KV Cone Beam CT Imaging Doses and Associated Cancer Risks

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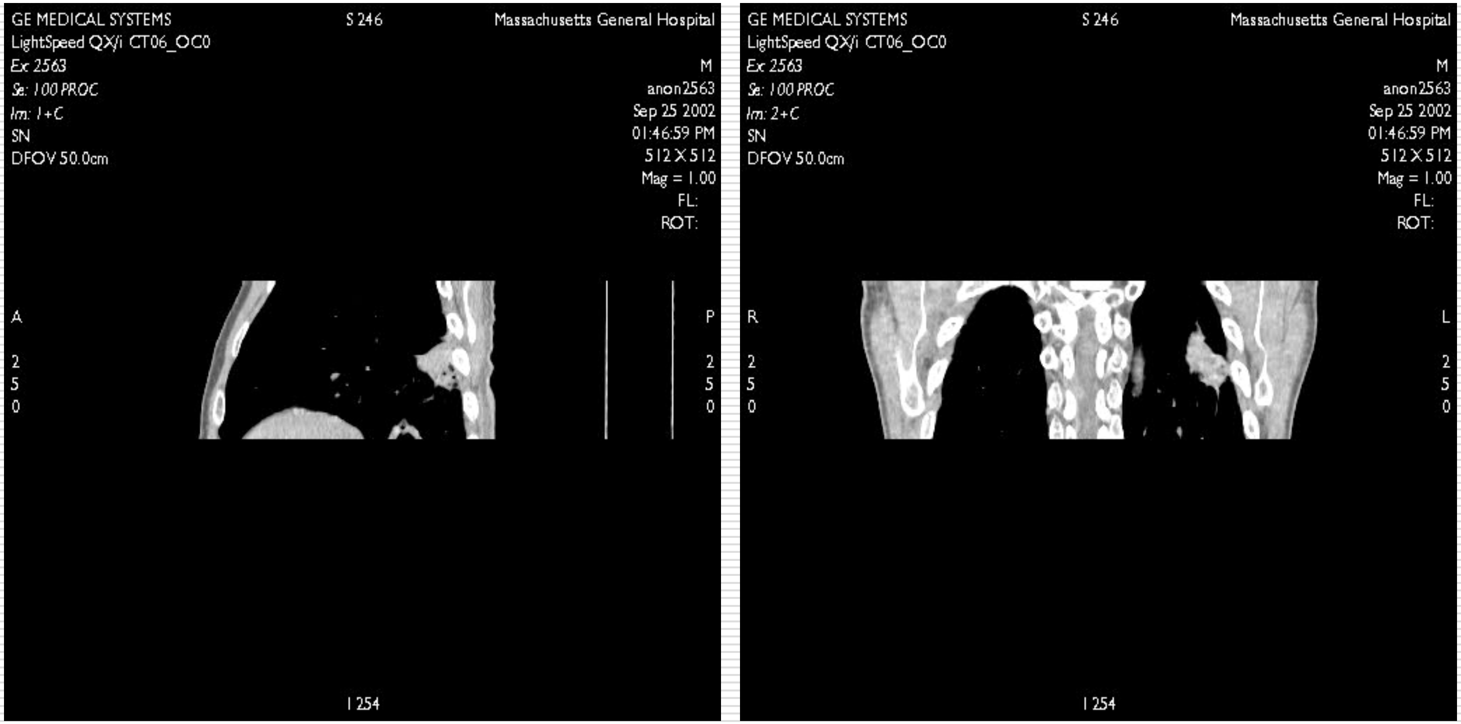
Conflict of Interest Notification

There is no actual or potential conflicts of interest in association with this work

Because tumor moves



Courtesy of Steve Jiang, UCSD

IGRT is widely used clinically

- To improve local-regional tumor control
- To reduce normal tissue complications

Many Definitions of IGRT

"use of modern imaging modalities, especially those incorporating functional or biological information, to augment target delineation"

and

"use of imaging, particularly in-room approaches, to adjust for target motion and positional uncertainty, and, potentially, to adapt treatment to tumor response"

Broad Definition – 6 D's of IGRT

- Detection and diagnosis
- Delineation of target and organs at risk
- Determining biological attributes
- Dose distribution design
- Dose delivery assurance
- Decipher treatment response through imaging

Greco C and Ling C, Acta Oncologica,47:7,1193 -1200, 2008.

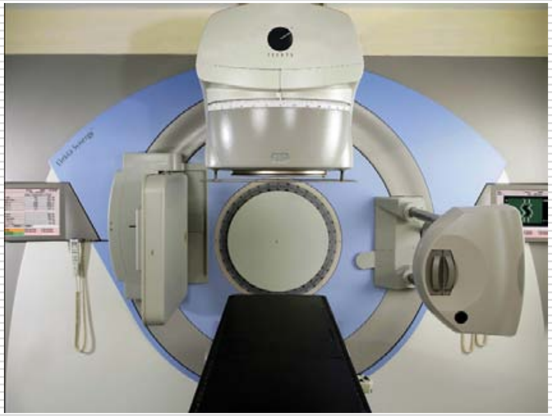
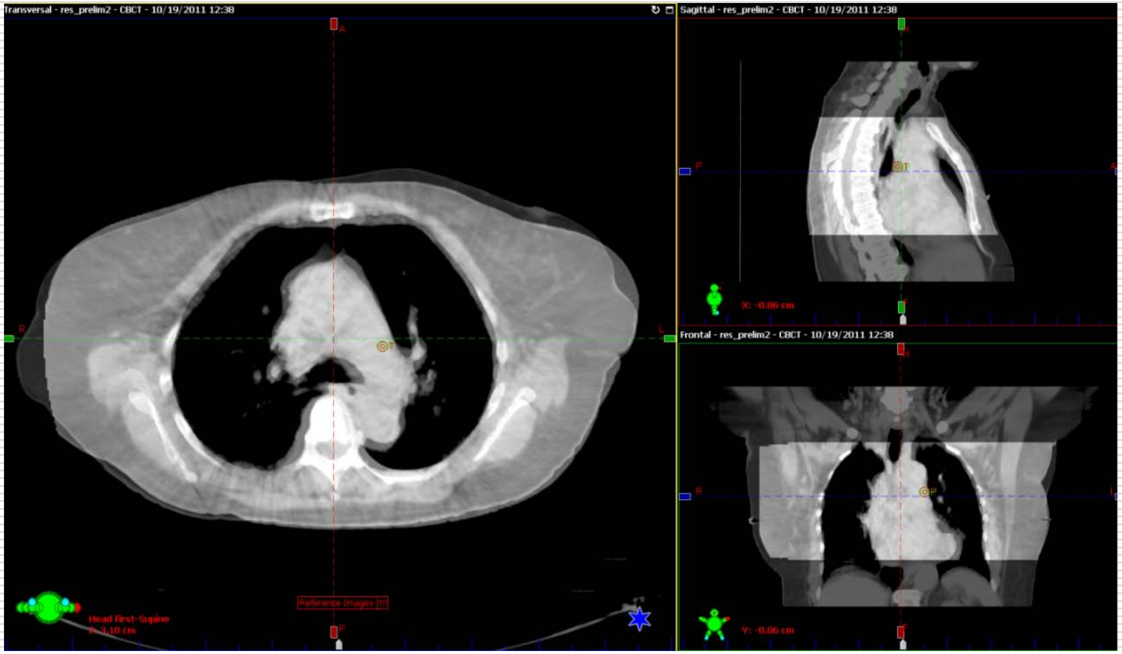


Image-Guided Treatment Delivery Platforms

Technologies: X-ray, fluoro, CT, MRI, kVCBCT, MVCBCT, PET, PET/CT, 4D-CT, 4D-PET/CT, 4D-MRI, SPECT, IR, US, MRS, and electromagnetic transponders etc.

kVCBCT is one of the most applied techniques in IGRT

- **Good for patient setup, tumor localization, margin reduction & dose calculation**
- **But the imaging dose is a major concern**



The more imaging doses

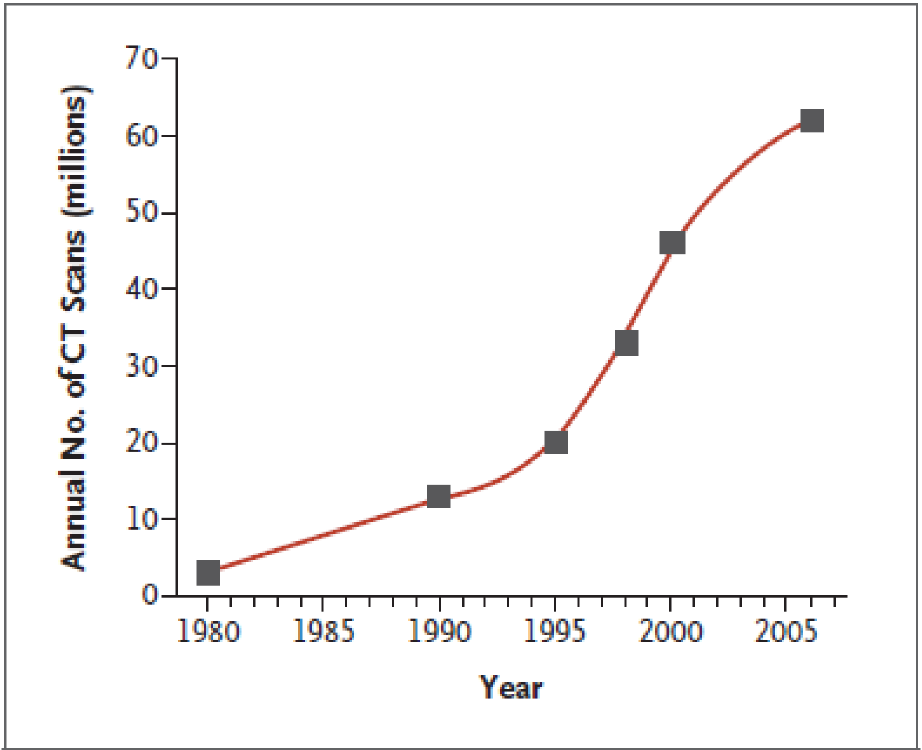
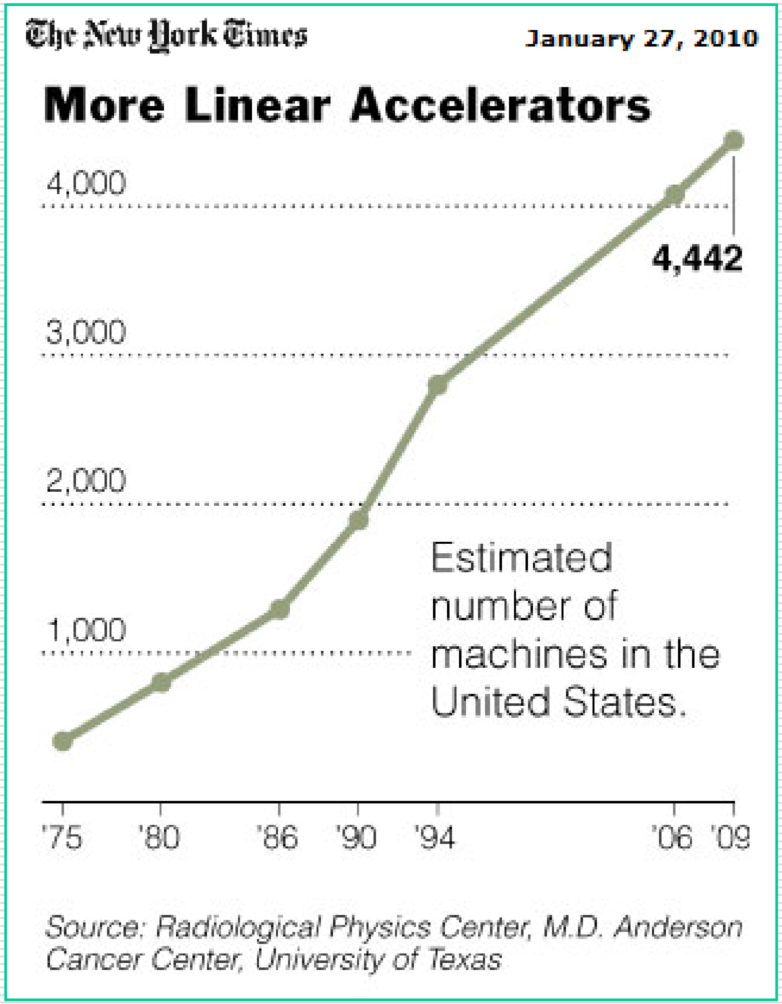


Figure 2. Estimated Number of CT Scans Performed Annually in the United States.

The most recent estimate of 62 million CT scans in 2006 is from an IMV CT Market Summary Report.[3]



Brenner DJ and Hall EJ, N Engl J Med 2007;357:2277-84.

The higher risk of death from cancer

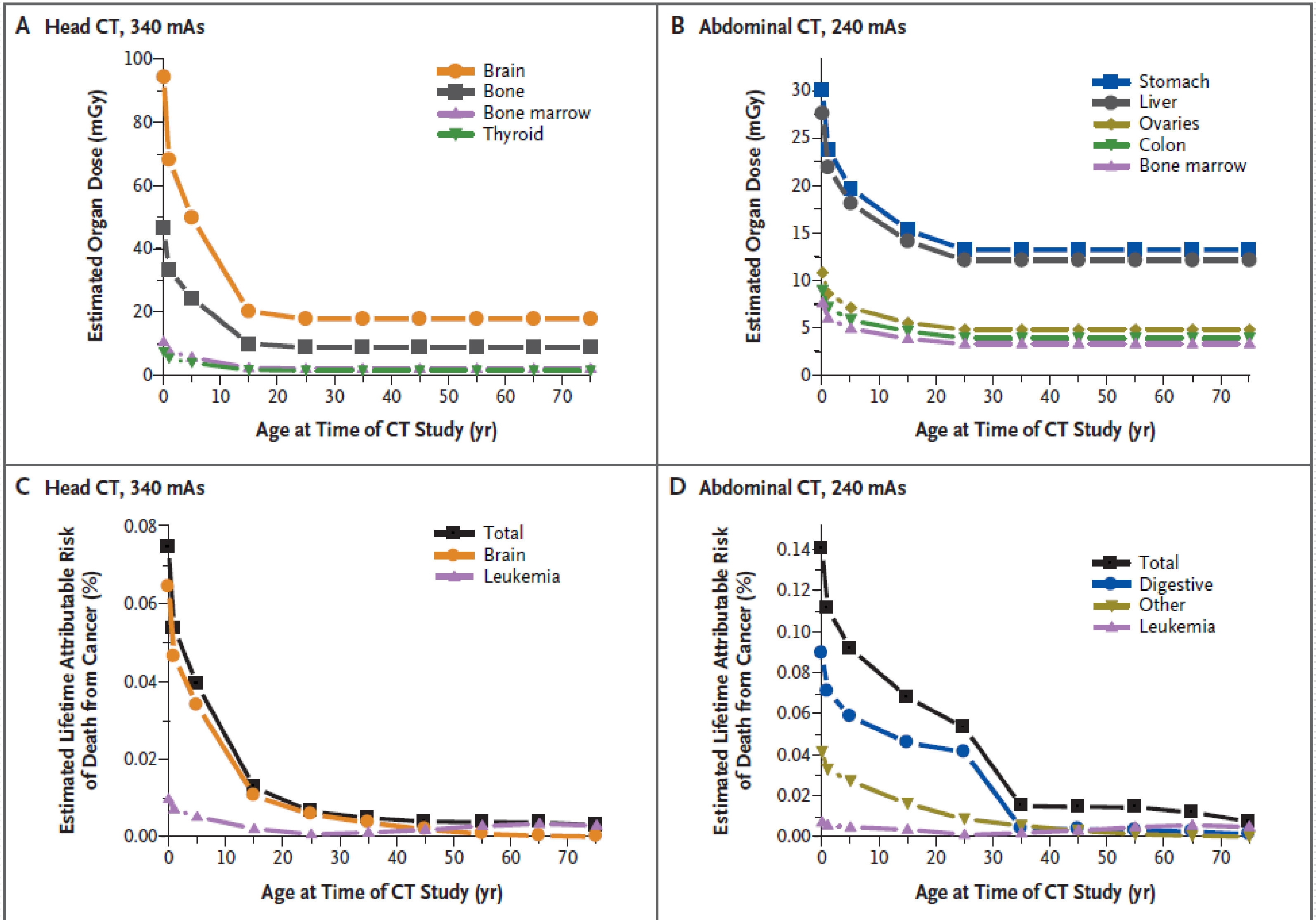


Figure 3. Estimated Organ Doses and Lifetime Cancer Risks from Typical Single CT Scans of the Head and the Abdomen.

With even higher risk* for children

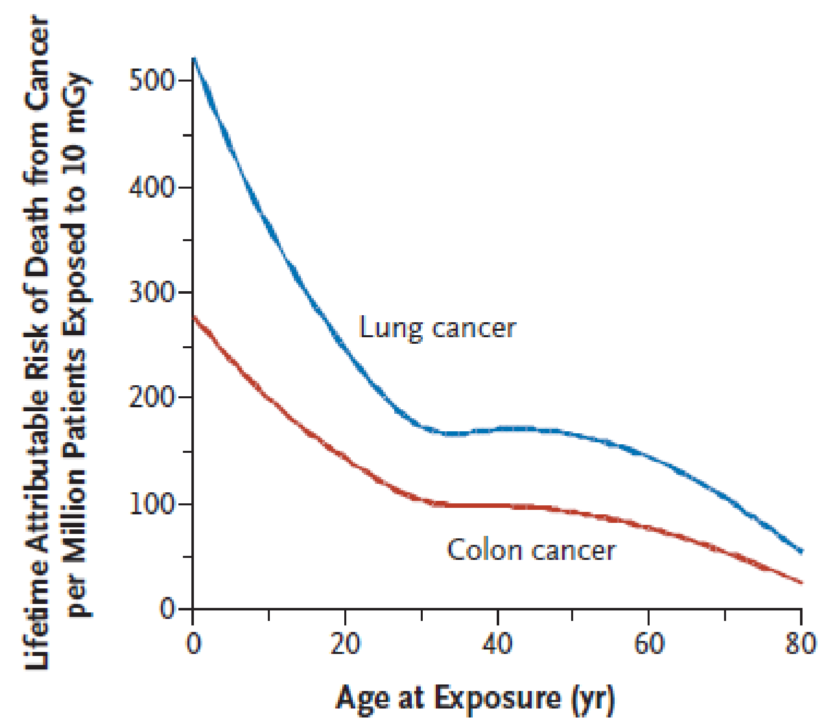
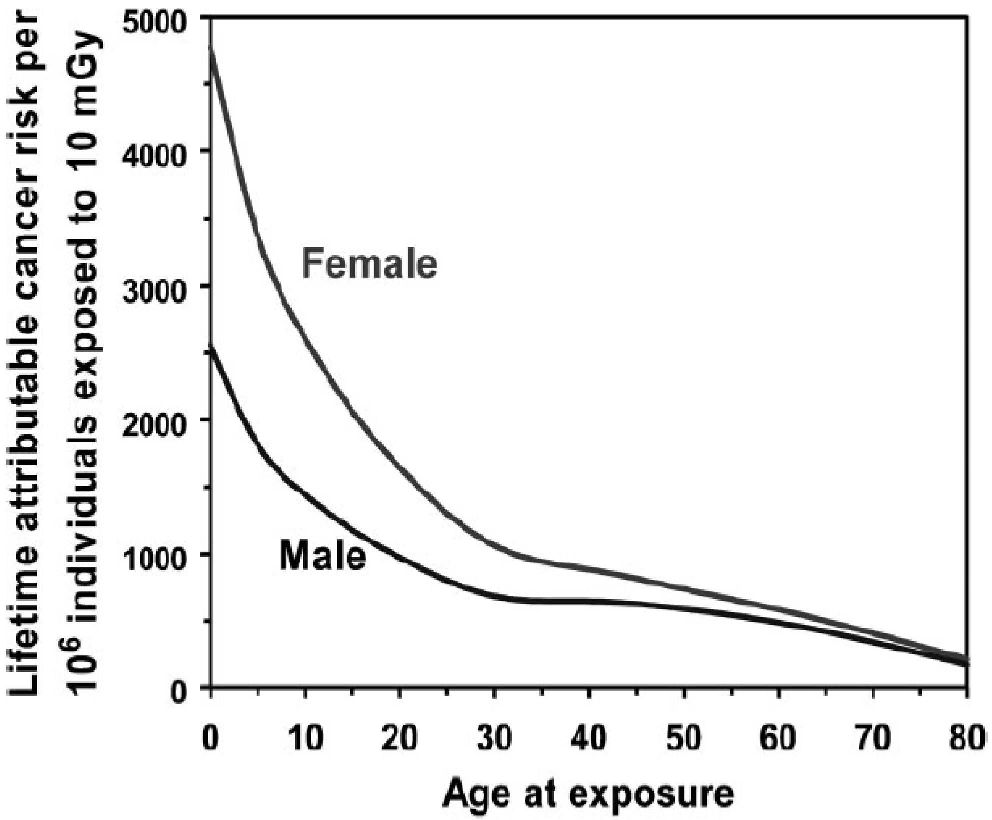


Figure 4. Estimated Dependence of Lifetime Radiation-Induced Risk of Cancer on Age at Exposure for Two of the Most Common Radiogenic Cancers.



Brenner DJ and Hall EJ, N Engl J Med 2007;357:2277-84.

Hall EJ and Brenner DJ, Bri J Radi 2008;81:362-78.

*Cancer risk assessment is based on BEIR V and ICRP 60, assuming a linear extrapolation of risks from intermediate to low doses

Conventional CT

- **CT is and will remain the primary imaging modality for radiotherapy treatment planning because**

  - soft tissue, bony landmarks, DRRs, electron densities

- **By far the largest contribution to the radiation exposure, but may be overtaken due to increased CBCT applications**

- **A variety of scan protocols have been proposed to reduce the CT doses to the patients while maintaining clinically acceptable image quality**

McCollough et al. Strategies for reducing radiation dose in CT. *Radiol Clin North Am.* 2009; 47(1): 27-40.

KVCBCT

- Widespread applications in the clinic with additional imaging doses often unaccounted for
- Current site-specific scan protocols offered by the manufacturers provide certain dose reduction, but are essentially non-personalized and non-differentiable with no consideration of individual patient being scanned
- So far, no tool available to help clinicians choose appropriate scan settings efficiently to protect patients while maintaining necessary image quality

A wise man once said:

"Don't use a cannon to kill a mosquito"

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Why not?

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Overkill and collateral damage

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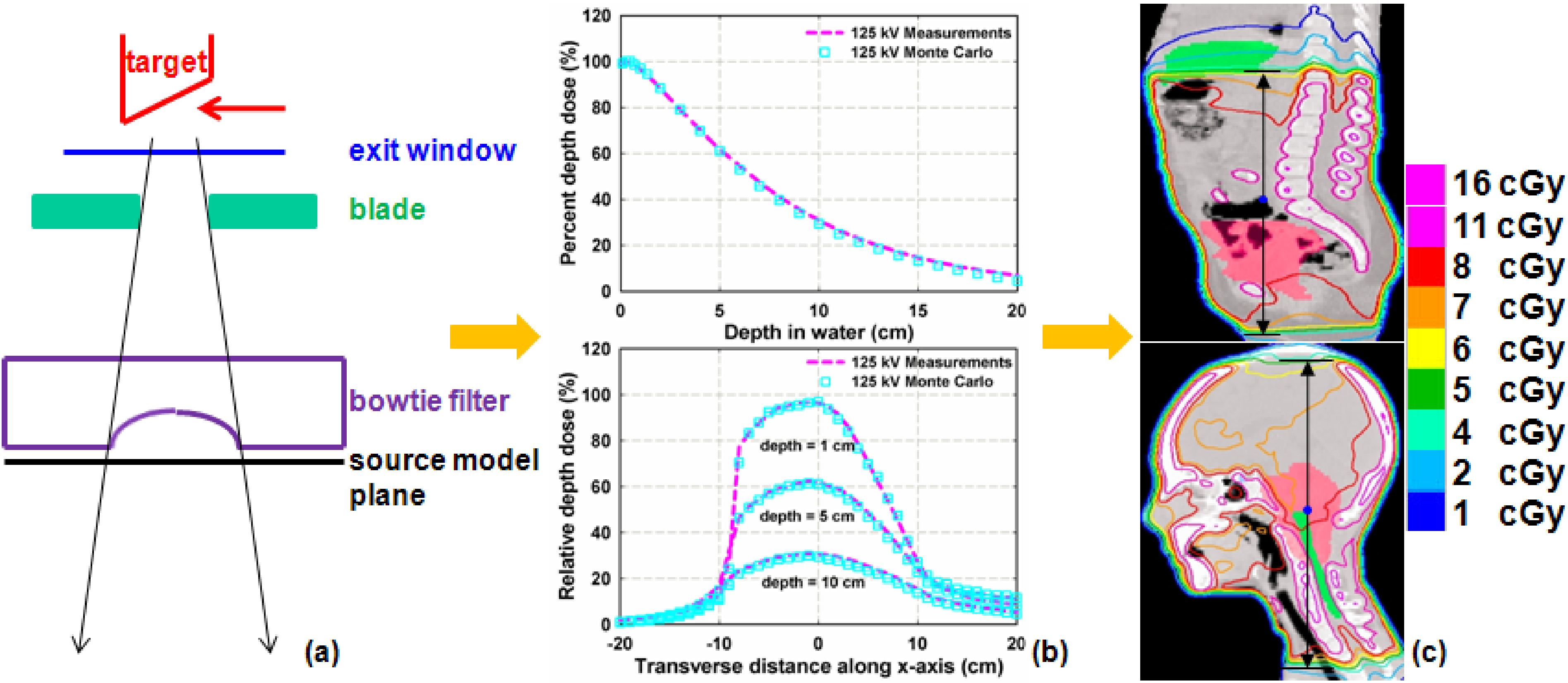
Overkill and collateral damage

We need to find a balanced approach to our current kVCBCT practices

Four questions to be addressed

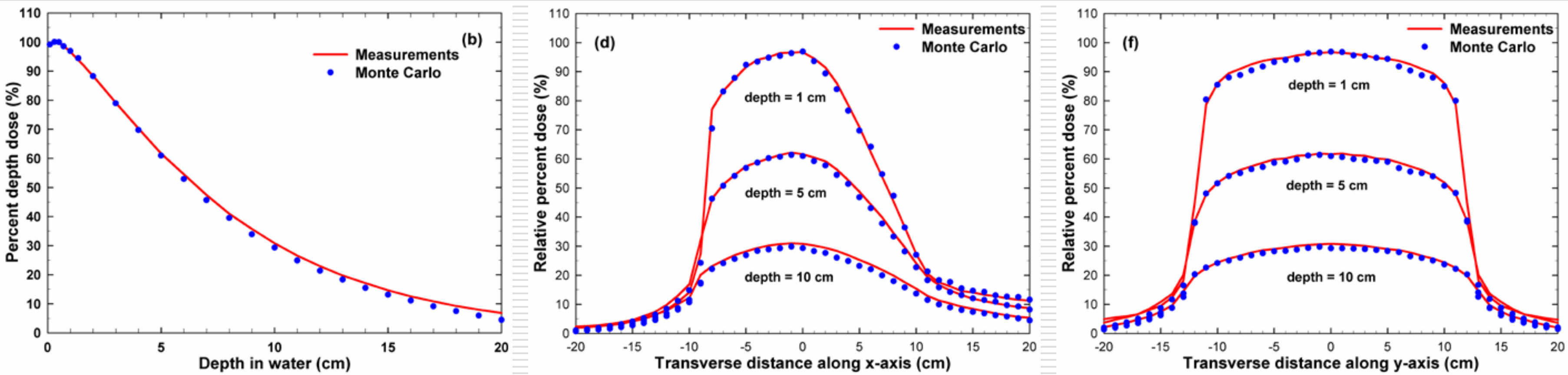
- How large are the kVCBCT imaging doses and how to reduce them?
- How are the kVCBCT imaging doses dependent on patient size?
- How to optimize the kVCBCT scan protocol to keep the imaging doses low while maintaining acceptable image quality?
- How large is the cancer risk associated with the kVCBCT imaging doses?

Monte Carlo Multiple-Source Modeling



(a) multiple-source modeling, (b) validation, and (c) 3D Monte Carlo absolute dose calculations in patient anatomy.

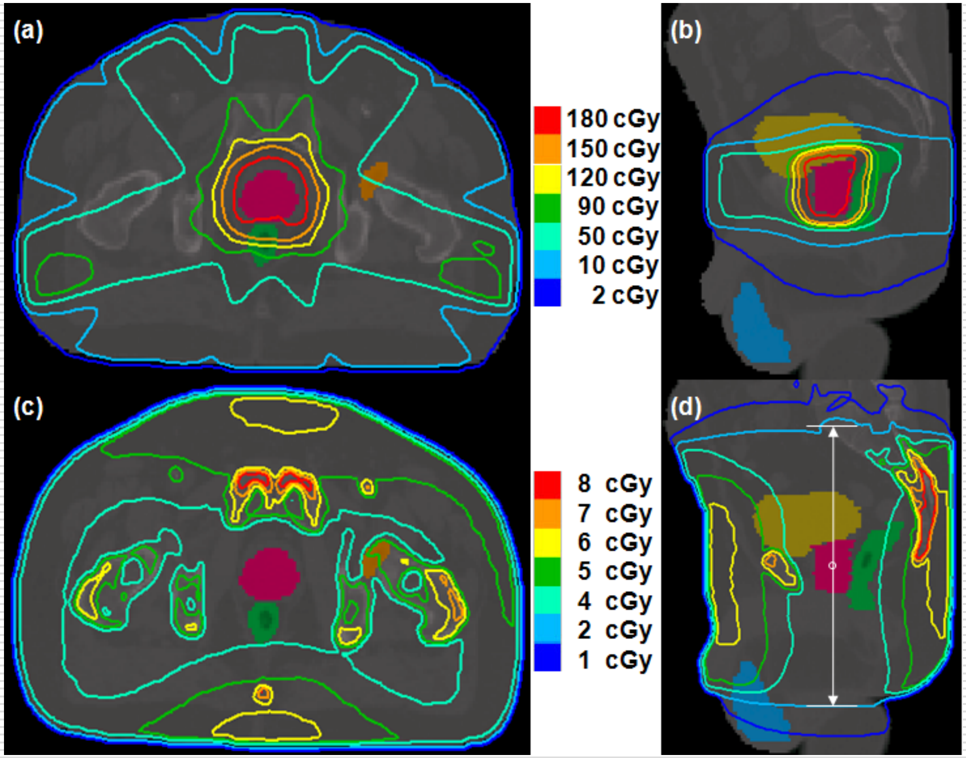
Benchmark of Monte Carlo



	kVCBCT half-fan pelvis protocol				kVCBCT full-fan high-quality head protocol			
	60 kVp 680 mAs	80 kVp 680 mAs	100 kVp 680 mAs	125 kVp 680 mAs	60 kVp 720 mAs	80 kVp 720 mAs	100 kVp 720 mAs	125 kVp 720 mAs
Measurements (cGy)	0.62	1.48	2.66	4.67	0.65	1.58	2.77	4.89
Monte Carlo (cGy)	0.61	1.51	2.64	4.62	0.67	1.62	2.82	4.96
(MC-Mea)/Mea (× 100%)	-1.6	2.0	-0.8	-1.1	3.1	2.5	1.8	1.4

	kVCBCT half-fan pelvis protocol				kVCBCT full-fan high-quality head protocol			
	60 kVp 1360 mAs	80 kVp 340 mAs	100 kVp 170 mAs	125 kVp 680 mAs	60 kVp 920 mAs	80 kVp 180 mAs	100 kVp 720 mAs	125 kVp 360 mAs
Measurements (cGy)	1.16	0.76	0.66	4.57	0.76	0.39	2.85	2.54
Monte Carlo (cGy)	1.19	0.75	0.65	4.56	0.74	0.40	2.82	2.52
(MC-Mea)/Mea (× 100%)	2.4	-1.1	-1.9	-0.2	-2.0	1.9	-1.1	-0.9

KVCBCT Doses to Prostate Patient

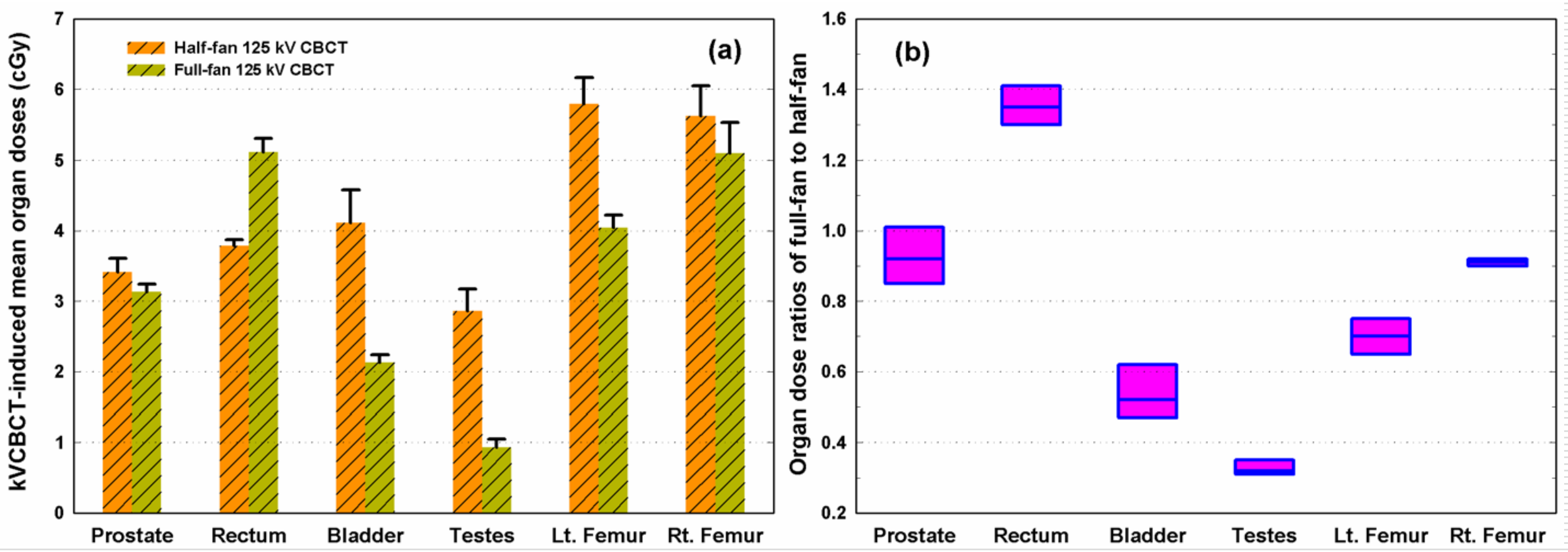


Compared to IMRT, kVCBCT-contributed doses to the prostate, rectum, bladder and femoral heads are 1.7%, 3.2%, 3.2% and 8.4%, respectively while dose to the testes is 400% more

	PO-IMRT	kVCBCT half-fan pelvis protocol				kVCBCT full-fan high-quality head protocol			
Organs	10 MV	60 kV	80 kV	100 kV	125 kV	60 kV	80 kV	100 kV	125 kV
Prostate	203.3	0.4	1.0	1.8	3.4	0.4	0.9	1.7	3.1
Rectum	117.3	0.5	1.2	2.1	3.8	0.9	1.8	3.1	5.1
Bladder	126.4	0.7	1.5	2.4	4.1	0.2	0.6	1.1	2.1
Testes	0.7	1.1	1.5	2.0	2.9	0.2	0.3	0.5	0.9
Left femoral head	69.1	0.8	2.0	3.3	5.8	0.5	1.2	2.3	4.0
Right femoral head	67.1	0.8	1.9	3.2	5.6	0.7	1.6	2.9	5.1

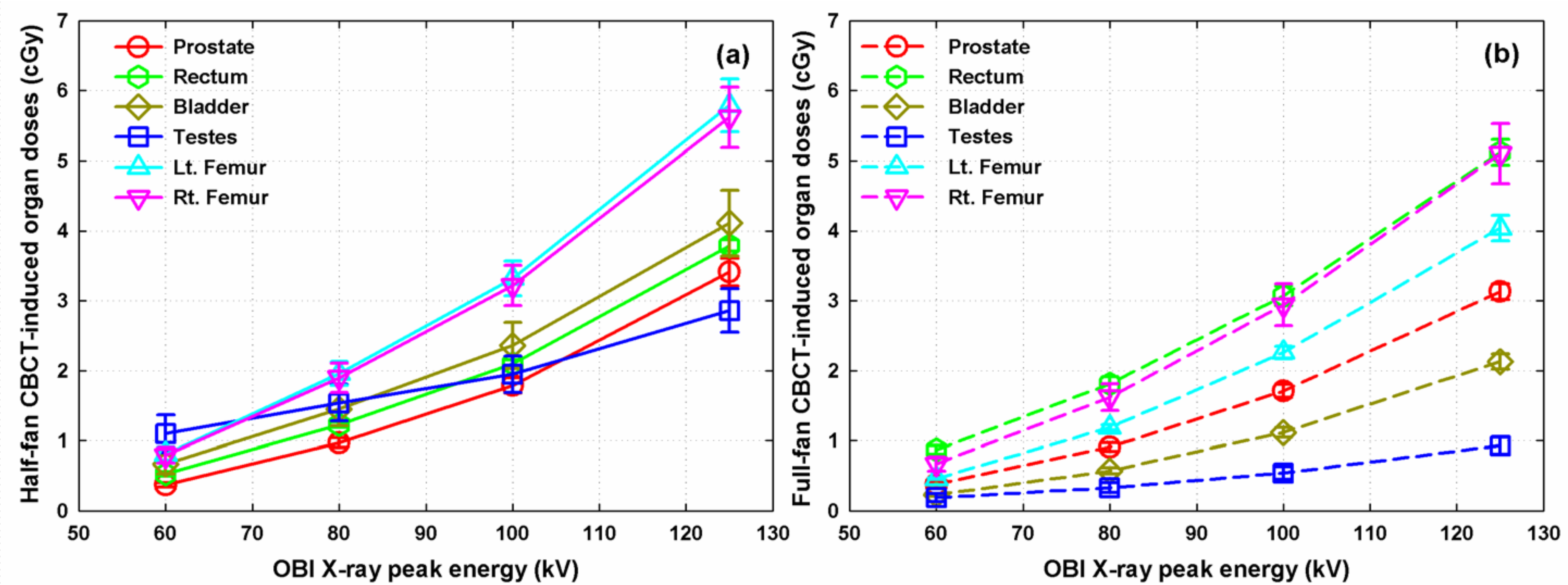
Deng J, Chen Z, Yu J, Roberts K, Peschel R, Nath R, Int J Radiat Oncol Biol Phys 2011

KVCBCT Doses to Prostate Patient



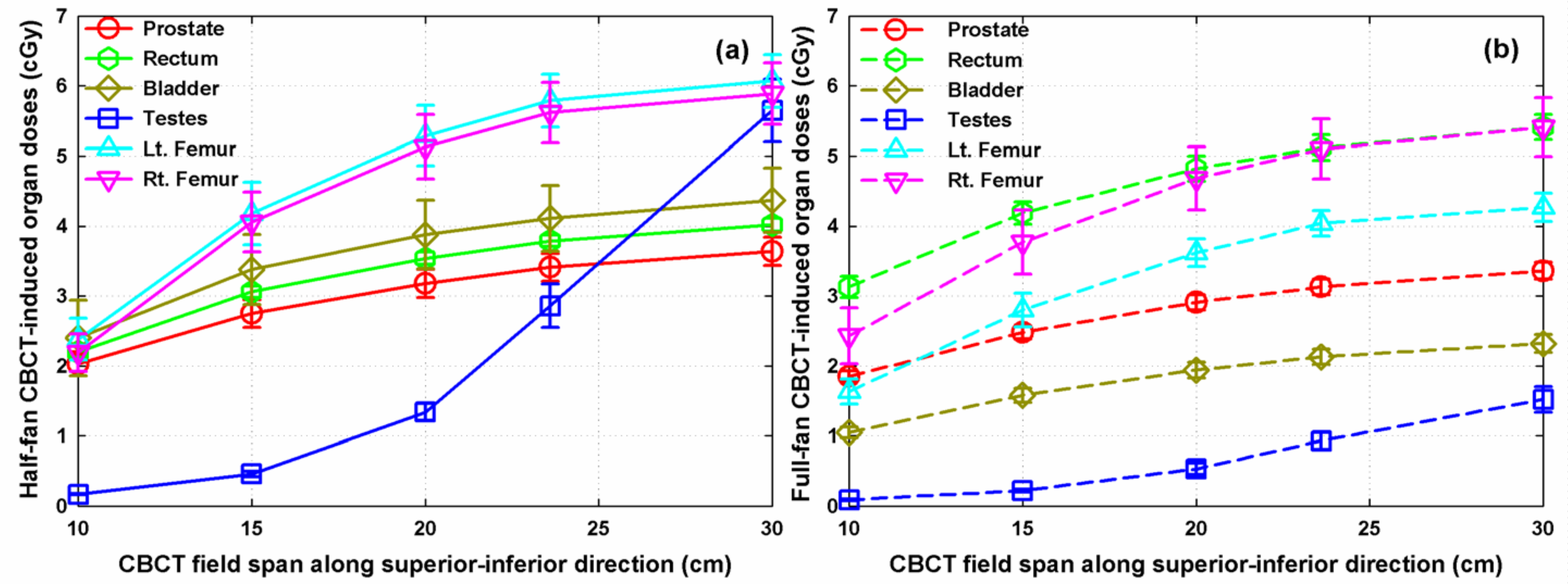
Full-fan CBCT usually deposits much less dose to organs (except for rectum) than half-fan mode in prostate patients

KVCBCT Doses to Prostate Patient



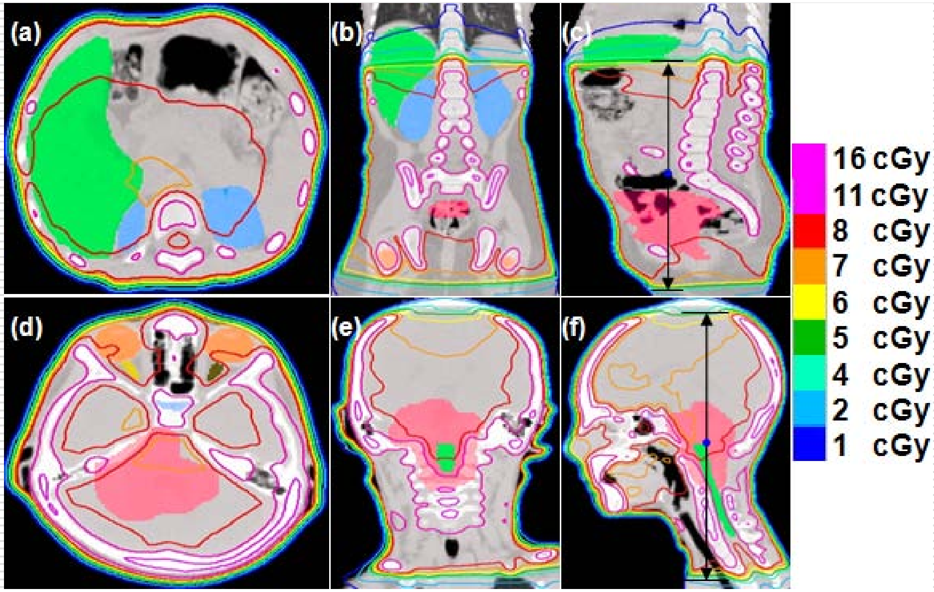
kVCBCT-contributed doses increase exponentially with photon energy

KVCBCT Doses to Prostate Patient



Reducing CBCT field significantly cuts doses to testes and other organs

KVCBCT Doses to Children

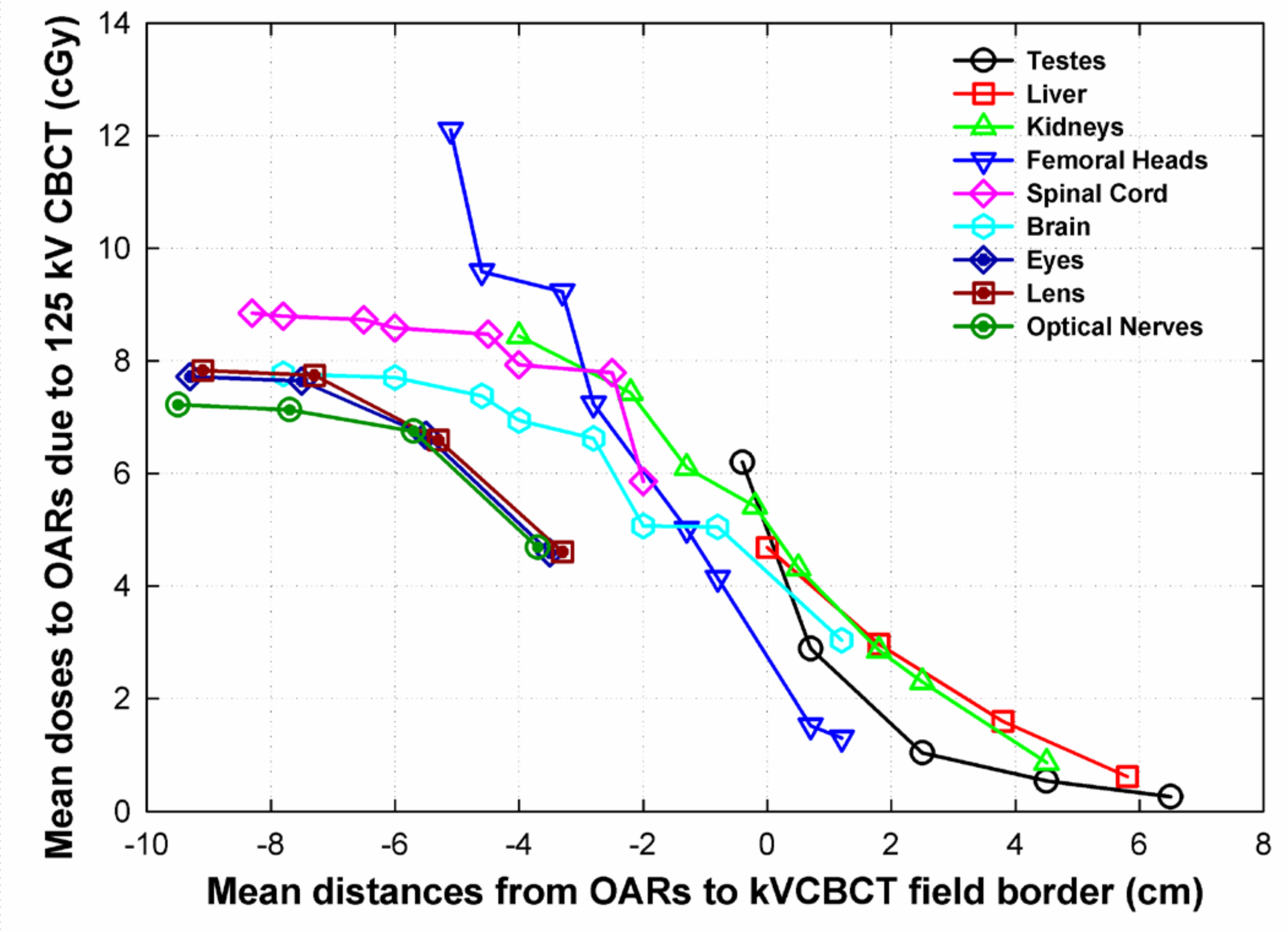


kVCBCT deposits much larger doses to critical structures in children than in adult, usually by a factor of 2 to 3

	kVCBCT half-fan pelvis protocol			
OARs	60 kV	80 kV	100 kV	125 kV
Testes	1.2	1.6	2.0	2.9
Liver	1.6	2.4	3.2	4.7
Kidneys	2.4	3.9	5.2	7.7
Femur Heads	3.5	5.9	7.7	10.5
Spinal Cord	1.9	3.7	5.5	8.8
Brain	1.6	3.2	4.8	7.6
Eyes	3.3	4.5	5.5	7.7
Lens	4.7	5.4	6.0	7.8
Optical Nerves	1.6	3.1	4.6	7.2

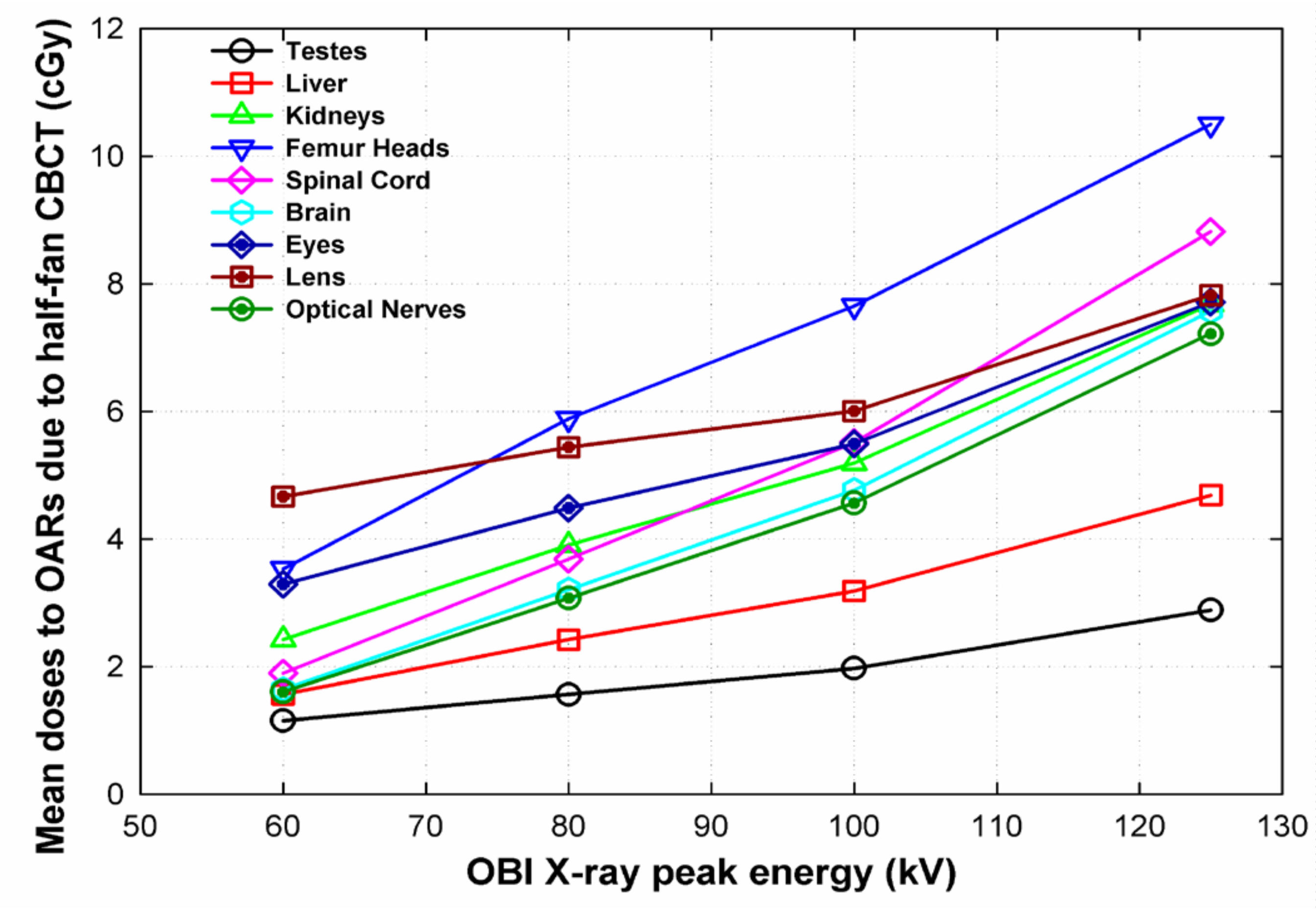
Deng J, Chen Z, Roberts K, Nath R, Int J Radiat Oncol Biol Phys 2011

KVCBCT Doses to Children



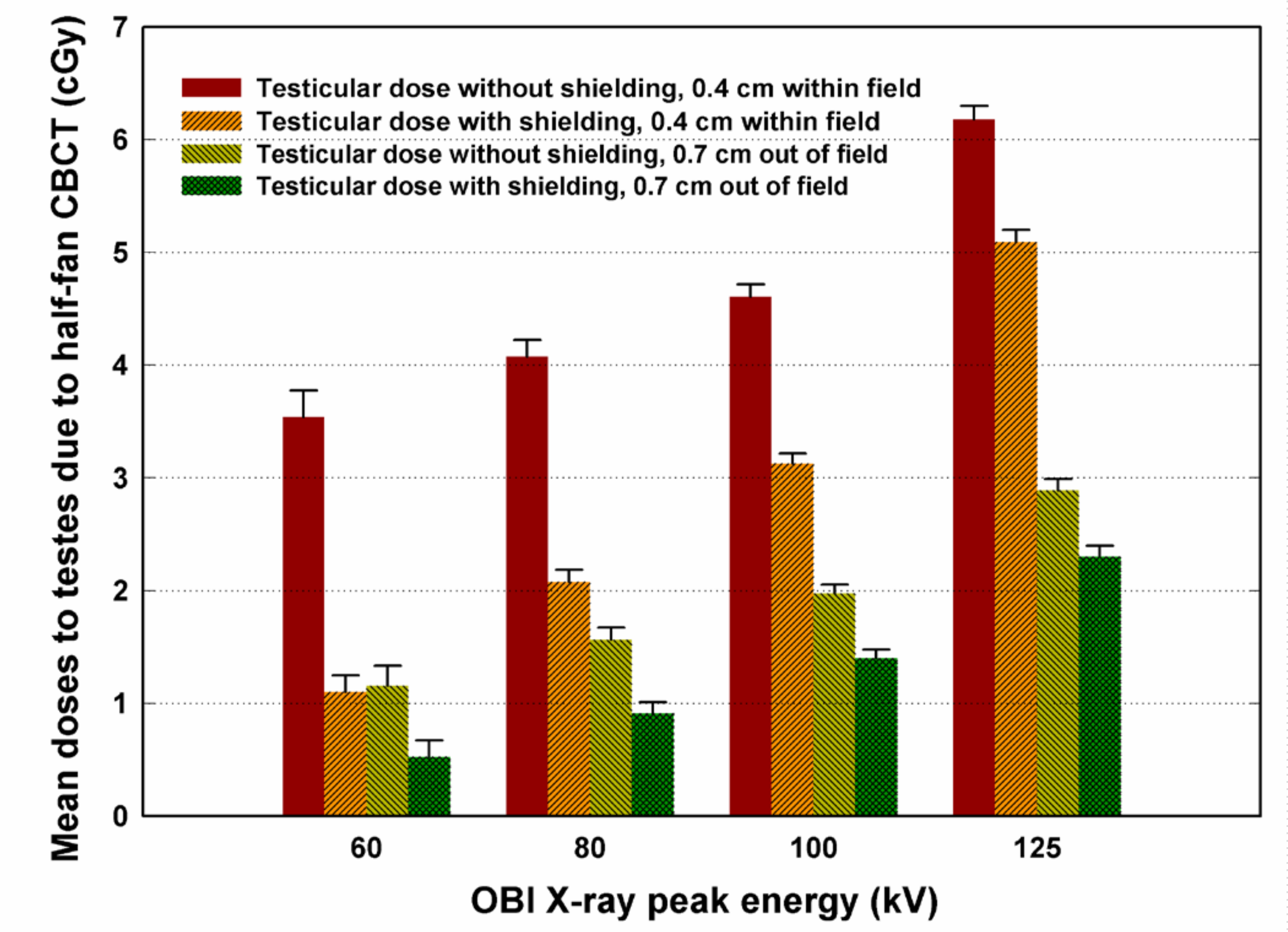
Increasing the distances from OARs to kVCBCT field border greatly reduces doses to OARs

KVCBCT Doses to Children



Depending on OARs, kVCBCT-induced doses increase linearly or exponentially with photon beam energy

KVCBCT Doses to Children



The testicular shielding works more efficiently at lower kV energies

Answer to question #1

- **How large are the kVCBCT imaging doses and how to reduce them?**
    - **1-12 cGy per scan depending on beam energy kVp, mAs, scan range, scan protocol and OARs**
    - **Reduce kVp**
    - **Reduce mAs**
    - **Reduce scan range**
    - **Choose appropriate scan protocol**
    - **Use shielding for more protection of OAR**

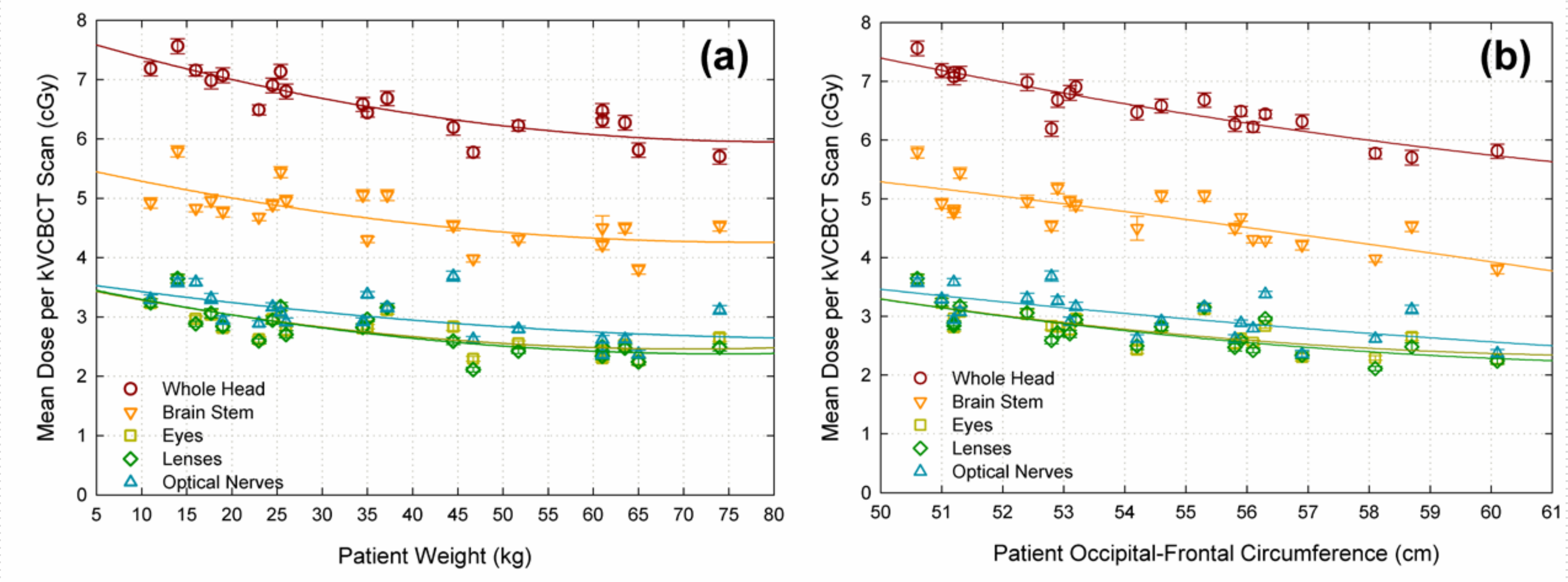
Typical Imaging Doses to OARs

Manufacturer	Technique	Dose Range	References
Elekta	kVCBCT	1 – 6 cGy	1-3
Siemens	MVCBCT	5.5 – 6.5 cGy	4-5
Tomotherapy	MV-CT	1 – 4 cGy	6
Varian	kVCBCT	1 – 12 cGy	7-10

1. Islam et al. Med Phys 2006; 33: 1573–1582.
2. Song et al. Med Phys 2008; 35: 480-486.
3. Spezi et al. Int J Radiat Oncol Biol Phys. 2011.
4. Morin et al. Med Dosim. 2006; 31(1): 51-61.
5. Morin et al. Med Phys. 2007; 34(5): 1819-27.
6. Fast et al. Phys Med Biol. 2012; 57(3): N15-24.
7. Ding et al. Int J Radiat Oncol Biol Phys 2009; 73: 610-617.
8. Cheng et al. Int J Radiat Oncol Biol Phys. 2011; 80(1): 291-300.
9. Deng et al. Int J Radiat Oncol Biol Phys. 2012; 82(1): e39-47.
10. Deng et al. Int J Radiat Oncol Biol Phys. 2012.

Size-dependent kVCBCT Doses

Head Scan

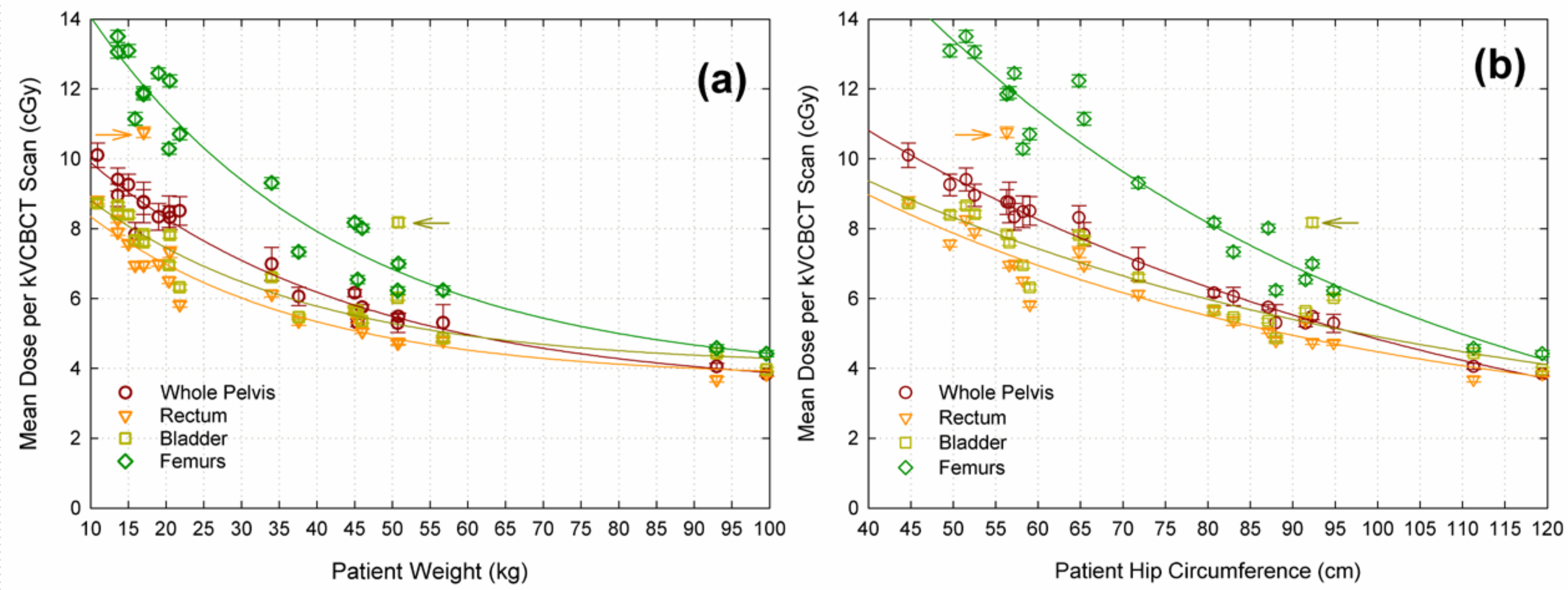


	$Dose = y_0 + a * weight + b * (weight)^2$			$Dose = y_0 + a * OFC + b * (OFC)^2$		
	y_0	a	b	y_0	a	b
Whole Head	7.807	-4.619E-2	2.875E-4	31.491	-0.746	5.278E-03
Brain Stem	5.687	-4.120E-2	3.033E-4	14.568	-0.226	8.176E-04
Eyes	3.594	-3.295E-2	2.392E-4	28.281	-0.838	6.773E-03
Lenses	3.624	-3.464E-2	2.417E-4	27.893	-0.818	6.515E-03
Optical Nerves	3.614	-2.043E-2	1.007E-4	12.674	-0.263	1.581E-03

Zhang Y, Yan Y, Nath R, Bao S, Deng J, Int J Radiat Oncol Biol Phys 2012 (in press)

Size-dependent kVCBCT Doses

Pelvis Scan

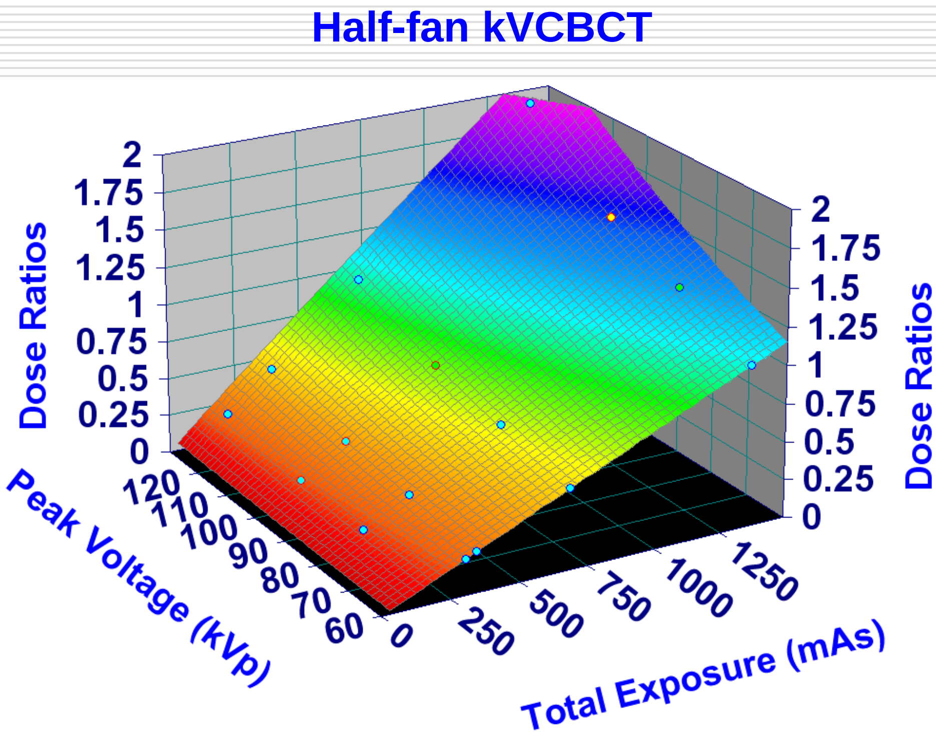


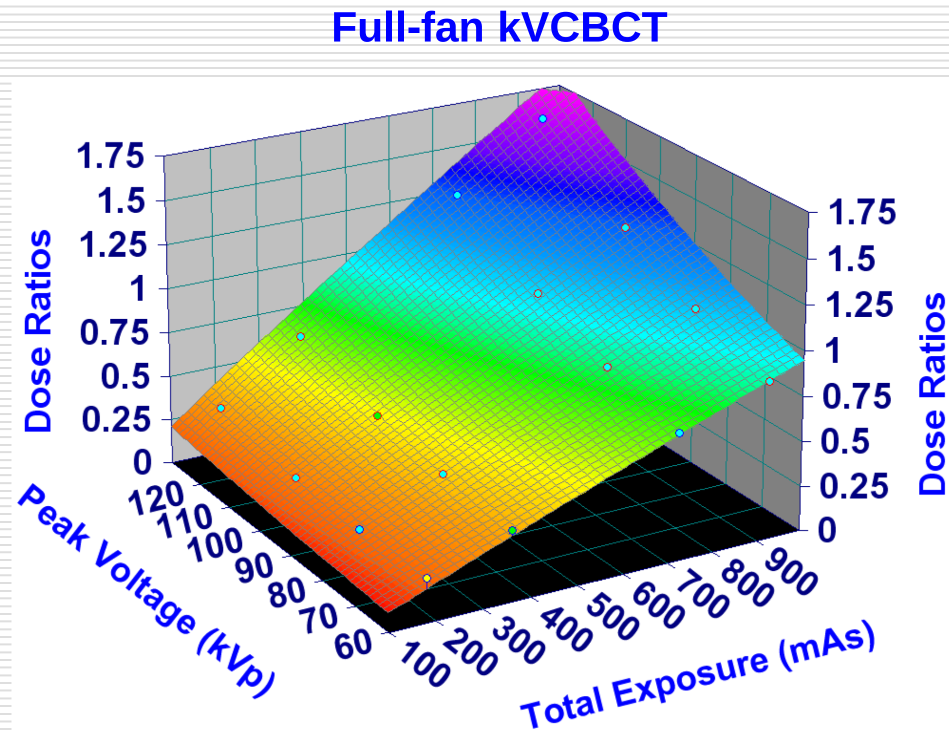
	$Dose = y_0 + a * e^{-b*weight}$			$Dose = y_0 + a * e^{-b*HIP}$		
	y_0	a	b	y_0	a	b
Whole Pelvis	3.36	8.65	2.80E-2	5.18E-9	18.47	1.34E-2
Rectum	3.80	6.96	4.00E-2	1.89	13.81	1.67E-2
Bladder	4.10	6.83	3.60E-2	1.63	13.56	1.41E-2
Femurs	3.88	14.30	3.25E-2	7.67E-9	31.07	1.68E-2

Answer to question #2

- How are the kVCBCT imaging doses dependent on patient size?
  - KVCBCT doses to OARs are highly correlated with patient size
  - Weight is primary index for dose assessment
  - Occipital-frontal circumferences (OFC) and hip circumference (HIP) are secondary indexes
  - With empirical functions, a personalized quantitative dose evaluation will be possible without exposing unnecessary radiation to pediatric patients

Imaging Doses vs. mAs and kVp





$$\ln(D / D_{default}) = \ln f(mAs, kVp) = a + b\ln(mAs) + ckVp$$

Fitting of empirical functions	a	b	c	Coefficients of determination (R^2)
Half-fan	-7.6537	0.9861	0.009710	0.9992
Full-fan	-7.1082	0.9399	0.009378	0.9975

CBCT Scan Protocol Optimizer

- A conjugated gradient searching algorithm in multi-dimensions has been implemented to minimize an objective function which incorporates mAs and kVp in both dose and image quality components

$$F_{obj} = \sum_{\lambda \in organs} \left(u_\lambda \frac{\overline{D_\lambda}}{TD_\lambda} + v_\lambda \frac{\overline{D_{body}^{default}}}{\overline{D_\lambda}} \right)$$

dose   image quality

$$\overline{D_\lambda} = \overline{D_\lambda^{default}} \cdot f\left(mAs, kVp\right)$$

$$\ln f(mAs, kVp) = a + b\ln(mAs) + ckVp$$

Zhang Y, Nath R, Bao S, Deng J, Med Phys 2012 (to be submitted)

CBCT Scan Protocol Optimizer

- **Input to optimizer**
  - Monte Carlo-calculated mean organ doses due to kVCBCT at default mode in patient CT anatomy
  - User-defined weighting factors for normal tissue sparing and image quality
  - Organ-specific tolerance doses from literature
- **Output of optimizer**
  - Recommended mAs and kVp settings

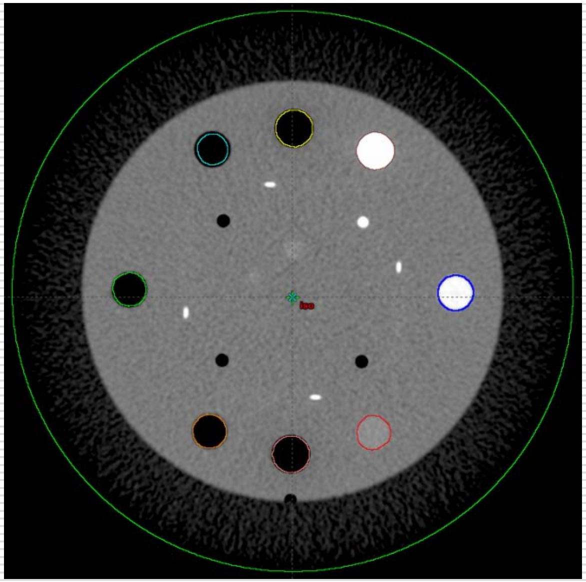
CBCT Scan Protocol Optimizer

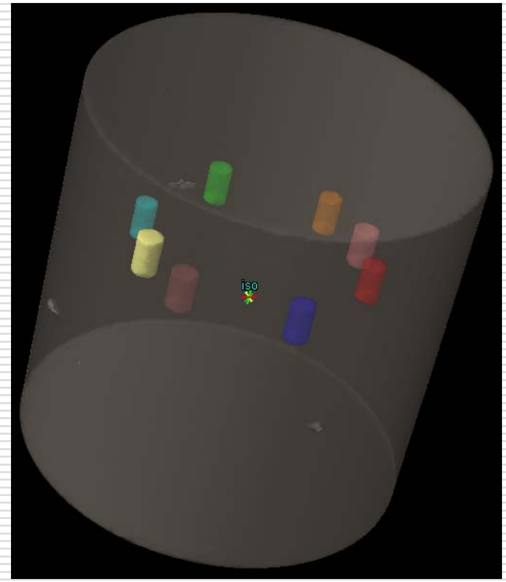
- **Based on user-defined weighting factors, three major scenarios can be generated for each patient:**
  - **best image quality for soft tissues, but highest doses**
  - **maximum soft tissue sparing, but worst image quality**
  - **balanced protocol with much reduced imaging doses and acceptable image quality**
- **The most appropriate scan protocol for a patient may be the tradeoffs among a variety of factors, and often requires an informed decision from the clinician who is clear about the treatment goal of his/her patient**

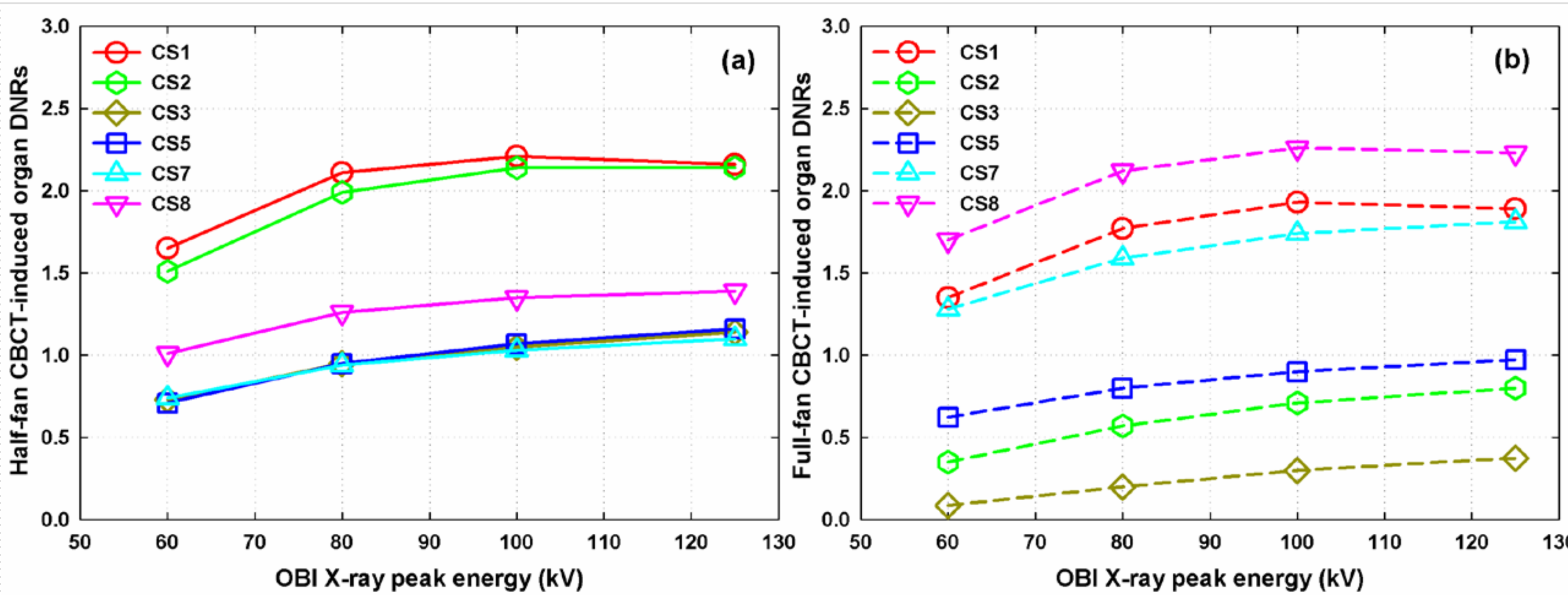
CBCT Image Quality Analysis

- Usually CNR and SNR, but lacks organ dose info
- Dose-to-noise ratio (DNR) to analyze image quality
  = mean organ dose / mean background dose
- The higher the organ dose, the higher the DNR, and the better image quality
- The first time that a dose-based ratio is used for image quality analysis

Image Quality Analysis - DNR



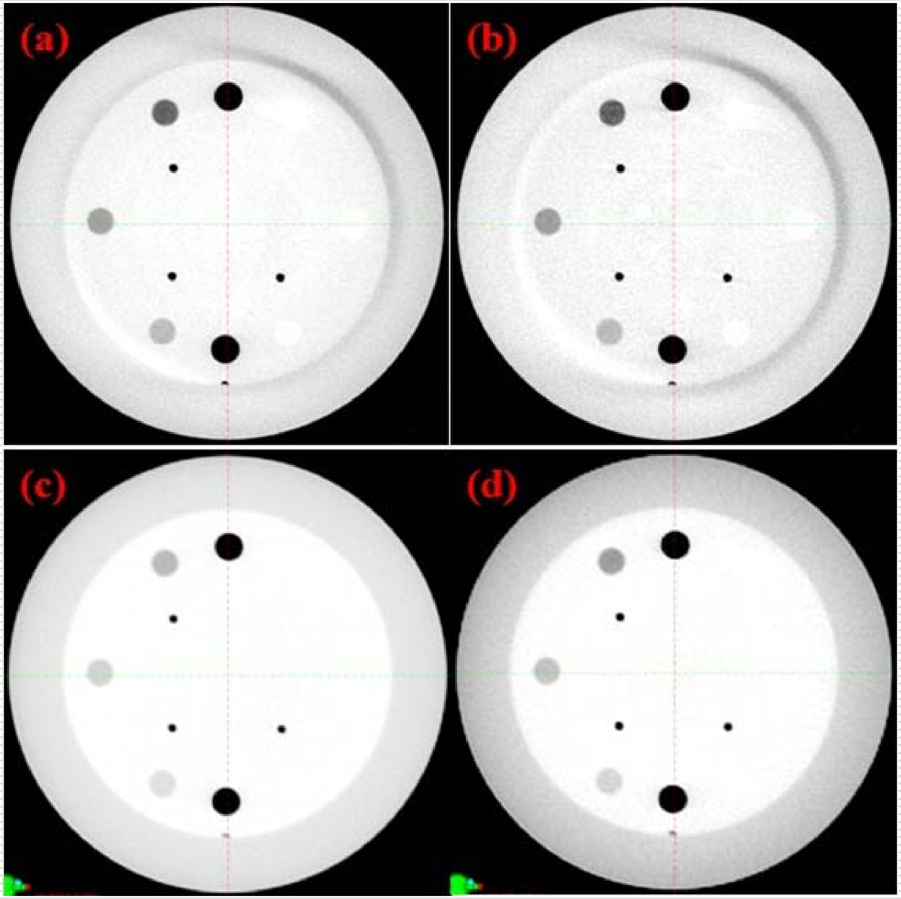




Testing of Optimizer on Catphan

default
head protocol
720 mAs, 100 kVp

recommended
head protocol
400 mAs, 95 kVp



default
pelvis protocol
680 mAs, 125 kVp

recommended
pelvis protocol
310 mAs, 108 kVp

doses reduced by 51% and 60% for head and pelvis protocol, respectively, with excellent image quality maintained

Testing of Optimizer on Patients

	CBCT half-fan pelvis protocol					CBCT full-fan high-quality head protocol				
Pelvis Patients	Scanning Protocols	Rectum	Bladder	Femur	Kidneys	Eyes	Lens	OptNe	Brainstem	Head Patients
Patient 1 Age = 3 yrs	Default	7.5	8.6	12.5	7.8	3.0	3.0	3.2	4.9	Patient 6 Age = 2 yrs
	Optimized	1.1	1.2	1.8	1.1	0.8	0.8	0.85	1.3	
	(Opt-Def)/Def (× 100%)	-85	-86	-86	-86	-73	-73	-73	-73	
Patient 2 Age = 6 yrs	Default	6.6	7.3	7.1	7.7	3.1	3.2	3.1	5.4	Patient 7 Age = 7 yrs
	Optimized	1.0	1.1	1.1	1.2	0.75	0.77	0.75	1.3	
	(Opt-Def)/Def (× 100%)	-85	-85	-85	-84	-76	-76	-76	-76	
Patient 3 Age = 19 yrs	Default	1.2	0.9	0.7	1.9	2.6	2.6	2.8	4.3	Patient 8 Age = 16 yrs
	Optimized	0.45	0.34	0.26	0.70	0.68	0.68	0.73	1.1	
	(Opt-Def)/Def (× 100%)	-63	-62	-63	-63	-74	-74	-74	-74	
Patient 4 Age = 42 yrs	Default	1.6	1.5	1.4	0.9	2.7	2.7	2.9	4.0	Patient 9 Age = 26 yrs
	Optimized	0.30	0.28	0.26	0.17	0.68	0.68	0.73	1.0	
	(Opt-Def)/Def (× 100%)	-81	-81	-81	-81	-75	-75	-75	-75	
Patient 5 Age = 69 yrs	Default	1.9	1.4	1.1	1.2	2.3	2.3	2.6	3.4	Patient 10 Age = 65 yrs
	Optimized	0.40	0.30	0.23	0.25	0.43	0.43	0.48	0.63	
	(Opt-Def)/Def (× 100%)	-79	-79	-79	-79	-81	-81	-82	-81	

Answer to question #3

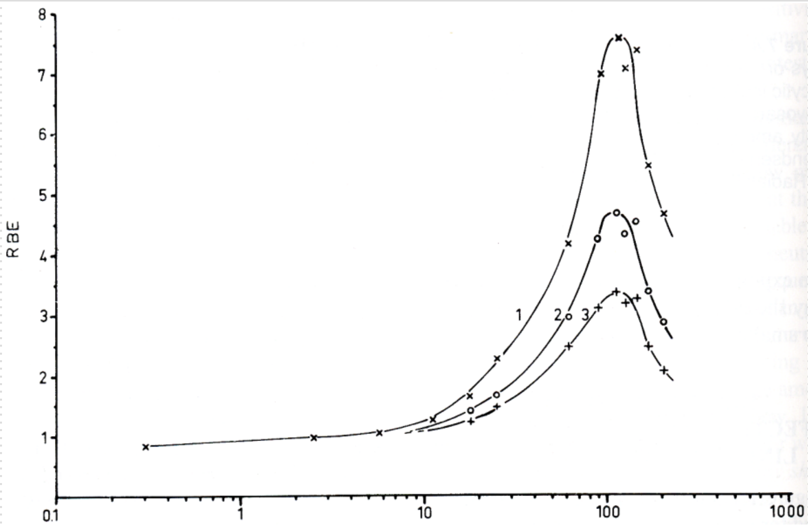
- **How to optimize the kVCBCT scan protocol to keep the imaging doses low while maintaining acceptable image quality?**
  - **Organ dose and dose-to-noise ratio of each organ can be incorporated into an optimizer for clinically relevant solution**
  - **Correlation between clinically acceptable image quality and scan protocol parameters needs to be fine-tuned**
  - **Different correlations for different kVCBCT imaging devices**

KV vs. MV Photons

- **Linear Energy Transfer (LET)**

Radiation	Linear Energy Transfer, KeV/μm	
Cobalt-60 γ-rays	0.2	
250-kV x-rays	2.0	
10-MeV protons	4.7	
150-MeV protons	0.5	
	Track Avg.	Energy Avg.
14-MeV neutrons	12	100
2.5-MeV α-particles	166	
2-GeV Fe ions	1,000	

Hall EJ, Radiobiology for the radiologist, 5th ed.

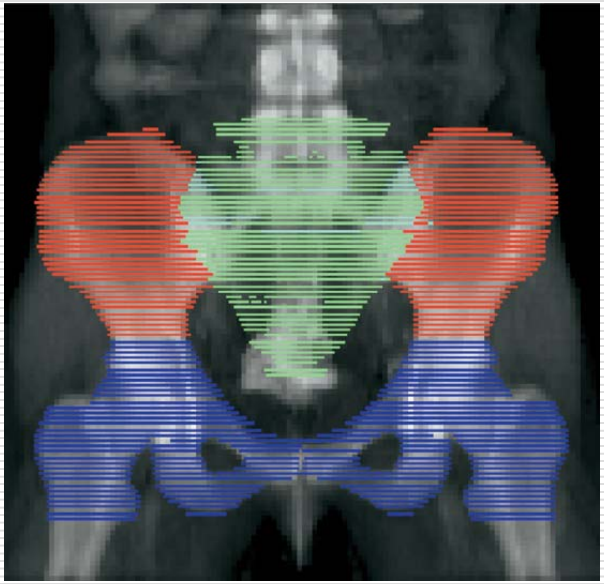


- **RBE vs. LET**
  - RBE ranges from 1 to 2 for 40-125 kV photons in CBCT

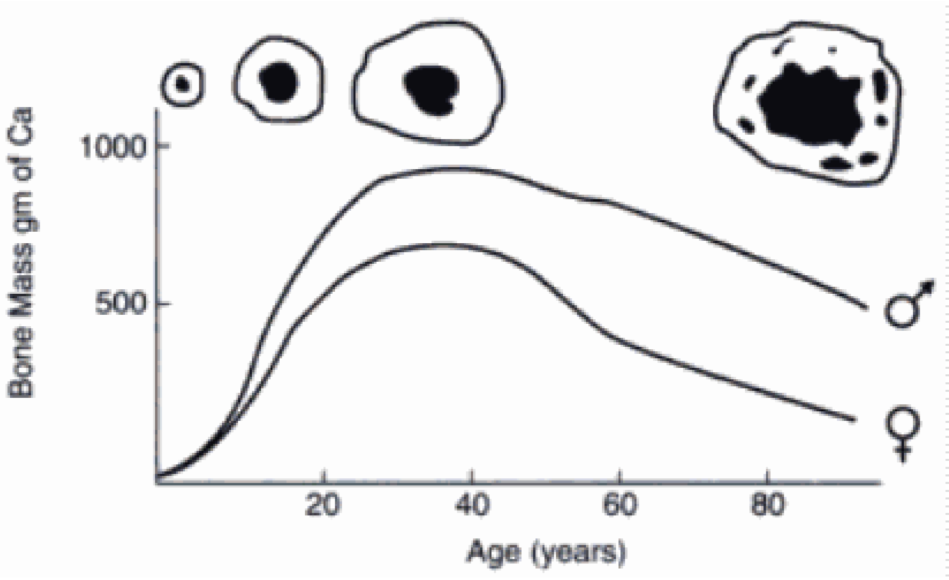
- **Relative Biologic Effectiveness (RBE)**
  - depends on radiation quality (LET), dose, number of dose fractions, dose rate as well as biologic system

Red Bone Marrow

- **Bone and bone marrow doses due to kVCBCT**
  - **Bone density varies with age and gender**
  - **Bone marrows at iliac, lumbosacral, and lower pelvic account for >50% of total BM**
  - **Reducing BM irradiation may reduce CRT toxicity and consequently, improve treatment efficacy**



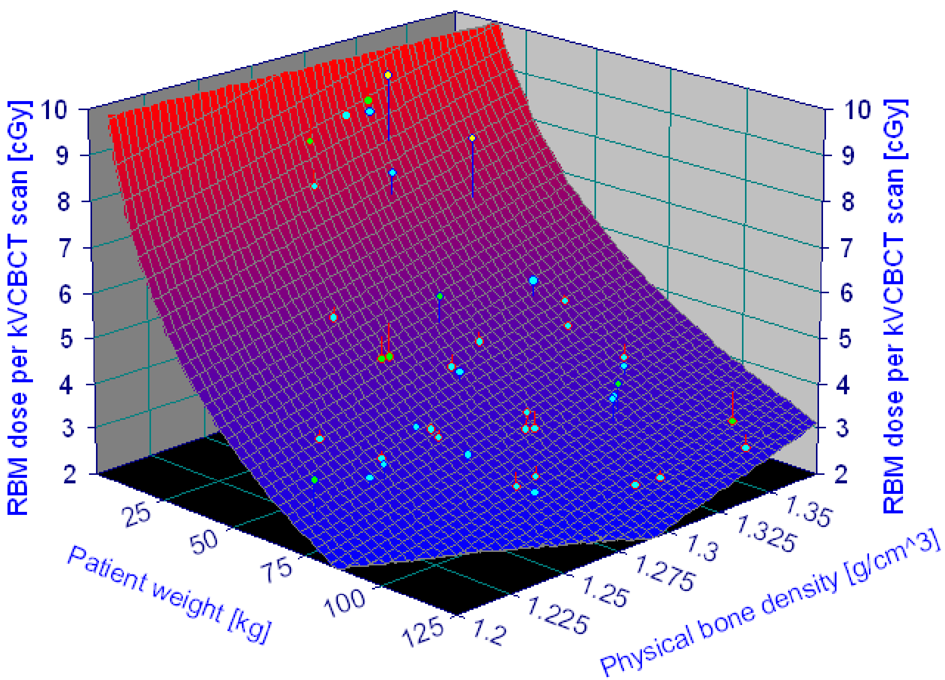
Mell LK et al, IJROBP, 1356-65, 2006

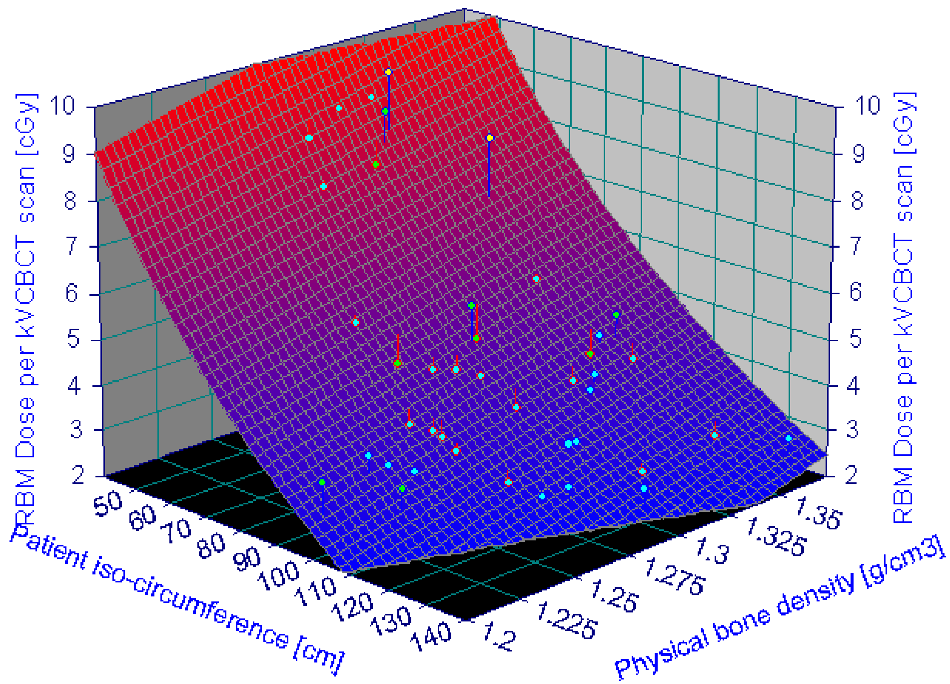


Kaplan FS et al, Form and function of bone, in Simon SR (ed.) Orthopaedic Basic Science (1994)

Leukemia Risk Attributable to kVCBCT

- **Empirical functions proposed to estimate dose deposition to patients due to kVCBCT, based on Monte Carlo study of forty-two patients of various ages and sizes**





Zhang Y, Yan Y, Nath R, Bao S, Deng J, Phys Med Biol 2012 (accepted)

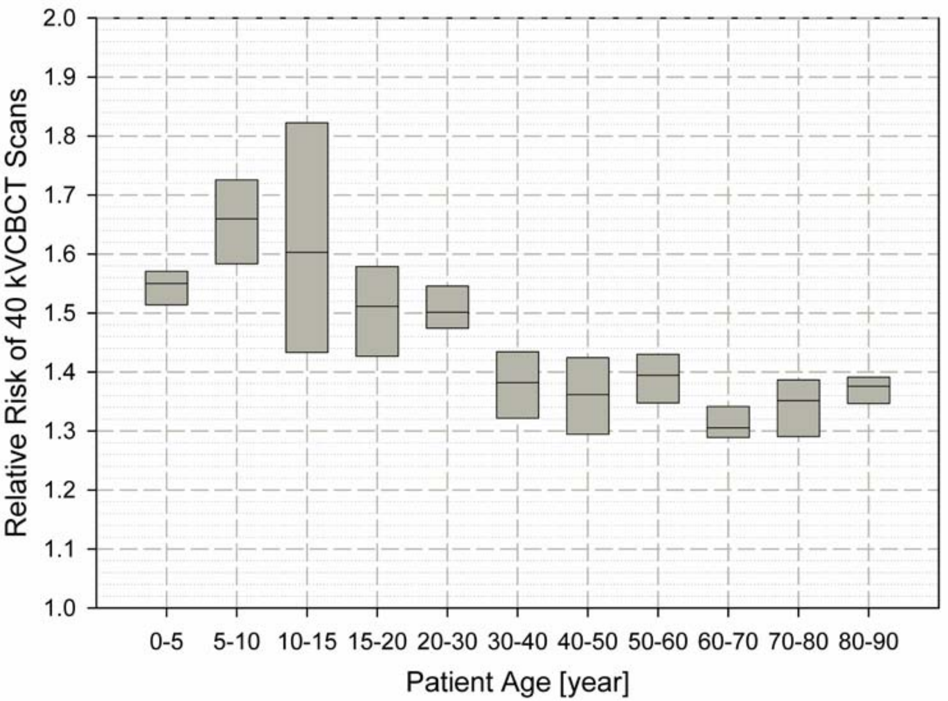
Improved Boice's Model for Risk Assessment

- **An improved Boice's model developed for customized risk assessment of radiogenic leukemia due to kVCBCT**
- **During a typical RT course, 40 scans of pelvic kVCBCT could lead to increased leukemia risk by 29% to 81%, with higher risk observed for children**

$$I(D) = (a_0 + a_1 D + a_2 D^2)\exp(b_1 D + b_2 D^2)$$

a_i **- linear-quadratic induction,**
b_i **- coefficients for exponential term representing a dose-dependent reduction in risk that would result in a downturn of risk at sufficiently high doses (>4 Gy)**

Relative Risk $RR(D) = \frac{I(D)}{I(0)}$



Upton AC. Radiation Research, 71(1): 51-74, 1977.

Boice, Blettner, Kleinerman, et al. JNCI, 79(6): 1295-1311, 1987.

Leukemia Risk Attributable to kVCBCT

- Physical bone density strongly correlated with red bone marrow dose
- Considerable dose overestimation (9%~42%) if the whole bone was used as a surrogate of red bone marrow
- Relative leukemia risk attributable to the 40 pelvic kVCBCT scans varied from 1.29 to 1.82, with higher risks in children
- Personalized assessment of leukemia risk caused by pelvic kVCBCT scans is clinically feasible with proposed empirical functions and an improved Boice's model

Partial answer to question #4

- **How large is the cancer risk associated with the kVCBCT imaging doses?**
  - **Considerable leukemia risk (29%-82%) is associated with doses to red bone marrows from 40 kVCBCT pelvic scans**
  - **Higher cancer risks for younger patients**
  - **Large uncertainty due to limited number of subjects enrolled**
  - **Benefits of prudent medial imaging procedures at low dose levels outweigh the radiation-induced cancer risks**

Image Gently

- An initiative of the Alliance for Radiation Safety in Pediatric Imaging

- To change practice by increasing awareness of the opportunities to lower radiation dose in the imaging of children

- Pause and Pulse: pediatric fluoroscopy imaging

  - Pause and child-size the technique

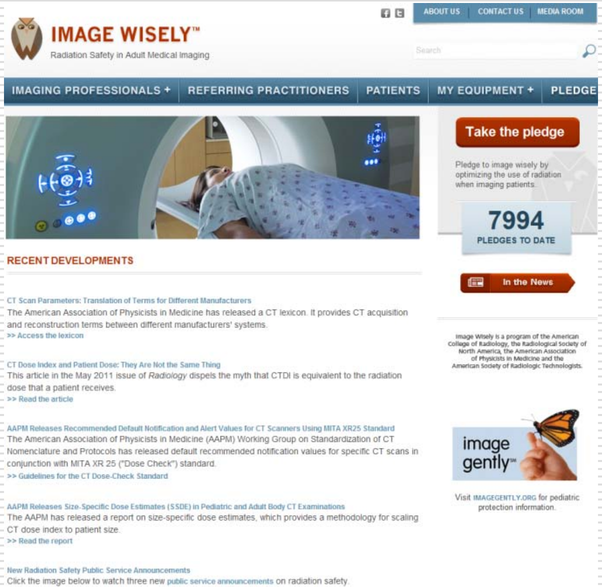
  - Use lowest pulse rate possible

  - Consider US or MRI when possible

www.imagegently.org

Image Wisely

- Awareness program of ACR, RSNA, AAPM & ASRT
- To change practice by increasing awareness of the opportunities to lower radiation dose in the imaging of adults
- Avoid unnecessary ionizing radiation scans and use lowest optimal radiation dose for necessary studies



www.imagewisely.org

AAPM, ASTRO & RSNA

- CT dose summit (AAPM, RSNA ACR, MITA)
  - An interdisciplinary approach to optimizing image quality and managing patient dose
- Reference CT scan protocols
  - Adult brain perfusion CT: http://www.aapm.org/pubs/CTProtocols/documents/AdultBrainPerfusionCT_2011-01-11.pdf
- Numerous publications
  - McCollough CH, et al, Strategies for reducing radiation dose in CT. Radiol Clin North Am. 2009;47(1):27-40.

AAPM Official Statement

AAPM Position Statement on Radiation Risks from Medical Imaging Procedures

December 13, 2011

The American Association of Physicists in Medicine (AAPM) acknowledges that medical imaging procedures should be appropriate and conducted at the lowest radiation dose consistent with acquisition of the desired information. Discussion of risks related to radiation dose from medical imaging procedures should be accompanied by acknowledgement of the benefits of the procedures. Risks of medical imaging at effective doses below 50 mSv for single procedures or 100 mSv for multiple procedures over short time periods are too low to be detectable and may be nonexistent. Predictions of hypothetical cancer incidence and deaths in patient populations exposed to such low doses are highly speculative and should be discouraged. These predictions are harmful because they lead to sensationalistic articles in the public media that cause some patients and parents to refuse medical imaging procedures, placing them at substantial risk by not receiving the clinical benefits of the prescribed procedures.

AAPM members continually strive to improve medical imaging by lowering radiation levels and maximizing benefits of imaging procedures involving ionizing radiation.

More Comments

- **No evidence of a carcinogenic effect for acute irradiation at doses less than 100 mSv or for protracted irradiation of doses less than 500 mSv (1)**
- **Fears associated with concept of linear no-threshold model and the idea that any dose, even the smallest, is carcinogenic, lack scientific justification (Hendee W, 2011, RSNA)**

[1]Tubiana et al. Radiology. 2009; 251(1): 13-22.

Conclusions

- KVCBCT imaging doses can be clinically significant and should be incorporated into treatment planning design and decision making
- It is feasible to personalize low-dose kVCBCT for individual patient with acceptable image quality
- More research work is needed to improve the efficiency of kVCBCT and patient safety
  - Better x-ray tube design
  - Better image reconstruction algorithm
  - Better x-ray detector

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Thank You!