New Developments in Proton Treatment Planning Systems

Daniel Yeung

Statement of Disclosure

Funded Research & Development:

Philips Medical Systems

IBA

Proton Planning Systems

	Commercial Systems	Academic Systems
Analytical/Semi-Analytical	CMS - Xio	MGH, HCL
	Varian – Eclipse Proton	PSI
	Varian – EyePlan	Clatterbridge
	Optivus - Odyssey	Loma Linda
	Dosigray	Orsay
	Others…	Others…
* Under Development	Philips – Pinnacle*	UF*
Monte Carlo	CMS*, Varian*,…	MGH, DKFZ,…

Proton Pencil Beam Algorithms

Hong et al, MGH 1996

A pencil beam algorithm for proton dose calculations

Linda Hong†‡, Michael Goitein†, Marta Bucciolini§, Robert Comiskey†, Bernard Gottschalk‖, Skip Rosenthal†, Chris Serago† and Marcia Urie†

† Department of Radiation Oncology, Massachusetts General Hospital, Boston, MA, USA
‡ Department of Radiation Oncology, Mt Sinai Medical Center, New York, NY, USA

Szymanowski et al, Institut Curie 2001

Experimental determination and verification of the parameters used in a proton pencil beam algorithm

H. Szymanowski[a)]
Service de Physique Médicale, Institut Curie, 26 rue d'Ulm, 75005 Paris, France

A. Mazal
Service de Physique Médicale, Institut Curie, 26 rue d'Ulm, 75005 Paris, France and Centre de Protonthérapie d'Orsay (C.P.O.), B.P. 65, 91402 Orsay, France

Beam Model

- dosimetry in water
- inhomogeneity correction
  - water equivalent thickness (wet)
  - HU → stopping power

Proton Pencil Beam Algorithm

Beam Model

CAX Depth Dose (DD)

- broad beam
- pristine peak ⟹ sobp

Radial Spread (RS)

- multi coloumb scatter
  - beamline: degrader, nozzle elements (wet only)
  - compensator: material dependent scattering power
  - patient: wet only
- gaussian kernel

$$\sigma^2_{total} = \sigma^2_{line} + \sigma^2_{comp} + \sigma^2_{patient}$$

Proton Pencil Beam Algorithm

Dose Calculation

- Dose from a pencil beam

$$D_{PB}(x,y,z) = C(z_{eq},x_0,y_0) \times \frac{1}{2\pi\sigma_{tot}^2(z_{eq})} \times \exp\left(-\frac{(x-x_0)^2+(y-y_0)^2}{2\sigma_{tot}^2(z_{eq})} \right),$$

- Convolve DD with RS for each pencil
- Sum dose from all pencils

Bortfeld Model of Pristine Peak

An analytical approximation of the Bragg curve for therapeutic proton beams

Thomas Bortfeld[a)]
Deutsches Krebsforschungszentrum (DKFZ), Abteilung Medizinische Physik and Universität Heidelberg, Fakultät für Physik und Astronomie, Heidelberg, Germany

(Received 28 October 1996; accepted for publication 17 September 1997)

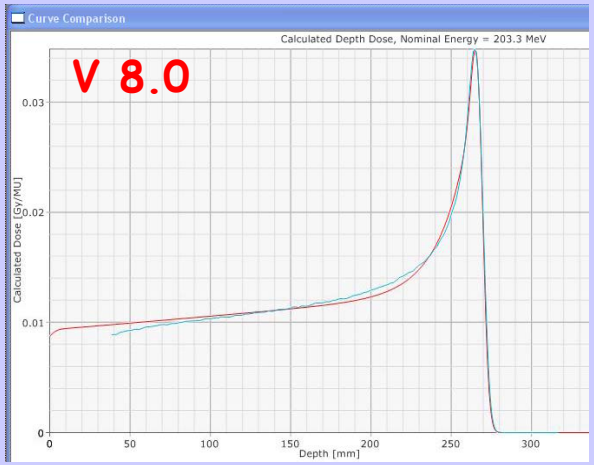
$$D(z)=\Phi_0\,\frac{e^{-\zeta^2/4}\sigma^{1/p}\Gamma(1/p)}{\sqrt{2\pi}\varrho p\alpha^{1/p}(1+\beta R_0)}\left[\frac{1}{\sigma}\mathscr{D}_{-1/p}(-\zeta)+\left(\frac{\beta}{p}+\gamma\beta+\frac{\epsilon}{R_0}\right)\mathscr{D}_{-1/p-1}(-\zeta)\right].$$

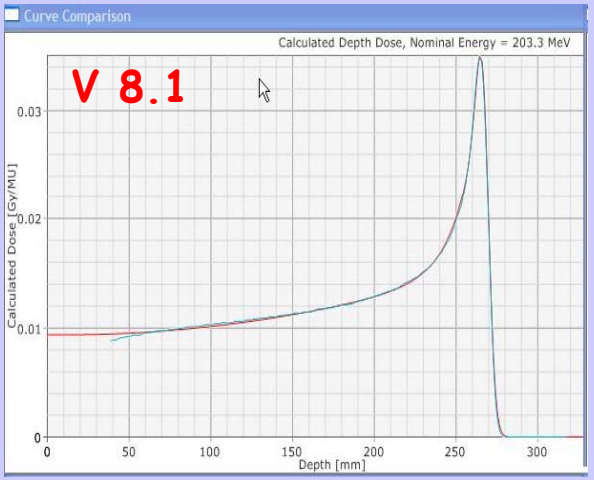
Analytical model of proton BP (up to ~ 200 MeV)

- accounts for energy spread
- empirical model of nuclear fragmentation (data fitting)
- numeric depth dose calculation of fitted BP
- assumption – range straggling ‘constant’ with depth

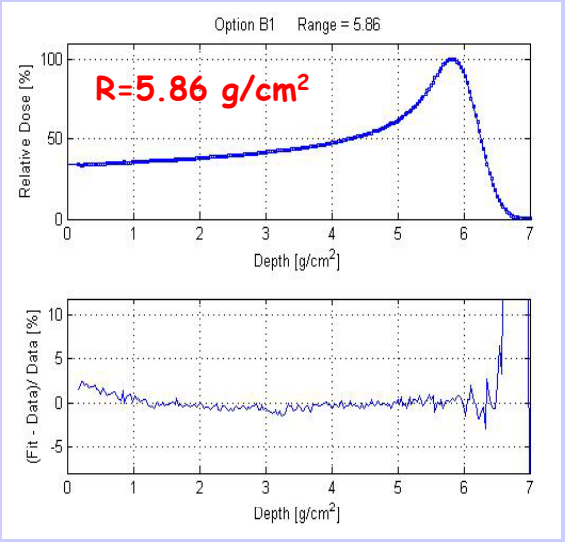
Pristine Peak - Analytical Model

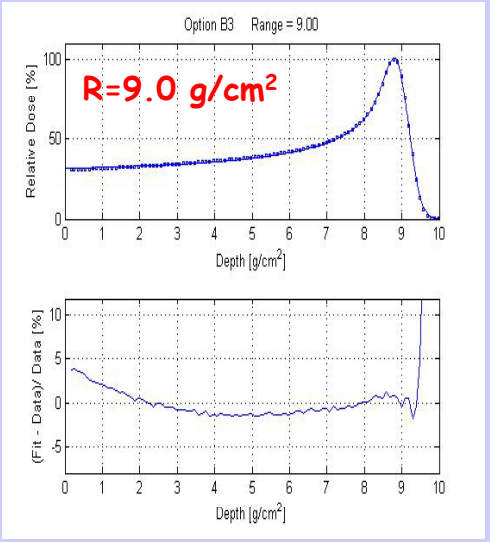
R=21.86 g/cm²





Eclipse Model





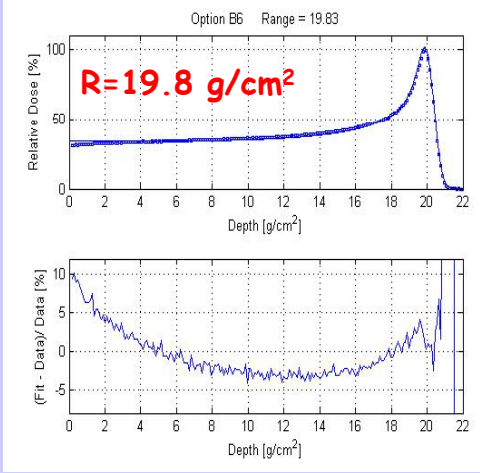
For R > 15 g/cm²,

Range straggling ↑ depth

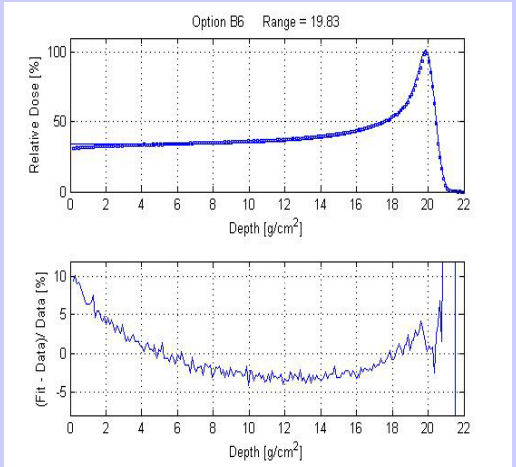
↓

Error in Bortfeld model

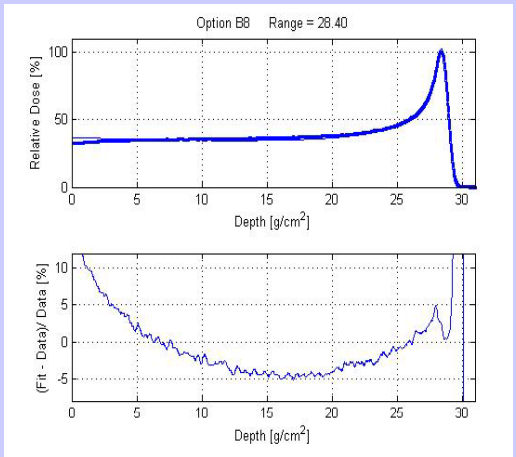
Bortfeld Model



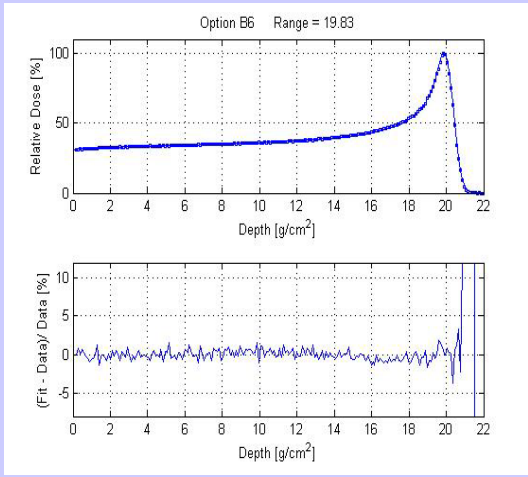
Pristine Peak – Bortfeld Model

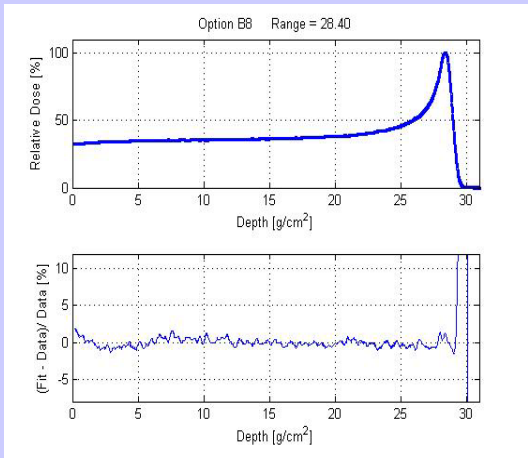


R=19.8 g/cm²



R=28.4 g/cm²

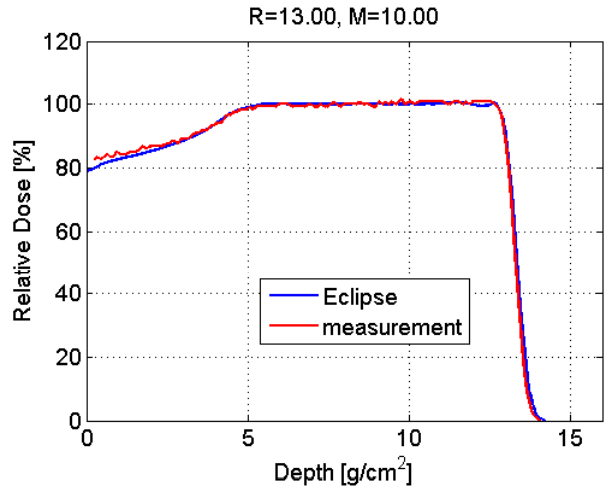


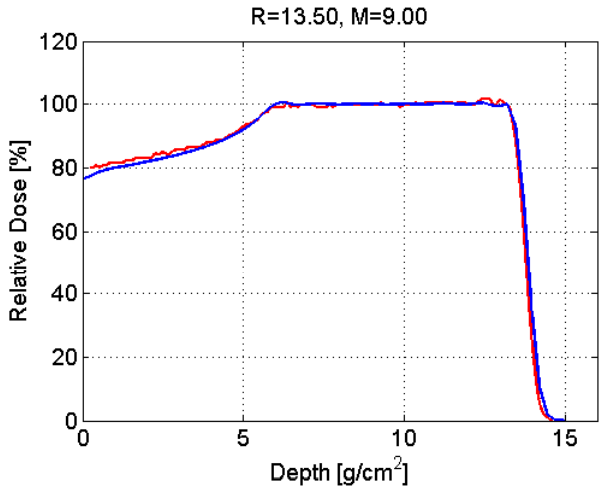


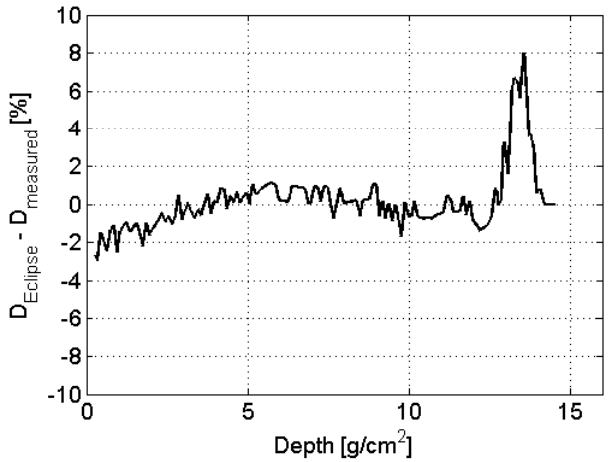
Bortfeld Model

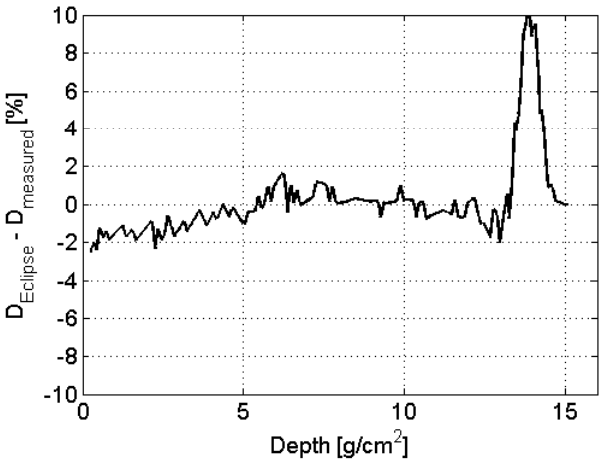
Bortfeld - Enhanced

SOBP
Calc vs Measurement





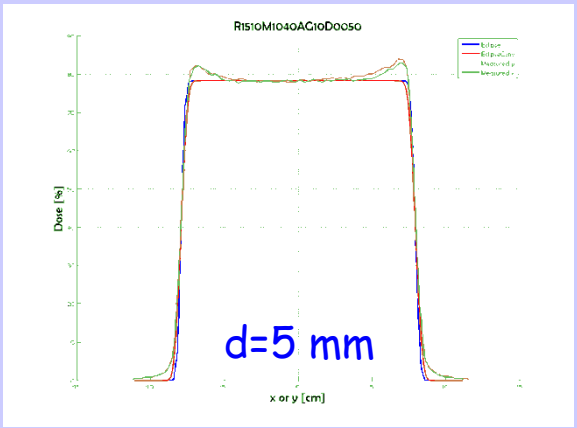


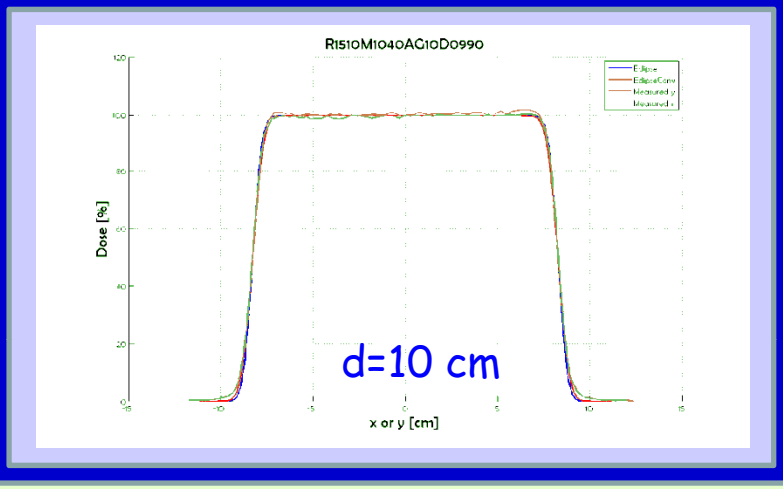


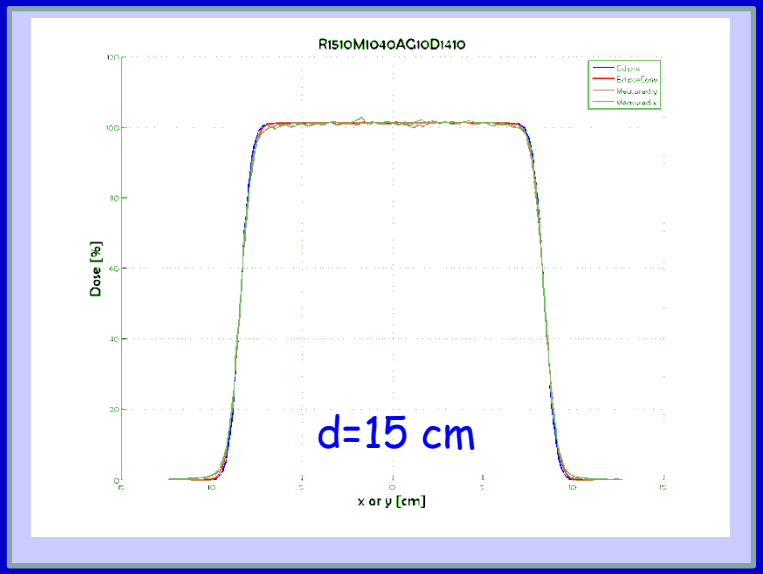
Courtesy R. Slopsema

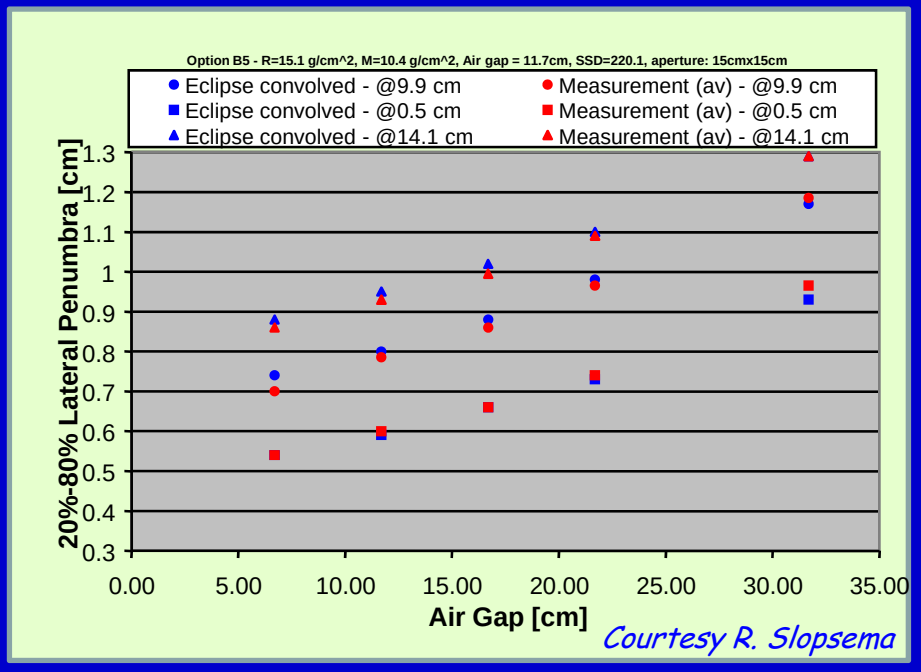
Beam Profile
Calc vs Measurement

R=15.1 M=10.4





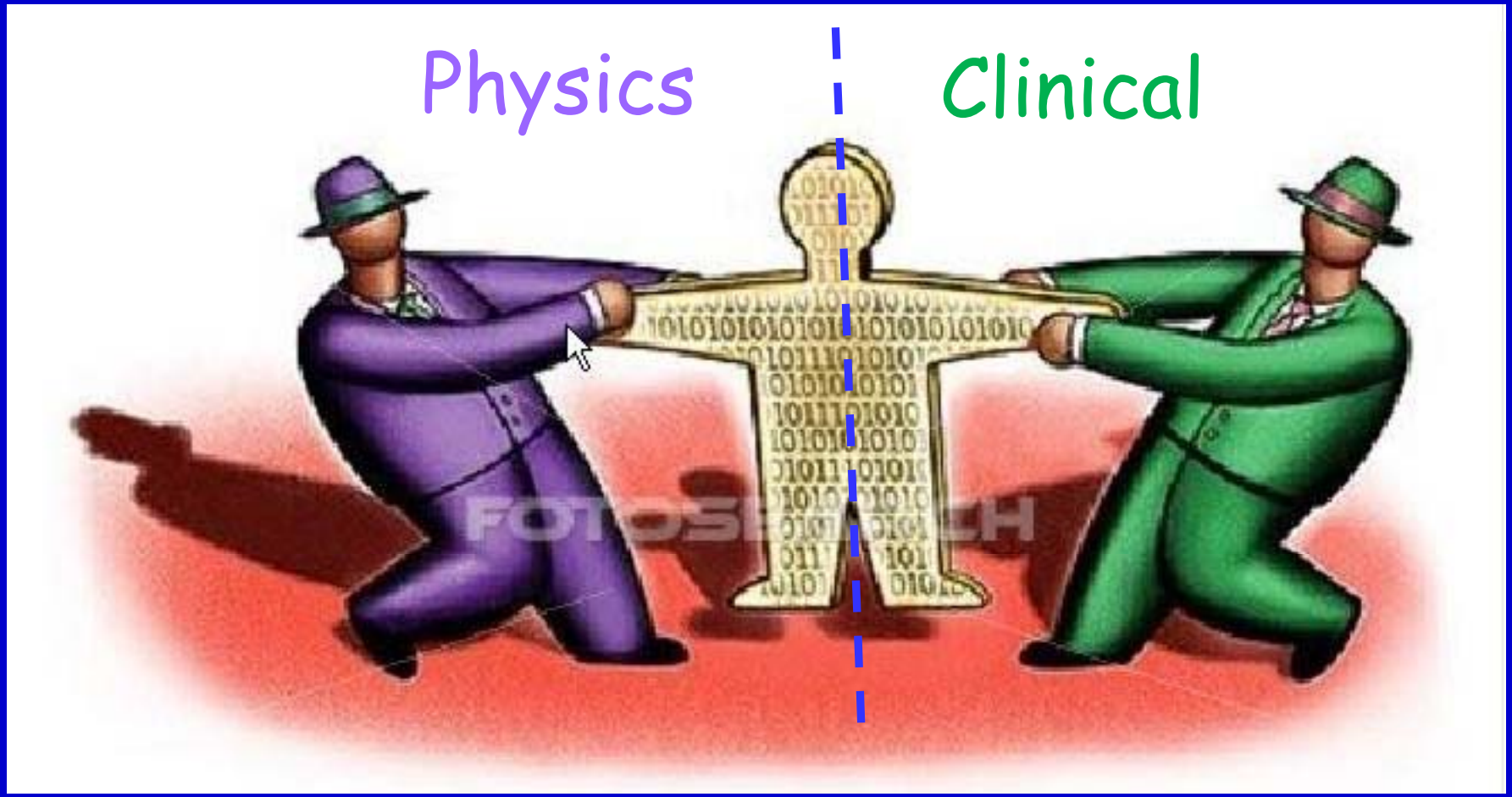




Courtesy R. Slopsema

Proton Dose Calc in water is generally accurate!

…ok, what about Clinical Issues?

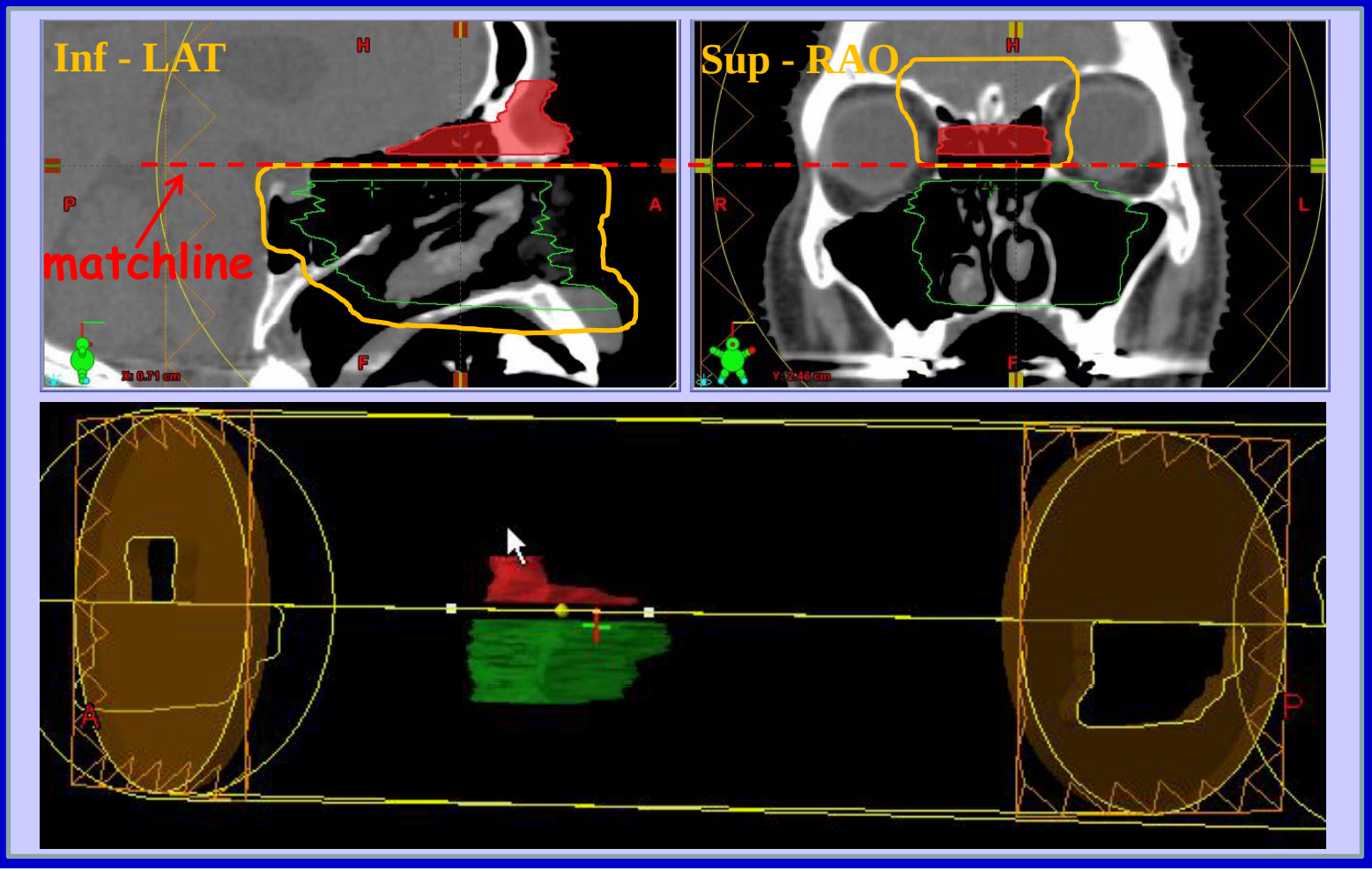


Match & Patch Fields

- used to avoid OARs adjacent to target
- partition target into segments (sub-targets)
  - sub-targets treated with ‘sub-beams’
  - angle sub-beams to avoid OARs
- combined with other fields for dose uniformity

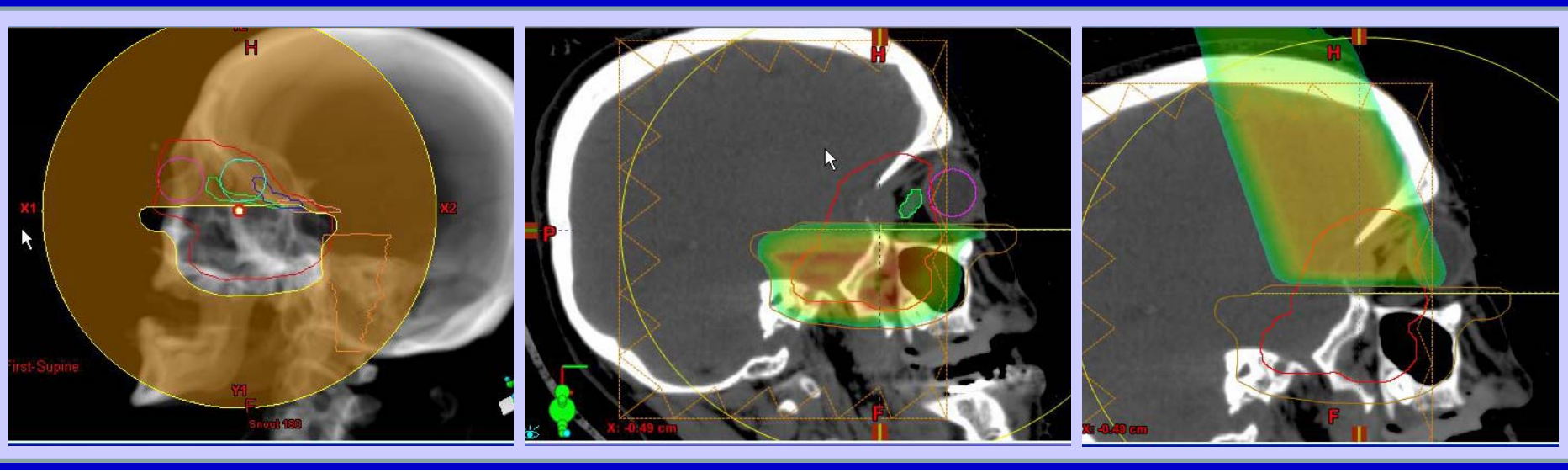
Match Fields

- match fields abutting each other
- penumbra matching penumbra



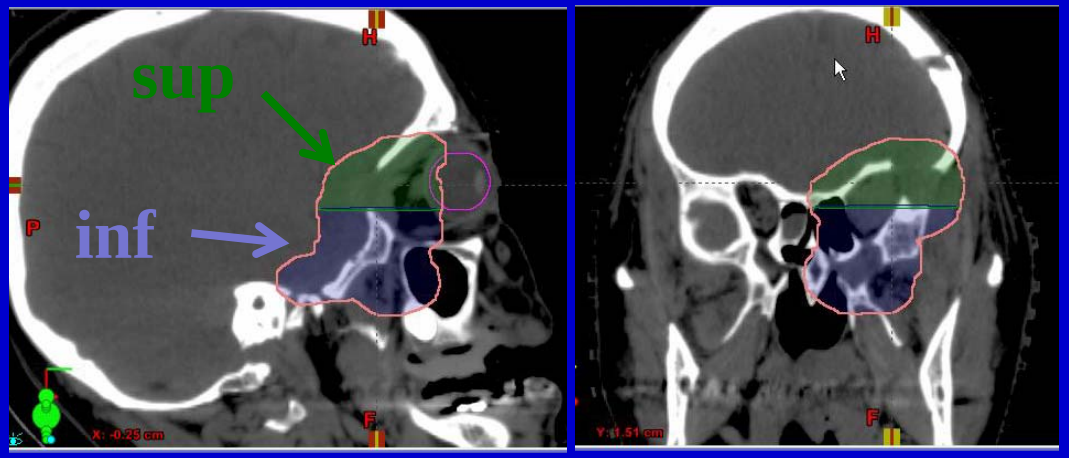
Patch Fields

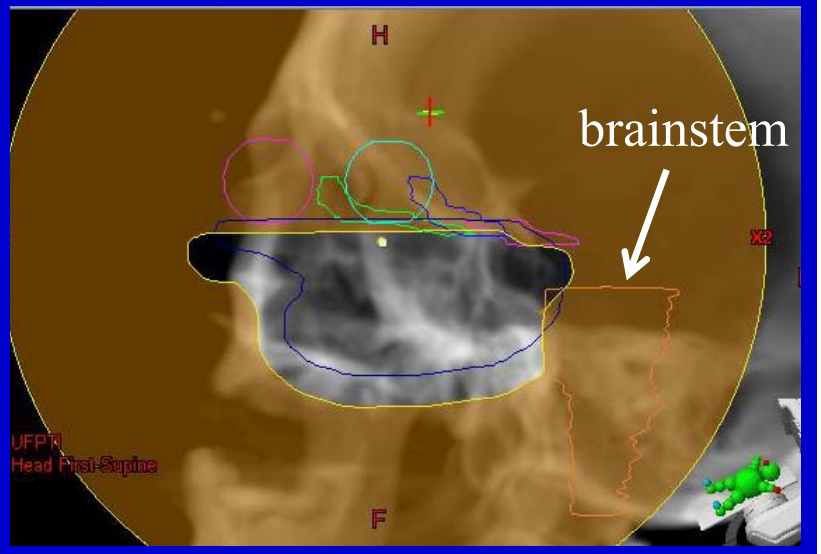
- thru beam txt partial target
- residual txt with patch
- lateral penumbra (t-beam) ‘matched’ with distal falloff (p-beam)
- LPO beam (inferior) patched with SPO (superior)



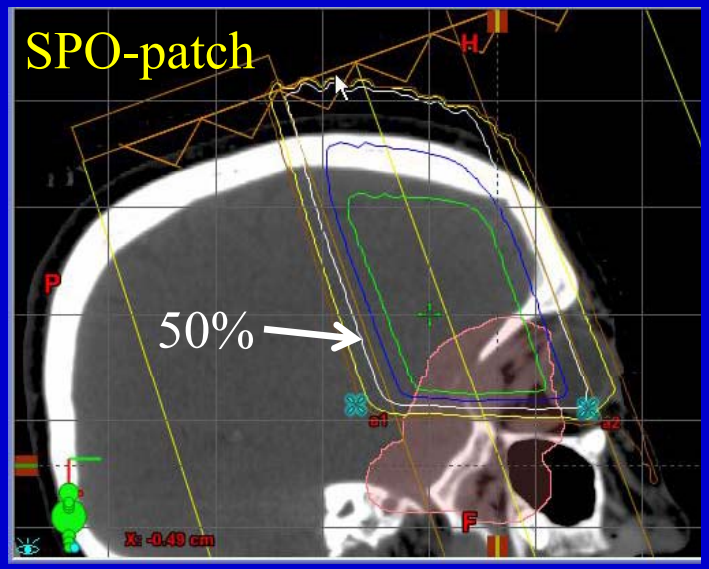
Lacrimal Gland Carcinoma
PTV 50.4

partition into sup + inf targets





LPO-Inf (spare optics & BS)



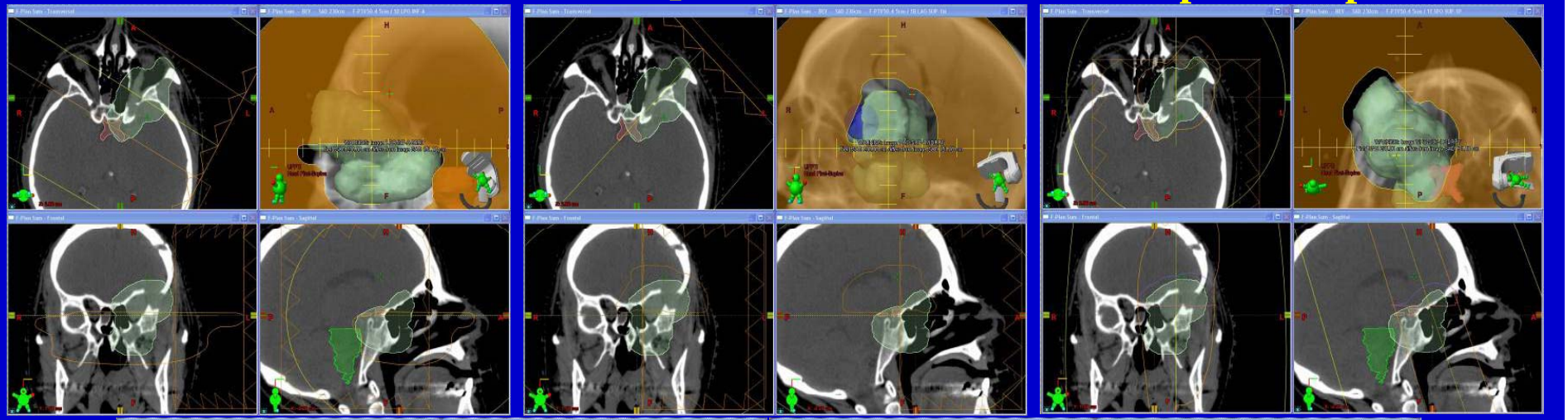
PTV50.4: 5 fields with match & patch		
Target	Fields	
PTV	LAO	LPO
PTV(Inf)	LPO-Inf	
PTV(Sup)	LAO-match	SPO-patch

Lacrimal Gland Carcinoma
PTV50.4 – 5 Fields

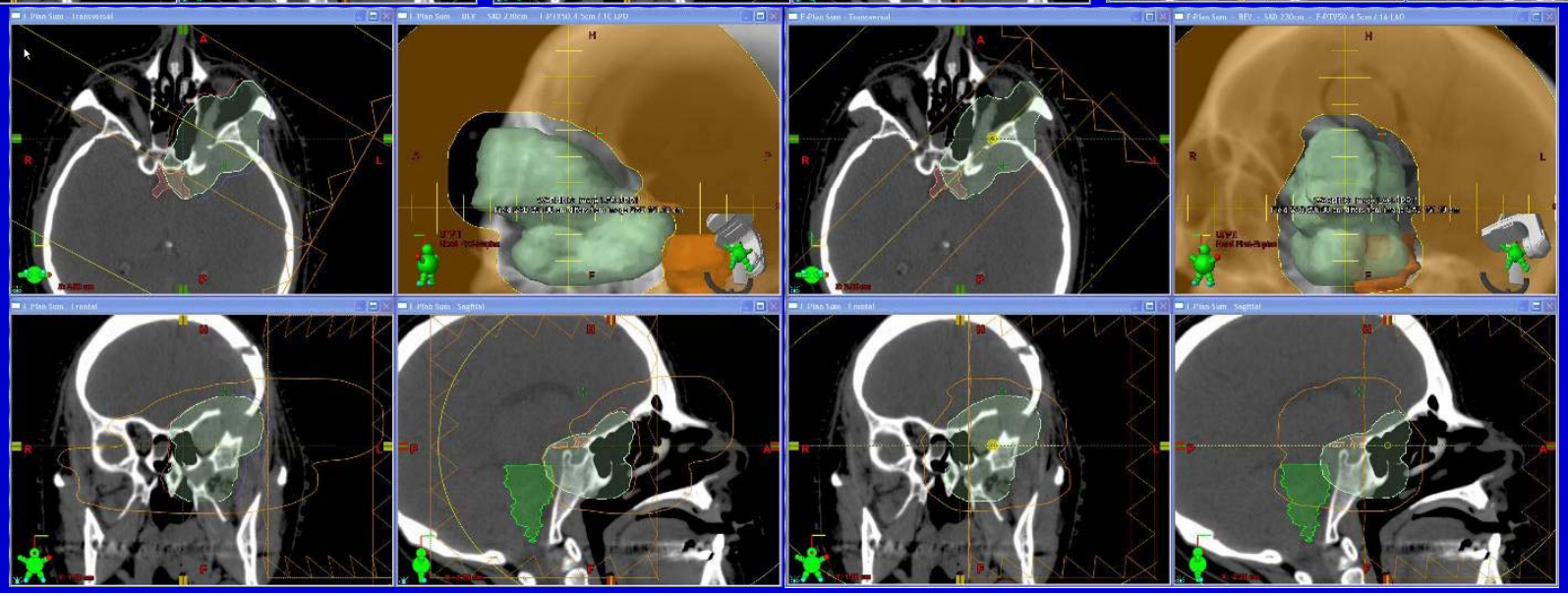
Inf - LPO

Sup – LAO match

Sup – SPO patch



LPO

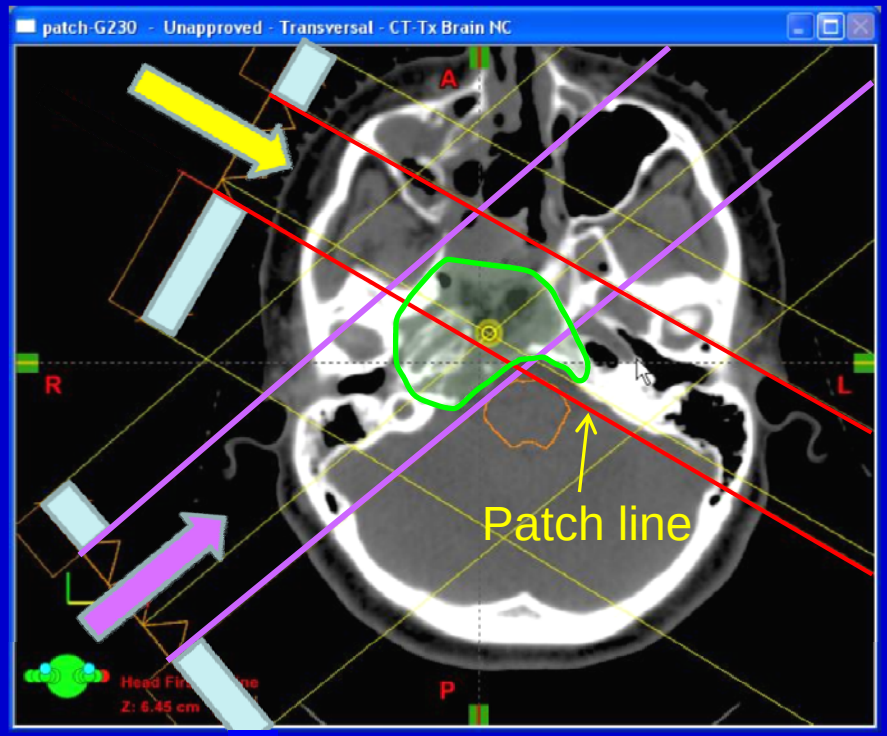


LAO

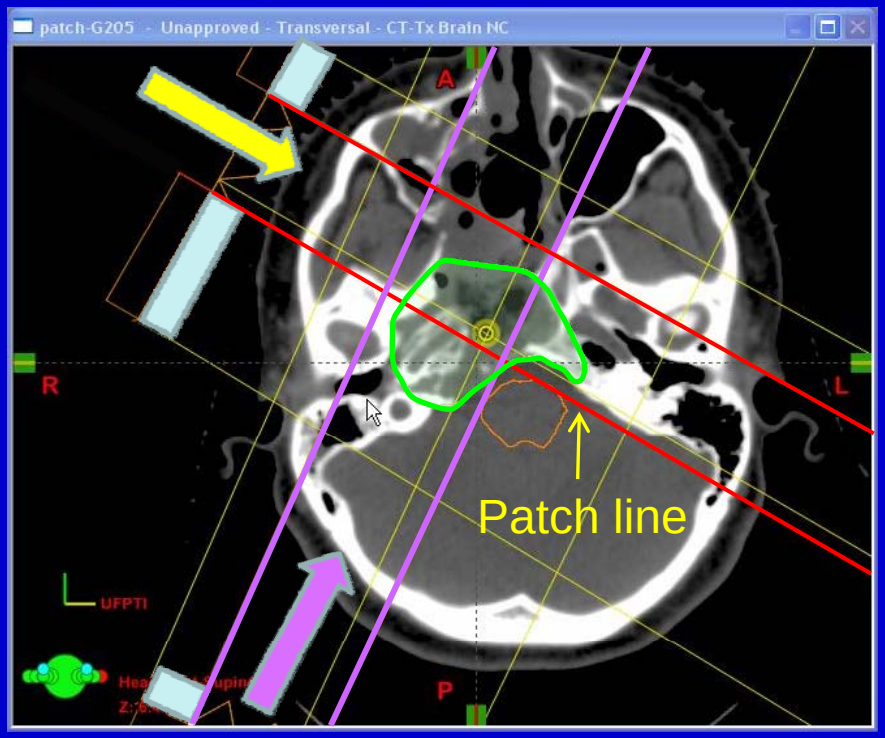
Patch Field Selection

Patch Field Angle Selection

- optimal geometric coverage (**G = 230**)
- avoid inhomogeneity along path (**G = 205**)

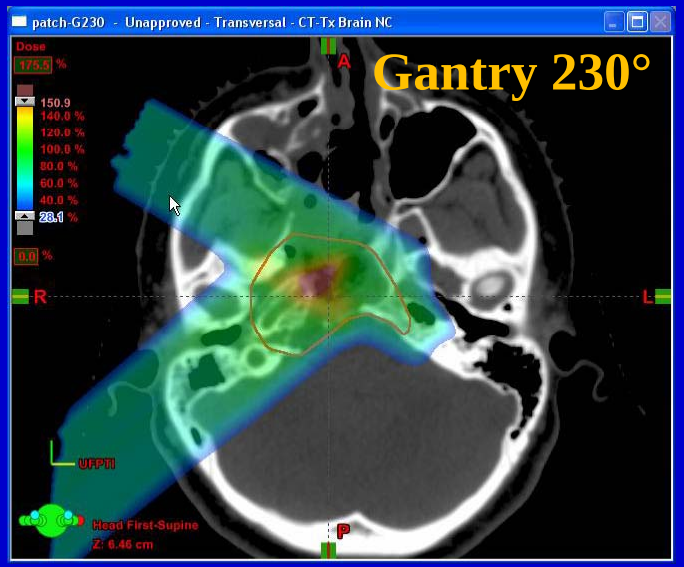


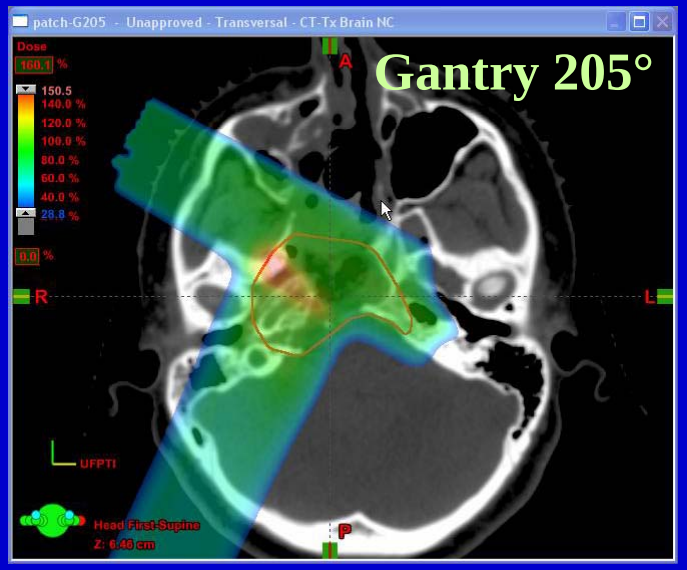
Gantry 230

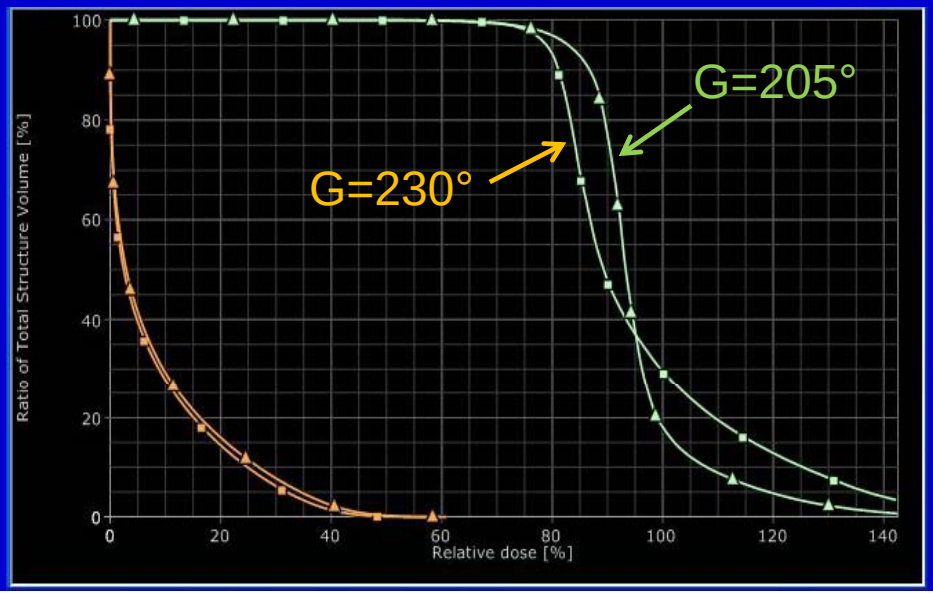


Gantry 205

Patch Field – Beam Angle Selection



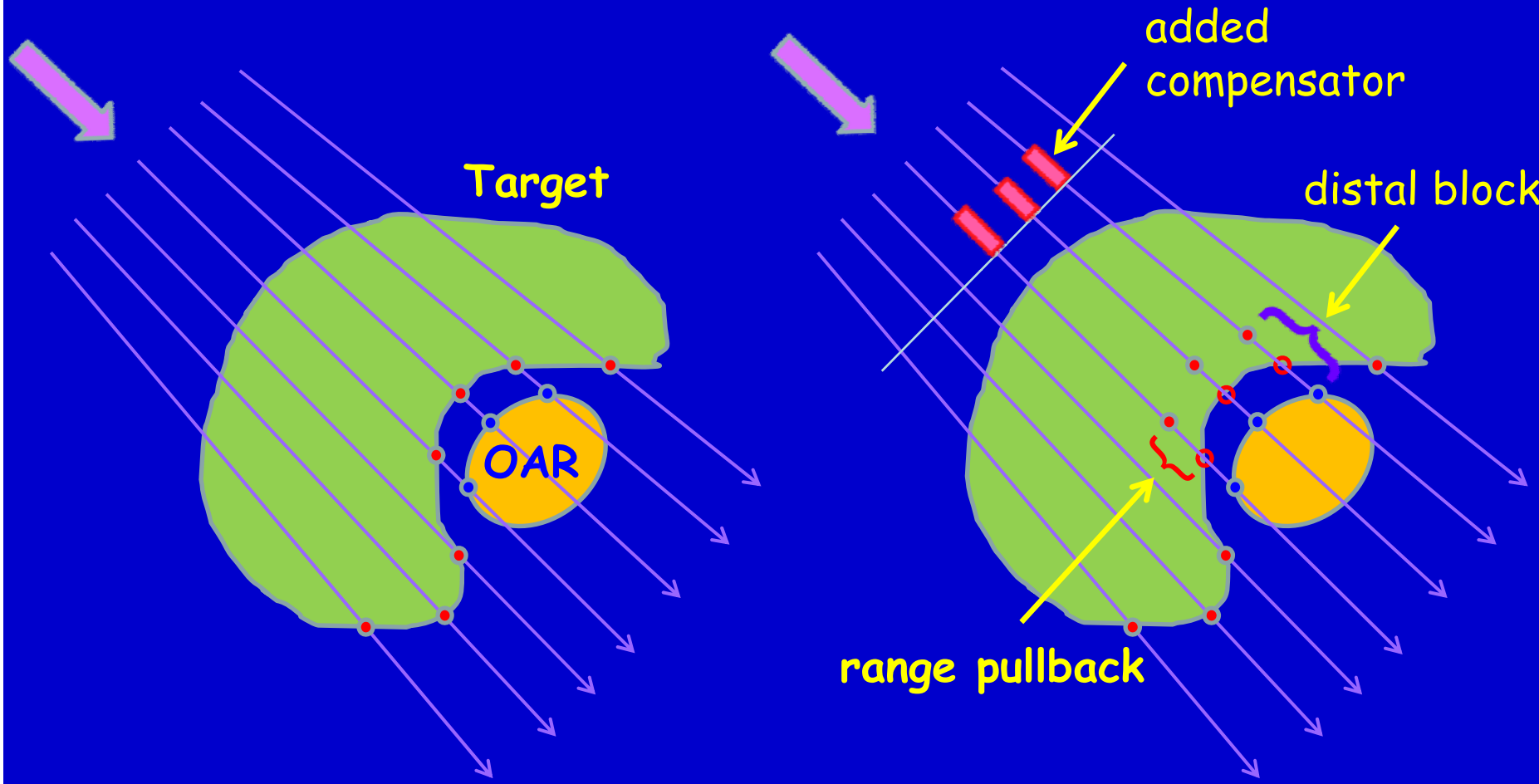




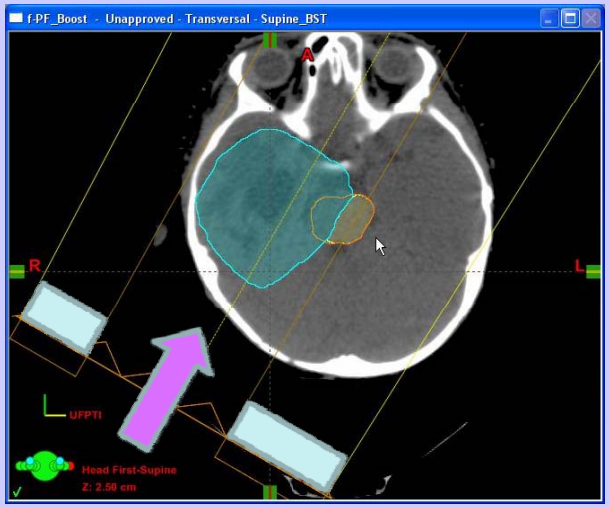
Distal Blocking

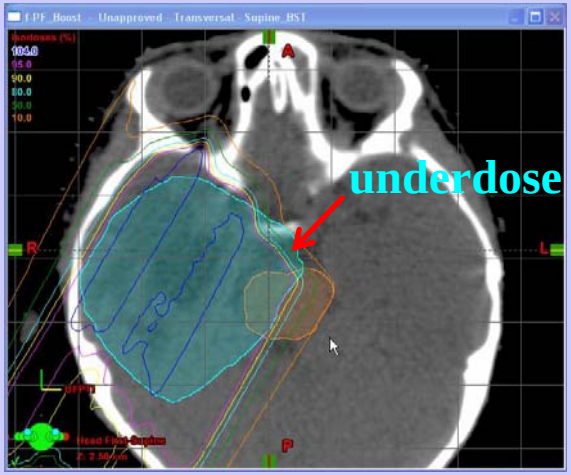
- selective pullback of range to spare OARs
- pullback achieved with added compensator
- potential pitfalls
  - setup error or motion may nullify sparing
  - 'simple' distal blocking may compromise target coverage
- assess robustness of approach

Distal Blocking



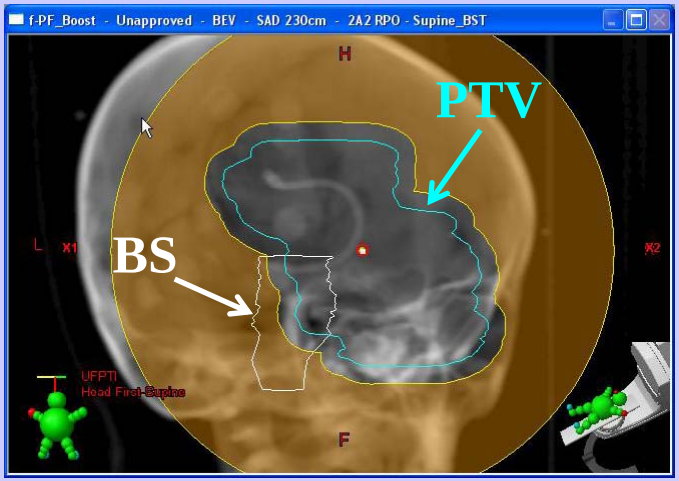
Distal Blocking





Whole BS

Partial BS



RPO Field

Clinical Tools

Integrate Clinical workflow

- clinical database
- web-based applications
  - mu model
  - physics qa
  - plan evaluation
- quality assurance
- clinical efficiency & efficacy

Plan/Dvh Evaluation

PROTON THERAPY

H&N Treatment Dosimetry Check List

Name: UFPTI Patient ID: 12345 Dosimetrist: _____ MD: _____
Age: _____ Disease Site: Nasal Cavity Tx. Room: P2
Scan Date: _____ Start Date: _____ Final Plan Name: PNS

Site / Protocol #	Oropharynx UFPTI 0601-OP01 ☐	Paranasal sinuses/ Nasal Cavity UFPTI 0604-SI01 ☑	Nasopharynx UFPTI 0605-NP01 ☐	Skin with perineural invasion UFPTI 0606-SK01 ☐
Initial Dose	Standard risk: 49.5 Gy@ 1.65 Gy/fx QD Intermediate/high risk: 54 Gy@ 1.8 Gy/fx QD IMRT	Pre-Op: 50.4 – 60 Gy@ 1.2 Gy/fx BID Post-Op: 69.6 – 74.4 Gy@ 1.2 Gy/fx BID	50.4 Gy@ 1.2 Gy/fx BID	Local RT: BID (-) skin invasion: 60 Gy@ 1.2 Gy/fx (+) skin invasion: 66 Gy@ 1.2 Gy/fx Local RT + involved nerve to skull base: BID 60 Gy@ 1.2 Gy/fx photons
Boost Dose	High Risk: concomitant boost 18 Gy@ 1.5 Gy/fx proton	(low neck photons) ☐ Y ☐ N 50 Gy@ 2Gy/fx QD	24 CGE@ 1.2 Gy/fx BID	Local RT + involved nerve to skull base: BID 14.4 Gy@ 1.2 Gy/fx

4D CT/ Image Fusion checked: Physician: _____ Date: __ Physicist: _____ Date: ____
CT without contrast, CT with contrast, MR: _____

Contours checked: Physician: _____ Date: _____ Physicist: _____ Date: _____

Normal Organs:

Dosimetrist:	Mandible ☐	Spinal Cord ☑	Cord+5 ☑	Retinas ☑
	Brainstem+3 ☑	Brain ☑	LT/RT O.N. ☑	Other: _____
Physician:	LT/RT SMG ☐	Brainstem ☑	LT/RT Lacrimal Gland ☐	☐
	LT Parotid ☐	RT Parotid ☐	Chiasm ☑	Other: _____
Targets:	GTV ☐	CTVs ☑	PTVs ☑	

DVH Physician: _____ Date: _____ Physicist: _____ Date: ____

PTV D95% = 100%? 95% ☐ YES ☐ NO PTV D99% ≥ 93%? 83% ☐ YES ☐ NO

PTV Hotspot: V110% ≤20%? 6% ☐ YES ☐ NO PTV D2% = 112%

BS Max dose 0.1cc = 30CGE
Brainstem Surface≤ 64 CGE ✓ Middle≤55 ✓ Post<50 ✓ Cord D0.1cc ≤ 50 Gy? 2 ☑ YES ☐ NO

Chiasm 0.1cc = 31 < 55 CGE? ☑ YES ☐ NO f OC+3mm(exp) 0.1cc= N/A (functional Chiasm: will effect vision)

RT O.N. 0.1cc = 32 < 55 CGE? ☑ YES ☐ NO LT O.N. 0.1cc = 37 < 55 CGE? ☑ YES ☐ NO

RT Retina (posterior globe) D0.1cc ≤ 50 Gy? 41 ☑ YES ☐ NO LT Retina (posterior globe) D0.1cc ≤ 50 Gy? 41 ☑ YES ☐ NO

Chart: Physician: _____ Date: _____ Physicist: _____ Date: ____

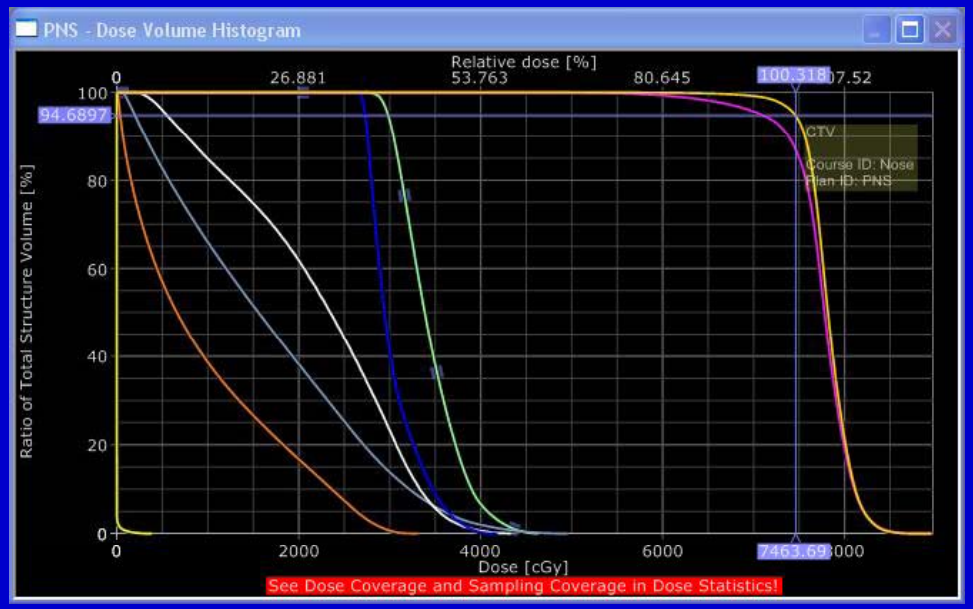
Prescription signed ☐

Dose: Initial: 74.4 CGE Boost: Ø CGE # Fields/Day: 3

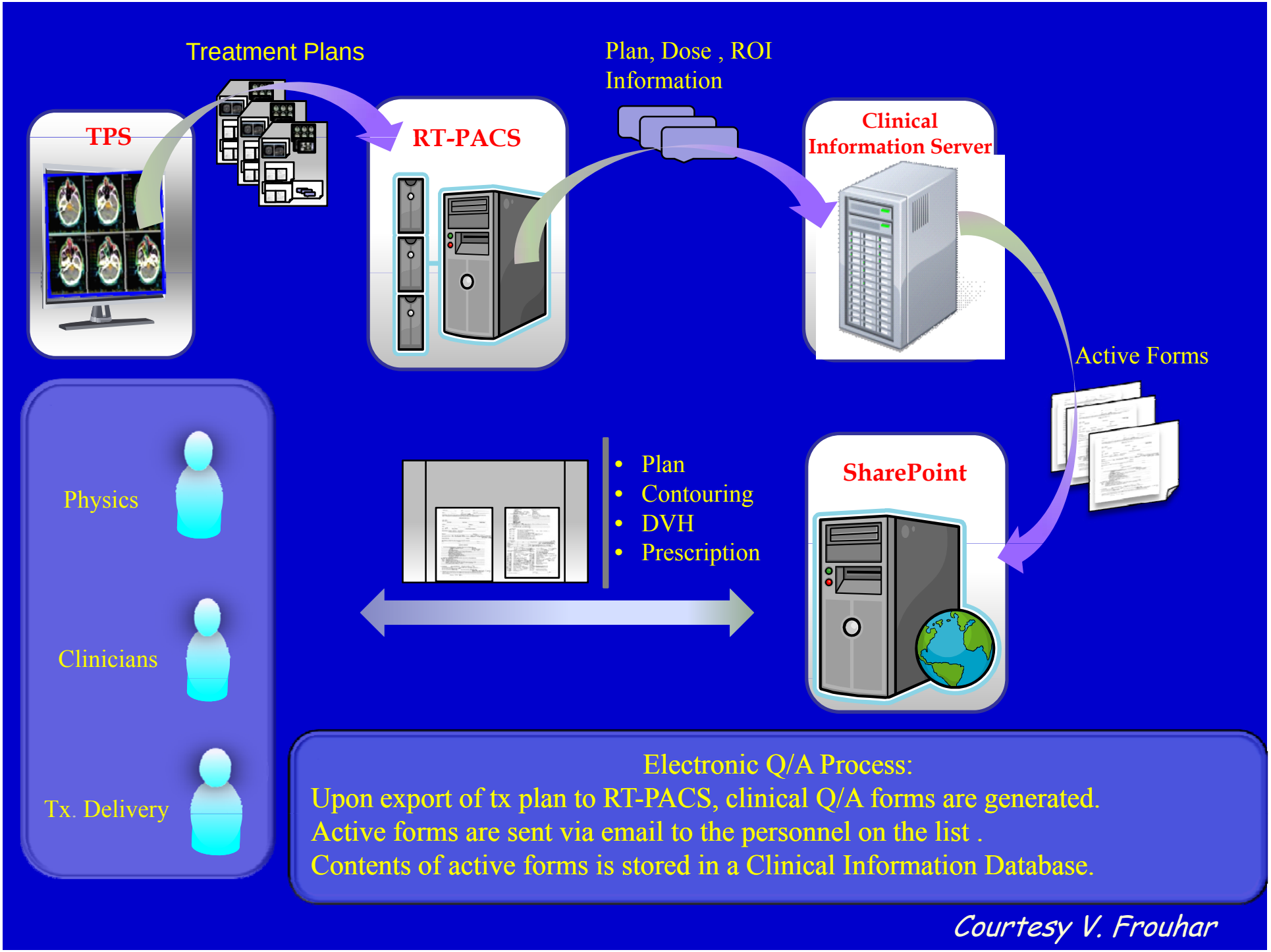
Distal Blocking Structure Margins **on Back**

Rev. 9/24/07

Courtesy R. Malyapa, C.McKenzie, Z. Li

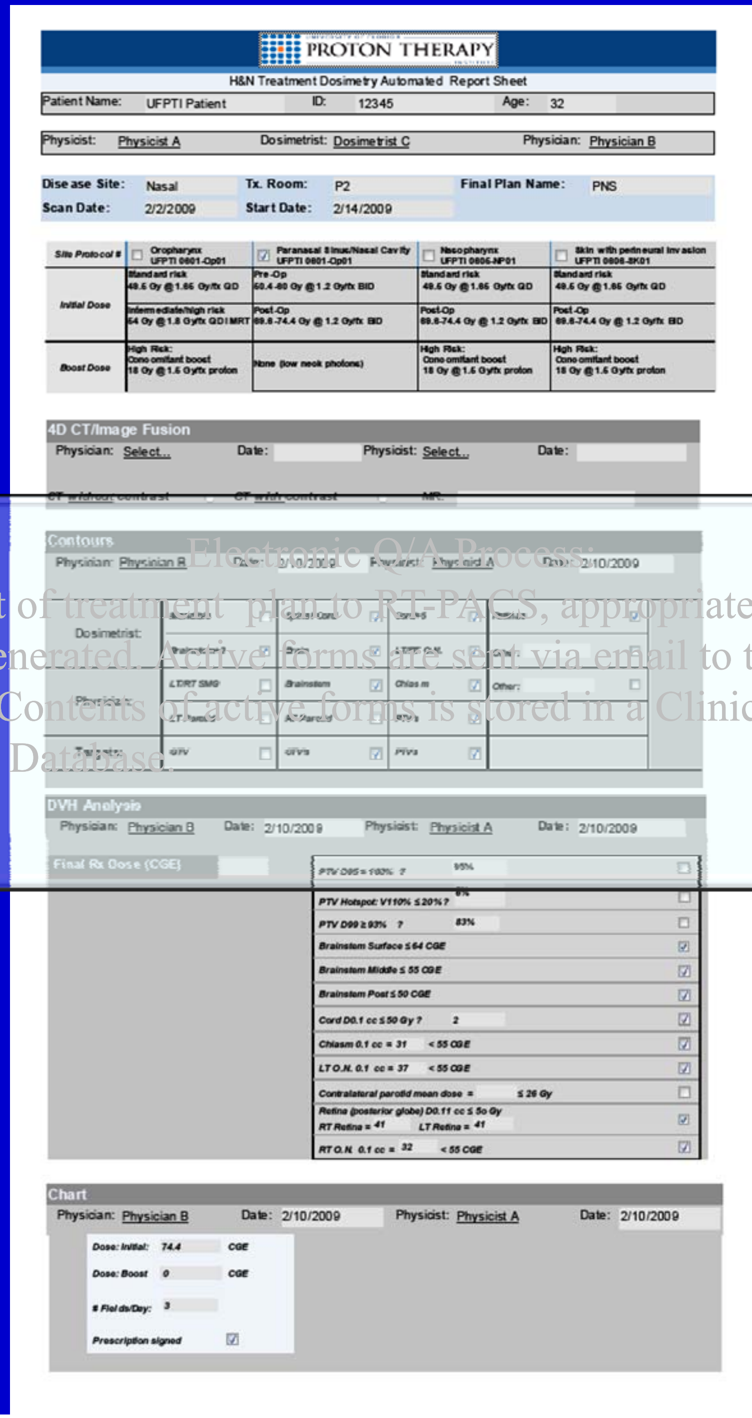


Dvh statistics for CTV, PTV, OARs are extracted **manually** from plots


Treatment Plans
TPS
RT-PACS
Plan, Dose , ROI Information
Clinical Information Server
Active Forms
SharePoint
Physics
Clinicians
Tx. Delivery
Plan
Contouring
DVH
Prescription
Electronic Q/A Process:
Upon export of tx plan to RT-PACS, clinical Q/A forms are generated.
Active forms are sent via email to the personnel on the list .
Contents of active forms is stored in a Clinical Information Database.
Courtesy V. Frouhar

Electronic Q/A Process:

Upon expert of treatment plan to RT-PACS, appropriate clinical Q/A forms are generated. Active forms are sent via email to the personnel on the list . Contents of active forms is stored in a Clinical Information Database.



PROTON THERAPY

H&N Treatment Dosimetry Automated Report Sheet

Patient Name:	UFPTI Patient	ID:	12345	Age:	32
Physicist:	Physicist A	Dosimetrist:	Dosimetrist C	Physician:	Physician B
Disease Site:	Nasal	Tx. Room:	P2	Final Plan Name:	PNS
Scan Date:	2/2/2009	Start Date:	2/14/2009		

Site Protocol #	Oropharynx UFPTI 0601-Op01	Paranasal Sinus/Nasal Cavity UFPTI 0601-Op01	Nasopharynx UFPTI 0606-NP01	Skin with perineural invasion UFPTI 0606-SK01
Initial Dose	Standard risk 49.5 Gy @ 1.65 Gy/fx QD	Pre-Op 60.4-60 Gy @ 1.2 Gy/fx BID	Standard risk 49.5 Gy @ 1.65 Gy/fx QD	Standard risk 49.5 Gy @ 1.65 Gy/fx QD
	Intermediate/high risk 54 Gy @ 1.8 Gy/fx QD IMRT	Post-Op 69.6-74.4 Gy @ 1.2 Gy/fx BID	Post-Op 69.6-74.4 Gy @ 1.2 Gy/fx BID	Post-Op 69.6-74.4 Gy @ 1.2 Gy/fx BID
Boost Dose	High Risk: Concomitant boost 18 Gy @ 1.5 Gy/fx proton	None (low neck photons)	High Risk: Concomitant boost 18 Gy @ 1.5 Gy/fx proton	High Risk: Concomitant boost 18 Gy @ 1.5 Gy/fx proton

4D CT/Image Fusion

Physician: Select... Date: Physicist: Select... Date:

CT without contrast CT with contrast MR

Contours

Physician: Physician B Date: 2/10/2009 Physicist: Physicist A Date: 2/10/2009

DVH Analysis

Physician: Physician B Date: 2/10/2009 Physicist: Physicist A Date: 2/10/2009

Final Rx Dose (CGE)

PTV D95 = 100% ?	95%	☐
PTV Hotspot: V110% ≤ 20% ?	0%	☐
PTV D99 ≥ 93% ?	83%	☐
Brainstem Surface ≤ 64 CGE		☑
Brainstem Middle ≤ 55 CGE		☑
Brainstem Post ≤ 50 CGE		☑
Cord D0.1 cc ≤ 50 Gy ?	2	☑
Chiasm 0.1 cc = 31	< 55 CGE	☑
LT O.N. 0.1 cc = 37	< 55 CGE	☑
Contralateral parotid mean dose =	≤ 26 Gy	☐
Retina (posterior globe) D0.11 cc ≤ 50 Gy RT Retina = 41 LT Retina = 41		☑
RT O.N. 0.1 cc = 32	< 55 CGE	☑

Chart

Physician: Physician B Date: 2/10/2009 Physicist: Physicist A Date: 2/10/2009

Dose: Initial:	74.4	CGE
Dose: Boost	0	CGE
# Fields/Day:	3	
Prescription signed	☑	

UNIVERSITY OF FLORIDA PROTON THERAPY INSTITUTE

H&N Treatment Dosimetry Automated Report Sheet

Patient Name:	UFPTI Patient	ID:	12345	Age:	32

Physicist:	Physicist A	Dosimetrist:	Dosimetrist C	Physician:	Physician B

Disease Site:	Nasal	Tx. Room:	P2	Final Plan Name:	PNS
Scan Date:	2/2/2009	Start Date:	2/14/2009		

Site Protocol #	☐ Oropharynx UFPTI 0601-Op01	☑ Paranasal Sinus/Nasal Cavity UFPTI 0601-Op01	☐ Nasopharynx UFPTI 0605-NP01	☐ Skin with perineural invasion UFPTI 0606-SK01
Initial Dose	Standard risk 49.5 Gy @1.65 Gy/fx QD	Pre-Op 50.4-60 Gy @1.2 Gy/fx BID	Standard risk 49.5 Gy @1.65 Gy/fx QD	Standard risk 49.5 Gy @1.65 Gy/fx QD
	Intermediate/high risk 54 Gy @1.8 Gy/fx QD IMRT	Post-Op 69.6-74.4 Gy @ 1.2 Gy/fx BID	Post-Op 69.6-74.4 Gy @ 1.2 Gy/fx BID	Post-Op 69.6-74.4 Gy @ 1.2 Gy/fx BID
Boost Dose	High Risk: Concomitant boost 18 Gy @1.5 Gy/fx proton	None (low neck photons)	High Risk: Concomitant boost 18 Gy @1.5 Gy/fx proton	High Risk: Concomitant boost 18 Gy @1.5 Gy/fx proton

4D CT/Image Fusion

Physician: Select... Date: Physicist: Select... Date:

CT ***without*** contrast ○ CT ***with*** contrast ○ MR:

Contours

Physician: Physician B Date: 2/10/2009 Physicist: Physicist A Date: 2/10/2009

Dosimetrist:	*Mandible* ☐	*Spinal Cord* ☑	*Cord+5* ☑	*Retinas* ☑
	Brainstem+3 ☑	*Brain* ☑	*LT/RT O.N.* ☑	*Other:* ☐
Physician:	*LT/RT SMG* ☐	*Brainstem* ☑	*Chiasm* ☑	*Other:* ☐
	LT Parotid ☐	*RT Parotid* ☐	*PTV's* ☑	
Targets:	*GTV* ☐	*CTV's* ☑	*PTVs* ☑	

DVH Analysis

Physician: Physician B Date: 2/10/2009 Physicist: Physicist A Date: 2/10/2009

Final Rx Dose (CGE)

PTV D95 = 100% ?	95%	☐
PTV Hotspot: V110% ≤ 20%?	6%	☐
PTV D99 ≥ 93% ?	83%	☐
Brainstem Surface ≤ 64 CGE		☑
Brainstem Middle ≤ 55 CGE		☑
Brainstem Post ≤ 50 CGE		☑
Cord D0.1 cc ≤ 50 Gy ?	2	☑
Chiasm 0.1 cc = 31	< 55 CGE	☑
LT O.N. 0.1 cc = 37	< 55 CGE	☑
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Retina (posterior globe) D0.11 cc ≤ 50 Gy RT Retina = 41 LT Retina = 41		☑
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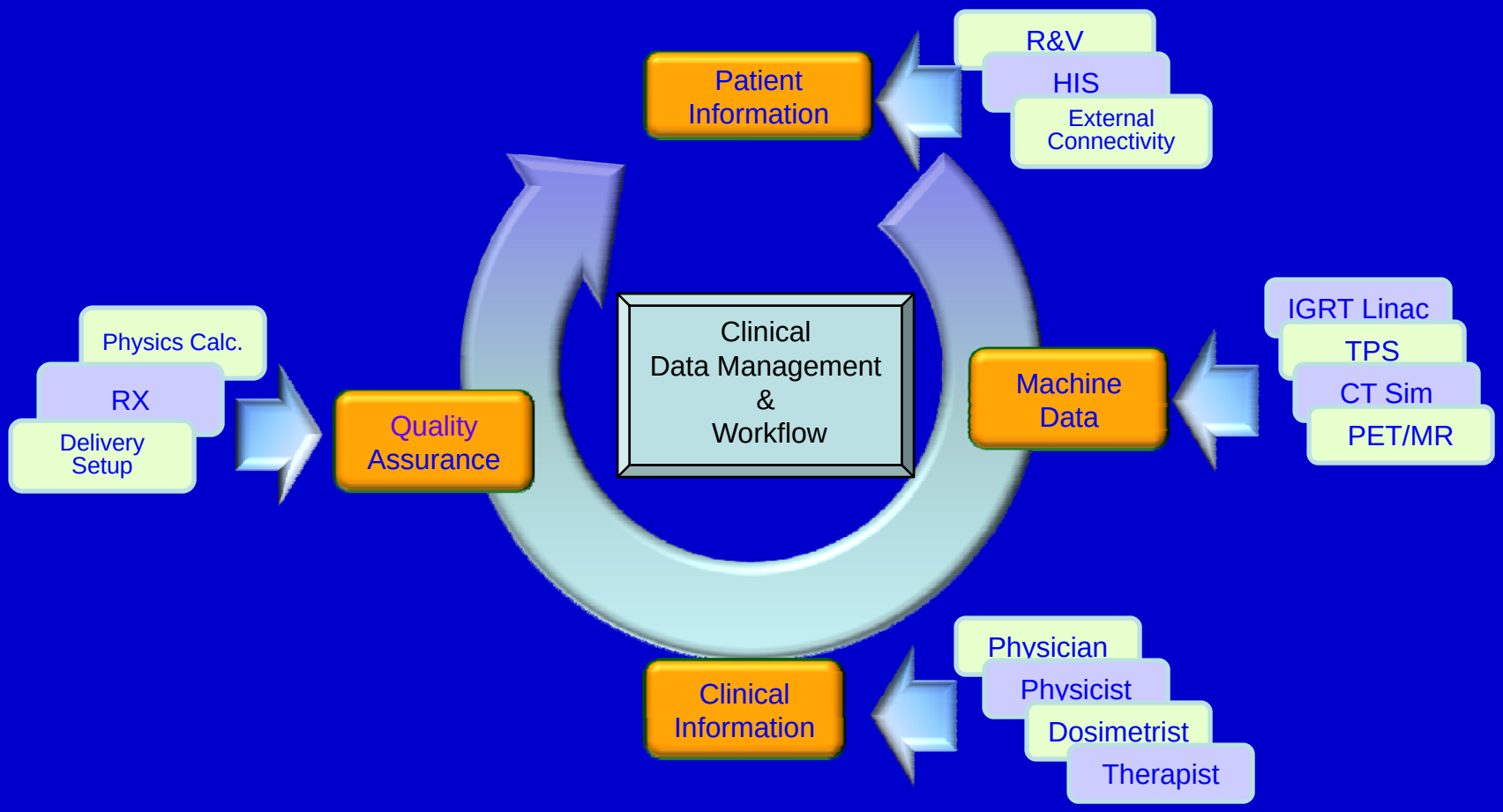
Chart

Physician: Physician B Date: 2/10/2009 Physicist: Physicist A Date: 2/10/2009

Dose: Initial:	74.4	CGE
Dose: Boost	0	CGE
# Fields/Day:	3	
Prescription signed	☑	

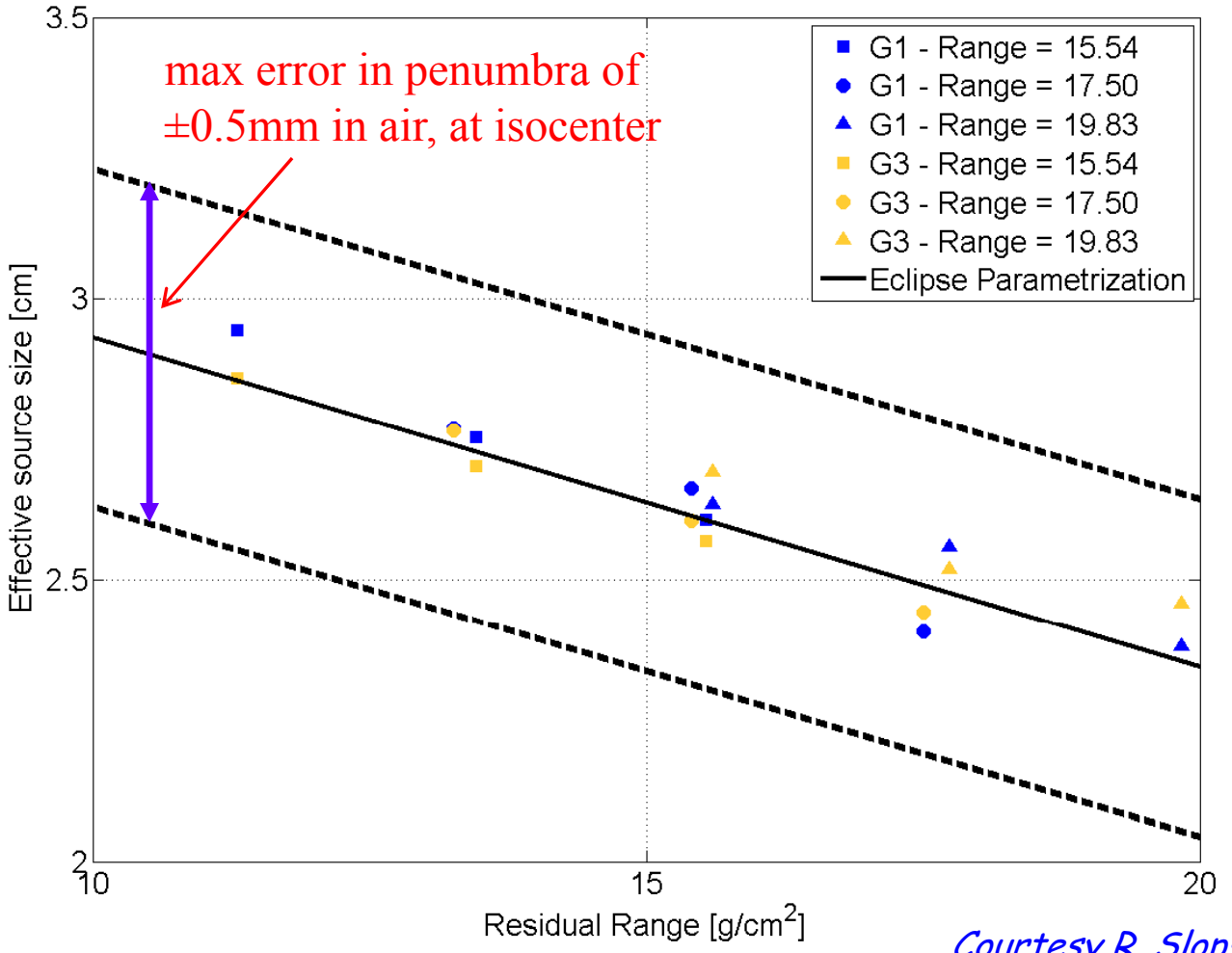
Integration of Clinical Workflow



Golden Beam Data

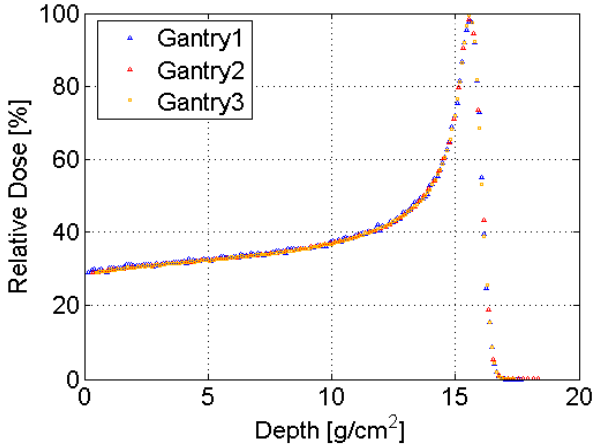
- TPS commissioning time consuming
- share beam data among gantries (institutions)?
  - golden beam data set
  - accuracy requirements on modeling parameters
    - pristine depth dose & sobp
    - effective source size
    - virtual sad
    - effective sad

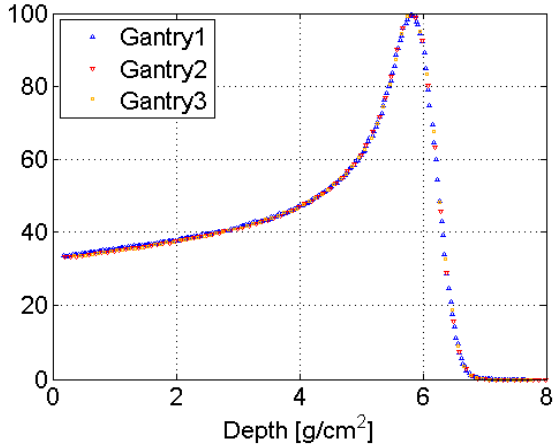
Golden Beam Data

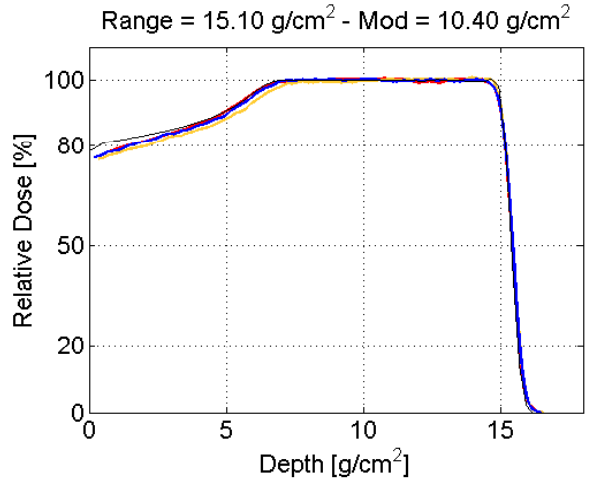


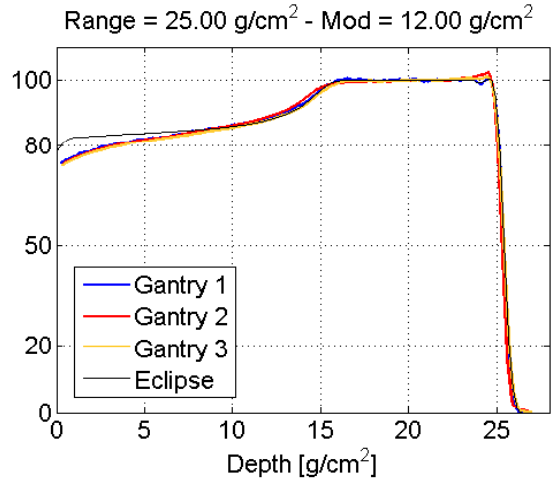
Courtesy R. Slopsema

Golden Beam Data









Summary

- Analytical Proton Algorithms provide accurate dose model
- Proton specific clinical planning issues requires vigilance
- Dose plan is a snap shot of dose distribution
- Dose delivered depends on
  - uncertainties in range, setup, organ motion, etc.
- Select beams and parameters to minimize uncertainties
- Tools to integrate clinical workflow are essential
- Golden beam data looks feasible

Thanks!