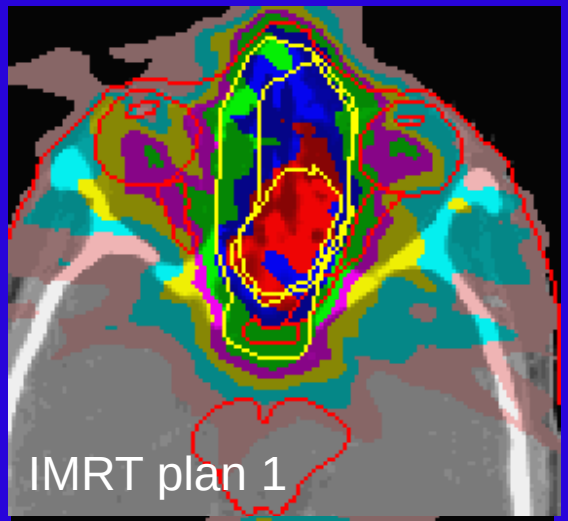


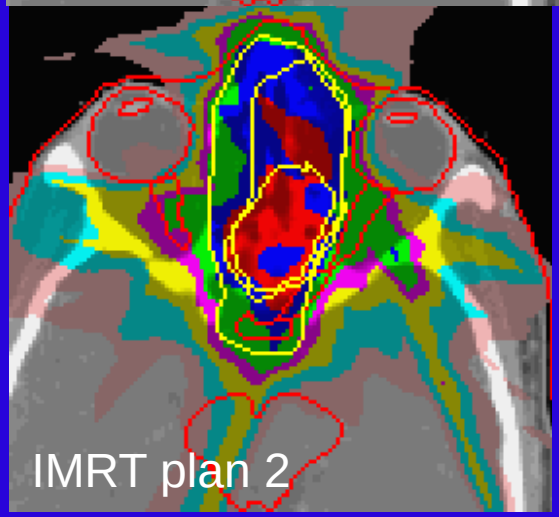
Significantly reduced dose in globe through use of stricter constraint…

..at cost of slightly decreased target homogeneity

The quality of an ‘optimised’ plan depends on the defined constraints

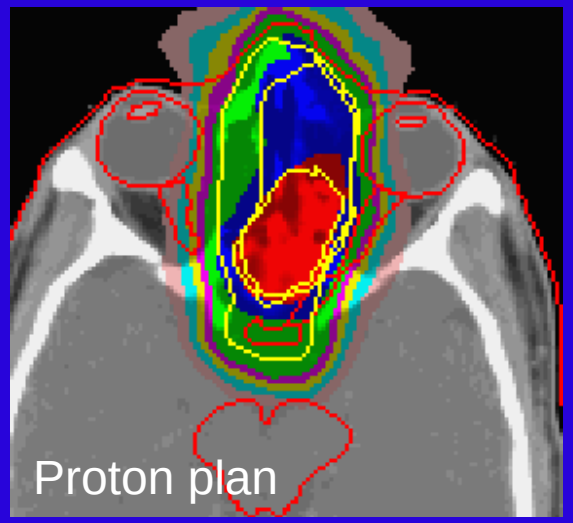
What is an optimal plan?
An example





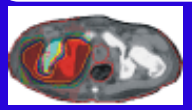
Two ‘optimised’ X-ray plans, with two quite different dose distributions.

Which is optimal, or even, which is best?



Scoring and evaluating plans

1. What is an optimal plan?
2. Biological based scoring

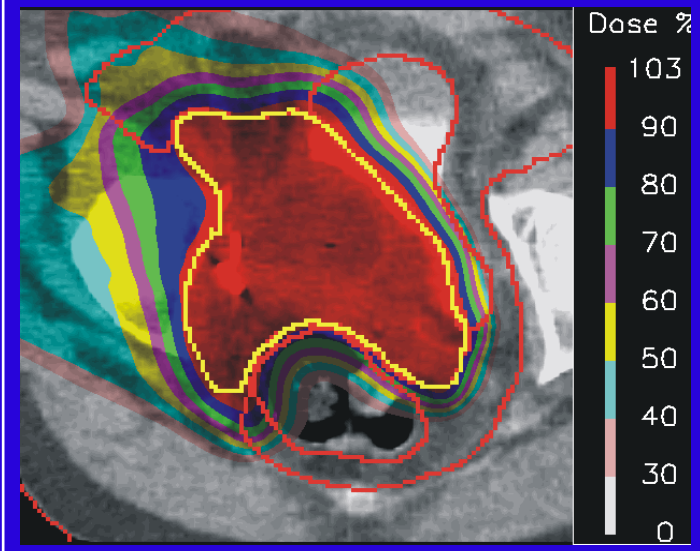


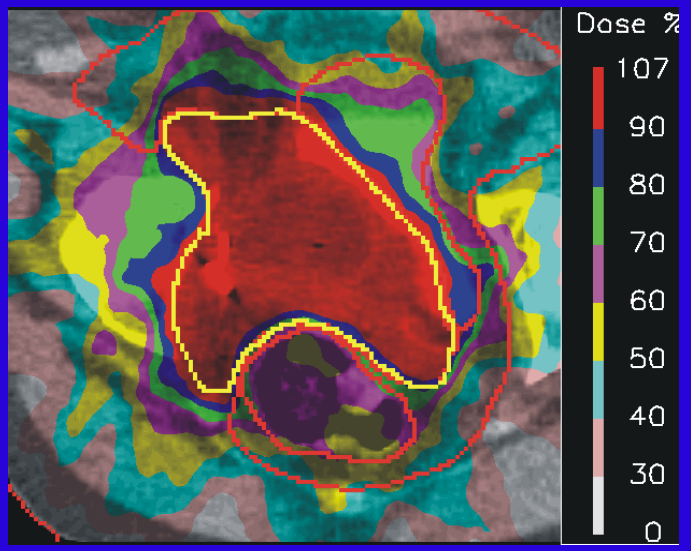
Biological based scoring

Problems with ‘dose only’ based scoring

Visual assessments difficult to quantify.

Many, often conflicting indices required to fully characterise a plan

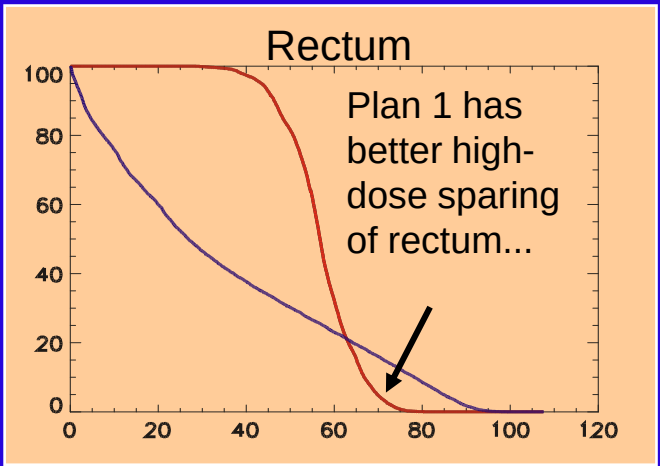




Biological based scoring

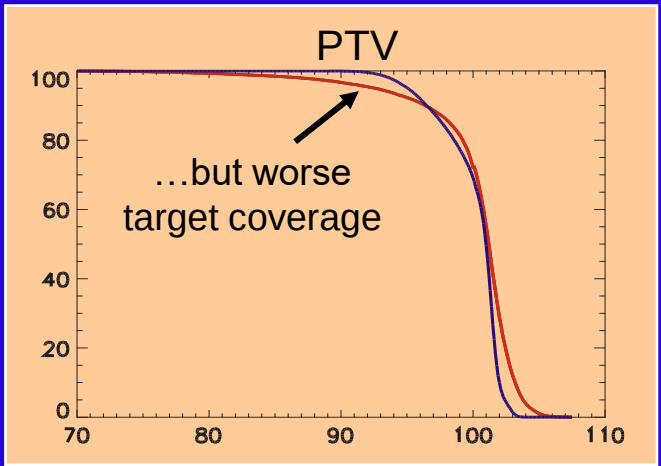
Problems with 'dose only' based scoring

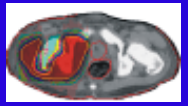
Visual assessments difficult to quantify.



Many, often conflicting indices required to fully characterise a plan

E.g.

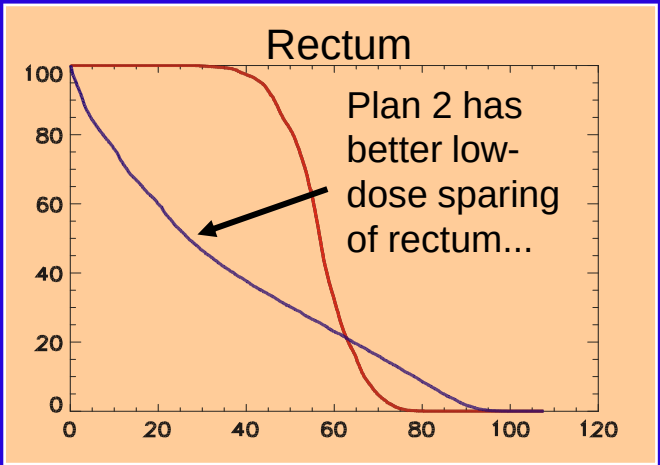




Biological based scoring

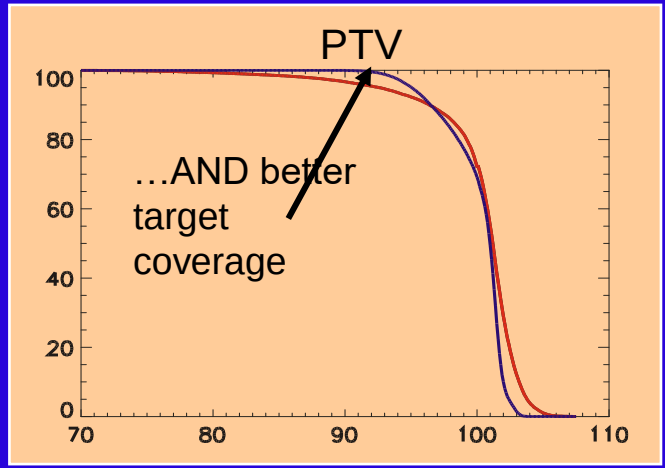
Problems with 'dose only' based scoring

Visual assessments difficult to quantify.

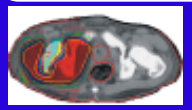


Many, often conflicting indices required to fully characterise a plan

Or..



Comparison of DVH's that cross impossible without knowledge of underlying biology

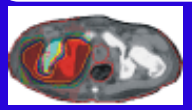


Biological scoring.

Plan scoring based on biological indices

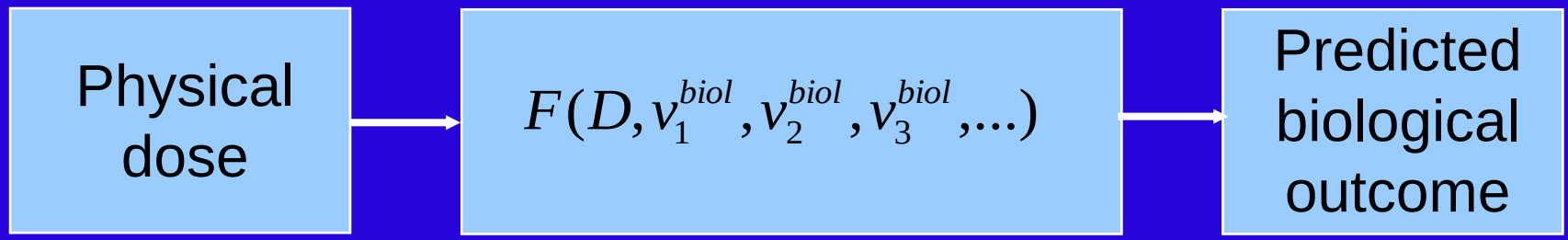
Advantages

1. Clinically relevant scoring function
2. Small number of indices required to characterise plan
3. In theory, can be reduced to single quality figure (weighted combination of tumour control and normal tissue complication probabilities)



Biological models.

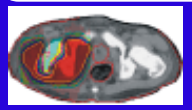
Biological models attempt to transform the physical dose (or DVH) into some biologically relevant end-point. E.g.



Two types of biological models can be considered:

NTCP - Normal Tissue Complication Probability

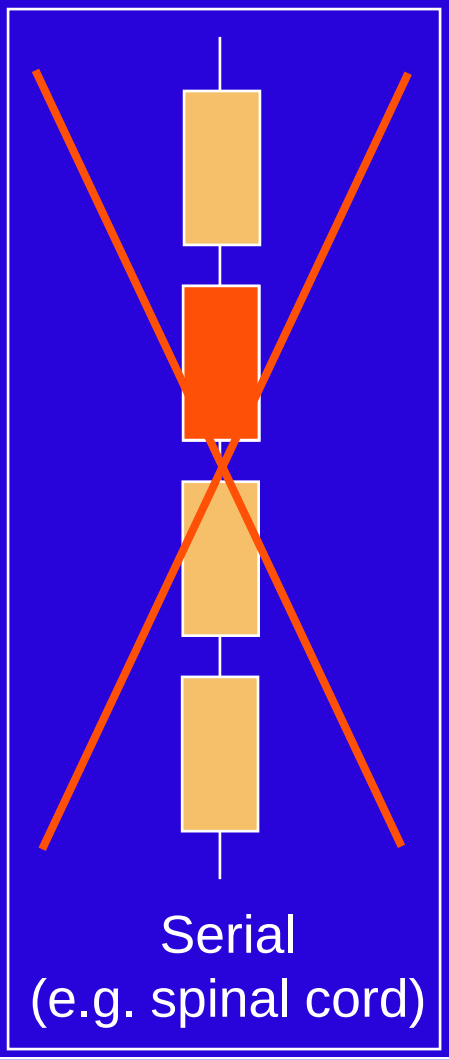
TCP - Tumour Control Probability



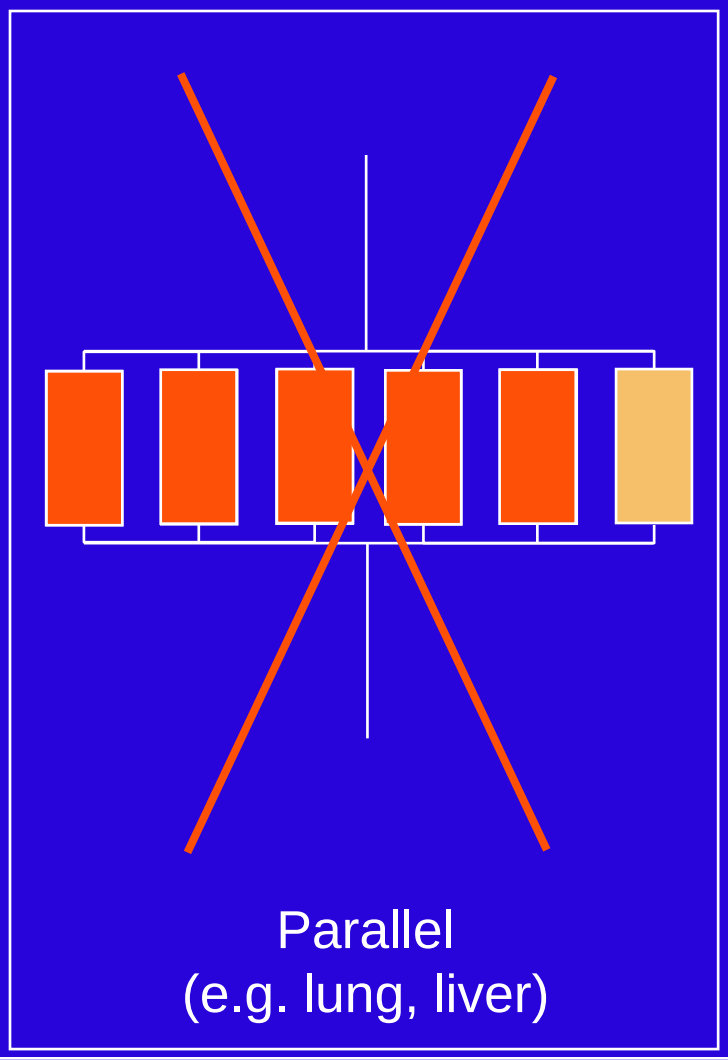
Biological models.

All models must make some assumptions about tissue architecture

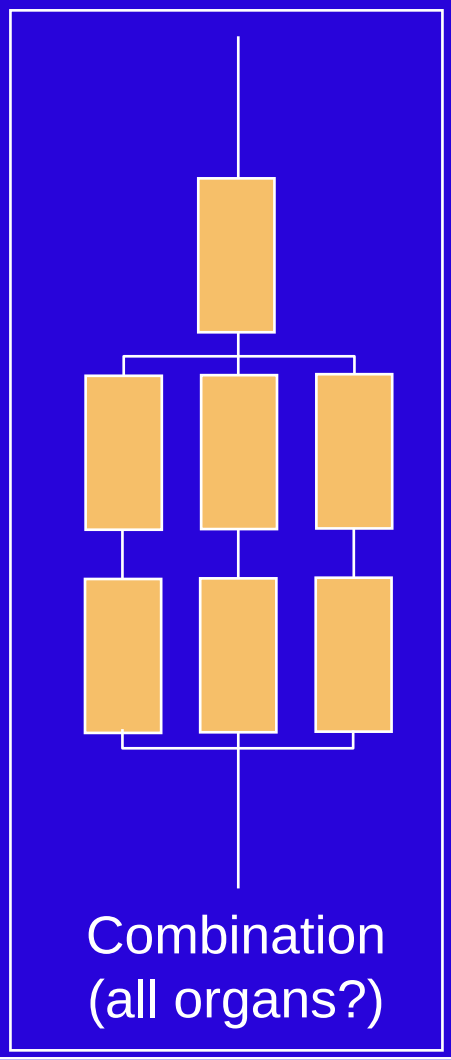
Functional Sub-unit (FSU)



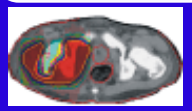
Serial
(e.g. spinal cord)



Parallel
(e.g. lung, liver)



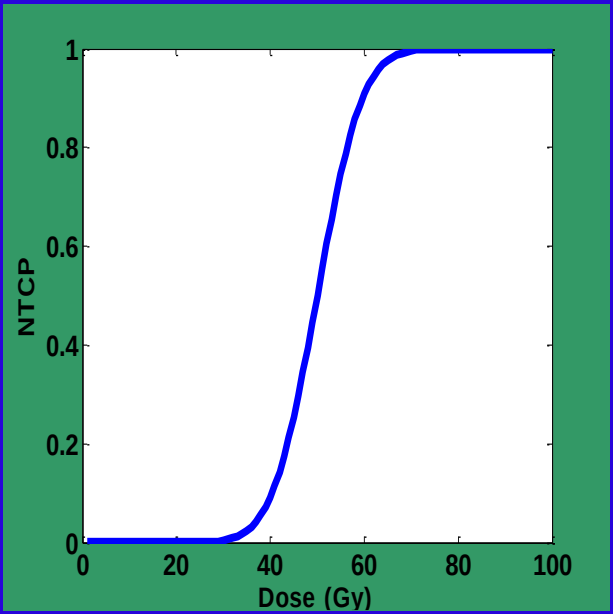
Combination
(all organs?)



Biological models.

E.g. The 'Lyman-Kutcher-Burmann' model for NTCP…

(Lyman LY, Wolbarst B, Int. J. Radiat. Oncol. Biol. Phys, 13:103-109 1987)



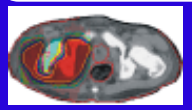
$$NTCP = \Phi(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} \exp(-t^2/2)dt$$

Where:

$$x = \frac{D_{eff} - D_{50}}{mD_{50}} \quad \text{and} \quad D_{eff} = \left(\sum_i v_i D_i^{1/n} \right)^n$$

Φ - Probit function

Models the probability of a complication as a sigmoid function



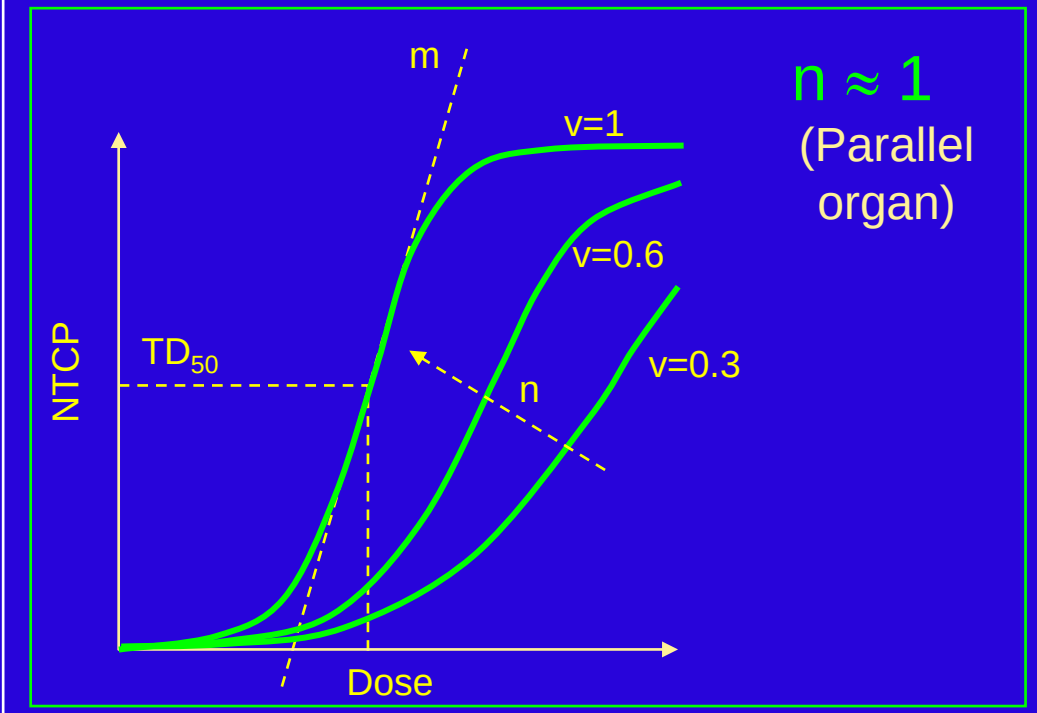
Biological models.

E.g. The 'Lyman-Kutcher-Burmann' model for NTCP…

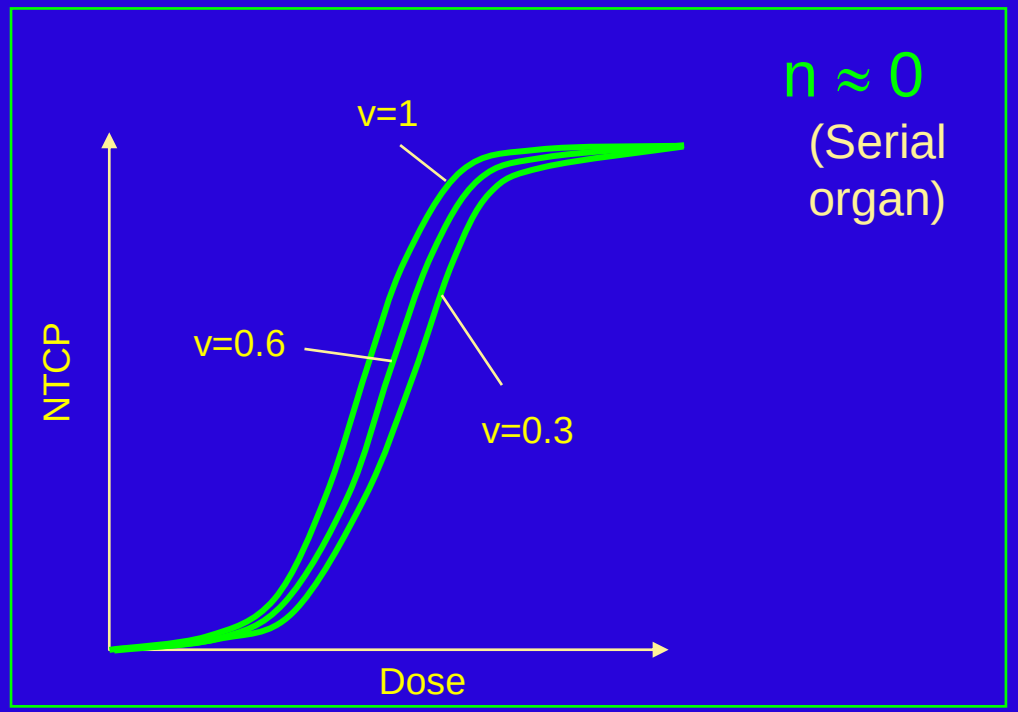
(Lyman LY, Wolbarst B, Int. J. Radiat. Oncol. Biol. Phys, 13:103-109 1987)

A 3 parameter 'phenomological' model

- TD_{50} Dose to *whole* organ resulting in 50% probability of complication
- m Gradient of response curve at TD_{50}
- n 'Volume' parameter



n ≈ 1 (Parallel organ)

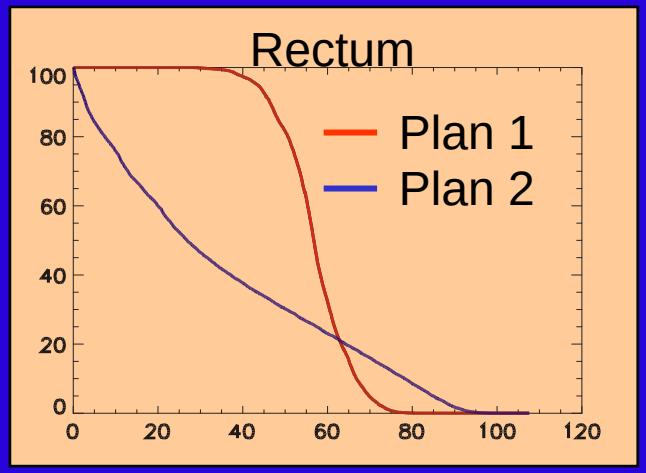


n ≈ 0 (Serial organ)

Biological scoring – reasons to be cautious.

1. Validity of the biological parameters.

Consider two competing DVHs for the rectum



Apply Lyman's NTCP model with standard volume parameter n=0.12 (Emami and Burman)

Plan 1 - 10.4%

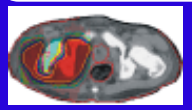
Plan 2 - 24.2%

Apply Lyman's NTCP model with modified volume parameter n=0.2

Plan 1 - 8.4%

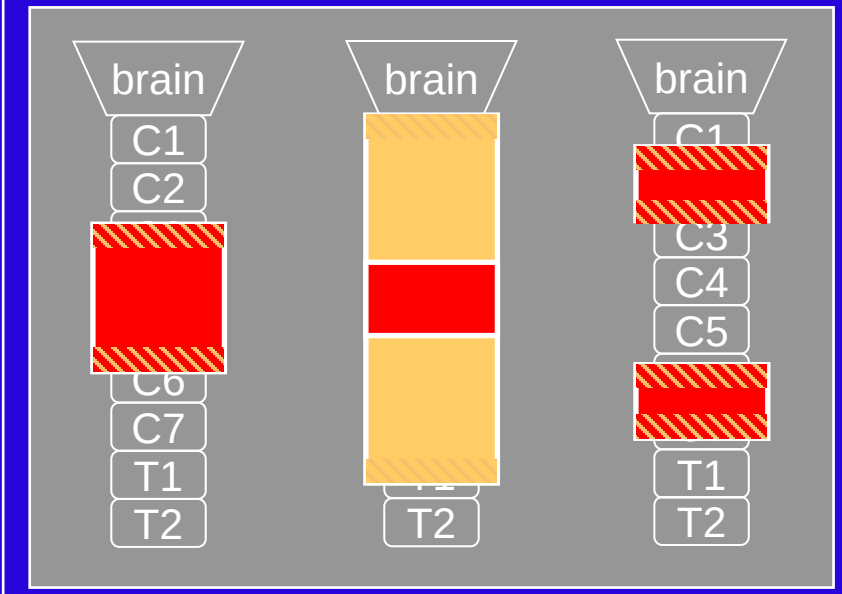
Plan 2 - 7.1%

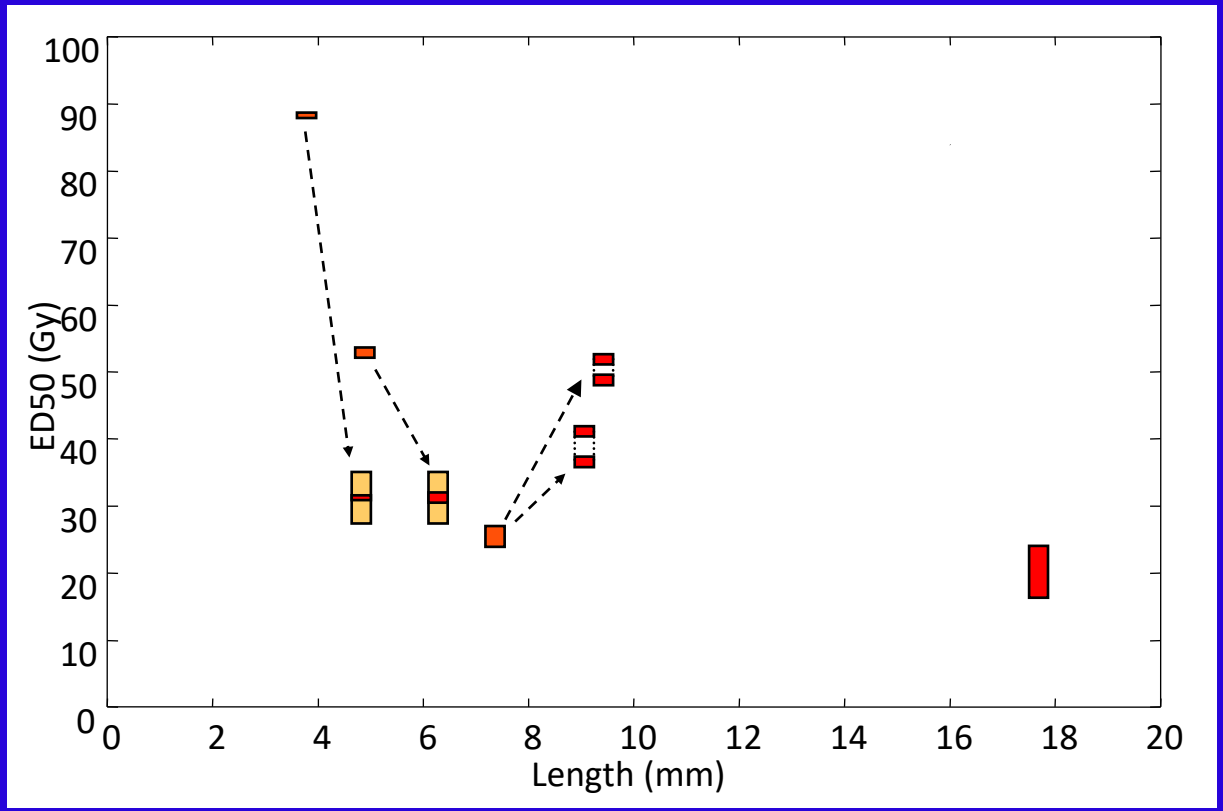
Ranking of plan changes for even a moderate change of a single input parameter



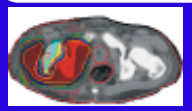
Biological scoring – reasons to be cautious.

2. Know your organ – Is the spinal cord actually serial?



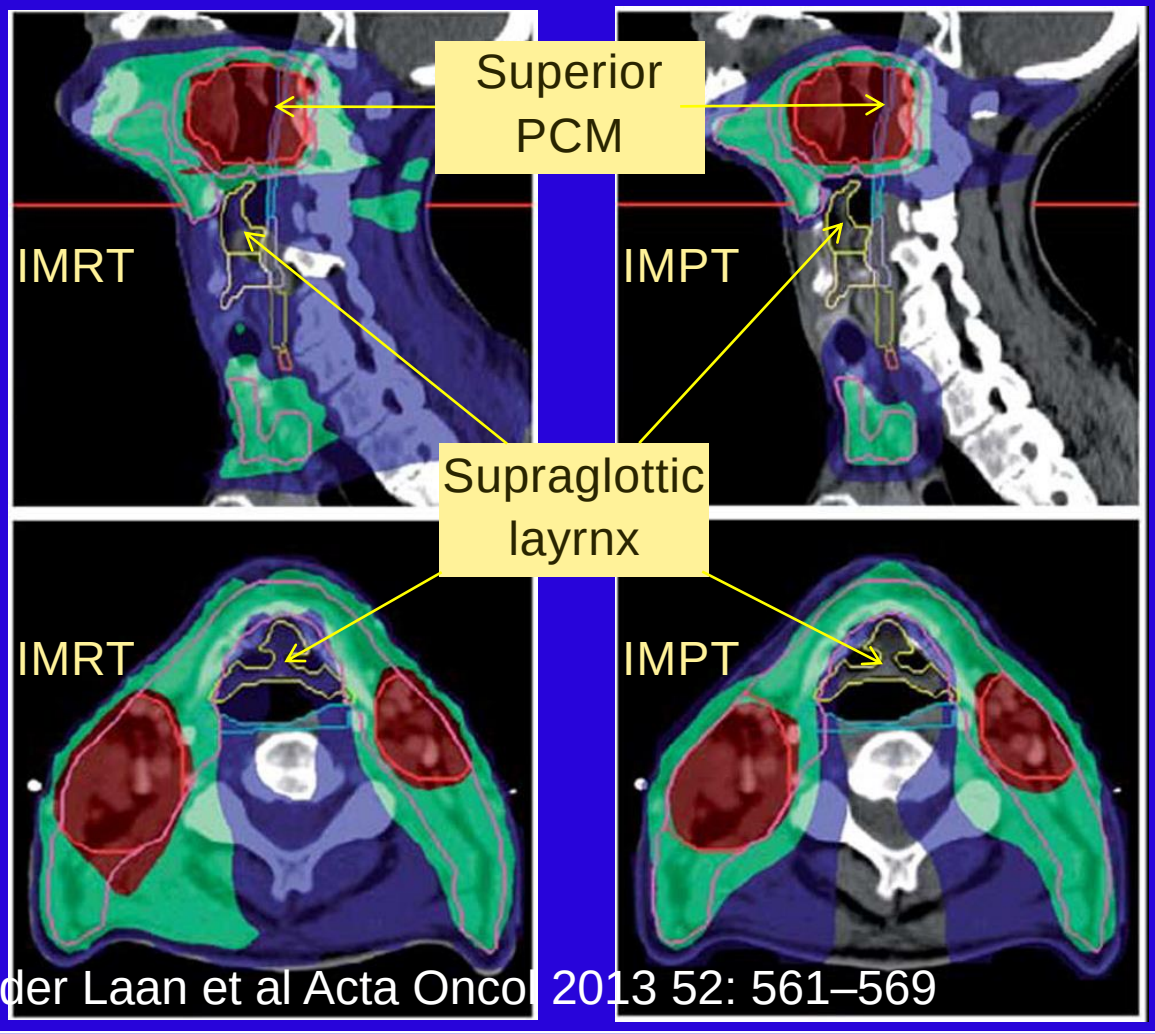


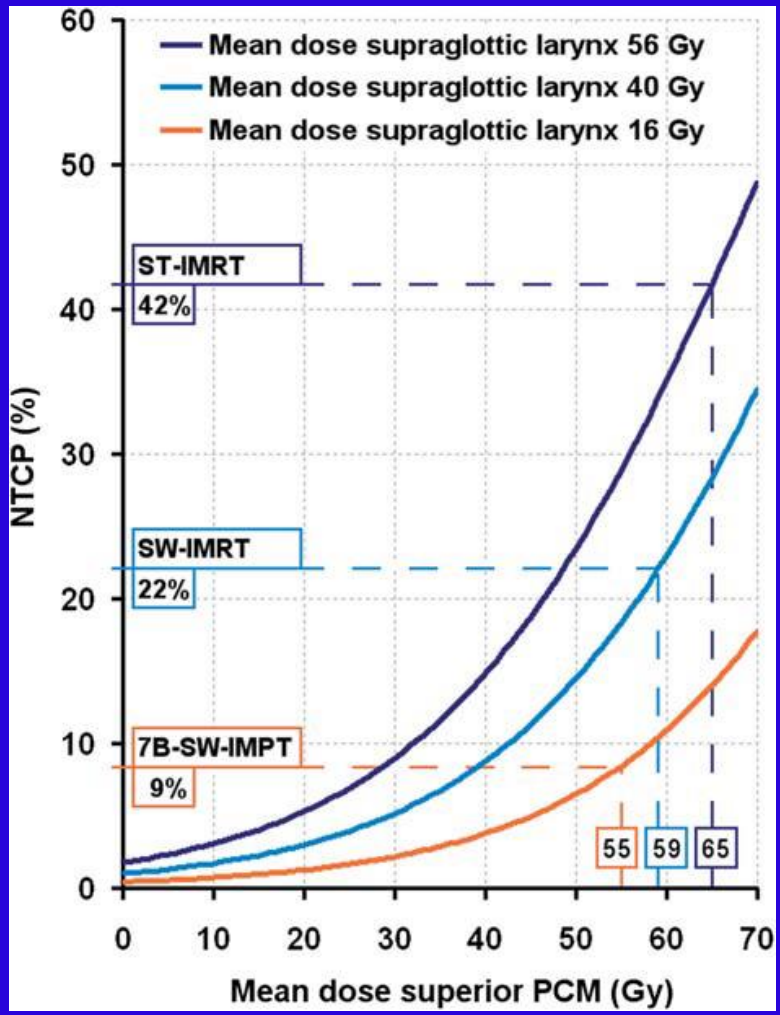
van Luijk et al 2005, IJROBP, 61:892-900



Biological scoring – reasons to be cautious.

3. NTCP may not be dependent on dose to a single organ



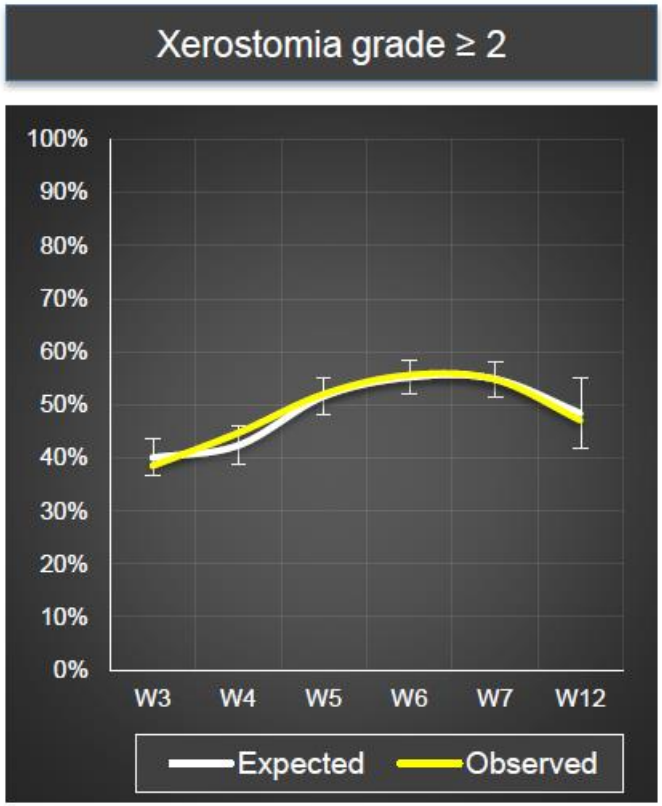


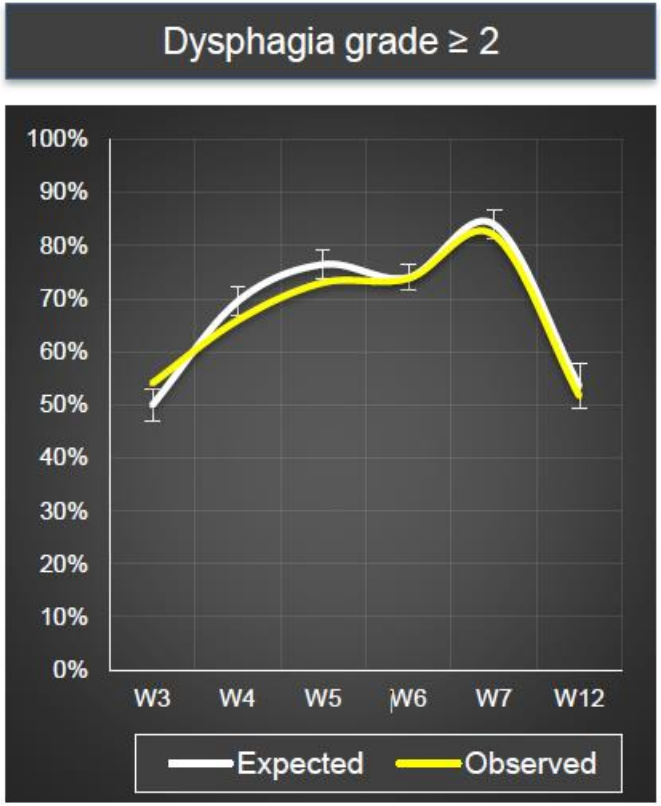
Van der Laan et al Acta Oncol 2013 52: 561–569

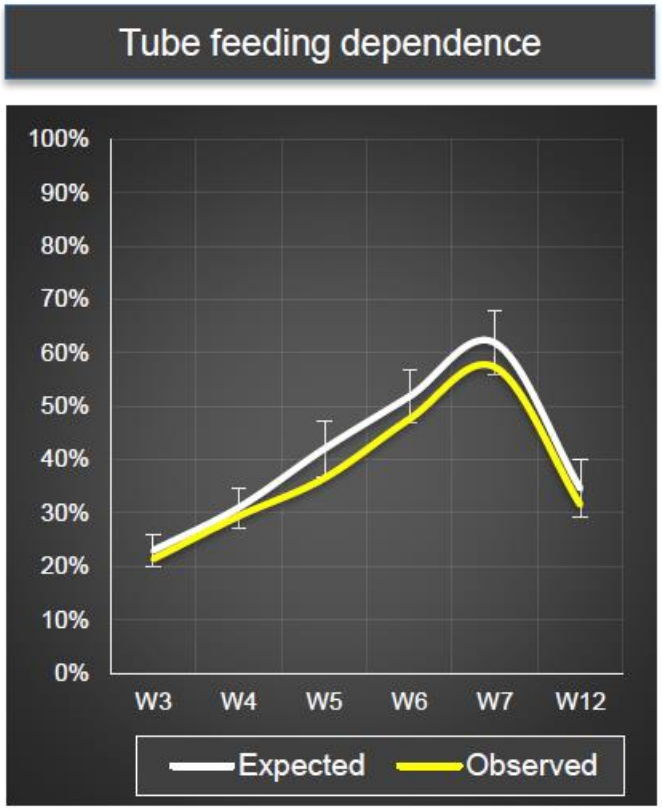
Biological models in the clinic – an example.

Validated NTCP models for patient selection for protons

Predicted and observed toxicity for 126 *photon* patients (VMAT)







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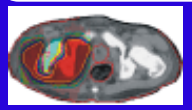
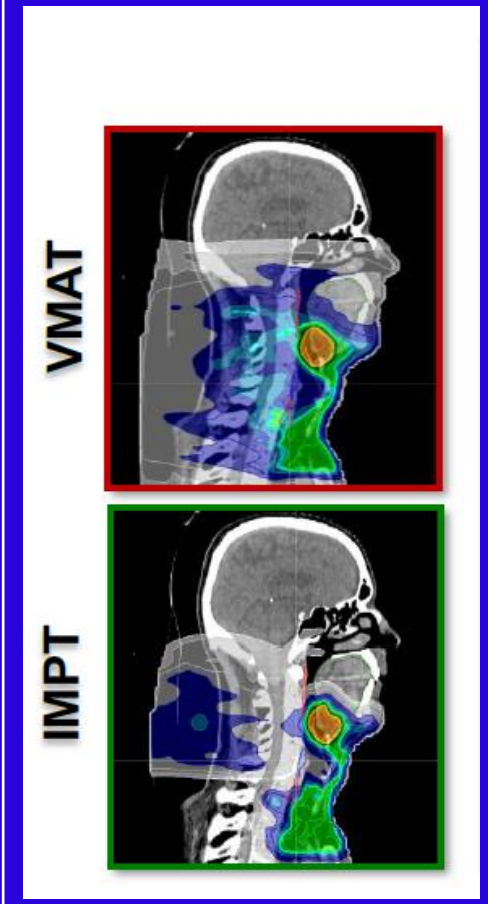


Biological models in the clinic – an example.

Validated NTCP models for patient selection for protons

Dysphagia NTCP comparison (IMPT vs VMAT) for an example patient



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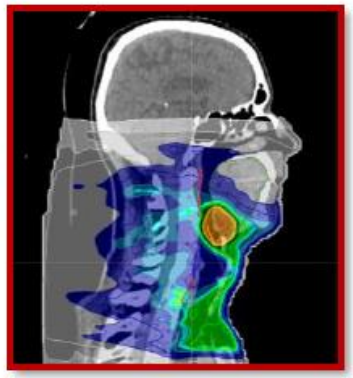
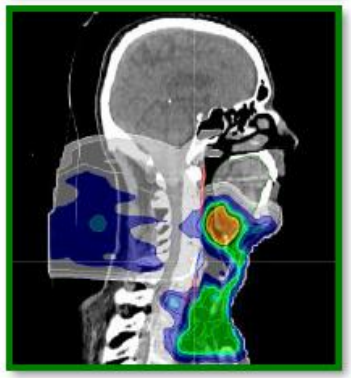
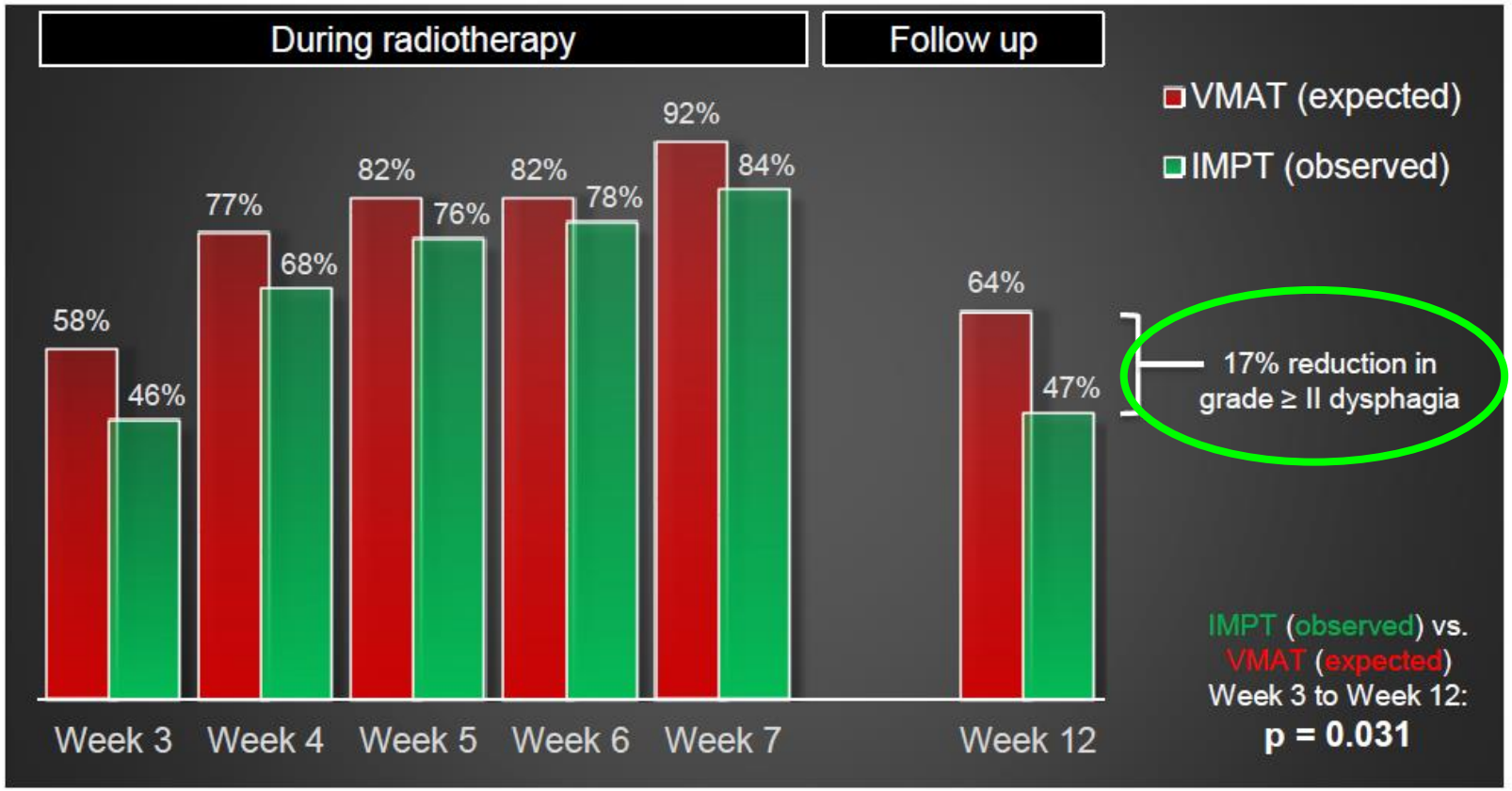
Biological models in the clinic – an example.

Validated NTCP models for patient selection for protons

Dysphagia NTCP comparison (IMPT vs VMAT)







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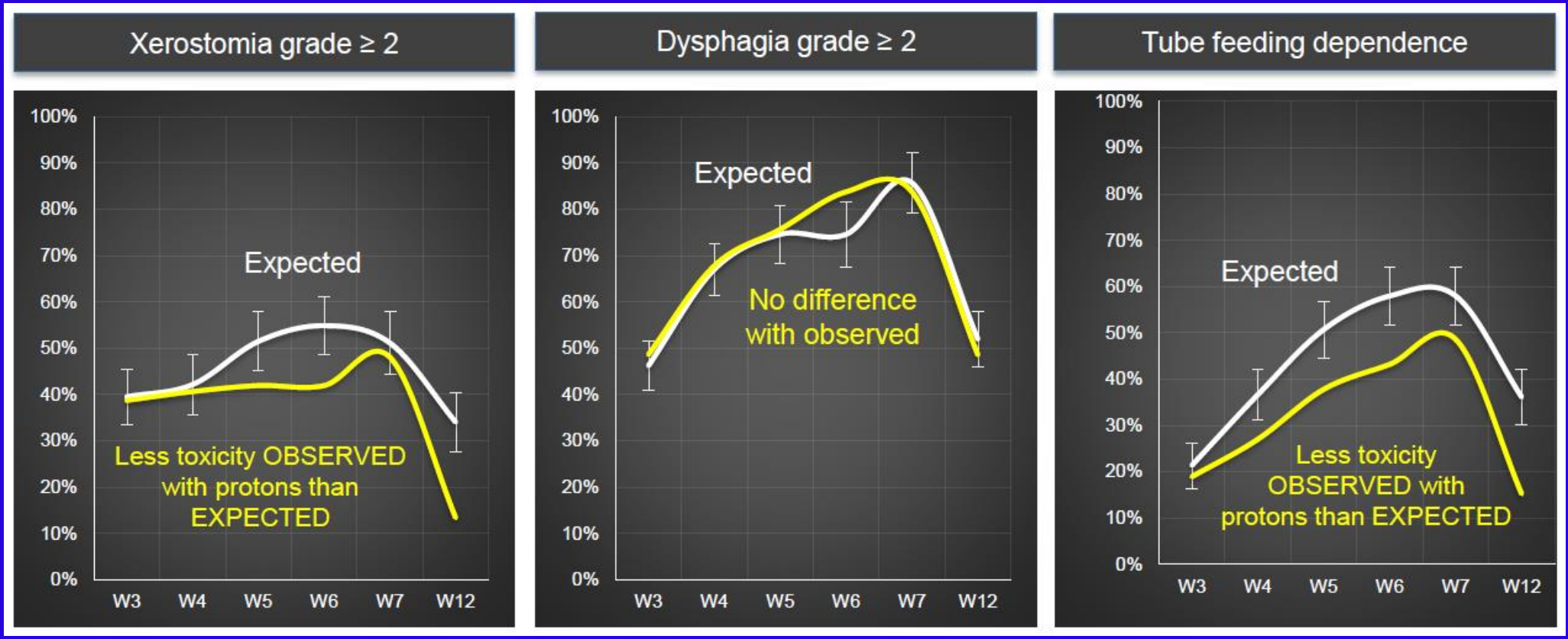
Biological models in the clinic – an example.

Validated NTCP models for patient selection for protons

Predicted and observed toxicities for *proton* patients selected using NTCP



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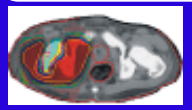
Overview

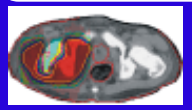
1. Displaying and interpreting dose distributions
2. Scoring and evaluating plans
3. Summary



Summary 1.

Visual assessment of dose distributions

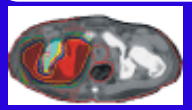
- The most direct and informative representation of a treatment plan available - however….
- 3-D dose distributions are large and cumbersome and difficult to analyse quantitatively



Summary 2.

Dose volume histograms

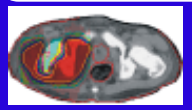
- Provide a succinct and quantitative method of representing 3-d dose within selected VOI's - however…
- DVH's should only be used in conjunction with careful visual analysis of 3-d dose distributions
- In particular, care should be taken when analysing large volumes using DVH's
- DVH's should always be assessed in conjunction with dose-volume statistics.



Summary 3.

Plan scoring.

- Dose based assessment is the ‘gold standard’, but can be difficult to quantify
- Biological scores give succinct results, but must always be interpreted with great caution – interesting research area though!



Course overview

Monday, 30th September

08:00-09:30 Basic physics	Prof. Tony Lomax
10:00-11:30 Delivery and verification	Dr. Nicolas Perichon
11:30-13:00 Lunch	
13:00-14:30 Imaging	PD Dr. Jean-Francois Germond
15:00-16:30 Beam shaping	Prof. Uwe Schneider

Tuesday, 01st October

08:00-09:30 Treatment planning	Prof. Uwe Schneider
10:00-11:30 TPS evaluation	Prof. Tony Lomax
11:30-13:00 Lunch	
13:00-14:30 Brachytherapy	Dr. Dario Terribilini
15:00-16:30 Radiation protection	Prof. Uwe Schneider
16:30-17:30 Tour of the department	*Optional*

Wednesday, 02nd October

08:00-09:30 Dosimetry	Dr. Jürgen Besserer
10:00-12:00 Special techniques	Prof. Tony Lomax & Prof. Raphael Moeckli