Proton Therapy Treatment Planning: Challenges and Solutions

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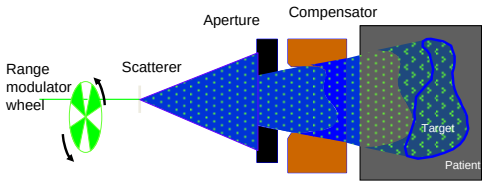
Proton treatment delivery

Passive scattering in practice



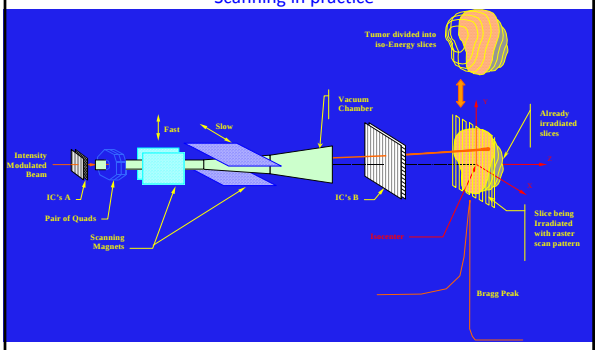
Range compensator conforms dose to distal edge target volume; the aperture shapes field in lateral direction.

Brass aperture

Lucite range compensator

Proton treatment delivery

Scanning in practice



Courtesy IBA

Physics of Proton Therapy

I. basic interactions
   - energy loss
   - scattering
   - nuclear interactions

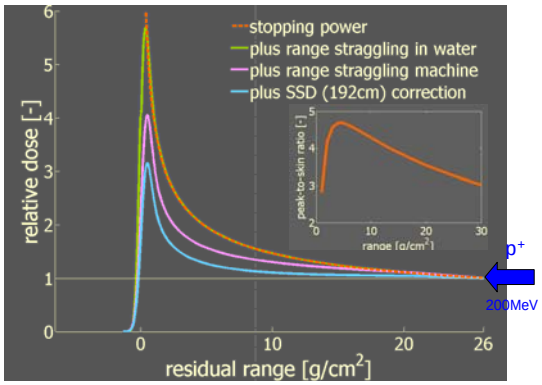
II. clinical beams
   - percentage depth dose
   - lateral penumbra

Proton interactions: Energy loss

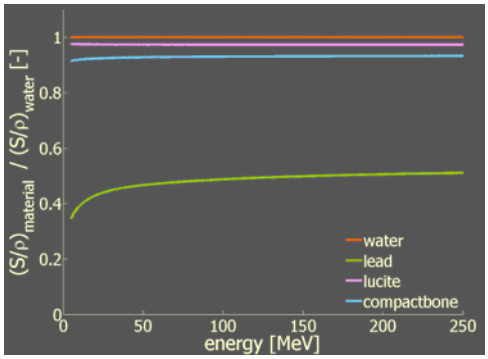
Primarily protons lose energy in coulomb interactions with the outer-shell electrons of the target atoms.

- excitation and ionization of atoms
- loss per interaction small → 'continuously slowing down'
- range secondary e^+ <1mm → dose absorbed locally
- no significant deflection protons by electrons

Bragg peak



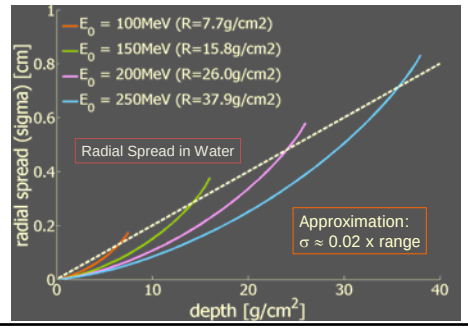
Stopping power



Graph based on NIST data

Proton interactions: Scattering

Primarily protons scatter due to elastic coulomb interactions with the target nuclei.



Radial spread in water

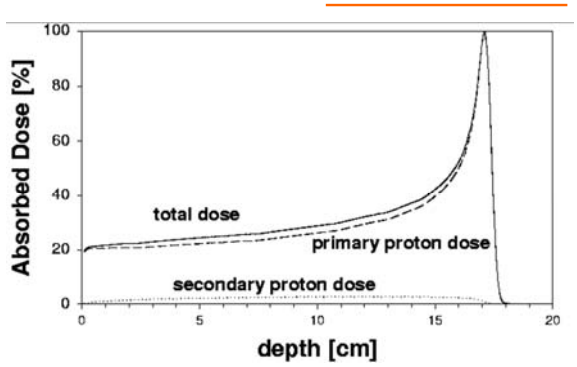
Same general shape applies to different (relevant) materials.

Proton interactions: Nuclear

About 20% of the incident protons have a non-elastic nuclear interaction with the target nuclei.

- reduction of proton fluence with depth → shape Bragg peak
- secondaries:
  - charged (p,d,α,recoils) ~60% of energy → absorbed 'locally'
  - neutral (n,γ) ~40% of energy → absorbed 'surroundings'
- production of unstable recoil particles (activation)
  - radiation safety
  - dose verification using PET/CT

Nuclear interactions



Graph courtesy Harald Paganetti.

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

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

❖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

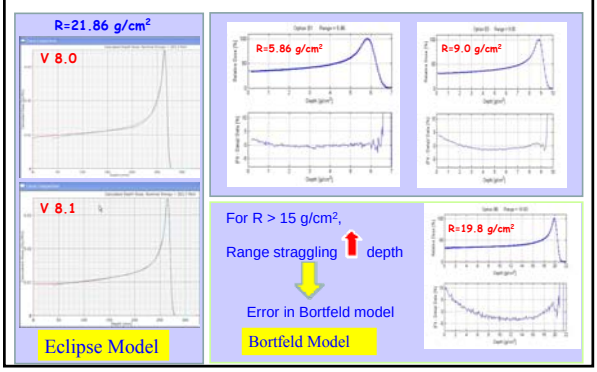
(Received 28 October 1996; accepted for publication 17 September 1997)

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

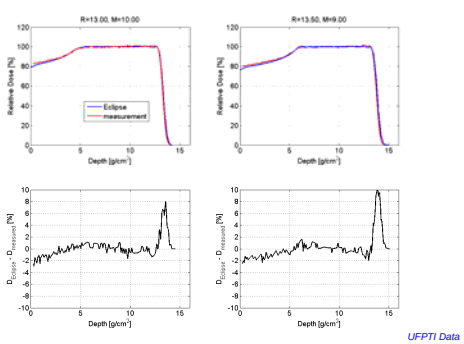
Analytical model of proton BP (up to ~ 200 MeV)

- 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



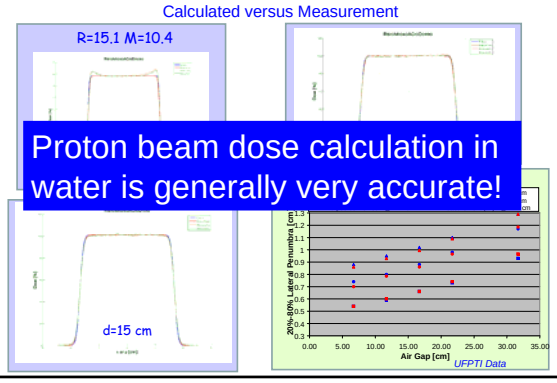
SOBP
Calculated versus Measurement



UFPTI Data

Beam Profile

Calculated versus Measurement



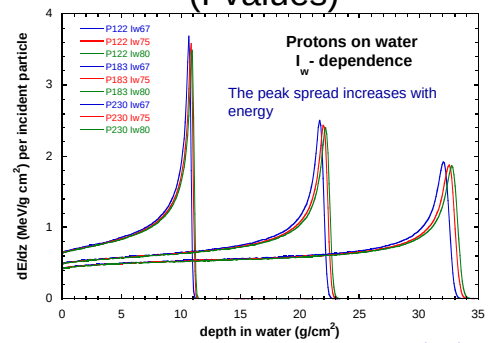
Proton beam dose calculation in water is generally very accurate!

UFPTI Data

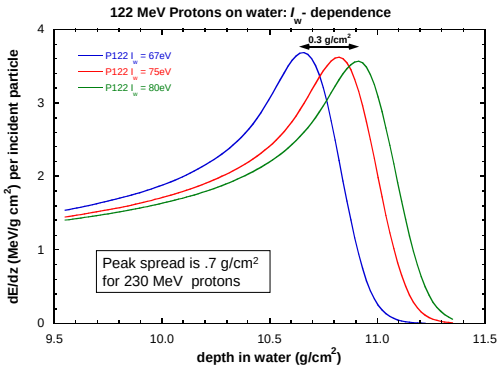
Challenges in Proton Therapy Planning

1. Uncertainties:
   - Intrinsic basic physics uncertainty (I-values)
   - CT numbers (stopping powers; range),
   - Dose calculation errors due to complex inhomogeneities,
   - Intra-fractional organ motion,
   - Inter-fractional changes in anatomy and motion patterns,
   - Mis-registration of tissue compensators (passively scattered proton beams,
   - Uncertainties in immobilization devices and patient support devices
2. Evaluation of proton plans
   - How to evaluate a proton plan in the presence of various uncertainties?
     - PTV?
     - Error bars of dose distributions?

Intrinsic basic physics uncertainty (I-values)

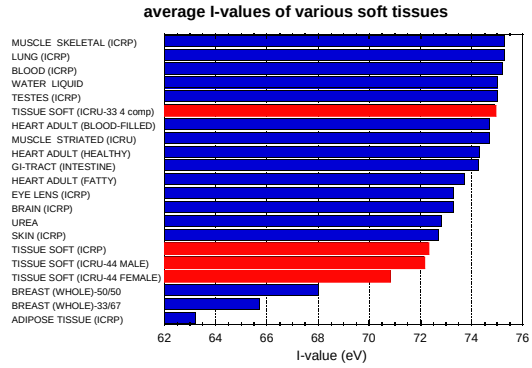


P Andreo, Phys Med Biol, 2009

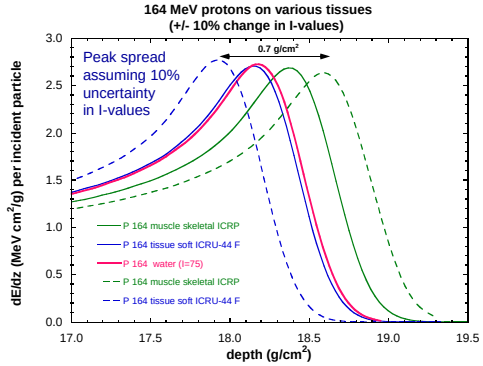


Intrinsic basic physics uncertainty makes the argument of "sub-millimeter precision" an issue, which deserves careful consideration

P Andreo, Phys Med Biol, 2009

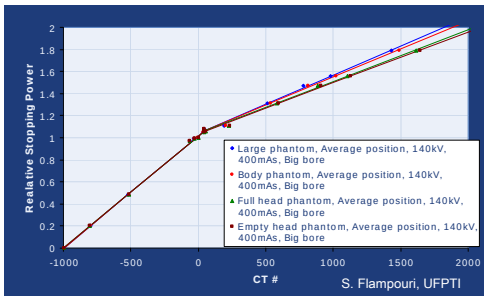


P Andreo, Phys Med Biol, 2009



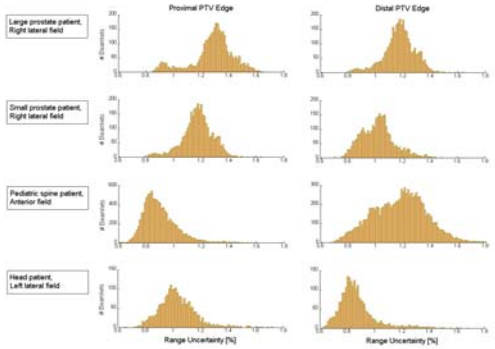
P Andreo, Phys Med Biol, 2009

HU-Stopping Power Calibration Curve



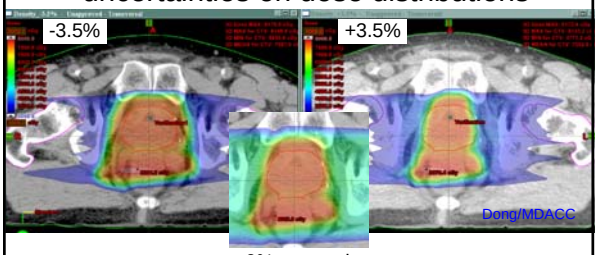
Range uncertainty due to CT calibration is generally taken as 3.5%. However, it can be minimized with better calibration techniques.

HU-Stopping Power Conversion Uncertainties Results in Range Uncertainties



S Flampouri, UFPTI, 2007

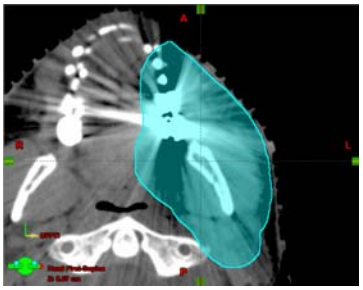
Impact of CT Hounsfield number uncertainties on dose distributions



0% uncertainty

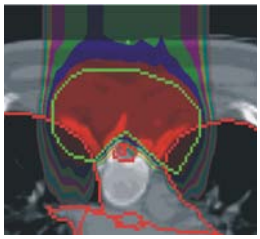
Individualized patient determination of tissue composition along the complete beam path, rather than CT Hounsfield numbers alone, would probably be required even to reach "sub-centimeter precision"

CT Artifacts and Hounsfield Numbers

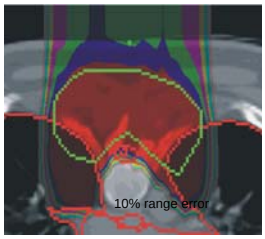


"It is imperative that body-tissue compositions are not given the standing of physical constants and their reported variability is always taken into account" (ICRU-44, 1989).

Proton Range Uncertainties



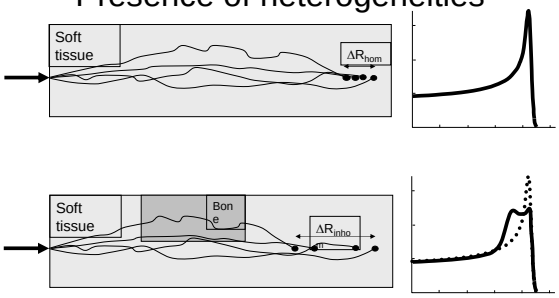
The advantage of protons is that they stop.



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

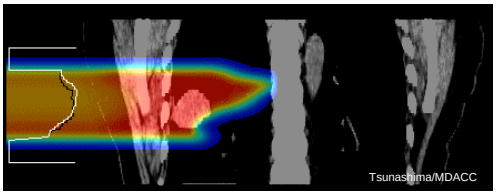
Lomax: PTCOG47

Proton Range Uncertainty in the Presence of heterogeneities



Lomax : AAPM SS 2003

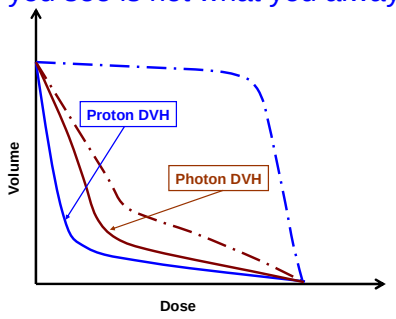
Impact of Organ Motion on Proton Dose Distributions



Dong: ASTRO 2008

Plan DVH Evaluation (PRV)

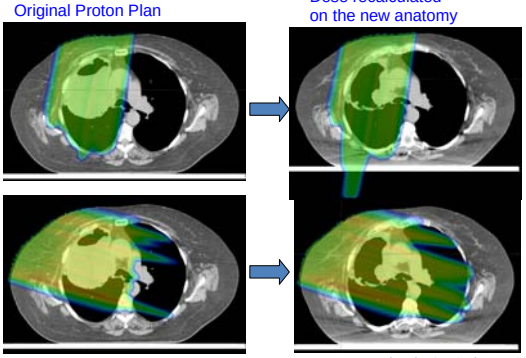
What you see is not what you always get..



Impact of Tumor Shrinkage on Proton Dose Distribution

Original Proton Plan

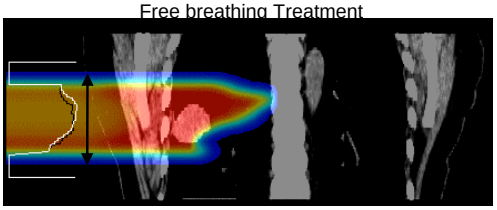
Dose recalculated on the new anatomy



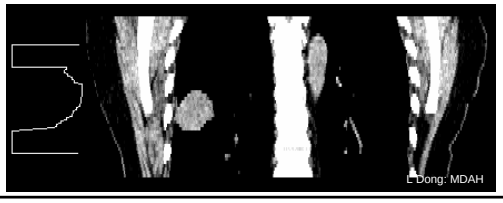
Bucci et al. ASTRO Abstract, 2007

Practical Solutions

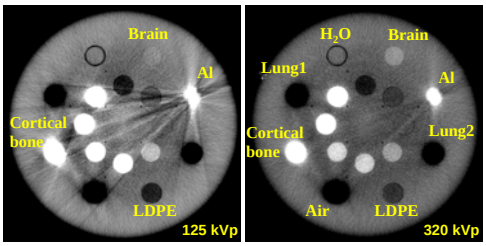
Free breathing Treatment



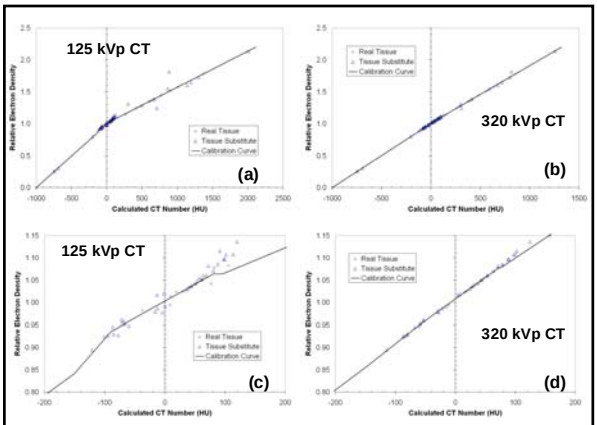
Gated treated on exhale



Improving CT number accuracy and reducing metal artifacts with Orthovoltage CT imaging



Yang et al. Med Phys 35 (5):1932-1941, 2008



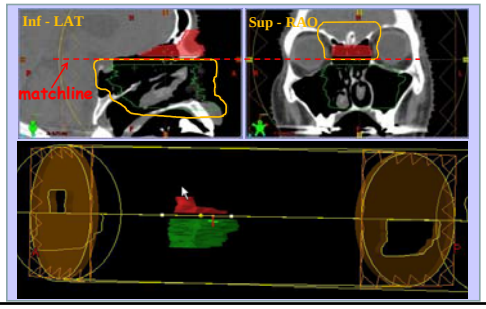
Yang et al. Med Phys 35 (5):1932-1941, 2008

Match and 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

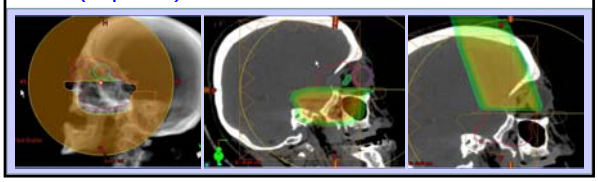
Match Fields

- match fields abutting each other
- penumbra matching penumbra



Patch Fields

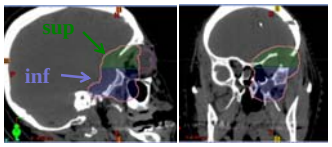
- thru beam txt partial target
- residual txt with patch
- lateral penumbra (t-beam) 'matched' with distal falloff (p-beam)
- LPO beam (inferior) patched with SPO (superior)

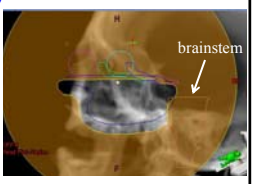


Lacrimal Gland Carcinoma

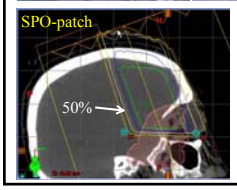
(PTV 50.4)

partition into sup + inf targets





LPO-Inf (spare optics & BS)

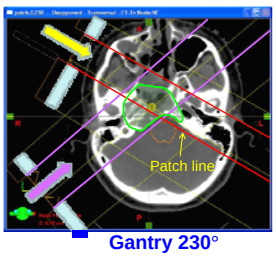


PTV50.4: 5 fields with match & patch		
Target	Fields	
PTV	LAO	LPO
PTV(Inf)	LPO-Inf	
PTV(Sup)	LAO-match	SPO-patch

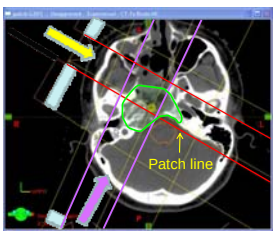
Patch Field Selection

Patch Field Angle Selection

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

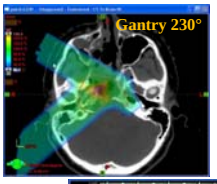


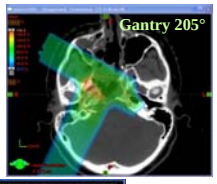
Gantry 230°

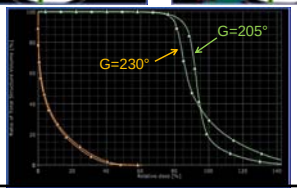


Gantry 205°

Patch Field – Beam Angle Selection



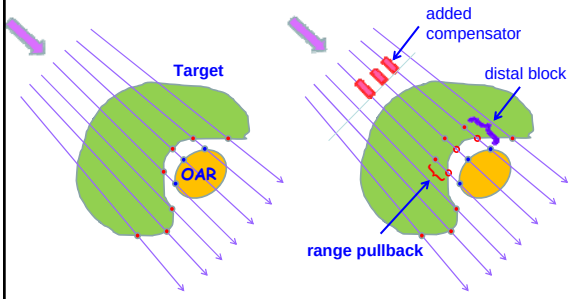




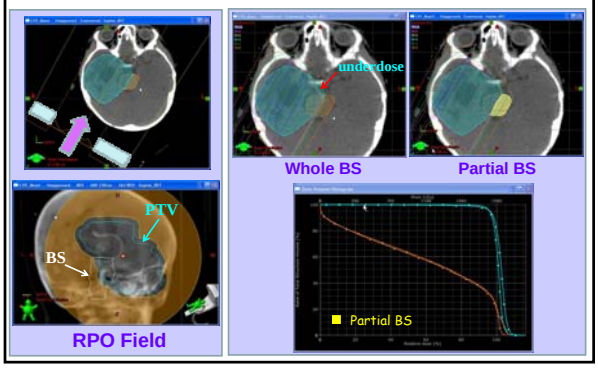
Distal Blocking

- 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



Things to remember!

- Proton beams stop - no exit dose
  - Although we don't know exactly where they stop
- Proton beams are more sensitive to
  - CT Hounsfield number/Stopping Power accuracy
  - Organ motion
  - Anatomy changes
- Proton plans are difficult to evaluate
  - "What you see is not what is delivered"
- Protons demonstrate excellent low dose sparing

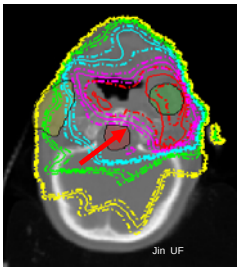
Things to remember!

- Inter/Intra-fractional variations have far more significant consequences in patients treated with proton therapy
  - Approaches and data to deal with this issue is still lacking
    - Minimize it and develop strategies to deal with the residual motion
- Empirical approaches used in defining margins for range uncertainties, smearing, and smoothing are questionable
  - No real data exist to support any of these approaches
- Repeat imaging and reevaluation based on deformable registration may be necessary
  - In some cases repeat planning may be clinically beneficial

Final thought

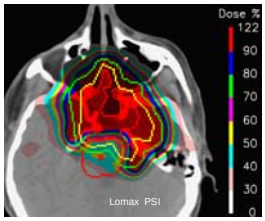
What you see is not what you always get….

IMXT Plan
(with Confidence-weighted Isodose Distribution)



180 160 120 80 40 cGy

IMPT Plan



There is no easy way to show what patient will get in proton therapy