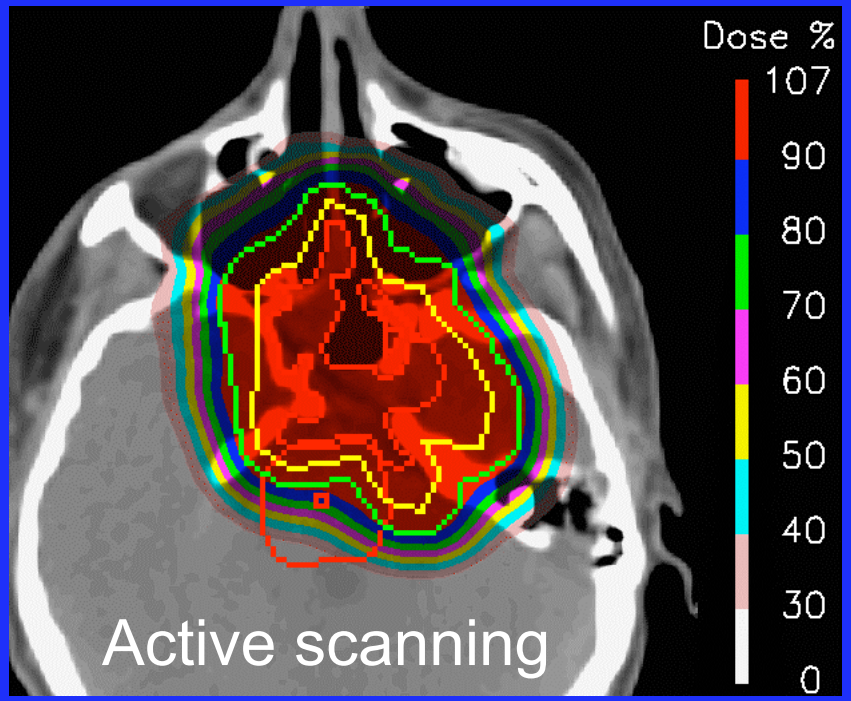
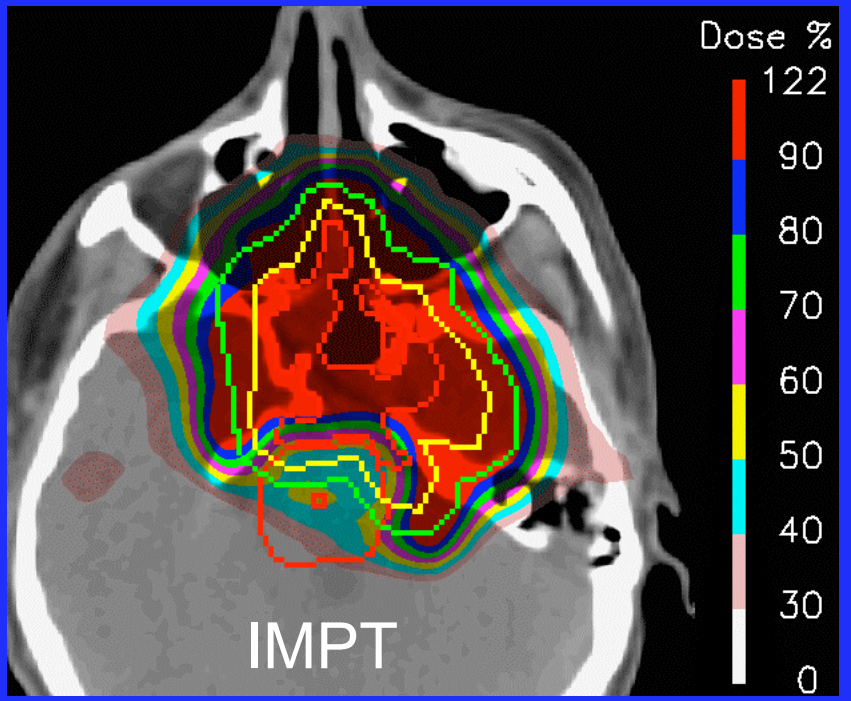
Treatment planning for scanned proton beams and IMPT





Tony Lomax, Centre for Proton Radiotherapy,
Paul Scherrer Institute, Switzerland

Treatment planning for scanning

1. Single Field, Uniform Dose (SFUD)
2. Intensity Modulated Proton Therapy (IMPT)
3. Field selection in proton therapy
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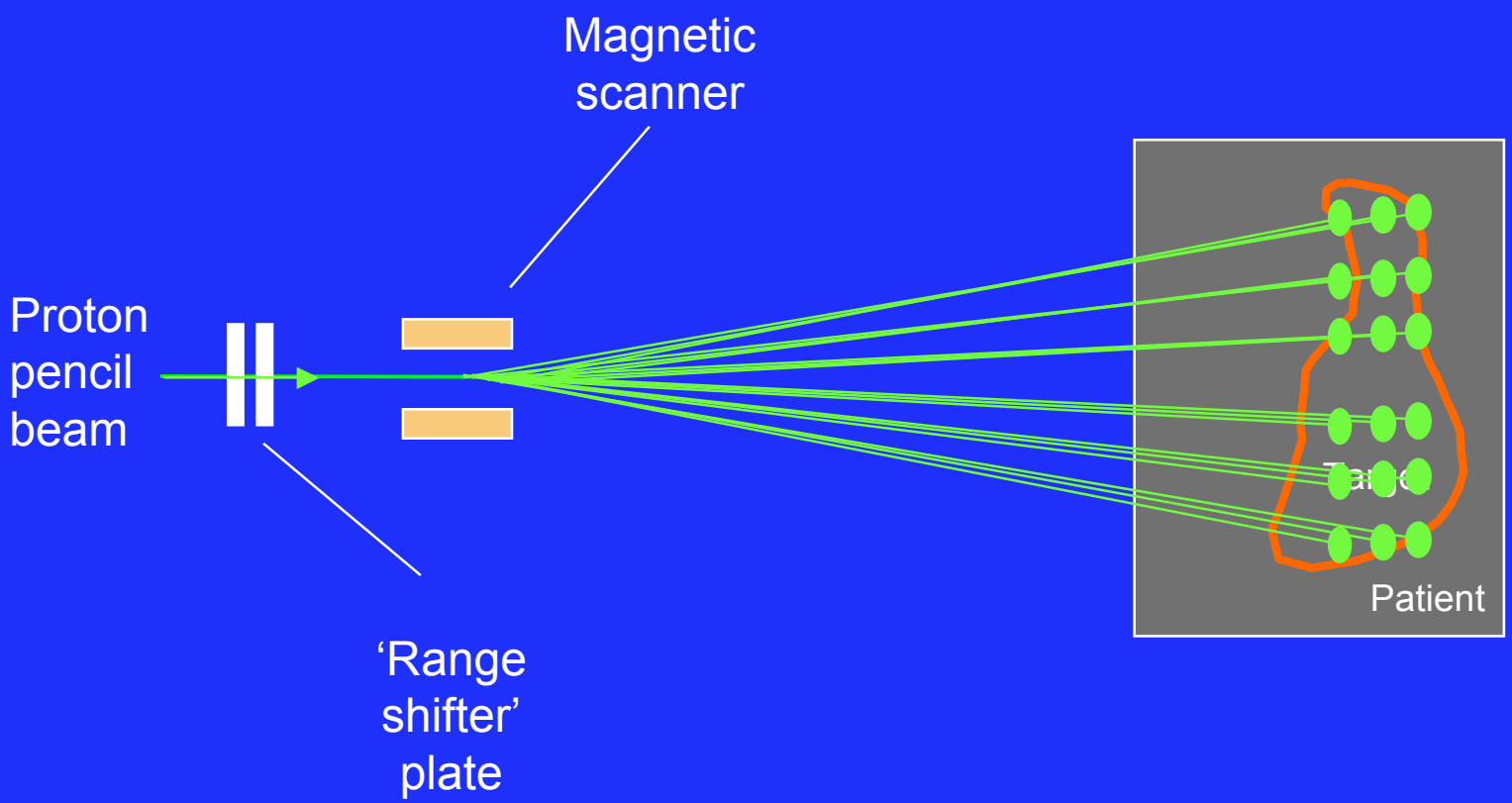
Spot scanning – the prinicple



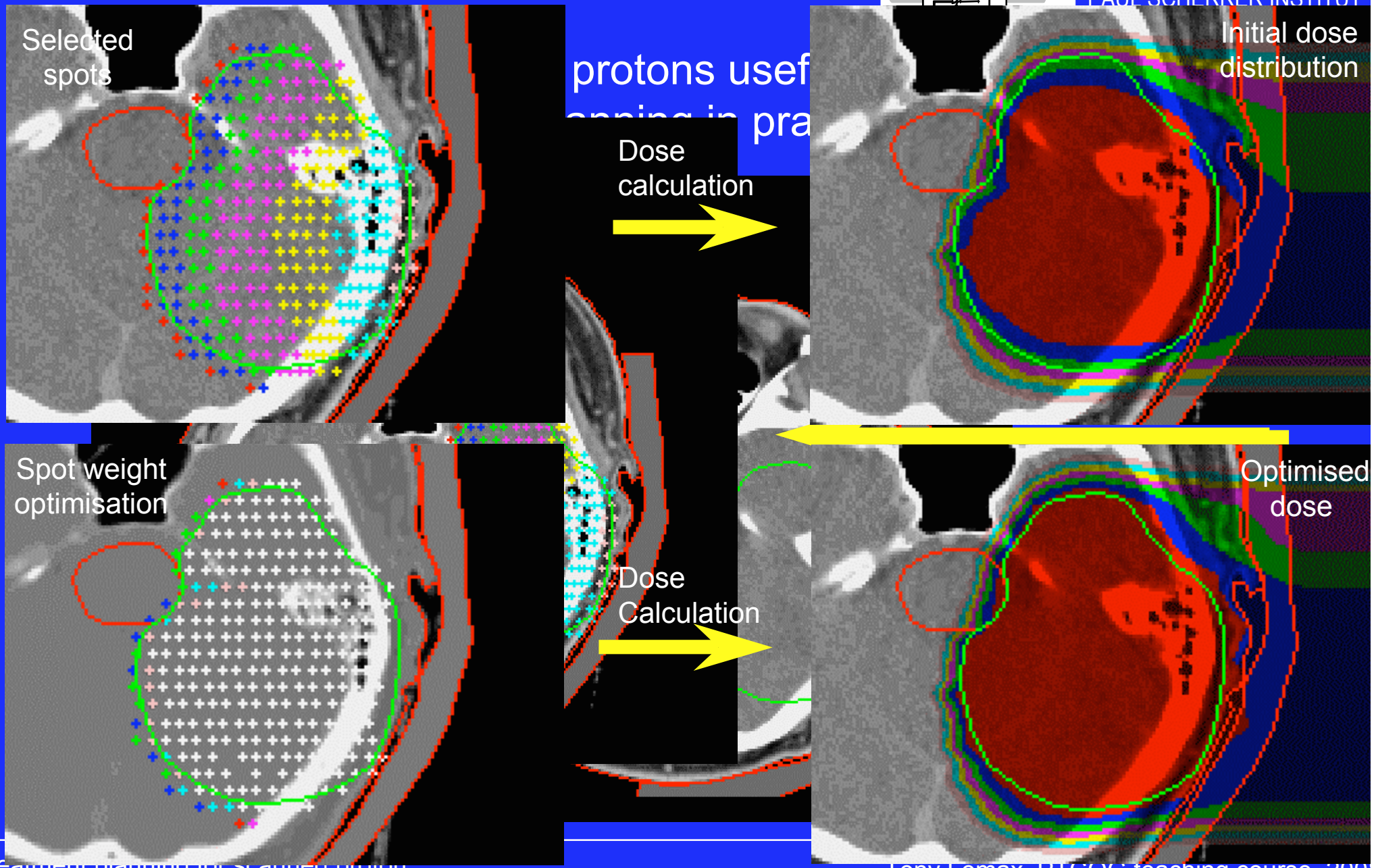
Pedroni et al, *Med Phys*. 22:37-53, 1995

Single field, uniform dose (SFUD) planning

The combination of individually optimised fields, each of which deliver a (more or less) homogenous dose across the target volume

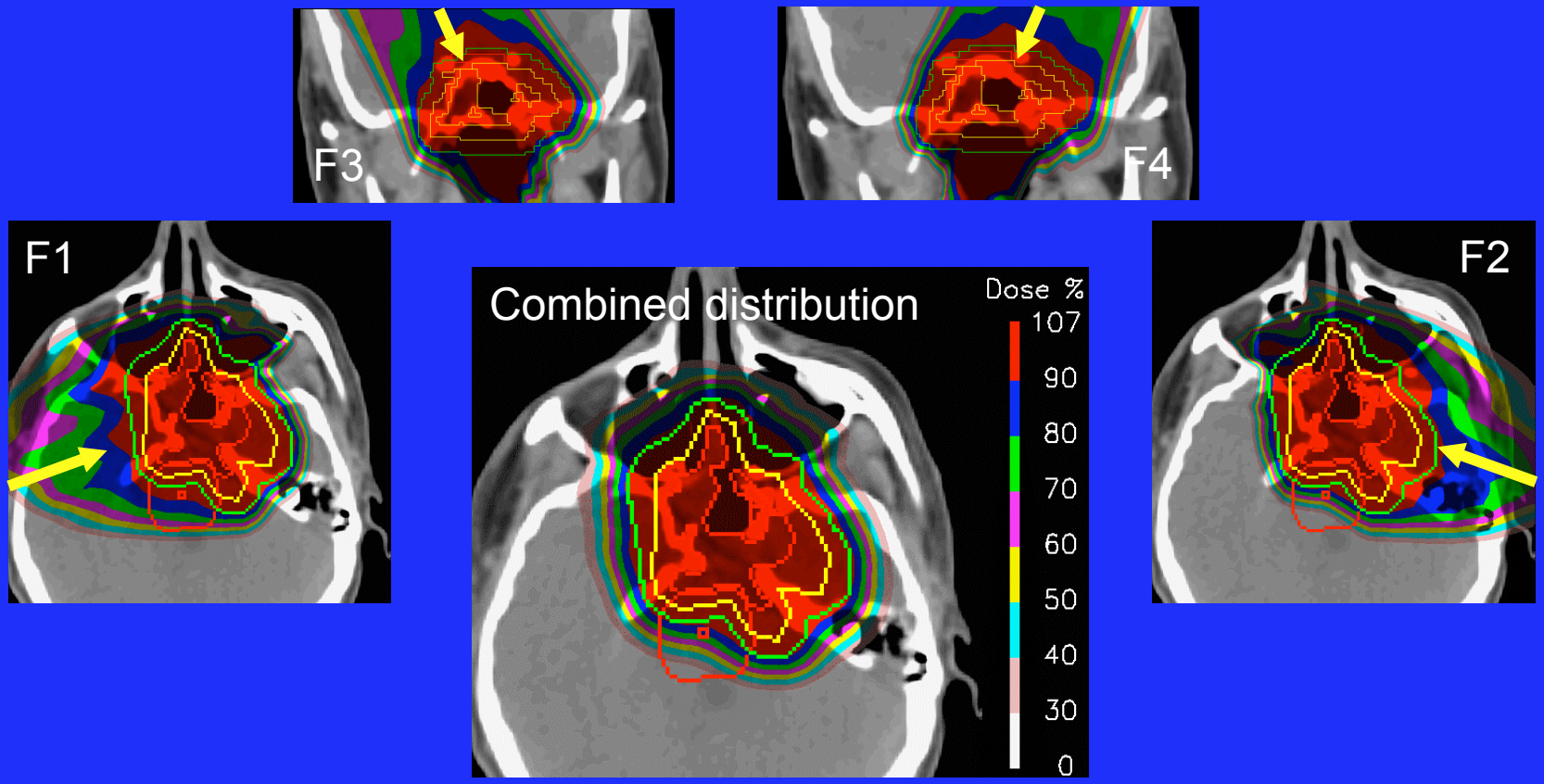
SFUD is the spot scanning equivalent of treating with ‘open’ fields.

Single Field, Uniform Dose (SFUD)



Single Field, Uniform Dose (SFUD)

A SFUD plan consists of the addition of one or more individually optimised fields.



Note, each individual field is homogenous across the target volume

Single Field, Uniform Dose (SFUD)

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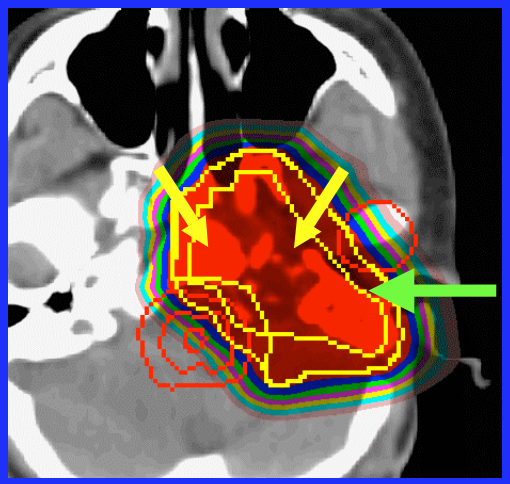
1st series
(0-40CGE)

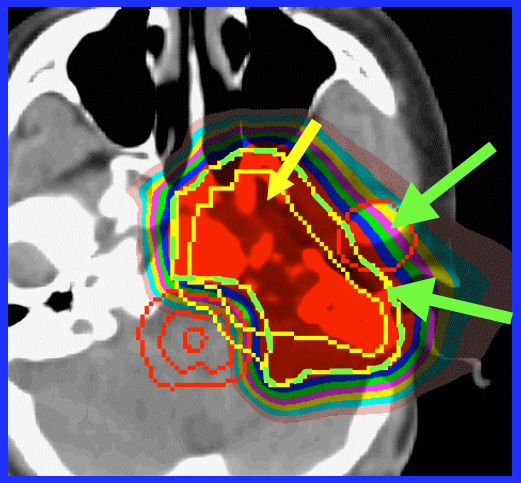
3 field 'hand' plan to PTV



+

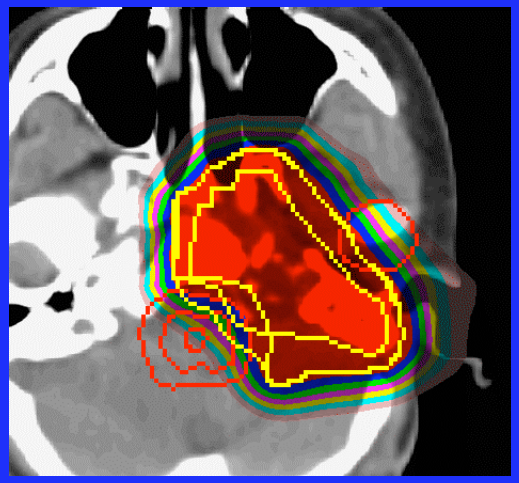
2nd series
(40-74CGE)

3 field 'hand' plan to 'TechPTV'



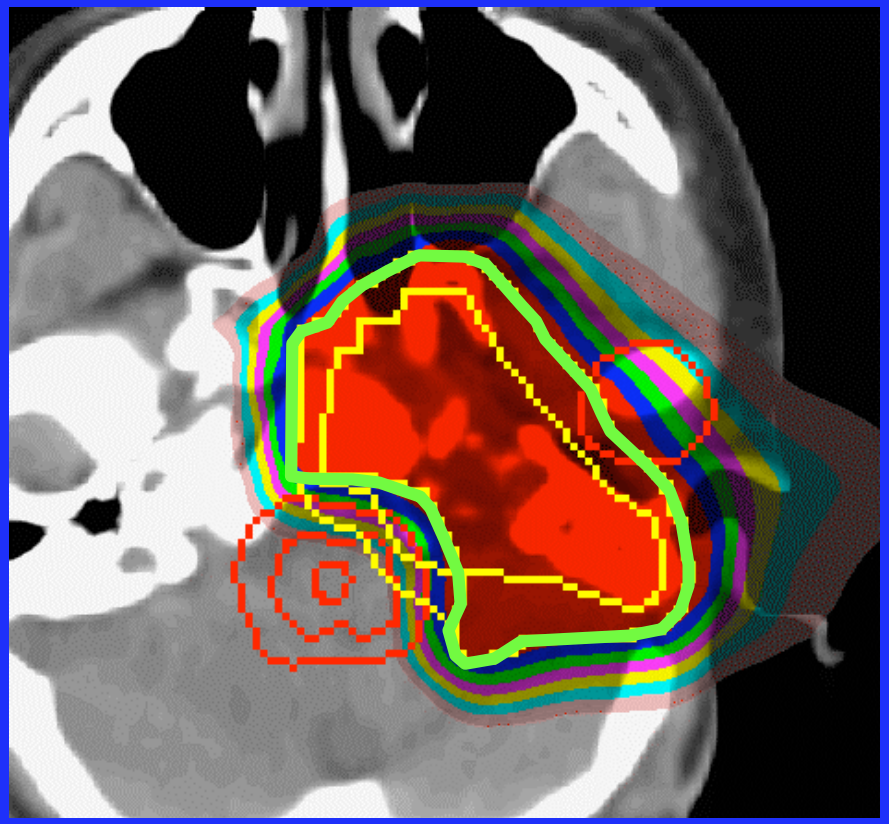
=

An example
SFUD treatment



Full treatment

The TechPTV or ‘Virtual 3d block’



In order to carve-out dose to neighbouring critical structures, need to be able to ‘block’ out dose

Modified target volume used to define ‘Virtual 3d blocks’

Currently, such volumes are defined manually on a slice-by-slice basis

Treatment planning for scanning

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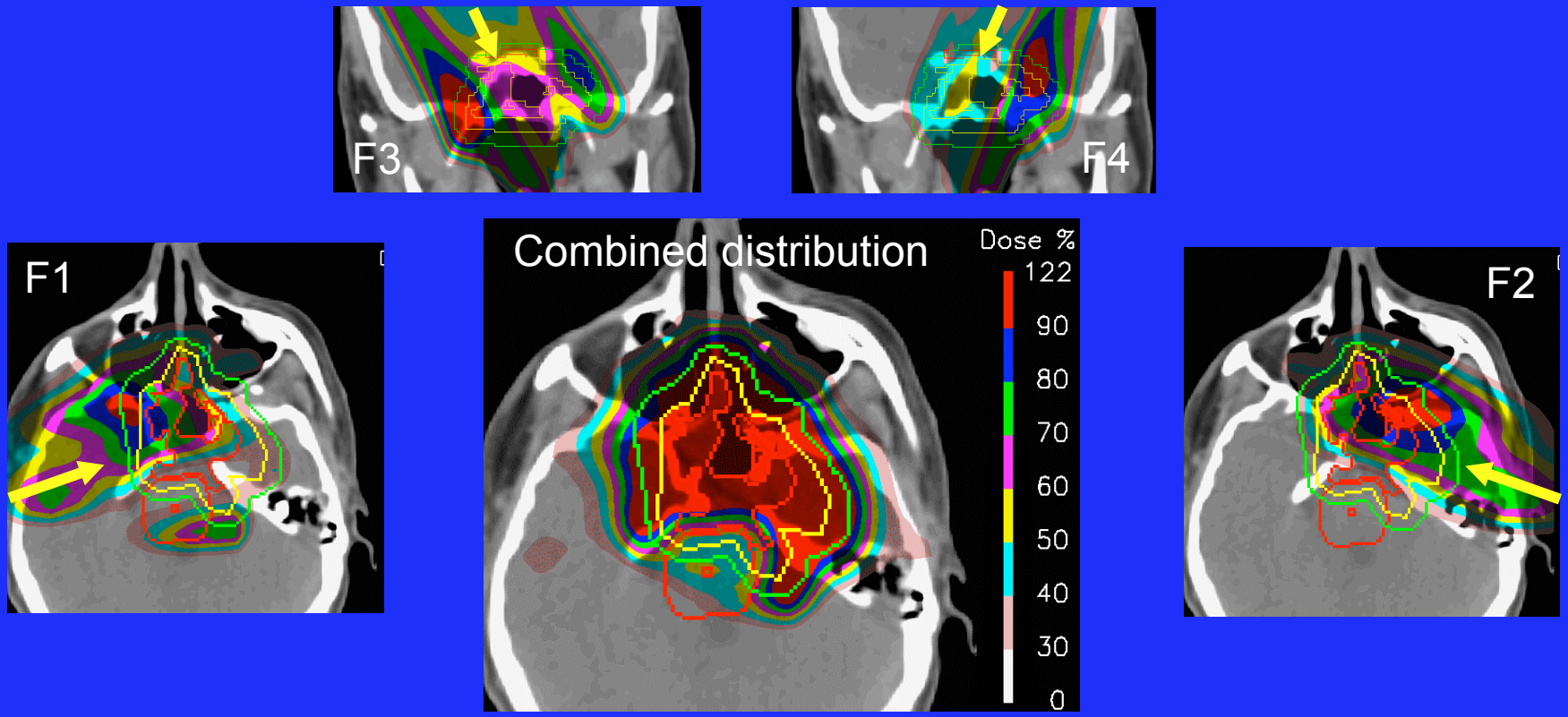
Intensity Modulated Proton Therapy (IMPT)

The simultaneous optimisation of all Bragg peaks from all fields (with or without additional dose constraints to neighbouring critical structures)

IMPT is the spot scanning equivalent of IMRT (and field patching for passive scattering proton therapy).

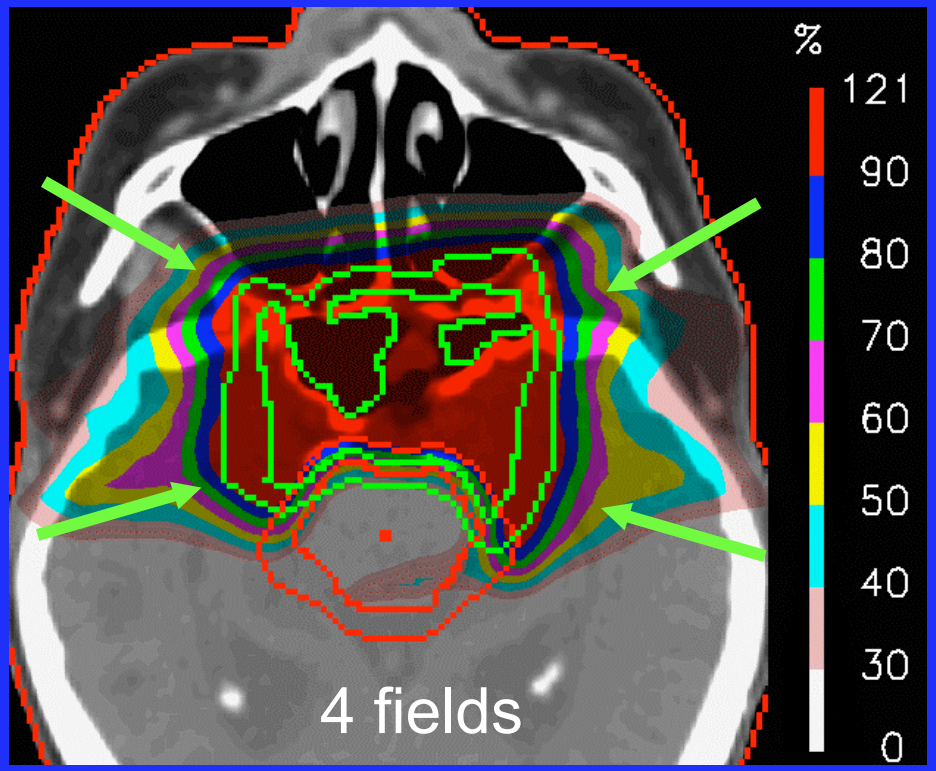
The simultaneous optimisation of all Bragg peaks from all incident beams. E.g..



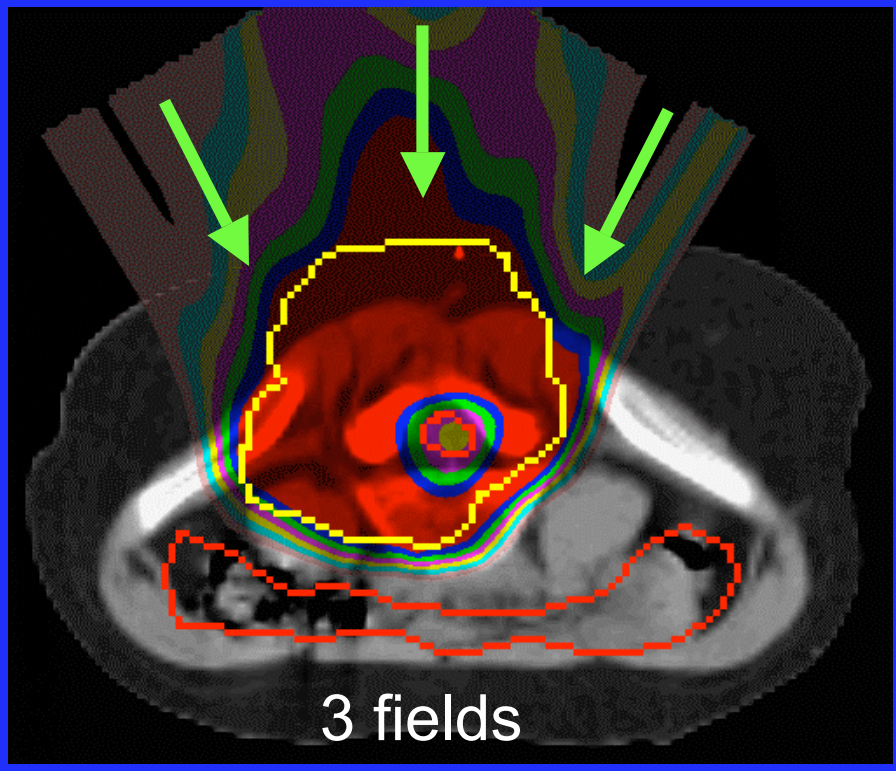
Lomax 1999, PMB 44: 185-205

Example clinical IMPT plans delivered at PSI

Skull-base chordoma



3 field IMPT plan to an 8 year old boy



Spot weight degeneracy in IMPT.

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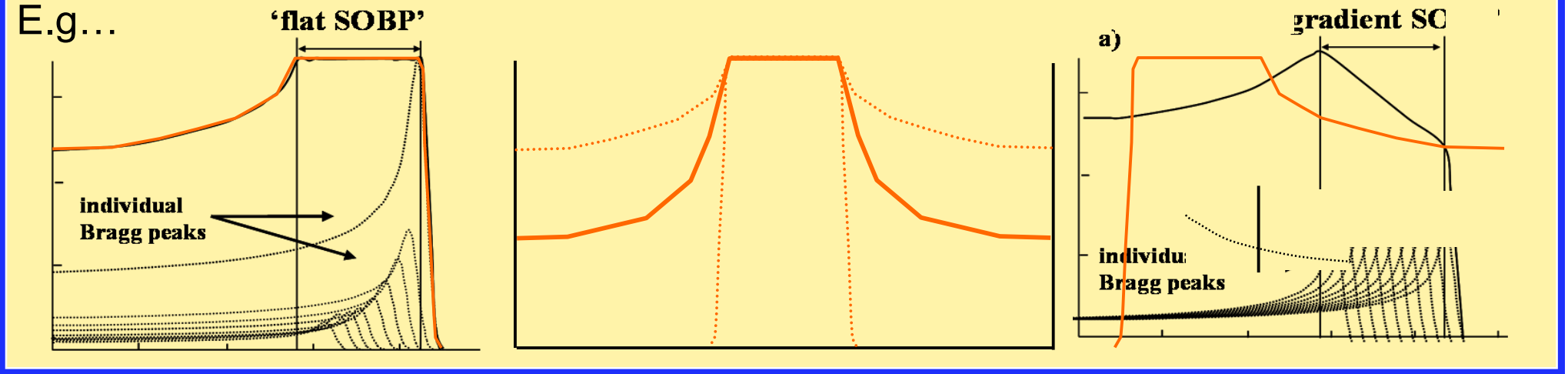
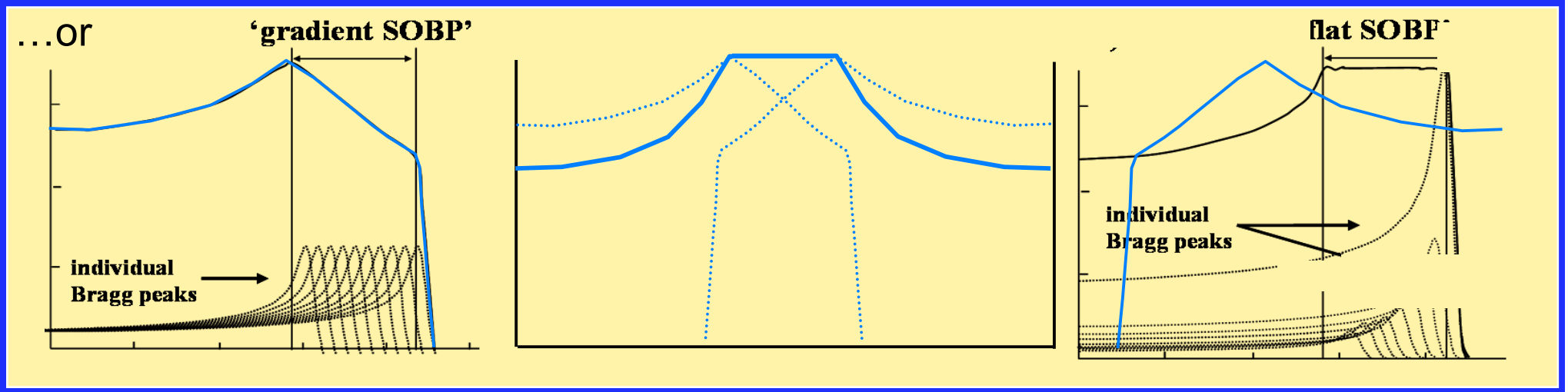
There's more than one way to optimise an IMPT plan…

E.g…



…or

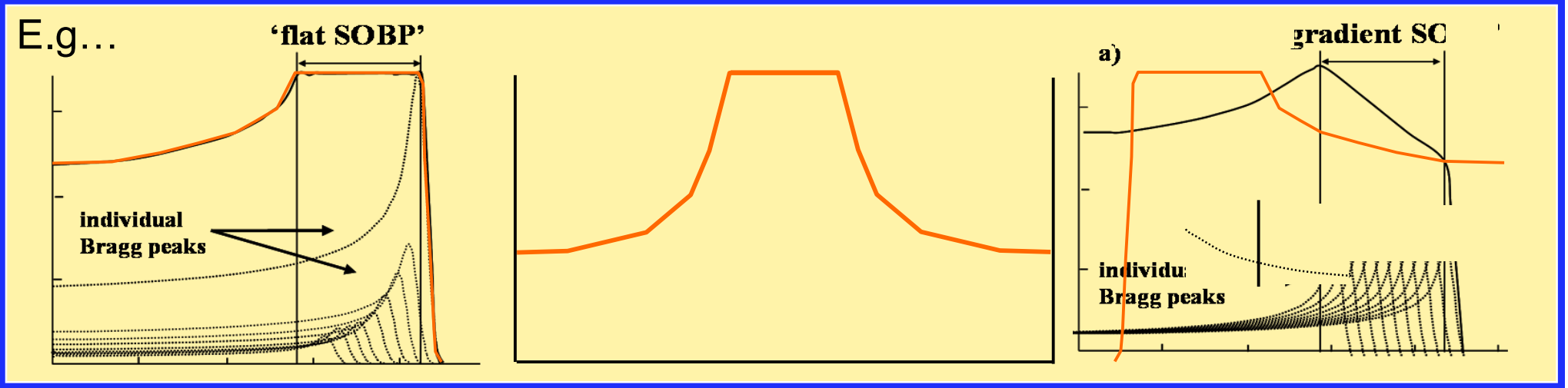


Albertini and Lomax 2007, IJROBP

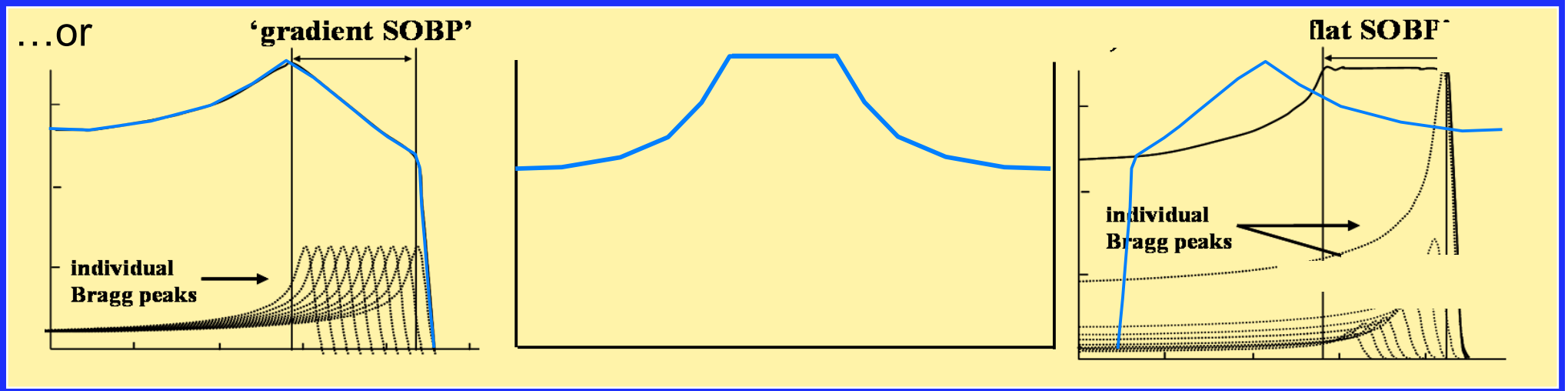
Spot weight degeneracy in IMPT.

There's more than one way to optimise an IMPT plan…

E.g…



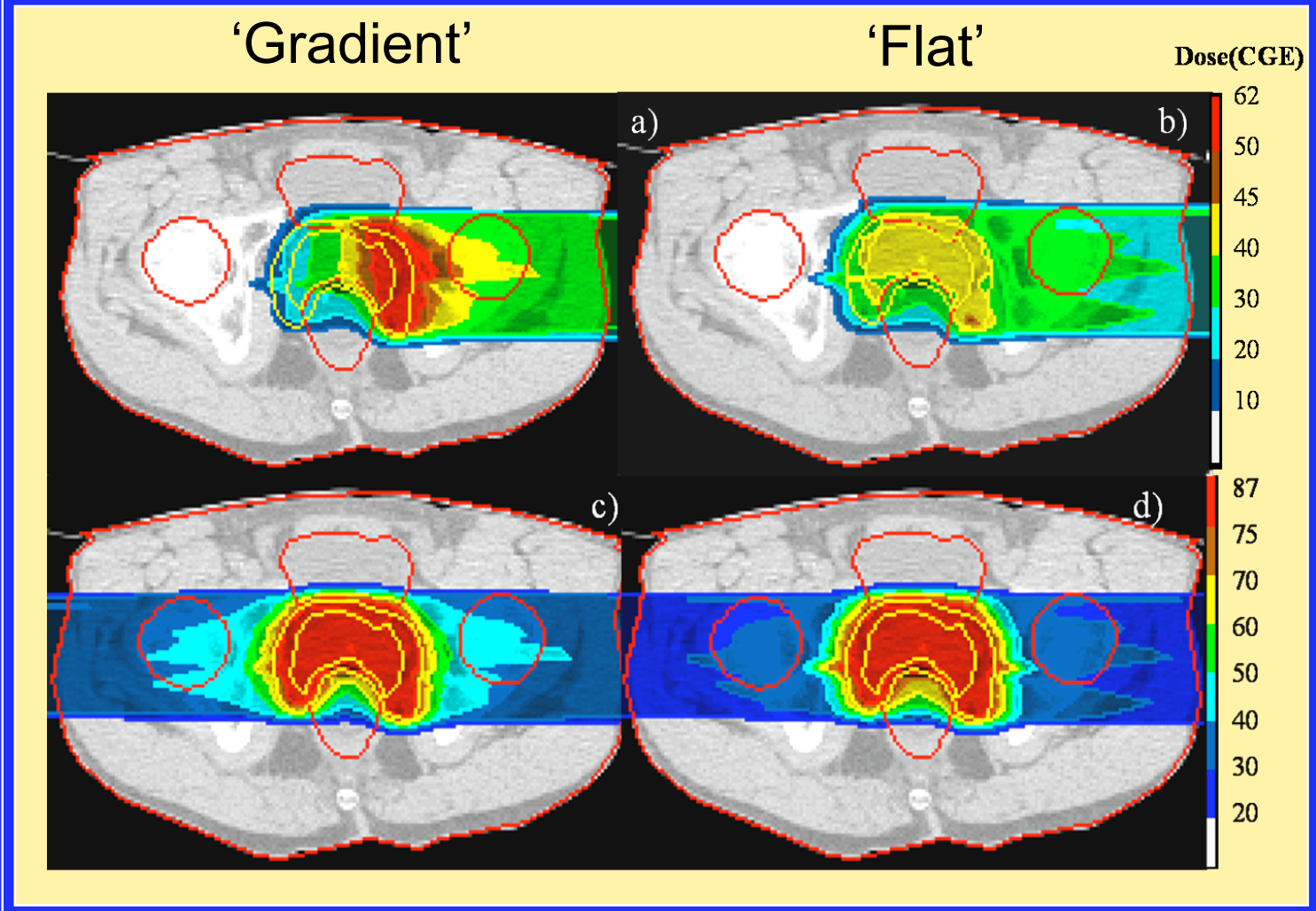
…or



Albertini and Lomax 2007, IJROBP

Spot weight degeneracy in IMPT.

There's more than one way to optimise an IMPT plan…



Very similar PTV coverage but with significantly higher dose in entrance region for 'Gradient' SOBP

This can be an 'invisible' consequence of the starting conditions for optimisation

Albertini and Lomax 2007, IJROBP

Spot weight degeneracy in IMPT.

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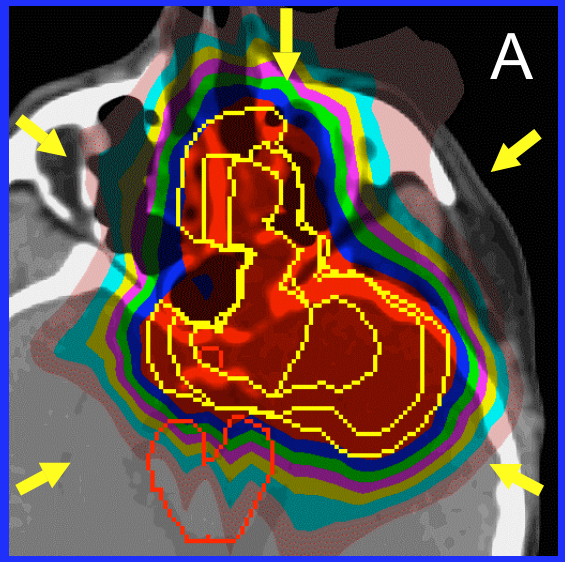
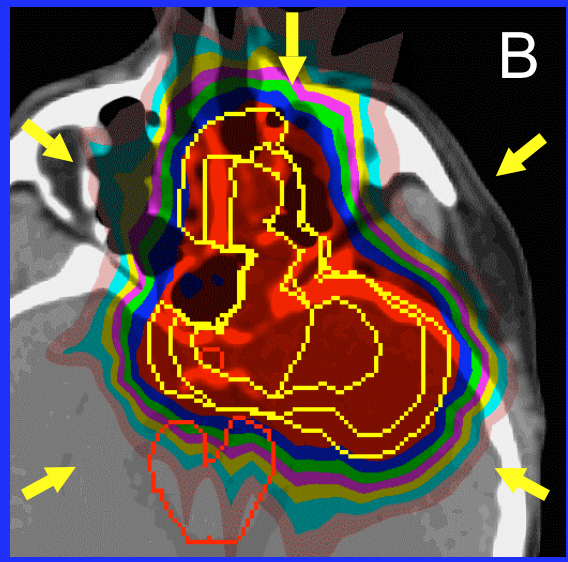
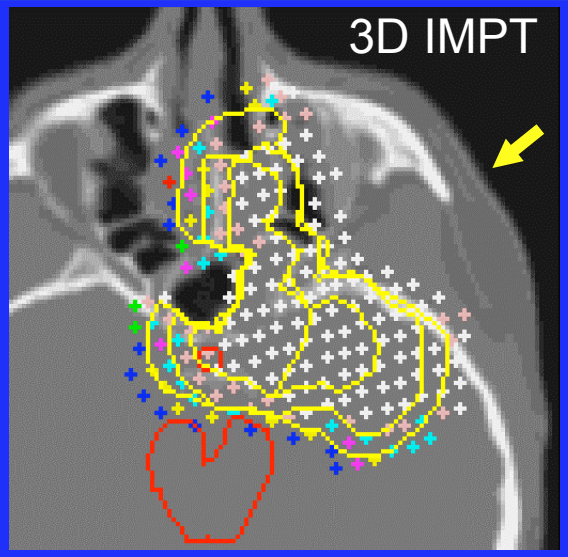
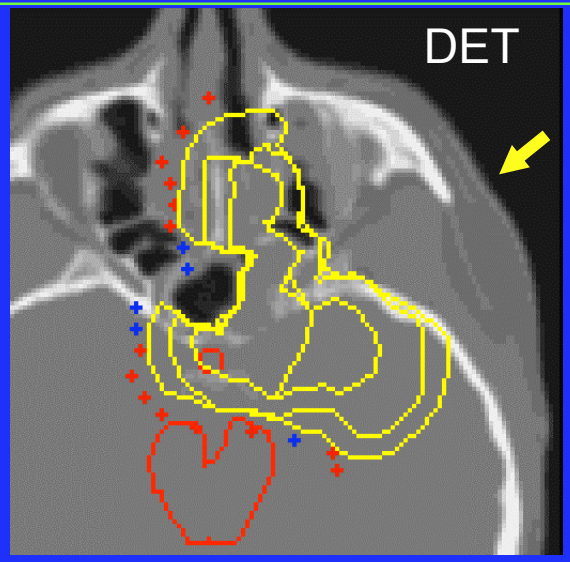
Two, 5 field IMPT dose distributions





Corresponding spot weight distributions from field 2





Treatment planning for scanning

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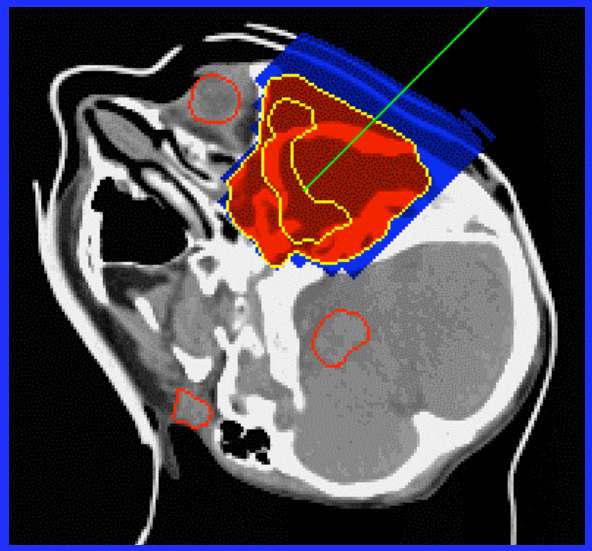
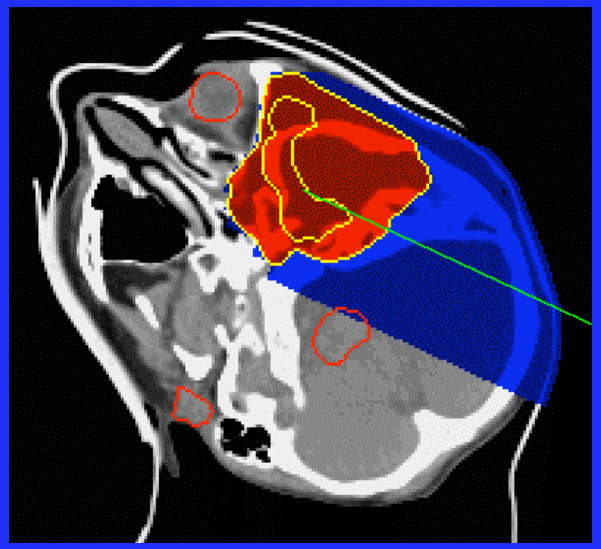
Field selection for proton therapy .

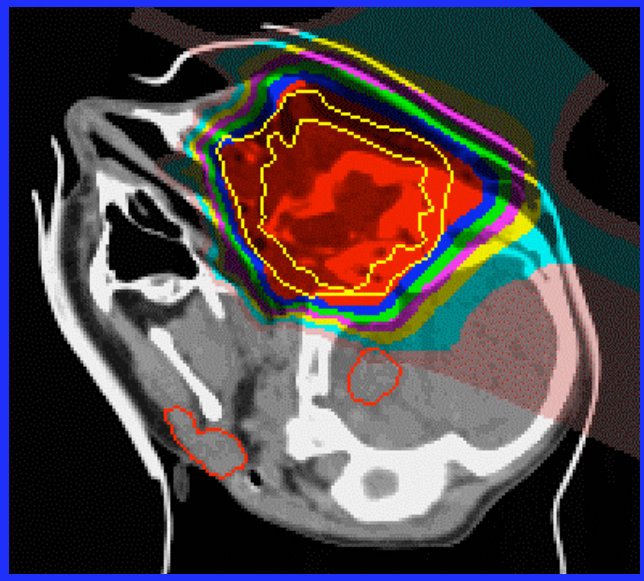
Geometric avoidance of organs at risk.





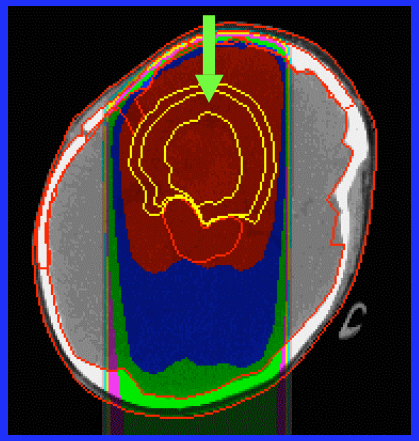
The selection of beam incidences which avoid critical structures leads…

…‘automatically’ to reduced doses to the critical structures

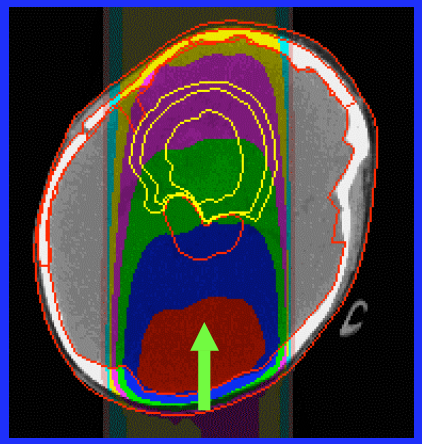


Field selection and integral dose – protons vs photons

For same mean dose to target, 15MV photons deliver an integral dose of….

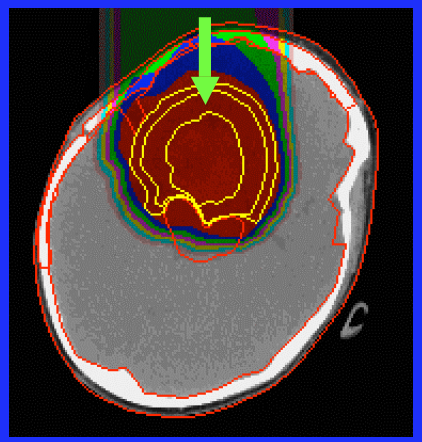


16%…

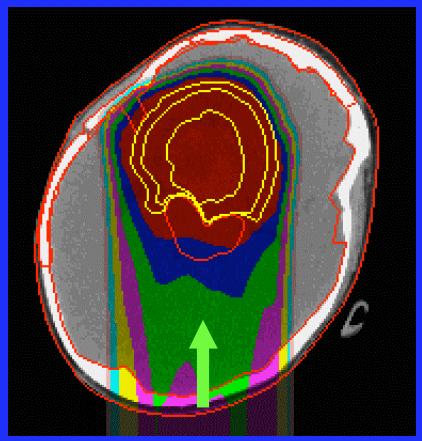


…and 19%

The corresponding values for two proton fields are..



7%…



…and 13%

Avoidance of coarse density heterogeneities.

- Accuracy of dose calculations
- Effects on dose homogeneity and conformity
- Sensitivity of a plan to spatial delivery uncertainties.

Field selection for proton therapy .

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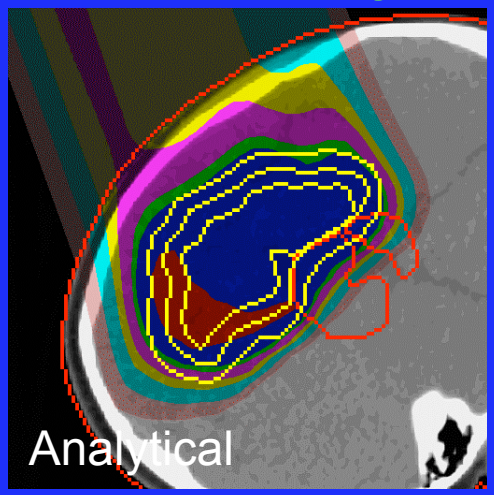
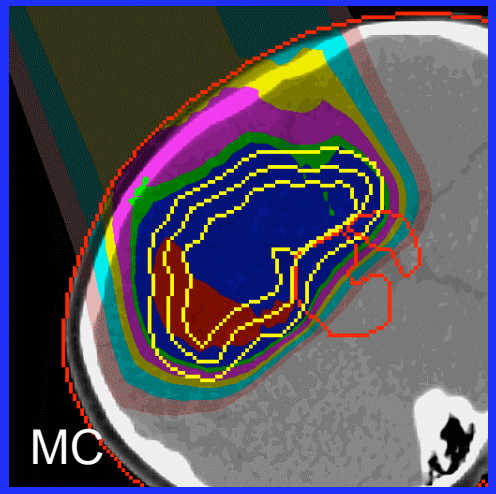
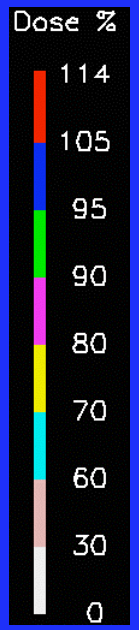
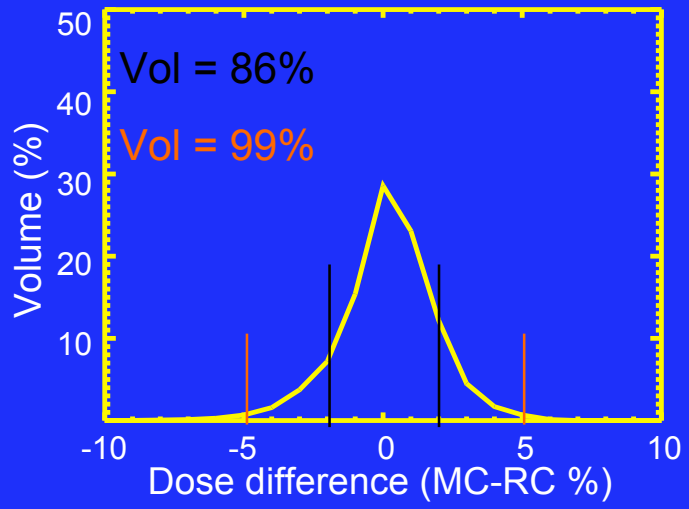
A 'homogenous' field direction



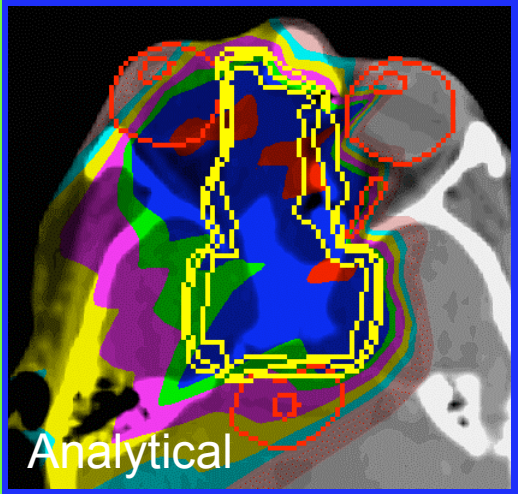


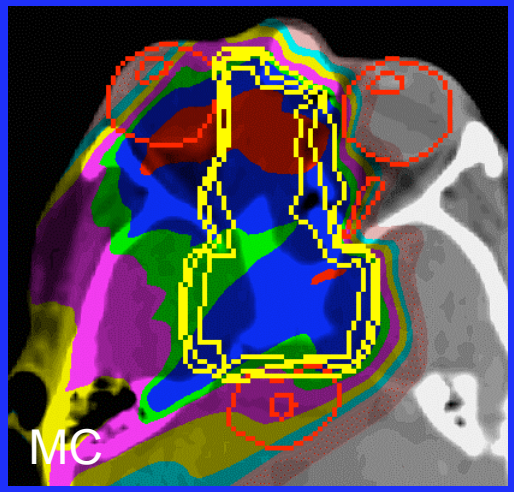


Difference histogram

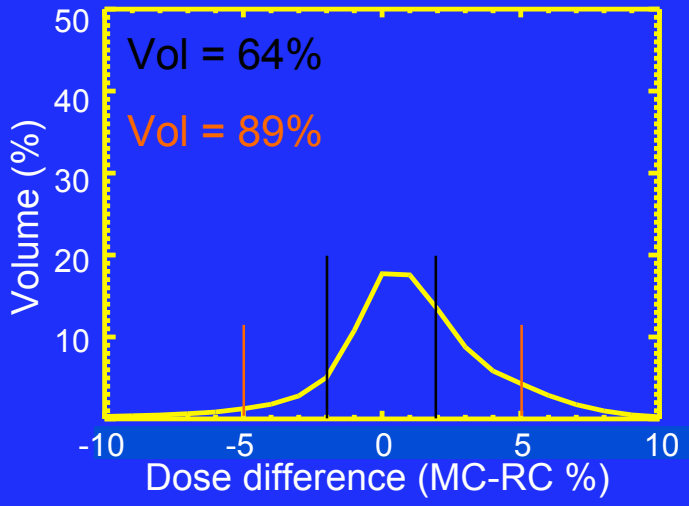


An 'inhomogenous' field direction





Difference histogram



Field selection for proton therapy .

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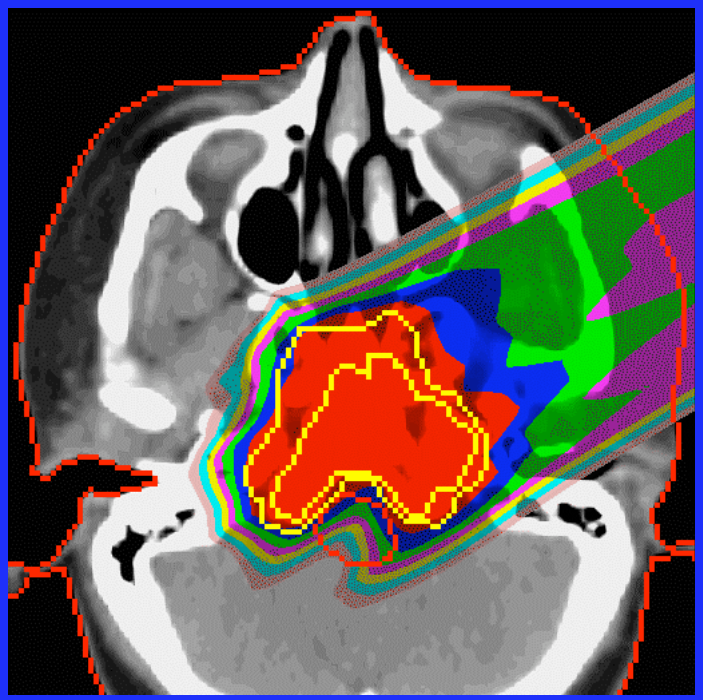
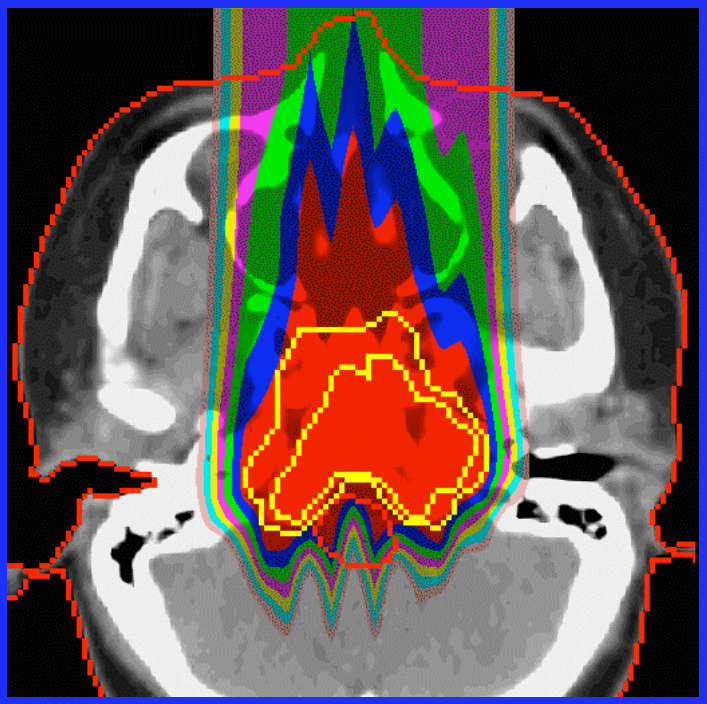
Effects on (single field) dose conformity

Example field through relatively homogenous anatomy



Example field through very inhomogenous anatomy



Field selection for proton therapy .

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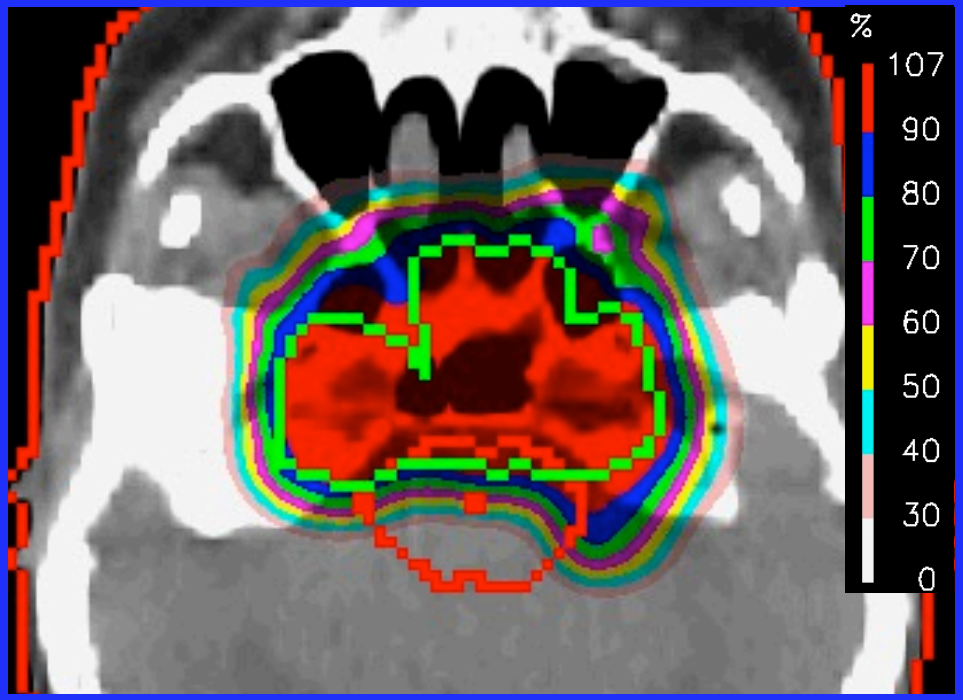
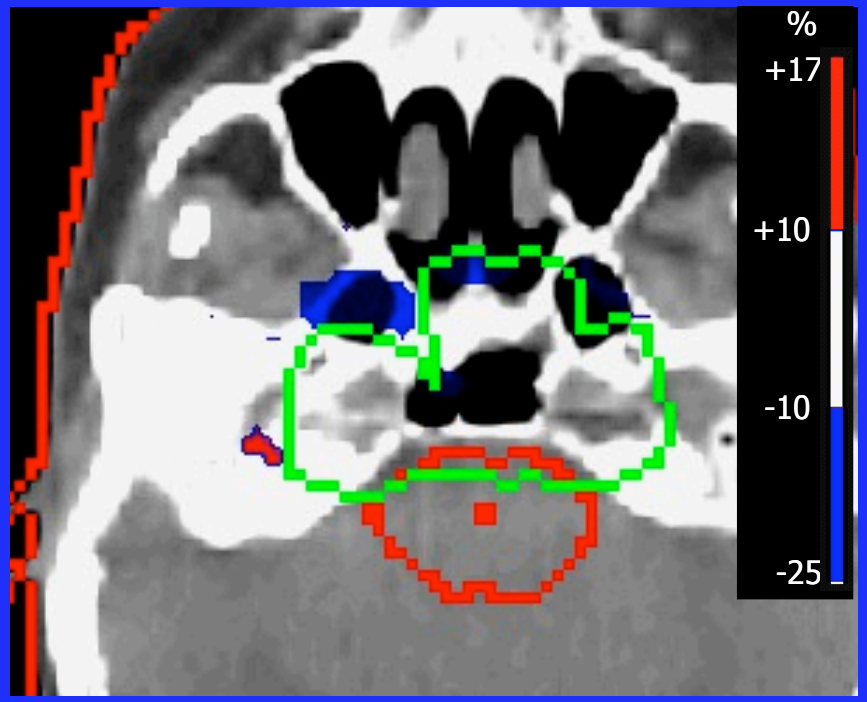


Nominal 3 field spot scanned proton plan



Dose differences after recalculation in repeated CT (residual error ~1mm!)

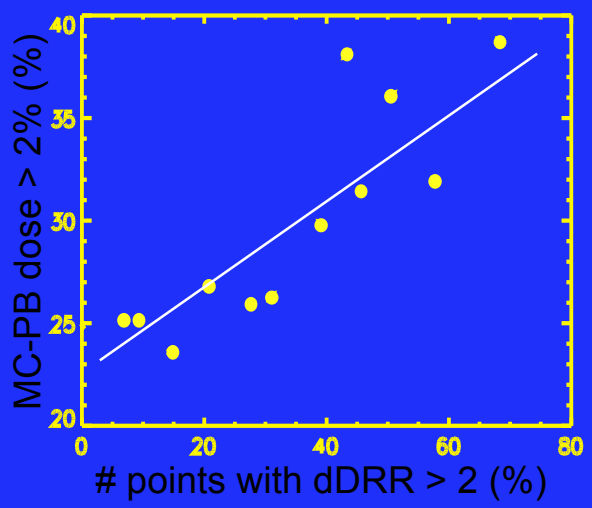
Alessandra Bolsi, PSI

Field selection for proton therapy .

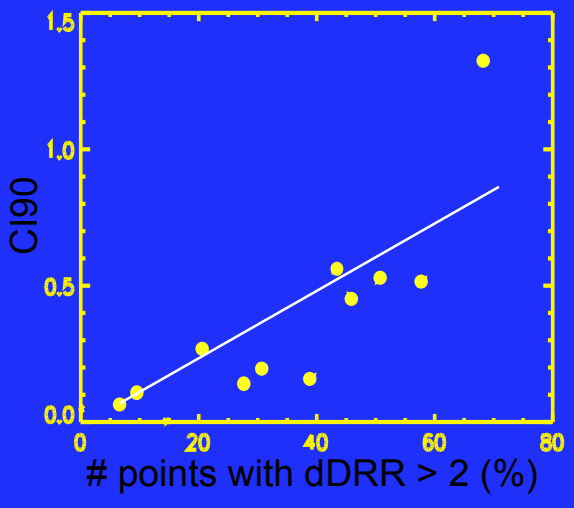
Can the order of density heterogeneity in a field be quantified?

The Heterogeneity index – a measure of the local integral density gradient for points that lie on the proximal surface of the target (after B Schaffner et al 1999).

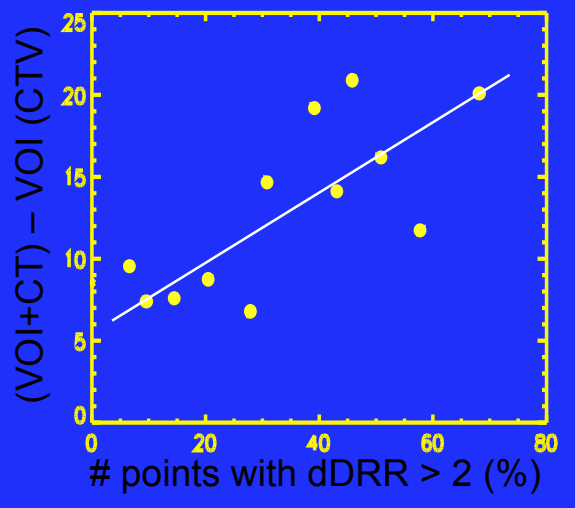
Dose calculation accuracy



Single field dose conformity



Set-up error sensitivity



Field selection for proton therapy .

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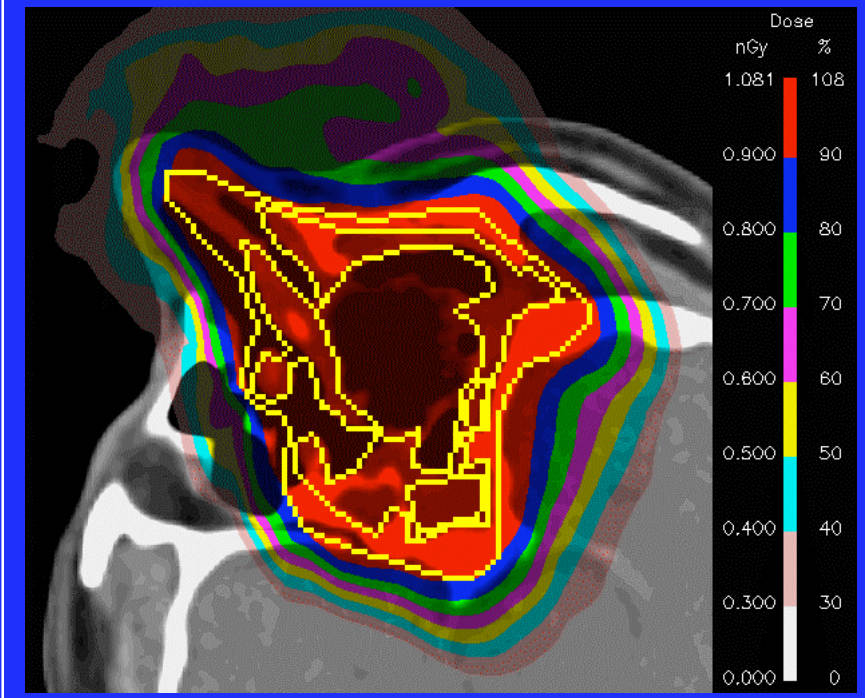
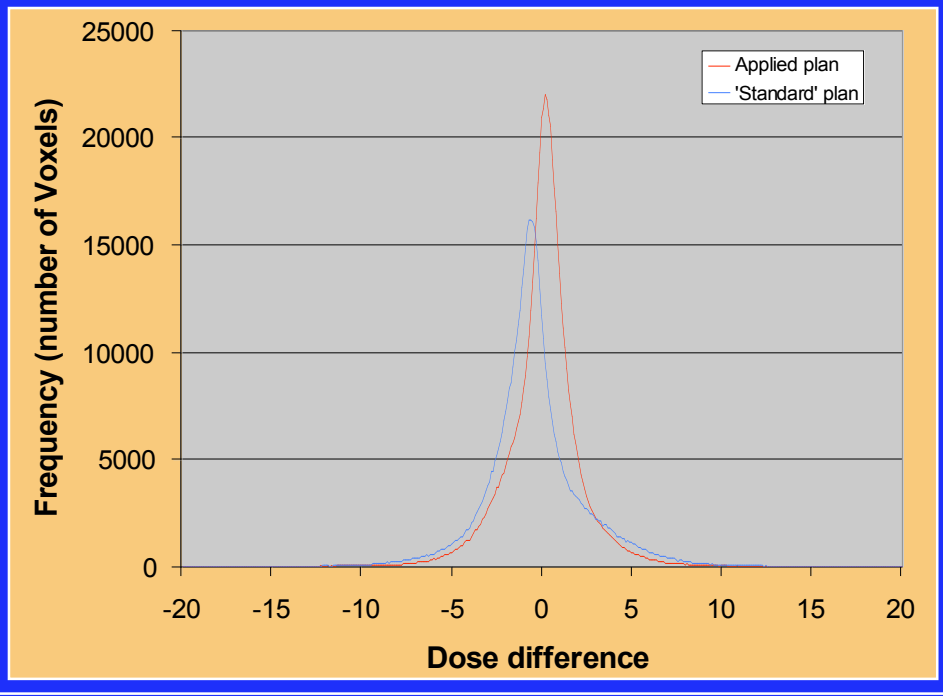
Can the order of density heterogeneity in a field be quantified?

Field	Applied plan			'Standard' plan		
	Gantry angle	Table angle	Density heterogeneity index	Gantry angle	Table angle	Density heterogeneity index
1	-45	-90	**20.4**	-90	-120	**28.2**
2	-10	0	**12.9**	-90	-60	**30.2**
3	-120	-120	**12.7**	60	0	**26.2**





Field selection for proton therapy .

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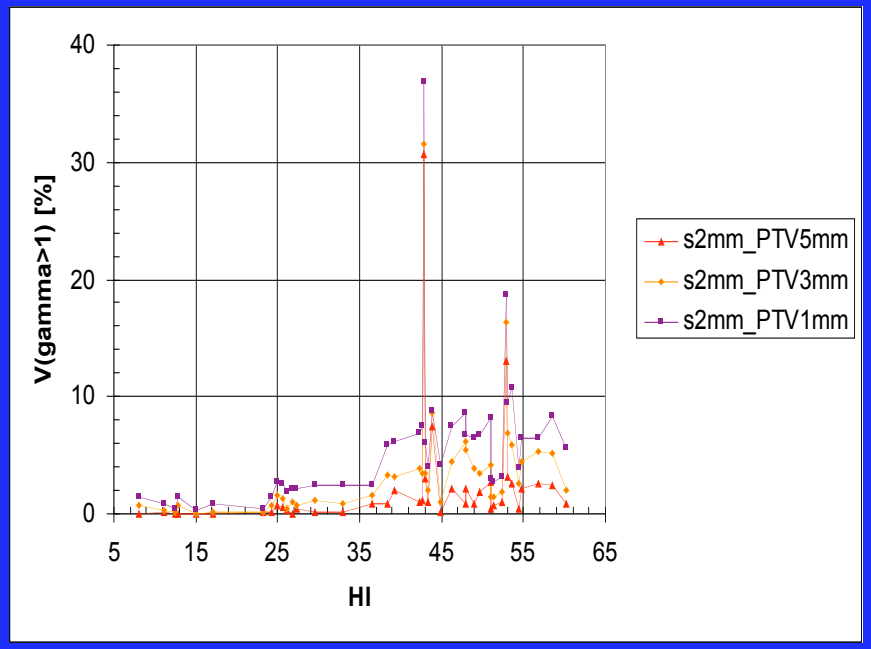
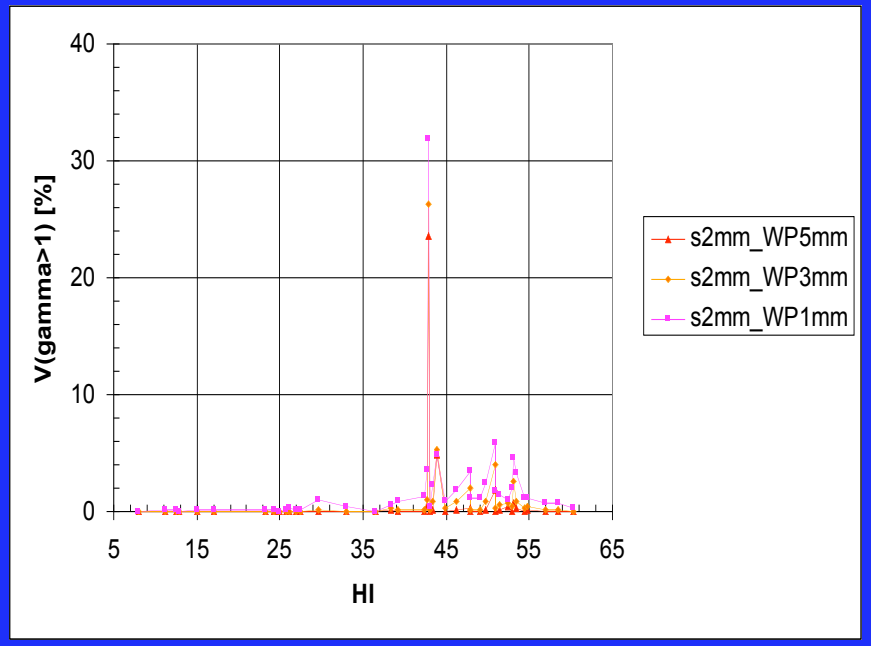
Can the order of density heterogeneity in a field be quantified?

Analysis of differences (gamma analysis) between doses calculated on nominal and spatially shifted CT's (σ=2mm) for 42 fields of varying heterogeneity index

With internal heterogeneities



Homogenous CT



Cezarina Negreanu, PSI (supported by Siemens)

Treatment planning for scanning

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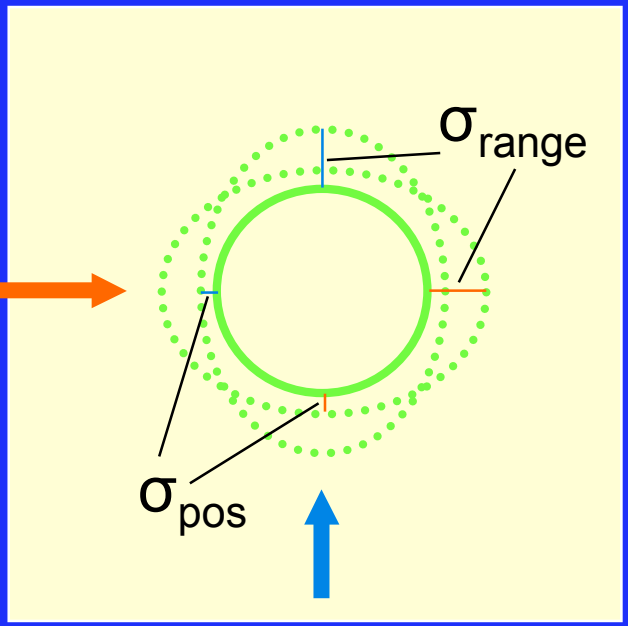
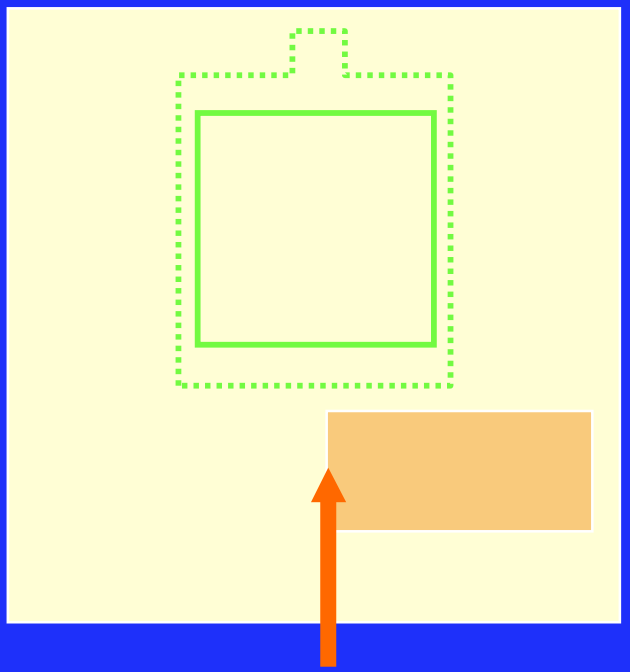
To PTV or not to PTV? – that is the question

- Definition of a PTV is conventional way of dealing with potential delivery errors
- For passive scattering protons, PTV often not used with uncertainties dealt with through expansion of apertures and smoothing and shaving of compensator
- No collimators or compensators for scanning, therefore current method is to define PTV
- Is this necessarily the best approach?

Do we need field specific PTV's?

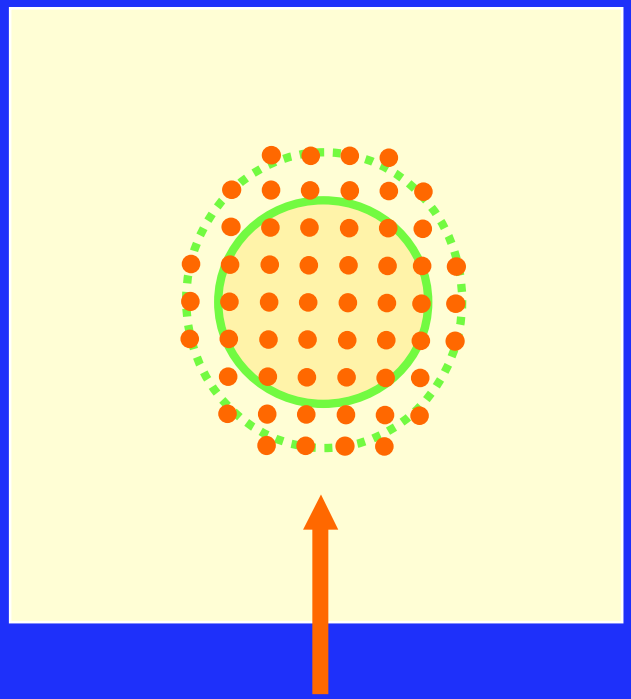


E.g. could be necessary if σ_{pos} <> σ_{range}

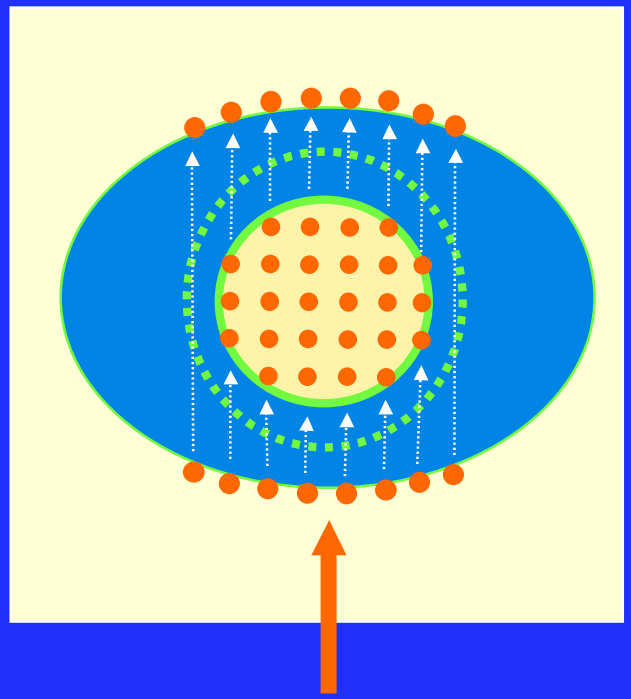


..or when passing along strong density interfaces (c.f. smearing of compensators)

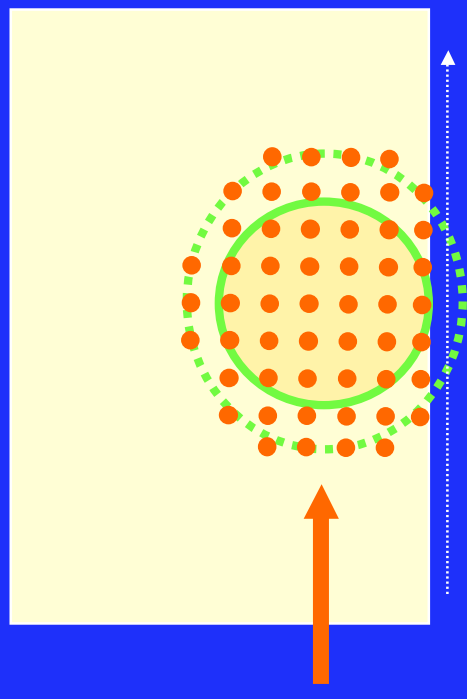
PTV's in the presence of areas of low density



'Normal' situation. More or less regular grid of spots covering whole PTV

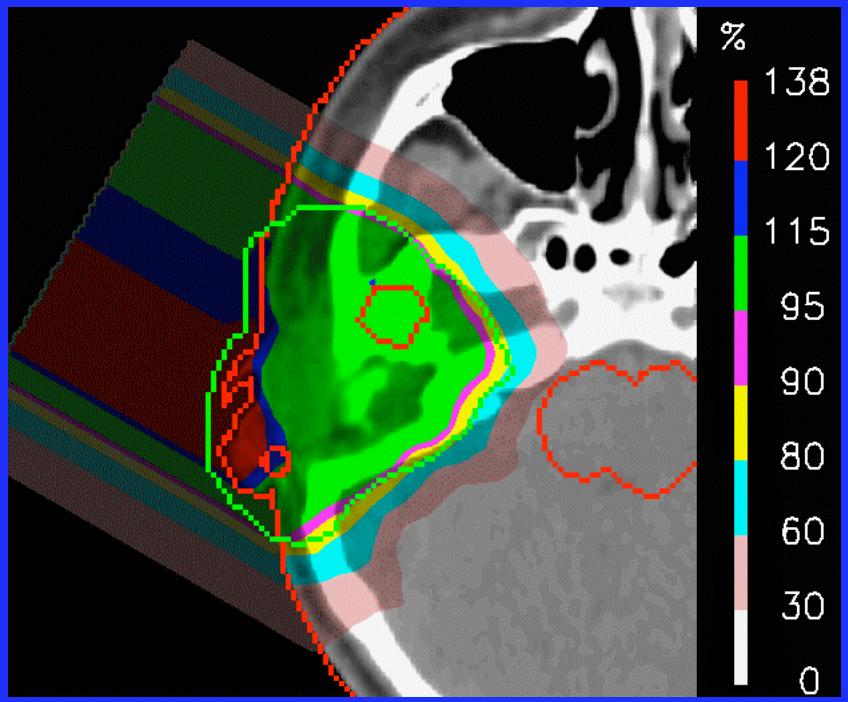


Situation in lung. No Bragg peaks can be placed in PTV due to low density.

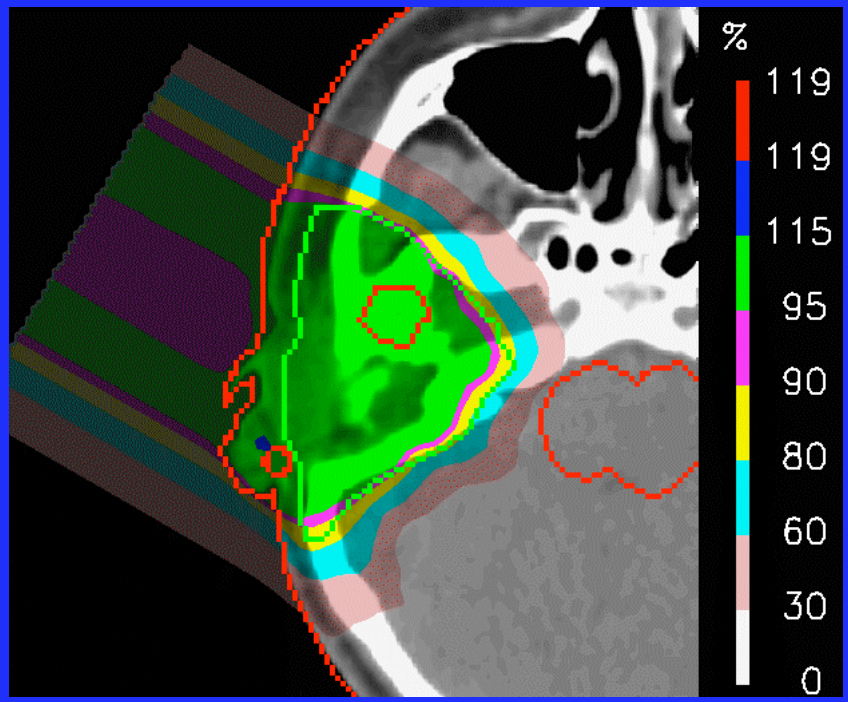


Situation for superficial CTV's. No Bragg peaks can be placed in part of PTV that extends into air.

Example of hot-spots on surface due to 'missing spots' in PTV



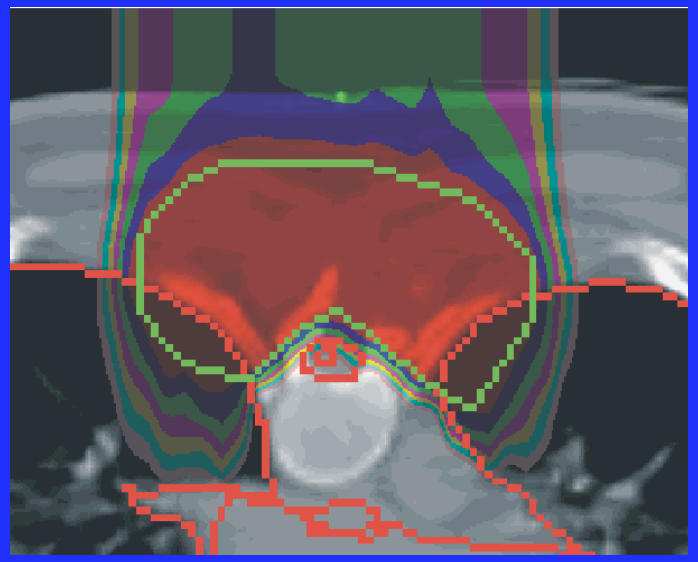
Planned to actual PTV



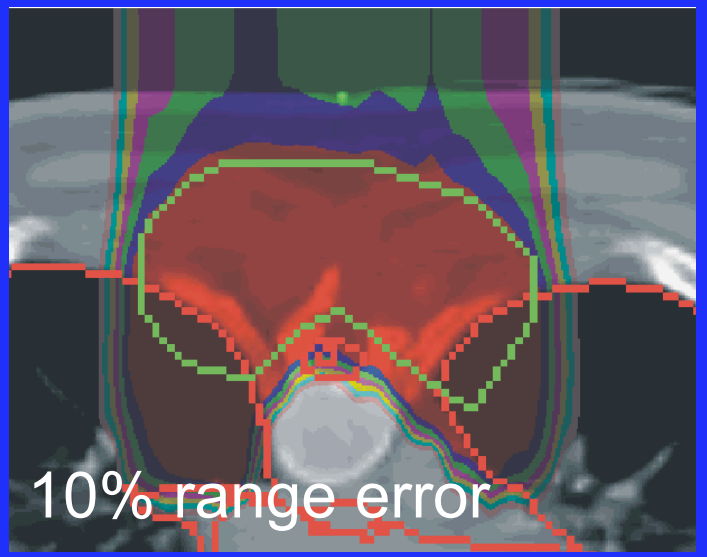
Planned to 'TechPTV', pulled 5mm away from surface

Dealing with uncertainties – range uncertainties.

The advantage of protons is that they stop.



The disadvantage of protons is that we don't always know where…



Sources of range uncertainties

- Limitations of CT data (beam hardening, noise, resolution etc) [Σ ~ 1%]
- Uncertainty in energy dependent RBE [Σ ~ 2%]
- Calibration of CT to stopping power [Σ ~ 1-2%]
- CT artifacts [Σ]
- Variations in patient anatomy [Σ,σ]
- *Variations in proton beam energy [σ]*
- *Variations in patient positioning [σ]*

Range errors are generally systematic!

Dealing with uncertainties – range uncertainties.

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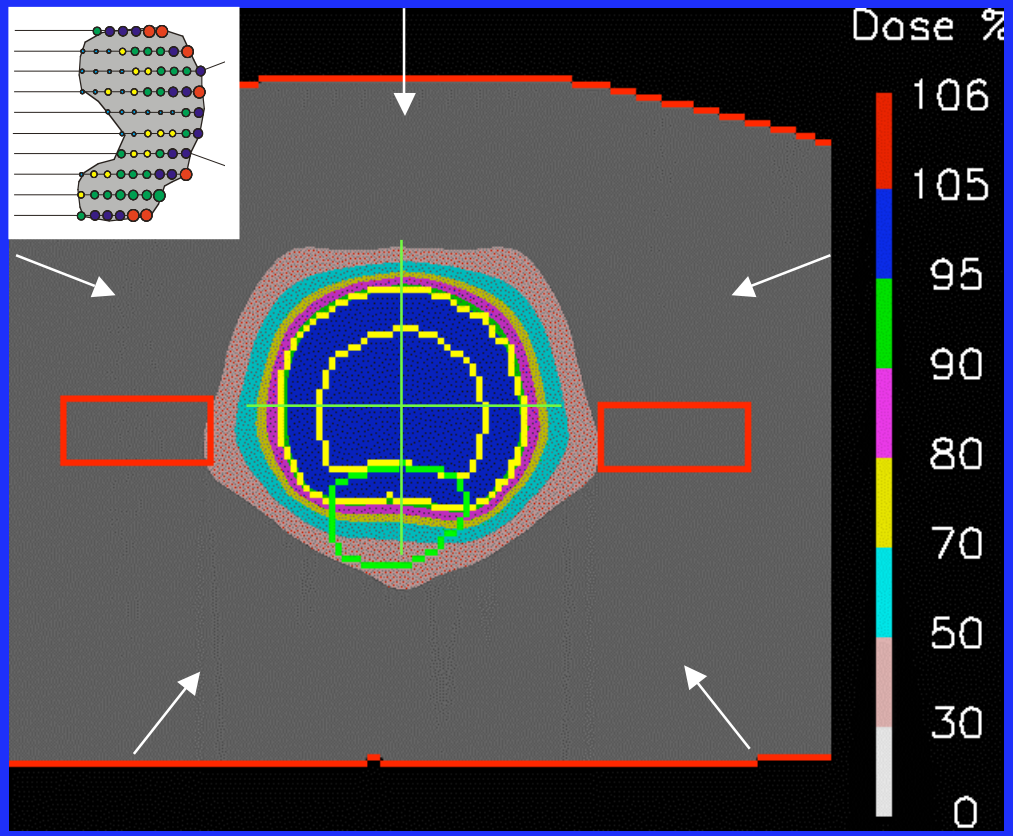
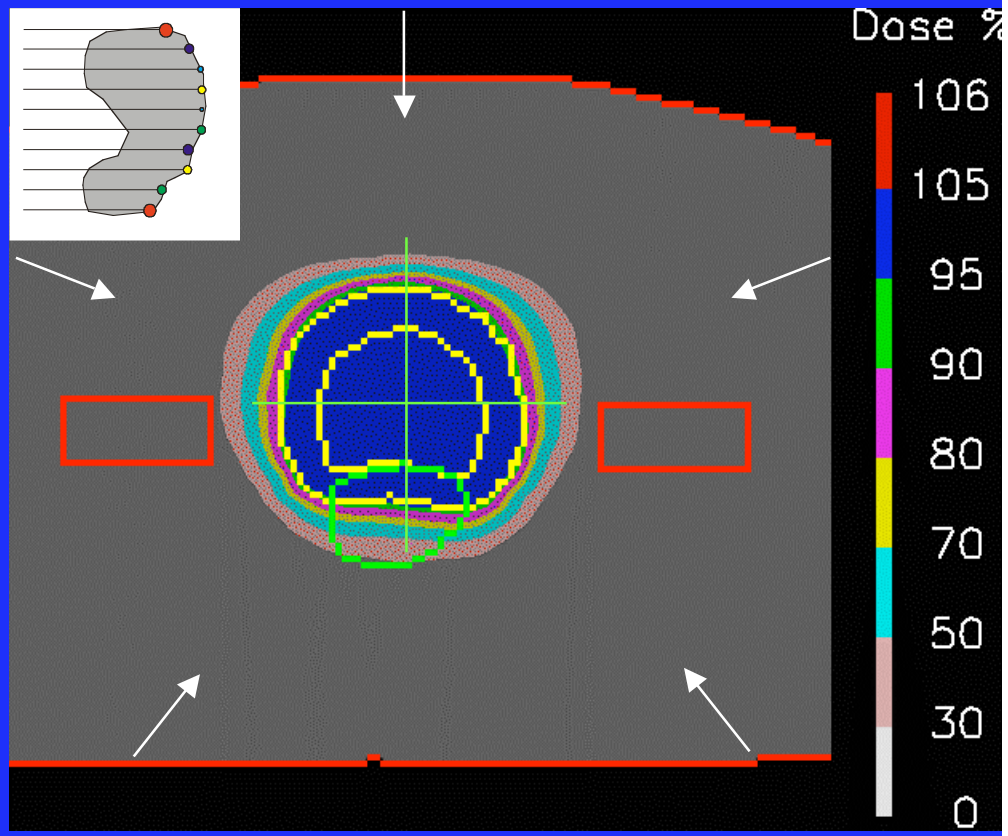
Consider 5 field 3D-IMPT and DET plans for a prostate case simulated in a homogenous phantom.

3D IMPT

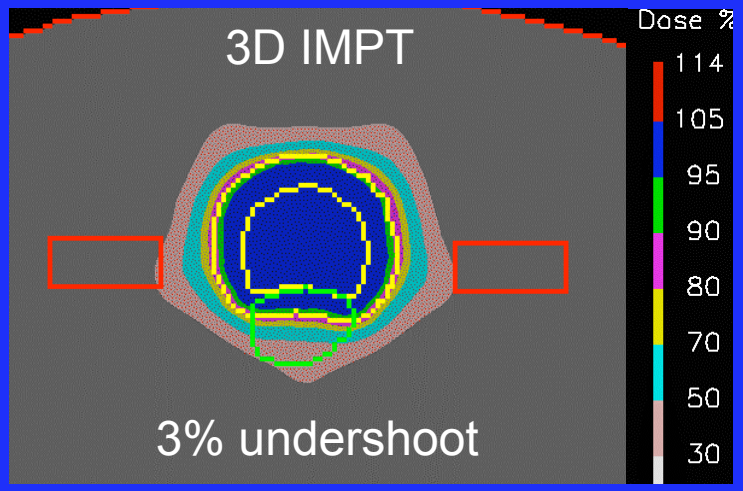


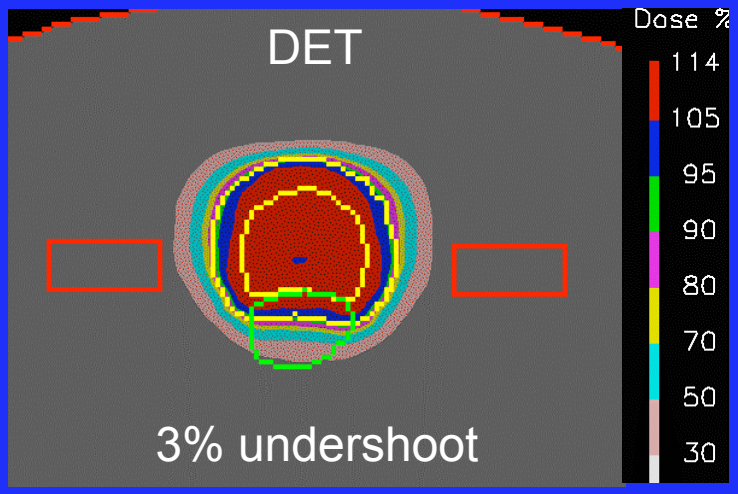
DET

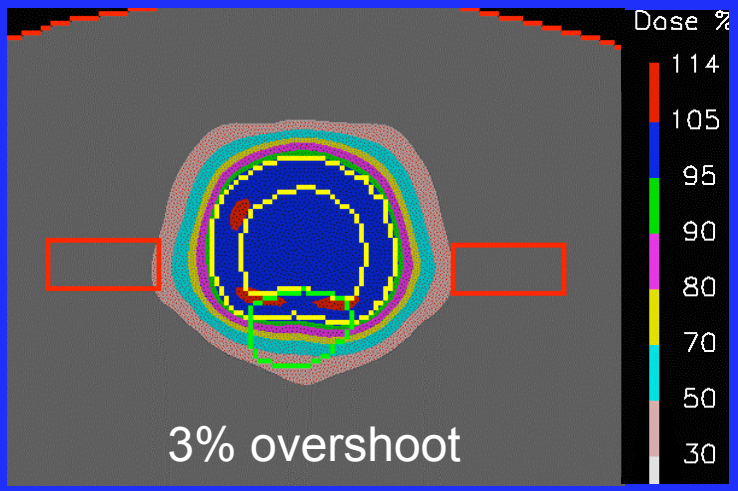


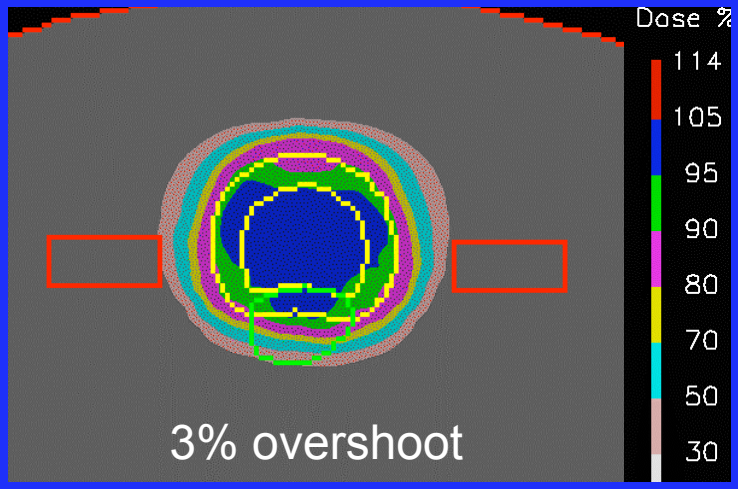
Dealing with uncertainties – range uncertainties.

Now recalculate assuming a 3% over- or undershoot of all Bragg peaks…









DET appears to be VERY sensitive to even modest range uncertainties!

Note: DET is just one ‘flavour’ of IMPT

Dealing with uncertainties – range uncertainties.

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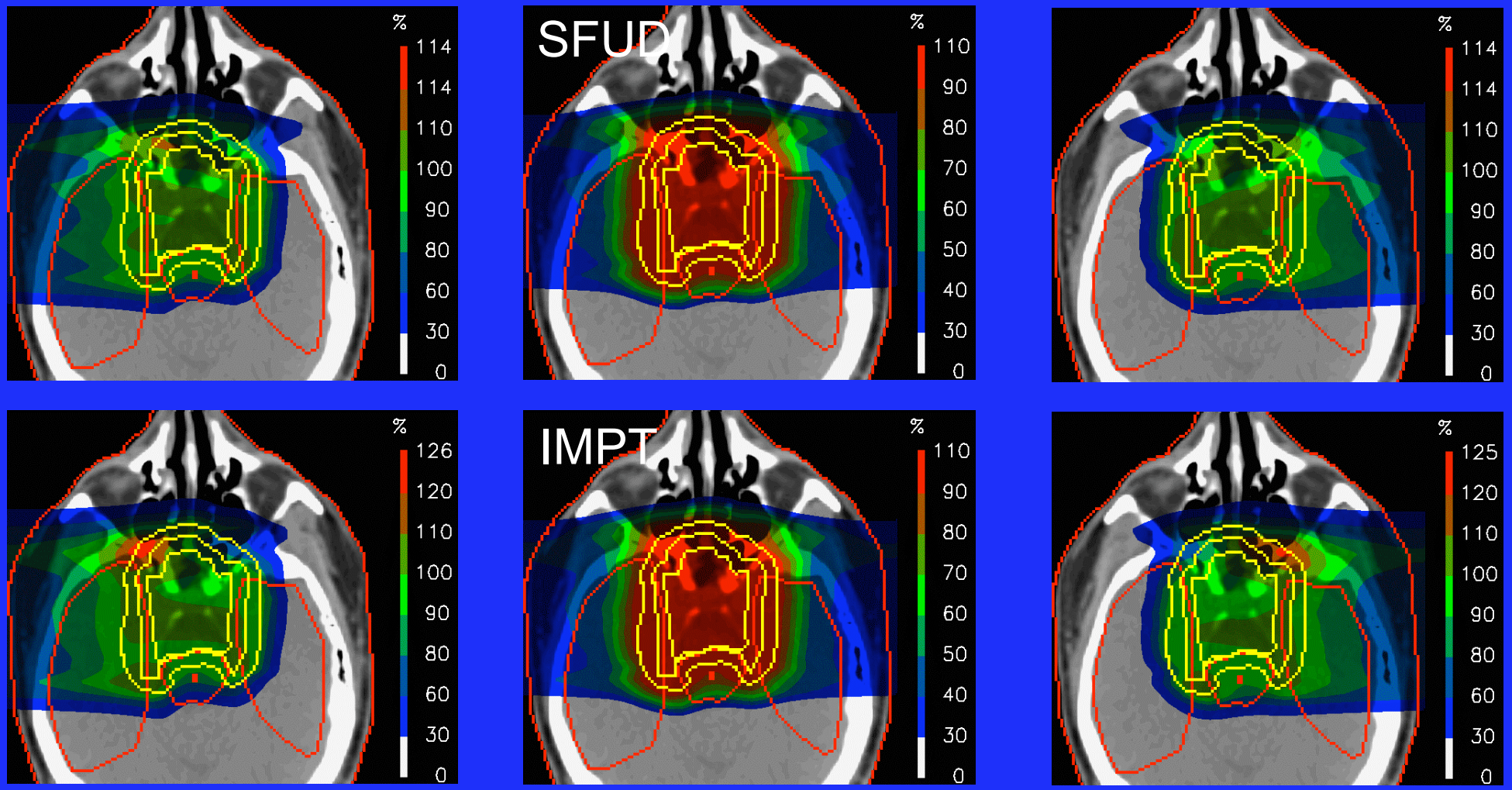
Range uncertainty for SFUD and IMPT plans



Lomax AJ (2007) in 'Proton and charged particle Radiotherapy', Lippincott, Williams and Wilkins

Dealing with uncertainties – range uncertainties.

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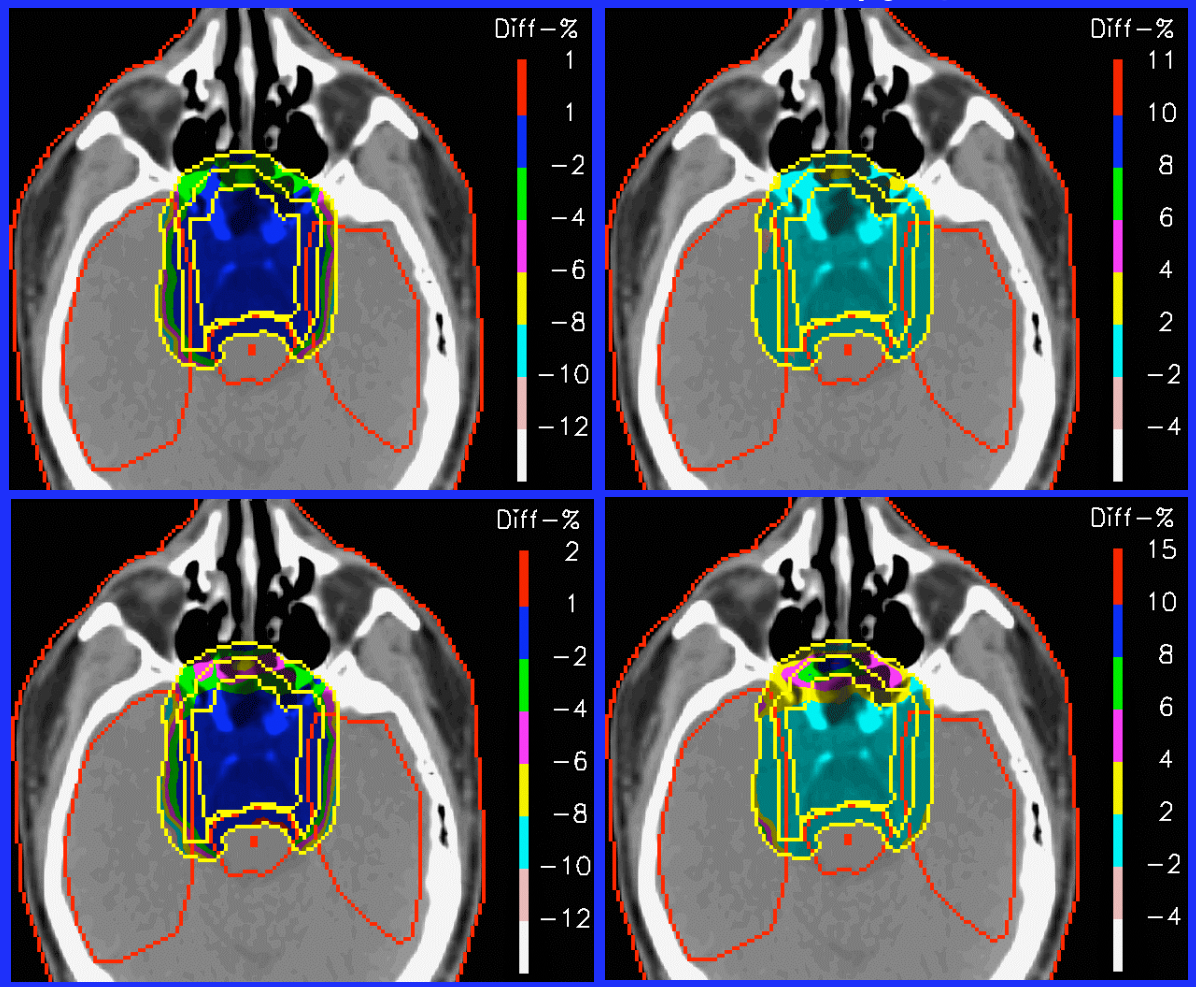
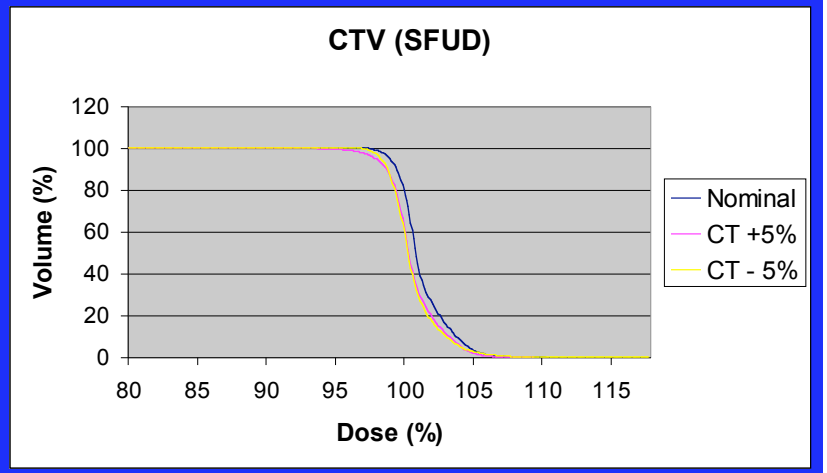
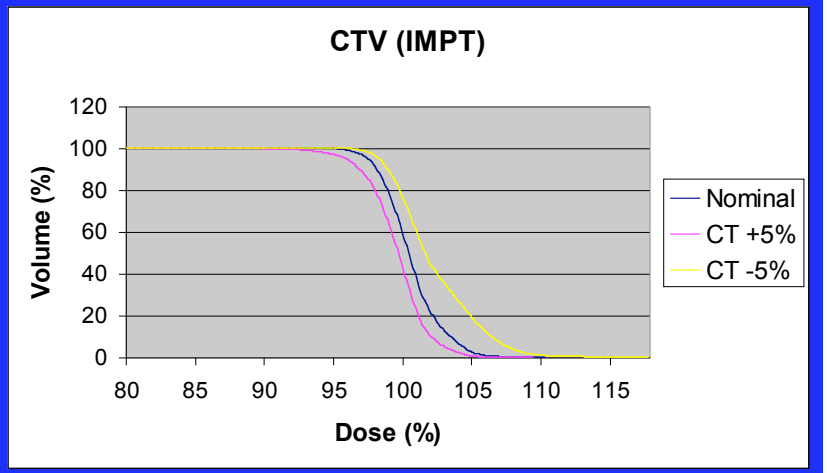
Range uncertainty for SFUD and IMPT plans

+5% CT

-5% CT







Lomax AJ (2007) in 'Proton and charged particle Radiotherapy', Lippincott, Williams and Wilkins

Dealing with uncertainties – range uncertainties.

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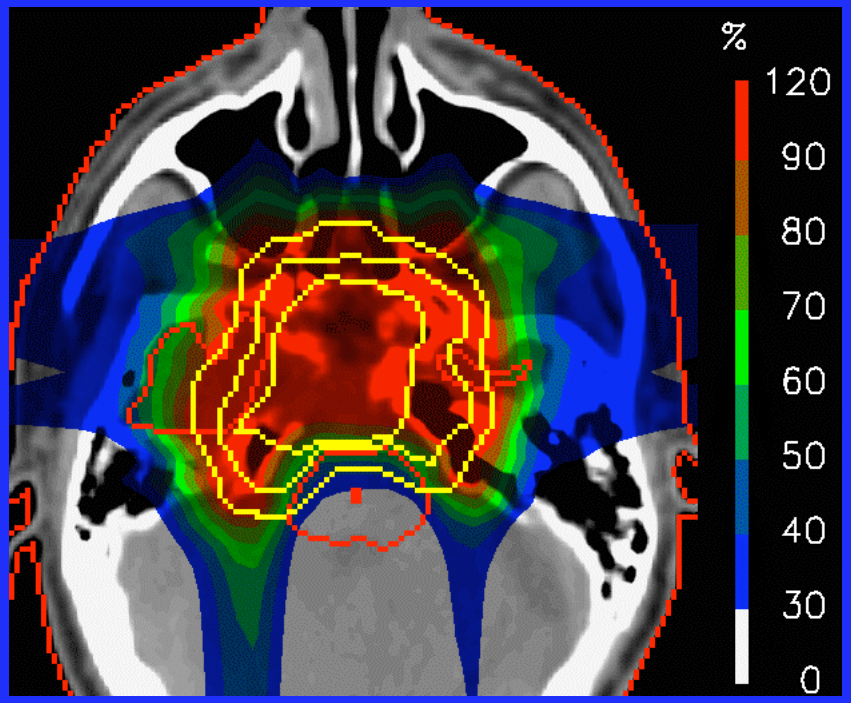
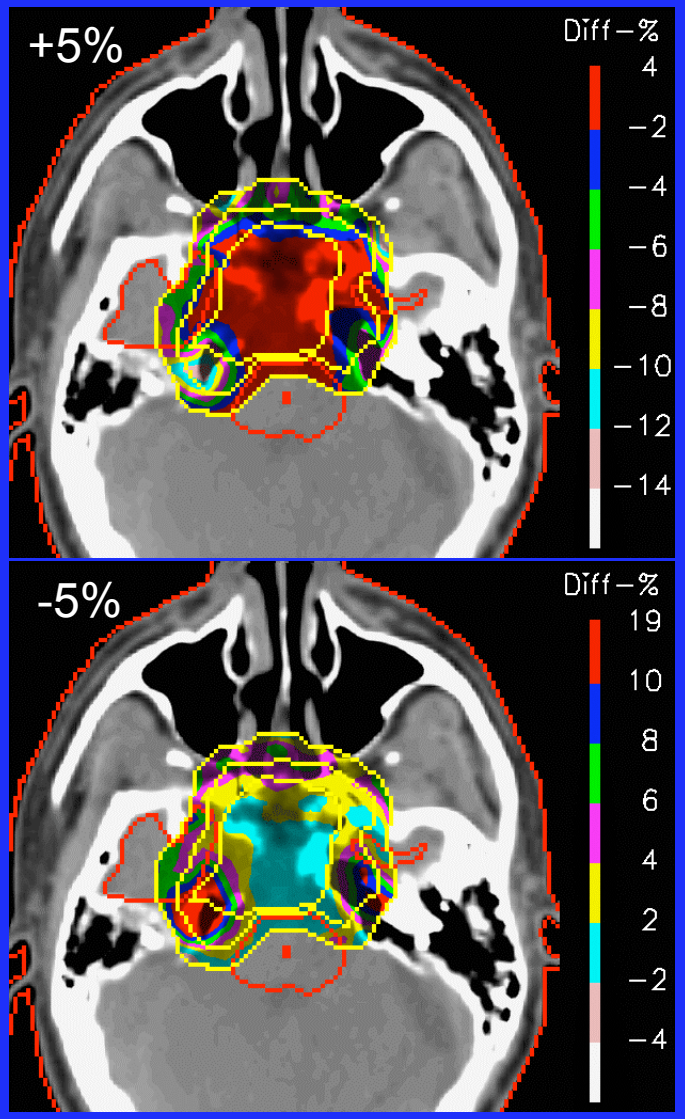
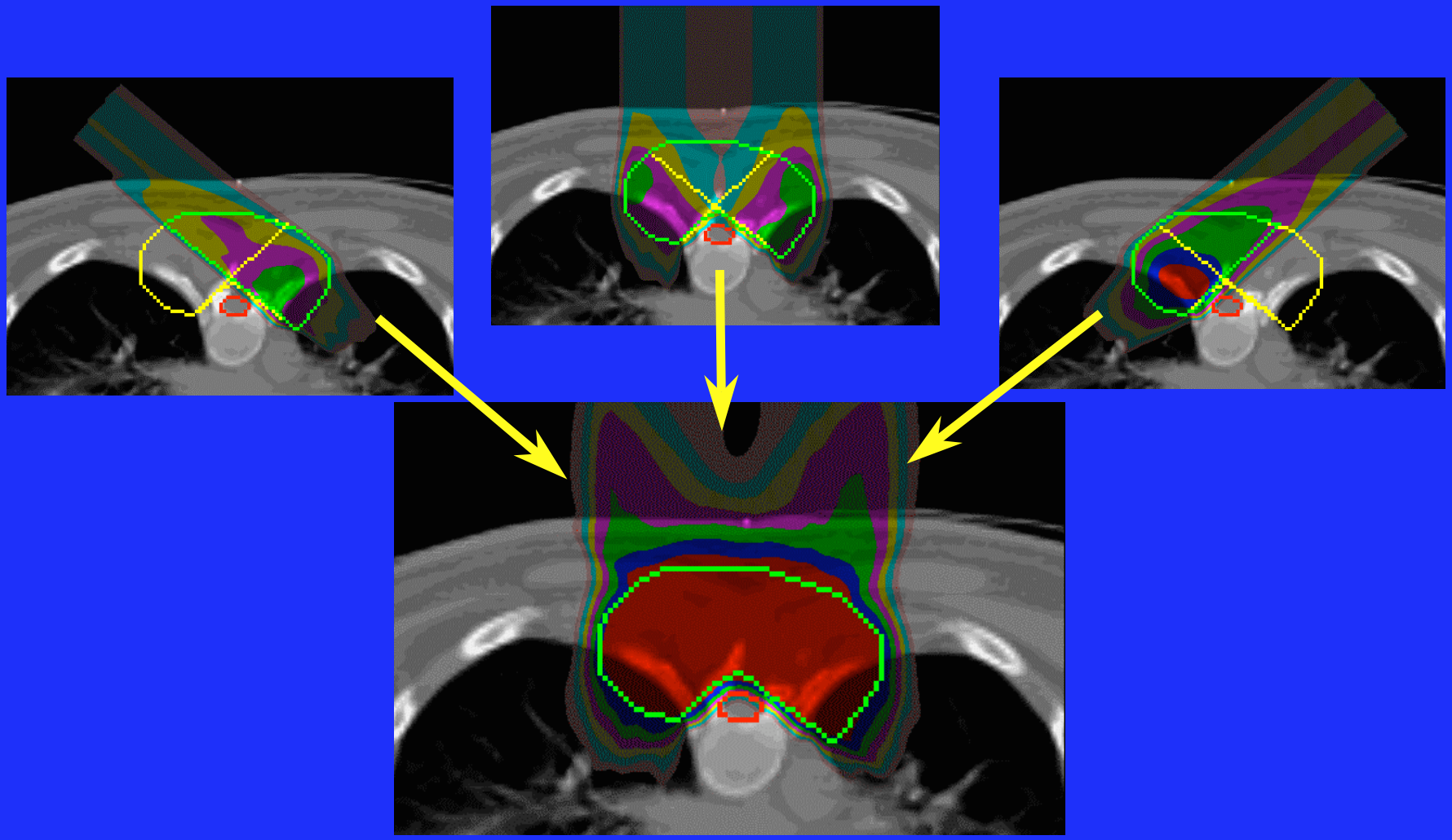
Range uncertainty for SFUD and IMPT plans





Lomax AJ (2007) in 'Proton and charged particle Radiotherapy', Lippincott, Williams and Wilkins

Dealing with range uncertainties - robust IMPT planning?



Lomax et al 2001, Med. Phys. 28:317-324

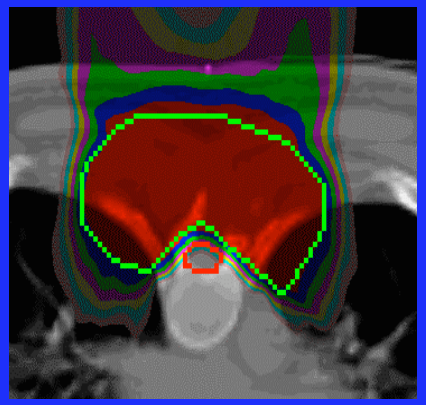
Dealing with range uncertainties - robust IMPT planning?

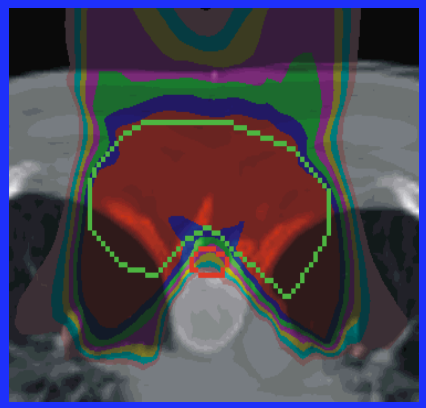
Nominal

-10% CT

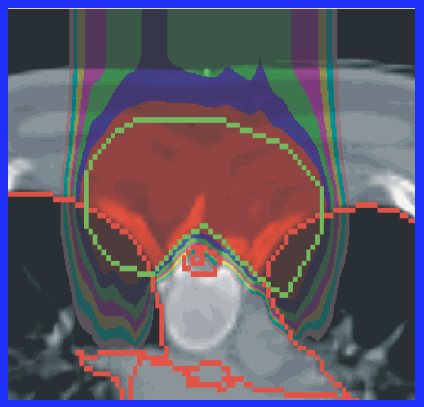
DVH analysis

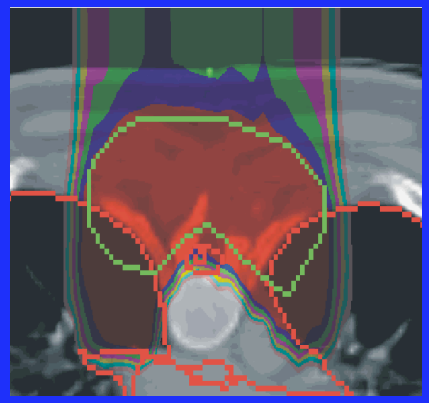
IMPT

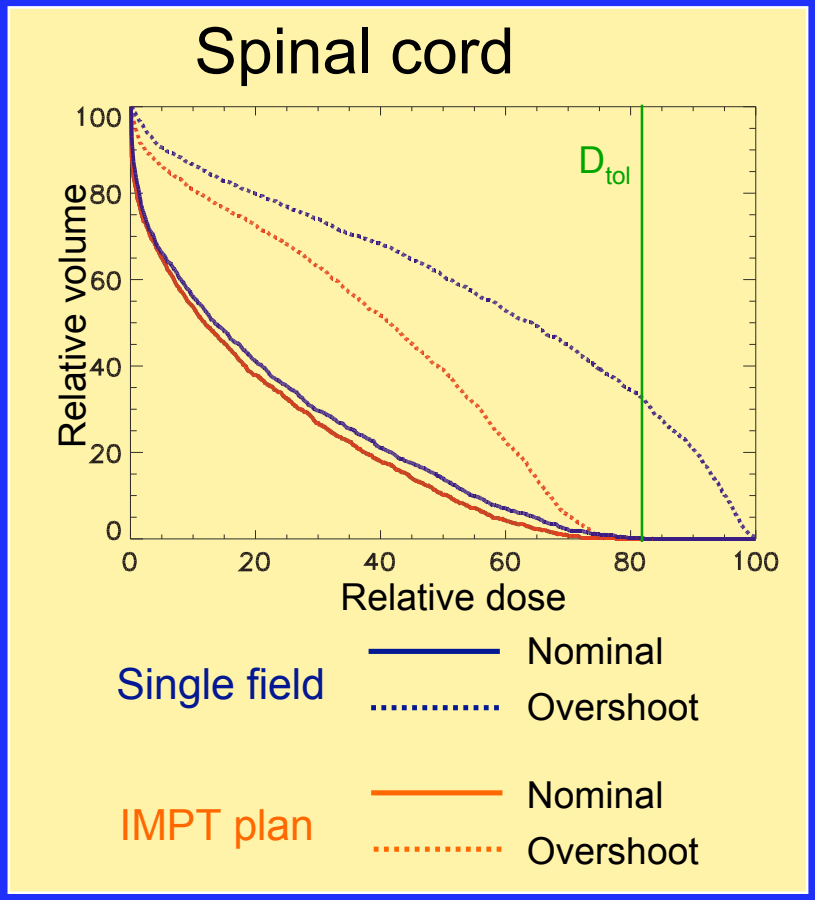




Single field







Lomax et al 2001, Med. Phys. 28:317-324

Summary

- Although many similarities with conventional therapy, there are some significant differences and issues for planning active scanned proton and IMPT plans
- Is the conventional PTV criteria still valid? Are field specific PTV's required?
- Active scanned plans (fields) have a large degeneracy – many distributions of pencil beam intensities give very similar dose distributions
- In general, spot scanned plans are more sensitive to errors than conventional photon plans and IMPT plans more sensitive to simple spot scanned plans

Don't abandon 'simple' planning techniques (e.g. SFUD)!