Bottleneck Issues in Proton Monte Carlo Clinical Implementation and Companion Imaging Techniques – Report of NRG Survey Results

Liyong Lin, PhD, DABR, FAAPM, Associate Professor
Department of Radiation Oncology, Emory University

@Session
"Bottleneck Issues in the Clinic Implementation of Monte Carlo Method in Proton Therapy"
Virtual AAPM 2021
07/25/2021

EMORY WINSHIP CANCER INSTITUTE
National Cancer Institute-Designated Comprehensive Cancer Center

AAPM 2021
JULY 25–29 | VIRTUAL
63RD ANNUAL MEETING & EXHIBITION

NRG ONCOLOGY™

Two Following Talks in Session

- Jan Schumann “Proton Monte Carlo Platforms – The way towards treatment planning and latest developments”

- Shuai Leng “Dual Energy CT and Metal Artifact Reduction - Fundamentals and Recent Development”

Why NRG survey?

- No publication about how proton therapy centers implement Monte Carlo (MC) and complimentary imaging

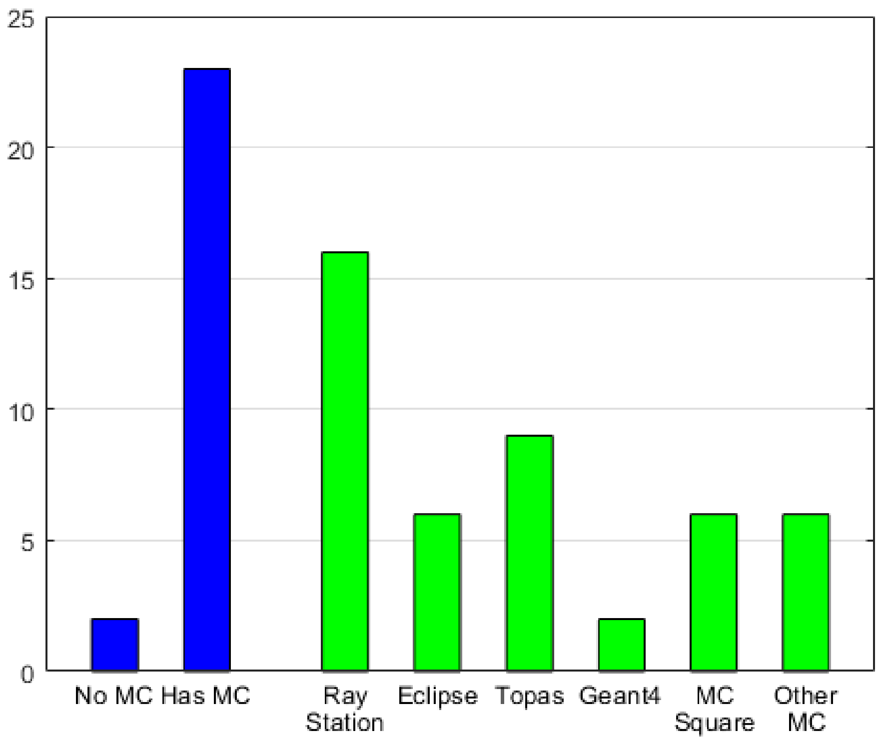
- Current practice pattern assessment is required to determine the feasibility of including them in clinical trials.

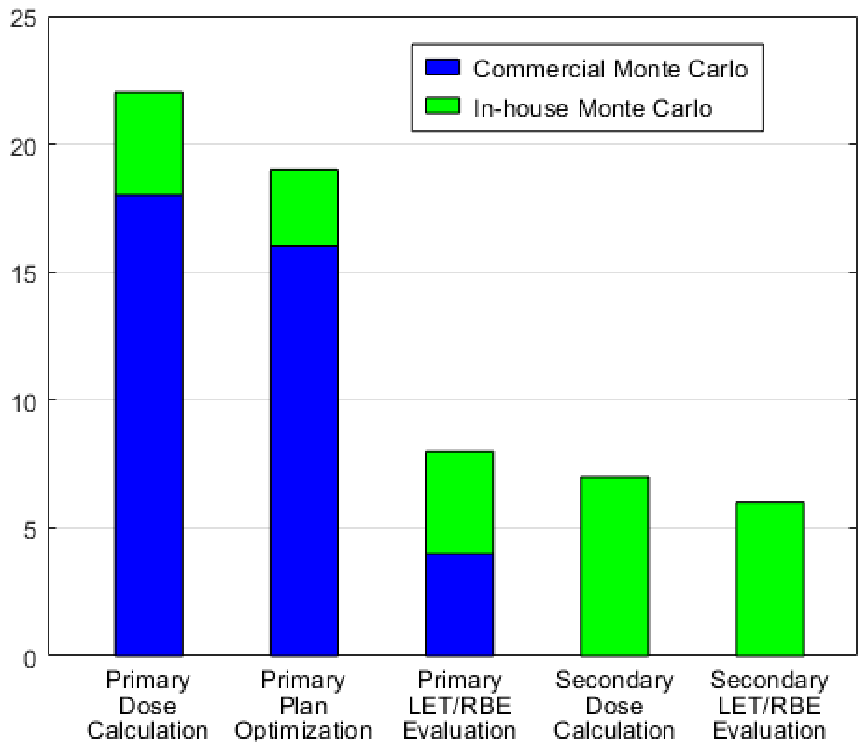
Lin et al “NRG Oncology Survey of Monte Carlo Dose Calculation Use in US Proton Therapy Centers” IJPT In Press

Goals of NRG survey

- Scope of MC utilization
- Validation methods in heterogeneous phantoms
- Clinical site-specific imaging guidance and proton range uncertainties
- How metal implants are handled in MC

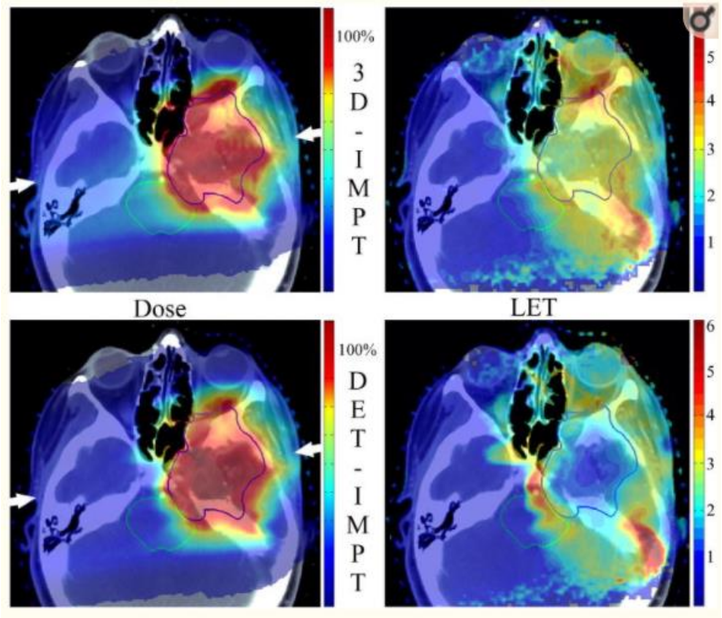
NRG survey result 1





1. 25/28 centers responded to the survey distributed on 5/13/19
2. Commercial Monte Carlo are in the super majority

Discussion of survey results 1a



$$LET_d(v) = \frac{\sum_{events} dE \cdot (dE/dx)\frac{1}{\rho}}{\sum_{events} dE}$$

$$LET_d(v) = \frac{\sum_F LET_d^F(v) \times D_F(v)}{\sum_F D_F(v)}$$

3D modulation IMPT (3D-IMPT) vs. Distal Edge Tracking IMPT (DET-IMPT).

(a) In DET-IMPT the optimization routine assigns weights only to the distal beam spots, fewer # of spots.

(b) In 3D-IMPT, Bragg peaks are selected that cover the whole target volume.

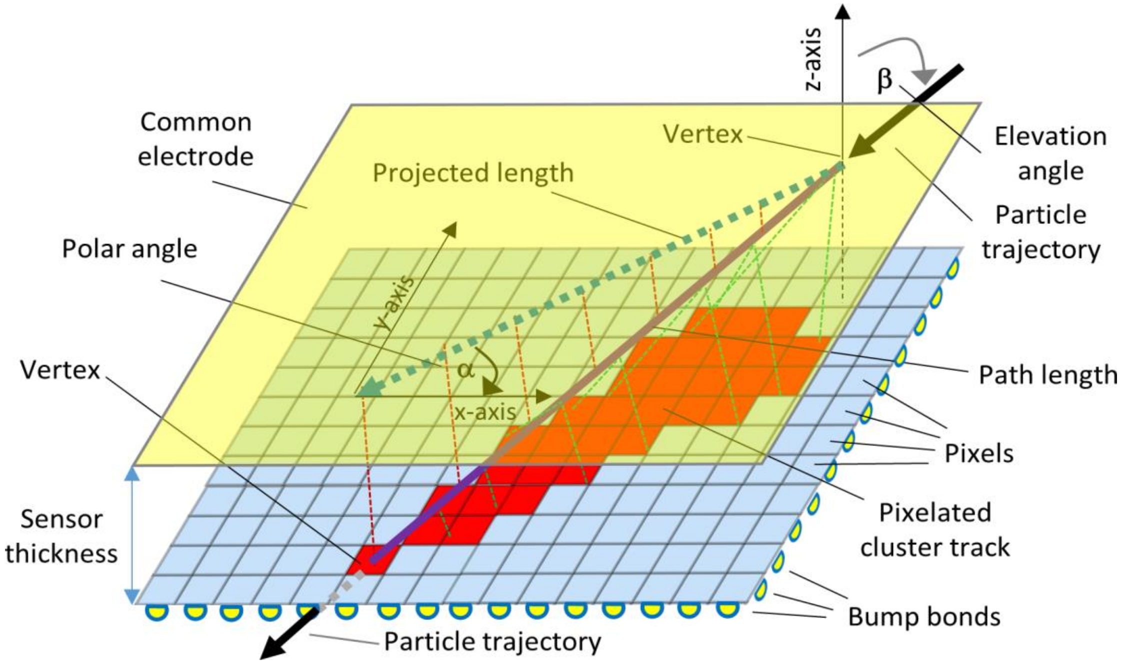
1. Dose-averaged LET (LETd) should be considered for central serial OAR (brainstem as shown; optic chiasm, rectum and bladder Not shown)

2. LET feature is not available at current clinical commercial MC but they are available at in house and research versions.

3. RBE (relative biological effectiveness): Paganetti “Report of the AAPM TG-256 on the relative biological effectiveness of proton beams in radiation therapy” Medphys 2019

Grassberger et al “Variations in linear energy transfer within clinical proton therapy fields and the potential for biological treatment planning” IJROBP 2011

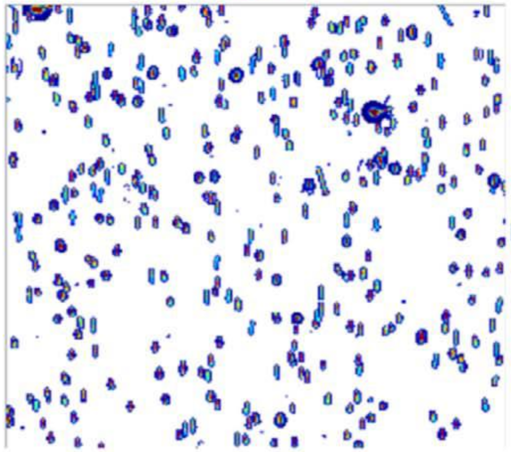
Discussion of survey results 1b



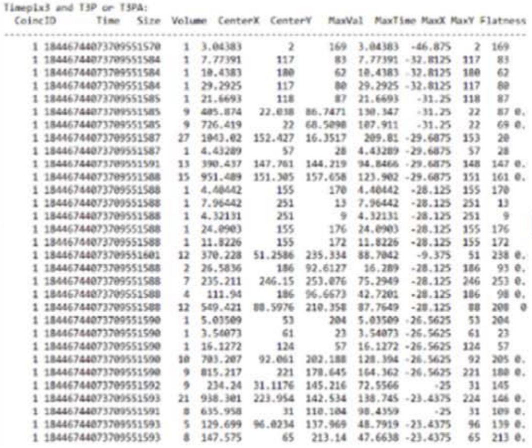
LET distributions can be detected by pixelated proton counting detectors by characterizing simultaneous events extracting multi parameters at micron and nano second levels.

1. Granja C et al 2018 Resolving power of pixel detector Timepix for wide-range electron, proton and ion detection Nucl. Instrum. Methods Phys. Res. A 908 60–71
2. Charyyev S et al 2021 A novel proton counting detector and method for the validation of tissue and implant material maps for Monte Carlo dose calculation Phys. Med. Biol. 045003

STEP 1



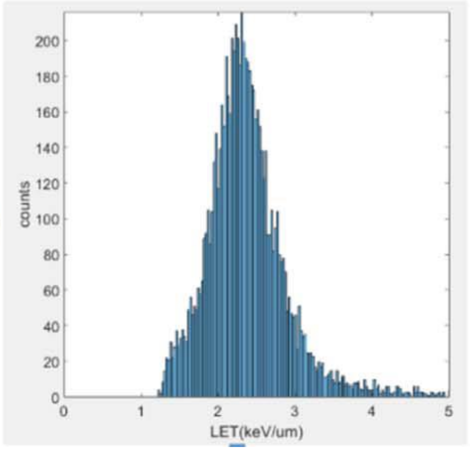
STEP 2



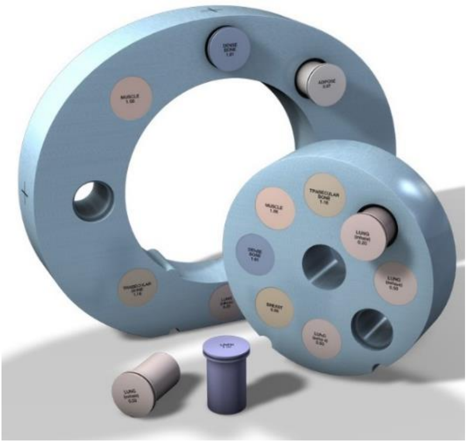
Timepix3 and T3P or T3PA:

CoincID	Time	Size	Volume	CenterX	CenterY	MaxVal	MaxTime	MaxX	MaxY	Flatness
1	18446744073709551570	1	3.04383	2	169	3.04383	-46.875	2	169	
1	18446744073709551584	1	7.77391	117	83	7.77391	-32.8125	117	83	
1	18446744073709551584	1	10.4383	180	62	10.4383	-32.8125	180	62	
1	18446744073709551584	1	29.2925	117	80	29.2925	-32.8125	117	80	
1	18446744073709551585	1	21.6693	118	87	21.6693	-31.25	118	87	
1	18446744073709551585	9	405.874	22.038	86.7471	130.347	-31.25	22	87	0.
1	18446744073709551585	9	726.419	22	68.5098	107.911	-31.25	22	69	0.
1	18446744073709551587	27	1043.02	152.427	16.3517	209.81	-29.6875	153	20	
1	18446744073709551587	1	4.43289	57	28	4.43289	-29.6875	57	28	
1	18446744073709551591	13	390.437	147.761	144.219	94.8466	-29.6875	148	147	0.
1	18446744073709551588	15	951.489	151.305	157.658	123.902	-29.6875	151	161	0.
1	18446744073709551588	1	4.40442	155	170	4.40442	-28.125	155	170	
1	18446744073709551588	1	7.96442	251	13	7.96442	-28.125	251	13	
1	18446744073709551588	1	4.32131	251	9	4.32131	-28.125	251	9	
1	18446744073709551588	1	24.0903	155	176	24.0903	-28.125	155	176	
1	18446744073709551588	1	11.8226	155	172	11.8226	-28.125	155	172	
1	18446744073709551601	12	370.228	51.2586	235.334	88.7042	-9.375	51	238	0.
1	18446744073709551588	2	26.5836	186	92.6127	16.289	-28.125	186	93	0.
1	18446744073709551588	7	235.211	246.15	253.076	75.2949	-28.125	246	253	0.
1	18446744073709551588	4	111.94	186	96.6673	42.7201	-28.125	186	98	0.
1	18446744073709551588	12	549.421	88.5976	210.358	87.7649	-28.125	88	208	0
1	18446744073709551590	1	5.03509	53	204	5.03509	-26.5625	53	204	
1	18446744073709551590	1	3.54073	61	23	3.54073	-26.5625	61	23	
1	18446744073709551590	1	16.1272	124	57	16.1272	-26.5625	124	57	
1	18446744073709551590	10	703.207	92.061	202.188	128.394	-26.5625	92	205	0.
1	18446744073709551590	9	815.217	221	178.645	164.362	-26.5625	221	180	0.
1	18446744073709551592	9	234.24	31.1176	145.216	72.5566	-25	31	145	
1	18446744073709551593	21	938.301	223.954	142.534	138.745	-23.4375	224	146	0.
1	18446744073709551591	8	635.958	31	110.104	98.4359	-25	31	109	0.
1	18446744073709551593	5	129.699	96.0234	137.969	48.7919	-23.4375	96	139	0.
1	18446744073709551593	8	147.575	65	213.14	47.6638	-23.4375	65	213	0.

STEP 3

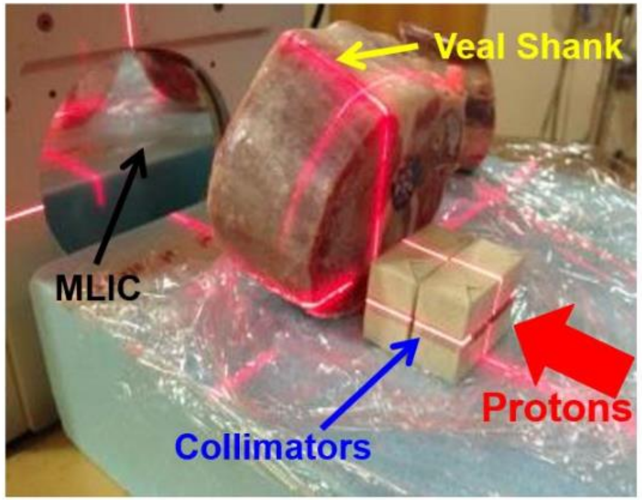


NRG survey result 2- Heterogenous validation

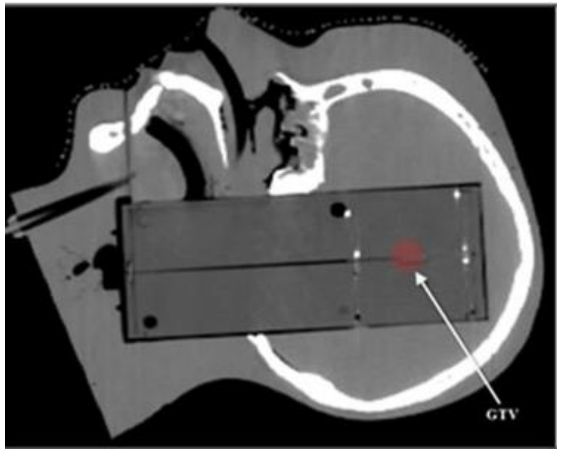


Electron density phantom (84%)

Stoichiometric calibration

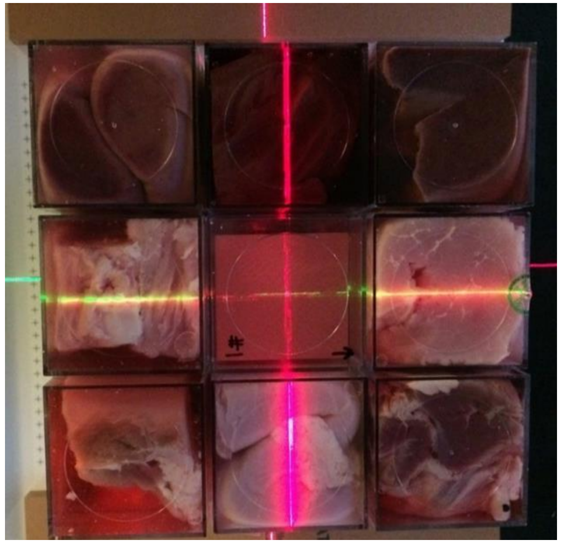


Animal tissues (40%)



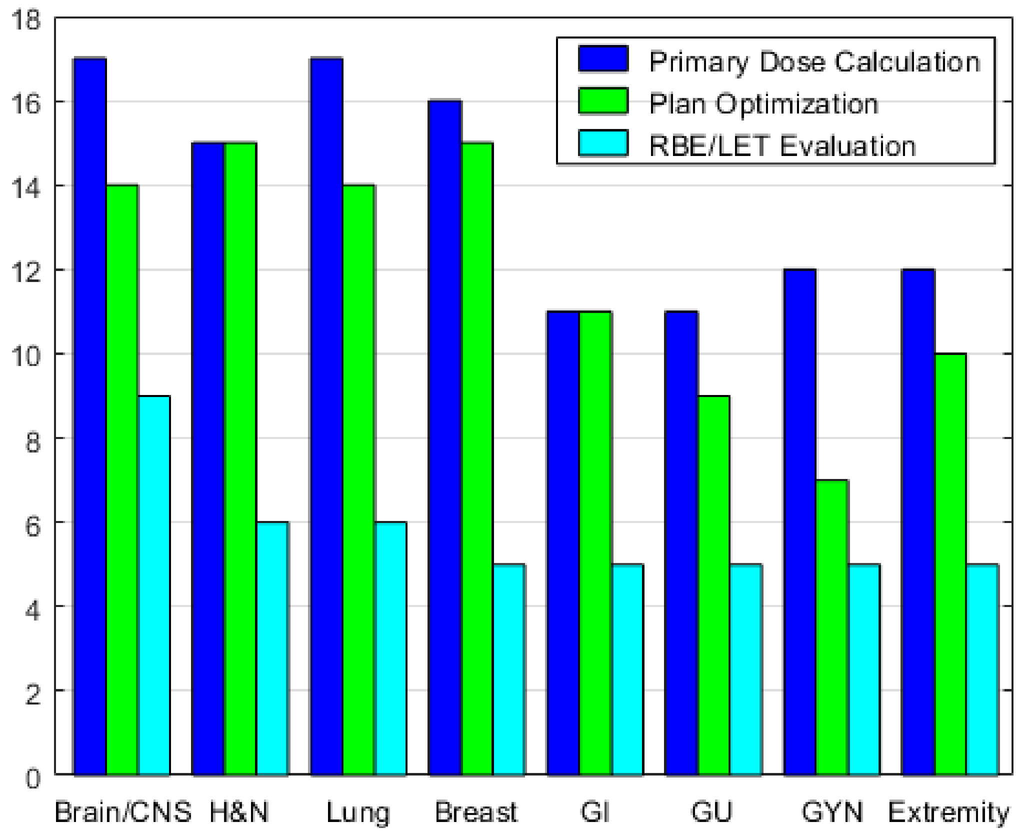
IROC phantom (92%)

Heterogeneous validation



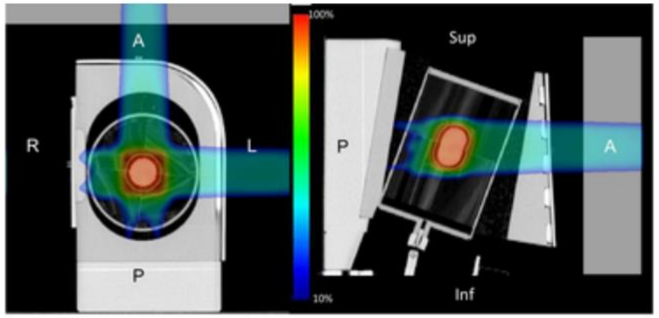
Animal tissues (28%)

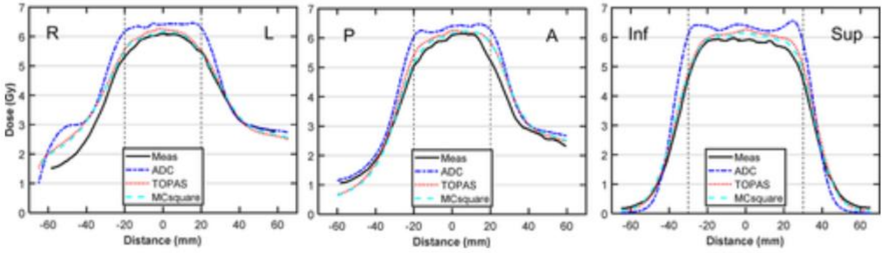
NRG survey result 3



1. 17/25 centers primary dose calculation while 15/17 primary dose optimization
2. More heterogenous sites used MC more often.
3. Some centers don’t have MC optimization capability yet.

Discussion of survey result 3

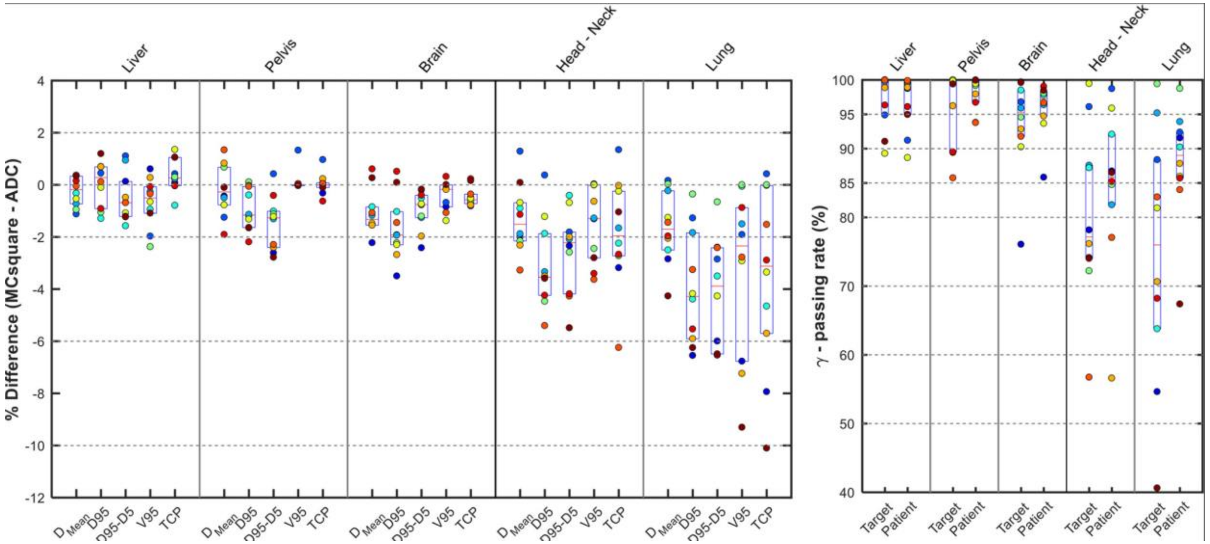


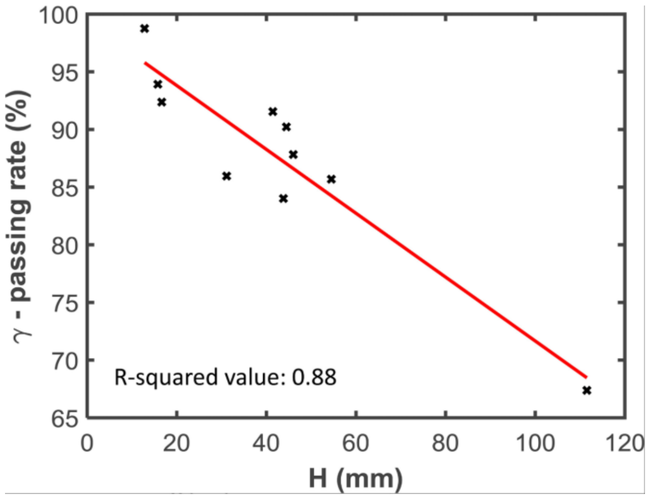


Two main issues of analytical dose calculations:

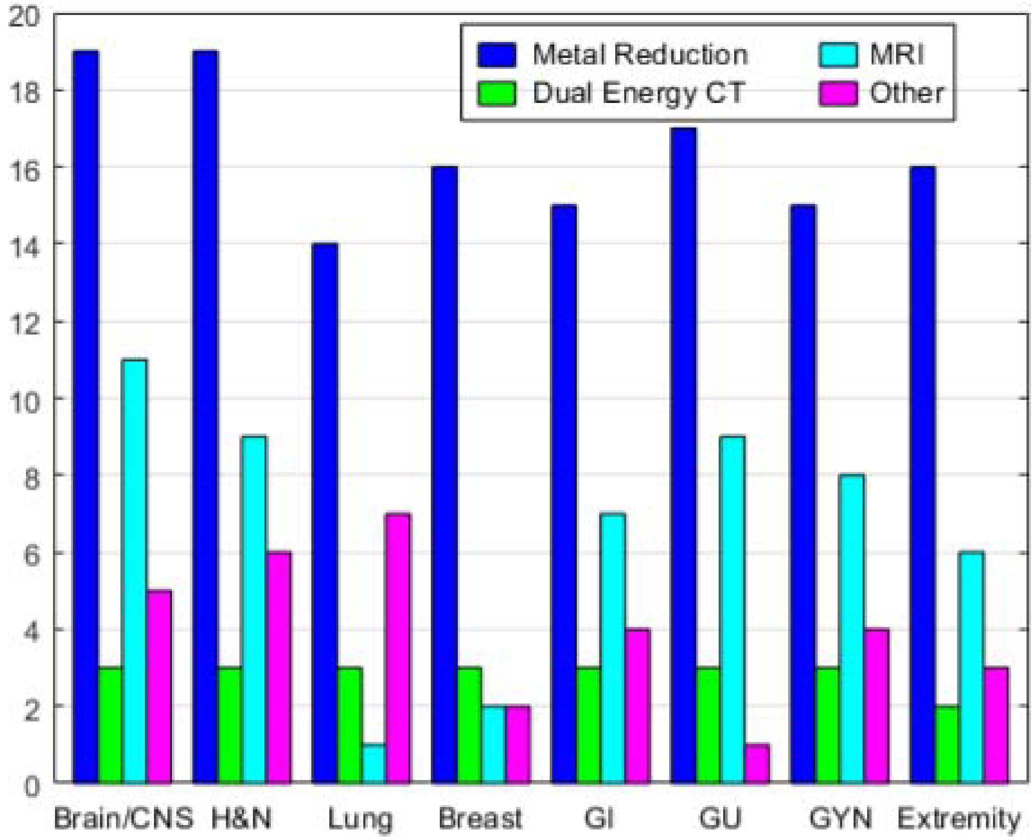
1. Absolute output due to modelling of variable air gaps and large angle scattering of range shifters
2. Multi Coulomb scattering over heterogenous tissues (shown too sharp in analytical method)

Huang et al "Validation and application of a fast Monte Carlo algorithm for assessing the clinical impact of approximations in analytical dose calculations for pencil beam scanning proton therapy" Med Phys 2018



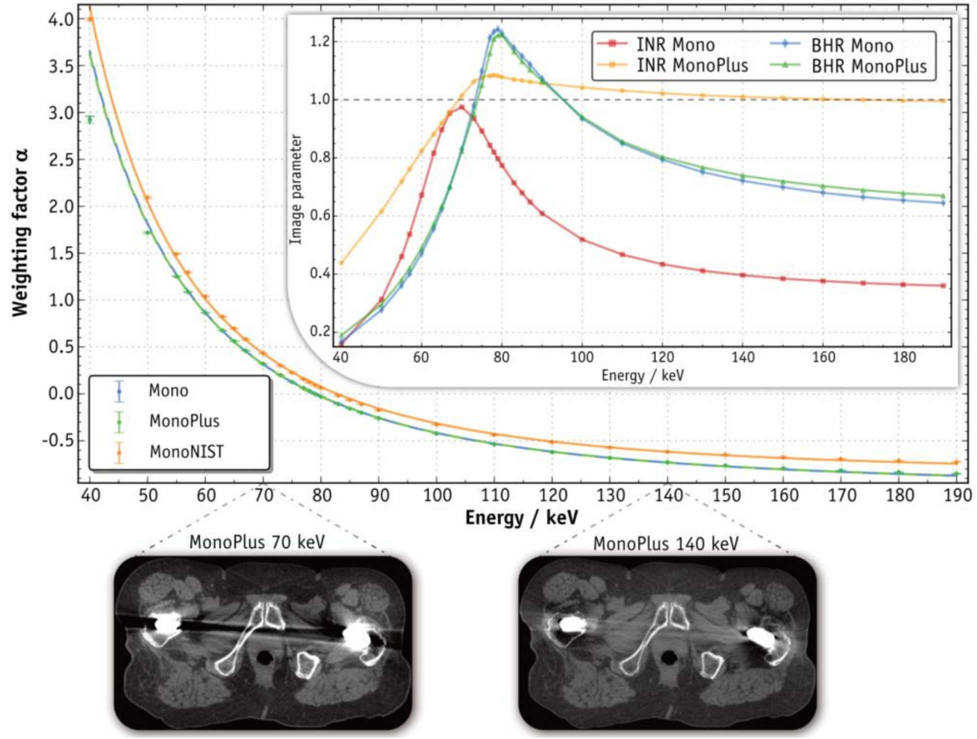


NRG survey result 4



1. 19/25 centers used MAR but only 3/25 centers used DECT
2. 11/25 centers used MRI and 7/25 centers used other proton imaging methods

Discussion of survey result-4a

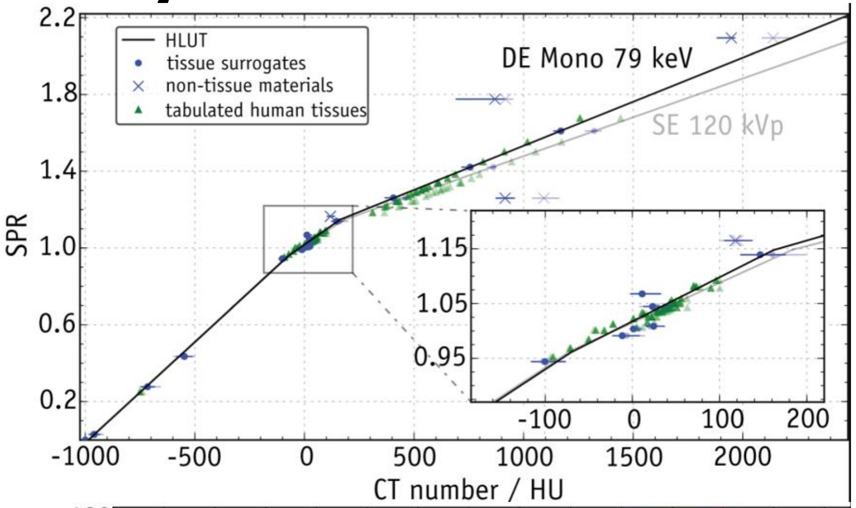


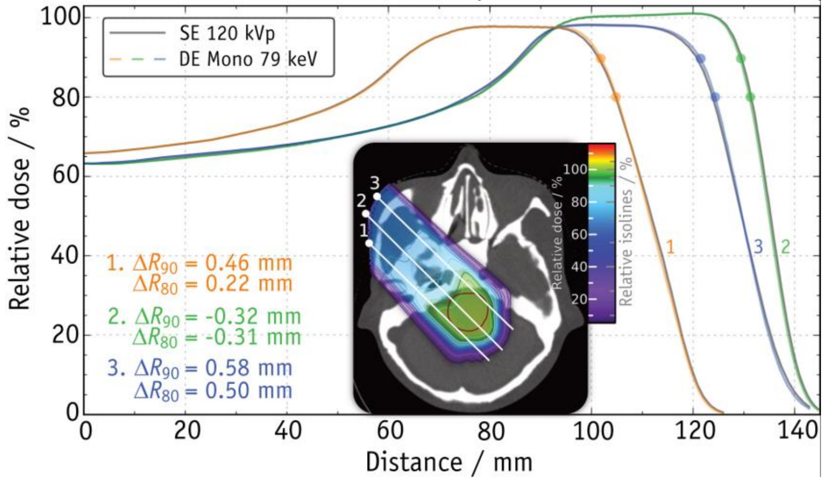
$$H\left(E_{\mathrm{mono}}\right)=\alpha\left(E_{\mathrm{mono}}\right)\ H_{80\,\mathrm{kVp}}+\left[1-\alpha\left(E_{\mathrm{mono}}\right)\right]\ H_{140\,\mathrm{kVp}} \quad (1)$$

$$\mathrm{INR}\left(E_{\mathrm{mono}}\right)=\sqrt{\frac{1}{n}\sum_{i=1}^{n}\frac{\sum_{s\in\mathcal{S}}\sigma^{2}_{120\,\mathrm{kVp},\,s,\,i}}{\sum_{s\in\mathcal{S}}\sigma^{2}_{s,\,i}\left(E_{\mathrm{mono}}\right)}} \quad (2)$$

and beam-hardening ratio (BHR):

$$\mathrm{BHR}\left(E_{\mathrm{mono}}\right)=\frac{\sum_{i}^{n}\left(\max_{s\in\mathcal{S}}\{H_{120\,\mathrm{kVp},\,s,\,i}\}-\min_{s\in\mathcal{S}}\{H_{120\,\mathrm{kVp},\,s,\,i}\}\right)}{\sum_{i}^{n}\left(\max_{s\in\mathcal{S}}\{H_{s,\,i}(E_{\mathrm{mono}})\}-\min_{s\in\mathcal{S}}\{H_{s,\,i}(E_{\mathrm{mono}})\}\right)} \quad (3)$$

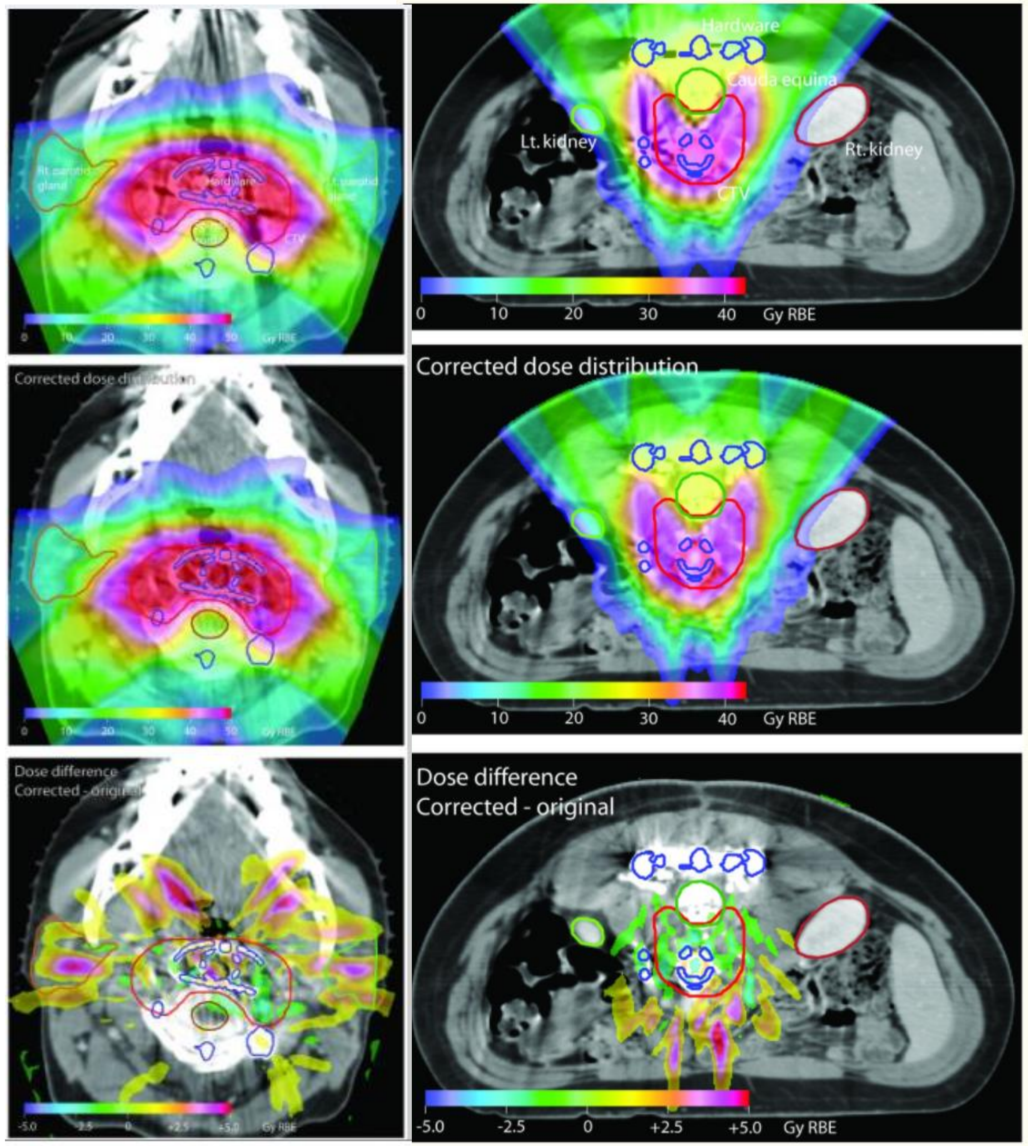




Issues for virtual mono energy images of 79 keV from DECT to replace SECT: (1) not optimal for implant (2) 140 keV images sub optimal INR and BHR

Wolfhart P "Clinical Implementation of Dual-energy CT for Proton Treatment Planning on Pseudo-monoenergetic CT scans" IJROBP 2017

Discussion of survey result -4b



1. Compared Metal Artifact Reduction (MAR) images to images without MAR
2. Compared Analytical dose calculation to Monte Carlo method
3. Concluded that extra 10 mm treatment margins are needed
4. Limited to titanium implant & did NOT consider complex implant structure that contain materials beyond titanium
5. Did not consider residual artifacts in MAR images
6. Most clinics overwrite implant & surrounding tissues without consensus on how to overwrite (NRG surveys)

Vurberg et al "Dosimetric accuracy of proton therapy for chordoma patients with titanium implants" Med Phys 2013

Acknowledgement

- NRG Proton Monte Carlo workgroup members
- AAPM TG-349 members
- Emory radiation oncology colleagues and trainees

Thank you for your attention! Questions...

EMORY WINSHIP CANCER INSTITUTE
National Cancer Institute-Designated Comprehensive Cancer Center

AAPM 2021
JULY 25–29 | VIRTUAL
63RD ANNUAL MEETING & EXHIBITION

NRG ONCOLOGY™