Imaging Refresher for Standard of Care Radiation Therapy

Review of CT Imaging Including CBCT

Zacariah Labby, Ph.D.

Conflict of Interest

- None to disclose
- Mention of specific vendors or products does not imply endorsement of these vendors or products

Outline

- What are the basic principles governing x-ray computed tomography (CT)?
- How are CT images formed?
- What are the different ways CT technology is used in clinical radiation therapy?
- What trade-offs must be considered in CT imaging?

Basic Physical Principles of X-ray CT

- X rays generated in x-ray tube

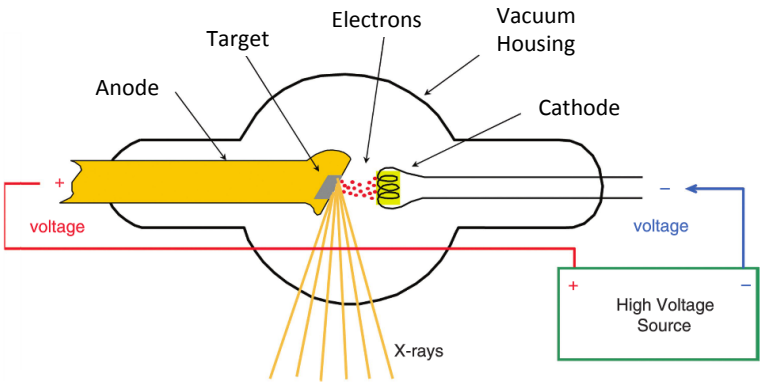

Fig 6-1, Bushberg et al, The Essential Physics of Medical Imaging, 3rd Ed.

Basic Physical Principles of X-ray CT

- Spectrum of Bremsstrahlung x rays have characteristic shapes

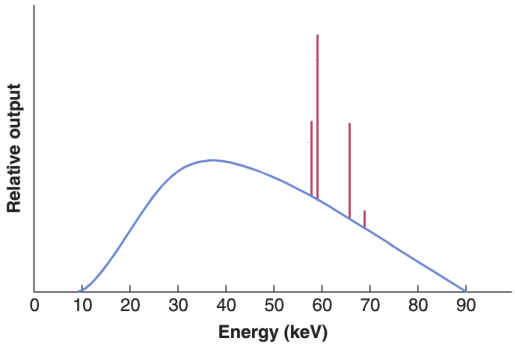

Fig 6-5, Bushberg

Basic Physical Principles of X-ray CT

- Generated X rays interact in matter via one of two main processes
  - Photoelectric Interaction
  - Compton Interaction

Basic Physical Principles of X-ray CT

- Photoelectric Effect
  - Incident photon is absorbed (leads to contrast!)
  - Output: Characteristic x rays, electrons
  - Interaction Probability per mass ≈ Z^3/E^3

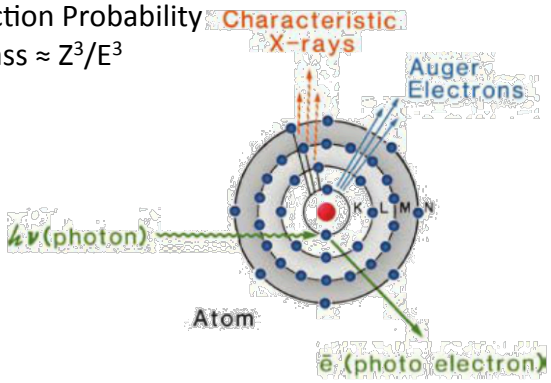

Fig 5.5, Khan, The Physics of Radiation Therapy, 4th Ed.

Basic Physical Principles of X-ray CT

- Compton Scattering
  - Incident photon absorbed
  - Output: Scattered photon and electron
  - Interaction Probability approx. constant over diagnostic energy range; depends on electron density

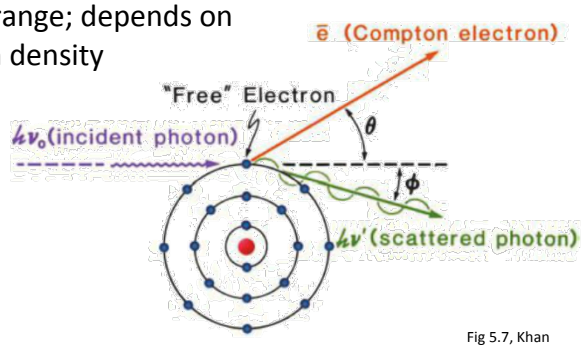

Fig 5.7, Khan

Basic Physical Principles of X-ray CT

- Balance of interactions changes with energy and material ($Z_{effective}$)
- Higher Z_{eff}, more Photoelectric, more contrast

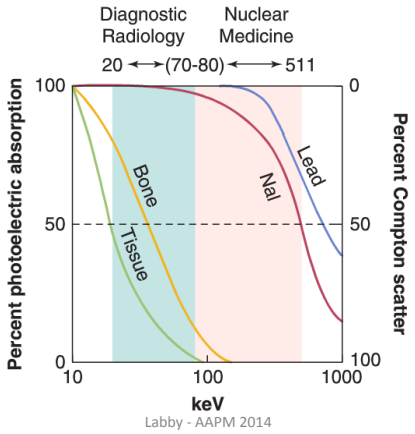

Fig 3-11, Bushberg

Basic Physical Principles of X-ray CT

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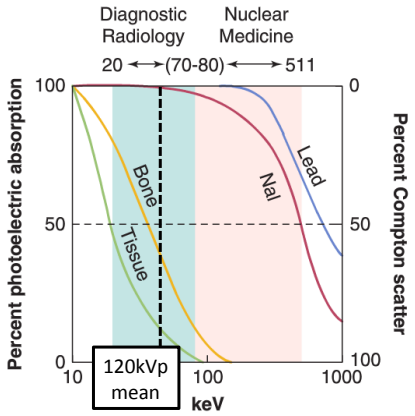


Fig 3-11, Bushberg

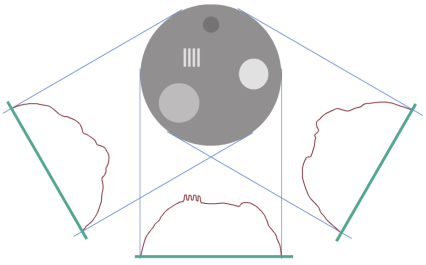
Basic Physical Principles of X-ray CT

- X rays that penetrate the object (and are not blocked by anti-scatter grid) are detected

Fig 7-22, Bushberg

CT Image Formation

- Projections from object are "reconstructed" into a tomographic (i.e., sectioned) representation of the object
- Acquire projections at multiple axial positions to get a 3D image volume



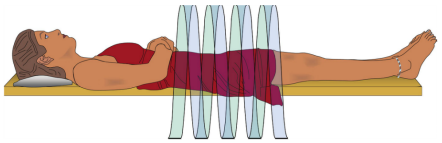


Fig 10-34, 54, Bushberg

CT Image Formation

- Reconstructed images are "maps" of apparent attenuation coefficient values
  - Named "Hounsfield Units"
  - Attenuation averaged over x-ray tube spectrum
  - Attenuation averaged within volume of voxels
  - Calculated against known attenuation of water

$$HU\left(x,y,z\right)=1000\left[\frac{\mu\left(x,y,z\right)-\mu_{water}}{\mu_{water}}\right]$$

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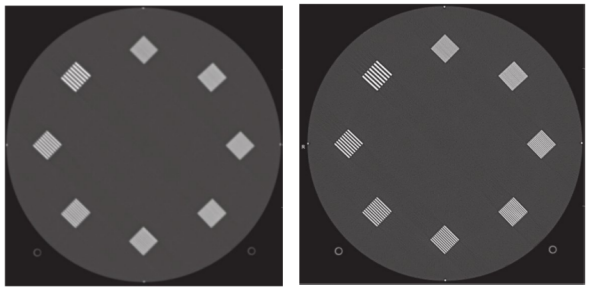
CT Image Formation

- Contrast: Inherent difference in attenuation between structures
  - Much more Compton Interaction in Soft Tissue
  - Contrast due to electron density differences
  - Photoelectric: Z_{eff} causes contrast
- Noise: Apparent difference in attenuation within uniform structures from random fluctuations

CT Image Formation

- Different reconstruction parameters lead to different trade-offs
  - Kernels affect balance between noise and resolution

ACR phantom –spatial resolution section



A. soft tissue kernel **B**. bone kernel

Fig 10-57, Bushberg

Utility of CT

- Main use of CT Imaging in Radiation Therapy:
- Develop a Patient Model!
  - Geometric localization of patient anatomy
  - Mapping the (approximate) composition of the patient
  - Calculating how radiation will interact with the patient

Major assumptions of CT-in-RT Model

- MV interaction properties are adequately modeled with information only from the kV CT
  - HU-to-electron density curve approximates the MV Compton interaction properties
- Luckily, even kV spectra are dominated by Compton

Gammex Tissue Characterization Phantom, Model 467

Major assumptions of CT-in-RT Model

- In traditional treatment planning, assume a static patient model
  - Any temporary features in CT scan (i.e., radiopaque inserts, highly-concentrated contrast like iodine or barium, etc.) should be treated with caution
  - Structures are assumed to not change (i.e., static model over the course of treatment)
    - Re-scanning during the course of treatment is often prudent if doubts exist

Applications of CT in RT

- Patient Simulation
  - 3D CT
  - 4D CT
- Patient Alignment
  - Cone beam CT
  - MV CT

Applications of CT – 3D Sim

- Simulation CT
  - Typically multi-slice
  - Used to build patient treatment model
  - Helical acquisition, pitch ≈ 1.0
- Large bore accommodates patients in various treatment positions

Philips Brilliance Big Bore CT

Applications of CT – 3D Sim

- Model the patient **in treatment geometry**, usually for dose calculations and structure definitions
- Often using immobilization equipment
  - May require larger bore, depending on patient population and intended treatments
- Requires image quality, spatial accuracy

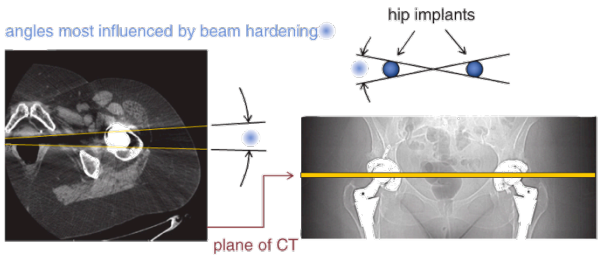
Quality assurance for computed-tomography simulators and the computed-tomography-simulation process: Report of the AAPM Radiation Therapy Committee Task Group No. 66

Sasa Mutic[a)]
Department of Radiation Oncology, Washington University School of Medicine, St. Louis, Missouri 63110

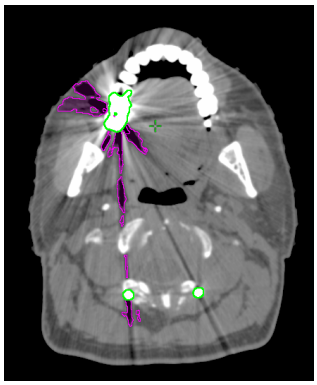
AAPM TG-66, MedPhys vol. 30, p. 2762 (2003)

Applications of CT – 3D Sim

- Most common artifacts: Beam Hardening and Streaks from high-Z or high-density objects
  - Some projections harden the poly-energetic spectrum
  - Data may be inconsistent
  - Commercial solutions reduce artifacts



Figs 10-65, Bushberg



Applications of CT – 4DCT

- Used to create dynamic patient model
  - Assess changes in geometry with respiratory cycle
- One strategy for motion management

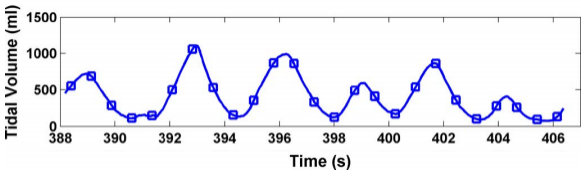
The management of respiratory motion in radiation oncology report of AAPM Task Group 76[a)]

Paul J. Keall[b)]
Virginia Commonwealth University (Chair)

AAPM TG-76, MedPhys vol. 33, p. 3874 (2006)

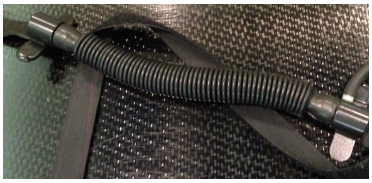
Applications of CT – 4DCT

- Individual projections sorted into phase bins

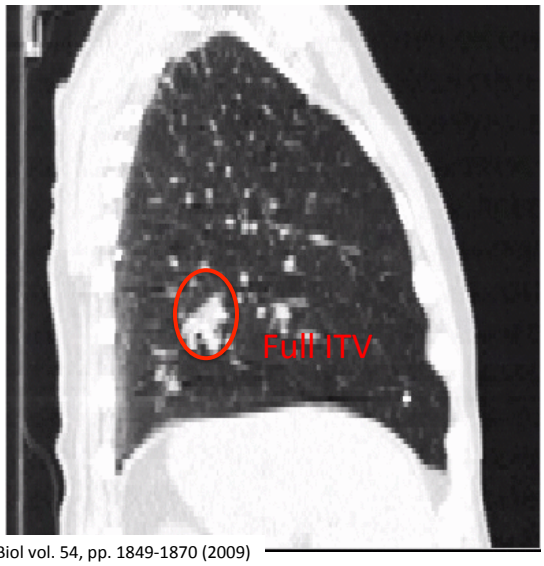


Lu et al, Med Phys vol. 33, p. 2964 (2006)

- Signal from spirometry surrogate (e.g., bellows belt)
- Create Internal Target Volume (ITV) by inspecting internal motion[ICRU report 62, 1999]



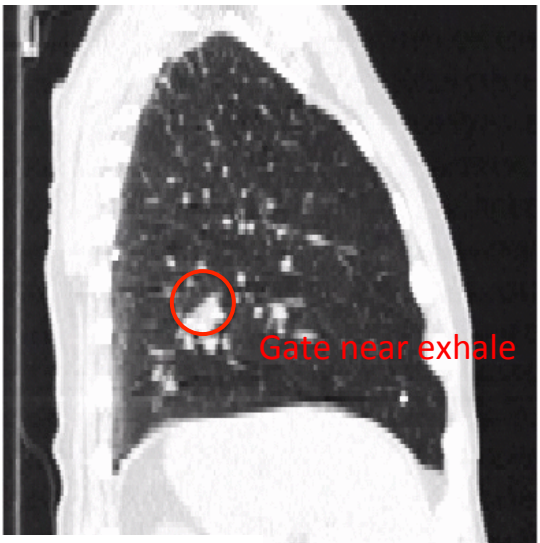
Applications of CT – 4DCT



Example 4DCT from www.DIR-Lab.com, courtesy of R. Castillo

Castillo, R., et al, Phys Med Biol vol. 54, pp. 1849-1870 (2009)

Applications of CT – 4DCT

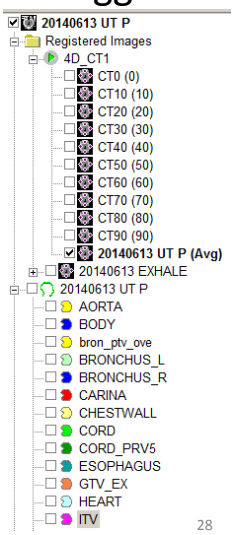


Example 4DCT from www.DIR-Lab.com, courtesy of R. Castillo

Castillo, R., et al, Phys Med Biol vol. 54, pp. 1849-1870 (2009)

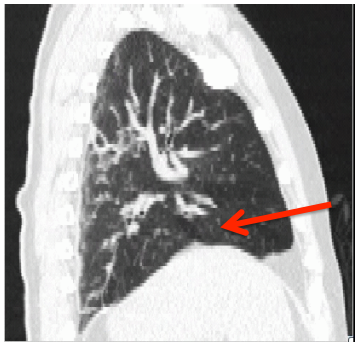
Applications of CT – 4DCT

- ITV from 4D scan, dose calc'ed on "untagged" or "average" reconstruction
- Not all 4D-CT are good enough for ITV delineation
  - Backup plan:
  - Acquire good quality breath-hold 3D-CT, then apply margins



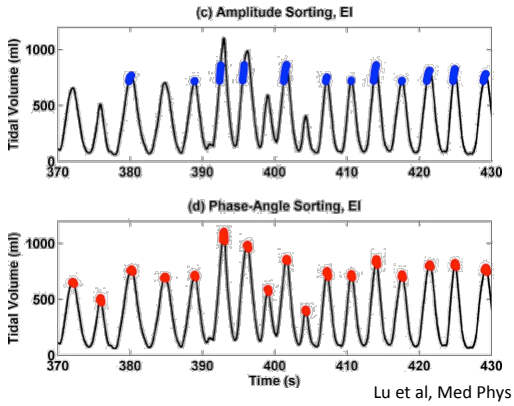
Applications of CT – 4DCT

- Artifacts from phase sorting resulting from irregular breathing cycle or inadequate table pitch
- Each axial position must be sampled at all phases



- Amplitude sorting can reduce artifacts

Applications of CT – 4DCT



Lu et al, Med Phys vol. 33, p. 2964 (2006)

- Amplitude sorting can reduce artifacts

Applications of CT – CBCT

- Most sim-CT scanners have small θ_{cone}
- Linac-mounted CT systems have θ_{cone} = 11-15°
- Single rotation, no table motion
  - Limited axial span
- Field of view limited by panel dimension, position

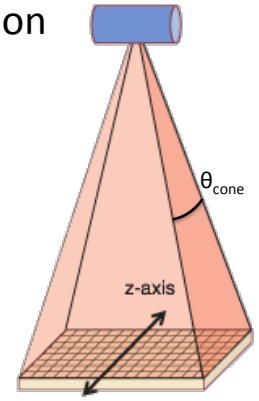


Fig 10-11, Bushberg

Applications of CT – CBCT

- Predominant use: volumetric imaging for alignment
  - Tomographic reconstruction better separates low-contrast (e.g., soft tissue) structures
- Identify rotations, deformations

Applications of CT – CBCT

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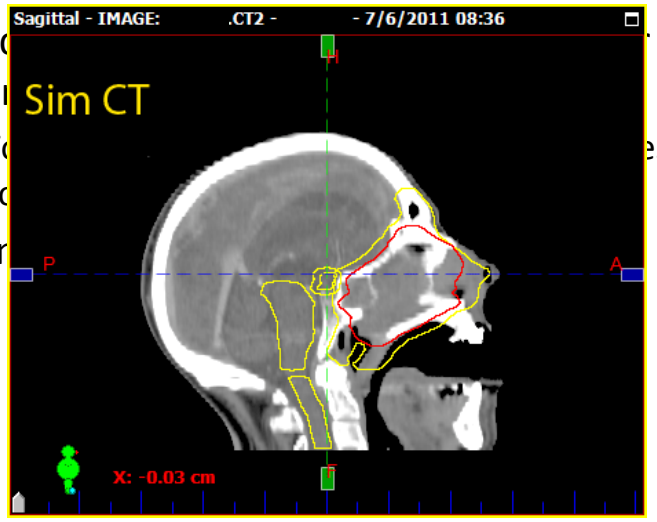

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Animation courtesy of Choonik Lee, Univ. of Michigan

Applications of CT – CBCT

- Functionality and utility depends on
  - Accurate registration of imager isocenter with machine isocenter
  - Image quality
  - Geometric accuracy
- QA and commissioning guided by TG-179

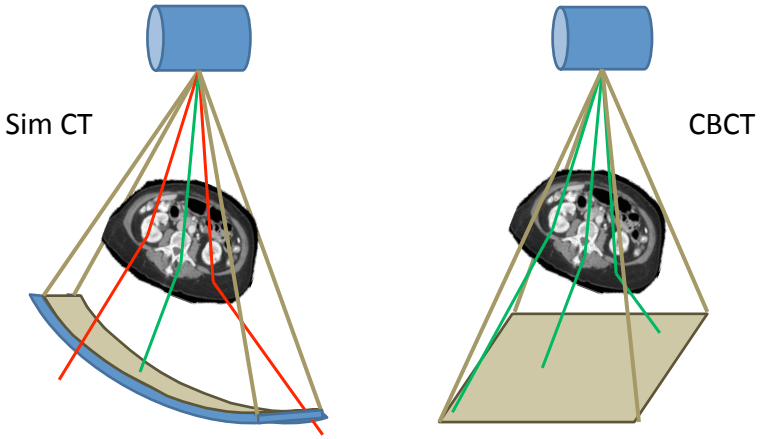
Quality assurance for image-guided radiation therapy utilizing CT-based technologies: A report of the AAPM TG-179

Jean-Pierre Bissonnette[a)]
Task Group 179, Department of Radiation Physics, Princess Margaret Hospital, University of Toronto, Toronto, Ontario, Canada, M5G 2M9

AAPM TG-179, Med Phys vol. 39, p. 1946 (2012)

Applications of CT – CBCT

- Additional artifacts in CBCT
  - Large 2D detector: large scatter detection



Applications of CT – CBCT

- Additional artifacts in CBCT
  - Large 2D detector: large scatter detection
  - Slow acquisition: abundant motion (respiratory and digestive)

Applications of CT – CBCT

- Additional artifacts in CBCT
  - Large 2D detector: large scatter detection
  - Slow acquisition: abundant motion (respiratory and digestive)
  - Filter positioning

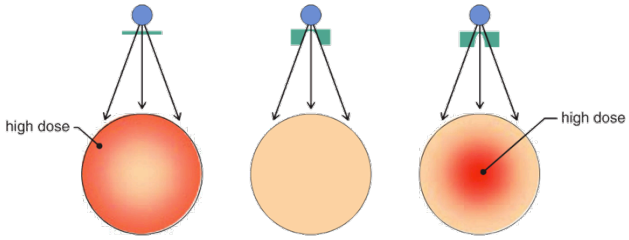


Fig 10-23, Bushberg

Applications of CT – CBCT

- Additional artifacts in CBCT
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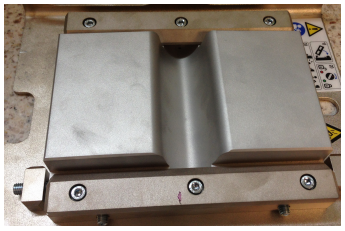
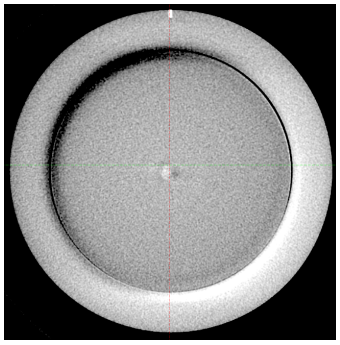
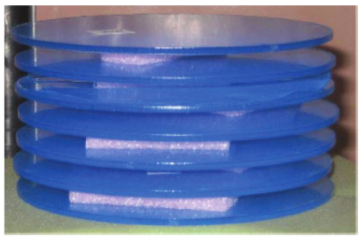


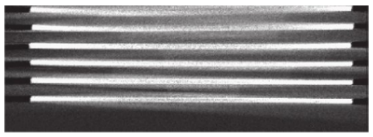


Applications of CT – CBCT

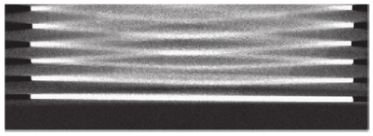
- Additional artifacts in CBCT
  - Cone beam reconstruction



A. Defrise phantom



B. Some cone beam artifacts



C. pronounced cone beam artifacts

Fig 10-69, Bushberg

Applications of CT – MVCT

- Like kV-CT, generates an attenuation map
- Ideally, a better patient model when imaging spectrum = treatment spectrum
- Not widely available
  - Accuray TomoTherapy uses detuned treatment beam (approx. 4MV)
  - No MV Sim CT

Applications of CT – MVCT

- Image contrast dominated by Compton interaction
  - Predominantly density-driven
  - More difficult to reject scatter with anti-scatter grid
  - Lower resolution, lower CNR at reasonable doses

Daily alignment MV CT images of prostate patient from TomoTherapy system

Animation courtesy of Choonik Lee, Univ. of Michigan

Tradeoffs in CT Imaging

- In general, trade-off between image quality and dose
  - Better quality requires more dose
- We need to accomplish our goal: accurate patient model
  - Identify structures
  - Delineate boundaries
  - Model radiation interactions
  - Align volumes

Tradeoffs in CT Imaging

- Noise proportional to

  mAs

  1/Sqrt(Voxel Volume)

- kVp dependence of dose less straightforward
  - Higher kVp = more photons generated
  - Higher kVp = less attenuation
  - Lower mAs with higher kVp? Not so fast
    - Loss of contrast at higher kVp might require more mAs to achieve identical task-specific SNR

Doses in CT Imaging

- Main metric for quantitative evaluation: CTDI
  - CT Dose Index is **not** patient dose
- Measured in standard phantoms
- $CTDI_w$ weights peripheral and central doses

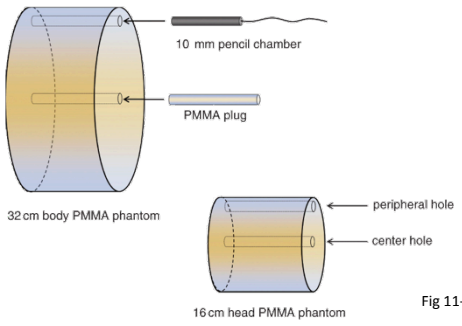


Fig 11-7, Bushberg

Doses in CT Imaging

- Example CTDI values (CTDI is **not** patient dose)
  - See session handout for references and specifics
  - Sim CT: 20-60 mGy
  - 4D CT: approx. 20 mGy (depends on pitch, 4D acquisition)
  - CBCT: 4-20 mGy
  - MVCT: 10-30 mGy

Doses in CT Imaging

- Good resource: TG-75

The management of imaging dose during image-guided radiotherapy: Report of the AAPM Task Group 75

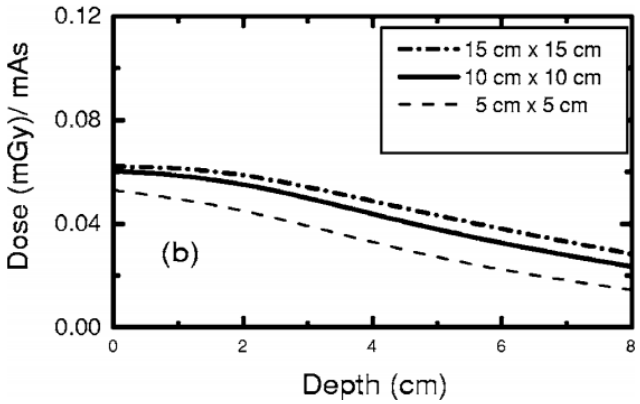
Martin J. Murphy
Department of Radiation Oncology, Virginia Commonwealth University, Richmond, Virginia 23298

AAPM TG-75, Med Phys vol. 34, p. 4041 (2007)

- CTDI only reports weighted dose in phantoms
- To estimate patient dose, use Size-Specific Dose Estimates (SSDE)
  - Useful to estimate SSDE for different body and scan types during commissioning of CT-sim

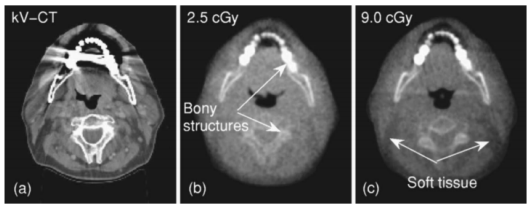
AAPM Report No. 204

Distribution of CT Dose

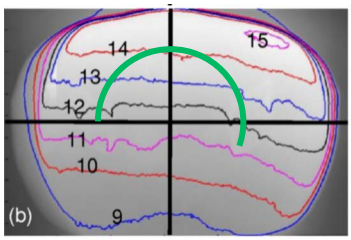


Dose per mAs from 100 kVp beam at different collimation settings in 16cm CTDI head phantom. Predominantly periphery-weighted.
Islam et al, Med Phys vol. 33, p. 1573 (2006)

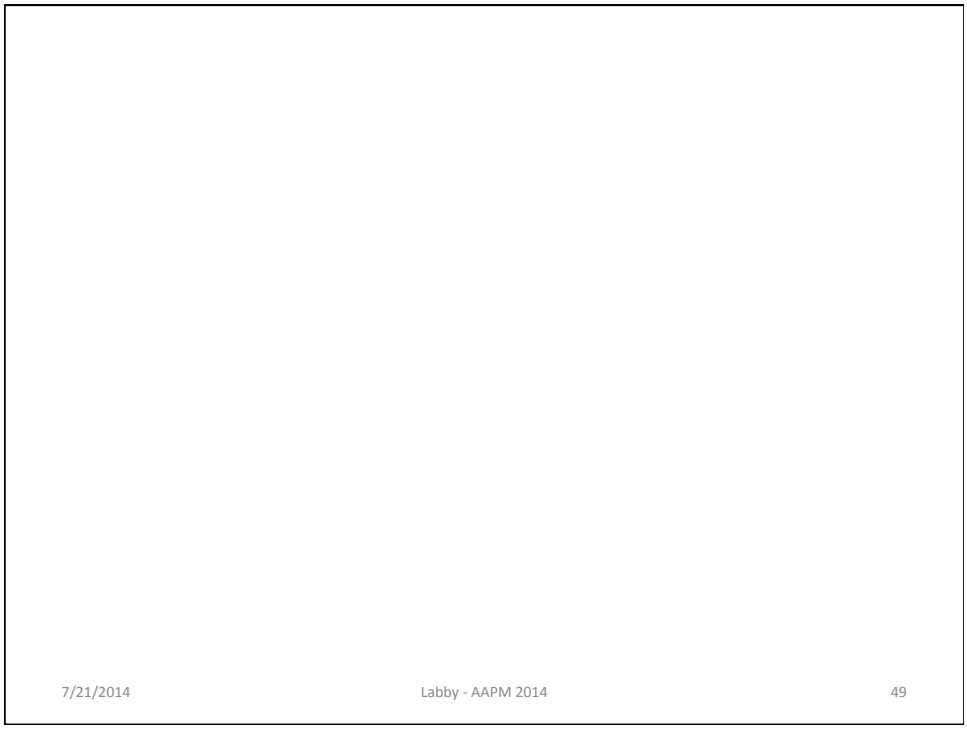
Distribution of MV CT Dose



Head MV-CT axial slice with different protocols. Siemens Primus linac.



Isodose lines [cGy] of pelvis MV CT, using Siemens 15MU protocol.
Arc rotation shown with green line.
Gayou et al, Med Phys vol. 34, p. 499 (2007)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Required Pitch for 4D-CT acquisition

By definition,

$$Pitch\ P = \frac{v_{table} * T_{rot}}{w_{detector}},$$

where v_{table} is the table motion velocity, T_{rot} is the period of CT gantry rotation, and $w_{detector}$ is the width of the detector (generally smaller than the full collimated beam width). The distance the table travels during one full respiratory cycle is given by

$$\frac{w_{detector} * P}{T_{rot}} * \frac{60}{BPM},$$

where BPM is the number of breaths per minute and T_{rot} is given in seconds. The requirement for full sampling of all axial positions during all respiratory phases is that the table translation during one full respiratory cycle cannot exceed the detector width. With that limit, we see that the pitch is limited by

$$P \leq \frac{BPM}{60} * T_{rot}.$$

Some CT vendors may suggest limiting the pitch further (i.e., limiting the pitch to $\alpha * BPM/60 * T\_rot$, where $\alpha \leq 1$) in order to account for irregular breathing patterns and/or detector binning methods.

Example CT Dose Index Values

Note: These values do **not** represent patient dose, and are given for example only. CTDI values for any other vendor/technique combination not shown here may be different than the values shown.

Type	CTDI Phantom	Technique	$CTDI_{vol}$
Sim CT [a]	Body	120 kVp, 300 mAs	15.9 mGy
Sim CT [a]	Head	120 kVp, 350 mAs	39.1 mGy
Sim CT (SRS) [a]	Head	140 kVp, 400 mAs	65.0 mGy
4D CT [a]	Body	120 kVp, effective 40 mAs/slice, pitch = 0.10	21.1 mGy
CBCT ("Std Dose Head") [b]	Head	100 kVp, 145 mAs	3.9 mGy
CBCT ("High Quality Head") [b]	Head	100 kVp, 720 mAs	19.4 mGy
CBCT ("Low Dose Thorax") [b]	Body	110 kVp, 262 mAs	4.7 mGy
CBCT ("Pelvis") [b]	Body	125 kVp, 680 mAs	17.7 mGy
MV CT [c]	Body	TomoTherapy beam	10-30 mGy

[a] Philips Brilliance Big Bore system, [b] Varian OBI Workstation ver. 1.5, [c] TG-75, p. 4050