University College London Hospitals NHS
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uclh

Proton Beam Therapy:
QA & Delivery Verification

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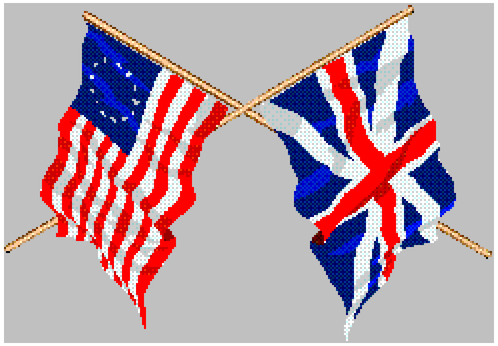
NPL
NPL Proton Physics Research & Implementation Group
Proton Therapy Physics Workshop
March 12th, 2014

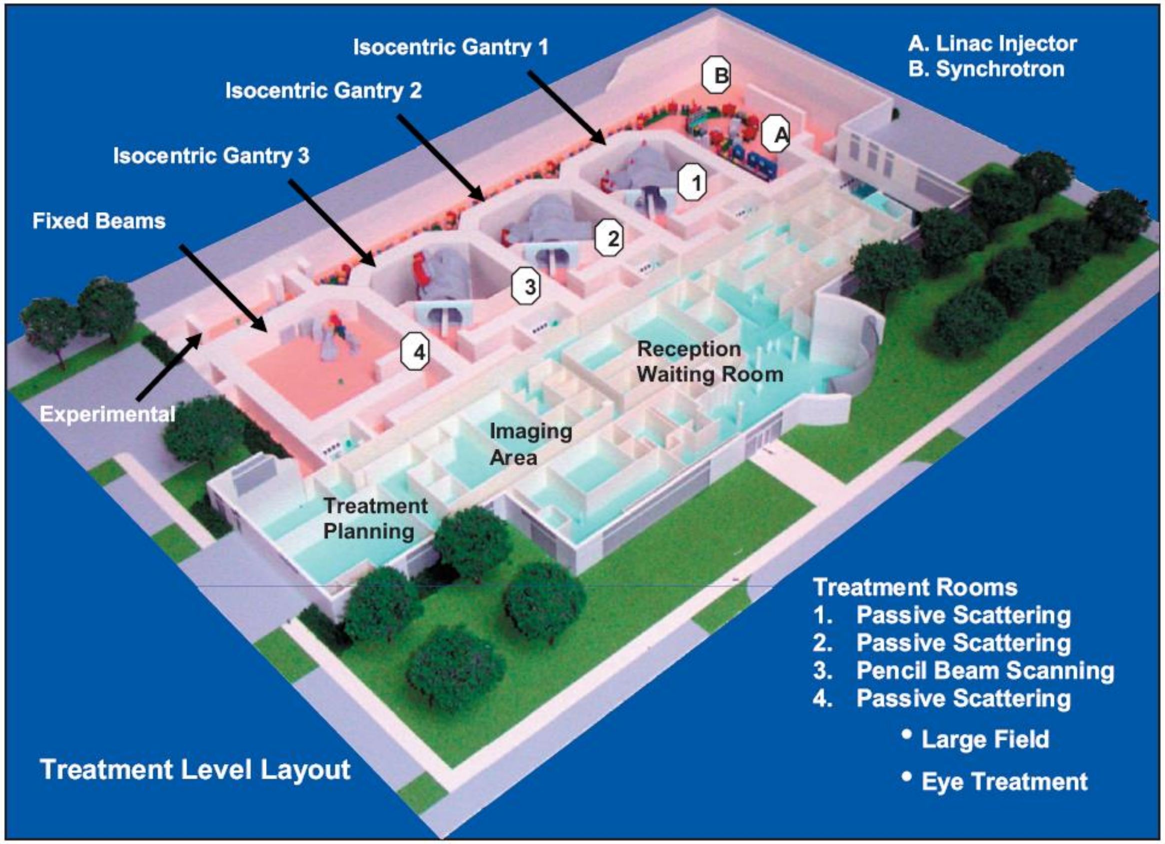
Spelling disclaimer:



"England and America are two countries separated by a common language"

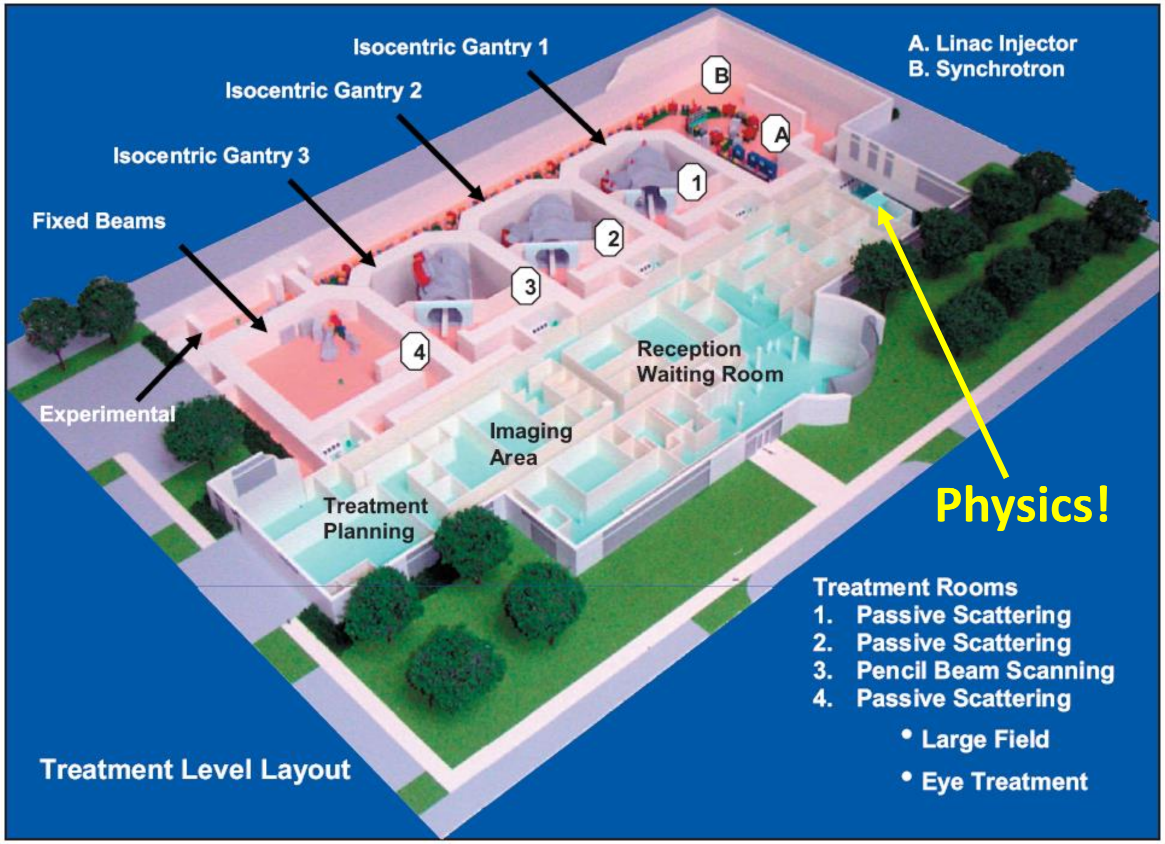
- George Bernard Shaw

UT MD Anderson Proton Therapy Center



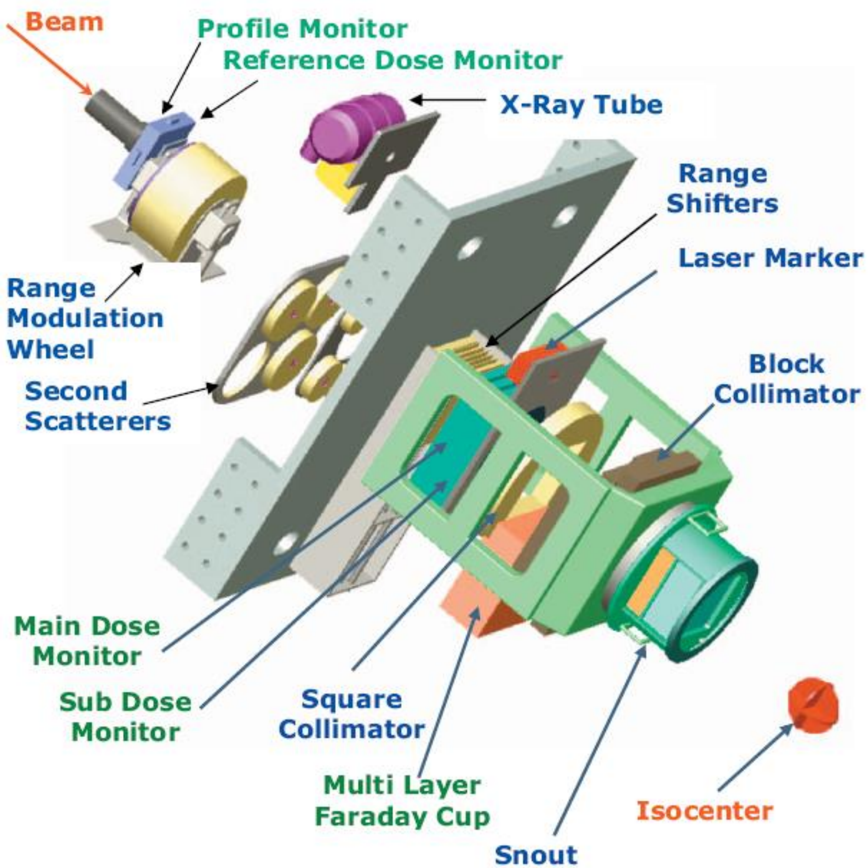
Smith *et al.* Med Phys 36 (9)

UT MD Anderson Proton Therapy Center

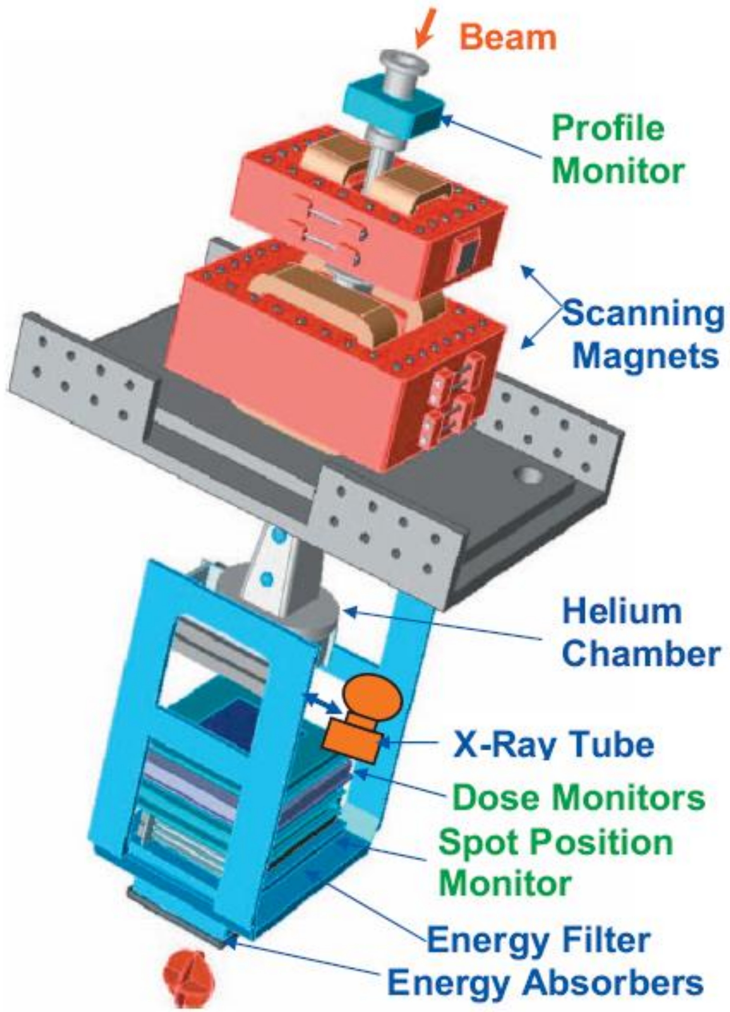


Smith *et al.* Med Phys 36 (9)

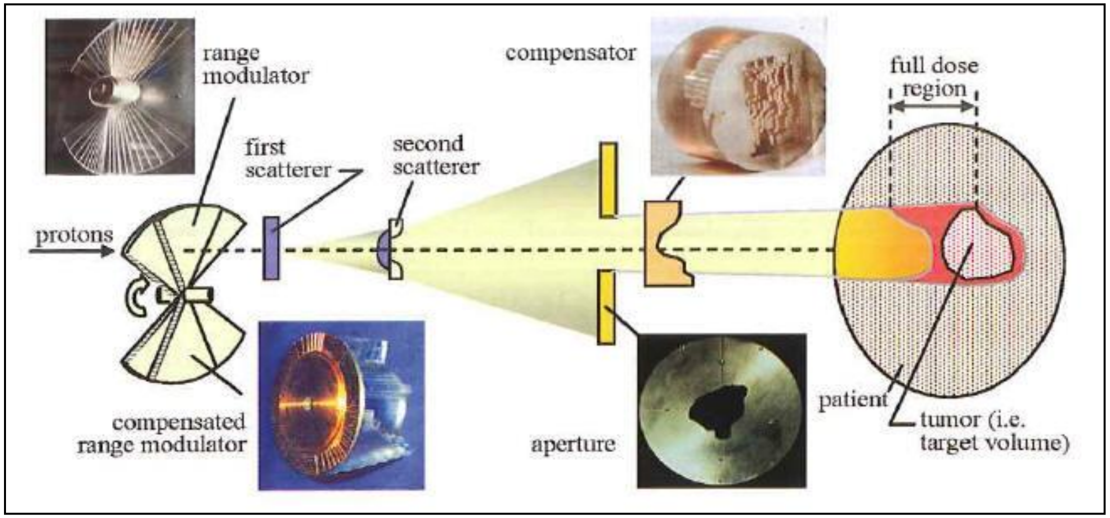
Passive scattering nozzle

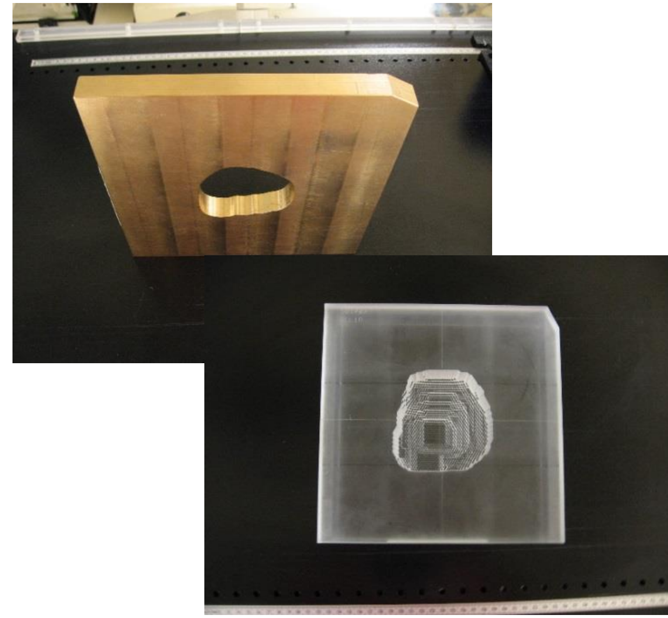


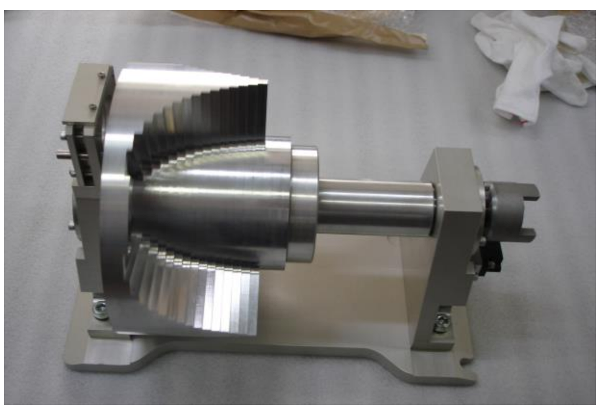
Active scanning nozzle

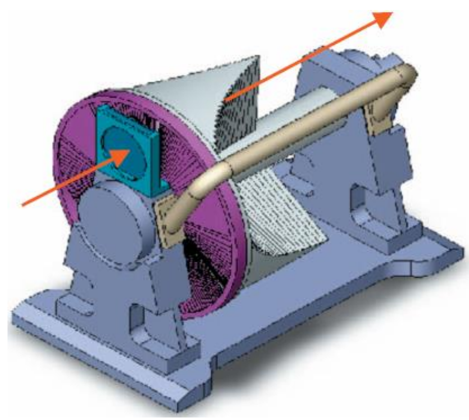


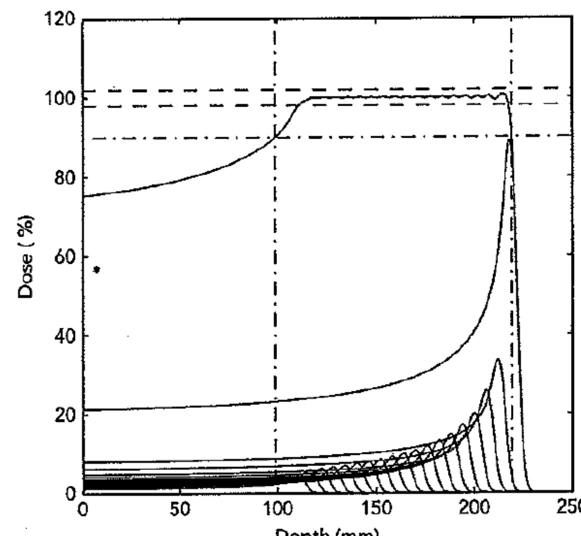
Beam delivery system: Passive scattering











Passive scattering at UT MDACC

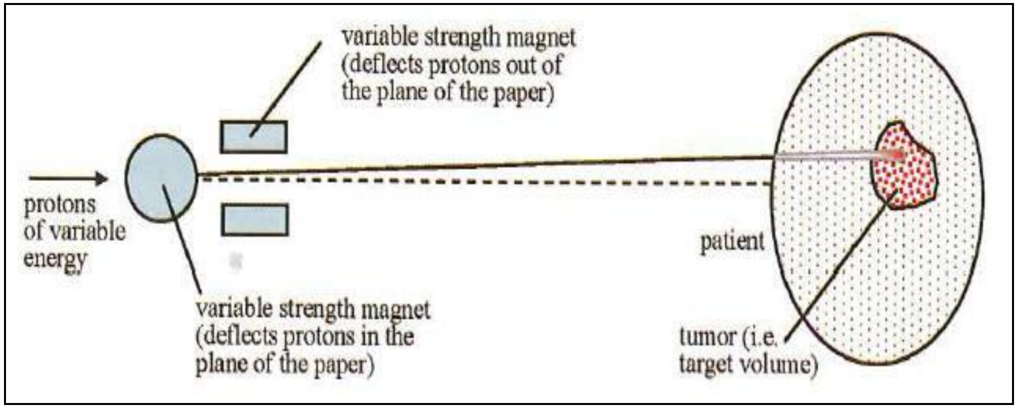
- 8 nominal energies x 3 *uncollimated* field sizes = 24 “options”
- 15 SOBP widths per option *(2 to 16 cm in 1 cm increments)*
- 3 rooms

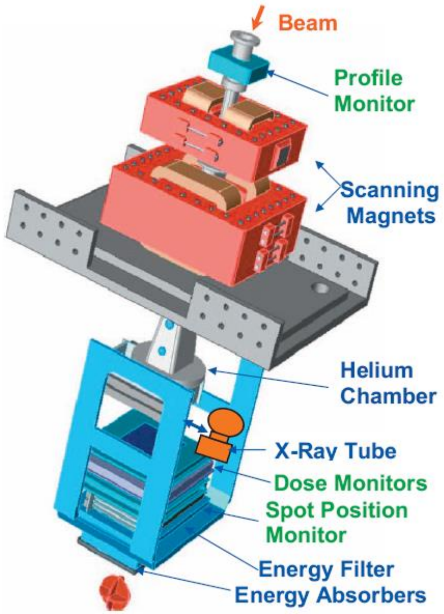
Uncollimated field size (cm)		
Small	**Medium**	**Large**
10 x 10	18 x 18	25 x 25

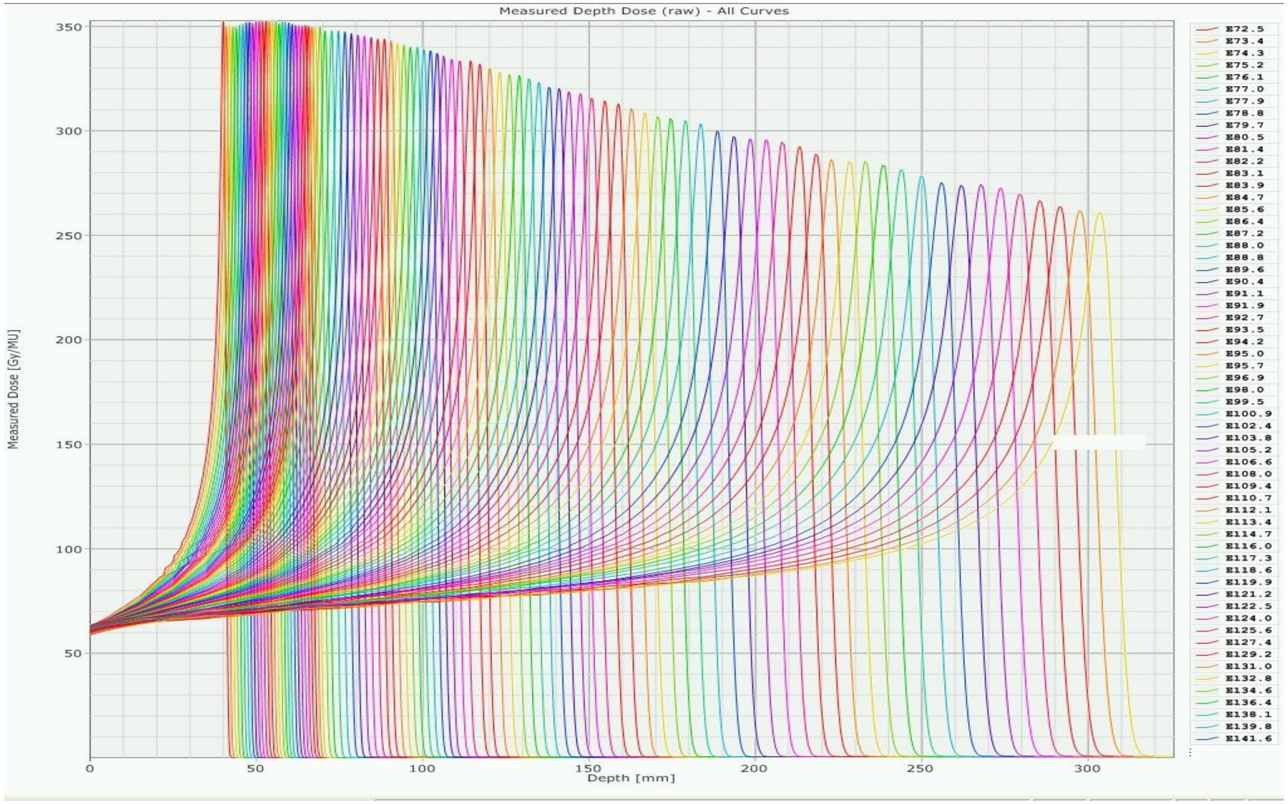
Nominal energy (MeV)	Range in water (cm)		
	Small	**Medium**	**Large**
250	32.4	28.5	25.0
225	26.9	23.6	20.6
200	21.8	19.0	16.5
180	16.9	16.1	13.7
160	13.4	13.0	11.0
140	10.2	10.0	8.4
120	6.9	6.4	6.3
100	4.9	4.3	4.3

Beam delivery system: Active scanning

- 94 Energies: 72.5 - 221.8 MeV
- Range: 4.0 – 30.6 cm
- Adjustability: 0.1 cm
- Max field size: 30x30 cm^2
- Beam size: 5 - 14 mm σ (air)
- Energy absorber (*range shifter*)







Patient specific QA – passive scattering

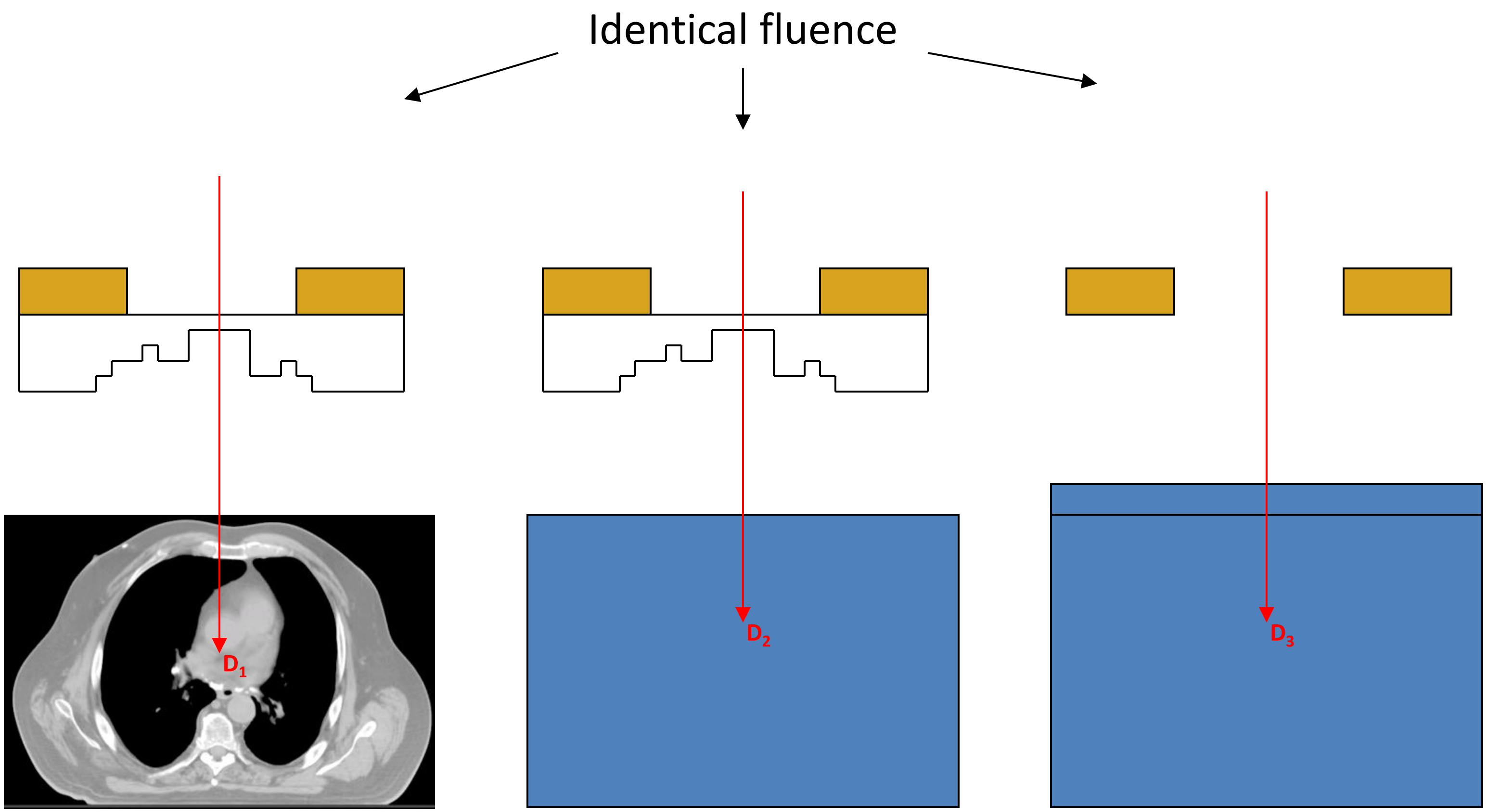
Med. Phys. 35 (11), November 2008

A procedure for calculation of monitor units for passively scattered proton radiotherapy beams

Narayan Sahoo,[a] X. Ronald Zhu, Bijan Arjomandy, George Ciangaru, MingFwu Lii, Richard Amos, Richard Wu, and Michael T. Gillin
Department of Radiation Physics, UT MD Anderson Cancer Center, 1515 Holcombe Boulevard, Box 1150, Houston, Texas 77030

- Relative Output Factors for different energies and different snouts from the calibration condition
- SOBP factors, i.e. changes in output as SOBP width changes
- Range Shifter factors, i.e. changes in the output as the range is decreased using range shifters
- Off-axis factors (both along and perpendicular to path of beam)
- Inverse Square factors

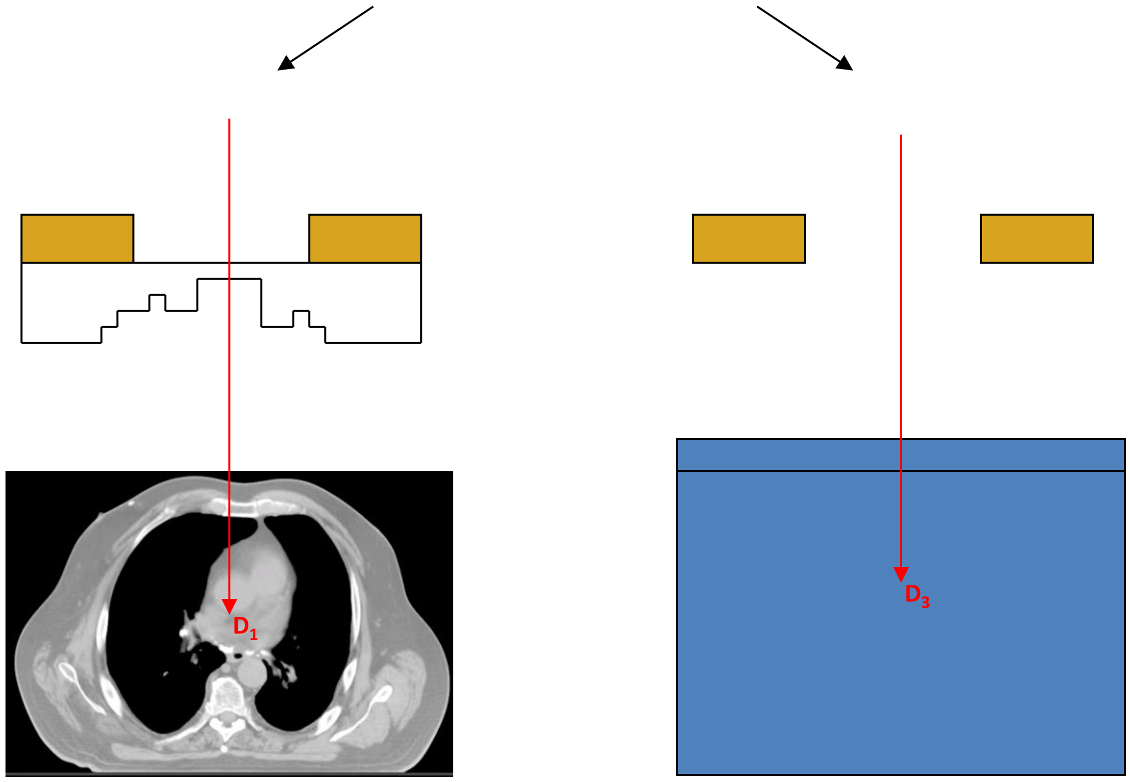
MU = Dose / (ROF.SOBPF.RSF.SOBPOCF.OCR.FSF.ISF)



D_1 / D_2 = “patient scatter factor” (PSF)

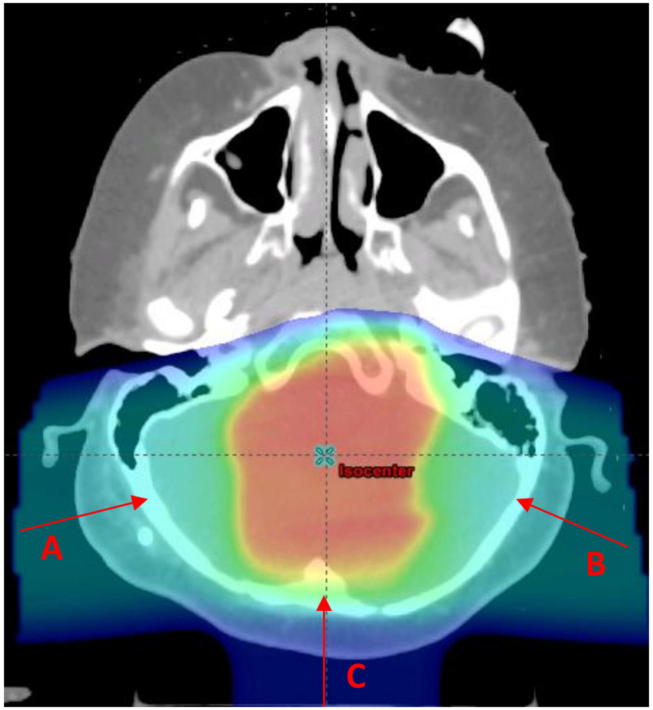
D_2 / D_3 = “compensator scatter factor” (CSF)

Identical fluence



D_1 / D_3 = “compensator & patient scatter factor” (CPSF)

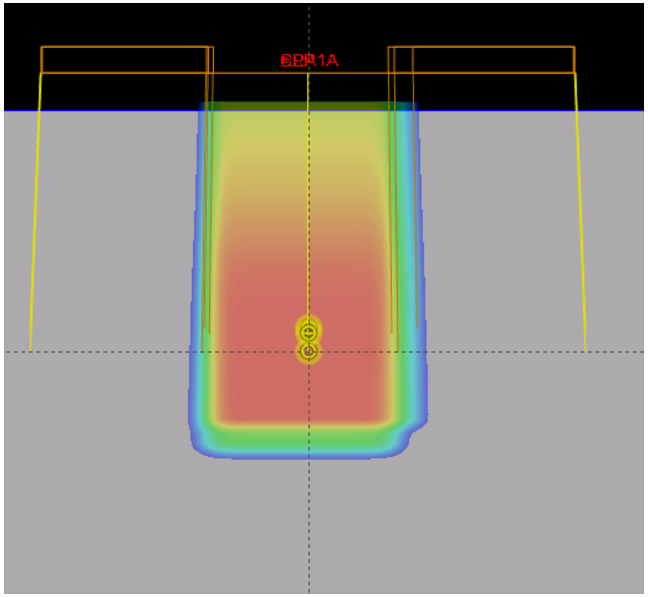
Point used at the center of the SOBP



ARP1A (RT POST SUP Post Fossa)

Machine Id:		G2
Nominal Energy:		160.0 MeV
Field Size:		18.0 cm x 18.0 cm
Gantry Angle:		260.00 deg
Patient Support Angle:		10.00 deg
Planned Distal Target Distance:		12.70 cm
Nominal SOBP Width:		7.00 cm
Snout Position:		40.0 cm
Field Weight Factor:		0.420
Range Modulator:		RM_84
Range Shifter	RS	8
Lateral Spreader	SS_8	IN
Compensator CAX Thickness:		1.4 cm
Dose for fractionation F1		
Reference Dose:		0.0 cGy
Reference Points:		2

Id	Fraction Dose	Point Type	PSSD	Depth	Eq. Path Length
CTV	75.6 cGy	[PRIMARY]	-	-	-
Isocenter	78.5 cGy		260.9 cm	9.1 cm	8.0 cm



ARP1A (RT POST SUP Post Fossa)

Machine Id:		G2
Nominal Energy:		160.0 MeV
Field Size:		18.0 cm x 18.0 cm
Gantry Angle:		270.00 deg
Patient Support Angle:		0.00 deg
Planned Distal Target Distance:		12.70 cm
Nominal SOBP Width:		7.00 cm
Snout Position:		40.0 cm
Field Weight Factor:		0.420
Range Modulator:		RM_84
Range Shifter	RS	8
Lateral Spreader	SS_8	IN
Dose for fractionation F1		
Reference Dose:		0.0 cGy
Reference Points:		4

Id	Fraction Dose	Point Type	PSSD	Depth	Eq. Path Length
Verification	57.5 cGy	[PRIMARY]	260.4 cm	0.5 cm	0.0 cm
CAXa-nc	77.9 cGy		260.4 cm	9.7 cm	9.2 cm
CAXb-nc	77.7 cGy		260.4 cm	8.8 cm	8.3 cm
CAXc-nc	77.8 cGy		260.4 cm	9.0 cm	8.5 cm

Patient Name	[redacted]	Date:	March 26, 2012
		MR #	[redacted]

Prescription

Dose (CcGyE)	Fractions	Isodose	Dose / fx. (CcGyE)	Dose / fx. To IDL (CcGyE)
5040	28	98.0%	180	183.7

Plan

Plan ID	APD_AM 50.4Gy	APD_AM 50.4Gy	APD_AM 50.4Gy	
Field ID	ARP1A	BLP1A	CPA1A	
Field Name	RT POST SUP Post Fossa	LT POST SUP Post Fossa	PA Post Fossa	
Energy (MeV) / RMW ID	160/RM_84	160/RM_84	160/RM_84	
Gantry/Couch angles (degrees)	260/10	100/350	180/0	
Snout Position (cm)	40	40	40	
Range (cm)	12.7	11.8	13	
SOBP Width (cm)	7	7	9	
SOBP Center (cm)	9.2	8.3	8.5	
Dose referene point (DRP)-Name	CAXa	CAXb	CAXc	
Depth in Water Phantom (cm)	9.2	8.3	8.5	
SSD (cm) (DRP)	260.8	261.7	261.5	
DRP Dose (CcGyE)(VP_NoComp)	77.9	77.7	29.6	DRP OK
DRP Dose (cGy)(VP_NoComp)	70.8	70.6	26.9	

Calculated MU

Patient Specific Parameters

Field	ARP1A	BLP1A	CPA1A
Location	RT POST SUP Post Fossa	LT POST SUP Post Fossa	PA Post Fossa
Range Shift (cm)	0.7	1.6	0.4
Relative OF	0.865	0.865	0.865
Range Shifter Fctr.	0.985	0.967	0.988
SOBP Factor	1.150	1.150	1.048
SOBP Off-Center Factor (OCF)	1.000	1.000	1.000
Other	1.000	1.000	1.000
MU Required	72.3	73.4	30.0

MU=PointDose (cGy)/(Relative OF*Range Shifter Fctr*SOBP factorr*other)

NOTE : Factors not considered in measurement and calculation

1. The end effect in dose measurement is not used. It was estimated to be in the range of 0.2 to 0.3 MU, which is less than 0.5% of the MU used for treatment.
3. Aperature factor, which is expected to be very small, is not considered in the calculated MU, but is included in the determination of measurement of required MU.

SOBP Factor

RMW ID (G1/G2/F2)	30/94	31/95	32/96	19/83	20/84	21/85	22/86	23
Energy (MeV)	250	225	200	180	160	140	120	100
Range (cm)	32.4	26.9	21.8	16.9	13.4	10.2	6.9	4.9
SOBP (cm)								
2.0	1.508	1.578	1.618	1.675	1.737	1.429	1.273	1.167
3.0	1.386	1.436	1.465	1.512	1.561	1.258	1.106	**1.000**
4.0	1.264	1.294	1.312	1.348	1.385	1.145	**1.000**	0.878
5.0	1.200	1.222	1.239	1.265	1.295	1.073	0.921	
6.0	1.136	1.149	1.166	1.181	1.205	**1.000**	0.837	
7.0	1.095	1.103	1.117	1.127	1.150	0.943	0.734	
8.0	1.054	1.057	1.067	1.073	1.095	0.885		
9.0	1.027	1.029	1.034	1.037	1.048	0.838		
10.0	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	0.772		
11.0	0.980	0.978	0.978	0.967	0.957			
12.0	0.959	0.956	0.956	0.934	0.913			
13.0	0.942	0.939	0.934	0.908	0.835			
14.0	0.924	0.922	0.911	0.882				
15.0	0.910	0.906	0.894	0.861				
16.0	0.895	0.889	0.876	0.840				

Small Field Size 160 MeV

RMW ID= 20/84 , E = 160 MeV, R = 13.4cm, SOBP = 2 cm

RS (cm)	RS Factor	Interpolation	
0	1.000	RSx=	1.5
1	0.985	RSF=	0.980
2	0.975		
3.1	0.958		

RMW ID= 20/84 , E = 160 MeV, R = 13.4cm, SOBP = 6 cm

RS (cm)	RS Factor	Interpolation	
0	1.000	RSx=	1.5
1	0.981	RSF=	0.971
2	0.962		
3.1	0.941		

RMW ID= 20/84 , E = 160 MeV, R = 13.4cm, SOBP = 10 cm

RS (cm)	RS Factor	Interpolation	
0	1.000	RSx=	1.5
1	0.970	RSF=	0.959
2	0.946		
3.1	0.902		

RMW ID= 20/84 , E = 160 MeV, R = 13.4cm, SOBP = 12 cm

RS (cm)	RS Factor	Interpolation	
0	1.000	RSx=	1.5
1	0.963	RSF=	0.943
2	0.926		
3.1	0.909		
From G2	Annual QA	2009	

RMW ID= 20/84 , E = 160 MeV, R = 13.4cm, SOBP = 13 cm

RS (cm)	RS Factor	Interpolation	
0	1.000	RSx=	1.5
0.4	0.987	RSF=	0.987
1	0.985		
2	0.988		
3.1	0.999		

Relative Output Factors

Output factors are relative to RMW ID 27/91, 250 MeV, Range 28.5 cm.

RMW ID	Scatter Size	E(MeV)/R(cm)	SOBP (cm)	ROF
30/94	Small	250/32.4	10	1.070
31/95	Small	225/26.9	10	1.033
32/96	Small	200/21.8	10	0.972
19/83	Small	180/16.9	10	0.960
20/84	Small	160/13.4	10	0.865
21/85	Small	140/10.2	6	0.927
22/86	Small	120/6.9	4	0.950
23	Small	100/4.9	3	0.912

Patient Specific Measurements

- “5 cm/10 cm” water filled phantom
- Farmer type chamber
- Solid water plates to obtain desired depths.
- Brass apertures and no compensator

Measured MU

Chamber :	markus	**Serial # :**	**3793**
Electrometer :	Wellhofer Dose 1	**Phantom :**	**acrylic**

Calibration Conditions :

E = 250 MeV, SOBP Width = 10 cm, Aperature = 10 x 10 cm

Range = 28.5, Chamber Depth = 23.5 cm, SCD = 270 cm

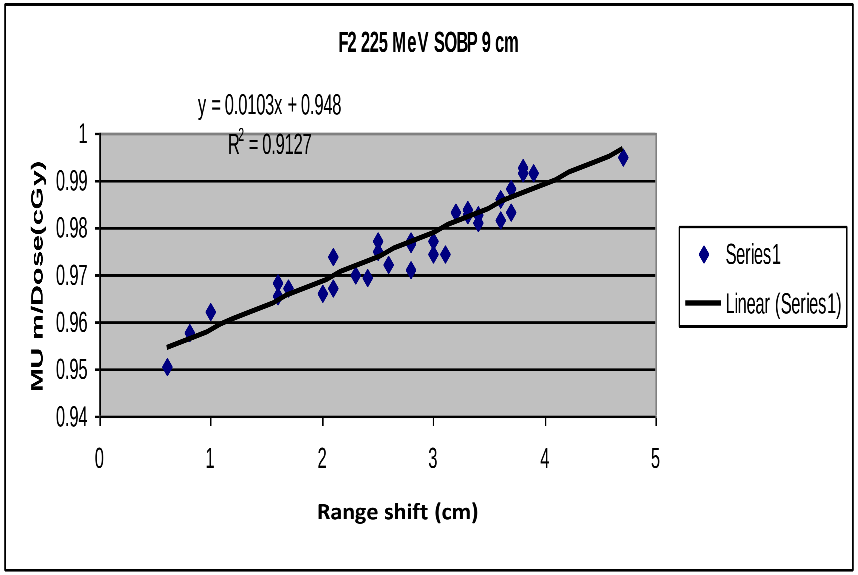
MU	100
Elec. Reading (nC)	1.7933
Dose (cGy)	*100.0

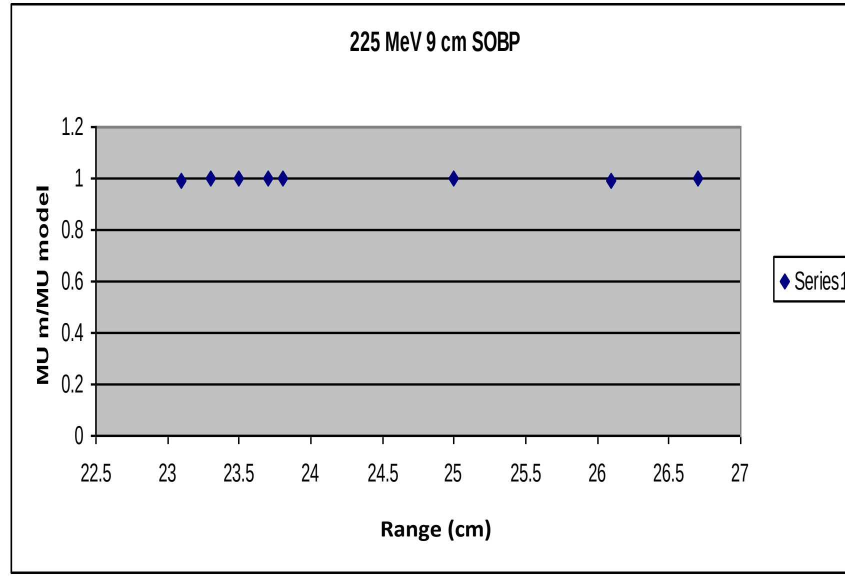
*Dose verified using IAEA 398 calibration protocol

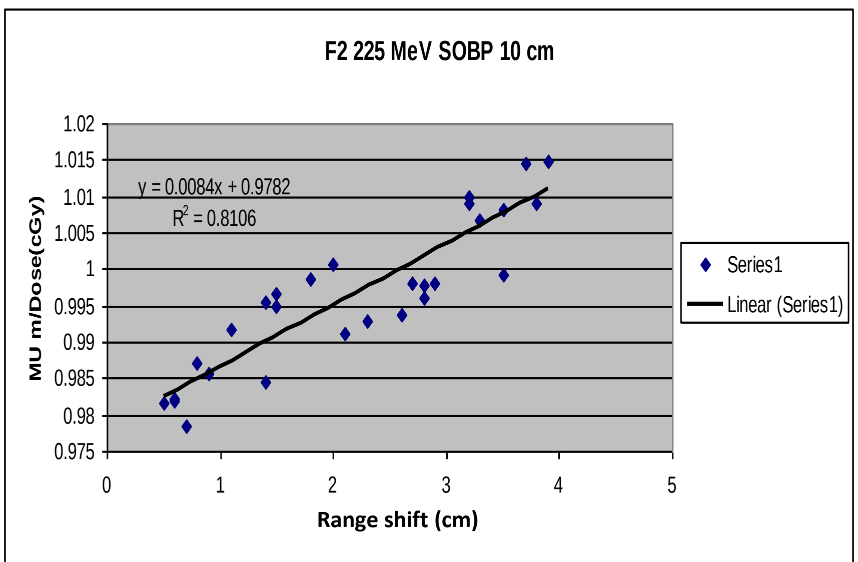
Field	ARP1A	BLP1A	CPA1A
Location	RT POST SUP Post Fossa	LT POST SUP Post Fossa	PA Post Fossa
SCD (cm)*	270.0	270.0	270.0
Snout Position (cm)	40.0	40.0	40.0
Range (cm)	12.7	11.8	13.0
SOBP Width (cm)	7.0	7.0	9.0
Is compensator used ?	No compensator	No compensator	No compensator
Depth of Measurement (cm)	9.2	8.3	8.5
MU Delivered	50.0	50.0	50.0
Elec. Reading (nC)	0.8751	0.8611	0.8016
Dose (cGy)	48.8	48.0	44.7
Dose / MU (cGy)	0.976	0.960	0.894
Measured MU	72.6	73.6	30.1
MU for treatment from calculation	72.3	73.4	30.0
Difference (calculation and Meas)	0.4%	0.2%	0.2%

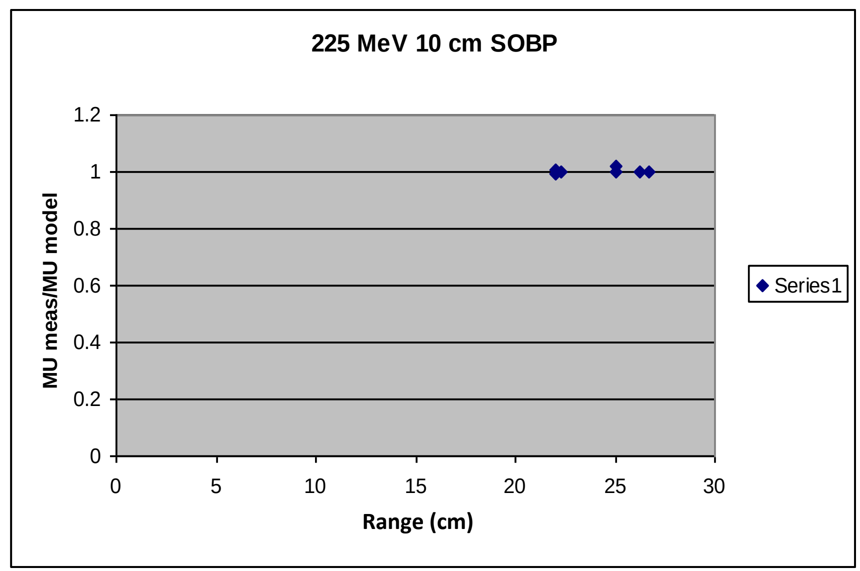
F2 small snout, 225 MeV, 9 cm and 10 cm SOBP:

MU determination using a linear model, with spot check measurements (two per week).









Patient specific QA – spot scanning

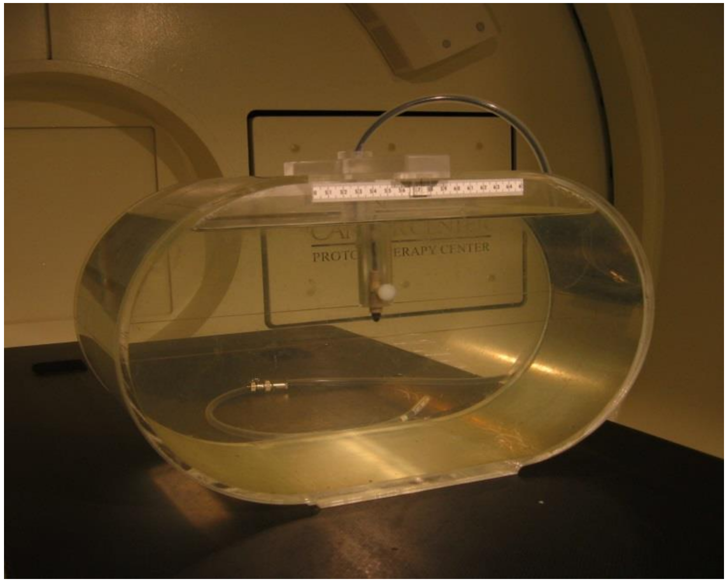
Patient specific QA process has two parts:

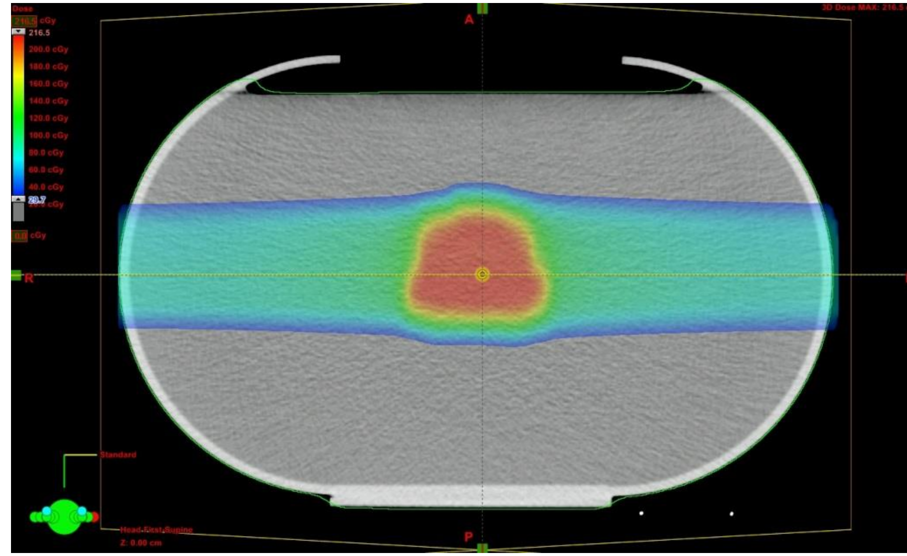
- End-to-end treatment plan data integrity test:
  - Each field in the patient plan delivered using the planned gantry angle with the Oncology Information System (OIS) in the QA mode and the scanning-beam accelerator control system (ACS) in the treatment mode.
  - 2D dose distribution in plane perpendicular to beam axis measured using ion chamber array.
  - Measurements compared with TPS calculations to verify transfer of data from TPS to OIS and to ACS.
  - Verification of scanning magnets function at each gantry angle.

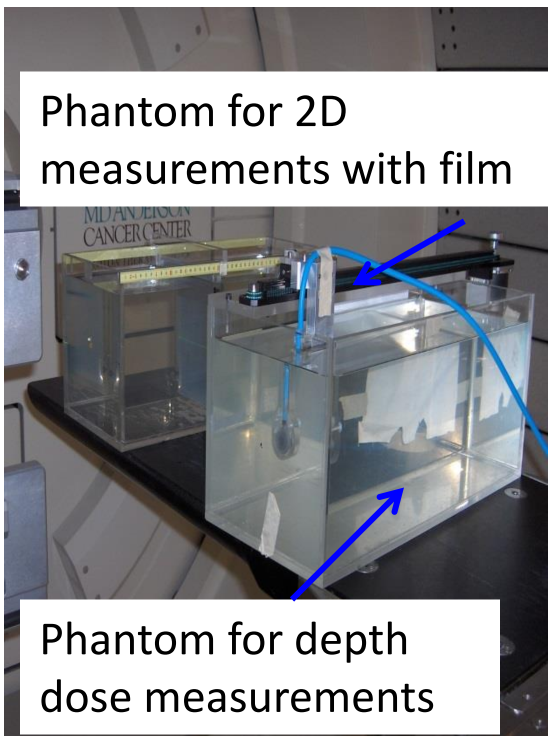
- Dose comparisons including 2D planar dose distribution and depth dose profile comparisons:
  - 2D plane comparisons to verify TPS calculation of dose top water for the spot positions, energies, and Mus.
  - Depth dose profile comparisons verify TPS calculation of buildup region, proximal portion of Bragg peak, peak dose region, and distal range.

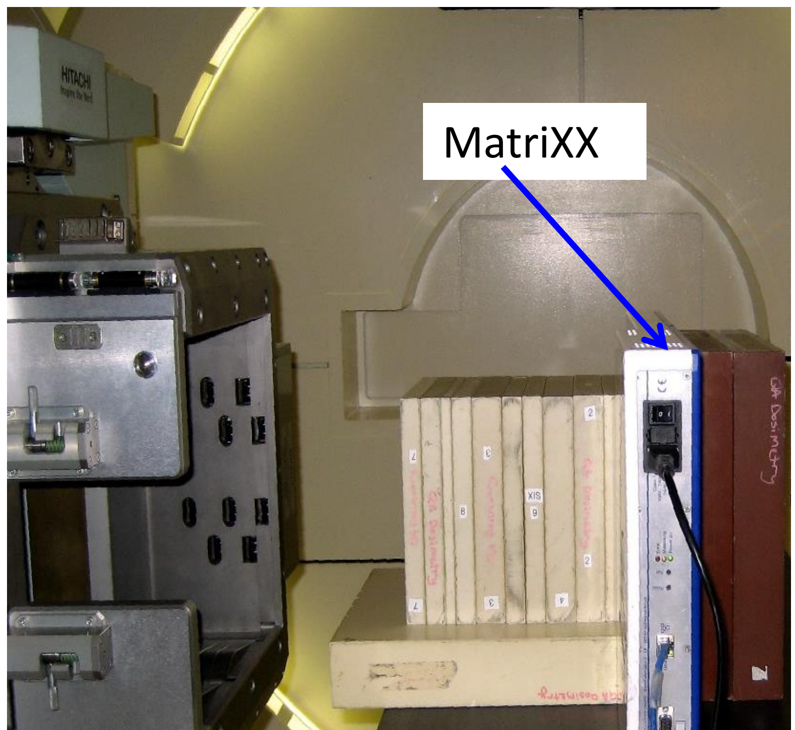
Patient specific QA – spot scanning

- Confirmation of dose in “Fish Bowl” phantom or in Plastic Water (PW) with a IC / MatriXX in treatment mode and through MOSAIQ - beam check Parameters are loaded to RV system
- Central Axis depth dose in a rectangular water phantom using a Markus chamber / MatriXX PW
- 2-D dose verification at multiple depths (3 from SFO / > 5 for MFO) for each field in a PW phantom with MatriXX






Phantom for 2D measurements with film
Phantom for depth dose measurements


MatriXX

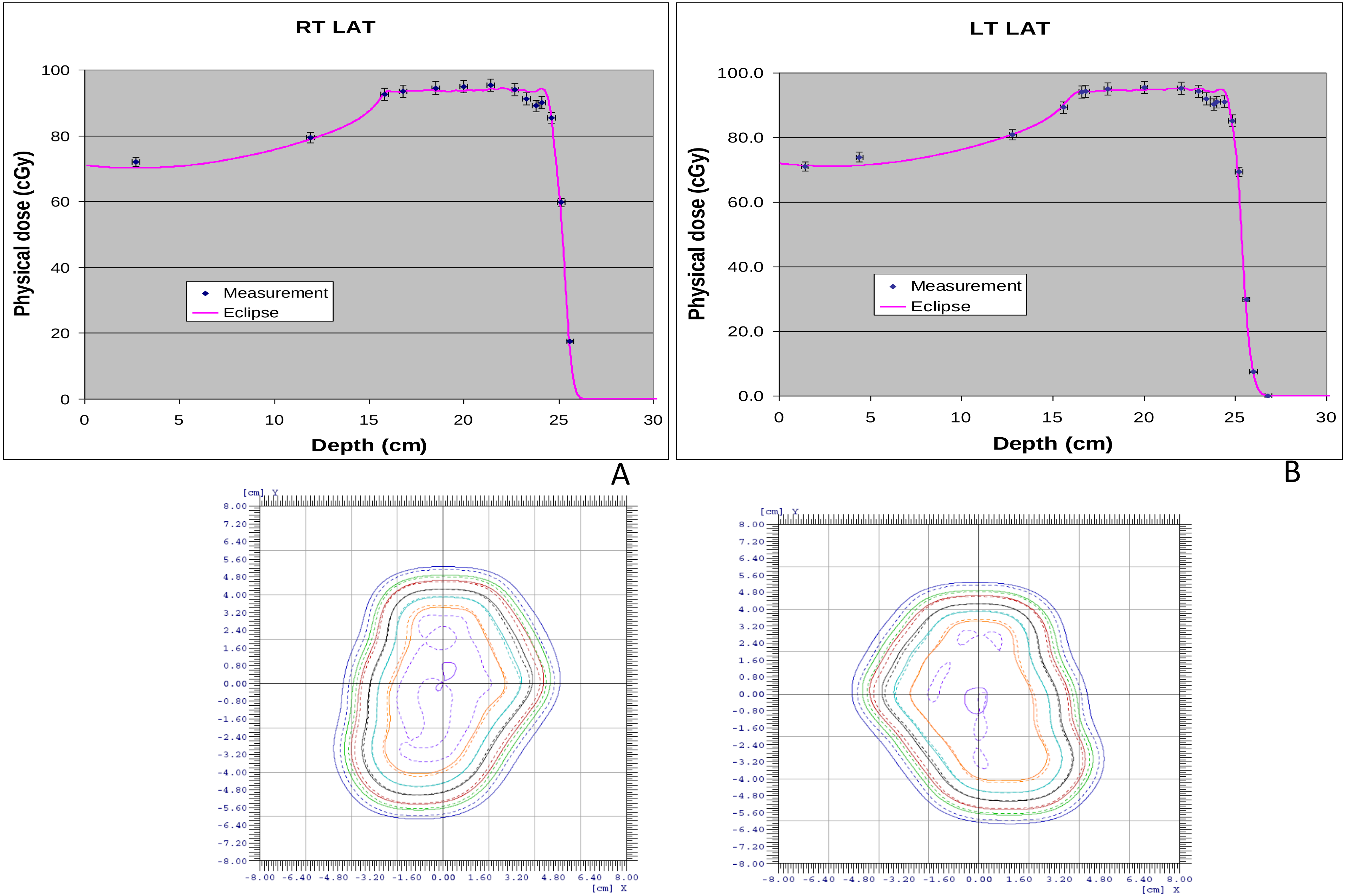
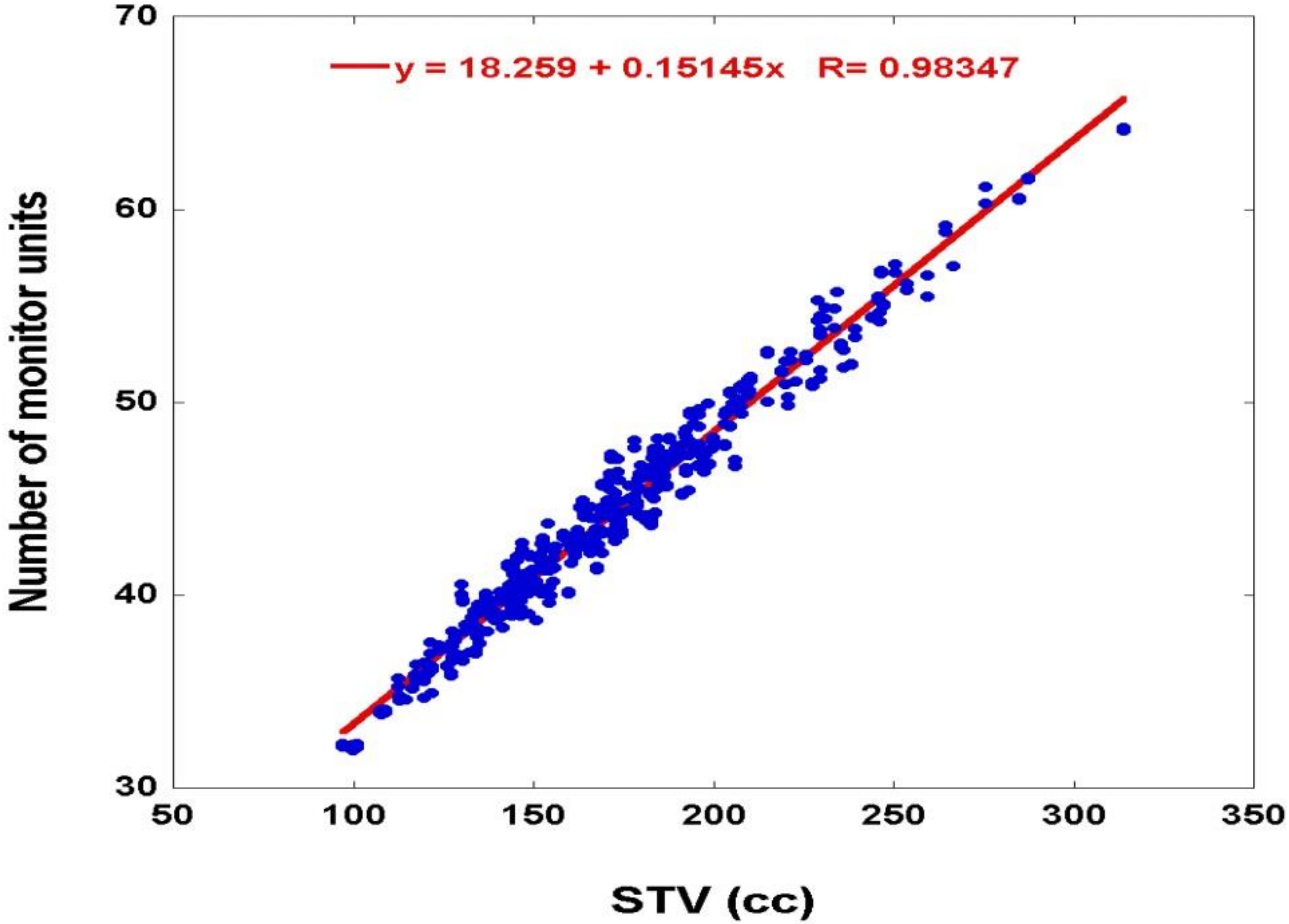
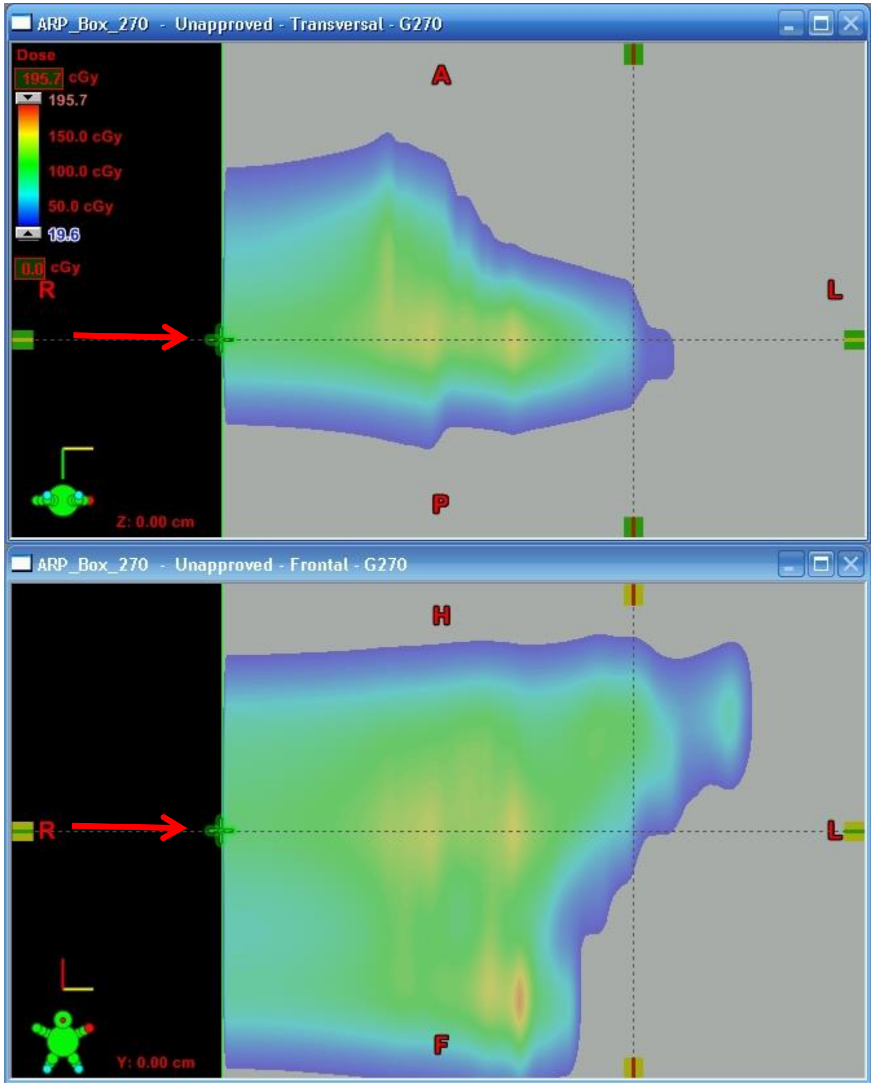

RT LAT
Physical dose (cGy)
Depth (cm)
Measurement
Eclipse
A
LT LAT
Physical dose (cGy)
Depth (cm)
Measurement
Eclipse
B
[cm] Y
[cm] X

Fig. 5



y = 18.259 + 0.15145x R= 0.98347
Number of monitor units
STV (cc)
70
60
50
40
30
50
100
150
200
250
300
350

MFO - Field   Depth Dose



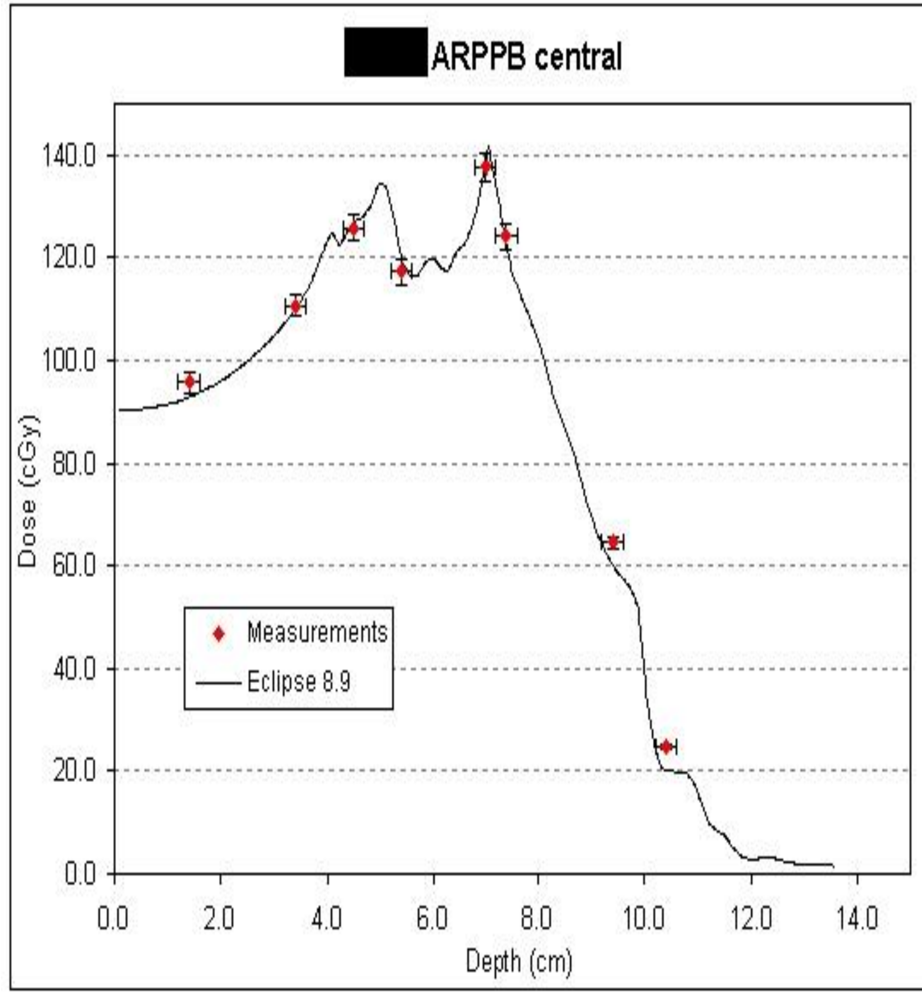
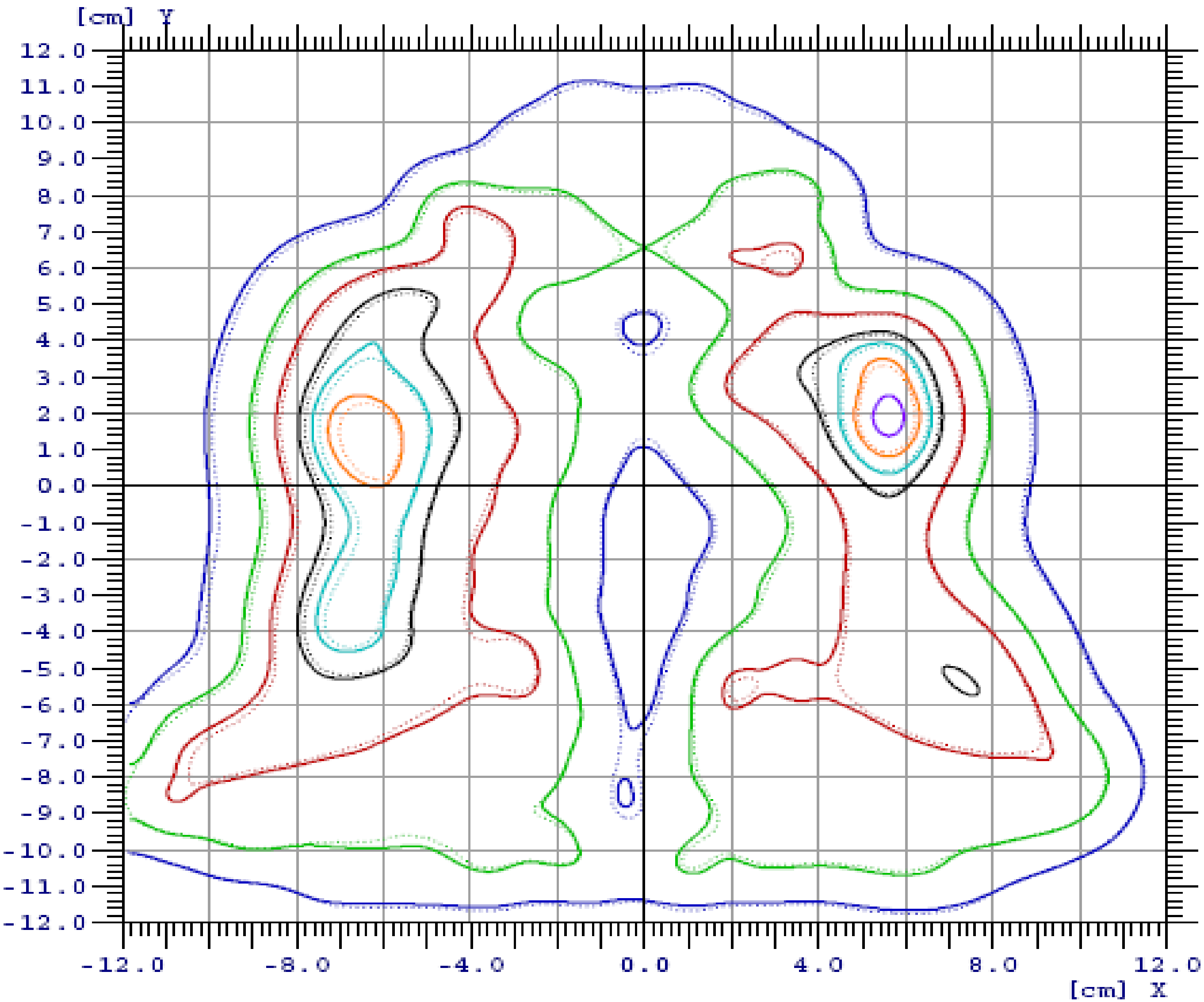


Fig. 3: Isodose comparison for the APAPB field at depth 3.9 cm.
Solid lines measurement; dashed lines TPS calculation. 98.48 % passes for 2% relative dose/2 mm criteria.

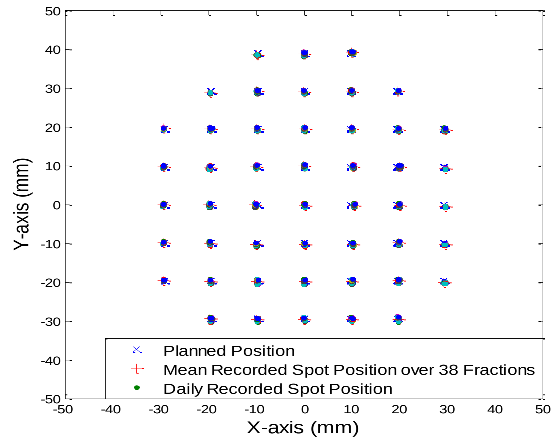


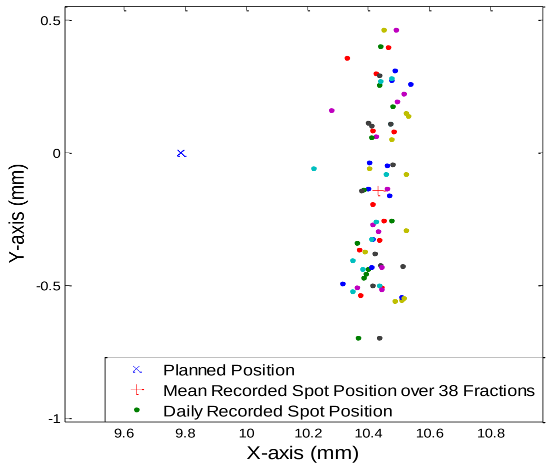
IMPT patient treatment field QA difficulties

- Instances of unacceptable differences between planned and delivered dose
- Usually for highly modulated, high dose gradient, small volume dose distributions
- Measurement difficulties: chamber size, phantom thickness uncertainties
- TPS model limitations
- Solution: Different planning approach (e.g. SFO, combination of passive and IMRT)

Spot positioning constancy check for each fraction of treatment

- Log files are available
- Compared with planned position
- Differences are analyzed
- Deviations larger than the tolerance for interlock will trigger additional evaluation through planning and measurement
- Automatic analysis and dose calculation process will alert us problem situation





From Heng Li, Ph.D., MDACC

Improving spot-scanning proton therapy patient specific quality assurance with HPlusQA, a second-check dose calculation engine

Dennis Mackin,[a] Yupeng Li, Michael B. Taylor, Matthew Kerr, Charles Holmes, Narayan Sahoo, Falk Poenisch, Heng Li, Jim Lii, Richard Amos, Richard Wu, Kazumichi Suzuki, Michael T. Gillin, X. Ronald Zhu, and Xiaodong Zhang
Department of Radiation Physics, The University of Texas MD Anderson Cancer Center, Houston, Texas 77030

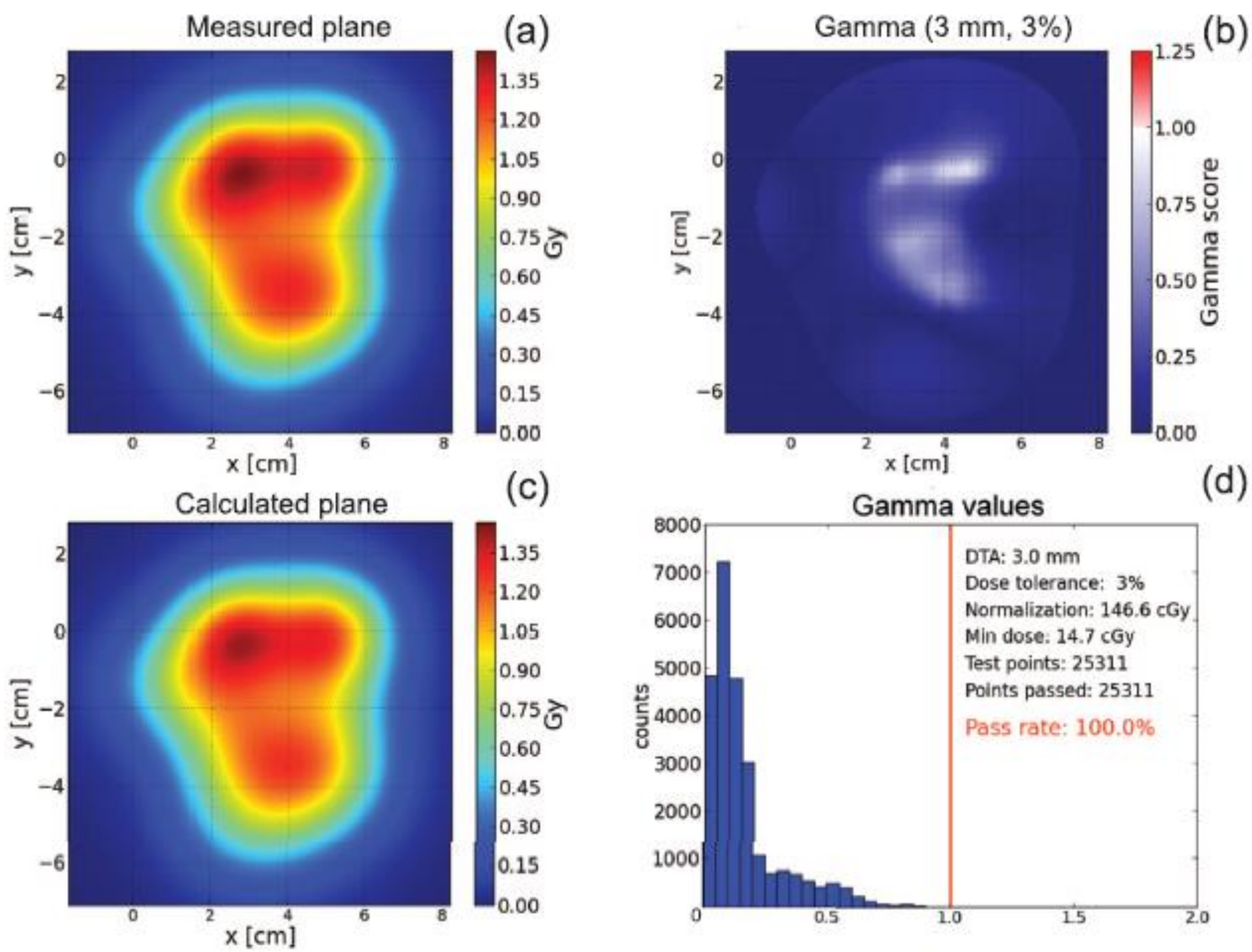
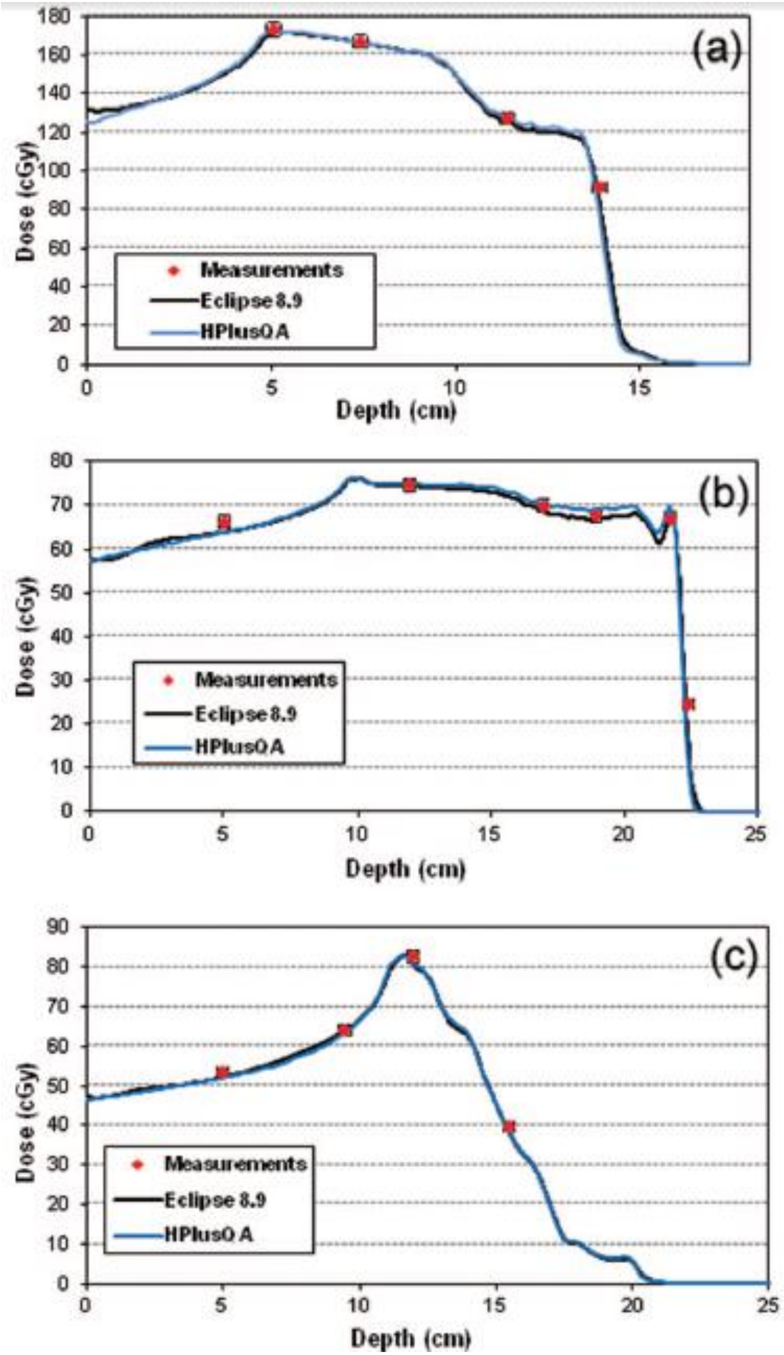


FIG. 4. PSQA dose plane comparisons for the right anterior field of a head and neck cancer treatment plan. The dose planes were measured and calculated for a depth of 7.4 cm. (a) The measured dose plane at a depth of 7.4 cm. Dose given in Gy; (b) 2D image of the gamma index comparison between the measured plane and the plane calculated with Eclipse; (c) dose plane calculated by Eclipse. Dose given in Gy; and (d) distribution of gamma index values.



5. CONCLUSIONS

We found HPlusQA to be reasonably effective (79% ± 10%) in determining when the comparison between measured dose planes and the dose planes calculated by the Eclipse treatment planning system had exceeded the acceptable tolerance levels. When used as described in this study, HPlusQA can reduce the need for patient specific quality assurance measurements by 64%. We believe that the use of HPlusQA as a dose calculation second check can increase the efficiency and effectiveness of the QA process.

In vivo range verification

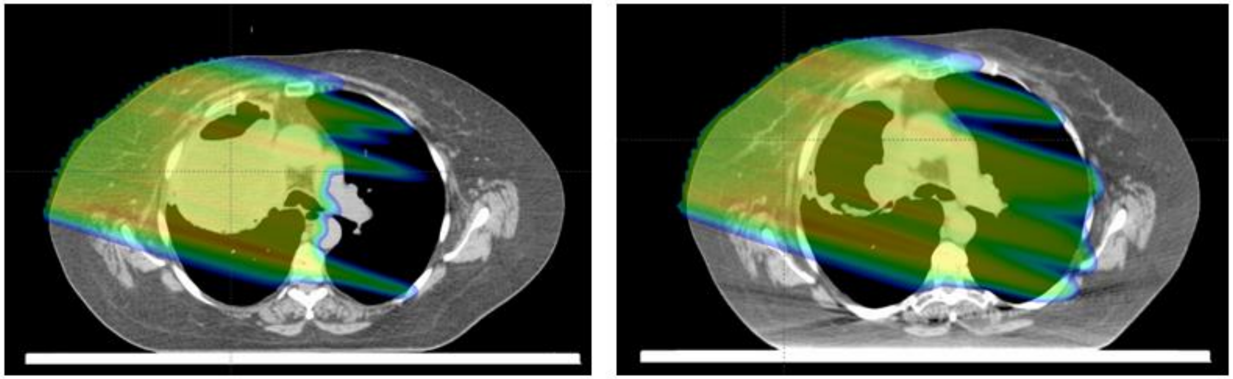


Fig.2 Comparison of dose distribution from single RAO field before and after tumor shrinkage as detected during third week of treatment. (This patient experienced the most dramatic tumor shrinkage).

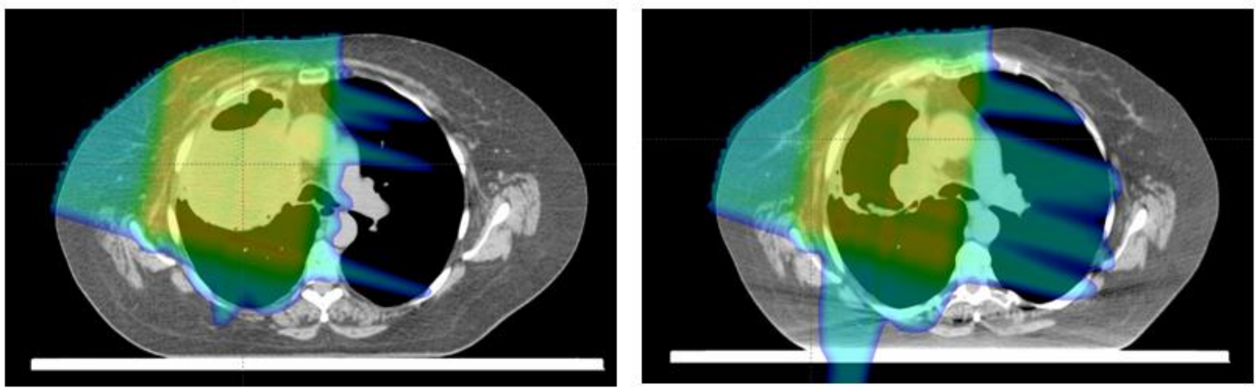


Fig.3 Comparison of total dose distribution before and after tumor shrinkage. (Same patient as Fig.2)

Amos, *et al.* Variation in dose distribution with tumor shrinkage for proton therapy of lung cancer
Poster presentation at PTCOG 46, Zibo, Shandong, China, 2007

Proton Beam Range Verification using Off-site PET by Imaging Novel Proton-Activated Markers

Jongmin Cho, Geoffrey Ibbott, Matthew Kerr, Richard Amos, and Osama Mawlawi

Proceedings: 2013 IEEE Nuclear Science Symposium & Medical Imaging Conference, Seoul, Korea.

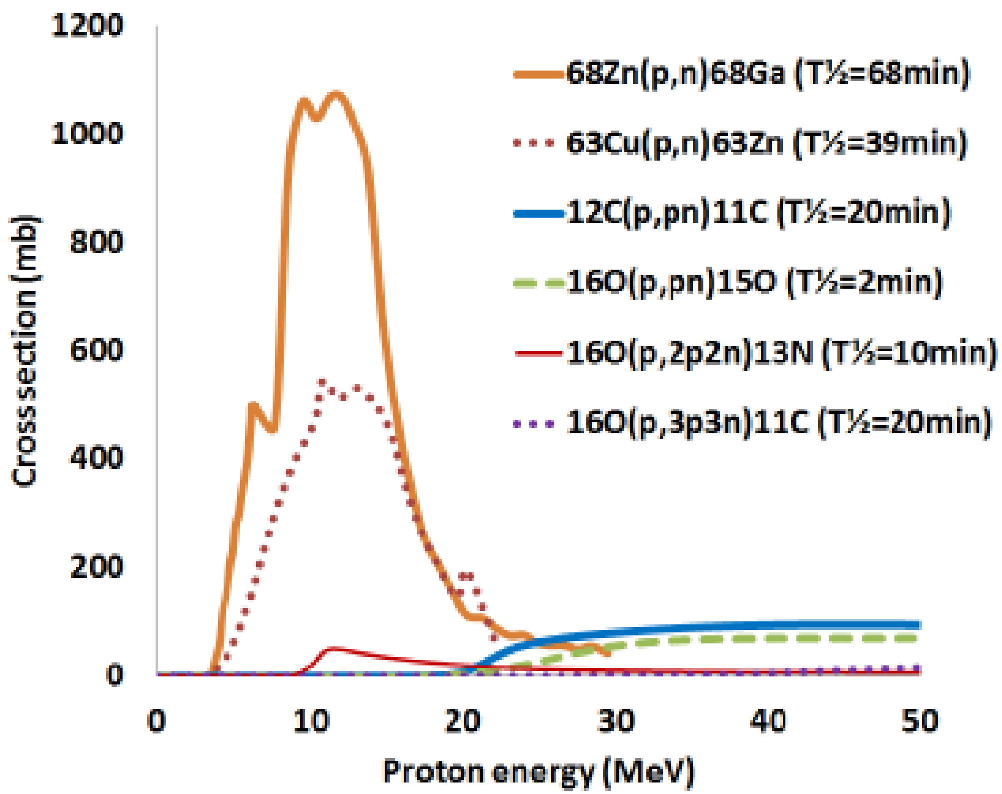


Fig. 1. Proton nuclear interaction cross sections of ^{63}Cu and ^{68}Zn in comparison with tissue endogenous elements – ^{12}C and ^{16}O.

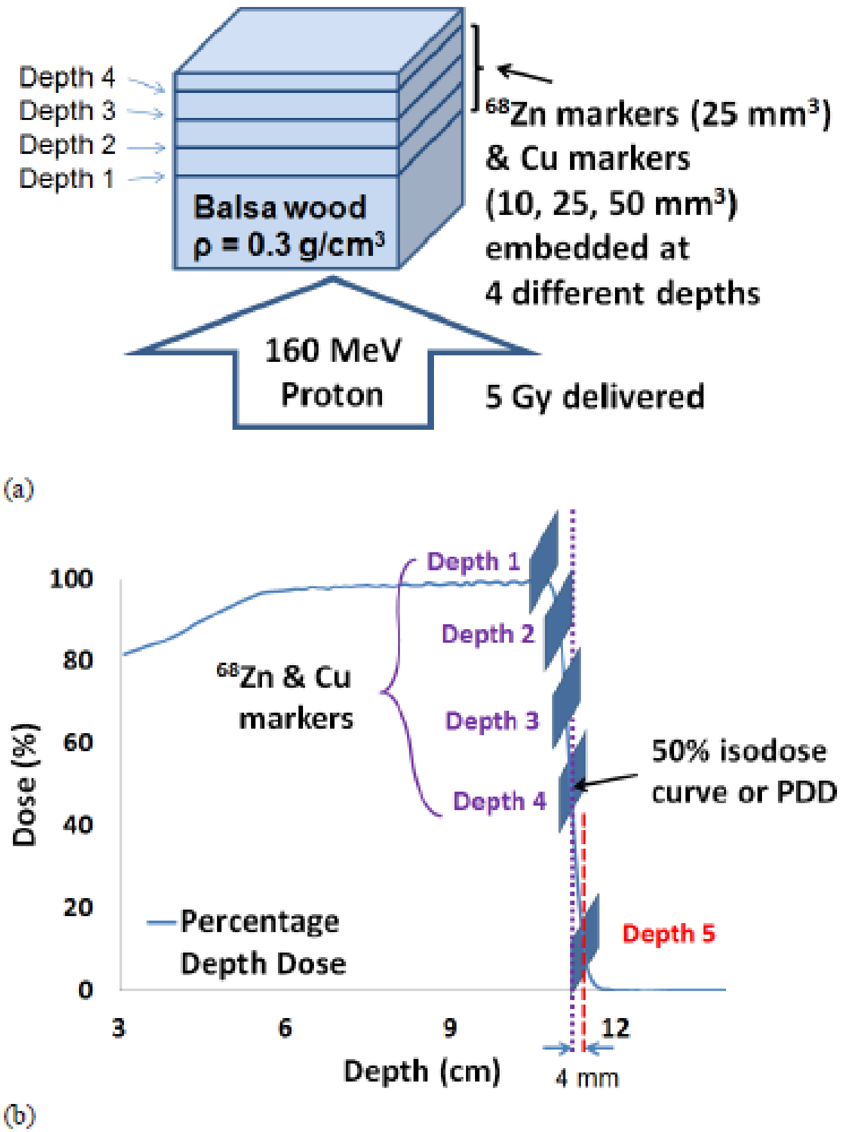


Fig. 2. (a) Balsa wood (as lung substitute) phantom with embedded ^{68}Zn and Cu markers at 4 distal fall-off depths and irradiated by a proton beam. (b) Locations of embedded markers relative to PDD (percentage depth dose). Natural Cu was used due to its relatively high ^{63}Cu content (69%).

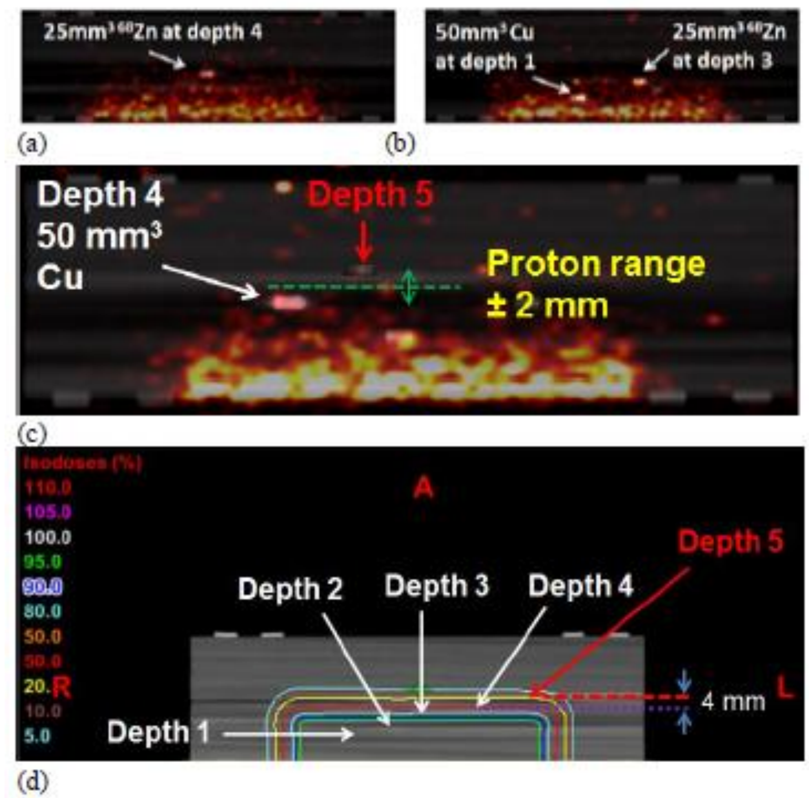
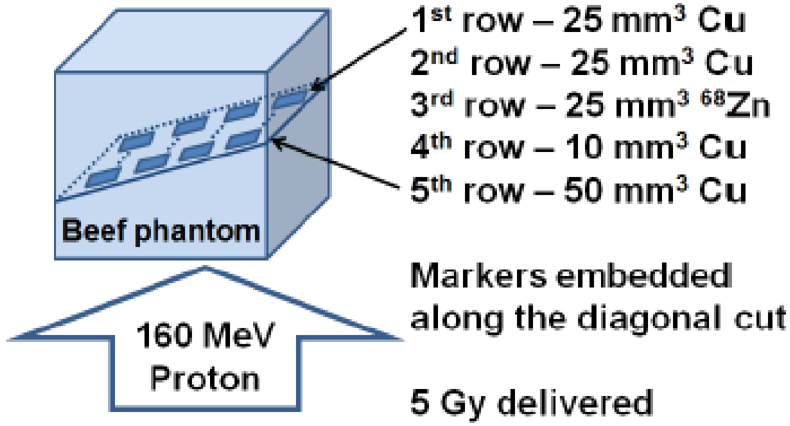
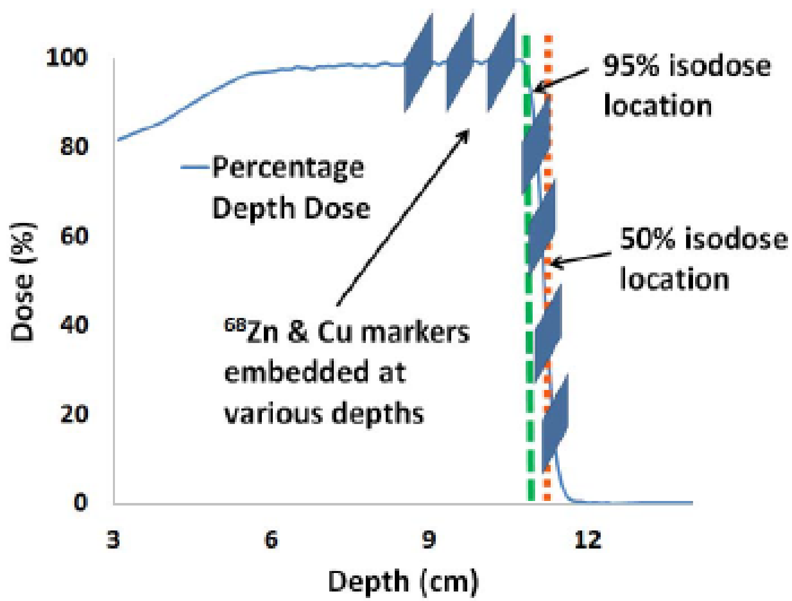


Fig. 4. PET/CT fusion images acquired for 30 min from a balsa wood phantom after a 1 hr post-irradiation delay. (a) and (b) are coronal views showing strong PET signals from markers. (c) Markers at depth 4 and depth 5 show signal and no signal, respectively. Proton range estimation within ± 2 mm is achievable if maker at depth 5 is separated by 4 mm from depth 4. (d) Isodose curves overlaid on CT coronal plane.

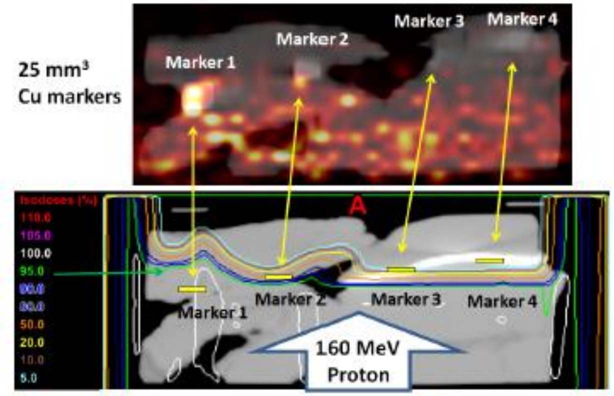


(a)

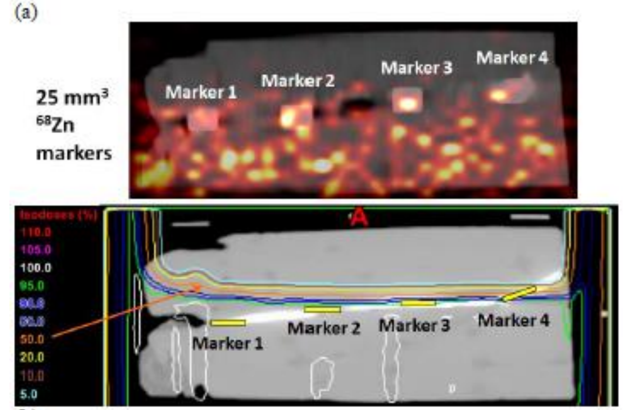


(b)

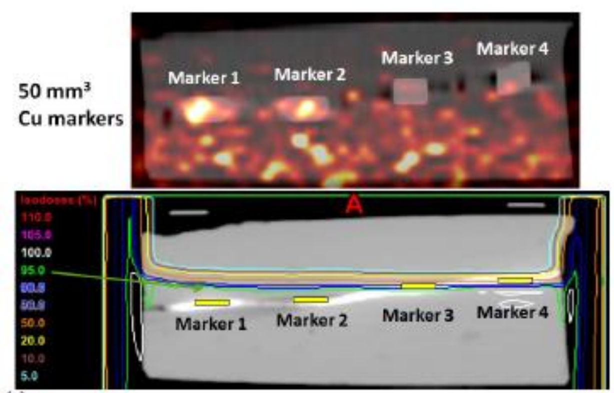
Fig. 3. (a) Beef phantom (as soft-tissue substitute) cut diagonally is embedded with ^{68}Zn and Cu markers and is irradiated by a 160 MeV proton beam. Each coronal plane contains a different marker volume. (b) Locations of embedded markers relative to PDD.



(a)



(b)



(c)

Fig. 5. Beef phantom experiment. In each subpart, the top image shows the PET/CT fusion images acquired for 30 min after a 2 hr post-irradiation delay and the bottom image shows the isodose curves overlaid on the CT of the same slice. Marker locations are shown for correlation. (a) 1st row - four 25 mm^3 Cu markers. (b) 3rd row - four 25 mm^3 ^{68}Zn markers. (c) 5th row - four 50 mm^3 Cu markers.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Thank you