DUKE UNIVERSITY MEDICAL PHYSICS GRADUATE PROGRAM

DukeHealth Clinical Imaging Physics Group

CT Radiation Dose: Retrospective Monitoring for Informed Prospective Optimization

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Outline | Utilization and Reduction

1. Utilization and Reduction
   a. Justification
   b. Appropriateness Criteria
   c. Tube Current Modulation
   d. Iterative Reconstruction
2. Monitoring
   a. Mandate
   b. Software Solutions, Basics
   c. Components of Solutions
3. Optimization

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Utilization | Justification

Justification

- any **decision** that **alters the radiation exposure** to an individual or population should have an **outcome that does more good than harm**.

Optimization (Part 3 of this talk)

- **application of radiation** in any situation should be developed to **minimize the risk of exposure while maximizing the benefit**.

Image Wisely, "How to Understand and Communicate Radiation Risk"
http://www.imagewisely.org/~/media/ImageWisely-Files/Medical-Physicist-Articles/IW-Peck-Samei-Radiation-Risk.pdf

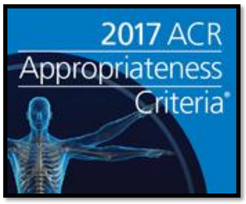
Utilization | RRLs

- There is a wide range of radiation exposures associated with different diagnostic procedures, relative radiation levels (RRLs) have been included for most imaging examinations.
- RRLs are based on effective dose

RRL	Adult Eff. Dose (mSv) Estimate Range	Ped Eff. Dose (mSv) Estimate Range	Example Examinations
O	0	0	Ultrasound; MRI
☢	<0.1	<0.03	Chest radiograph; Hand radiograph
☢☢	0.1-1	0.03-0.3	Pelvis radiograph; Mammography
☢☢☢	1-10	0.3-3	Abd CT; Nuclear medicine bone scan
☢☢☢☢	10-30	3-10	Abd CT w/o w/; Whole body PET
☢☢☢☢☢	30-100	30-100	CTA CAP w/; TIPPS

ACR Appropriateness Criteria® Radiation Dose Assessment Introduction
https://www.acr.org/~/media/ACR/Documents/AppCriteria/RadiationDoseAssessmentIntro.pdf

Utilization | Appropriateness



Variant 1:	Penetrating neck injury. Clinical soft injury signs.		
Radiologic Procedure	**Rating**	**Comments**	**RRL***
CTA neck with IV contrast	9	This procedure is the imaging study of choice. See references [2,5,6,8,11-17].	☢☢☢
X-ray neck	7	Use this procedure to screen and prior to MRI/MRA in gunshot wounds and in some stab wounds if there is any question as to the integrity of the weapon.	☢☢
US neck	5	See references [4,13-15,22,23].	O
			O
		ow- e	☢☢☢
			☢☢☢
			O
			*Relative Radiation Level

Variant 2:	Penetrating neck injury. Normal or equivocal CTA. Concern for vascular injury.		
Radiologic Procedure	Rating	Comments	RRL*
Arteriography neck	8	See references [2,6,8,20,21].	☢☢☢
MRA neck without and with IV contrast	5	See references [4,10,13,15,23].	O
MRA neck without IV contrast	4		O
US neck	4	See references [4,13-15,22,23].	O
Rating Scale: 1,2,3 Usually not appropriate; 4,5,6 May be appropriate; 7,8,9 Usually appropriate			*Relative Radiation Level

https://acsearch.acr.org/docs/3099165/Narrative/

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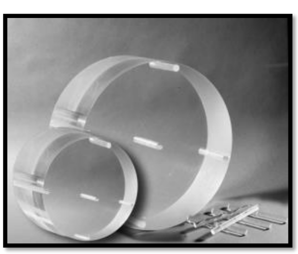
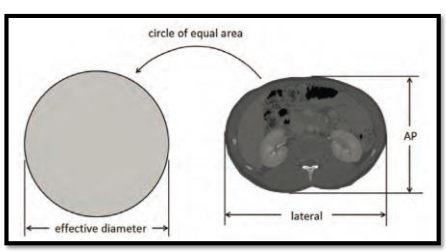
Dose Metrics | CT Radiation

$CTDI_{vol}$, DLP



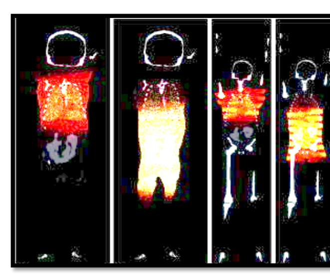
SSDE

– $SSDE = CTDI_{vol} \cdot f(size)$



Effective Dose

- $ED = DLP \cdot k(anatomy)$



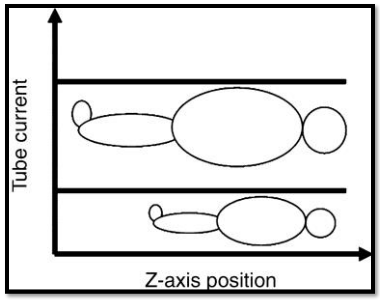
ICRP Publication 103 [ICRP 2007]: “Effective dose is calculated for a Reference Person and not for an individual.” … "Effective dose is not a real radiation dose to a person per se, but rather is a computed number representing an approximate measure of stochastic risk applied to a representative model."

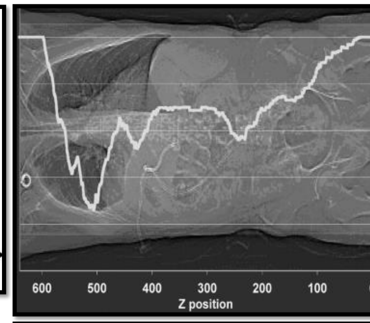
AAPM TG 204
Li et al. Medical Physics 2010
Fisher and Fahey, Health Physics, 2017

TCM | Tube Current Modulation

Challenge

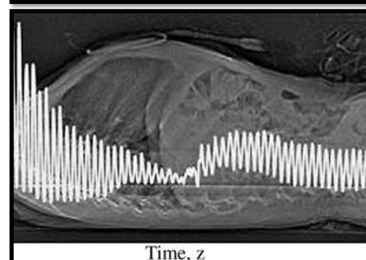
- Image noise dominated by projections with least signal (i.e., most attenuation) for a fixed mA. Result: wasted dose





Solutions

- Patient-Size: Change mA based on patient weight/size
- Z-axis: Reduce mA for lower attenuation regions along the patient (e.g., neck, lungs) and increase mA for regions with high attenuation (e.g., shoulders, pelvis)
- Angular: Reduce mA for projection angles with lower attenuation and increase mA for angles with higher attenuation



McCollough, RadioGraphics, 2006
Lee, RadioGraphics, 2008

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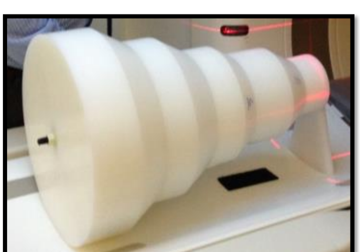
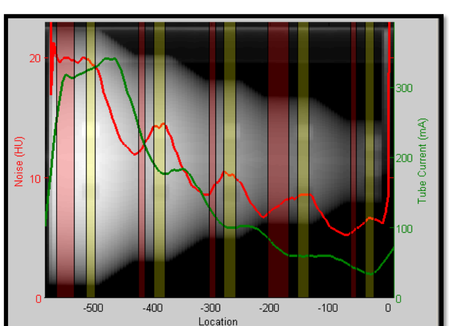
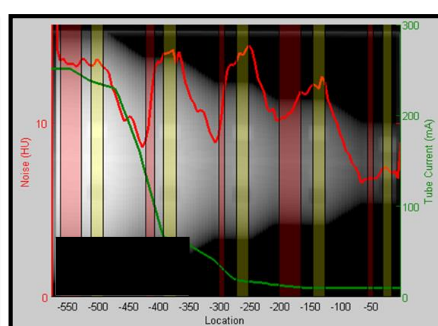
TCM | Image Quality Reference Parameters

Vendor	Algorithm	Parameter
GE	AutomA, SmartmA	Noise Index
Philips	D-DOM, Z-DOM	Reference Image
Siemens	CARE Dose, CARE Dose4D	Quality reference mAs
Toshiba	SURE Exposure, SURE Exposure 4D	Standard, Low-dose, High-quality
Hitachi	Adaptive mA, IntelliEC	Standard, Low-dose, High-quality



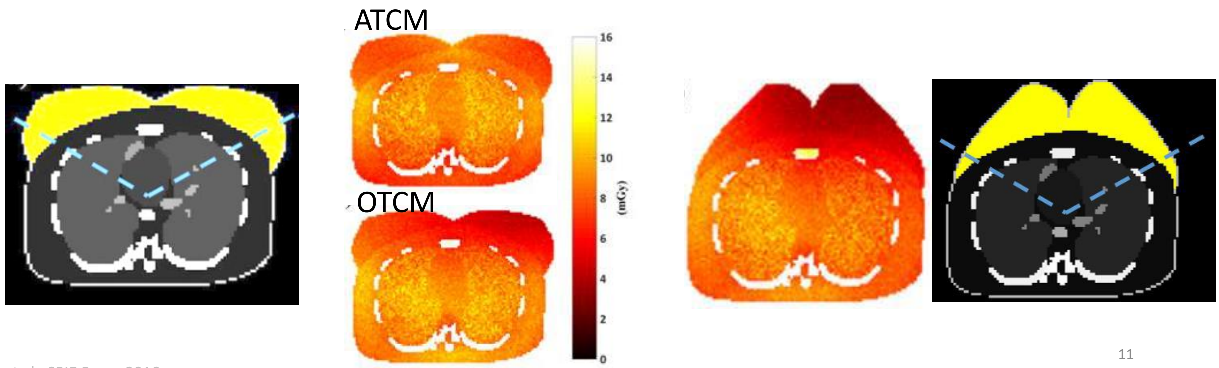




AAPM CT Lexicon

TCM | Organ

- Purpose: Organ Tube Current Modulation (OTCM) reduces radiation dose for superficial, radiosensitive tissues, such as breasts and orbits.
- TBD: mA reduction is limited. What is the impact on image quality? Would shields be as effective? Would optimized protocols be as effective?



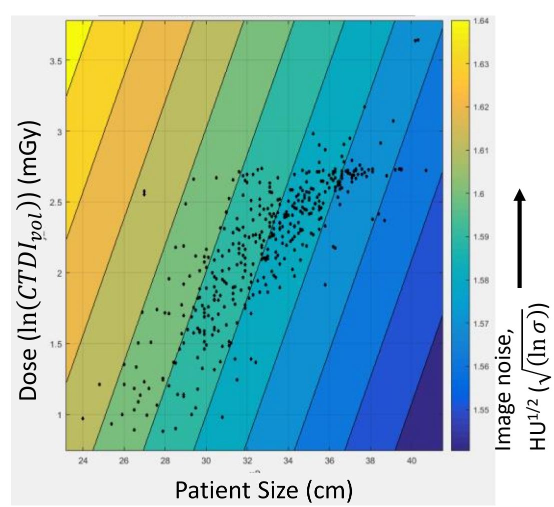
W. Fu et al., SPIE Proc., 2016

TCM | Adaptability and Consistency

- Dose, size, and noise are not mutually exclusive.
- TCM adjusts dose based on size to achieve target noise level(s).

How well does your TCM perform at adapting and consistently achieving the noise targets across your patients?

- Metric to simultaneously incorporate image noise and radiation dose across a patient population to
  1. Quantify how CT scanners balance image quality and radiation dose
  2. Assess the consistency and adaptability



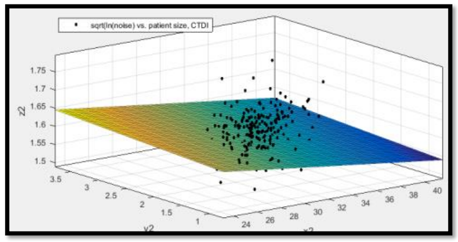
Data points are patient exams.

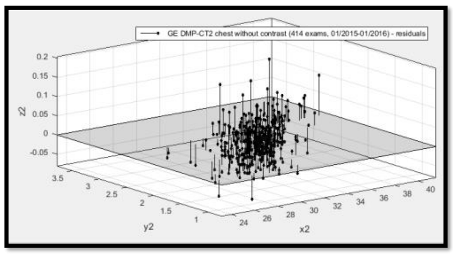
Ria et al., Medical Physics, 2017.

TCM | Adaptability and Consistency

1. 3D-fit performed per protocol-scanner with planar 1st degree function to characterize dependency of noise versus $CTDI_{vol}$ per protocol-scanner across a population.

2. RMSE calculated in the residuals' plots as a consistency metric of system adaptability.





Scanner-Protocol	Fit RMSE ($HU^{1/2}$)
CT1 A&P	0.0334
CT1 Chest	0.0344
CT2 A&P	0.0385
CT2 Chest	0.0361
CT3 A&P	0.0277
CT3 Chest	0.0215

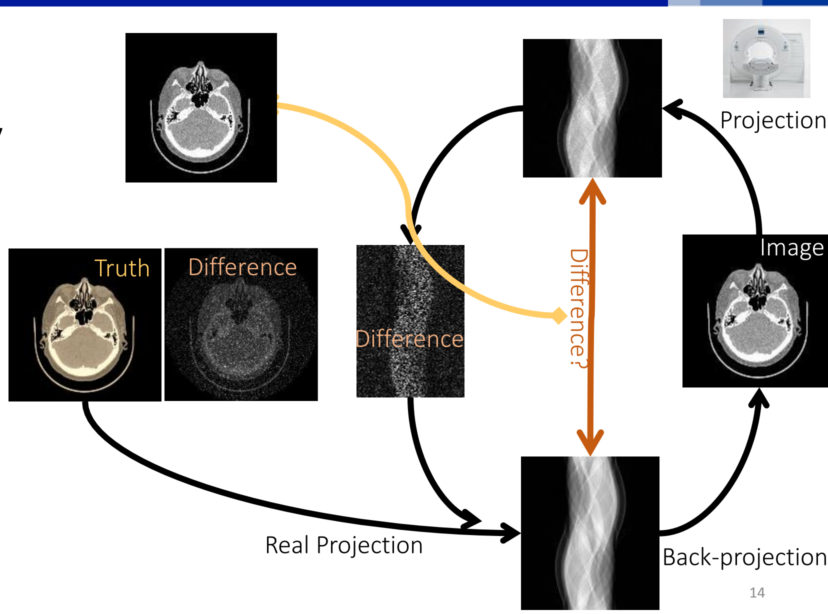
Manufacturers/Models have varying degrees of reproducibility of noise-dose values across sizes with TCM.

Ria et al., Medical Physics, 2017.

Iterative Reconstruction | Overview

"…iterative reconstruction may result in slightly longer reconstruction time but also in substantially less image noise from the same raw data through more complex modeling of detector response and of the statistical behavior of measurements."

Shuman, Image Wisely, 2016

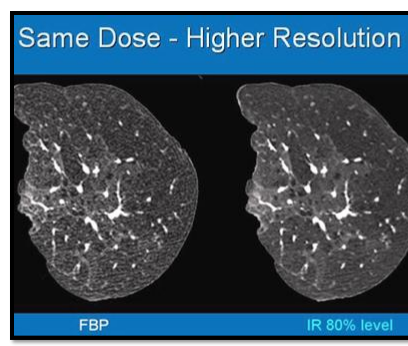


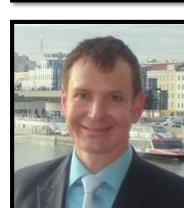
Iterative Reconstruction | The Promise

- You will be promised dose reduction allowed by reduced noise when enabling iterative recon algorithms.
- However, iterative recon may also degrade your low contrast detectability to varying degrees due to kernels, regularization/priors, and strength.
- So, you might be able to achieve substantial noise AND dose reduction, illustrated with select image cases no doubt.
- But at what cost(s)?

Iterative Reconstruction | Implementation

- It's going to look different…
- "Proper implementation of iterative reconstruction is a big project because CT protocol review is an indispensable part of the process."
- "You'll need to establish benchmark levels for radiation dose and adopt a healthy suspicion of your old protocols to get the most out of your IR software."





AuntMinnie.com International Editor, Eric Barnes.

Barnes, 2014, http://www.auntminnie.com/index.aspx?sec=sup&sub=cto&pag=dis&ItemID=108144

Outline | Monitoring

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Mandate | Concerned / Informed Users

Cedars-Sinai investigated for significant radiation overdoses of 206 patients
http://articles.latimes.com/2009/oct/10/local/me-cedars-sinai10

Huntsville Hospital notifying 60 patients of possible radiation overdose from brain scan
http://blog.al.com/breaking/2009/12/huntsville_hospital_notifying.html

Radiation overdoses from CT scans lead to maladies in patients
http://www.cleveland.com/nation/index.ssf/2010/08/radiation_overdoses_from_ct_sc.html

Radiation overdoses point up dangers of CT scans
http://www.nytimes.com/2009/10/16/us/16radiation.html

https://itunes.apple.com/us/app/xcatdose/id783266196?mt=8
http://www.tidalpool.ca/radiationpassport/

Mandate | CA, FDA, CMS, XR-29

California SB 1237 (July 2012)

- "... hospitals and clinics, as specified, that use computed tomography (CT) X-ray systems for human use to **record**, if the CT systems are capable, the **dose of radiation on every CT study produced** during the administration of a CT examination, as specified."

FDA, Initiative to Reduce Unnecessary Radiation Exposure from Medical Imaging

- "Implement quality control procedures to ensure that **dosing protocols are followed every time**, and that the **planned amount of radiation is administered**."
- "Tracking adverse events can **establish trends** and allow **prospective correction** of possible radiation safety problems related to equipment or operator training. …"

CMS, A-0537: 482.26(b)(2) Condition of Participation: Radiological Services

- "Any adverse events related to **over- or under-dosing must be identified and addressed**."

NEMA XR-29, HR 4302 SEC. 21 Quality Incentives for CT Diagnostic Imaging and Promoting Evidence-based Care

- "… equipment that is not consistent with the CT equipment standard, the **payment amount for such service shall be reduced**"
- NEMA XR-29, "attributes include **DICOM Dose Structured Reporting**, incorporation of the features and functionality that conform to **NEMA XR-25** Computed Tomography **Dose Check**, various forms of automatic exposure control, and reference pediatric and adult protocols."

www.fda.gov/Radiation-EmittingProducts/RadiationSafety/RadiationDoseReduction/ucm2007191.htm, www.leginfo.ca.gov/pub/0910/bill/sen/sb_12011250/sb_1237_bill_20100929_chaptered.html www.medicalimaging.org/wp-content/uploads/2015/05/Is-Your-CT-Smart-Dose-Compliant-Whitepaper.pdf, www.cms.gov/Regulations-and-Guidance/Guidance/Transmittals/Downloads/R141SOMA.pdf

Mandate | TJC

TJC, Diagnostic Imaging Requirements, PC.01.03.01 – 25,26, PI.02.01.01 - 6

- "… establishes or adopts diagnostic computed tomography (CT) imaging **protocols** based on current standards of practice, which address key criteria including **clinical indication**, contrast administration, age (to indicate whether the **patient is pediatric or an adult**), patient **size** and **body habitus**, and the **expected radiation dose index range**."
- "… **protocols are reviewed** and kept current with input from an interpreting radiologist, **medical physicist**, and lead imaging technologist to make certain that they adhere to current standards of practice and account for changes in CT imaging equipment."
- "… **reviews and analyzes incidents** where the radiation dose index … **exceeded expected dose index ranges identified in imaging protocols**. These incidents are then **compared to external benchmarks**.
- "$CTDI_{vol}$, DLP, and SSDE are useful indicators for monitoring radiation dose indices from the CT machine, they do not represent the patient's radiation dose."

www.jointcommission.org/assets/1/18/AHC_DiagImagingRpt_MK_20150806.pdf

Mandate | Image Wisely

Pledge for Imaging Facility, 2017

3. **Radiation doses are optimized** to levels assuring that only the necessary amounts of radiation are used to produce **images tailored** to patient **size** and the diagnostic **task**.

8. … **monitor dose indices** for common examinations, compare these indices with established benchmarks (Diagnostic Reference Levels), and evaluate outliers on a timely basis to prevent **unnecessary exposure to patients or images with insufficient diagnostic information**.

9. … participates in a **dose index registry** (local, regional or national) that includes routine evaluation of examination performance and dose indices.

http://www.imagewisely.org/Pledge/Facility-Pledge

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Mandate | It Just Makes Sense.

- Consistent clinical operation
  - Doses, protocols, users: assurance against repeated errors by evaluating outliers
- Establish appropriate dose ranges for patients based on trends
- Benchmark dose levels against peers
- Dose estimates that are personalized, meaningful, accurate, precise

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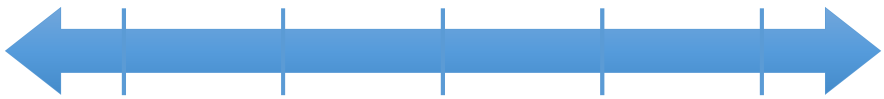
Solutions | Goal(s) to Accomplish?

Out-source | Co-source/ Partner | In-source



+ Least effort
- Captive audience

+ Reduce risk & bandwidth
- (Risk) mediocrity

+ Autonomy, Leadership
- Bandwidth

Beyond Dose
Dose monitoring CAN and SHOULD extend beyond dose.
RDIM can be a portal into operational consistency.

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Solutions | Basic Configurations

Specifications

Server:
OS is Physical or Virtual
Hardware:
Provided by Vendor or Institution
Location:
Local intranet/firewall
Remote/Cloud
Dataflow:
PACS to server
Modality to server
Server to dose registries
Data types receive/send:
Dose reports, (P-)RDSR, MPPS, HL7, IHE REM, Manual, etc. Configurable APIs.

Pricing

Model(s):
- License (per site, per equipment)
- SaaS
- per Exam
- Tiered model
- Maintenance
- Number of users

Additional Costs:
- Operational
- Hardware
- IT Support (internal and external)
- Training
- 3rd party integration
- Data and protocol review services
- Education

Install Base & Integration

How many sites live?

Sites comparable to our institution?

Proven Integration:
- EHR
- PACS
- Dictation

See also: "AAPM medical physics practice guideline 6.a.: Performance characteristics of radiation dose index monitoring systems," Gress et al. JACMP 2017; 18:4:12–22.

Solutions | 4 Examples

Specifications		Pricing	Install Base & Integration	
Server	Software installed on physical or virtual server on-site	Capital & SaaS	# Sites / Comparable to Duke	Some / Few
Dataflow	PACS to server (also MPPS from modality)		EHR	None.
Cloud	Currently testing in small markets.		Dictation	50% of sites.
Server	Software installed on virtual server, on-site.	License & Maintenance	# Sites / Comparable to Duke	Many / Several
Dataflow	Modality directly to server.		EHR	None.
Cloud	No current plan.		Dictation	1 WIP
Server	Server hardware (vendor) installed on-site.	SaaS & per Exam	# Sites / Comparable to Duke	Very few / 1
Dataflow	Modality, preferred, or PACS to Server; info sent to cloud		EHR	1 WIP
Cloud	Exclusively cloud hosted: software, analytics, & data		Dictation	Some
Server	Software installed on a physical or virtual server on-site	Tiered & per Exam	# Sites / Comparable to Duke	Many / Several
Dataflow	PACS or modality to server.		EHR	3
Cloud	No current plan.		Dictation	Many

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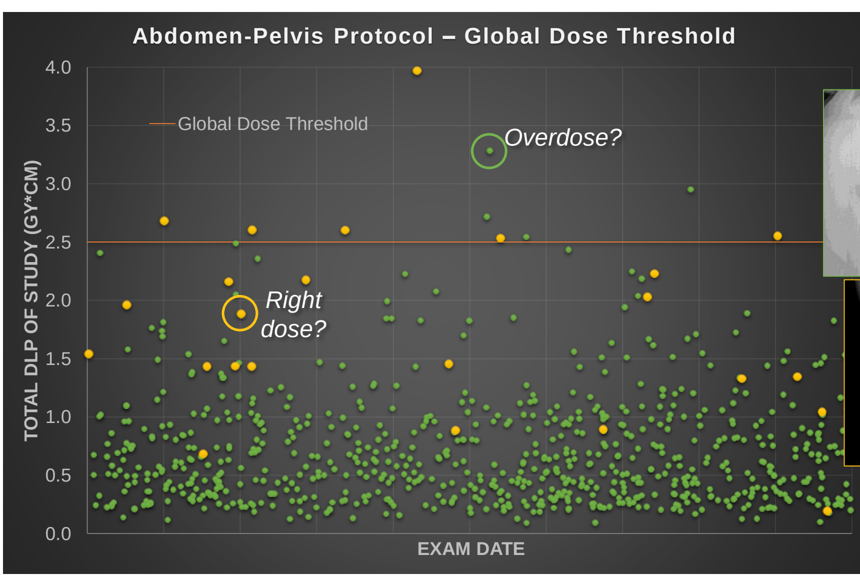
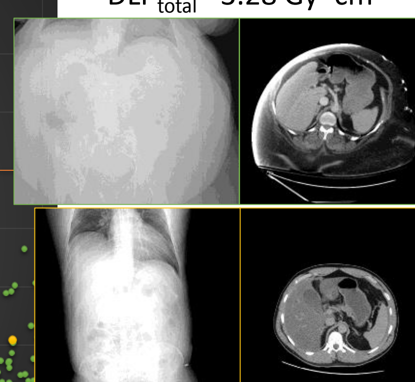
Applications | Outliers



Eff. Diam = 44.8 cm

DLP_{total}= 3.28 Gy*cm



Eff. Diam = 32.5 cm

DLP_{total} = 1.88 Gy*cm

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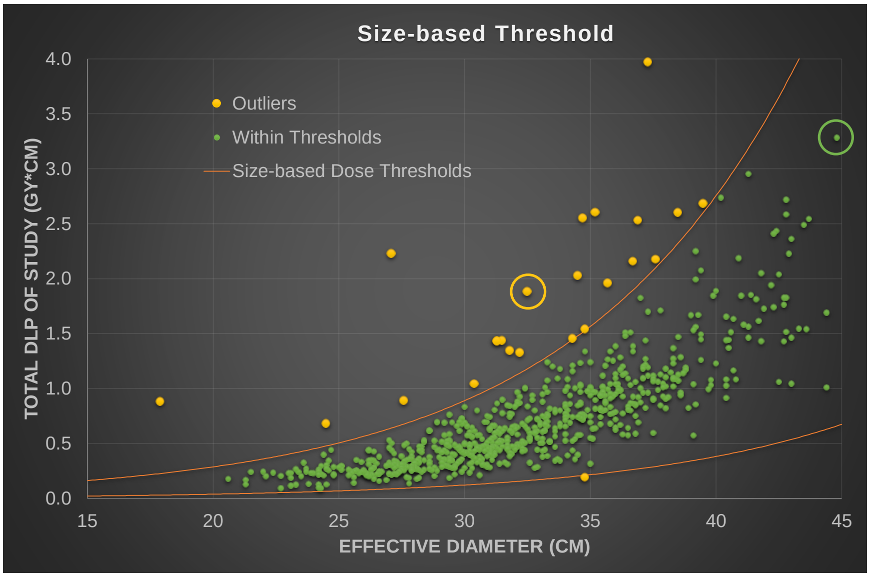
Applications | Outliers



Monitoring radiation dose irrespective of patient size is ***misleading***.

Combined ***dose and size*** tracking is ***essential*** for right-sizing personalized CT operation.

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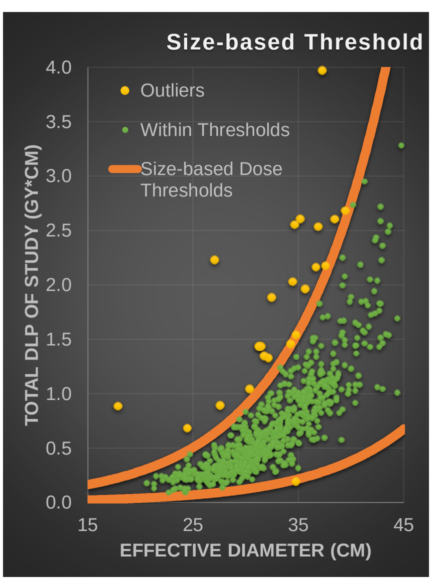
Applications | Establishing Thresholds



Where do those thresholds come from?

1. Scatter plot and fit 18-months of historic data
   - Linear (size-independent, Routine Brain)
   - Exponential (size-dependent, abd pelvis)
2. Remove residuals > 3 st. dev.
   - Avoid outliers when setting thresholds
3. Re-fit “cleaned data”
   - Set confidence intervals (95%, 99%)
4. Fit coefficients are stable until protocol change

Another Approach: Chen et al. “Tracking and Resolving CT Dose Metric Outliers Using Root-Cause Analysis,” JACR 2016.

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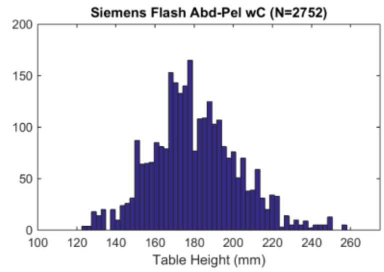
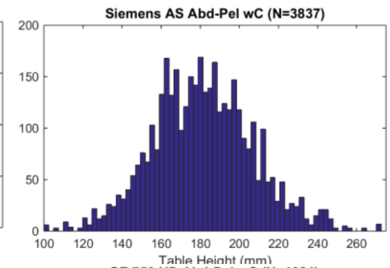
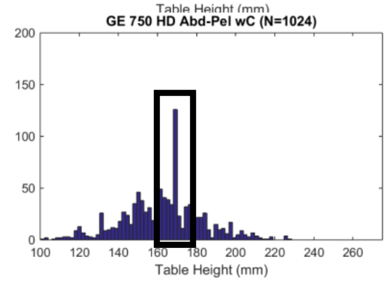
Applications | Correct and Consistent

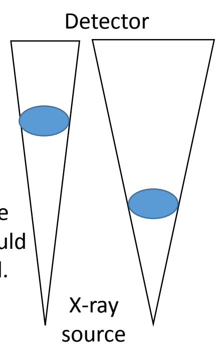
Systems are designed expecting correct patient positioning (bow-tie filter, TCM), typically positioned along the bore's central axis.

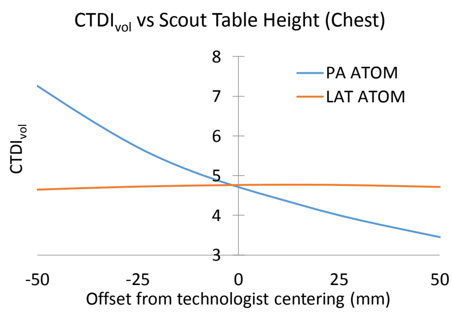






Patient will have a different projected size, so tube current would be adjusted.





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Solutions | What's Missing?*

Data curation and maintenance
- Wrong information **will be** entered. How do you identify and clean it?

Selective parameter retention
- "Kill them all and let God sort them out." –Amalric,
  or, you don't know today what you'll want tomorrow.
- Vendor (meta)data neutrality, dependency, and customization?

User-customizable data visualization
- User-defined reports and visualizations in the solution versus data export?

Alert thresholds
- Global are standard, but provide limited value
- Naïve to system model, system capabilities and patient size, age, gender

Portability
- Can you get all your data "out" in a usable, non-proprietary format?

Event tracking
- Software/hardware updates to the modality
- Software/algorithm updates to the RDIM
- Integration of new metrics and standards

**An incomplete list.*

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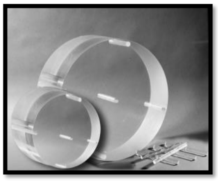
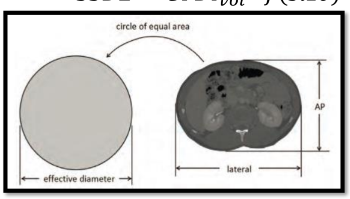
Dose Metrics | CT Radiation

- $CTDI_{vol}$, DLP

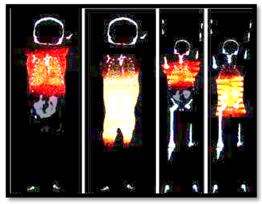


- SSDE
  - $SSDE = CTDI_{vol} \cdot f(size)$



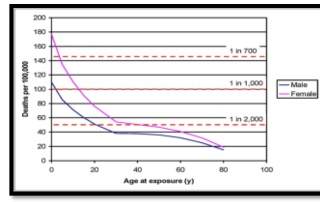
TG 204, Size-Specific Dose Estimates (SSDE) in Pediatric and Adult Body CT Examinations

- Effective Dose
  - $ED = DLP \cdot k(anatomy)$



Li et al. Medical Physics 2010

- Risk Estimate
  - $RI = DLP \cdot q(anatomy, age, gender)$



Fahey et al. JNM Tech, 2012

Method	Size	Organ	Age	Gender	Across modalities
CTDI					
SSDE	✔				
Effective Dose[1]	✔	✔			✔
Risk Estimate[2]	✔	✔	✔	✔	✔

[1]ED defined for ref. patient, but concept can be modified for a size adjustment factor.
[2]Dependent on BEIR VII data; relatively large uncertainties when applied to individuals.

Dose Metrics | Patient-specific Dose

CT

Metric	*Units*
$CTDI_{vol}$	mGy
SSDE	mGy
DLP	mGy . cm
Size-adjusted DLP	mGy . cm
Effective Dose	mSv
Risk Index	incidents/cohort
Organ Dose	mGy

Fluoro

Metric	*Units*
Fluoro Time	sec
KERMA	Gy
DAP	Gy . cm²
Peak Skin Dose	Gy
Effective Dose	mSv
Risk Index	incidents/cohort
Organ Dose	mGy

Radiography

Metric	*Units*
Rel. X-ray Exposure	Unitless
DAP	Gy . cm²
Effective Dose	mSv
Risk Index	incidents/cohort
Organ Dose	mGy

Mammo

Metric	*Units*
AGD	mGy
Effective Dose	mSv
Risk Index	incidents/cohort
Organ Dose	mGy

Standardized Dose Analytics
Standardized dose metrics will be the essence of meaningful monitoring.

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Outline | Optimization

1. Utilization and Reduction
   a. Justification
   b. Appropriateness Criteria
   c. Tube Current Modulation
   d. Iterative Reconstruction
2. Monitoring
   a. Mandate
   b. Software Solutions, Basics
   c. Components of Solutions
3. Optimization

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Optimization | Getting There from Here…

- Balancing (versus min-max) image quality tradeoffs that dose reduction strategies have been promising/selling
- Patient-specific protocols: Personalized/Precision healthcare
- Improving performance *and* consistency of clinical operations

Going to need

- ➢Patient-specific, meaningful dose metrics
- ➢Patient-specific image quality metrics
- ➢Comprehensive, integrated platform

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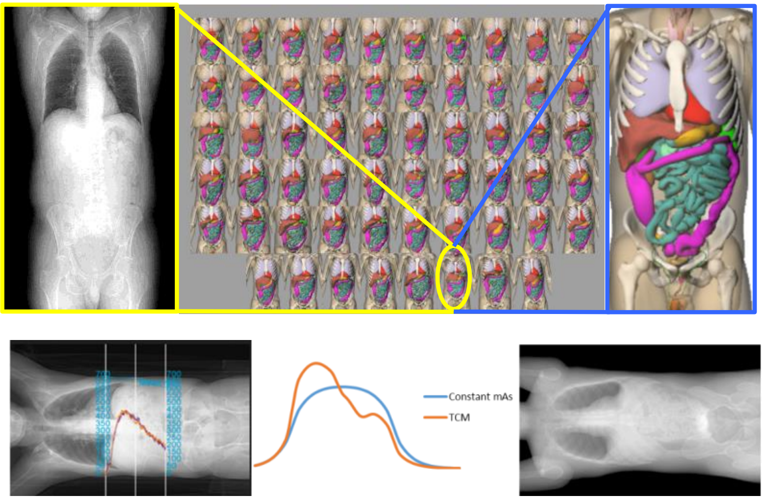
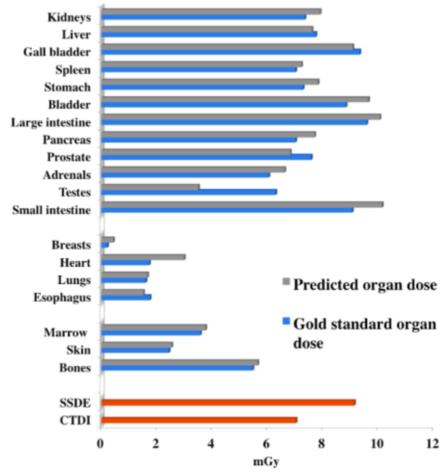
Dose Metrics | XCAT, Monte Carlo, AEC, & Organs





"A Framework for Organ-based Dose Monitoring System for Body CT Examinations."
X Tian, JM Wilson, WP Segars, F Zanca, P Guntzer, DE Miller, E Samei, RSNA 2016

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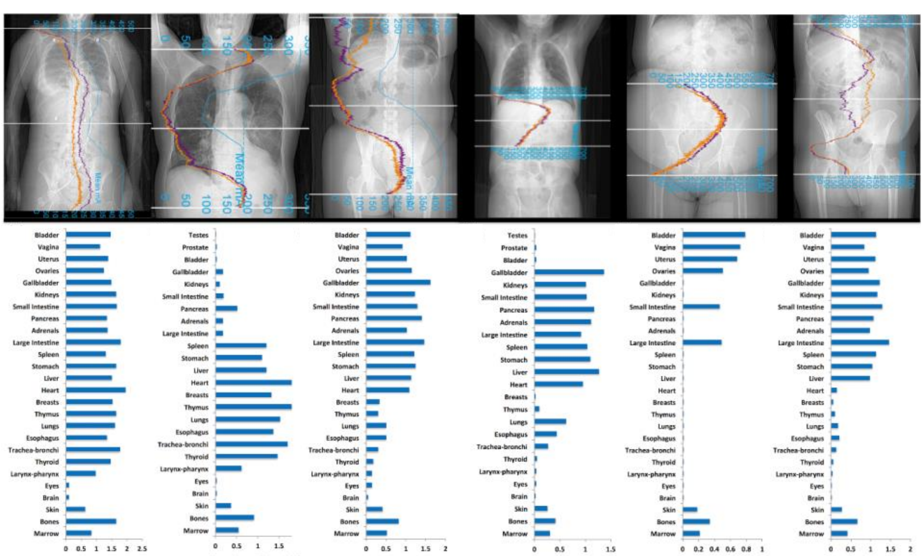
Dose Metrics | Patient-Specific Organ Dose

CAP Chest Abdomen-pelvis Abdomen Pelvic Kidney-to-bladder



Tian el al., RSNA 2016

Dose Metrics| Siloed Radiation Dose

Radiation dose as an FOM

Image Wisely
DRLs "represent the dose level at which an investigation of the appropriateness of the dose should be initiated"

DRL

Image quality FOMs
- Noise
- Contrast
- Resolution

IQ-RL

Clinical FOMs
- Task
- Utility
- Outcome

Comprehensive, Integrated Health Analytics
Dose is a place holder until we devise more comprehensive operational auditing that incorporates big data analytics integrated with EHRs.

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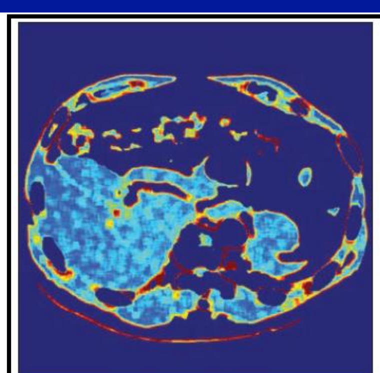
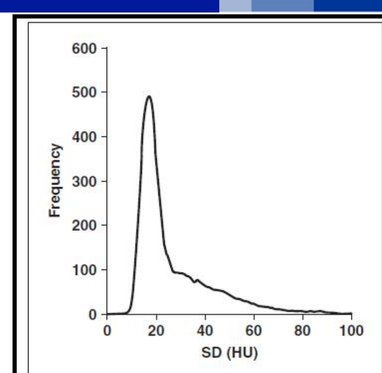
Image Metrics| Automatic Noise Magnitude

1. Patient CT image set



2. Soft tissue automatically segmented, ROIs applied, HU st. dev. measured



3. Noise histogram

Image Noise across CT slices characterized as a single value: *Global Noise Level*
Validated through phantom and observer study

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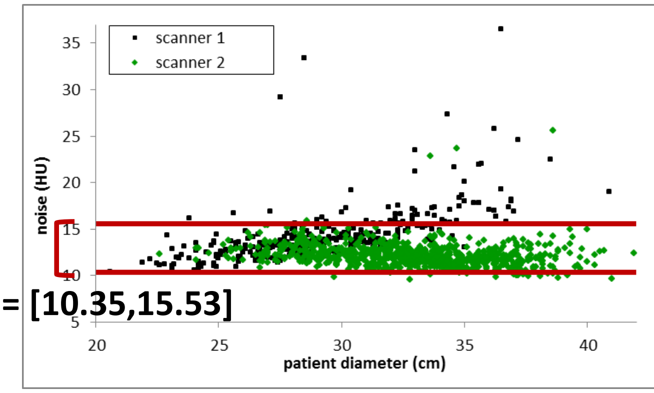
O. Christianson, J. Winslow, D. P. Frush, E. Samei, "Automated Technique to Measure Noise in Clinical CT Examinations", AJR, 2015.

Image Metrics | Noise Reference Level

Recommended image quality range, such as NRL, toward achieving consistency in clinical operations.

Chest w/o

- 1159 patients
- 2 scanners (2 vendors)
- Standard clinical protocols
  - kVp, AEC, slice thickness, pitch



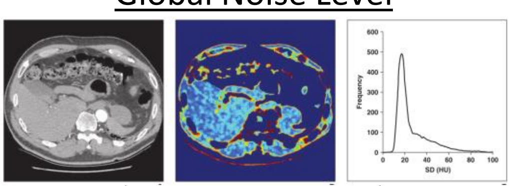
NRL = [10.35,15.53]

Proposed Noise Reference Level Interval = Median Noise ± 20%

TH-EF-**601**-06 **1:50pm**	"From Diagnostic Reference Level to Noise Reference Level: A First Step toward Quality-based Reference Level," F Ria et al. AAPM 2017

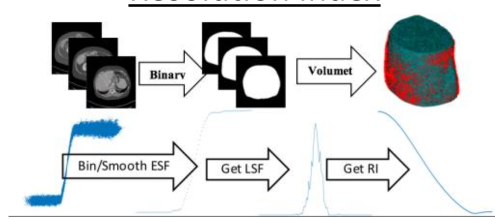
Image Metrics | Comprehensive Monitoring

Global Noise Level



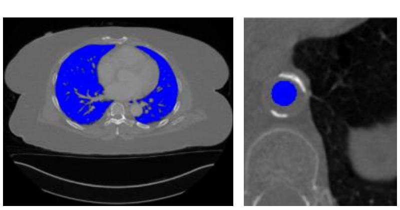
(Christianson et al., AJR, 2014)

Resolution Index



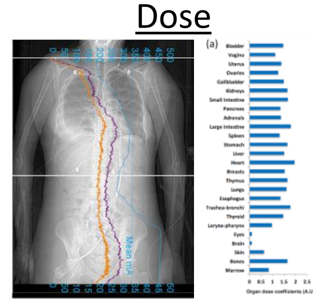
(Sanders et al., Medical Physics, 2016)

Organ-based HU Sampling



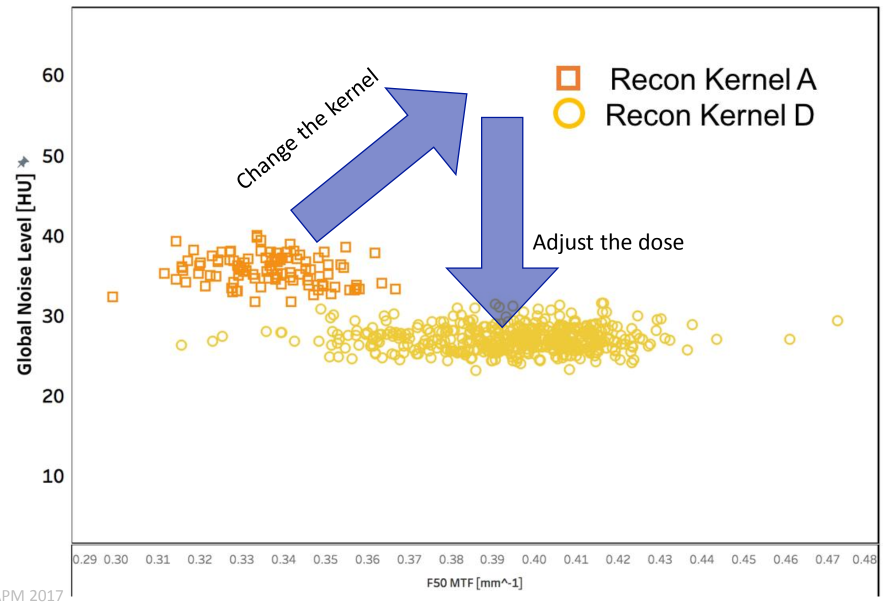
(Abadi et al., Medical Physics, 2017)

Dose



"Robustness and Accuracy of an Automated Solution for Measuring Image Noise, Spatial Resolution, Contrast, and Dose in Clinical CT Images," A Ding, et al. AAPM 2017

Image Metrics | *Informed* Protocol Optimization



Or ANY combination of:

- Dose
- Contrast
- Pitch
- Slice Thickness
- Rotation Time
- AEC
- etc.

A Ding, et al. AAPM 2017

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Recommended | Resources

- "Dispelling myths and making adjustments: How the physicist should account for size and age when designing CT protocols," Frank Ranallo, AAPM 2017.
- "Joint Commission Diagnostic Imaging Requirements: Survey Results Update," Andrea Browne, AAPM 2017.
- "Tube Current Modulation Approaches: Overview, Practical Issues and Potential Pitfalls," Michael McNitt-Gray, AAPM 2011

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Summary |

- Manufacturers/Models have varying degrees of reproducibility of noise-dose values across sizes with TCM.
- Beyond Dose: Dose monitoring CAN and SHOULD extend beyond dose. RDIM can be a portal into operational consistency.
- Standardized Dose Analytics: Standardized dose metrics will be the essence of meaningful monitoring.
- Comprehensive, Integrated Health Analytics: Dose is a place holder until we devise more comprehensive operational auditing that incorporates big data analytics integrated with EHRs.