Experiences in Optimization of Radiological Protection for Imaging in Radiotherapy

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Outline

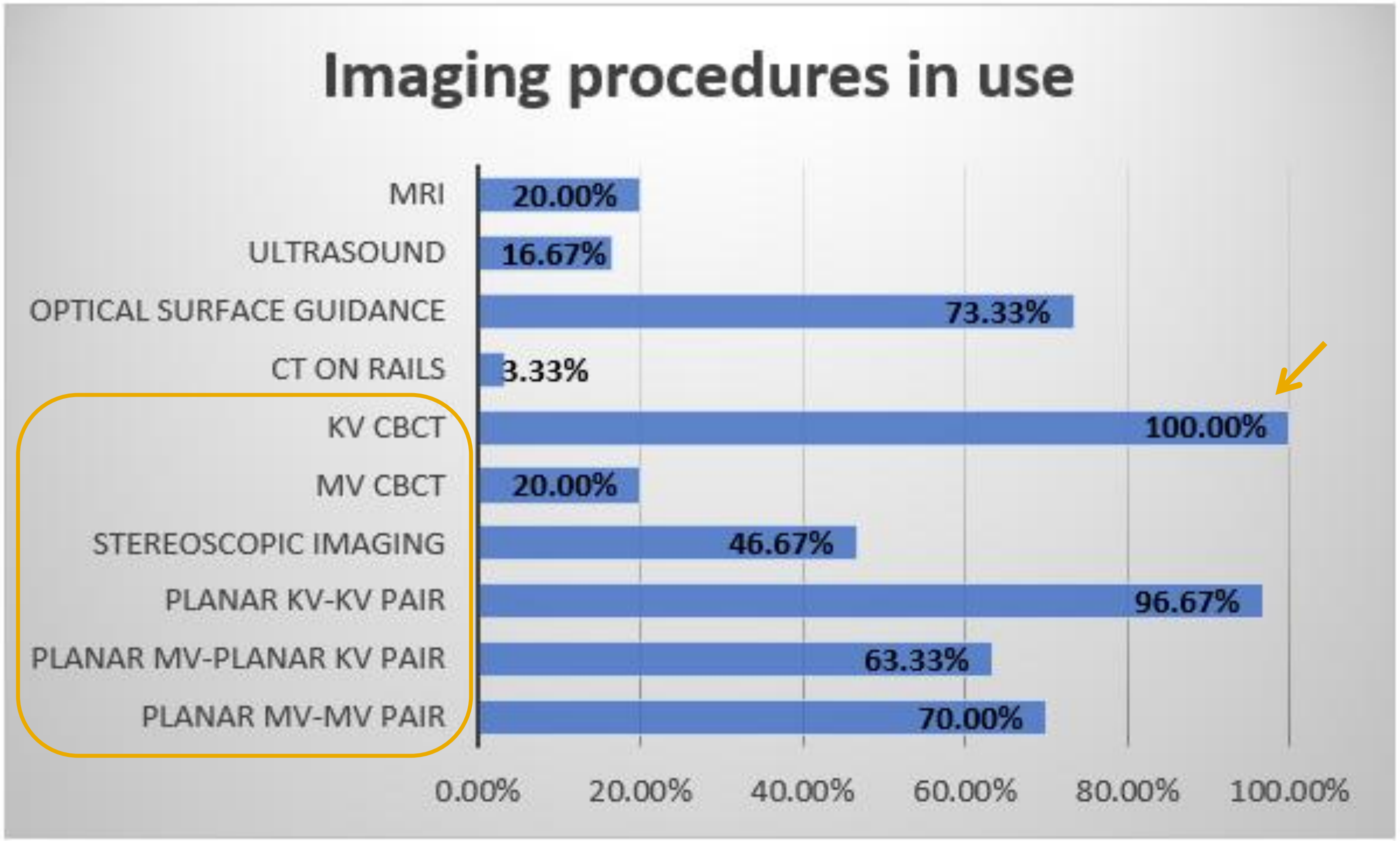
- Background
- Optimization methodology at Loyola
- Example cases
- Conclusion

INTRODUCTION

Background: 2020 survey on imaging practices ICRP TG-116

USA RESULTS FROM 30 CENTERS: IGRT PROCEDURES

- IGRT has become standard of care in the U.S.
- CBCT main modality for IGRT



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Original paper

An international survey of imaging practices in radiotherapy

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ABSTRACT

Improvements in delivery of radiation dose to target tissues in radiotherapy have increased the need for better image quality and led to a higher frequency of imaging patients. Imaging for treatment planning extends to function and motion assessment and devices are incorporated into medical linear accelerators (linacs) so that regions of tissue can be imaged at time of treatment delivery to ensure dose distributions are delivered as accurately as possible. A survey of imaging in 97 radiotherapy centres in nine countries on six continents has been undertaken with an on-line questionnaire administered through the International Commission on Radiological Protection mentorship programme to provide a snapshot of imaging practices. Responses show that all centres use CT for planning treatments and many utilise additional information from magnetic resonance imaging and positron emission tomography scans. Most centres have kV cone beam CT attached to at least some linacs and use this for the majority of treatment fractions. The imaging options available declined with the human development index (HDI) of the country, and the frequency of imaging during treatment depended more on country than treatment site with countries having lower HDIs imaging less frequently. The country with the lowest HDI had few kV imaging facilities and relied on MV planar imaging intermittently during treatment. Imaging protocols supplied by vendors are used in most centres and under half adapt exposure conditions to individual patients. Recording of patient doses, a knowledge of which is important in optimisation of imaging protocols, was limited primarily to European countries.

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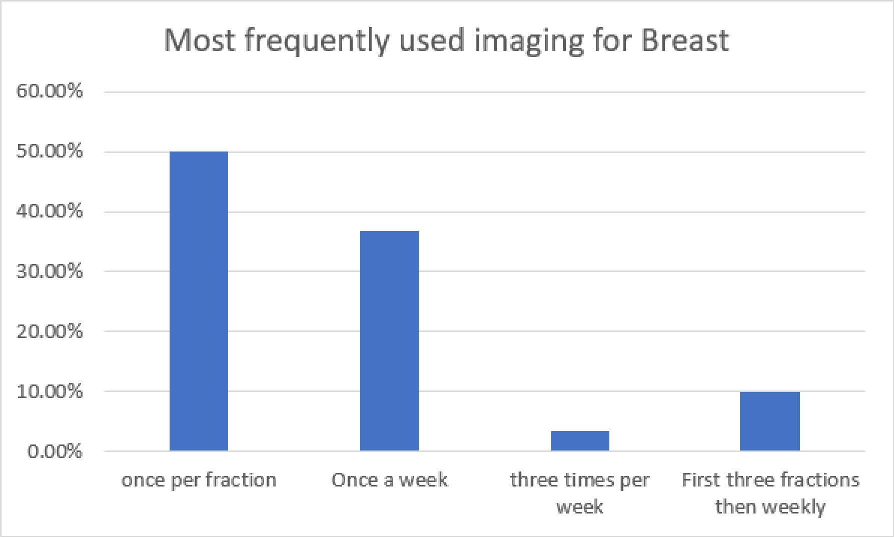
Background: 2020 survey on imaging practices ICRP TG-116

USA RESULTS FROM 30 CENTERS: IMAGING FREQUENCY

Highest imaging frequency for 6 sites:

- CNS/brain
- Head and Neck
- Lung
- GYN
- Prostate
- Breast

90% of US centers perform imaging once (or more) per fraction



Background: 2020 survey on imaging practices ICRP TG-116

USA RESULTS FROM 30 CENTERS

CBCT protocols use and optimization (adaptation)

- **~40% of centers adapt** their kV CBCT protocols to individual patients, mainly due to habitus for larger patients (e.g. 125 kV pelvis vs. 140 kV large pelvis)
- **~40% of centers adjust** blades and FOV for adult patients
- **30% of centers adjust** blades and FOV for pediatric patients
- **1 (3%) center consistently records CBCT dose** (CTDI)

Implementing imaging protocols optimization

- **1/3rd of centers (all academic)** reported working actively with diagnostic imaging physicists to optimize their RT imaging techniques
- Some centers commented that TMPs had prior training in diagnostic imaging or that they would benefit from help from a DMP

- Therapy Medical Physicists would optimize CBCT protocols for imaging dose but prevented by lack of experience, time, equipment and resources

Background: CBCT imaging dose measurement

OVERVIEW OF CURRENTLY PROPOSED METHODS

CTDI phantoms and 100 mm IC

- CTDI, $CTDI_w$ ($CTDI_{vol}$) for Diagnostic narrow beam CT scanning
  - *For CBCT: issues with detector length and lack of scatter equilibrium in phantom*

Wide beam

- CBDI: (100 mm pencil chamber, independent of chamber size)
- IAEA method (100 mm pencil chamber)
- AAPM TG-111 (0.6 cc Farmer chamber, similar to $CTDI_w$ with peripheral measurements)

- Great reference comparing these methods:

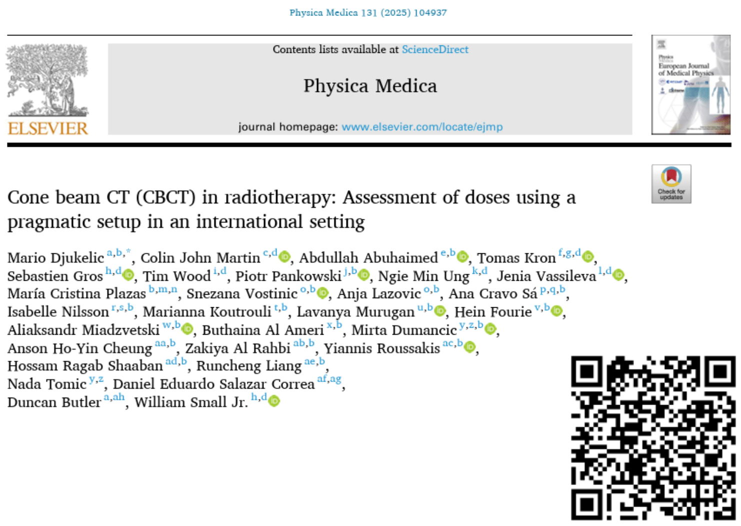
  Investigation of the radiation dose from cone-beam CT for image-guided radiotherapy: A comparison of methodologies, J Appl Clin Med Phys 2018; 19:1: 174–183, DOI: 10.1002/acm2.12239

Background: CBCT imaging dose measurement

TG-116 RECOMMENDATIONS

TG-116 recommendations → CBDI measurements

- Basis for DRL in U.K.
- Tests being performed since 2021
- Method developed with the help of **TG-116 mentees**
  - **TG-116 report ANNEX B**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Cone beam CT (CBCT) in radiotherapy: Assessment of doses using a pragmatic setup in an international setting

Mario Djukelic [a,b,*], Colin John Martin [c,d], Abdullah Abuhaimed [e,b], Tomas Kron [f,g,d], Sebastien Gros [h,d], Tim Wood [i,d], Piotr Pankowski [j,b], Ngie Min Ung [k,d], Jenia Vassileva [l,d], María Cristina Plazas [b,m,n], Snezana Vostinic [o,b], Anja Lazovic [o,b], Ana Cravo Sá [p,q,b], Isabelle Nilsson [r,s,b], Marianna Koutrouli [t,b], Lavanya Murugan [u,b], Hein Fourie [v,b], Aliaksandr Miadzvetski [w,b], Buthaina Al Ameri [x,b], Mirta Dumancic [y,z,b], Anson Ho-Yin Cheung [aa,b], Zakiya Al Rahbi [ab,b], Yiannis Roussakis [ac,b], Hossam Ragab Shaaban [ad,b], Runcheng Liang [ae,b], Nada Tomic [y,z], Daniel Eduardo Salazar Correa [af,ag], Duncan Butler [a,ah], William Small Jr. [h,d]

However:

- CTDI equipment not available in majority of RT centers (U.S. and low-middle income countries)
- In U.S. x-ray sources output verification are performed by contracted diagnostic physicists annually (per state regs)
- ICRP report and recommendations will be published in 1-2 years
- Hospitals, RT centers have tightened their budgets

What can TMP do now to optimize CBCT protocols with the equipment available in RT centers?

CBCT PROTOCOLS OPTIMIZATION

Equipment inventory

Dosimetry

Quantitative assessment of Image Quality

Qualitative assessment of Image Quality

Equipment inventory

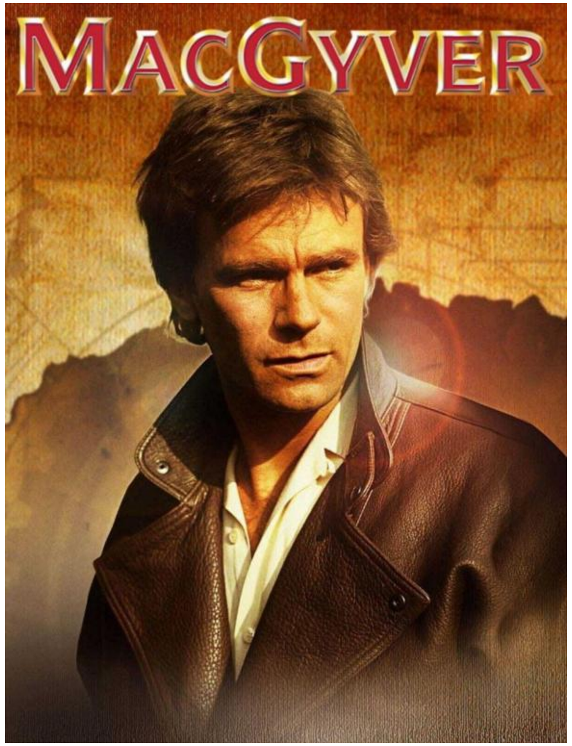
LINACS: 4 VARIAN Truebeams (XI), 1 VARIAN EX series (OBI)

- Default VARIAN CBCT protocols: good image quality, but not optimized
- Can we optimize our CBCT protocols?

Equipment available:

- Various ionization chambers + electrometers
- Solid/plastic water phantoms
- Anthropomorphic phantoms
- Winston-Lutz pointer holder
- Tape (!)
- …

… and some inspiration



Optimization of default Truebeam CBCT protocols

VARIAN Truebeam 3394 (V2.7)

- XI system
- Ti + Half/Full fan filters
- CBCT reconstruction algorithm
  - FDK with variable # frames

VARIAN default CBCT protocols

Protocol name	Filter	Scan length (cm)	FOV (cm)	kV	No. of frames	mA	ms	Total Exposure (mAs)	Angular range (deg)	*CBDI (mGy)	*$CBDI_w$ (mGy)	K_air (mGy)
head	Full Fan	21.4	28	100	500	15	20	150	200	3.3	3.2	5.3
thorax	Half Fan	21.4	49.4	125	900	15	20	270	360	3.7	5.0	17.8
pelvis	Half Fan	21.4	49.4	125	900	60	20	1080	360	13.5	18.1	64.3
Pelvis large	Half Fan	21.4	49.4	140	900	75	25	1688	360	29.1	38.3	132.0
spotlight	Full Fan	21.4	28	125	500	60	25	750	200	30.6	29.7	44.7

**CBDI values are from measurements performed in CTDI phantom.*

Imaging parameters of each protocol were modified in service mode to reduce the total exposure (imaging dose) via:

1. Reducing the number of frames used by the built-in FDK algorithm by 27%, 47%, 80%
2. Or reducing single frame exposure by 25%, 50% and 66-75%
3. A combination of both

➢ **Protocol optimization focused on dose (lowering exposure) and image quality**

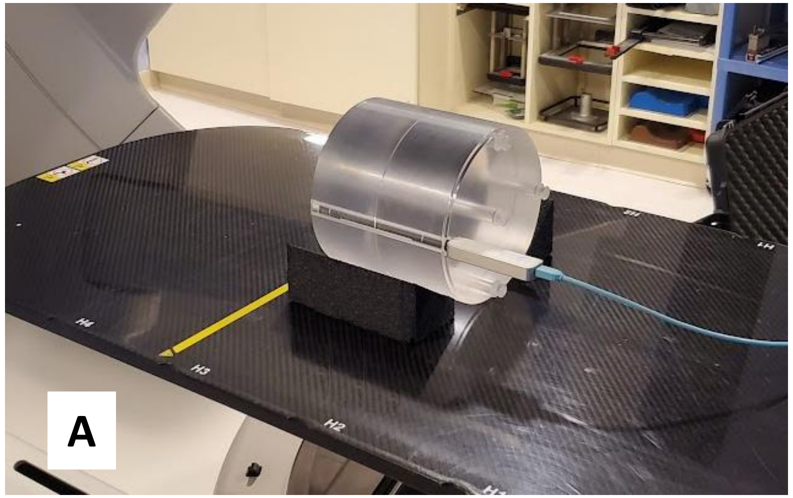
CBCT Dosimetry

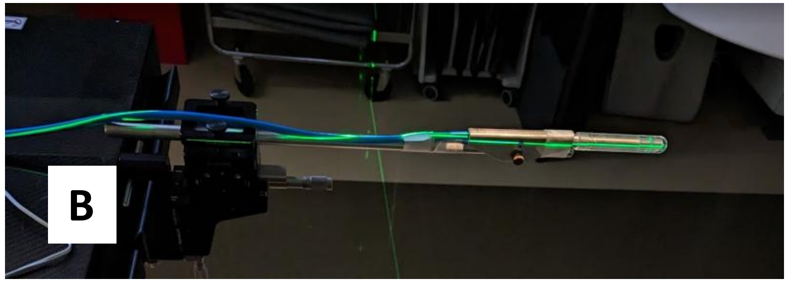
DOSIMETRY FOR EACH DEFAULT AND LOWER DOSE PROTOCOLS

A. CBDI, $CBDI_w$ measurements in CTDI phantom with a RaySafe X2 CT detector system (100 mm)

B. Air Kerma (K_{air}) in free air measurements with a 0.6 cc calibrated* Farmer chamber placed at isocenter

- Pre-requisites:
  1. HVL determination of kV beams for beam quality
  2. 3 points calibration at UW-ADCL for appropriate beam quality
  3. Interpolate for N_k





In air measurement	Beam Quality	HVL1 (mmAl)	Air Kerma Cal. Coeff. (Gy/C)	Exposure Cal. Coeff. (R/C)	Filters (mm)
10cm x 10cm square field 100 cm SSD	UW150-M	10.1	**4.807E+07**	5.49E+09	2.83 Al + 0.28 Cu
	UW120-M	6.77	**4.814E+07**	5.50E+09	3.0 Al + 0.1 Cu
	UW100-M	4.98	**4.797E+07**	5.48E+09	4.77 Al

UW-ADCL calibration data

HVL measurements*				
Protocol	**mm AL**	**Tube kV**	**Filters**	
Head	7.54	100 kV	Ti	Full Fan
Pelvis Thorax Spotlight	8.35	125 kV	Ti	Half Fan
Large Pelvis	8.93	140 kV	Ti	Half Fan

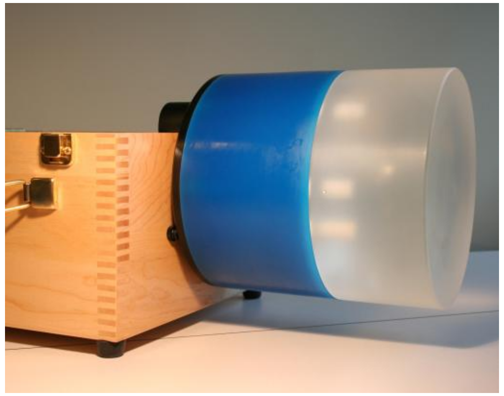
****Performed with RaySafe R/F sensor***

Calibration not necessary for relative measurements

Quantitative assessment of Image quality (IQ)

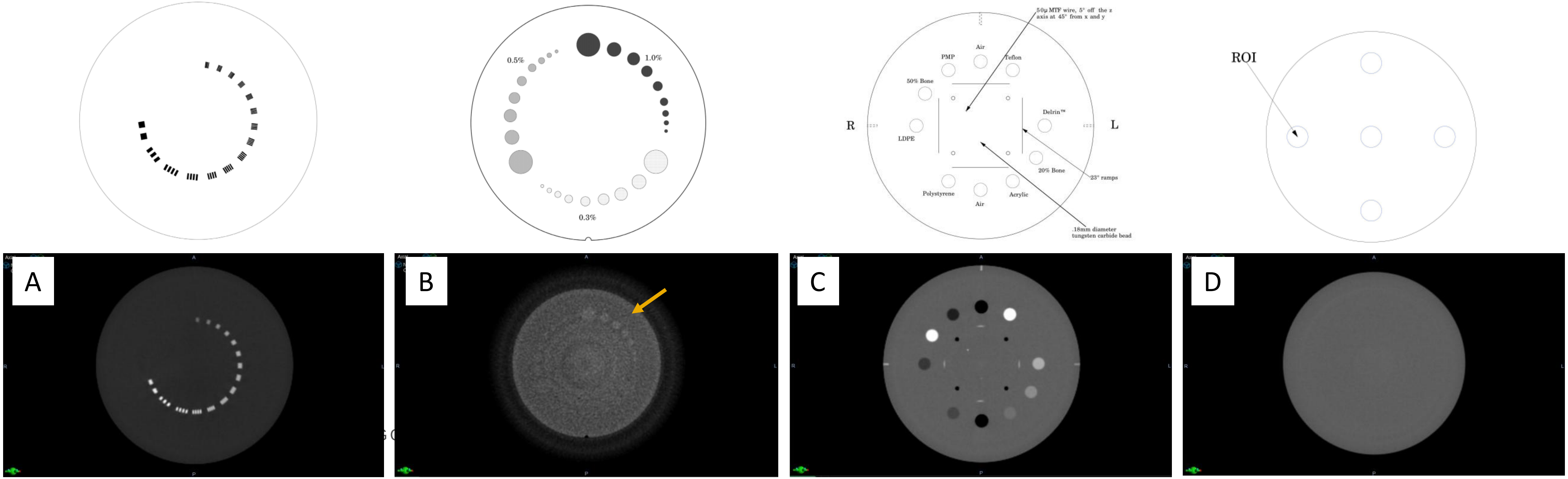
BASED ON MONTHLY QA PROCEDURE (AAPM TG-142) WITH A CATPHAN 604

Catphan 604



- Automated image analysis performed with in-house application based on *Pylinac* library
- Results saved as .txt file and PDF report
- IQ evaluated for decreasing output (dose) against default protocols values

Example monthly QA results for (A) high contrast resolution, (B) low contrast resolution, (C) sensitometry, and (D) Uniformity modules for the default PELVIS protocol.



Quantitative Image Quality Metrics

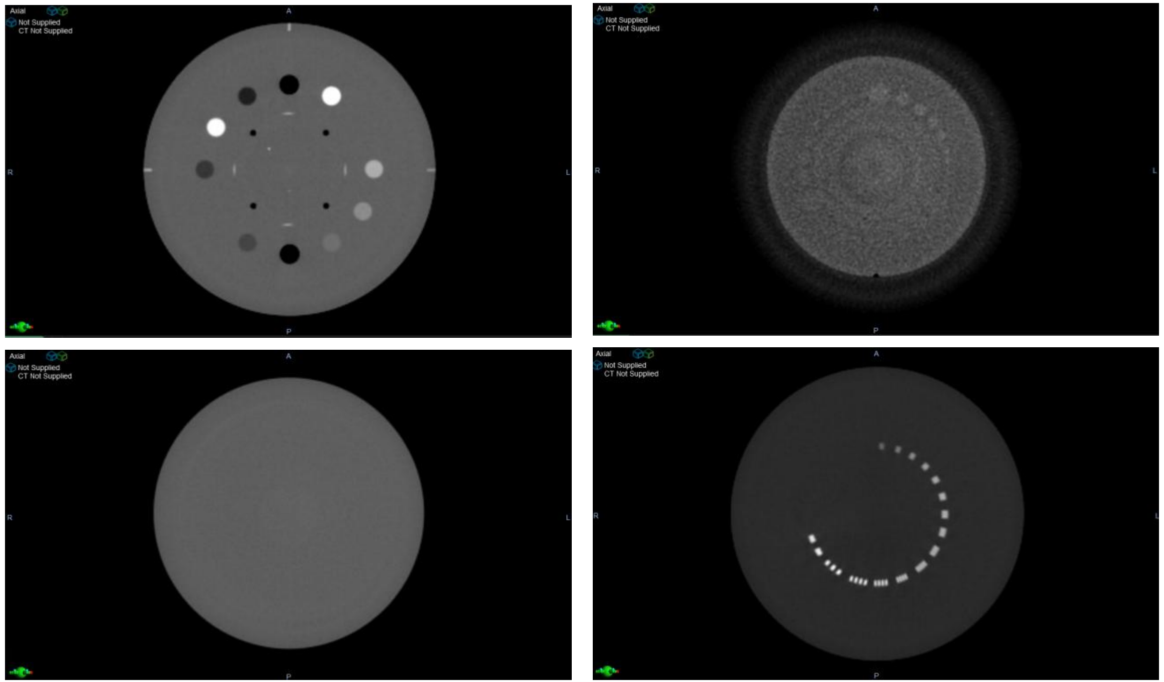
- Hounsfield Units (HU) constancy and uniformity: +/- 40 HU from baseline
  - *Baseline values: default protocols*
- Low contrast visibility (*pylinac*)

ROI size

$$Visibility\ (I) = Contrast(I) * \frac{\sqrt{\pi * I_{radius}^2}}{I_{std}}$$

noise

- High contrast resolution (MTF)
  - Comparison of relative MTF curves
  - MTF50: effective resolution
  - MTF10: limiting resolution
  - Visual detection of line pair separation
- Spatial integrity
  - Distance between hole centers
  - Slice thickness with 23° ramp

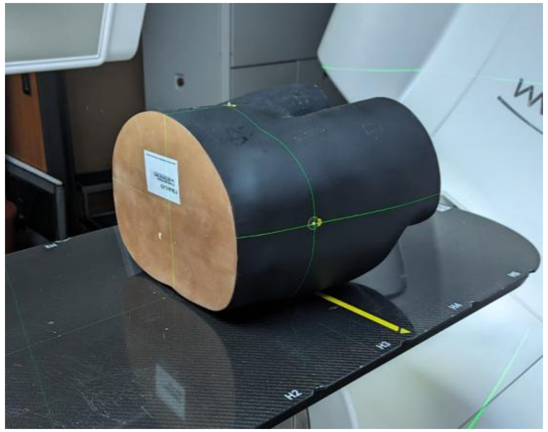


Quantitative Image Quality Metrics

QUALITATIVE IQ WAS ASSESSED FOR CLINICAL USE WITH ANTHROPOMORPHIC PHANTOMS

STEEV head phantom (CIRS)

Thorax phantom (RDS)

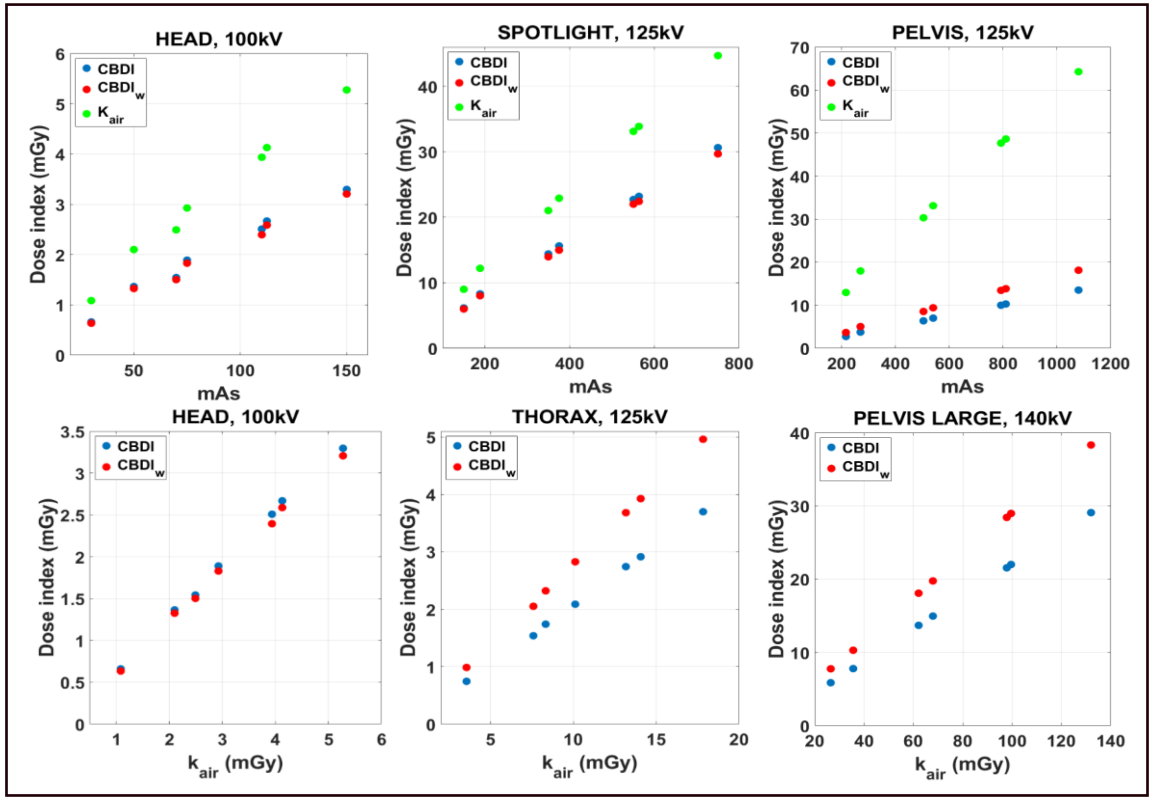


Pelvic phantom (Brainlab)

Results: Dosimetry

52 PROTOCOLS WERE EVALUATED (43 + 9 PEDS)

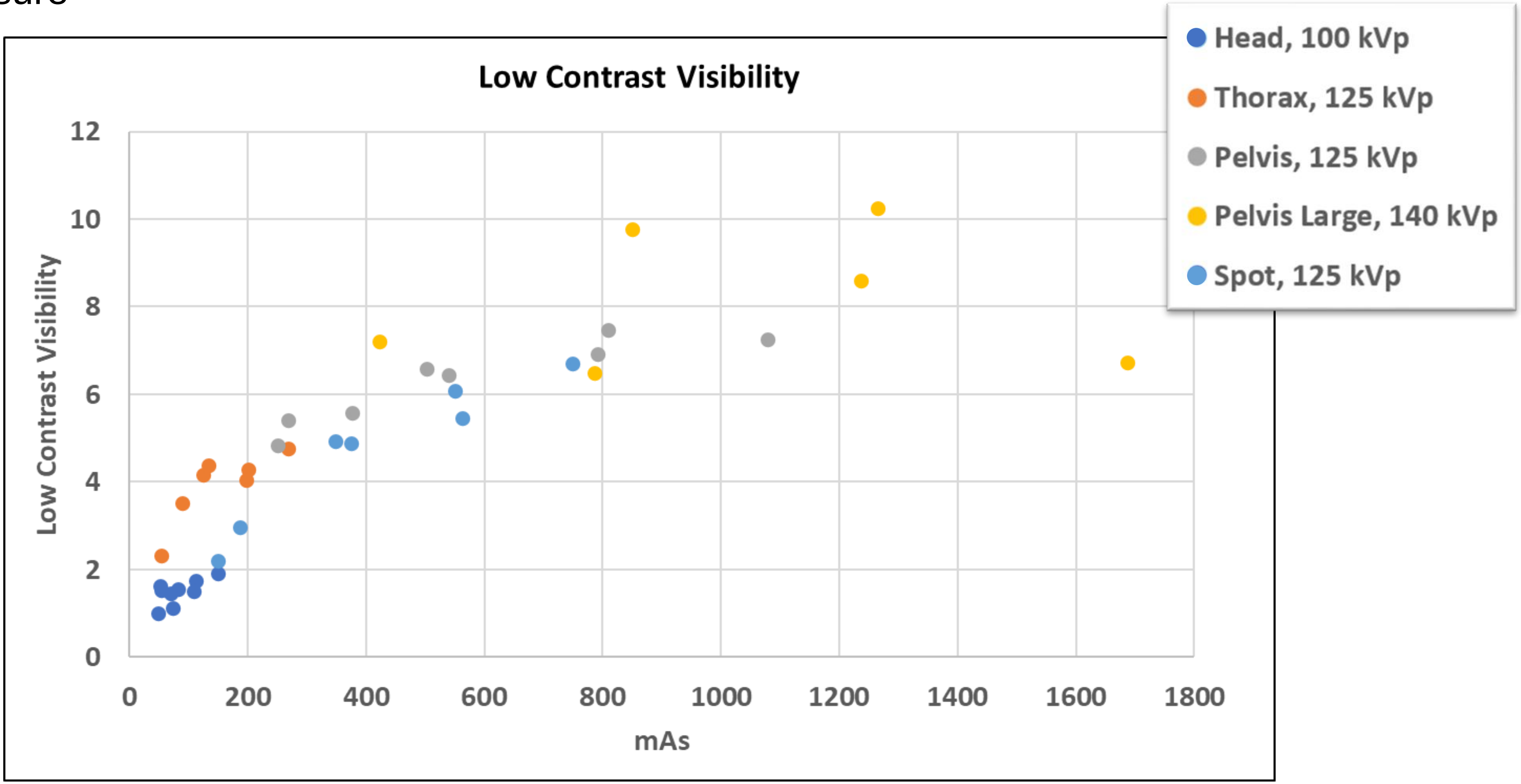
- Linear relationships between exposure, CBDI and $CBDI_w$ doses indices, and K_{air} were established for all protocols
- Conversion coefficients from CBDI and $CBDI_w$ to K_{air} can be used to compare XRS output with other CBCT protocols on other XI systems
- In a relative measurement setting, CBDI, $CBDI_w$, K_{air} can be determined by exposure ratios



Protocol name	CBDI (mGy/mAs)	$CBDI_w$ (mGy/mAs)	K_air (mGy/mAs)	CBDI / K_air	$CBDI_w$ / K_air
head	0.022	0.021	0.034	0.633	0.614
thorax	0.013	0.018	0.063	0.208	0.280
pelvis	0.012	0.017	0.059	0.211	0.283
Pelvis large	0.017	0.022	0.077	0.221	0.290
spotlight	0.040	0.039	0.059	0.687	0.665

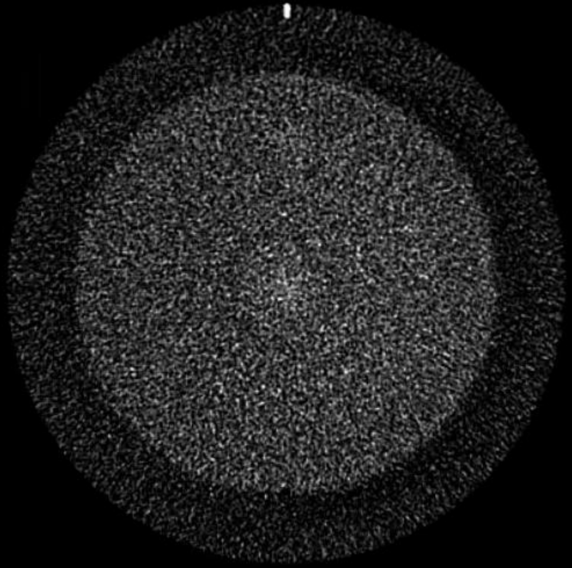
Results: Low contrast visibility

- Low Contrast Visibility decreases with exposure and beam quality
- Head, Spotlight, Thorax most affected by a reduction in exposure/dose due to high correlation and high sensitivity to exposure

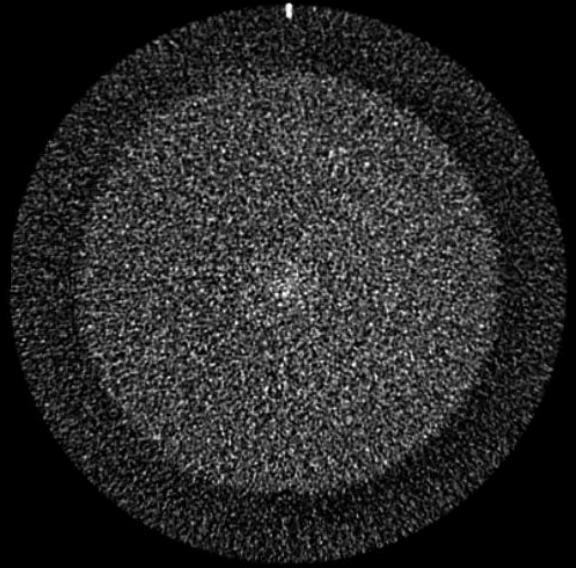


HEAD low contrast visibility module

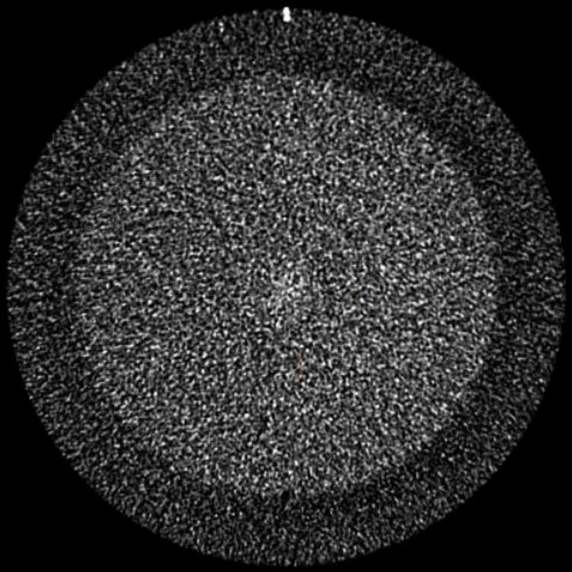
DEFAULT



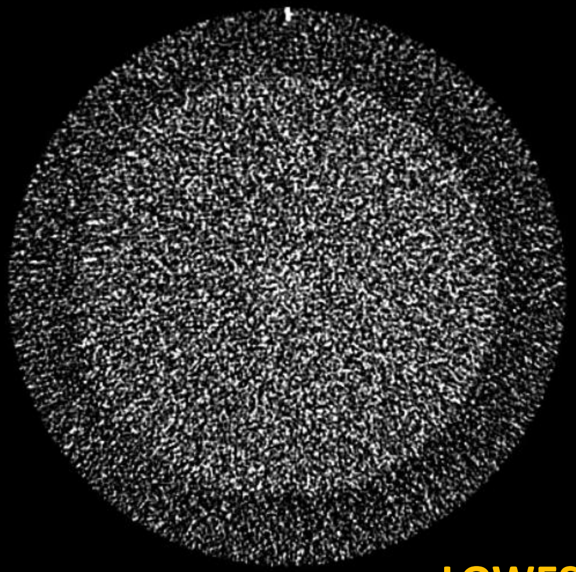
500 projections
150 mAs
CTDI: 3.3 mGy
A_k: 5.3 mGy



367 projections
110 mAs
CTDI: 2.5 mGy
A_k: 3.9 mGy

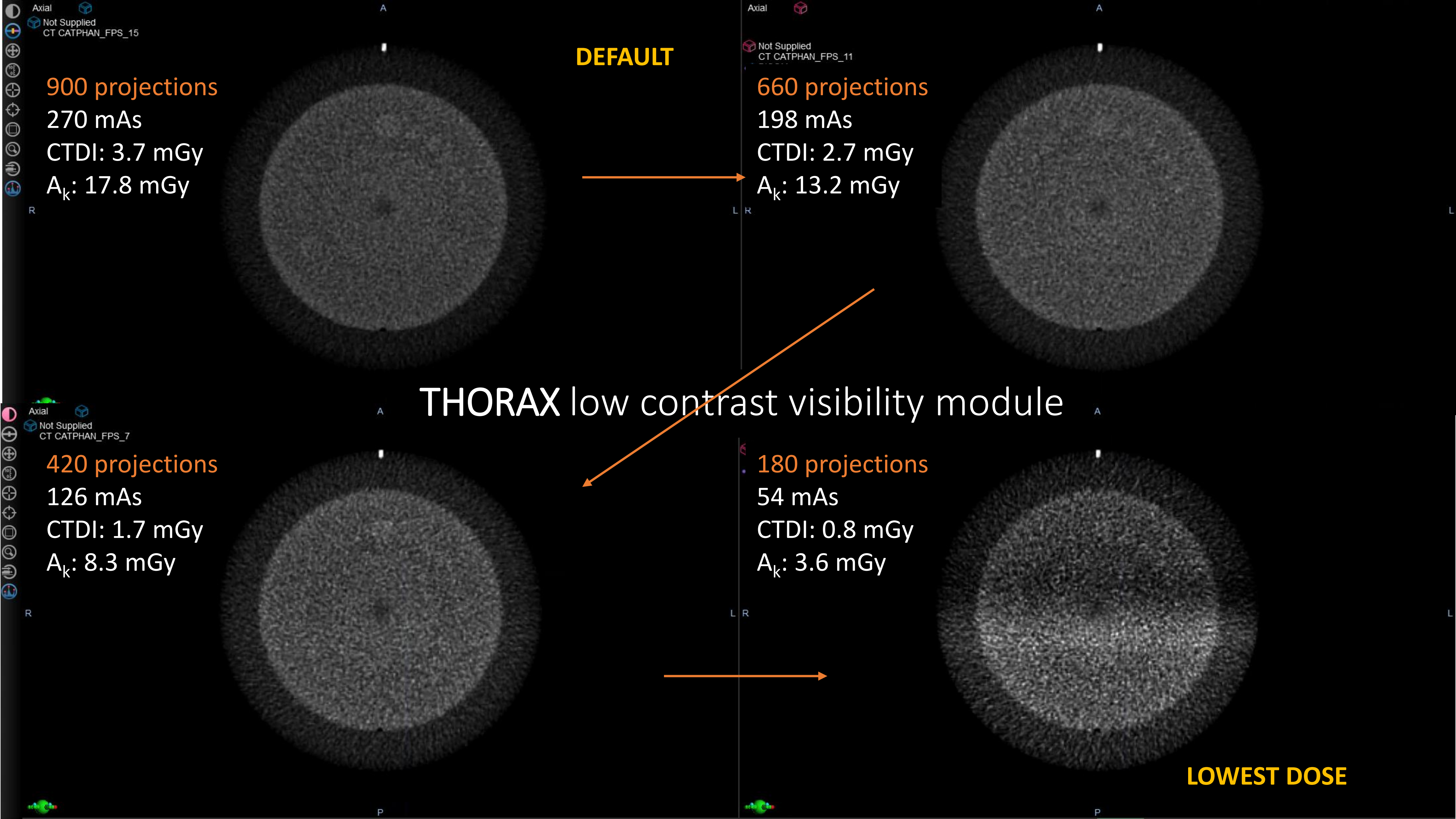


233 projections
70 mAs
CTDI: 1.5 mGy
A_k: 2.5 mGy

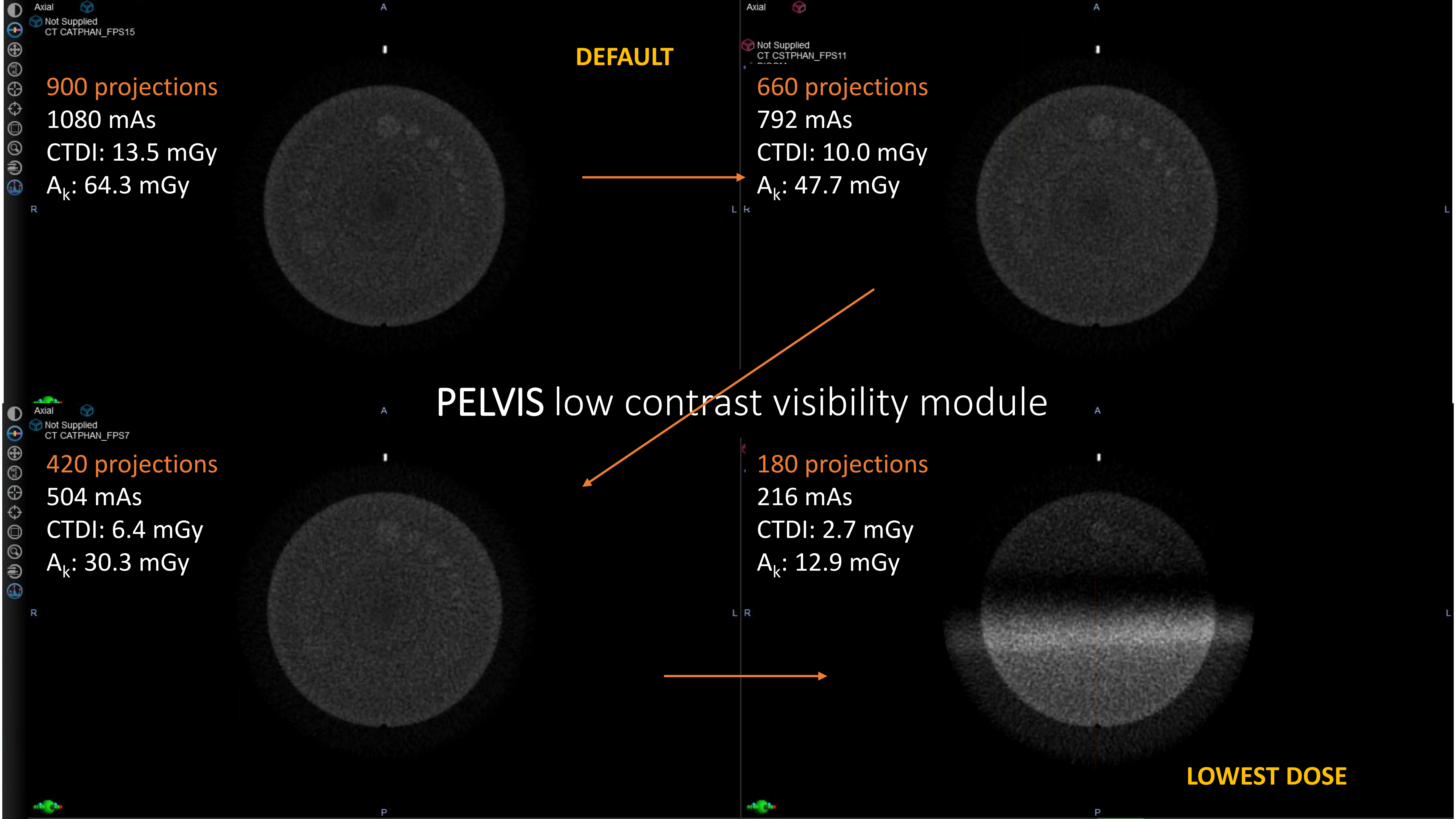


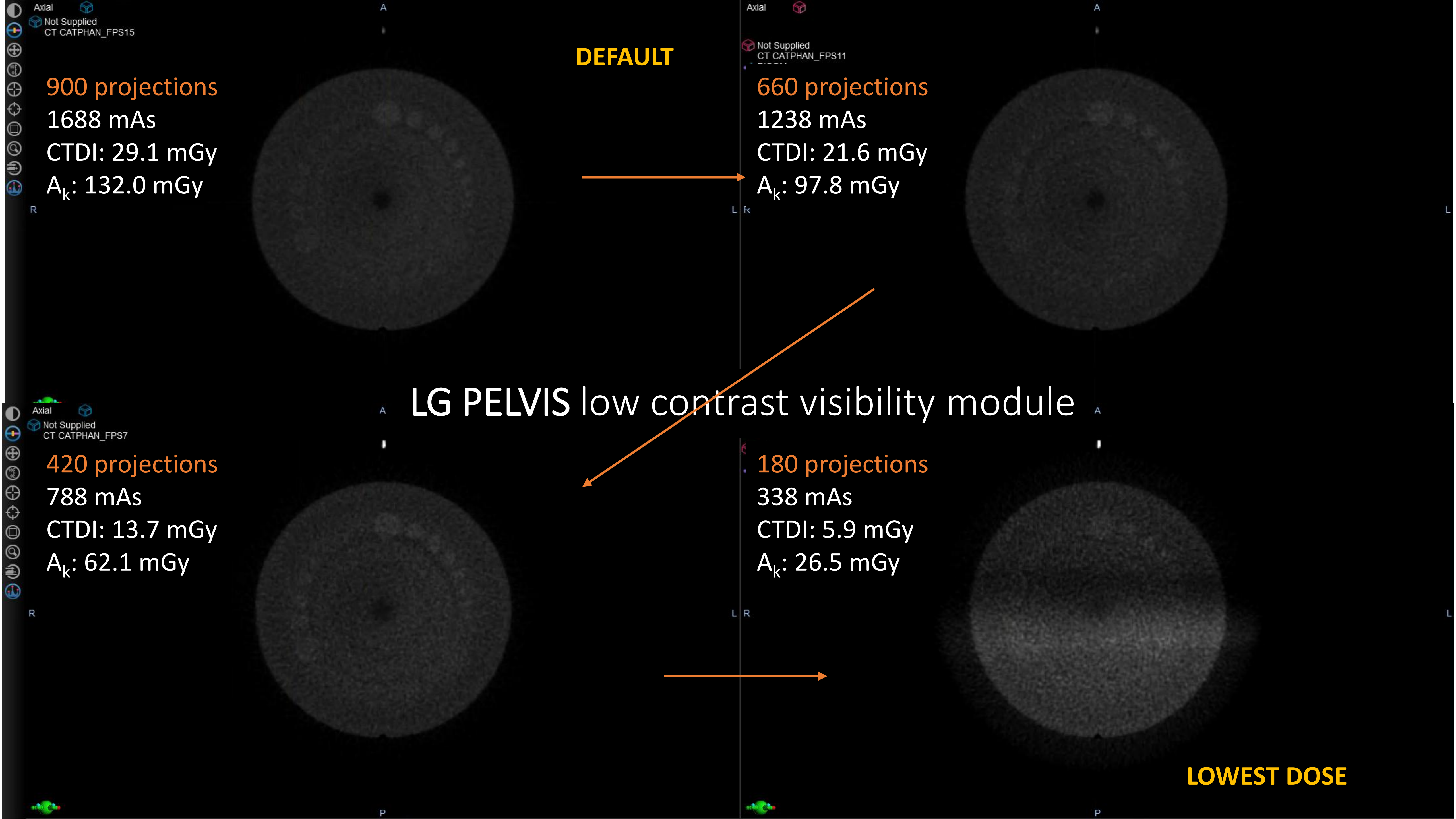
100 projections
30 mAs
CTDI: 0.7 mGy
A_k: 1.1 mGy

LOWEST DOSE



THORAX low contrast visibility module
DEFAULT
Axial
Not Supplied
CT CATPHAN_FPS_15
900 projections
270 mAs
CTDI: 3.7 mGy
A_k: 17.8 mGy
Axial
Not Supplied
CT CATPHAN_FPS_11
660 projections
198 mAs
CTDI: 2.7 mGy
A_k: 13.2 mGy
Axial
Not Supplied
CT CATPHAN_FPS_7
420 projections
126 mAs
CTDI: 1.7 mGy
A_k: 8.3 mGy
180 projections
54 mAs
CTDI: 0.8 mGy
A_k: 3.6 mGy
LOWEST DOSE

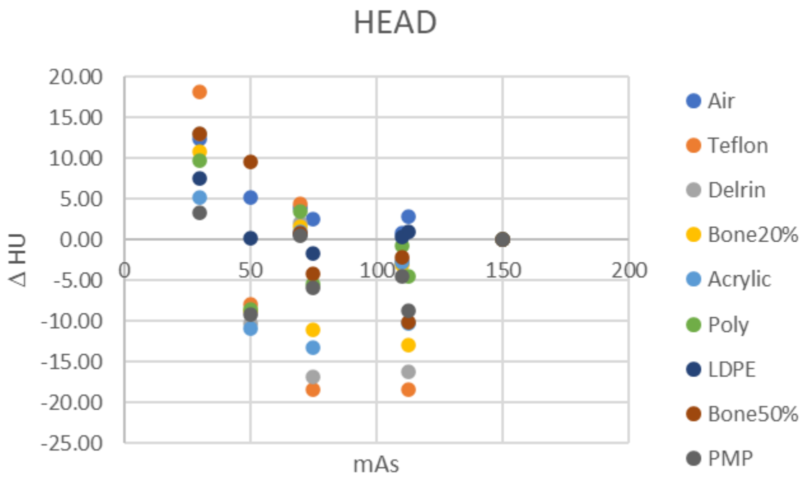

PELVIS low contrast visibility module
Axial
Not Supplied
CT CATPHAN_FPS15
DEFAULT
900 projections
1080 mAs
CTDI: 13.5 mGy
A$_k$: 64.3 mGy
Axial
Not Supplied
CT CSTPHAN_FPS11
660 projections
792 mAs
CTDI: 10.0 mGy
A$_k$: 47.7 mGy
Axial
Not Supplied
CT CATPHAN_FPS7
420 projections
504 mAs
CTDI: 6.4 mGy
A$_k$: 30.3 mGy
180 projections
216 mAs
CTDI: 2.7 mGy
A$_k$: 12.9 mGy
LOWEST DOSE

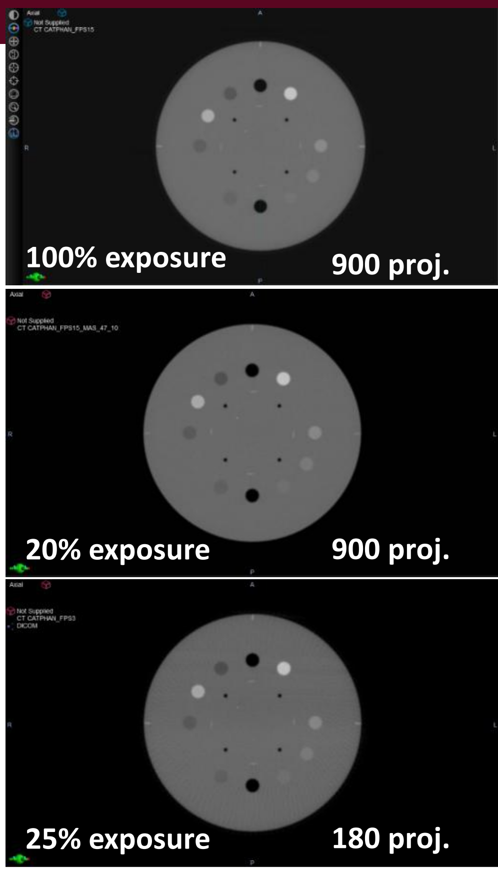


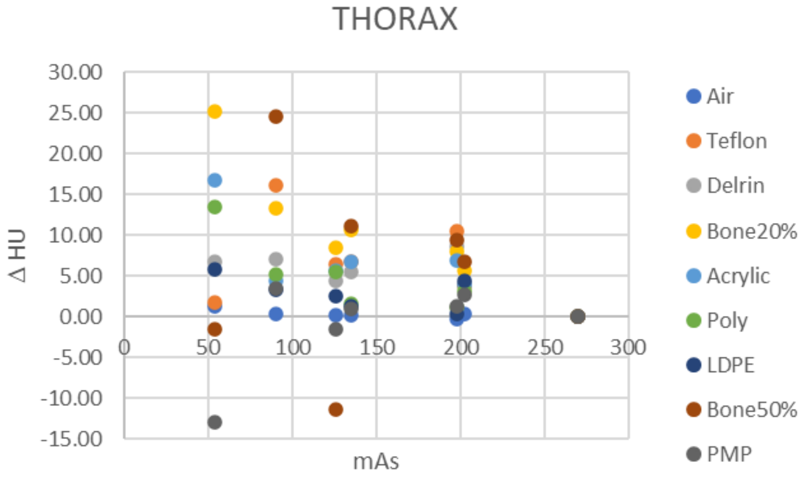
LG PELVIS low contrast visibility module
DEFAULT
Axial
Not Supplied
CT CATPHAN_FPS15
900 projections
1688 mAs
CTDI: 29.1 mGy
A_k: 132.0 mGy
Axial
Not Supplied
CT CATPHAN_FPS11
660 projections
1238 mAs
CTDI: 21.6 mGy
A_k: 97.8 mGy
Axial
Not Supplied
CT CATPHAN_FPS7
420 projections
788 mAs
CTDI: 13.7 mGy
A_k: 62.1 mGy
180 projections
338 mAs
CTDI: 5.9 mGy
A_k: 26.5 mGy
LOWEST DOSE

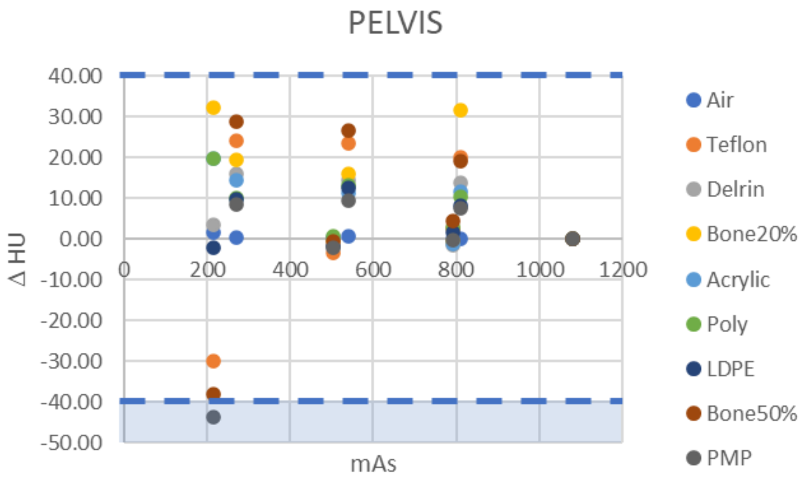
Results: HU linearity and conformity

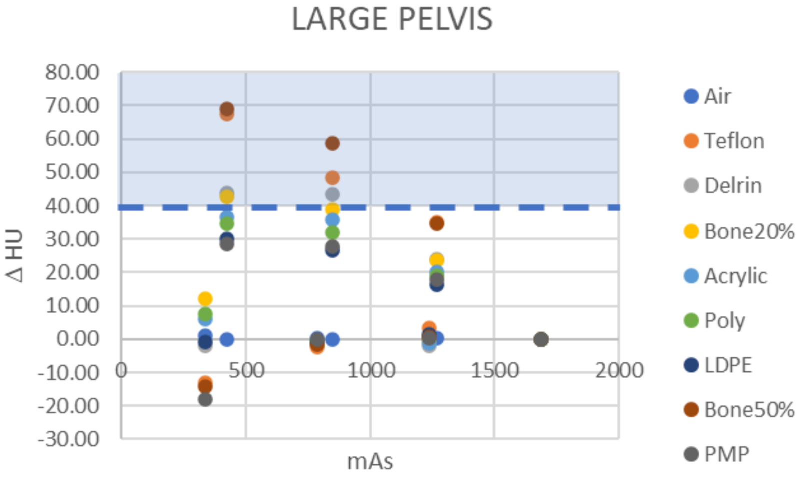
HU constancy and uniformity remained stable (<40HU from baseline) for all modified protocols except for the Large Pelvis below the 50% single frame exposure level.







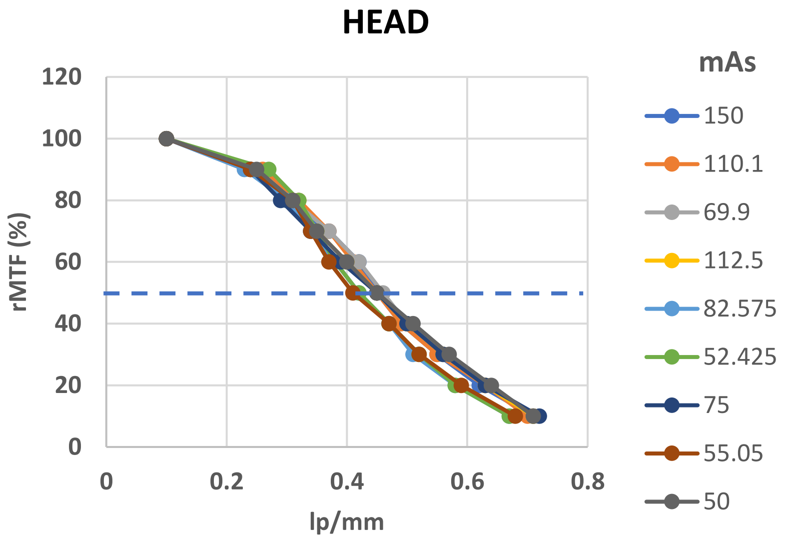


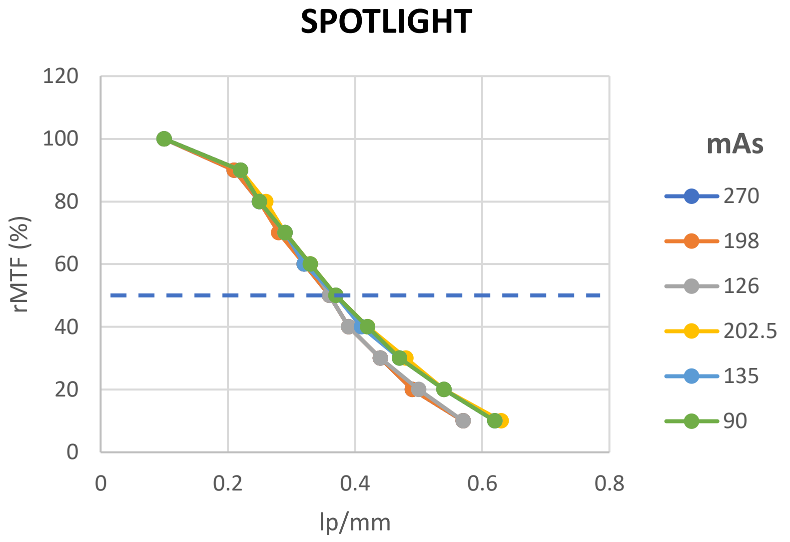


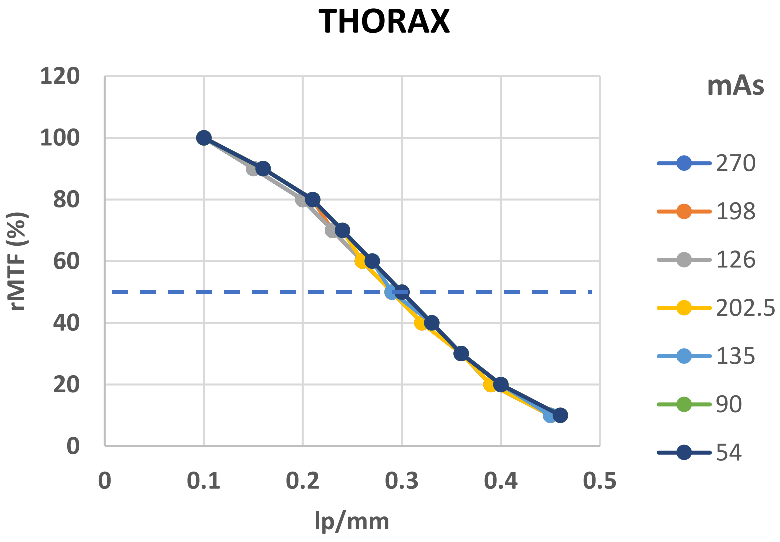
Results: high contrast resolution

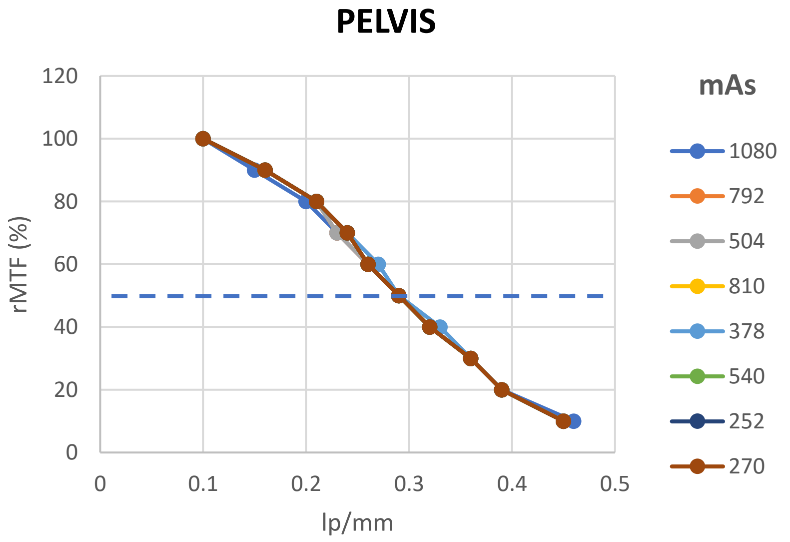
RELATIVE MTF (RMTF)

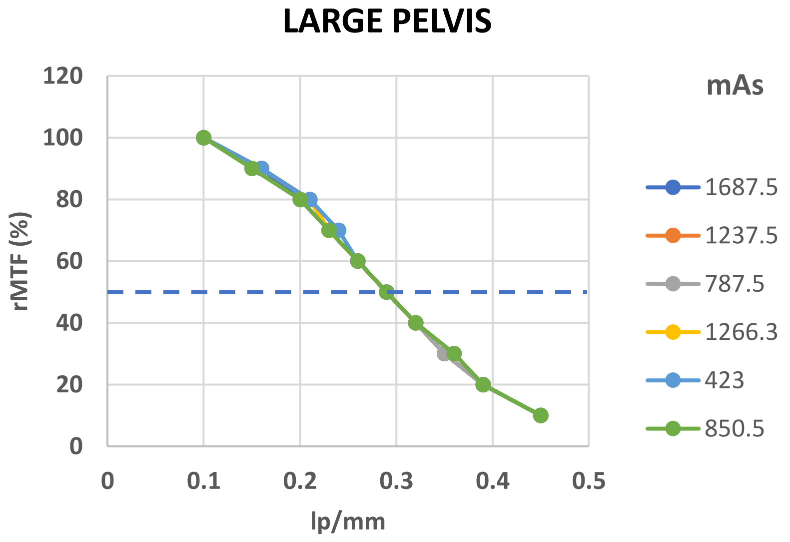
No correlation between high contrast resolution and reduction in exposure.







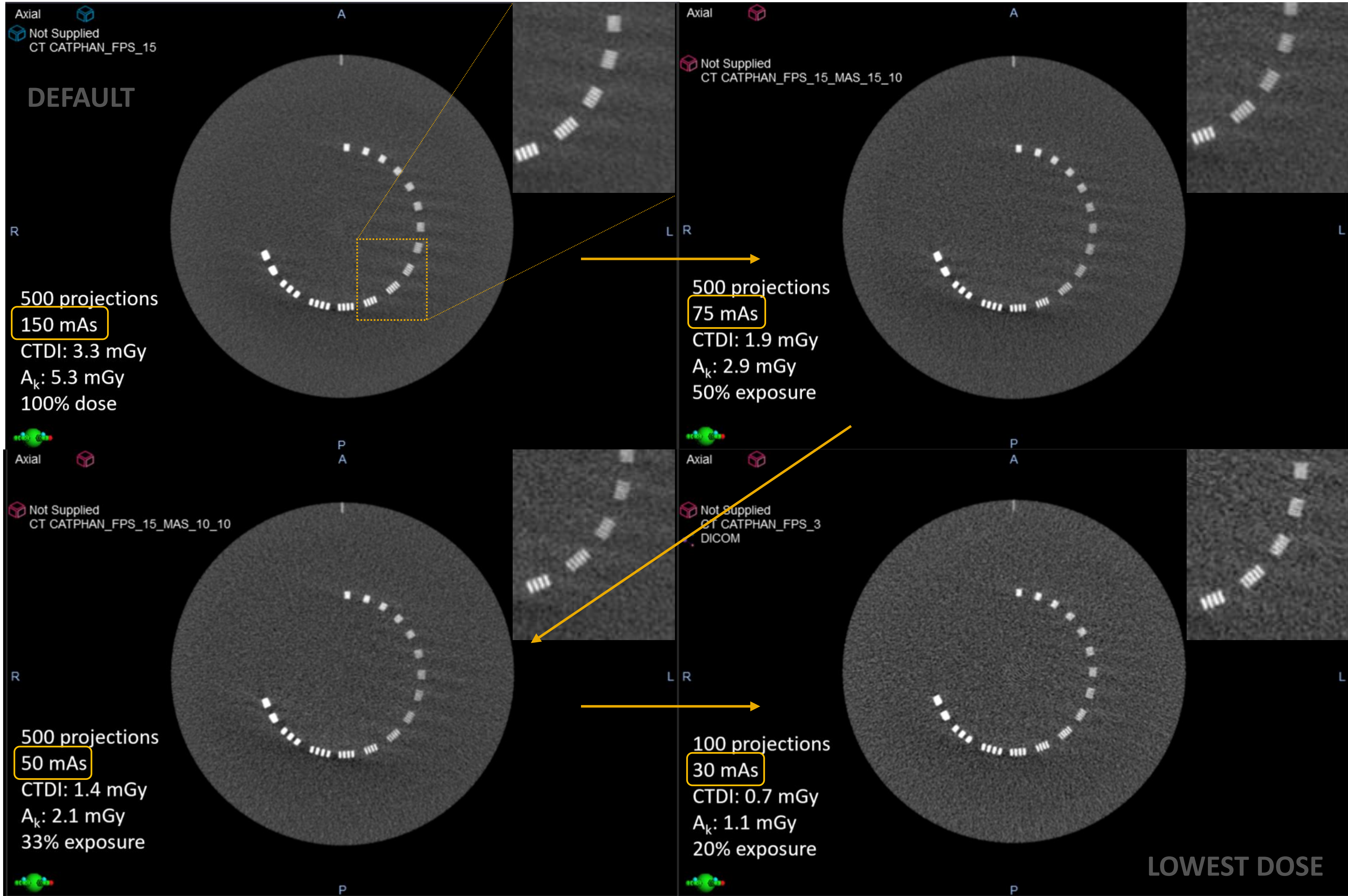




Results: High contrast resolution for HEAD protocol

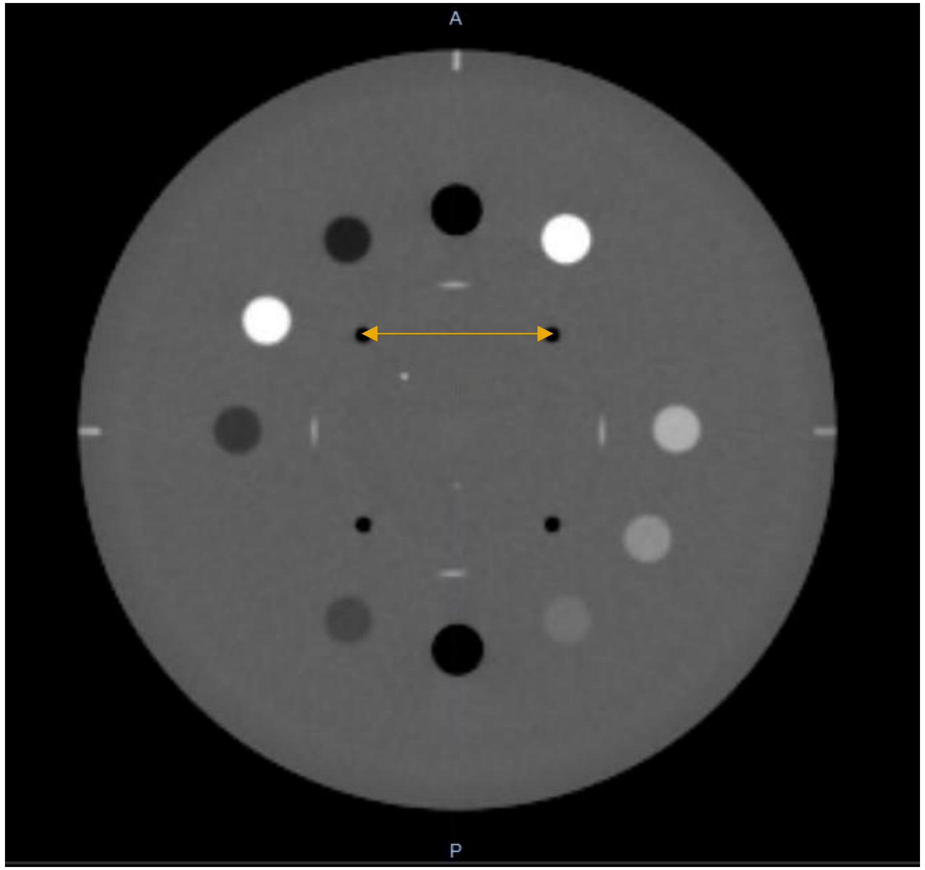
Dose reduction achieved by lowering the single frame exposure.

No visible change besides increase in noise.



Results: spatial integrity

- Spatial integrity metrics unaffected by changes in protocol parameters
- In-plane distances and slice thickness measurements remaining well within their respective tolerance ranges
- Accuracy of patient set-up positioning will be maintained by using lower dose CBCT protocols



Results: Statistical analysis

Pearson correlation (R) with statistical significance p <0.05

- $|R| \geq 0.7$: Strong correlation
- $0.5 \leq |R| < 0.7$: Moderate correlation
- $0.3 \leq |R| < 0.5$: Weak correlation
- $|R| < 0.3$: No correlation

Visibility and Uniformity: Strong/Moderate correlations (except for LG Pelvis), large changes → impact from dose reduction

High Contrast resolution and Spatial Integrity: Various correlations, small changes → unaffected by dose reduction

			Spatial integrity		High contrast resolution	
PROTOCOL	**Visibility**	**Uniformity**	**Line average**	**Slice thickness**	**MTF50**	**MTF10**
HEAD	0.754 *	-0.685 *	0.024	0.663 *	0.515	0.498
PELVIS	0.906 *	-0.665	-0.667	-0.626	0.404	0.417
LG PELVIS	0.093	-0.162	-0.180	0.196	0.548	0.548
THORAX	0.816 *	-0.593	-0.673	0.023	-0.752	-0.500
SPOTLIGHT	0.952 *	-0.008	-0.075	0.078	0.541	-0.093

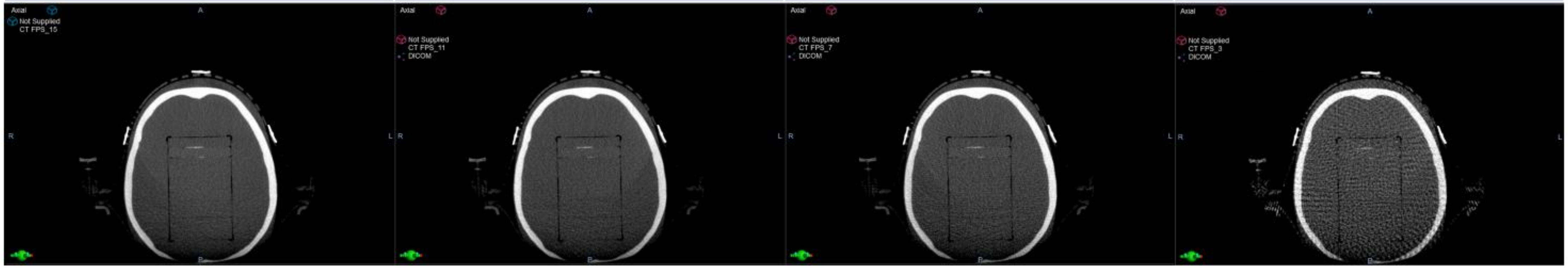
Correlation
Strong
Moderate
Weak
None

* ($p < 0.05$)

Qualitative image assessment: HEAD, 100 kVp

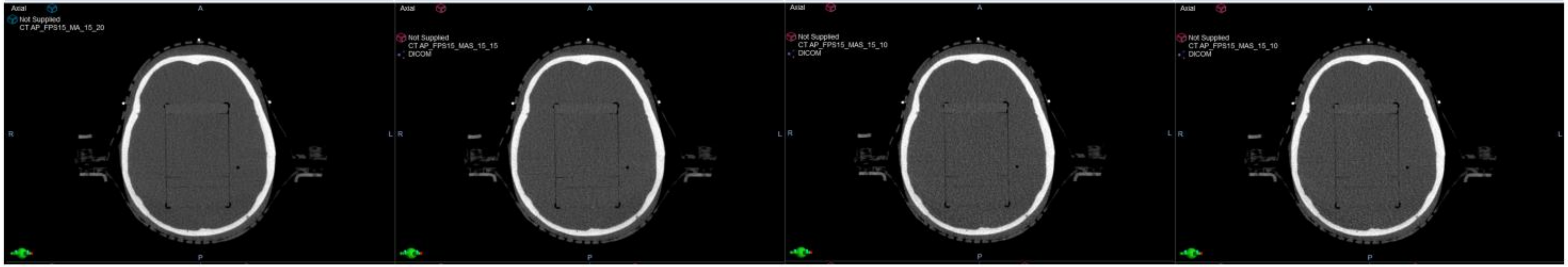
Constant exposure per frame: 15mA, 20 ms & reducing # frames

	500 frames (100%)	367 frames (73%)	233 frames (47%)	100 frames (20%)
CTDI / K_{air}	3.3 / 5.3 (mGy)	2.5 / 3.9 (mGy)	1.5 / 2.5 (mGy)	0.7 / 1.1 (mGy)



Constant # frames : 500 & reducing single frame exposure

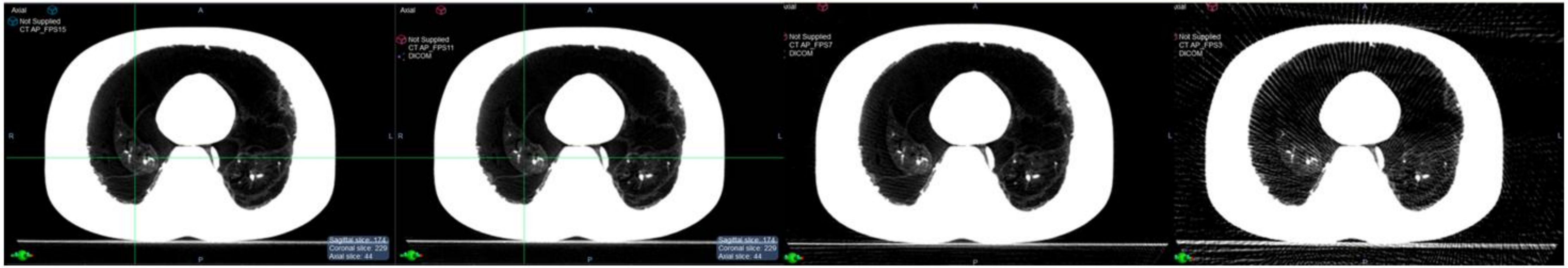
	15 mA, 20 ms (100%)	15 mA, 15 ms (75%)	15 mA, 10 ms (50%)	10 mA, 10 ms (33%)
CTDI / K_{air}	3.3 / 5.3 (mGy)	2.7 / 4.1 (mGy)	1.9 / 2.9 (mGy)	1.4 / 2.1 (mGy)



Qualitative image assessment: THORAX 125 kVp

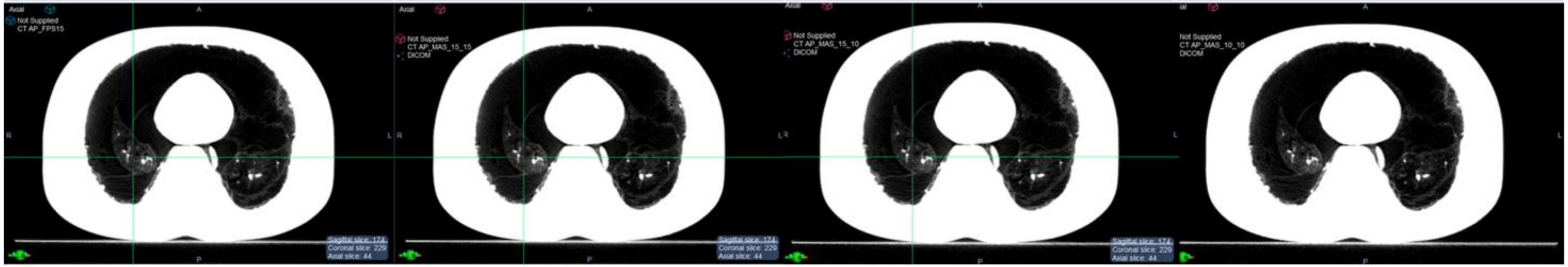
Constant exposure per frame: 15mA, 20 ms & reducing # frames

	900 frames (100%)	660 frames (73%)	420 frames (47%)	180 frames (20%)
CTDI / K_{air}	3.7 / 17.8 (mGy)	2.7 / 13.2 (mGy)	1.7 / 8.3 (mGy)	0.8 / 3.6 (mGy)



Constant # frames : 900 & reducing single frame exposure

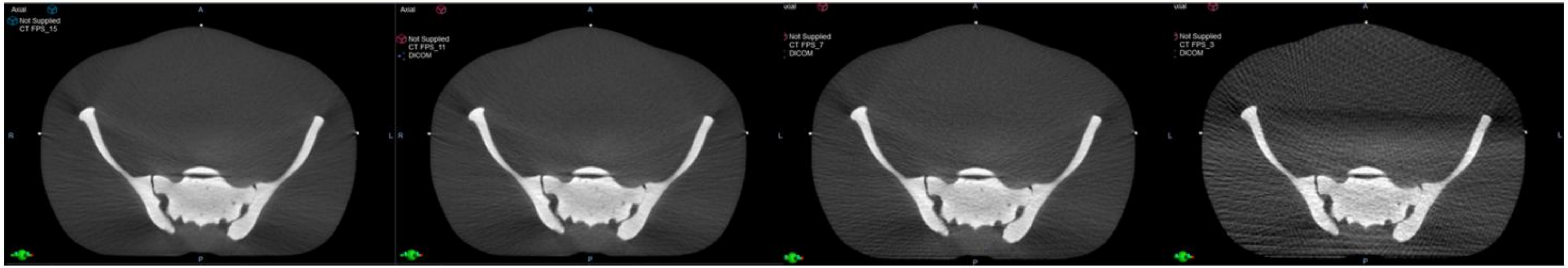
	15 mA, 20 ms (100%)	15 mA, 15 ms (75%)	15 mA, 10 ms (50%)	10 mA, 10 ms (33%)
CTDI / K_{air}	3.7 / 17.8 (mGy)	2.9 / 14.1 (mGy)	2.1 / 10.1 (mGy)	1.5 / 7.6 (mGy)



Qualitative image assessment: PELVIS 125 kVp

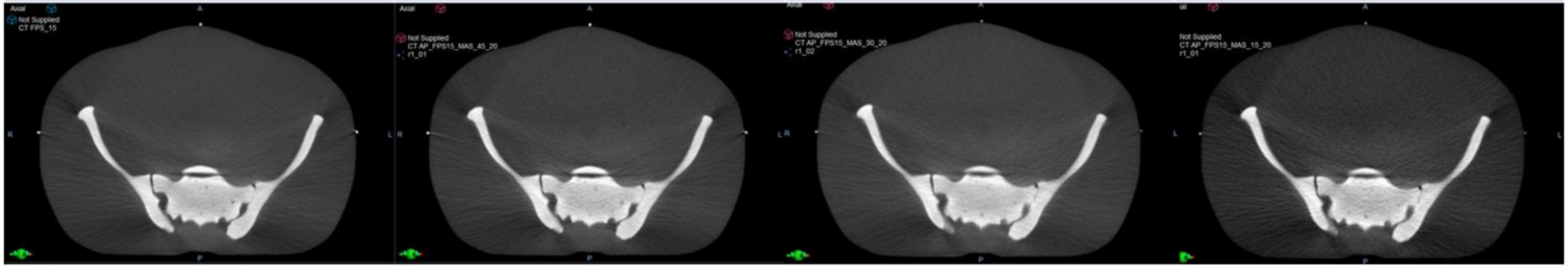
Constant exposure per frame: 60mA, 20 ms & reducing # frames

	900 frames (100%)	660 frames (73%)	420 frames (47%)	180 frames (20%)
CTDI / K_{air}	13.5 / 64.3 (mGy)	10.0 /47.7 (mGy)	6.4 / 30.3 (mGy)	2.7 / 12.9 (mGy)



Constant # frames : 900 & reducing single frame exposure

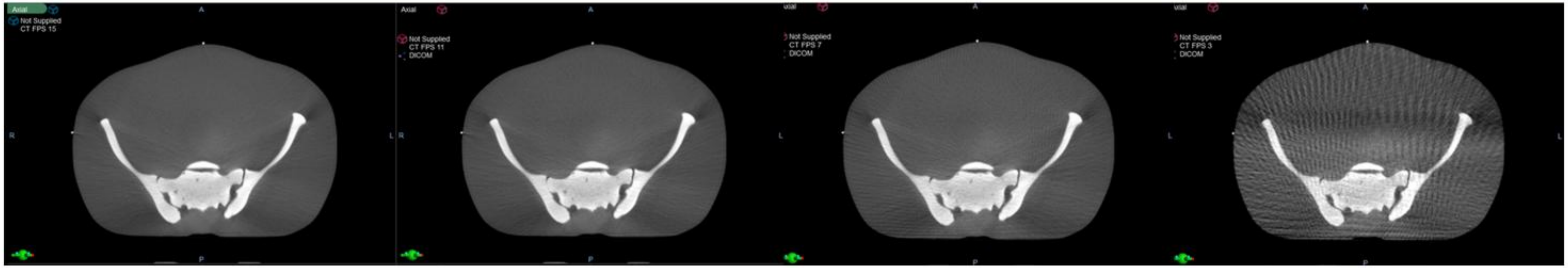
	60 mA, 20 ms (100%)	45 mA, 20 ms (75%)	30 mA, 20 ms (50%)	15 mA, 20 ms (25%)
CTDI / K_{air}	13.5 / 64.3 (mGy)	10.3 / 48.6 (mGy)	7.0 / 33.1 (mGy)	3.7 / 17.9 (mGy)



Qualitative image assessment: LARGE PELVIS 140 kVp

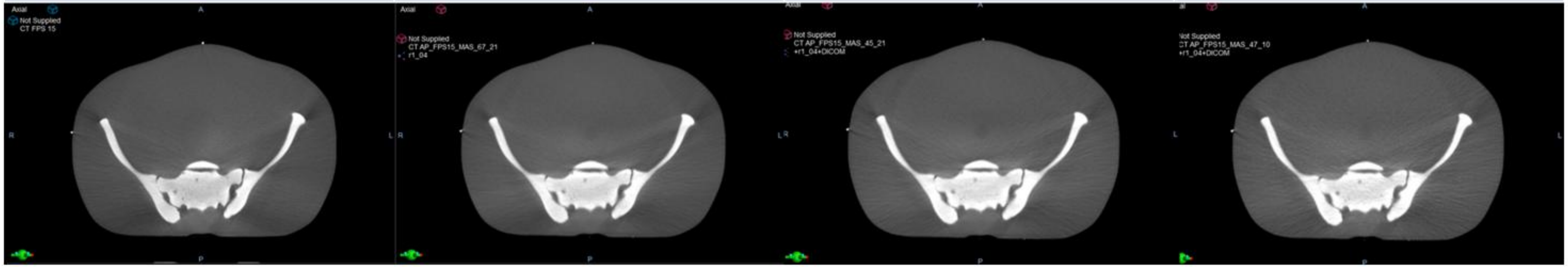
Constant exposure per frame: 75mA, 25 ms & reducing # frames

	900 frames (100%)	660 frames (73%)	420 frames (47%)	180 frames (20%)
CTDI / K_{air}	29.1 / 132.0 (mGy)	21.6 / 97.8 (mGy)	13.7 / 62.1 (mGy)	5.9 / 26.5 (mGy)



Constant # frames : 900 & reducing single frame exposure

	75 mA, 25 ms (100%)	67 mA, 21 ms (75%)	45 mA, 21 ms (50%)	47 mA, 10 ms (25%)
CTDI / K_{air}	29.1 / 132.0 (mGy)	22.0 / 99.6 (mGy)	17.8 / 35.6 (mGy)	15.0 / 67.9 (mGy)

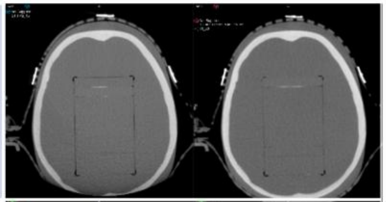
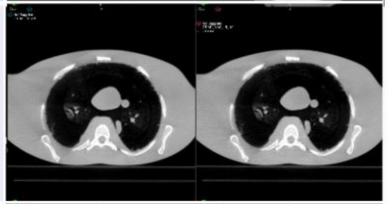
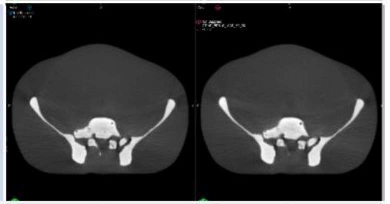
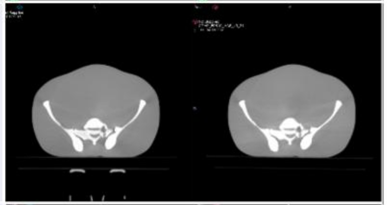
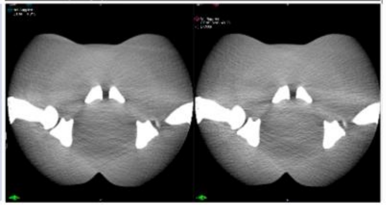


Implementation of low dose CBCT protocols

GOALS

1. Maintain clinically appropriate IQ
2. Lower dose
3. Limit artifacts

Lowering imaging dose by 80%-50% retained clinically acceptable imaging quality with minimal interference from aliasing artifacts (low frames) or noise (low

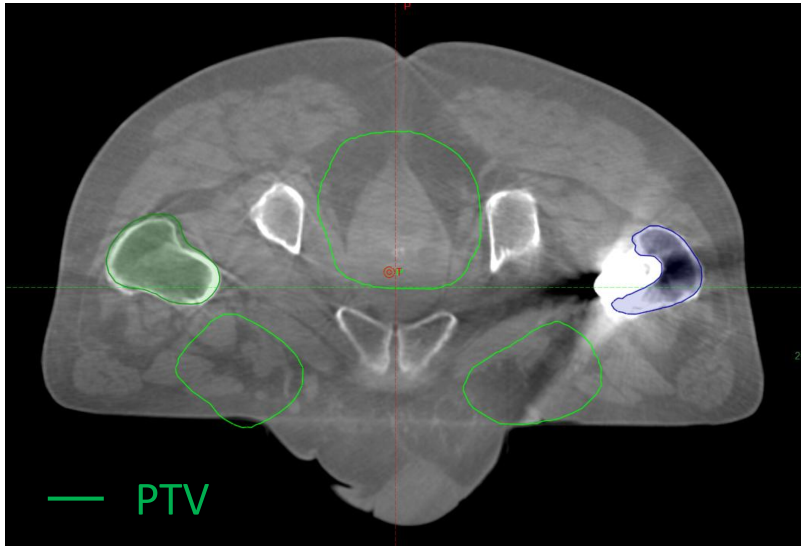
Protocol	Exposure (mAs)	Projections	K_{air} (mGy)	Dose relative to default	Example images Default Optimized
HEAD	112.5	500	4.13	78%	
THORAX	135	900	11.11	57%	
PELVIS	540	900	33.11	52%	
LARGE PELVIS	850.5	900	67.90	51%	
SPOTLIGHT	563.5	500	33.87	76%	

CLINICAL EXAMPLES

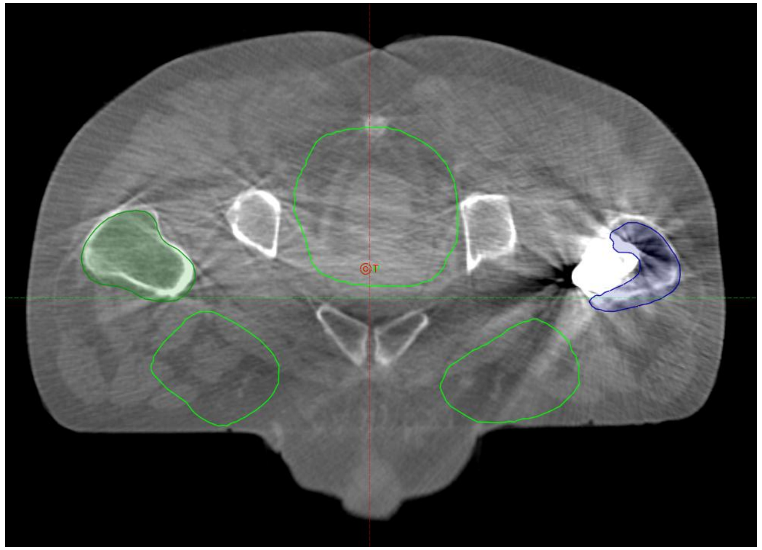
- 62 years old male with rectum cancer
- Rectum + LNs: 45 Gy, 1.8 Gy x 25 fx
- Rectum Boost: 5.4 Gy, 1.8 Gy x 3 fx
- CBCT daily
- Left hip prosthesis

48% dose reduction

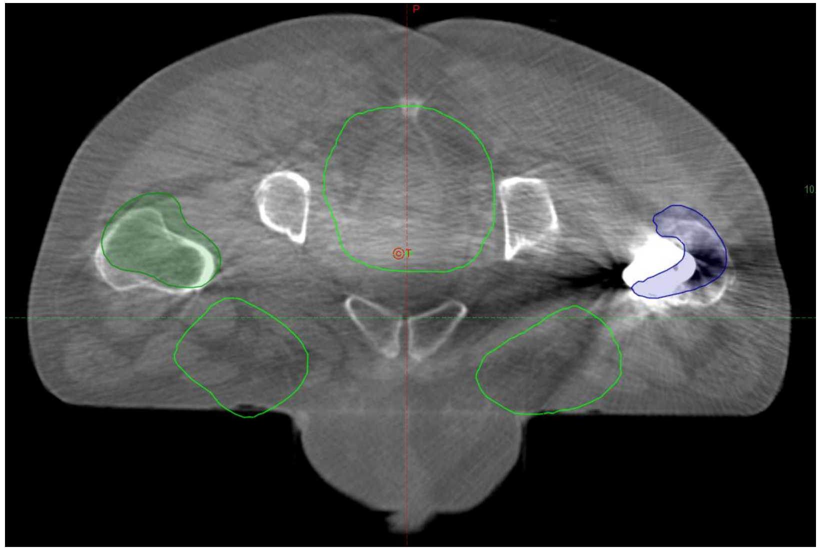
PELVIS default protocol



PELVIS Low Dose



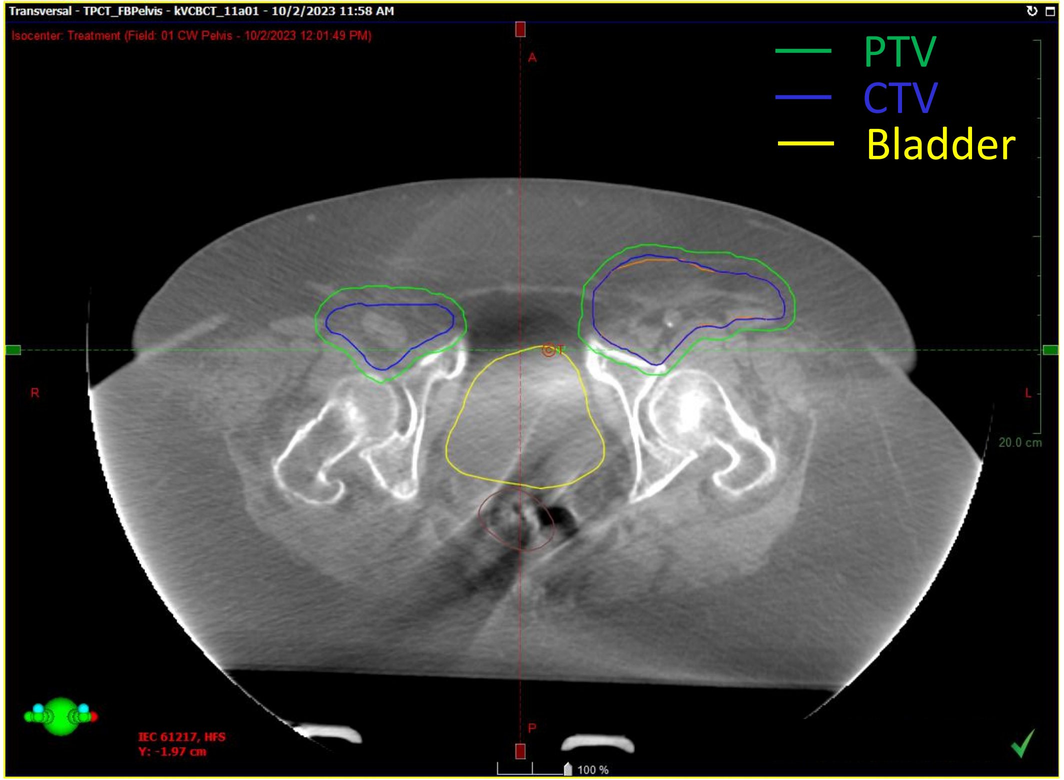
PELVIS Low Dose



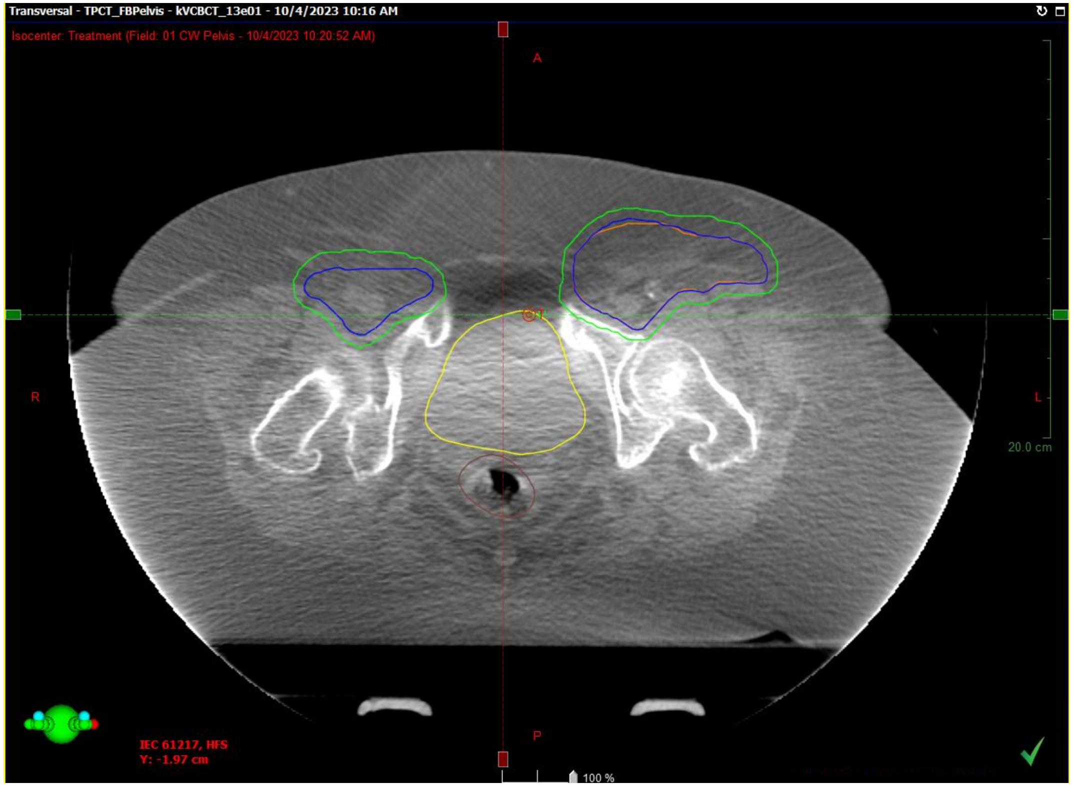
- 76 years old female with recurrent vulvar cancer
- Chemo+RT: 45/59.4/66 Gy volumes in 33 fx
- CBCT daily

49% dose reduction

LARGE_PELVIS



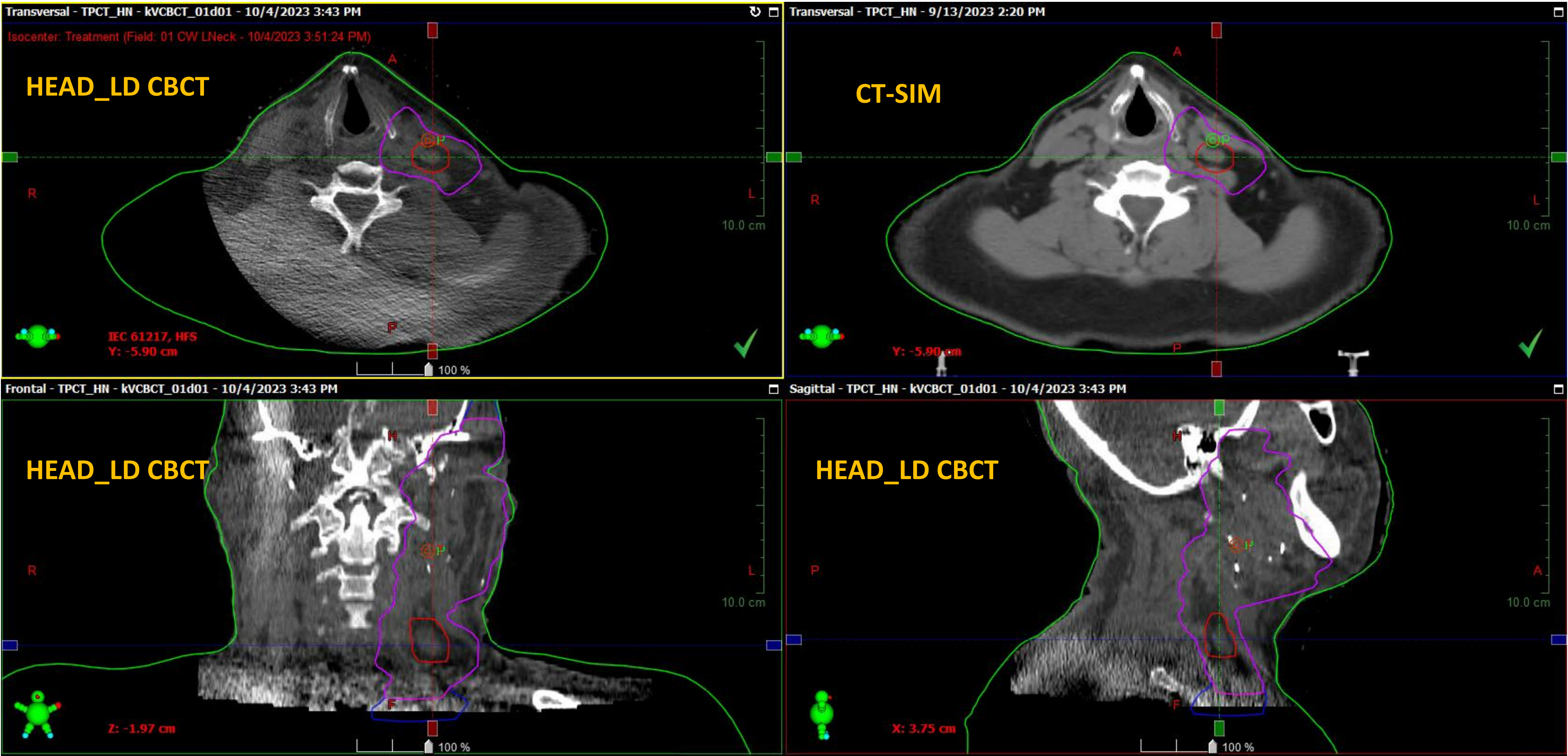
LARGE_PELVIS_LD



- 67 years old male left parotid carcinoma
- 54/60/66 Gy SIB

- Daily CBCT
- HEAD_LD protocol

22% dose reduction



CNS physician request: Implementation of Pediatric patient tailored Head CBCT protocol

- 11 years old boy with metastatic neuroblastoma in bilateral mastoid region
  - Multiple courses of palliative RT
  - 21.6 Gy, 1.8 Gy x 12
  - CBCT daily

- Pediatric low dose HEAD protocol implementation
  1. Default HEAD 100 kVp → 80 kVp: measured relative Ak
  2. Phantom study for IQ with lower exposure /dose reviewed with CNS physician
  3. Set 2 protocols:
     - HEAD_PEDS: 500 frames, 75% dose reduction
     - HEAD_PEDS_LD: 367 frames, 88% dose reduction

DEFAULT

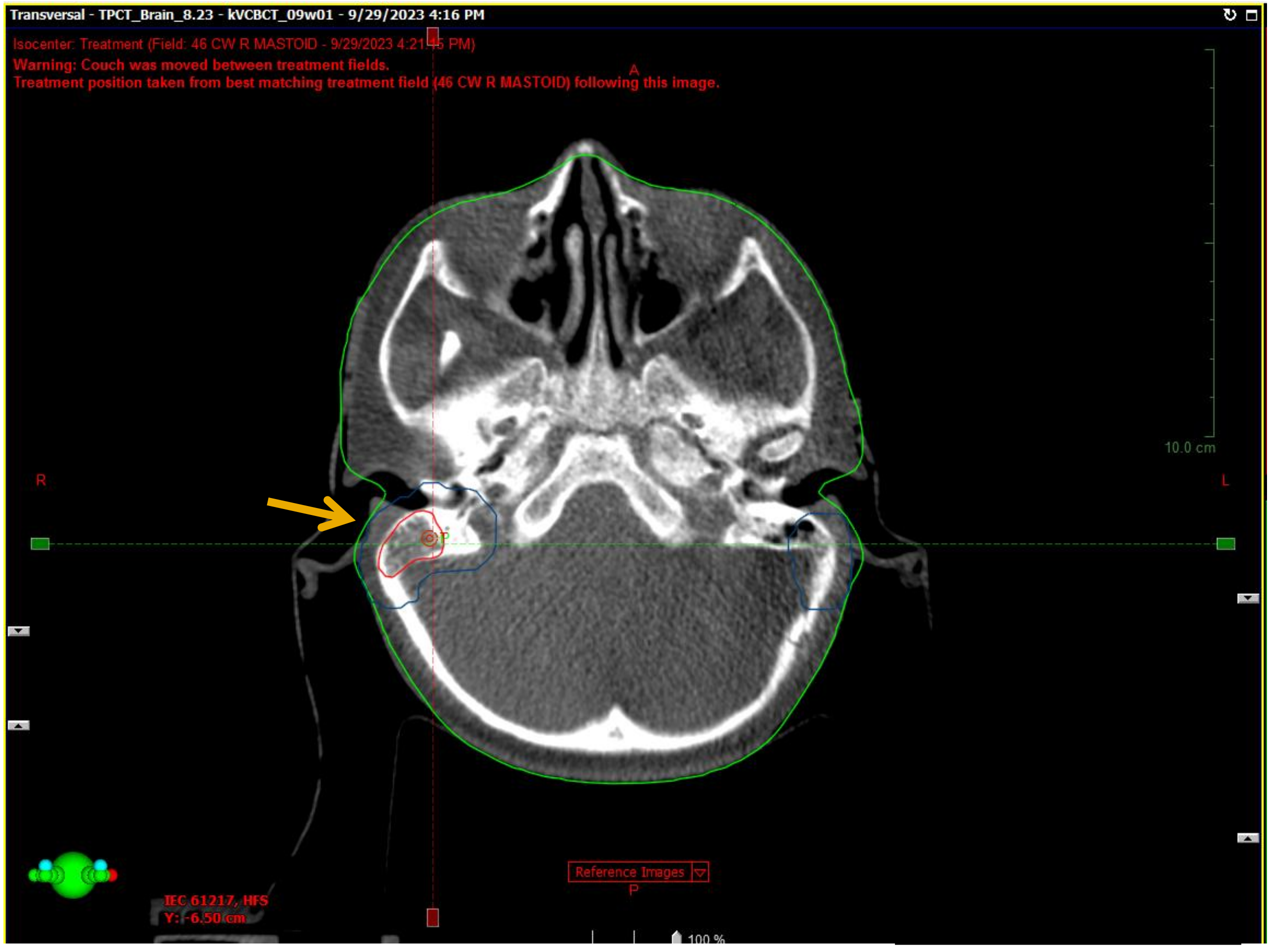
HEAD_PEDS

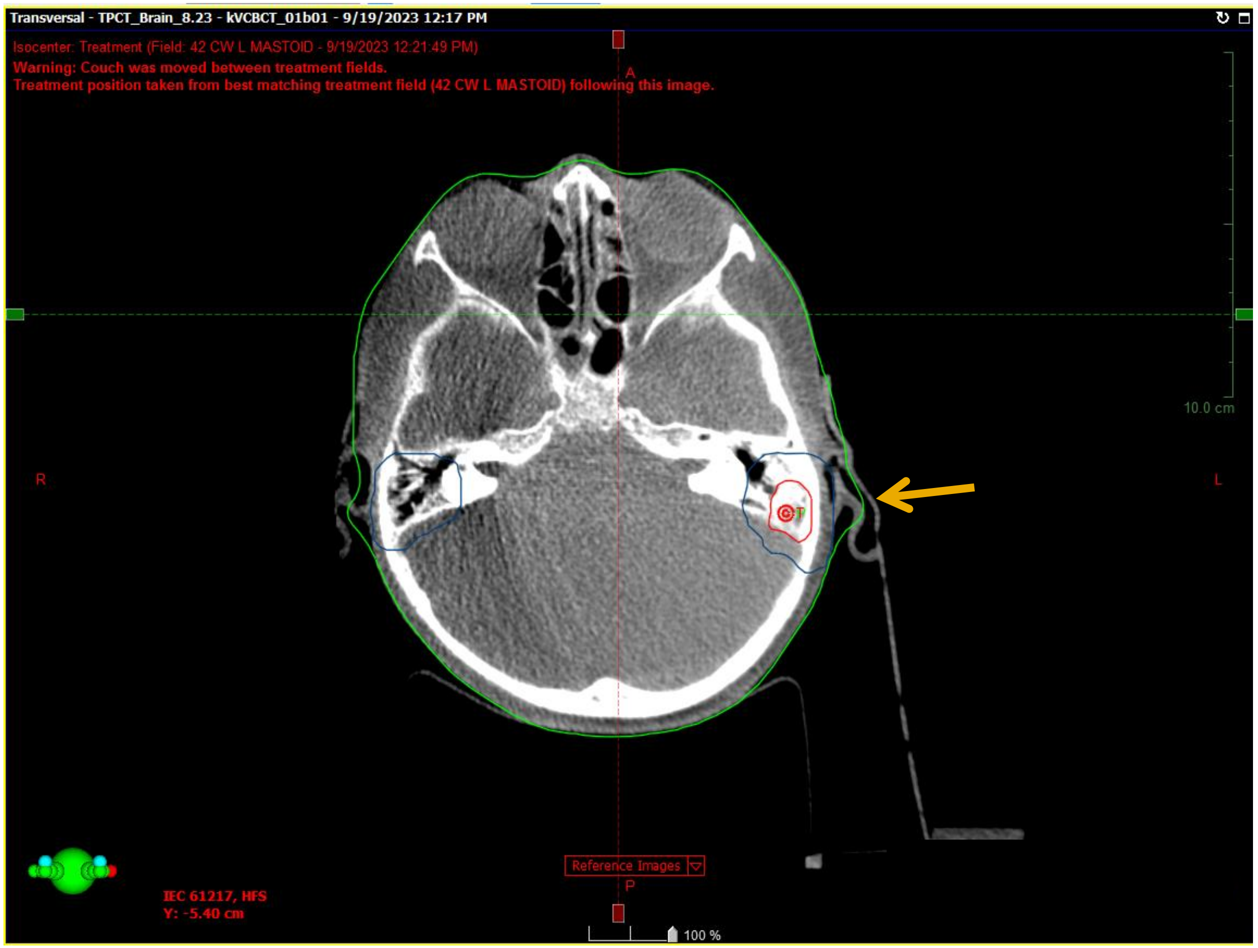
75% dose reduction

HEAD_PEDS_LD

88% dose reduction

- Left and right Mastoid targets aligned with HEAD_PEDS_LD CBCT protocol
  - GREAT bone/soft tissue contrast
  - NO soft tissue contrast





CONCLUSION

Conclusion

1. First step towards the management of imaging dose by optimizing protocols in a quantified and qualitative manner

   Imaging protocol optimization for IGRT should consider dose AND image quality and clinical use

2. Readily implementable in RT centers even if CTDI phantom and/or kV calibration unavailable
   - Perform relative measurements with Ionization Chamber
   - Use VARIAN provided values data for CBDI

3. Applicability to other CBCT based IGRT systems (Elekta linacs, Accuray Radixact systems, etc…)?

Comments on implementation

Team effort

- Physicists: technical expertise
- Users: Radiation Oncologists and RTTs
- Help from diagnostic/imaging physicists if possible
- In-service training should be implemented

Understand the requirement for the use of IGRT (justification):

- Alignment vs Adaptive RT
- Site: head vs. Thorax
- Focus: bone vs. soft tissue
- Patient: Adult vs. pediatric

Be conservative when deciding to lower exposure

- Use a higher dose protocol for the first fraction if you are not 100% certain of expected image quality

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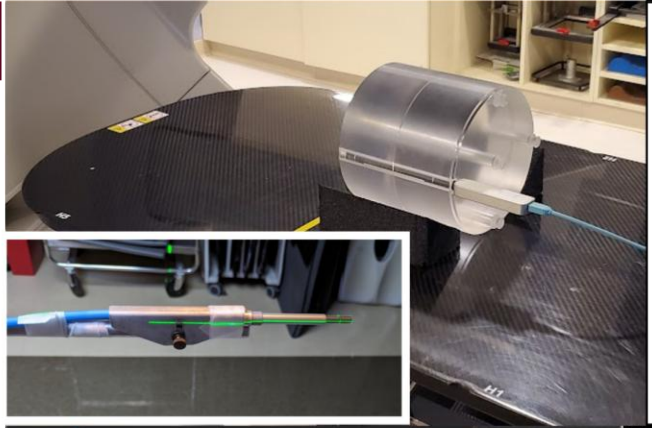

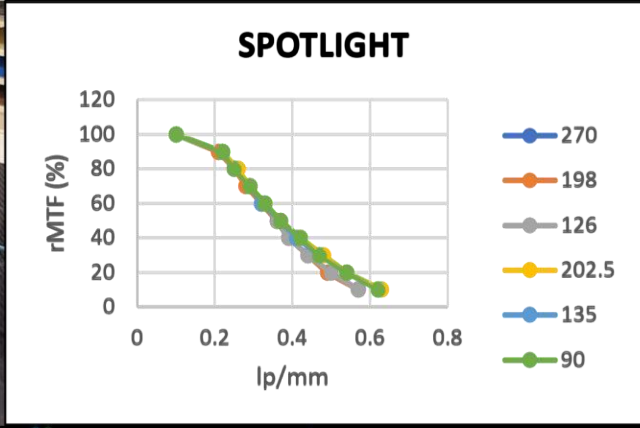

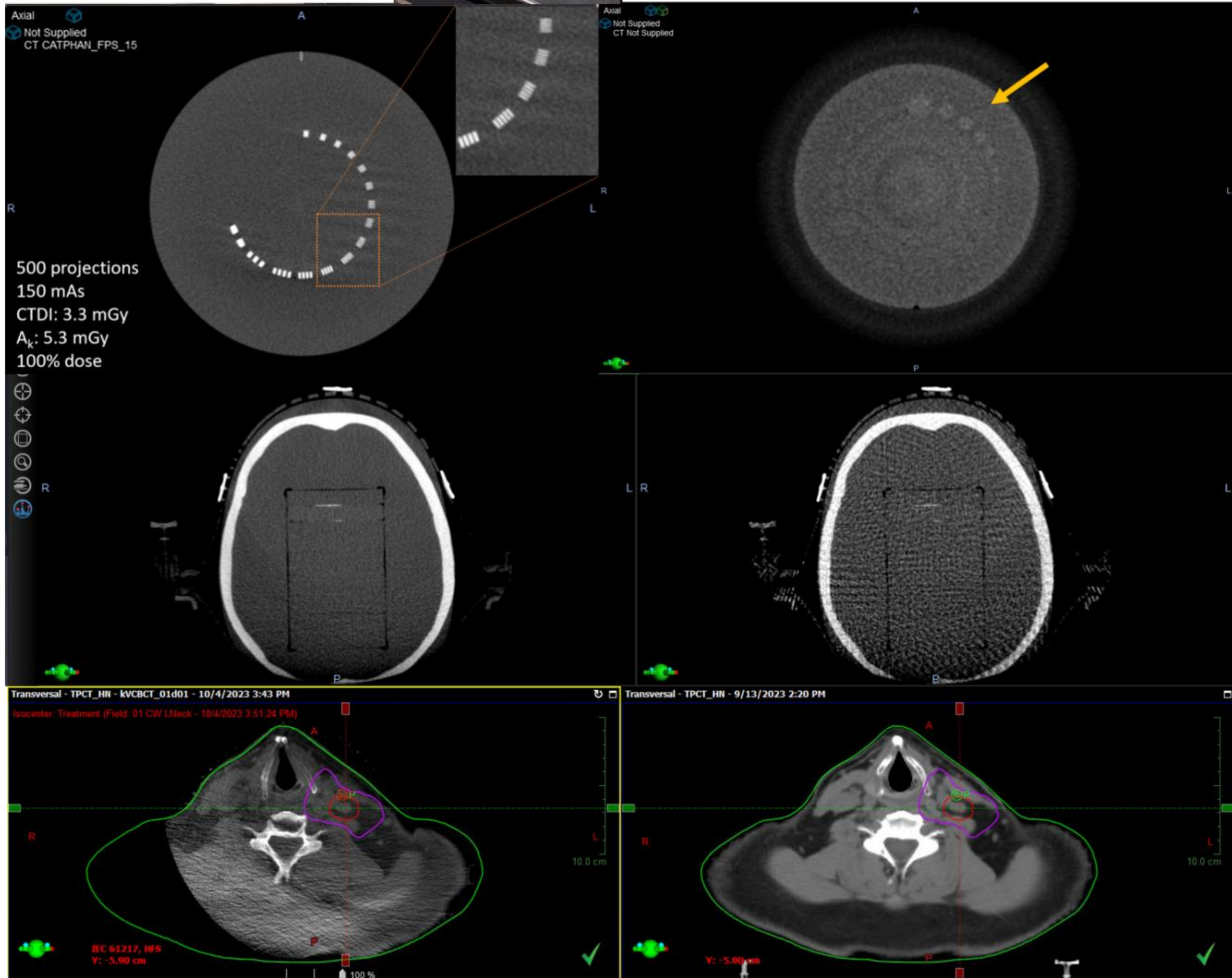

THANK YOU ☺

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