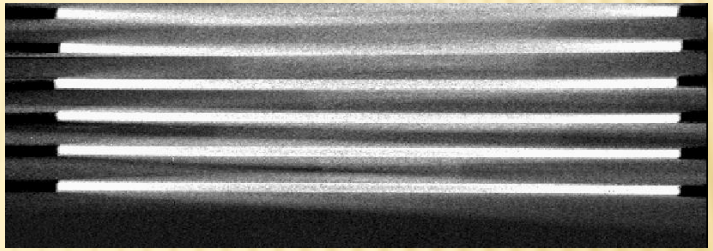
CALIFORNIA LAW AND RESPONSE
+
FIVE QUICK LESSONS ON CT DOSE OPTIMIZATION

John M. Boone, PhD
Professor and Vice Chair (Research) of Radiology
Professor of Biomedical Engineering
Department of Radiology

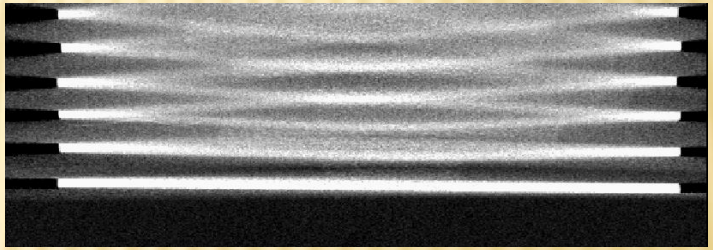
UCDAVIS
University of California, Davis

Visual demonstration of cone beam artifact

A. Defrise phantom



B. Some cone beam artifacts



C. pronounced cone beam artifacts

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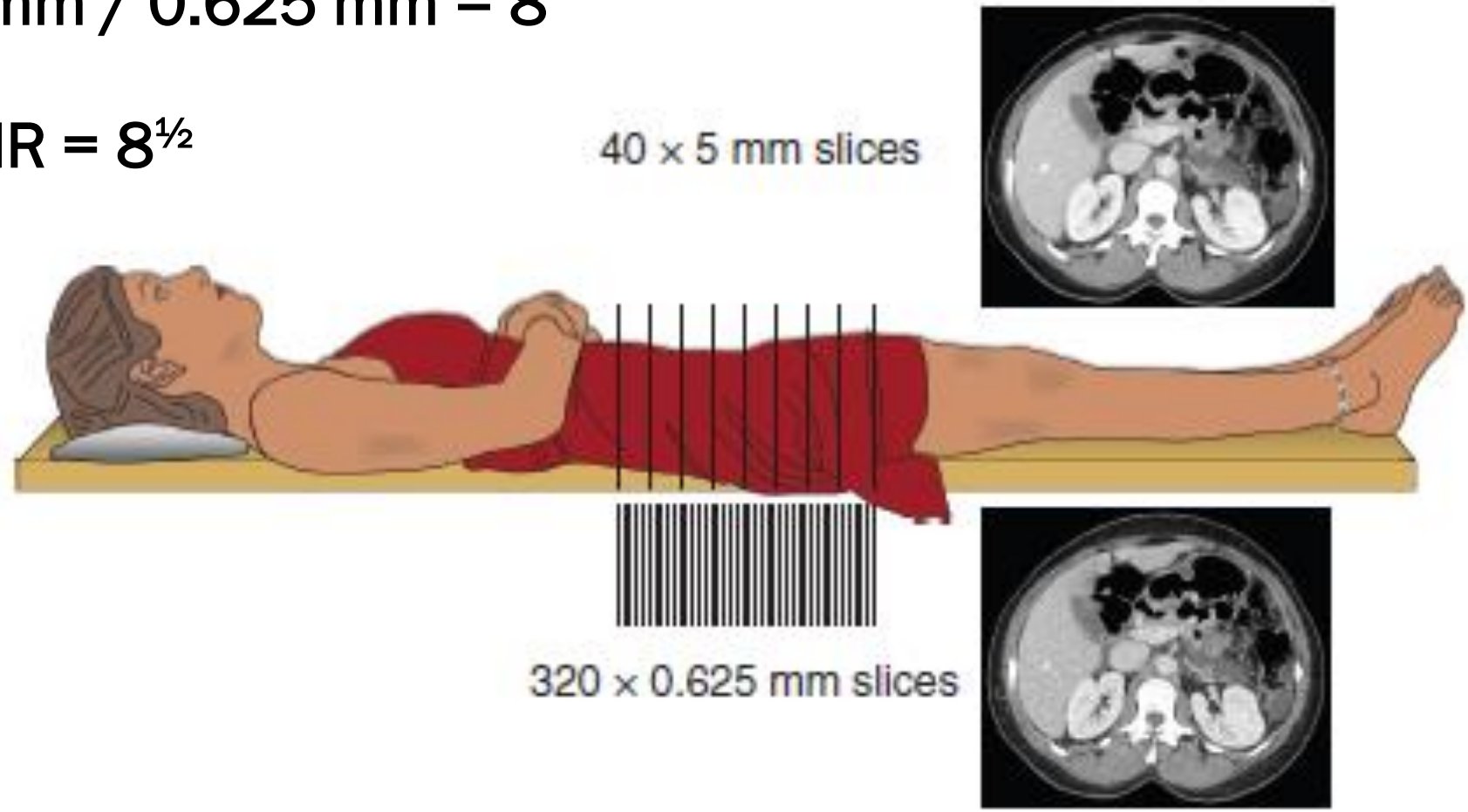
Five quick lessons on CT dose optimization

1. Slice thickness selection

Are your CT slices too thin?

5 mm / 0.625 mm = 8

SNR = $8^{1/2}$



2. Bow Tie Filters

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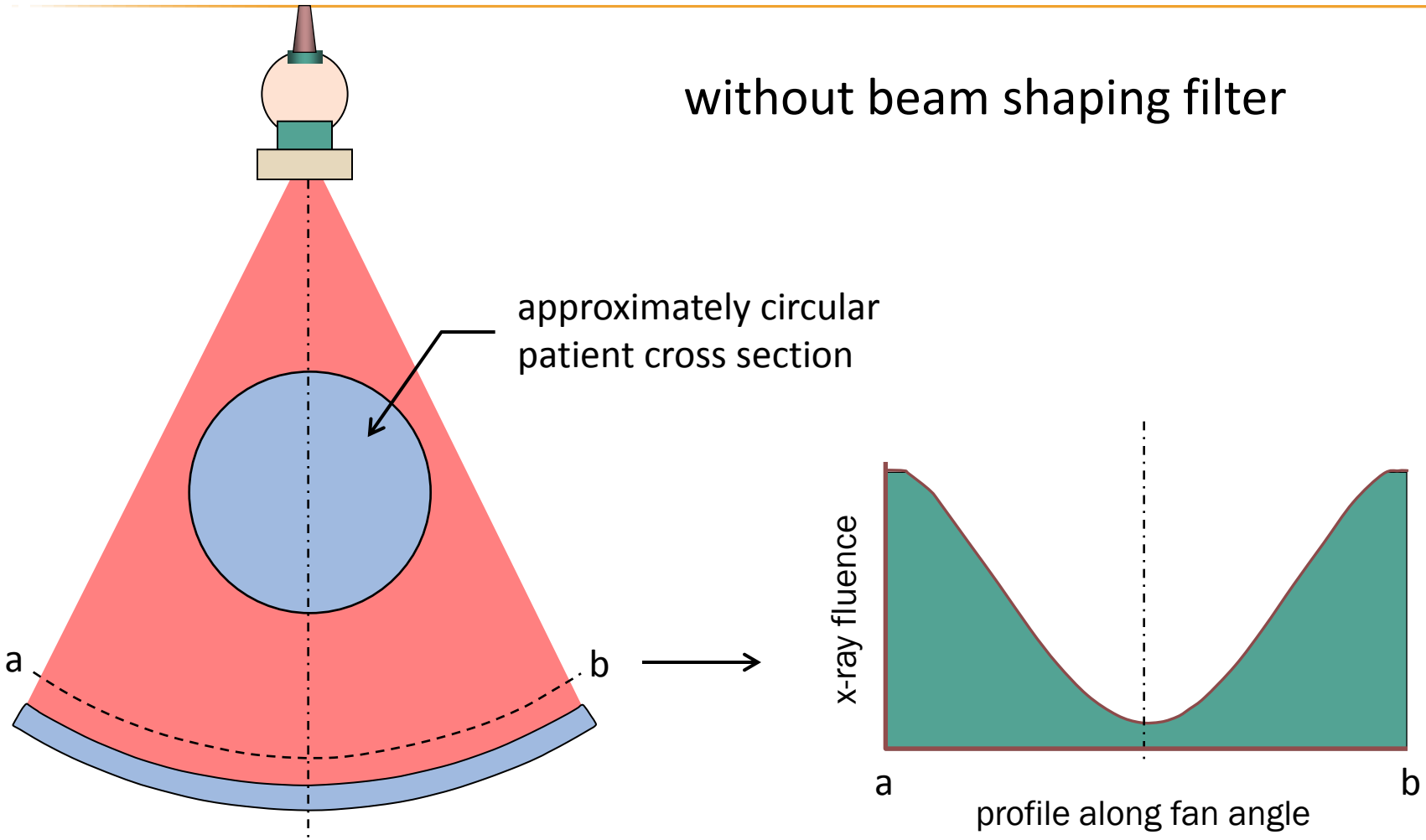

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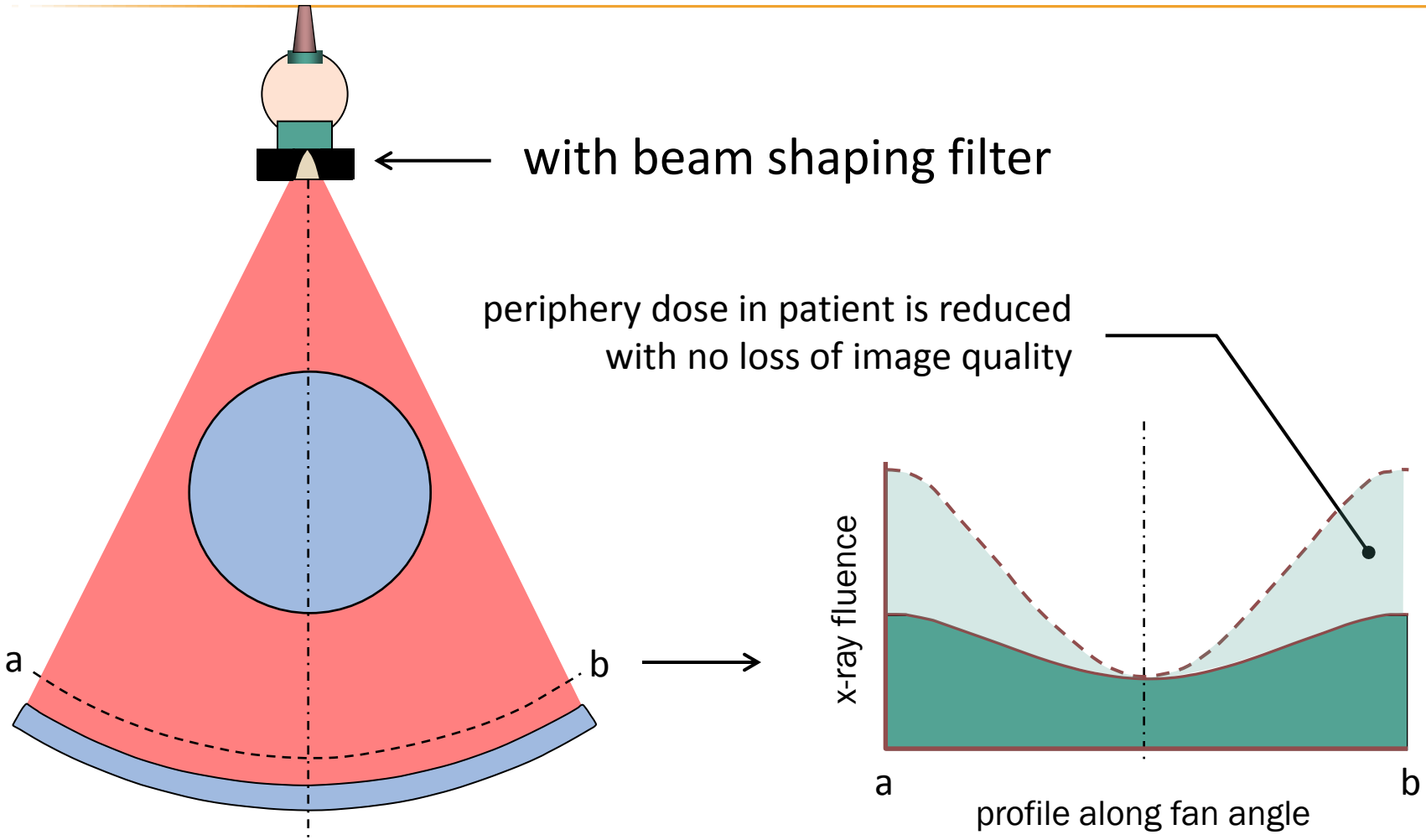

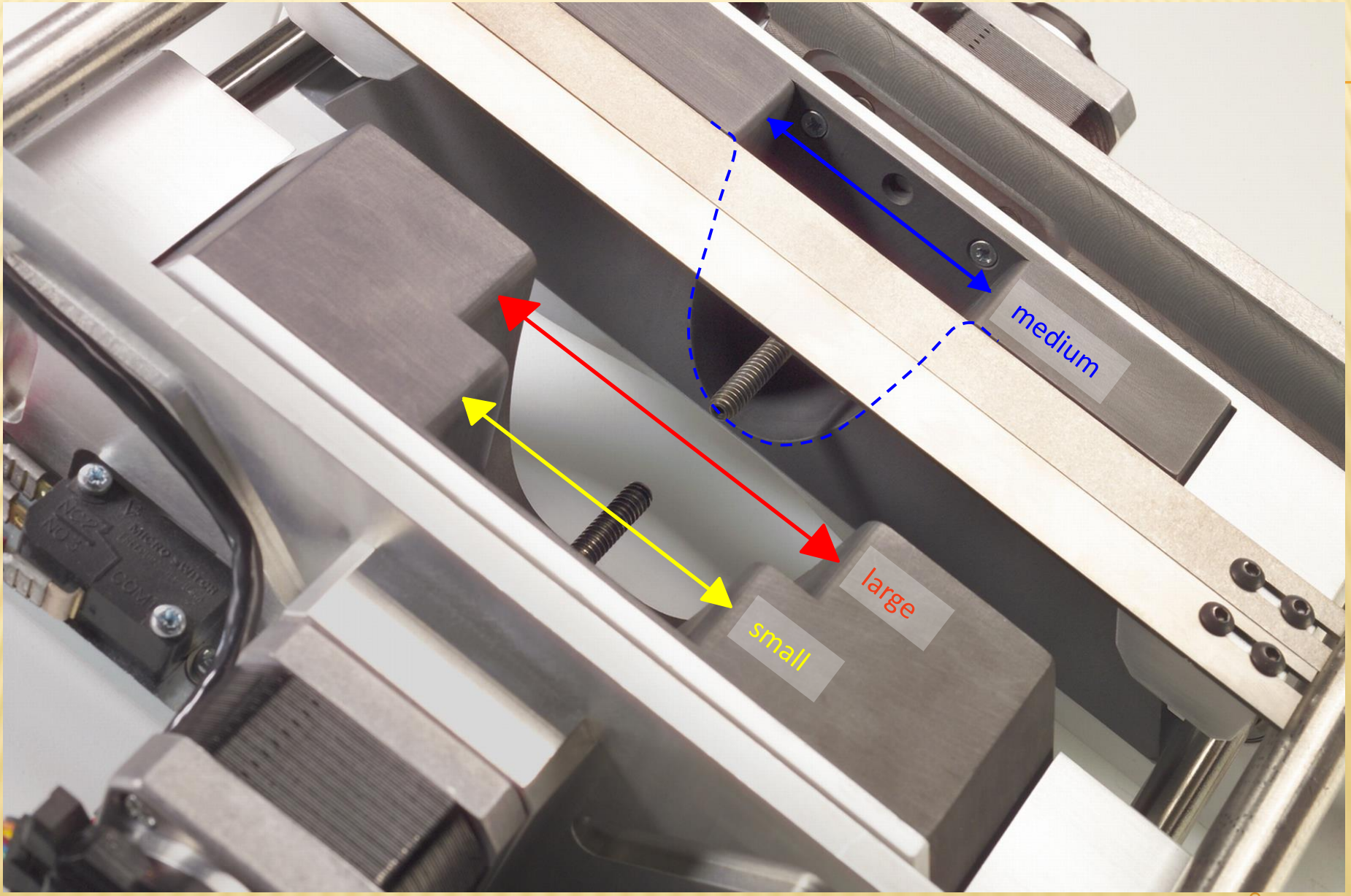
medium
large
small

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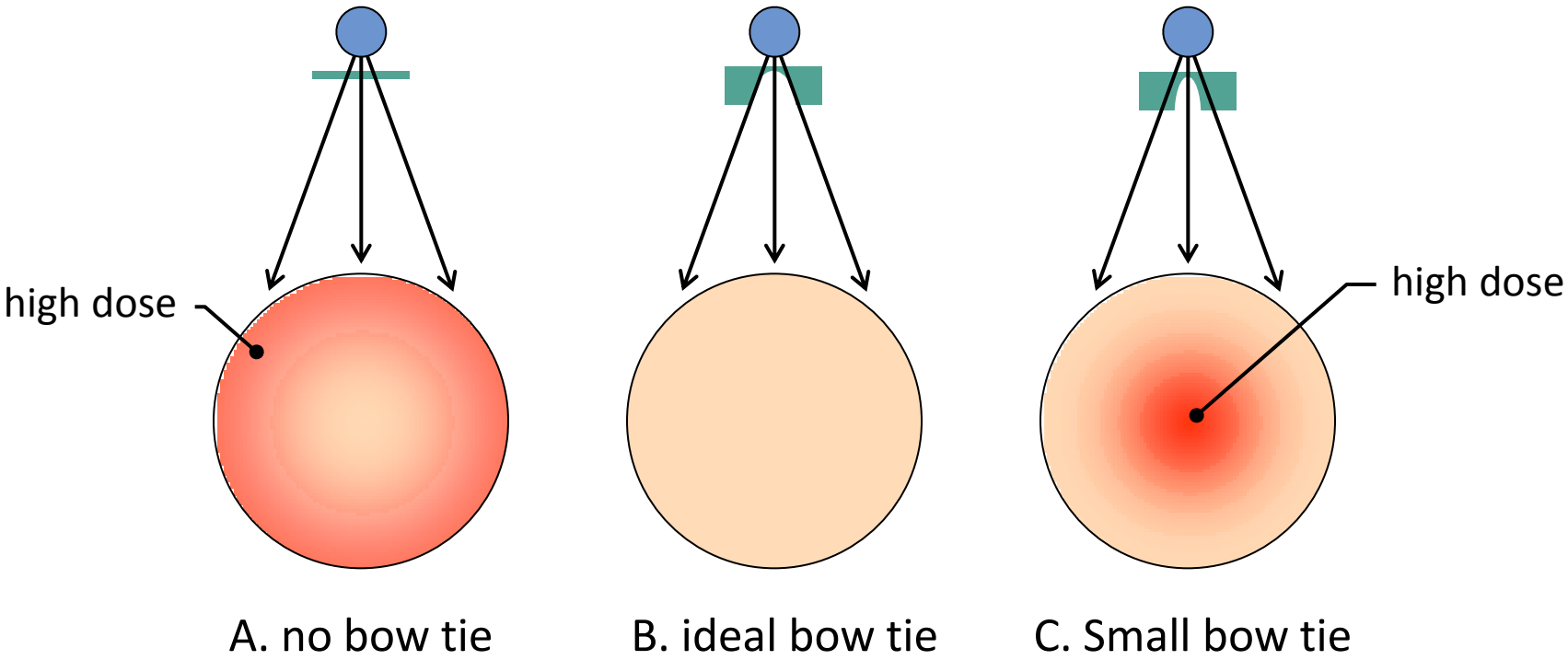
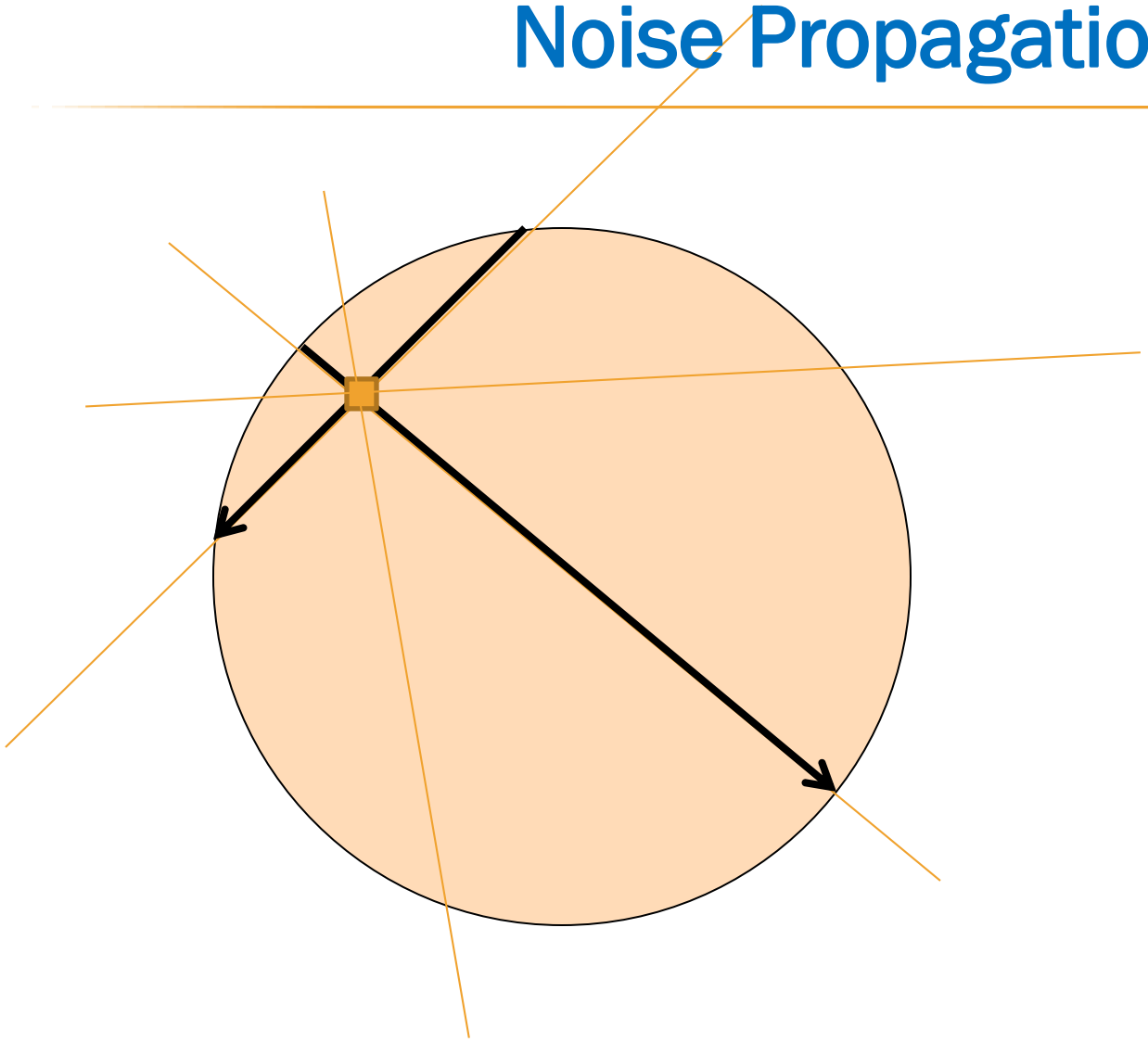


Noise Propagation



$$\sigma^2_{CTimage} = \sigma^2_{p1} + \sigma^2_{p2} + \sigma^2_{p3} + \ldots \sigma^2_{pN}$$

Five quick lessons on CT dose optimization

3. Automatic Exposure Control

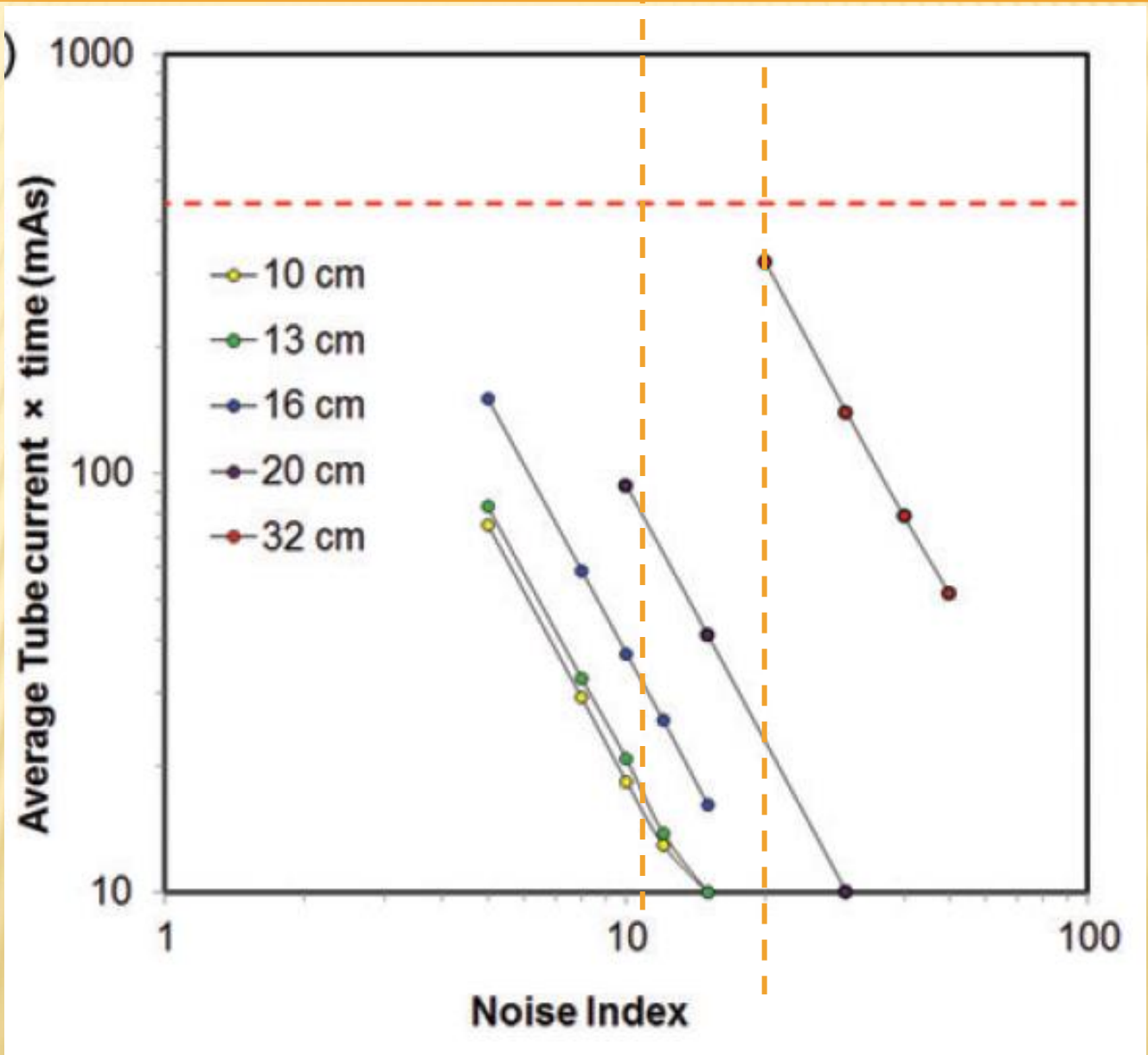
3a: overall dose control

3b: tube current modulation

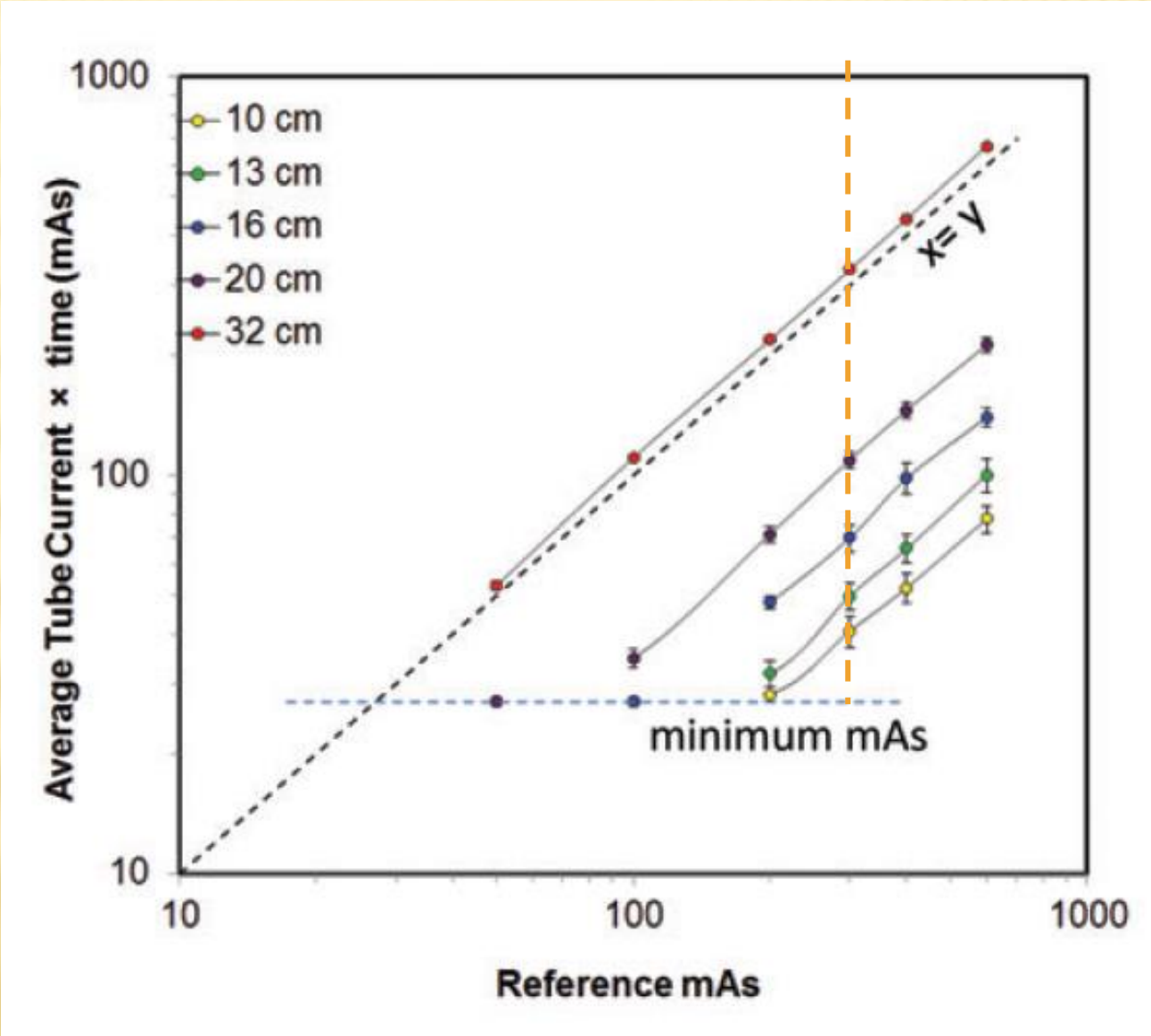
3. Automatic Exposure Control

- 3a: overall dose control
  3b: tube current modulation

General Electric AEC: Noise Index



Siemens AEC: Quality Reference mAs

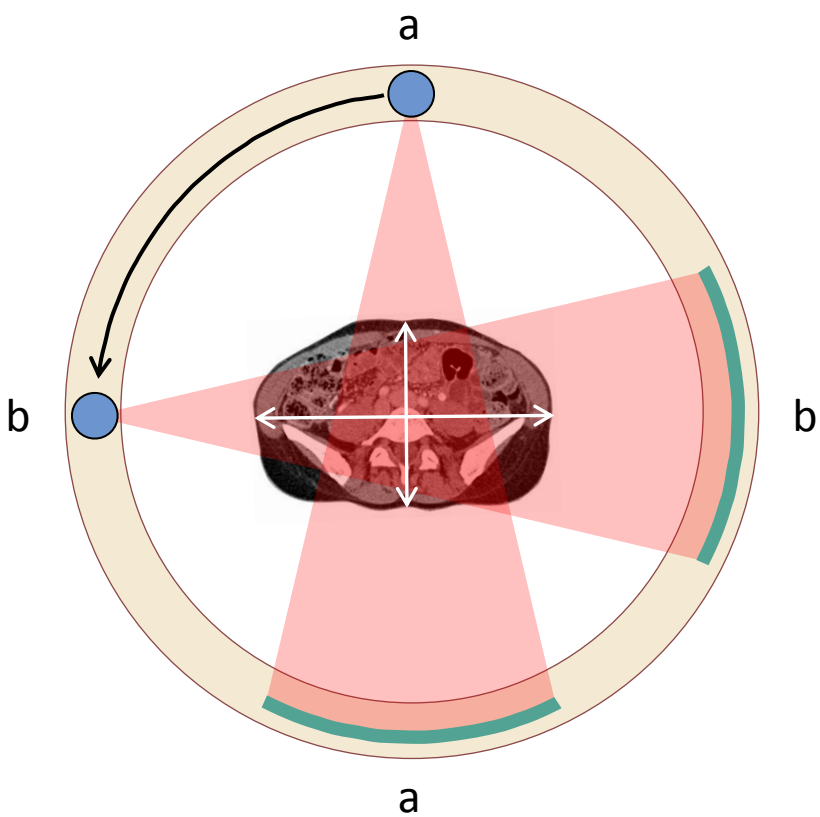


Five quick lessons on CT dose optimization

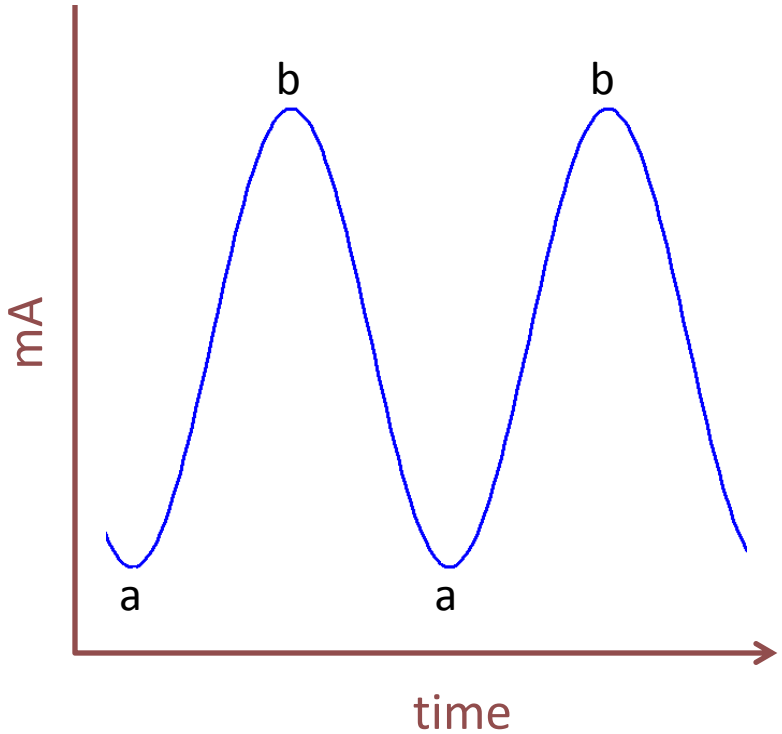
3. Automatic Exposure Control

- 3a: overall dose control
- 3b: tube current modulation

Five quick lessons on CT dose optimization



A. Tube rotation around oval patient



B. mA modulation

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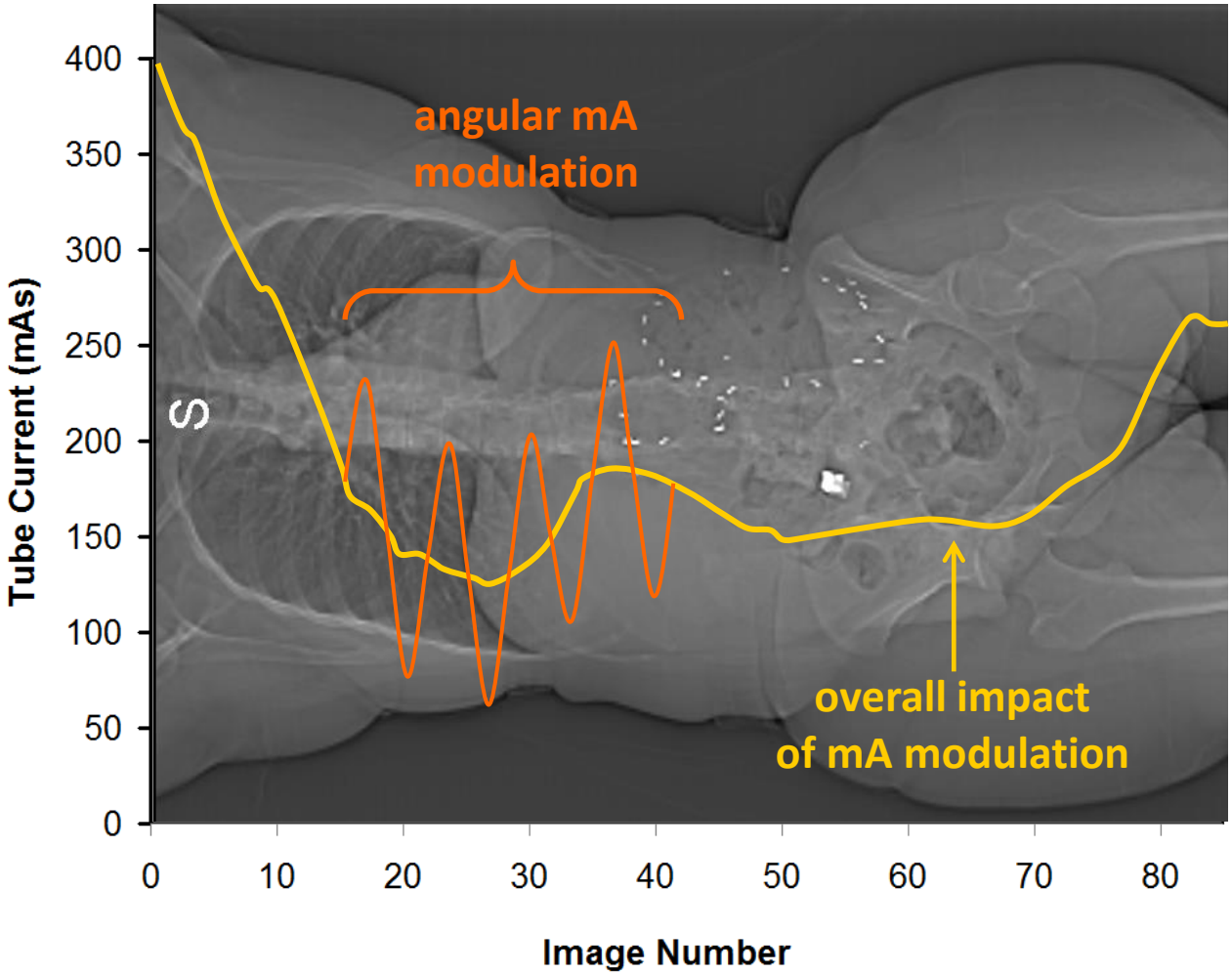

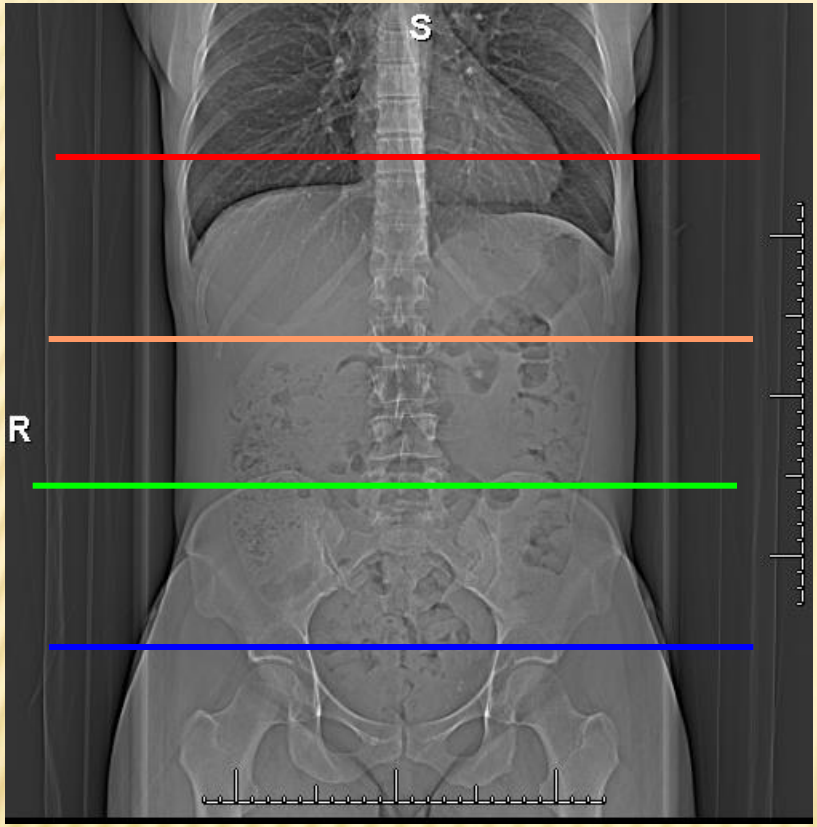

68 mAs

105 mAs

94 mAs

122 mAs

4. Adaptive Beam Filtration

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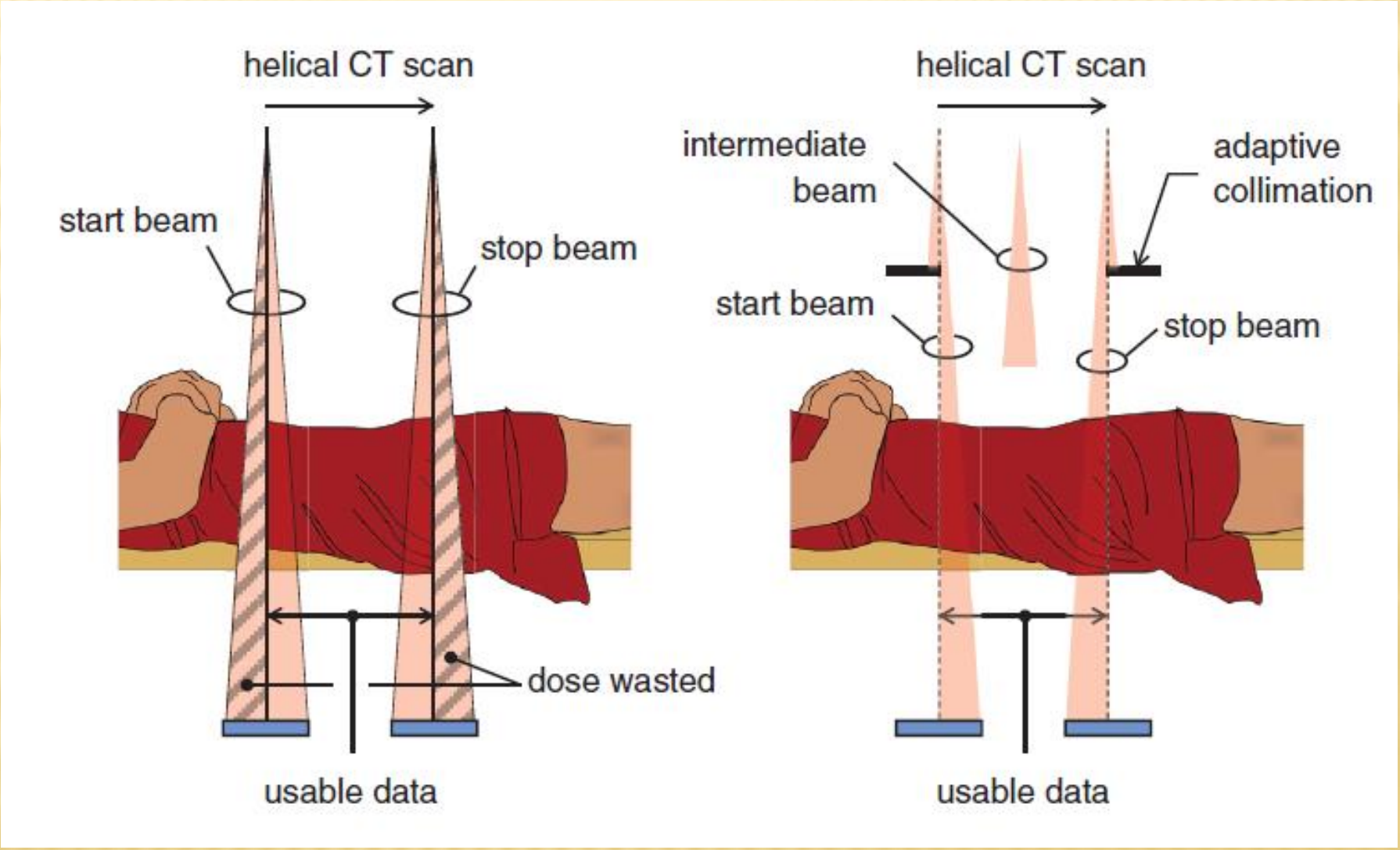
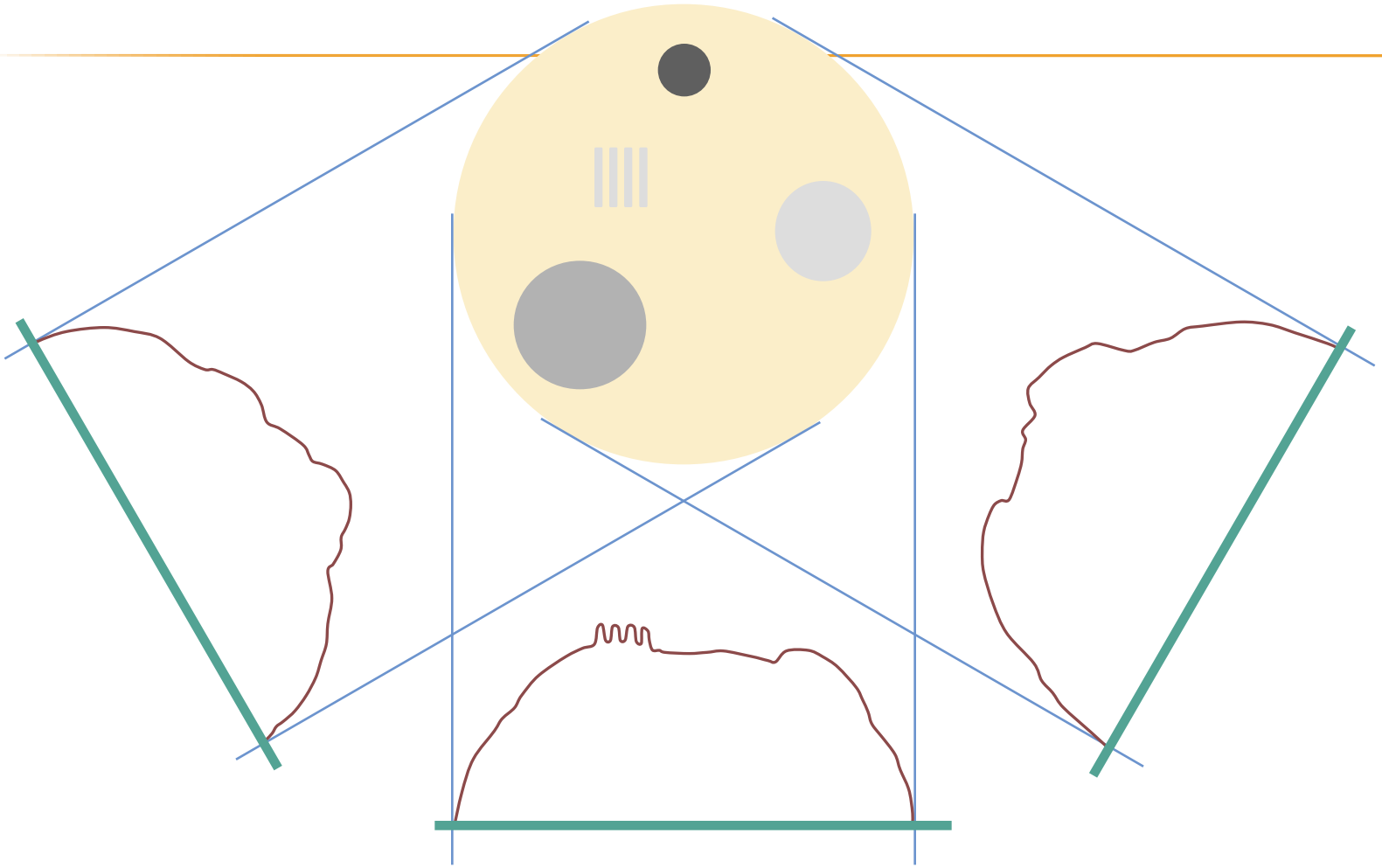


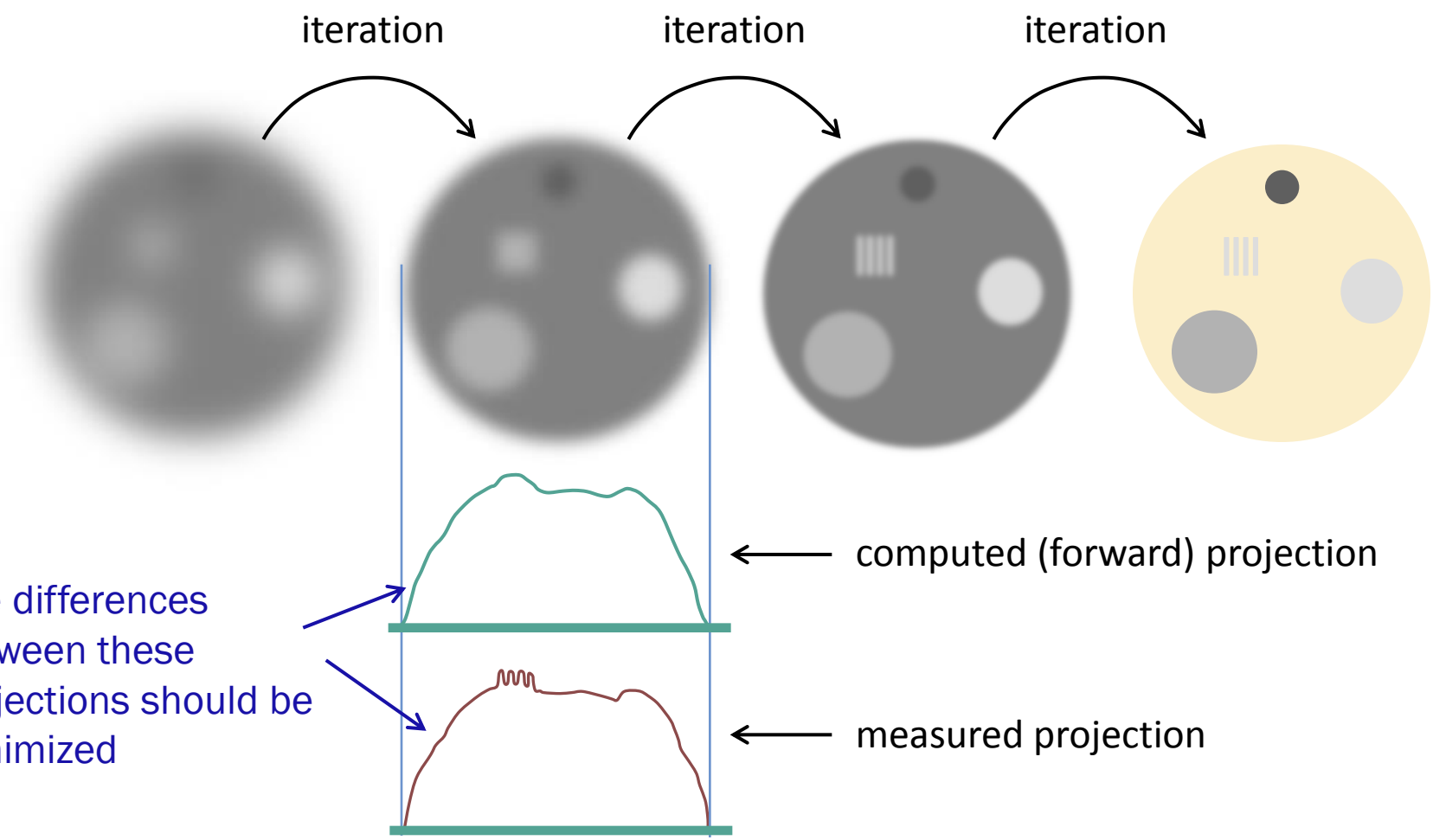
5. Iterative CT Reconstruction

actual object



measured projections

Iterative reconstruction algorithms use an initial guess of the image, and then updates that image depending on how well the computed projections (from the current image) match the measured projections.



The differences between these projections should be minimized

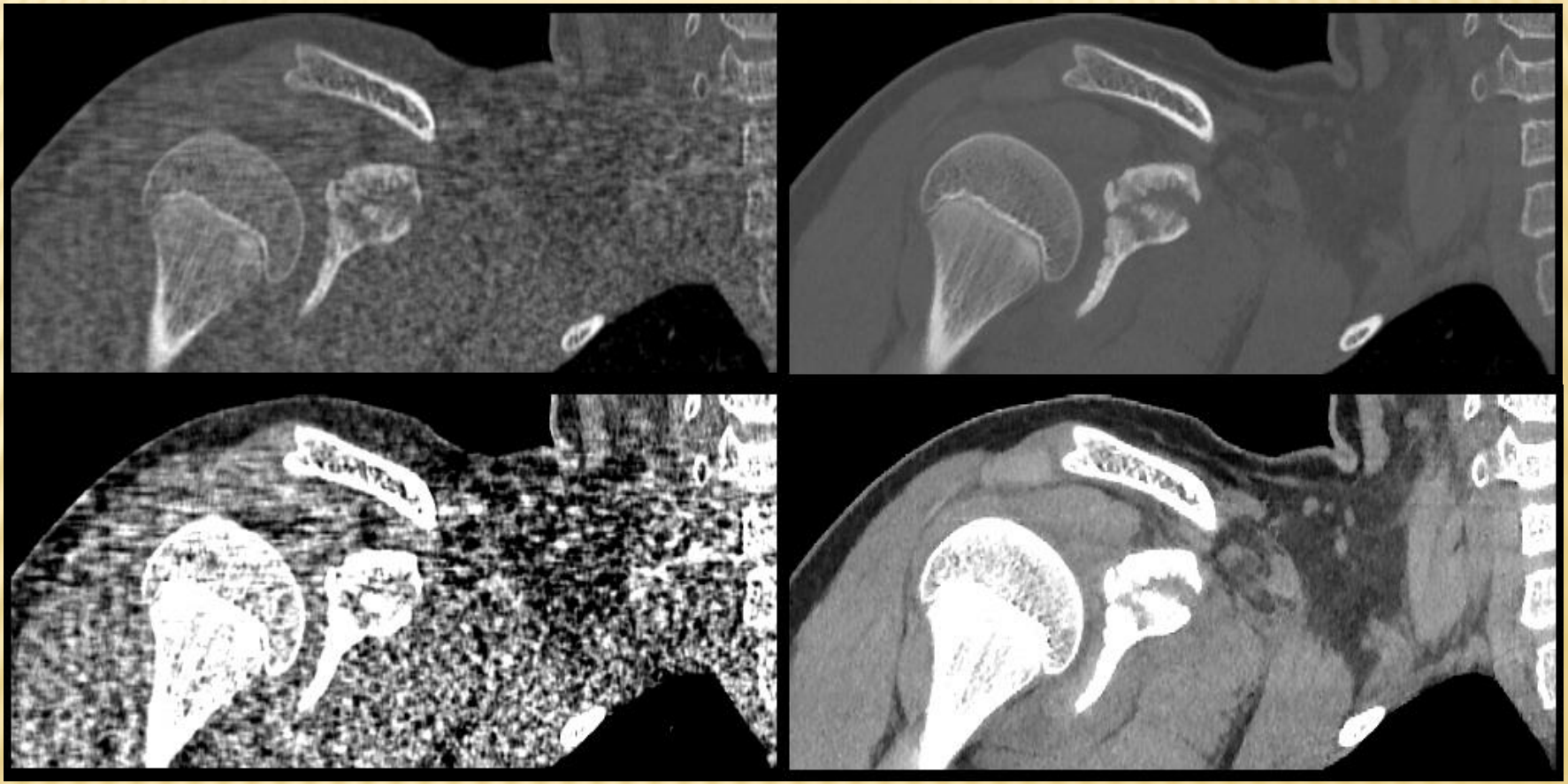
Five quick lessons on CT dose optimization

filtered backprojection

model-based iterative reconstruction

WW 2000

WW 400



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a. standard FPB

b. statistical iterative reconstruction

c. model-based iterative reconstruction

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HISTORICAL PERSPECTIVES

- Rapid increase in the availability, capability, and use of CT over the last decade
- Contribution of dose burden by CT for medical imaging of ~50% for 15% of performed exams
- Radiation overdose incidents with CT brain perfusion exams, chiefly in California, resulting in 200+ overexposures in 18 months

EQUIPMENT AND/OR USER FAILURE…..

- 2 ½ year old boy
- 150 scans to same area over a period of 1 hour…..
- Acute erythema in area of scan (5-10 Gy)
- Cataracts, cancer, cognitive impairment are possible outcomes

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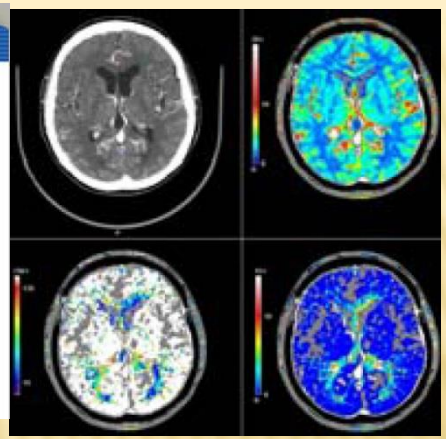
Home > Medical Devices > Medical Device Safety > Alerts and Notices (Medical Devices)

Safety Investigation of CT Brain Perfusion



October 2009

Cedars-Sinai, L.A.

RESULTING CALIFORNIA LEGISLATION

- Senate Bills 1237 & 38
  - Introduced by Alex Padilla

- Assembly Bill 510
  - Introduced by Bonnie Lowenthal

SENATE BILL 1237

- Effective July 1, 2012
- Adds sections 115111, 115112 and 115113 to the state Health and Safety code for Public Health

SB1237 – SECTION 115111

- Requires those responsible for CT system operation:
  - To record the dose of radiation for every CT study produced during an exam
  - To have on an annual basis, a medical physicist verify displayed doses within 20% of the true measured dose
  - To record the CT dose metrics in the radiology report
    - Volume computed tomography dose index ($CTDI_{vol}$)
    - Dose length product (DLP)

SB1237 – SECTION 115112

- Requires "facilities that furnish CT X-ray services ***shall be accredited*** by an organization that is approved by the federal Centers for Medicare and Medicaid Services, and accrediting agency approved by the Medical Board of California, or the State Department of Public Health"
- Date of required compliance: July 1, 2013

SB1237 – SECTION 115113

- Requires a report be sent to CA Dept of Health Services:
  - Repeating a CT exam, unless ordered by a physician or radiologist or movement / interference of patient, if the following dose values are exceeded:
    - 0.05 Sv (5 rem) effective dose equivalent
    - 0.5 Sv (50 rem) to an organ or tissue
    - 0.5 Sv (50 rem) shallow dose equivalent to the skin
  - Irradiating a body part other than the intended body part (with the same dosage requirements as above)

SB1237 – SECTION 115113

- Requires a report be sent to CA Dept of Health Services:
  - If an exam results in unintended patient harm (organ damage or erythema), as determined by a physician
  - Radiation exposure greater than 50 mSv (5 rem) to a fetus or embryo of a known pregnant individual unless approved by a physician
  - Irradiating the wrong person or wrong site
  - Delivered dose is >20% of the *prescribed* dose

AB510

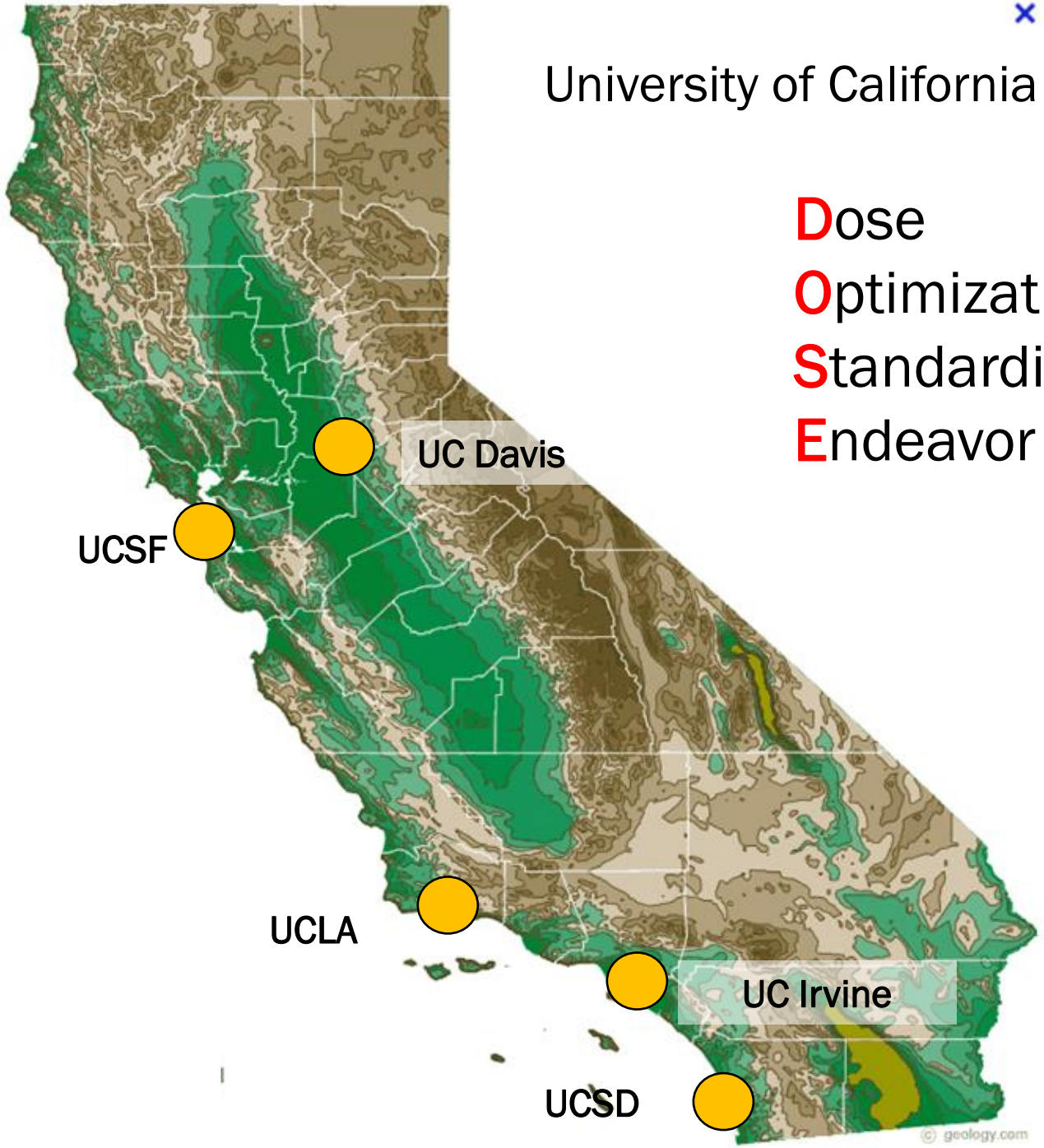
- Further clarifies SB1237
- Section 115111:
  - Nuclear Medicine excluded
  - Technical factors and dose shall be electronically sent to PACS
  - Displayed dose verified by physicist for typical adult brain, adult abdomen, and pediatric brain protocols – within 20% of measured dose
  - Dose reporting is limited to systems capable of reporting dose
  - Dose report shall be included in “interpretive report”, not just “Radiology report”, to account for other departments using CT

ISSUES

- Law does not indicate specifics of reporting $CTDI_{vol}$ and DLP…. Summed? By Series?
- Interpretation as to what "reporting" means
  - Access to PACS dose image adequate?
  - What about reconstruction/reformatting procedures that do not deliver dose?
- Failure to comply with law?

University of California DOSE consortium

Dose
Optimization and
Standardization
Endeavor



RECOMMENDATIONS FOR COMPLIANCE

- UCDOSE consortium of UC Medical Centers

UNIVERSITY OF CALIFORNIA

BERKELEY • DAVIS • IRVINE • LOS ANGELES • MERCED • RIVERSIDE • SAN DIEGO • SAN FRANCISCO SANTA BARBARA • SANTA CRUZ

UC-DOSE
University of California Health System
Recommendations for Compliance with California Senate Bill 1237 and related pending legislation
May 10, 2012

1. EXECUTIVE SUMMARY

The UC-DOSE project (University of California Dose Optimization and Standardization Endeavor) was funded by the University of California Office of the President (UCOP) to standardize and optimize computed tomography (CT) protocols across the University of California Medical Centers, and to develop a consistent solution for responding to California Senate Bill 1237.[1] This bill takes effect on July 1, 2012, will be enforced by the California Department of Public Health Radiologic Health Branch,[2] and requires the reporting of CT radiation dose, and the reporting of overdoses in particular settings.

UC DOSE GUIDELINES

2. DOSE REPORTING (115111) effective July 1, 2012

B. Guidelines on How to Comply with this Section of the Law

1. Electronically send ("Push") the scanner's "Dose Report" or "Protocol Page" to your electronic archive (e.g. PACS),

AND one of the following (2 or 3):

2. Report $CTDI_{vol}$ and DLP ***for each series*** in the Radiology Report (see Appendix A).
   a. Include the anatomic area imaged (head, neck, chest, abdomen/pelvis, spine, extremity)
   b. Include the phantom size reference (32cm or 16cm).

OR

3. Attach the protocol page / dose sheet that includes the radiation dose for each series, to the radiology report.

UC DOSE GUIDELINES

2. DOSE REPORTING (115111) effective July 1, 2012

3. Do not add the $CTDI_{vol}$ and DLP values from different series. Adding them is misleading, inappropriate and may be inconsistent with the meaning of the law; reporting values separately for each series is unambiguous and recommended.

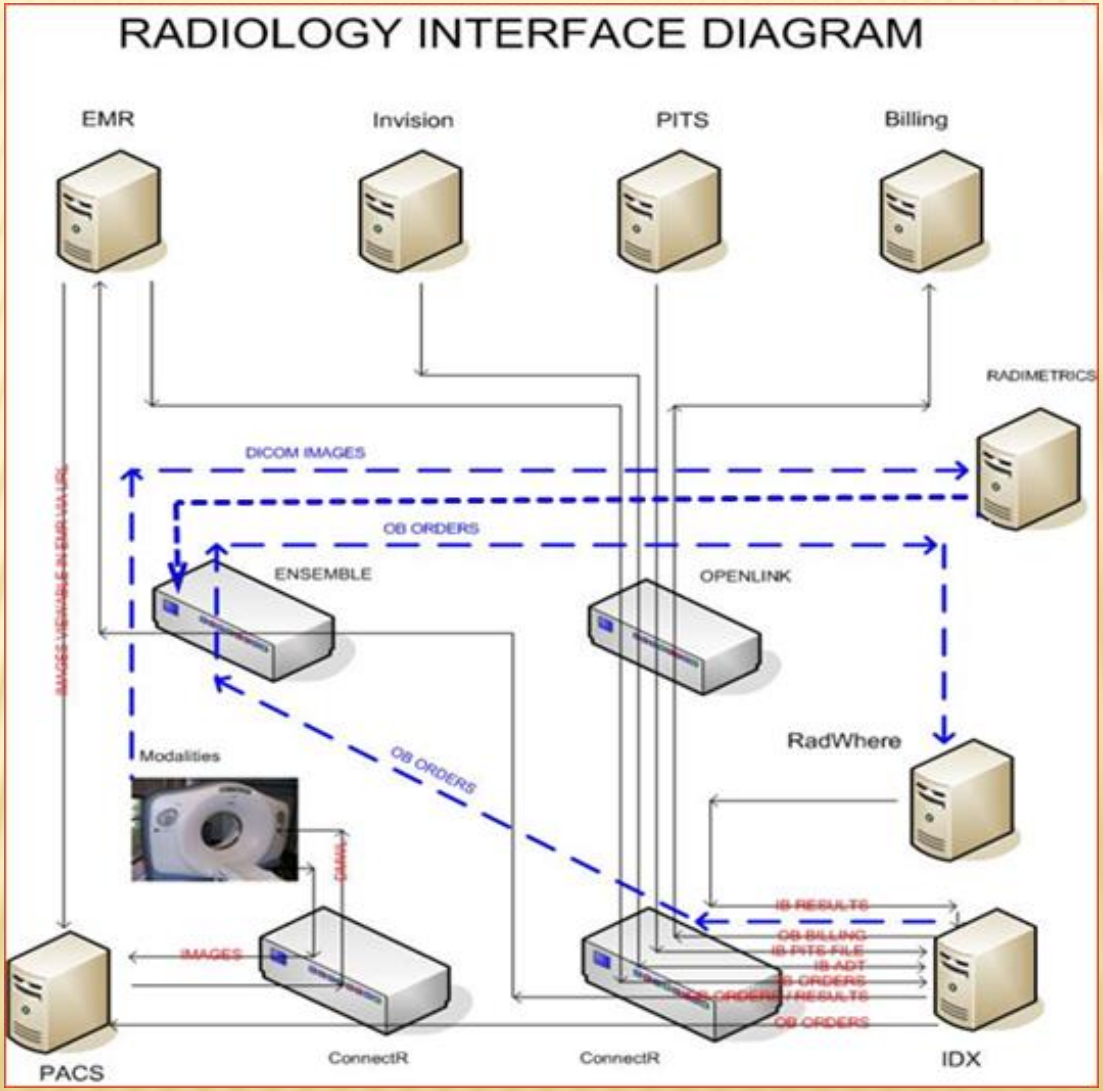
5. In the Radiology Report itself, the UC DOSE consortium recommends explanatory text accompany the reporting of the CTDIvol and DLP numbers.[4] Sample text might include:

   The dose indicators for CT are the volume Computed Tomography (CT) Dose Index (CTDIvol) and the Dose Length Product (DLP), and are measured in units of mGy and mGy-cm, respectively. These indicators are not patient dose, but values generated from the CT scanner acquisition factors and may substantially underestimate or overestimate the absorbed dose based on patient size and other factors. A medical physicist or other qualified health professional should be consulted for specific questions regarding the radiation dose for this exam.

REPORTING CTDI & DLP IN REPORT…..

- UC Davis: following UC DOSE recommendations
- Automated solution to include values in report
  - Implementation of dose calculation engine
  - Extraction of series by series CT dose metrics
  - Inclusion of user defined message in speech engine
  - Creation of final report in RIS with dose metrics

SYSTEMS INTEGRATION – DOSE REPORTING



DICOM / HL7 Application connector

Dose Calculation Software

CT scanner

Speech Recognition

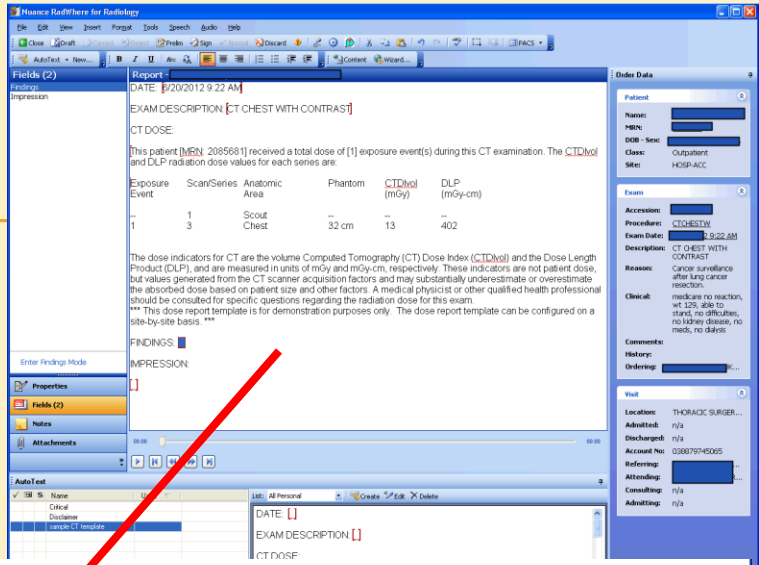
PACS

RIS

Broker & DICOM processor

PACS/RIS Broker

SINGLE ACQUISITION EXAM



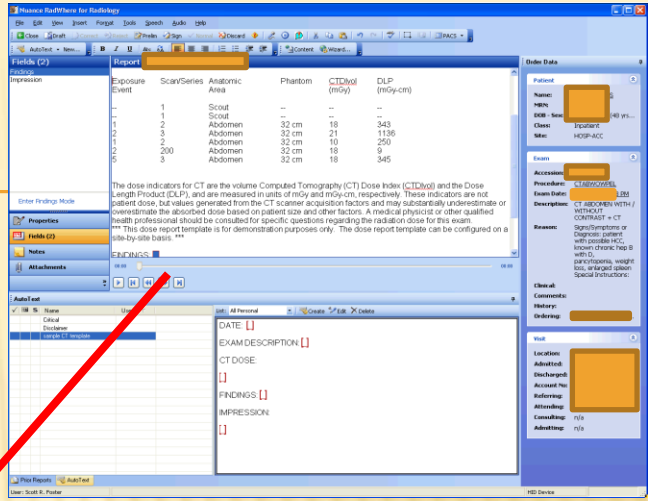
CT DOSE:

[This patient [MRN: 2085681] received a total dose of [1] exposure event(s) during this CT examination. The CTDIvol and DLP radiation dose values for each series are:

Exposure Event	Scan/Series	Anatomic Area	Phantom	CTDIvol (mGy)	DLP (mGy-cm)
--	1	Scout	--	--	--
1	3	Chest	32 cm	13	402

The dose indicators for CT are the volume Computed Tomography (CT) Dose Index (CTDIvol) and the Dose Length Product (DLP), and are measured in units of mGy and mGy-cm, respectively. These indicators are not patient dose, but values generated from the CT scanner acquisition factors and may substantially underestimate or overestimate the absorbed dose based on patient size and other factors. A medical physicist or other qualified health professional should be consulted for specific questions regarding the radiation dose for this exam.
*** This dose report template is for demonstration purposes only. The dose report template can be configured on a site-by-site basis. ***

MULTIPLE ACQUISITION EXAM



Exposure Event	Scan/Series	Anatomic Area	Phantom	CTDIvol (mGy)	DLP (mGy-cm)
--	1	Scout	--	--	--
--	1	Scout	--	--	--
1	2	Abdomen	32 cm	18	343
2	3	Abdomen	32 cm	21	1136
1	2	Abdomen	32 cm	10	250
2	200	Abdomen	32 cm	18	9
5	3	Abdomen	32 cm	18	345

The dose indicators for CT are the volume Computed Tomography (CT) Dose Index (CTDIvol) and the Dose Length Product (DLP), and are measured in units of mGy and mGy-cm, respectively. These indicators are not patient dose, but values generated from the CT scanner acquisition factors and may substantially underestimate or overestimate the absorbed dose based on patient size and other factors. A medical physicist or other qualified health professional should be consulted for specific questions regarding the radiation dose for this exam.
*** This dose report template is for demonstration purposes only. The dose report template can be configured on a site-by-site basis. ***

EXAMPLE REPORTS

- Our radiologists want short reports
- No more “consult with Medical Physicist”

DOSE REPORT: This study involved (1) CT acquisition(s). The CTDIvol and DLP values are included below as required by state law:

1; Series: 3; Abdomen; 32 cm; CTDIvol=17.7 mGy; DLP=856.7 mGy-cm

For further information on CT radiation dose, see http://www.ucdmc.ucdavis.edu/radiology/RadiationDose.html

RADIATION DOSE:
This study involved (3) CT acquisition(s). The CTDIvol and DLP values are included below as required by state law:
1; Series: 2; Chest; 32 cm; CTDIvol=2.9 mGy; DLP=3 mGy-cm
2; Series: 3; Chest; 32 cm; CTDIvol=26.4 mGy; DLP=26 mGy-cm
3; Series: 5; Chest; 32 cm; CTDIvol=13.5 mGy; DLP=692 mGy-cm
For further information on CT radiation dose, see http://www.ucdmc.ucdavis.edu/radiology/RadiationDose.html

EXAM: CT ABDOMEN + CT PELVIS, WITH CONTRAST

DATE OF STUDY: 10/9/2012 11:29 AM

CLINICAL INFORMATION: Pain(acute), location: Pelvis: Left Other, specify: left hernia Bowel Comments:

TECHNIQUE: Helically acquired contrast enhanced multidetector CT of the abdomen and pelvis acquired in the portal venous phase, extending from the lung bases through the groins. Uneventful administration of 125 ml of Omnipaque 350 injected at a rate of 2.5 ml/sec. Images are reconstructed in the axial pane with subsequent reformatting in coronal and sagittal planes.

No P.O. contrast was administered.

DOSE REPORT: This study involved (1) CT acquisition(s). The CTDIvol and DLP values are included below as required by state law:

1; Series: 3; Abdomen; 32 cm; CTDIvol=17.7 mGy; DLP=856.7 mGy-cm

For further information on CT radiation dose, see http://www.ucdmc.ucdavis.edu/radiology/RadiationDose.html

COMPARISON: None.

FINDINGS:

LOWER CHEST:

There is a calcified granuloma noted in the posterior left lung base. The lung bases are otherwise clear.

DATE: 10/9/2012 11:42 AM

EXAM TYPE: CT ANGIO CHEST WITH / WITHOUT CONTRAST

COMPARISON: 8/12/2011

INDICATION: History of 4-cm ectatic aorta. Follow-up CT.

TECHNIQUE: Helical scanning from the thoracic inlet through the adrenals was performed following the uneventful administration of 100 mL of Omnipaque 350 at a rate of 4.0-mL/s through a 20-gauge left antecubital vein. Reconstruction of 5-mm and 1.0 mm contiguous axial images was performed. 5-mm contiguous coronal and sagittal images and 10 mm contiguous MIP axial images were reformatted.

RADIATION DOSE:
This study involved (3) CT acquisition(s). The CTDIvol and DLP values are included below as required by state law:
1; Series: 2; Chest; 32 cm; CTDIvol=2.9 mGy; DLP=3 mGy-cm
2; Series: 3; Chest; 32 cm; CTDIvol=26.4 mGy; DLP=26 mGy-cm
3; Series: 5; Chest; 32 cm; CTDIvol=13.5 mGy; DLP=692 mGy-cm
For further information on CT radiation dose, see http://www.ucdmc.ucdavis.edu/radiology/RadiationDose.html

FINDINGS:

Neck: The visualized portion of the lower neck shows normal caliber of vessels. Normal trachea. No masses.

EXAMPLE REPORTS WITH DOSE DATA

- Linked studies often have same dose data; others have different accession numbers

INDICATION:

Severe aortic stenosis. Screening for TAVR.

TECHNIQUE:

Imaging using the Siemens Definition 64-slice CT scanner with ECG gating, acquiring 83 msec images throughout the cardiac cycle. Following a dynamic flow study and appropriate timing selection was a bolus of Omnipaque 350, followed by a mixed bolus of saline and contrast and subsequently followed by a bolus of saline uneventfully administered at 4 mL/s with helical acquisition of 0.75 mm overlapping axial images during a single breath hold. The total amount of contrast administered was 132-mm. Images were then reconstructed using a TeraRecon workstation.

Radiation dose:

This study involved (3) CT acquisition(s). The CTDIvol and DLP values are included below as required by state law:

1; Series: ; Chest; 32 cm; CTDIvol=26.4 mGy; DLP=26 mGy-cm
2; Series: 2; Chest; 32 cm; CTDIvol=57.7 mGy; DLP=1312 mGy-cm
3; Series: 3; Abdomen; 32 cm; CTDIvol=16.1 mGy; DLP=635 mGy-cm

The following accession numbers are related to this dose report {3563977}:
3563978

Radiation dose:

This study involved (3) CT acquisition(s). The CTDIvol and DLP values are included below as required by state law:

1; Series: ; Chest; 32 cm; CTDIvol=26.4 mGy; DLP=26 mGy-cm
2; Series: 2; Chest; 32 cm; CTDIvol=57.7 mGy; DLP=1312 mGy-cm
3; Series: 3; Abdomen; 32 cm; CTDIvol=16.1 mGy; DLP=635 mGy-cm

The following accession numbers are related to this dose report {3563977}:
3563978

WEBSITE FOR INFORMATION

- Reduce verbiage in report
- Currently “too technical”

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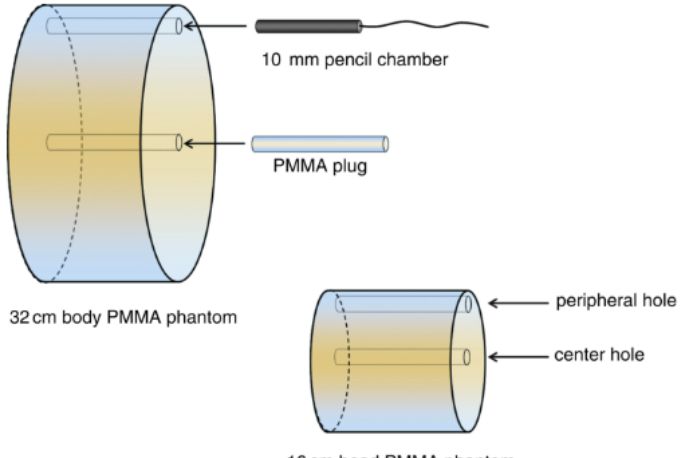
Radiation Dose Reporting

CT Dose Reporting:

Starting on July 1, 2012, new California legislation requires that specific CT scanner dose metrics be included in the radiology report, for all patients undergoing diagnostic CT scans. These reporting requirements do not apply to CT scans used for purposes other than diagnosis[1]. Two specific dose metrics are required to be reported: the volume computed tomography dose index ($CTDI_{vol}$) and the dose length product (DLP). This document is intended to help physicians, patients, and other interested parties to understand what these dose metrics mean.

What is $CTDI_{vol}$?



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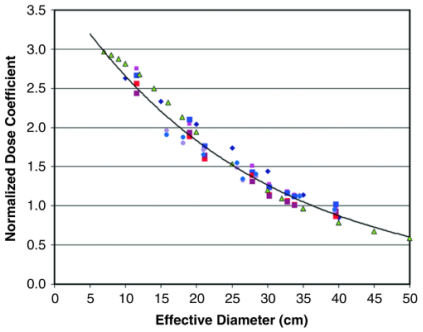
Large CTDI phantom: The 32 cm diameter phantom is about equivalent to somebody with a 47" waist line. In general, for body CT, most patients are smaller than the 32 cm diameter phantom, and this means that their actual dose from the scan will be higher than the $CTDI_{vol}$ value. The curve below provides an approximate correction factor, which can be a used to adjust the $CTDI_{vol}$ value for the size (effective diameter) of the patient.

Normalized $CTDI_{vol}$ Correction Factor: 32 cm diameter phantom

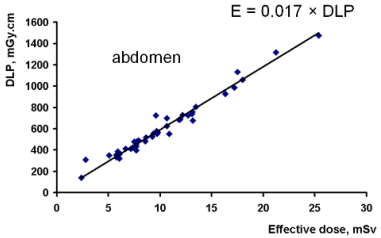


For patients who are larger than the body phantom, their actual dose values would be lower than the reported $CTDI_{vol}$ value. For most adult patients, the correction factors range from about +40% to -40%. For smaller pediatric patients (on Siemens and Philips scanners which use the 32 cm phantom), the reported $CTDI_{vol}$ *underestimates* the actual dose values in the range of 150% to 250%.

Absorbed dose is a measure of the x-ray energy absorbed per unit mass, and this ratio can sometimes be misleading. For example: compare a dose of 10 mGy to one finger (with a mass of about 10 grams) versus a dose of 1 mGy to the entire abdomen (a mass of about 25,000 grams). Clearly the lower dose to the torso involves a lot more x-ray energy being absorbed in the patient[3]. So in addition to dose, it is also useful to have an understanding of how much tissue was exposed. That is where DLP comes in...

What is DLP?

CT scans are performed over a length of the patient - sometimes they can be performed over a relatively short range in the patient, but more commonly they can extend greater distances, such as from the upper abdomen to the lower pelvis. The length of the scan is determined in centimeters (1 inch = 2.54 cm, 1 cm is about 3/8 inch), and the DLP is determined by multiplying the $CTDI_{vol}$ value by the scan length, resulting in the units of mGy-cm.



As mentioned above, the DLP is a metric which is related to the total *energy imparted* in the patient. Therefore, when reading a radiology report which has both the $CTDI_{vol}$ and DLP listed, the DLP value has a more direct bearing on the overall radiation risk of the procedure. Indeed there is a linear relationship between the *effective*

What is Effective Dose?

The effective dose is a quantity which is a risk metric, and is not a dosimetric quantity per se. The computation of effective dose is performed by estimating organ absorbed doses (for a list of 15 different organs), and then multiplying each of those by a tissue weighting factor. The tissue weighting factors were computed from radiation epidemiological data, and takes into consideration that some organs (*e.g.* breasts, stomach, lung) are more radiosensitive than others (*e.g.* brain, skin). The total effective dose is the sum of all of these products.

While it is technically possible to compute the effective dose for a specific patient, the effective dose concept was not designed for individual risk assessment.

Other factors to consider

The California law requiring dose reporting in CT has made everyone more aware of radiation dose issues in CT. The Department of Radiology at UC Davis Medical Center uses a number of different dose-optimization technologies to assure that the radiation dose levels used on our several CT scanners are well tuned to each patient's CT examination.

There are a number of ways to assure that a CT scan provides a maximum benefit/risk ratio to the patient:

(1) When a physician recommends that a patient have a CT scan, make sure that it is necessary and appropriate. The American College of Radiology publishes *appropriateness criteria* for a large number of imaging procedures. Radiologists are trained to recognize the most appropriate imaging study for a given patient's circumstances, and consultation with a radiologist can provide guidance in many cases.

(2) In certain circumstances, other imaging modalities such as ultrasound (US) and magnetic resonance imaging (MRI) that do not use ionizing radiation can be used instead of CT. However, not all CT examinations can be replaced with US or MRI.

(3) Younger patients (<30) are more radiosensitive than older patients (>40), and this fact should be considered when a CT scan is recommended.

DETERMINATION OF REPORTABLE DOSE

- Section 3 (115113)
  - – An Effective Dose (E.D.) that exceeds 0.05 Sv (5 rem)
  - – A dose in excess of 0.5 Sv (50 rem) to any organ or tissue
  - – Shallow dose to the skin of 0.5 Sv (50 rem) to the skin
  - – D**ose to fetus that is greater than 50 mSv (5 rem)**
- Reporting dose with the current limits is unlikely except for dose to the fetus in certain circumstances
- A medical physicist should be involved in any formal dose estimation

RECOMMENDATIONS:

4. MEDICAL EVENT REPORTING (115113) Effective July 1, 2013

- California Clinical and Academic Medical Physicists (C-CAMP)

http://aapm.org/government_affairs/documents/SB-1237Section3_v7.pdf

  - *John M. Boone: University of California Davis*
  - *Christopher Cagnon: University of California, Los Angeles*
  - *Melissa Martin: Therapy Physics, Inc. Gardena, CA*
  - *Michael McNitt-Gray: University of California, Los Angeles*
  - *Thomas R. Nelson: University of California, San Diego*
  - *J. Anthony Seibert: University of California Davis*

PATIENT EFFECTIVE DOSE ≥ 50 mSv

- Determine DLP with appropriate k-factor that would result in effective dose ≥ 50 mSv
- Two tables required
  - $CTDI_{vol}$ and DLP determined with 16 cm diameter phantom for pediatric body exams
  - $CTDI_{vol}$ and DLP determined with 32 cm diameter phantom for pediatric body exams

DLP VALUE: REPORTING THRESHOLDS

Effective Dose = DLP × k

Effective Dose / k = DLP

DLP VALUE: REPORTING THRESHOLDS

- $CTDI_{vol}$ and DLP with 16 cm phantom for pediatric body exam

DLP in mGy·cm

	0 year old	1 year old	5 year old	10 year old	adult
head & neck	3840	5880	8770	11900	16120
head	4540	7460	12500	15620	23800
neck	2940	4160	4540	6320	8470
chest	1280	1920	2770	3840	3570
abd/pelvis	1020	1660	2500	3330	3330
trunk (C/A/P)	1130	1780	2630	3570	3330

- $CTDI_{vol}$ and DLP with 32 cm phantom for pediatric body exam

DLP in mGy·cm

	0 year old	1 year old	5 year old	10 year old	adult
head & neck	3840	5880	8770	11900	16120
head	4540	7460	12500	15620	23800
neck	2940	4160	4540	6320	8470
chest	550	830	1200	3840	3570
abd/pelvis	440	720	1080	3330	3330
trunk (C/A/P)	490	770	1140	3570	3330

ORGAN DOSE THRESHOLD: 500 mSv

- "Cumulative $CTDI_{vol}$" if same anatomic region scanned multiple times (and organ included)
  - Scans with table movement
    - Pediatric: cumulative **$CTDI_{vol} \geq 200$ mGy**
    - Adult: cumulative **$CTDI_{vol} \geq 250$ mGy**
  - Scans with no table movement (e.g., neuroperfusion)
    - Pediatric: cumulative **$CTDI_{vol} \geq 650$ mGy**
    - Adult: cumulative **$CTDI_{vol} \geq 650$ mGy**

SKIN DOSE THRESHOLD: 500 mSv

- Want to identify scans resulting in a *peak* skin dose that exceeds 500 mGy (multiple scans with no table motion)
  - DLP tends to underestimate
  - $CTDI_{vol}$ tends to overestimate (30 to 100%)
- Use recommendations for organ dose threshold

FETAL DOSE THRESHOLD: 50 mSv

- This event may occur in certain clinical scenarios
  - Scans with table movement
    - Cumulative $CTDI_{vol}$ of abd/pelvis ≥ **25 mGy**
  - Scans with NO table movement (abd/pelvis perfusion)
    - Cumulative $CTDI_{vol}$ of abd/pelvis ≥ **65 mGy**

NEXT STEPS

- Work with the state on developing meaningful ways to report dose metrics and dose
- Educate technologists, radiologists, referring physicians, physicists, nurses, and general public
- UC DOSE Virtual Symposium on Radiation Safety and Computed Tomography was held May 8th-10th, 2013 to the state, national, and international audience; **still available on web**

SUMMARY

- California dose reporting law – national attention
- Resultant emphasis on CT dose and safety
- Compliance & oversight by state is imminent
- Non-compliance? Notice of Violation (NOV)
- Multiple NOV's: financial $$ penalties