Workflow Hurdles and Methodology (WHAM!)

Technical/Physics-related questions

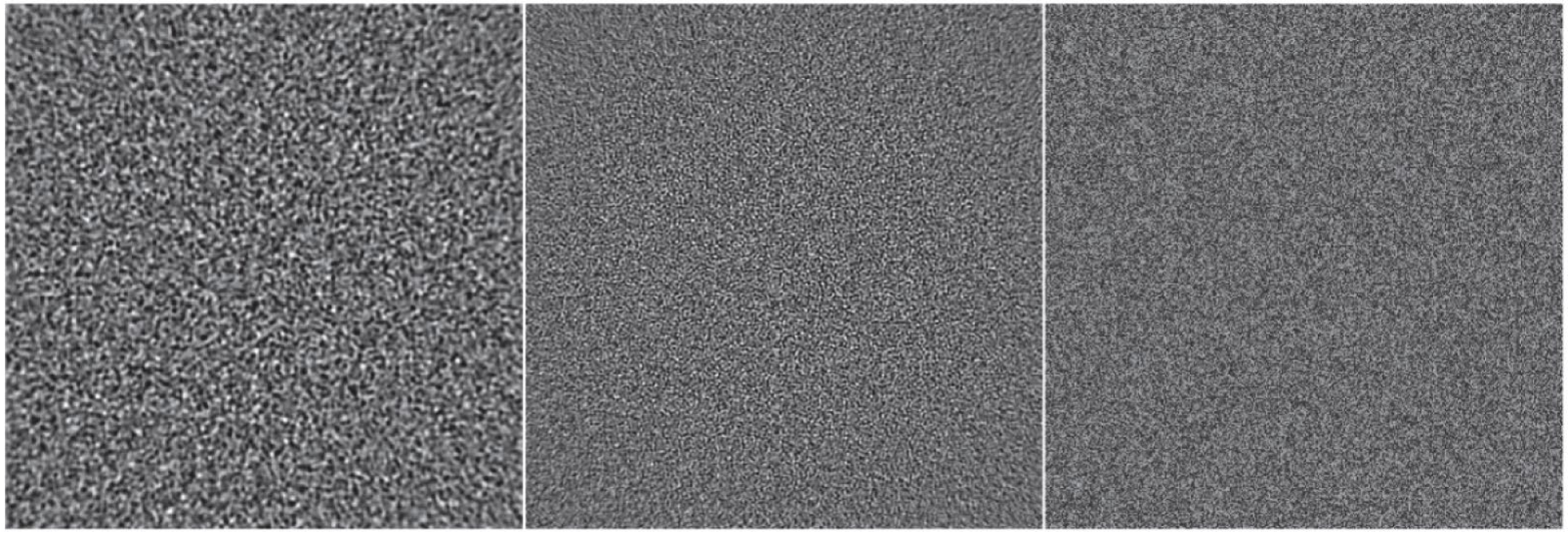
PROBLEM #1

Submitted by Hooryia Bajwa, Peter MacCallum Cancer Centre

How can image quality be standardized across various CT scanner platforms?

- Can task-based image quality assessment be used for this goal?
- What role could AI and model observers serve in this process?
- Is measuring image noise and contrast “good enough”?

Noise magnitude is NOT good enough

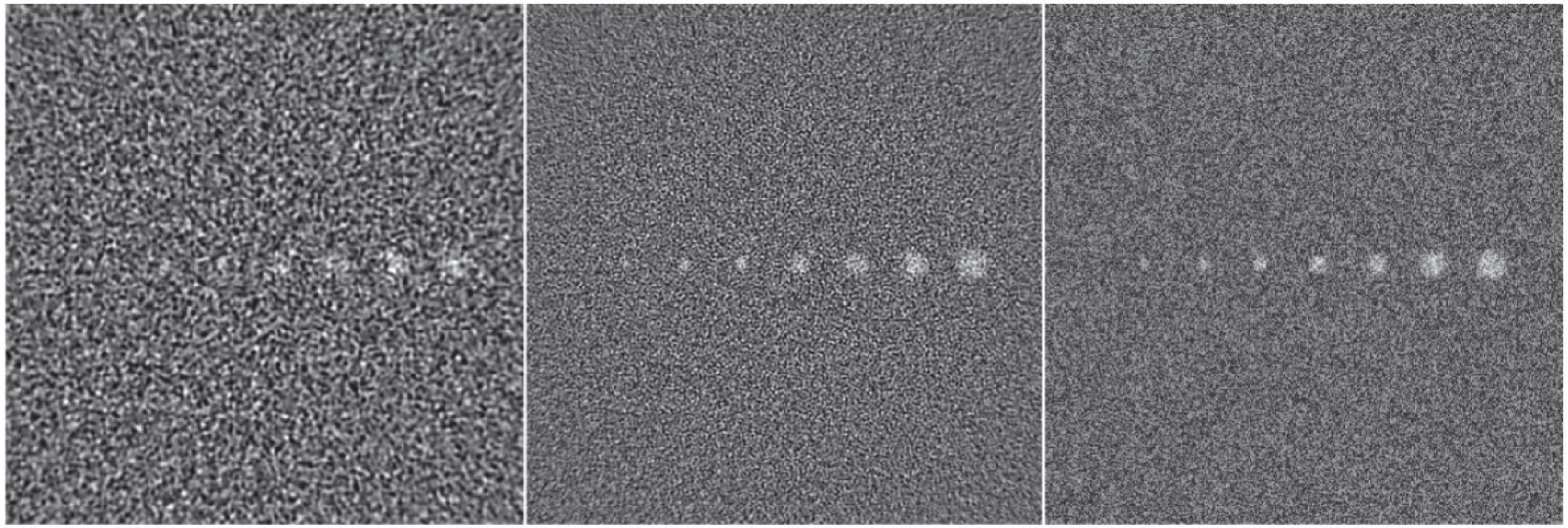


(a) (b) (c)

(a-c) have the same noise variance

Hsieh, J. Computed tomography: principles, design, artifacts, and recent advances.

Noise magnitude is NOT good enough



(a) (b) (c)

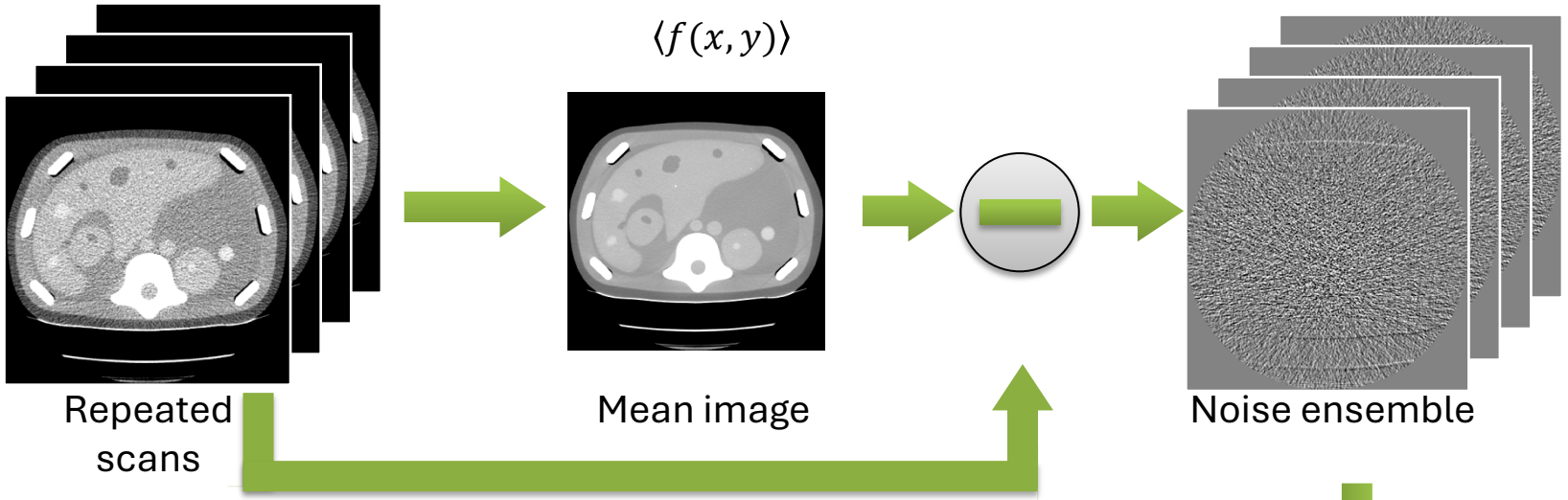
(a-c) have the same noise variance

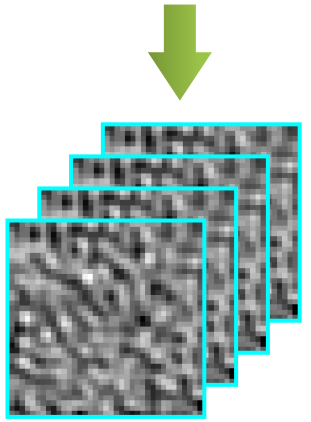
CT Noise Power Spectrum (NPS)

- Motivation: We need to characterize both the magnitude and spatial correlation (texture) of noise in reconstructed images

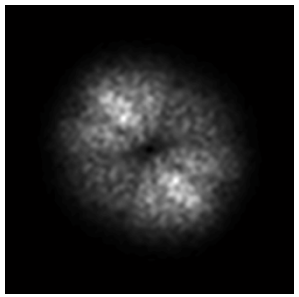
- NPS describes the distribution of noise variance as a function of spatial frequency

NPS Measurement Method I (Rigorous Approach)





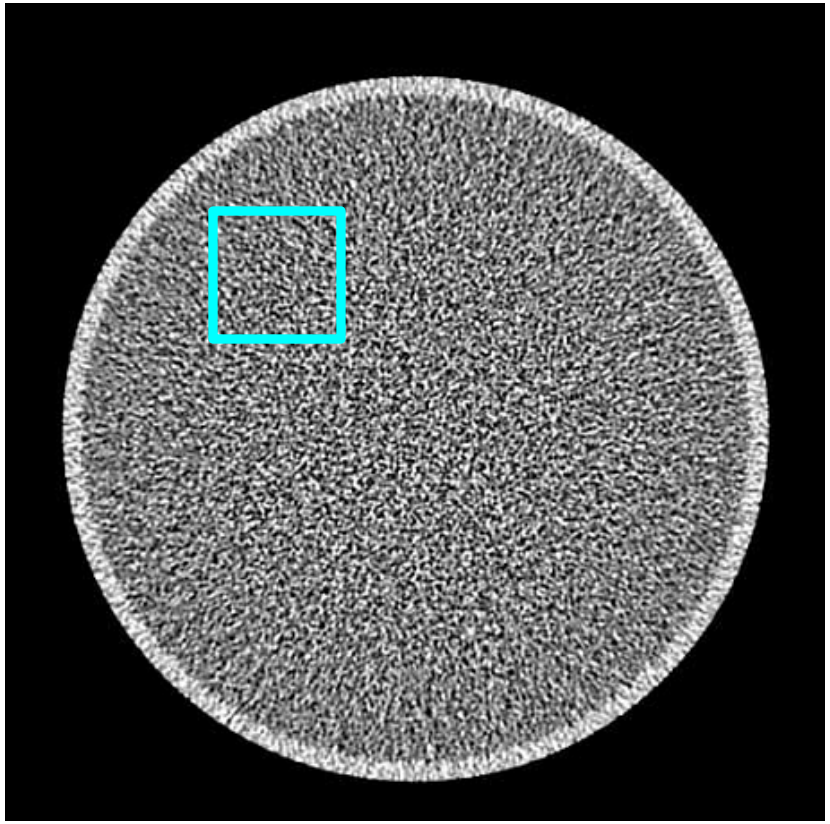
ROI

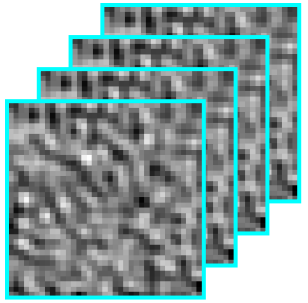


NPS

$$\mathrm{NPS}(f_x, f_y) = \mathbb{E}\left\{|\mathcal{F}\{n(x,y)\}|^2\right\}.$$

NPS Measurement Method II (a commonly-used but not-so-rigorous approach)



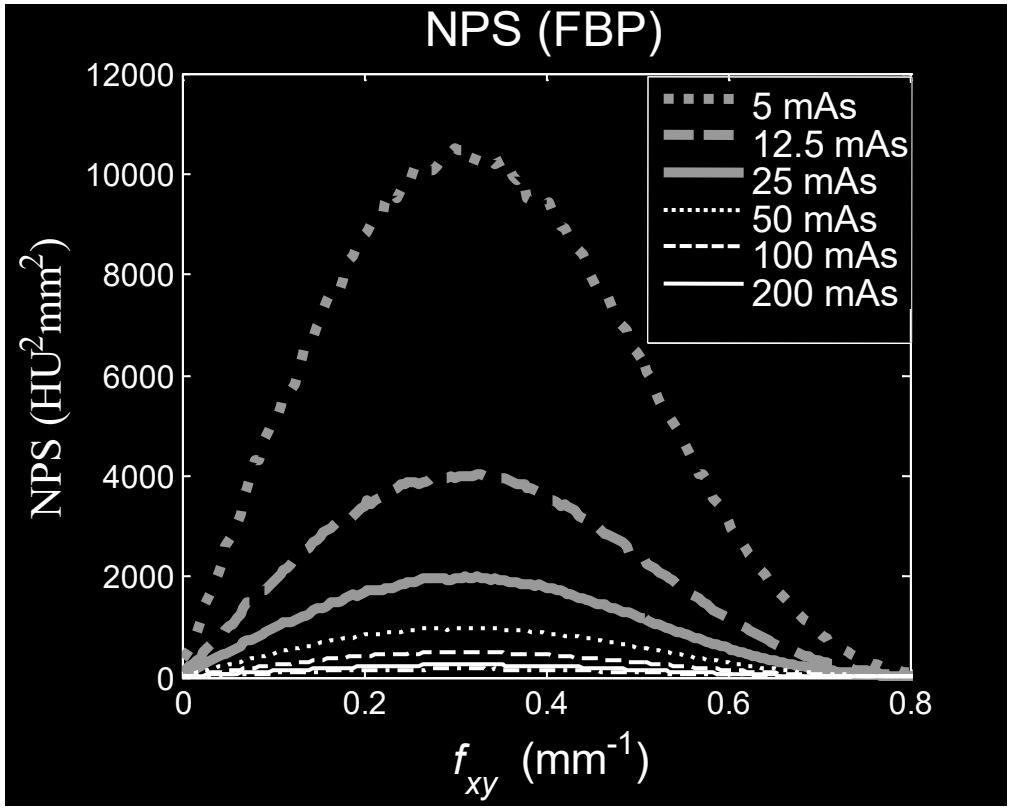


$$\widehat{\mathrm{NPS}} \approx \frac{1}{K}\sum_{k=1}^{K}\left|\mathcal{F}\{I_k - \bar{I}_k\}\right|^2.$$

This method replaces the **ensemble** average with a **spatial** average: assumes stationarity and ergodicity

Shift the location of the ROI to obtain multiple measurements

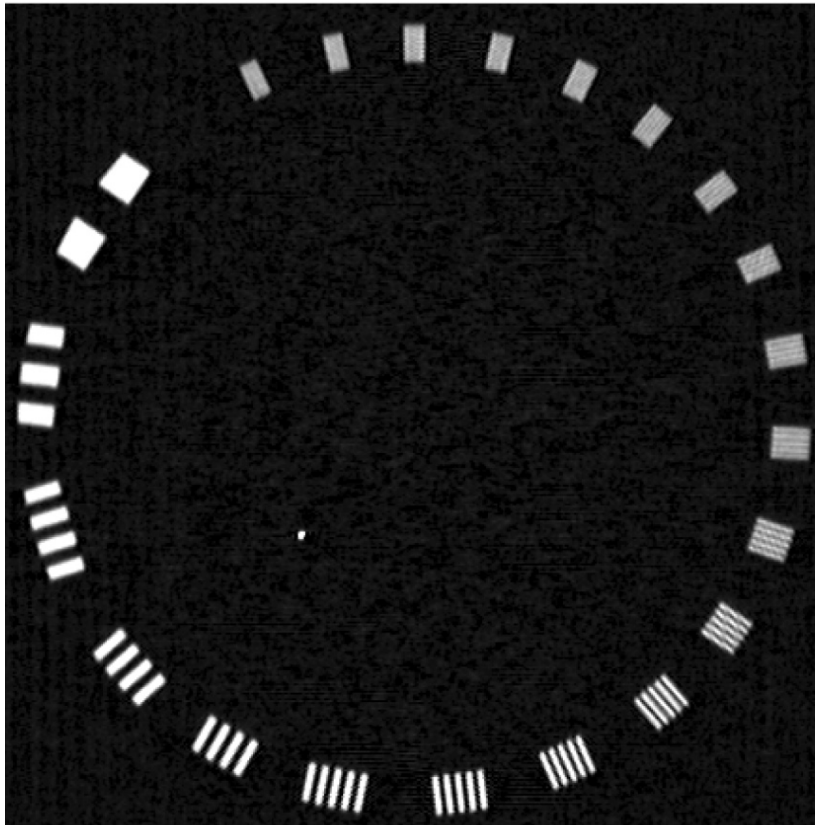
Example CT 1D NPS (Radial average of 2D NPS)



What information can we get from NPS?

- Area under the NPS curve: related to noise variance
- Mean and peak frequencies: related to the noise texture
- Higher mean and peak frequencies indicate “fine texture”

Spatial resolution in CT

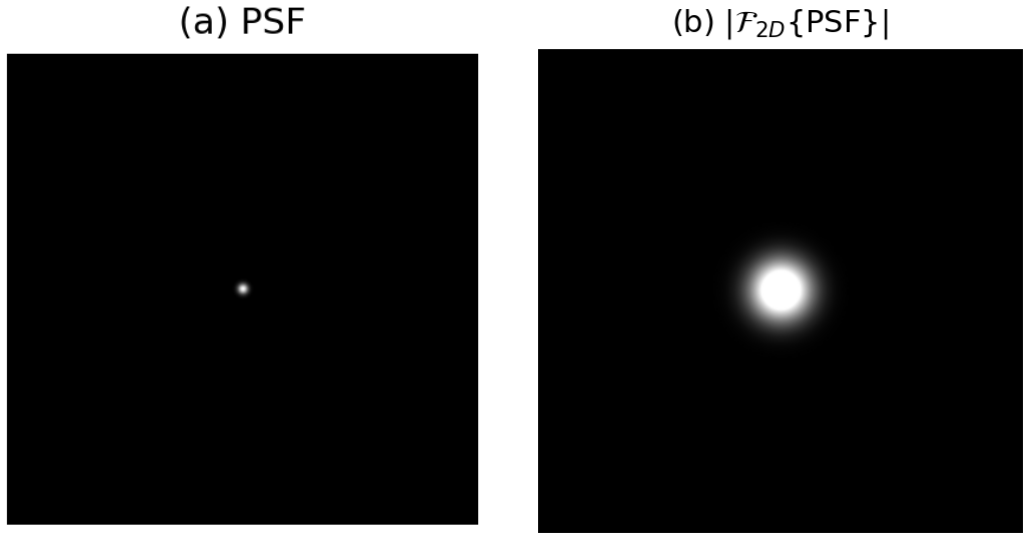


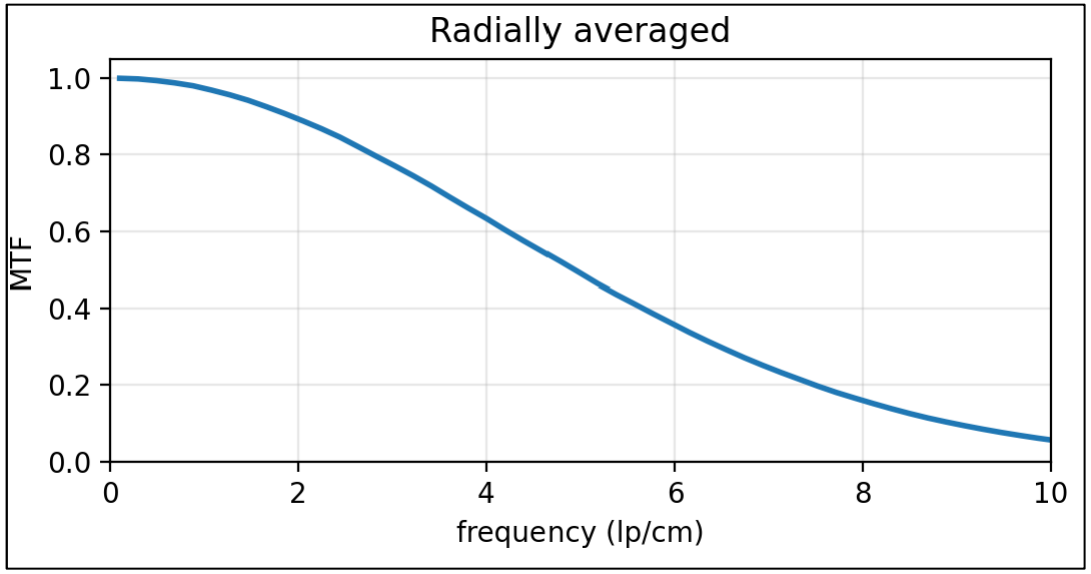
- Direct method
  - Using line-pair test patterns
  - Simple to interpret, but somewhat subjective (window level, decision criteria)
  - Only provide the **limiting** spatial resolution

- Indirect method
  - Modulation Transfer Function (MTF)
  - Commonly used FoM: 50% MTF, 10% MTF, 2% MTF
  - Commonly used phantoms: microbead, thin wire, narrow slit, sharp edge, cylinder

MTF Measurement

- Microbead (small sphere)
- Thin wire aligned along z-axis so each axial slice sees a “point”
- Size consideration: diameter of the sphere should be smaller than the limiting spatial resolution of the system
- MTF can be calculated from PSF, LSF, or ESF





Model Observers and detectability index

- Objective physical image quality metrics
  - Noise variance, NPS
  - Spatial resolution, MTF
  - CNR
- Task-based image quality assessment
  - Image quality is measured by the performance of observers on some specific tasks
  - The observer can be a human, such as radiologists, other physicians trying to make a diagnosis
  - The observer can also be a mathematical model or a computer algorithm, i.e., **model observers**
  - If the model observer can accurately predict the performance of the human, then it can be used for system optimization and evaluation

Ideal Observer

For a detection task, the SNR of the model observer is often referred to as the “detectability index” or d'. For an ideal observer:

$$(d')^2 = SNR^2 = \int \frac{\left|S(\vec{k})\right|^2}{NPS(\vec{k})} \mathrm{d}\vec{k}$$

$$(d')^2 = \int \frac{\left|S_0(\vec{k})\right|^2 \mathrm{MTF}^2(\vec{k})}{NPS(\vec{k})} \mathrm{d}\vec{k}$$

$S_0(\vec{k})$: the object signal before the imaging system, i.e. the “task function”

Example task function

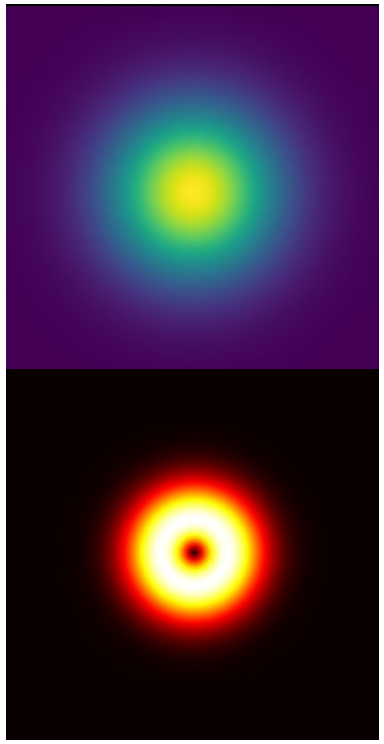
- Define the task function S_0:
  - A uniform 5-mm diameter disk with +10 HU to the background
  - Signal-known-exactly, location-known-exactly

$$S_0 = \mathcal{F}\{$$  $$\}$$

Binary disk

MTF

NPS



d'_{ideal}

d'_{NPW}

Challenges & Discussions

- Nonstationary noise, resolution when using Iterative Reconstruction or Deep Learning Reconstruction
  - NPS and MTF become object-dependent

- Model observer can be a repeatable quantitative observer only after validation against human performance for the same task, size range, scanner, reconstruction family

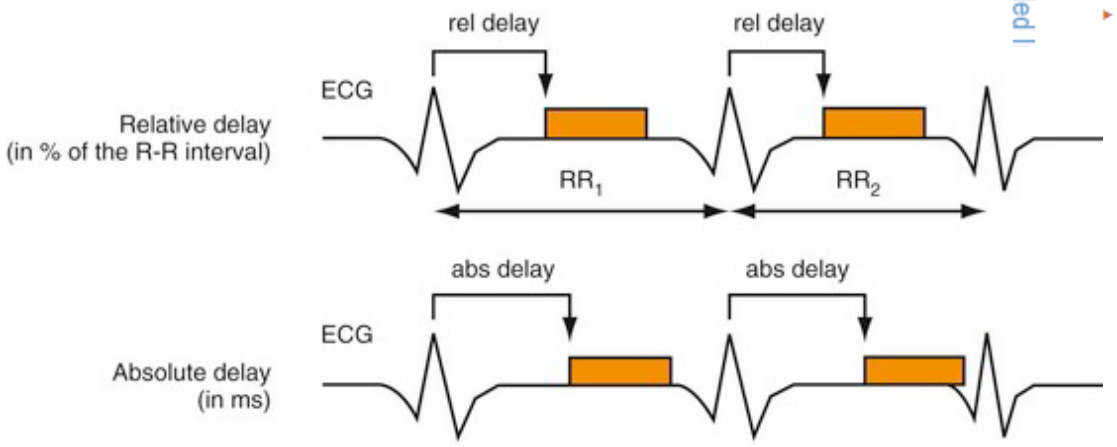
- Are we trying to match diagnostic performance, or dose efficiency?

PROBLEM #2

Submitted by Humberto Monsivais, MD Anderson

Our cardiac CT program has low volume (a few cases per week), and technologists have limited experience with ECG-gated workflows. In CCTA exams, techs often struggle with selecting appropriate cardiac phases and correcting motion-affected automatic reconstructions, and they rely on radiologists to choose prospective vs. retrospective gating. Although we've optimized protocol settings based on heart rate and variability, image quality remains inconsistent.

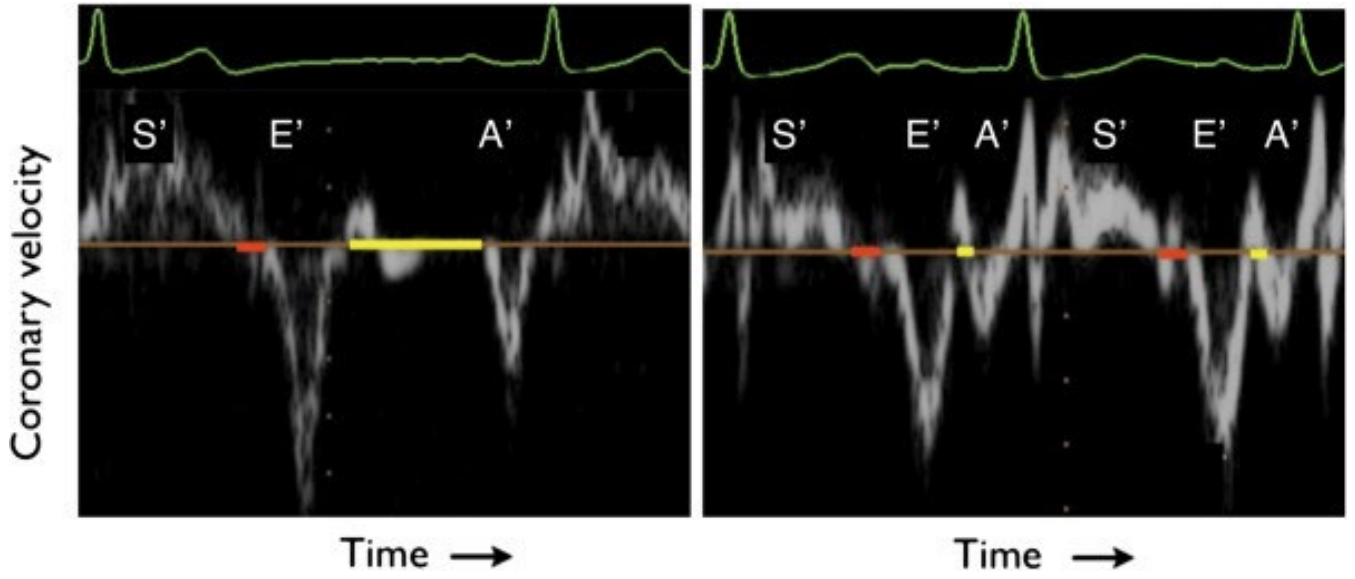
CCTA Basics



BMC Med Imaging. 2013; 13: 5.
Published online 2013 Feb 1. doi: 10.1186/1471-2342-13-5
PMCID: PMC3570333
PMID: 23375107

Defining the mid-diastolic imaging period for cardiac CT – lessons from tissue Doppler echocardiography

James M Otton,[1,2] Justin Phan,[2] Michael Feneley,[1,2] Chung-yao Yu,[1] Neville Sammel,[1] and Jane McCrohon[1,2]

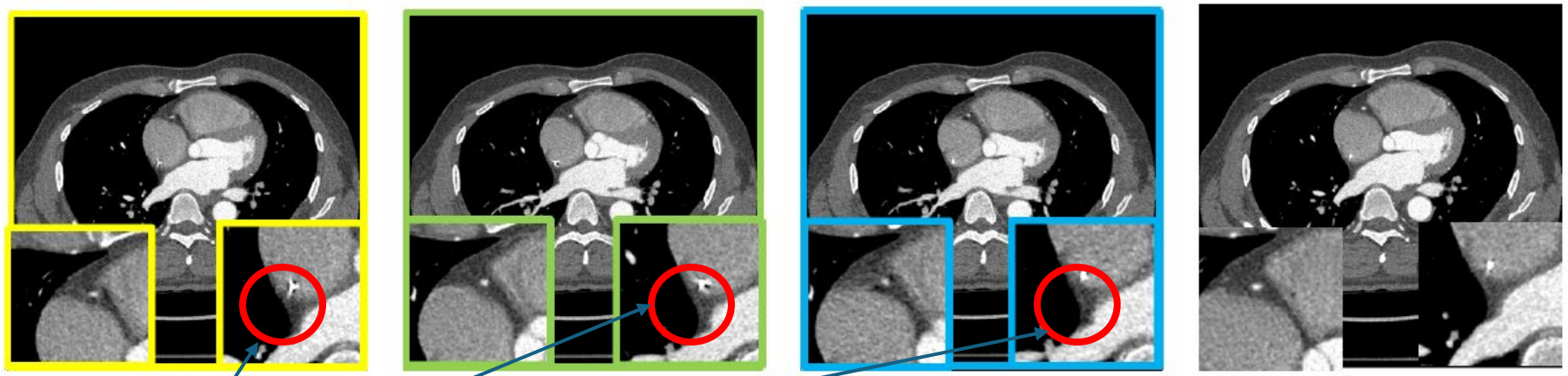


Patients will present with a wide range of heart rates

- There exists and optimal time post contraction which varies as function of HR

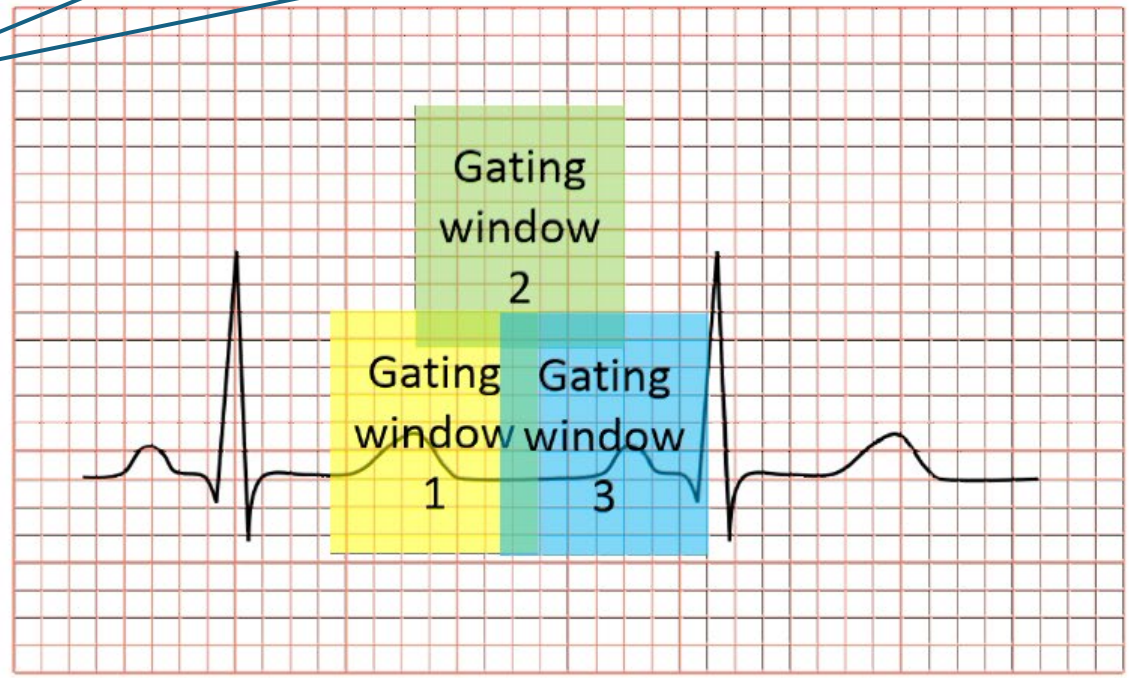
Low heart rate, best time to image is later in cardiac cycle (yellow line)

high heart rate, best time to image is earlier in cardiac cycle (red line)



(a) (b) (c) (d)

Motion artifact is highly dependent on phase/cycle location



(e)

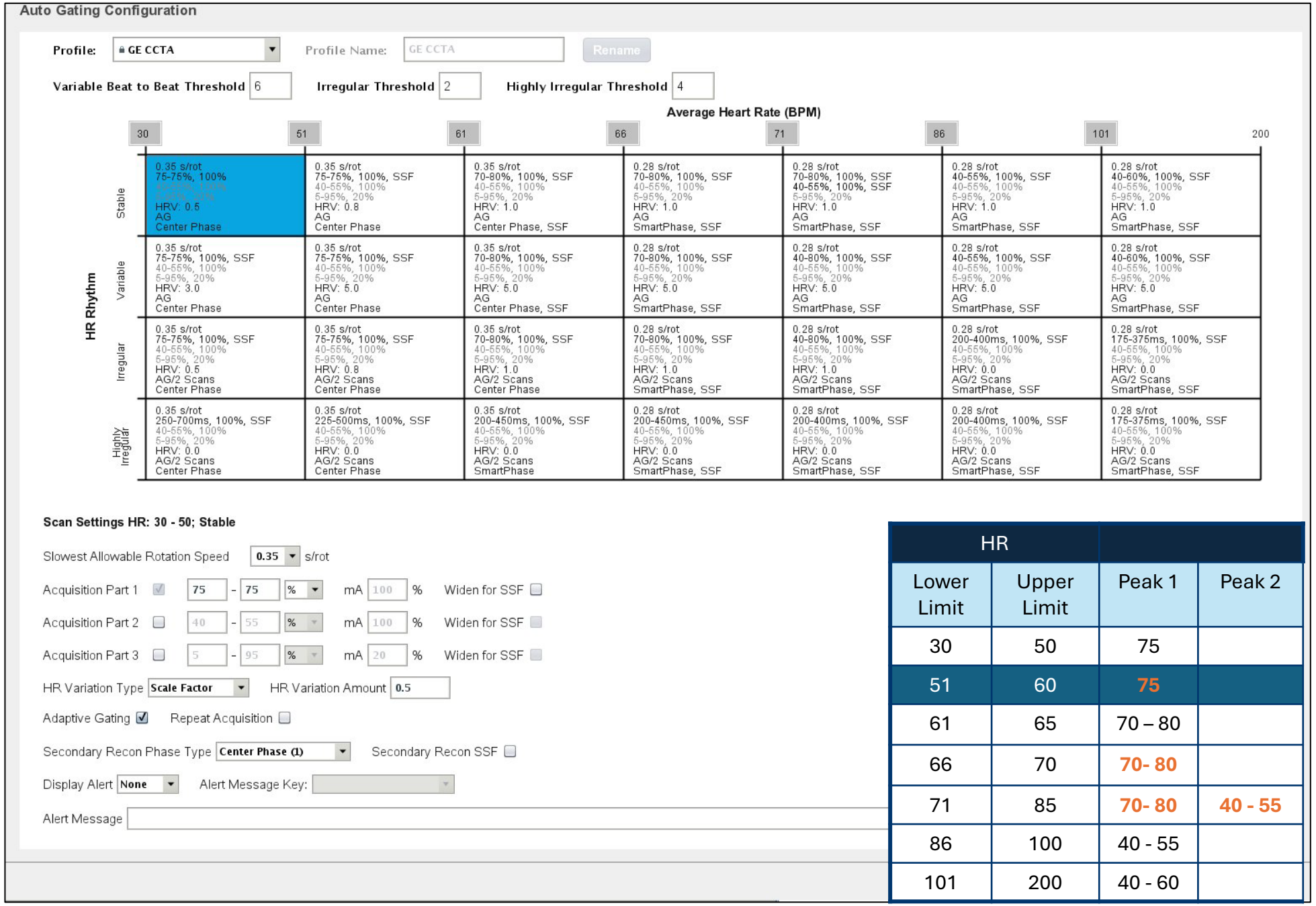
How we do it here at UW Health

- Non apex scanners (legacy)—we have HR based protocols.
  - <60 bpm with regular HR = Gated at 70% prospectively (*snapshot pulse cine*)
  - 60-70 bpm = Gated retrospectively. (*snap-shot segment helical*)
  - Over 70bpm = do not scan
- Apex Scanners = we use Auto-Gating profiles built from radiologist/GE recommendations. Techs do not have to select cardiac phases. After recording HR during scan, scanner places patient in a “bin” that has specific phases based off HR and variability.
- Are you using DLIR/ASIR?—Our rads prefer DLIR High on all cardiac imaging.

Technical rationale for HR based protocols on legacy system

UW Health approach	Physiologic/technical rationale	Tradeoff
<60 bpm, regular: prospective at 70%	the R–R interval is long and stable. We can confidently target a narrow window.	Lowest dose, but limited ability to reconstruct another phase.
60–70 bpm: retrospective, whole beat	Diastole is shorter and the optimal phase becomes less predictable. Full-cycle data allow reconstruction in both diastole and end-systole.	More rescue flexibility, but higher dose (~2X)
>70 bpm: do not scan on legacy system	Coronary motion becomes too fast for the legacy scanner's temporal resolution, and multi-heartbeat acquisition becomes more vulnerable to misregistration.	Avoids spending radiation and contrast on a likely nondiagnostic study.

Auto-Gating profiles for Apex scanners



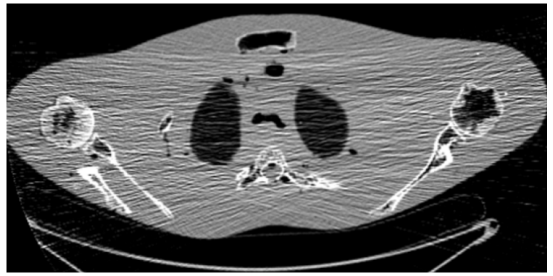
HR			
Lower Limit	Upper Limit	Peak 1	Peak 2
30	50	75	
51	60	75	
61	65	70 – 80	
66	70	70- 80	
71	85	70- 80	40 - 55
86	100	40 - 55	
101	200	40 - 60	

PROBLEM #3

Submitted by Jen Moroz, Mass General Brigham

A trauma neck CT scan with photon starvation in the shoulder region. Radiologist complains that the image quality around the shoulders and upper chest is poor. Since it's a trauma protocol, they don't want to increase the scan time. Our protocol uses 120 kV, rotation time 0.5s, Pitch 0.8-1 and tube modulation.

TCM may hit the mA ceiling in this region



Optimal TCM profile: $\mathrm{mA}(\theta) \propto \mathrm{e}^{\mu L(\theta)/2}$

$$\frac{mA_{lat}}{mA_{AP}} = e^{\mu(L_{lat}-L_{AP})/2} = e^{0.20\times 30/2} = e^{3.0} = 20.1$$

Tube current can’t change 20 times! Not enough to totally counteract angular attenuation

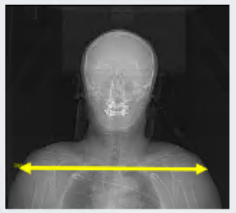
Possible Strategies

- Use higher kV, our routine neck uses 140 kV for large bin
  - Questions: soft tissue or CTA? Standalone or part of a pan-scan?

Size Selection for Neck and C-Spine

NOTE - if the patient has lymphoma and the study is a follow-up, use the small neck protocol (regardless of the patients actual size) since it will provide a lower dose

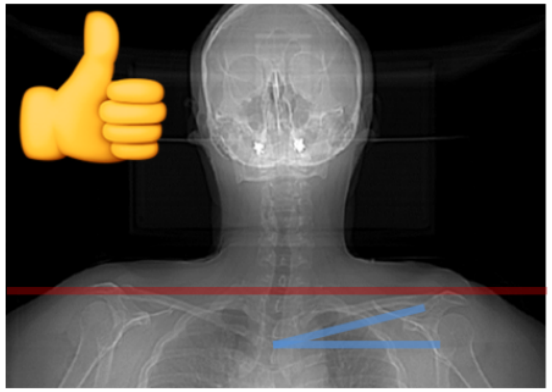
- Verify that the arms are outside of the CT wrap, and that the shoulders are relaxed down toward the feet as far as possible. Measure the width of the shoulders through the level of the mid-humeral head, as shown below.
- Check BMI
- Select small, medium and large based on the table below.

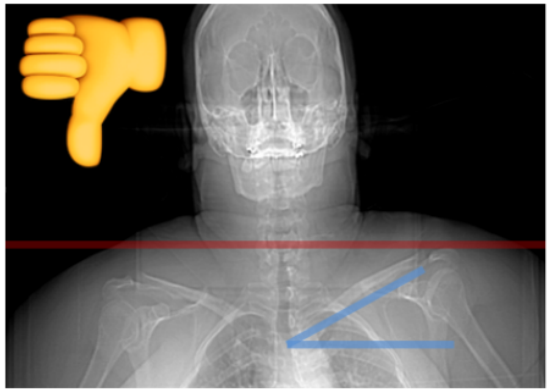
Measure width through mid-humeral heads	Small	Medium	Large
	**Shoulder width less than 46 cm *OR* BMI less than 26**	**Shoulder Width 46 to 50 cm**	**Shoulder width greater than 50 cm *OR* BMI greater than 35**

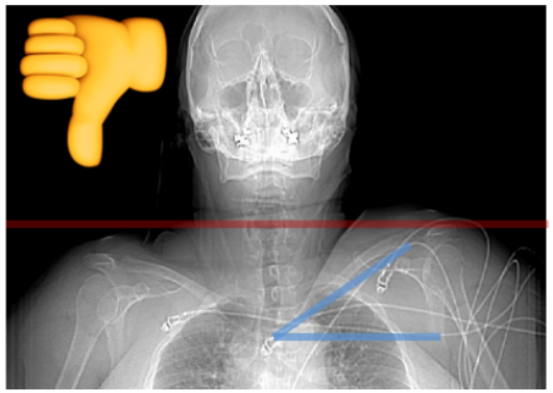
More important: Neck shoulder positioning!

Shoulder Relaxation

- Lowering the position of the shoulders is important in both allowing adequate visualization of the cervicothoracic junction and in lowering the dose required for the exam.
- Fastening the CT table strap around the torso only, as compared to around the torso and arms, decreases the level of the shoulders by one vertebral body level.
- Simply encouraging appropriate patients to “pull” their shoulders down has also been found to be effective.
- Having patients “walk” their hands down a folded bedsheet wrapped around the feet is also helpful for challenging cases.







Examples of good and bad shoulder position relative to the neck. The techniques listed above can get a patient from having a poor positioning of the shoulder to a good position. Note: try to recognize improper shoulder relaxation before you scout. If, however, you only notice this after you scout, there is no need to re-scout the patient after they move their shoulders.

Bad shoulder positioning. Patient has shrugged their shoulders up.

Good shoulder positioning, patient has walked their hands down their sides lowering their

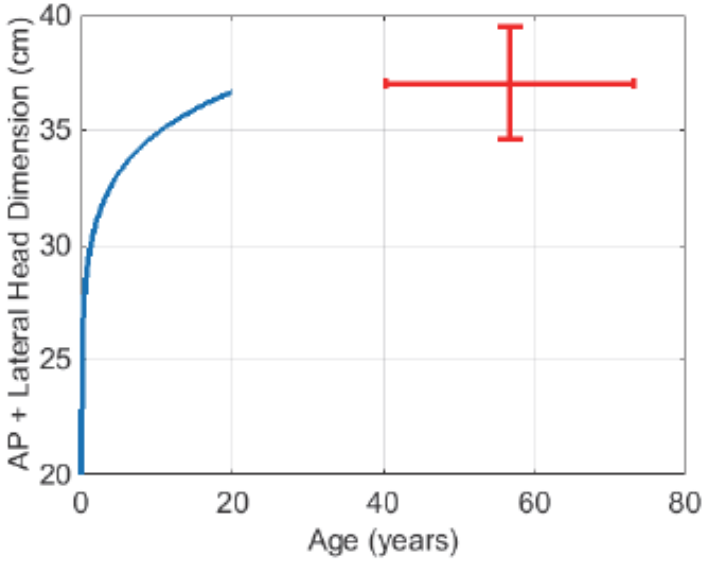
PROBLEM #4

Submitted by Matt Lucas, One Physics

Administration is questioning Leapfrog results specifically adolescent (10-14 & 15-17 age groups) head exams results. Should different adolescent age groups have separate protocols?

We base ped head protocols on age, since age correlates with skull thickness. **And use AEC on all peds protocols.** We use 0-2, 3-6, then adult (which we label as peds so people don't get scared about using adults on peds, but kids over 6 have adult head sizes)

Figure 13.4 Curve for pediatric head sizes modeled from data presented by Kleinman et al. 2010. The adult data is from 20 adult head scans measured in the same manner as the Kleinman curve. This plot reinforces what Figure 13.3 pictorially shows: the human head changes size rapidly in the first few years of life and then remains relatively constant in size. This data should guide the breakdown of pediatric and adult head protocols into size bins. The data shows adult head scans can get away with a "one-size-fits-all" approach, and pediatrics need a few size bins to cover the range from 0 to 10 years. You may, therefore, use adult head protocols for pediatric scans between the ages of ≈6 and 18 if your scanner is using AEC.



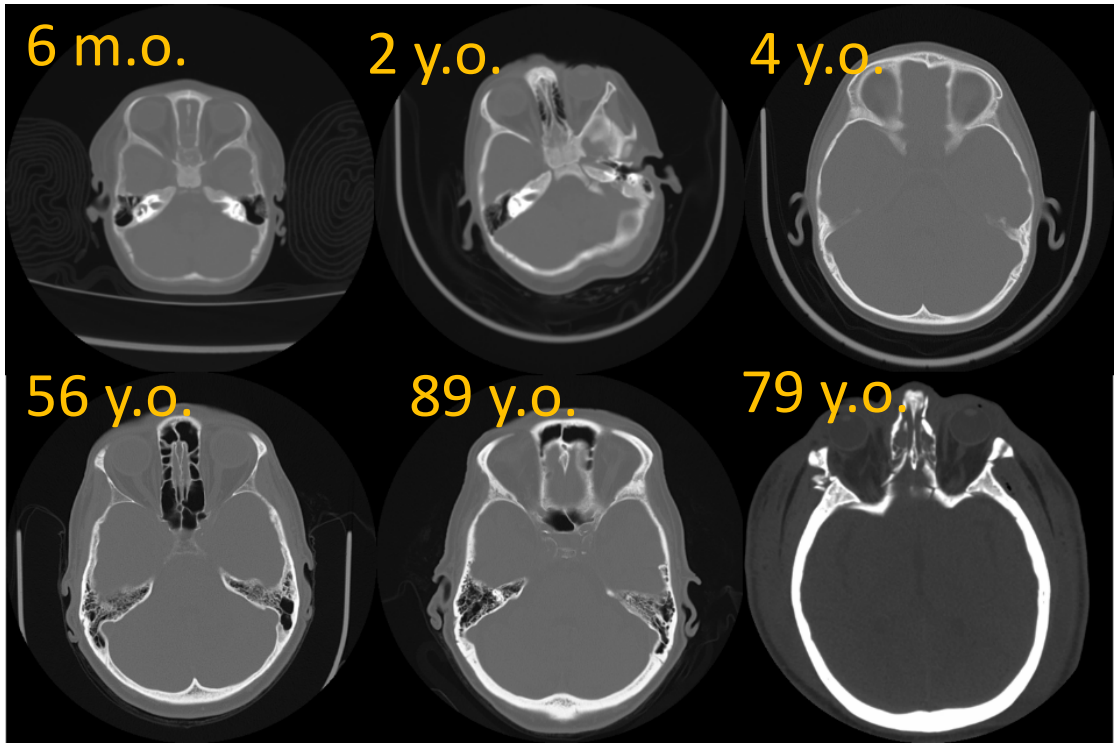


Table 4.3 Head, neck, and cervical spine doses from Kanal et al. 2017 [41]

Examination and Median Size (Thickness or Diameter)	Size (cm)	No. of Facilities	No. of Patients	$CTDI_{vol}$ (mGy)		DLP (mGy-cm)	
				AD (50th Percentile)	DRL (75th Percentile)	AD (50th Percentile)	DRL (75th Percentile)
Head and brain without contrast material*	12–14	227	19,993	47	56	767	936
	14–16	290	137,755	49	56	811	962
	16–18	256	57,292	52	60	902	1,020
	18–20	160	5,390	51	60	926	1,069
	All†	347†	223,908	49	57	849	1,011

Table 3: Age-based Achievable Doses and Diagnostic Reference Levels

Examination Type and Age (y)	No. of Examinations*	$CTDI_{vol}$ (mGy)		SSDE (mGy)		DLP (mGy · cm)	
		AD	DRL	AD	DRL	AD	DRL
Head without contrast material							
0 to <1	66 307	19	23	NA	NA	267	344
1 to <2	42 462	22	27	NA	NA	350	440
2 to <6	108 808	25	31	NA	NA	409	518
6–18	593 573	46	55	NA	NA	748	910

See how the kid doses go to the adult doses? These are both from Kalpana seminal ACR dose registry papers in radiology. We should not have a piecewise constant approach here, we need AEC on.

PROBLEM #5

Submitted by Daniel Vergara, UW

Our MSK radiologists are interested in creating an optimized Murphy protocol using PCCT and DECT with radiation doses at or near the radiographic level. The current Murphy protocol is built into a GE Revolution and Siemens SOMATOM FORCE CT scanners using 120 kVp SECT and ~10 mGy med. CTDIvol. We are targeting effective doses of ~1 mSv

Let’s do the calculation

- E = DLP × k = CTDIvol × scan length × k
  - K factor for pelvis: ~0.015
  - K factors for knees and ankles: ~0.0003 to 0.0007
  - The pelvis k is 20–50 times higher
- For 1 mSv target, we just need to focus on the pelvis dose
  - DLP_pelvis = 1 mSv / 0.015 = 66.7 mGy·cm
  - For 8 cm coverage: CTDIvol = 8.3 mGy
  - For 12 cm coverage: CTDIvol = 5.6 mGy
- Current CTDIvol is 10 mGy

How to do this protocol optimization

- It is really just figuring out scan coverage and image quality requirement for the hips

- A femoral anteversion measurement doesn’t require high dose
  - High contrast between bone and soft tissue
  - No high spatial resolution requirement
  - No low contrast detection demand
  - No spectral information needed
  - PCCT rejects electronic noise, ideal for low-dose settings

PROBLEM #6

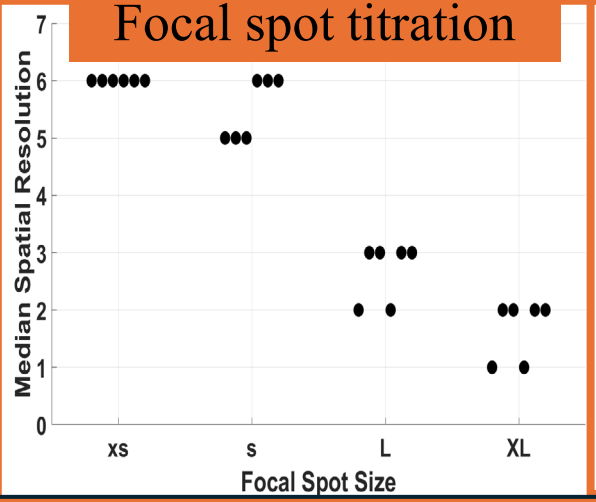
Submitted by Mahsa Servati, MD Anderson

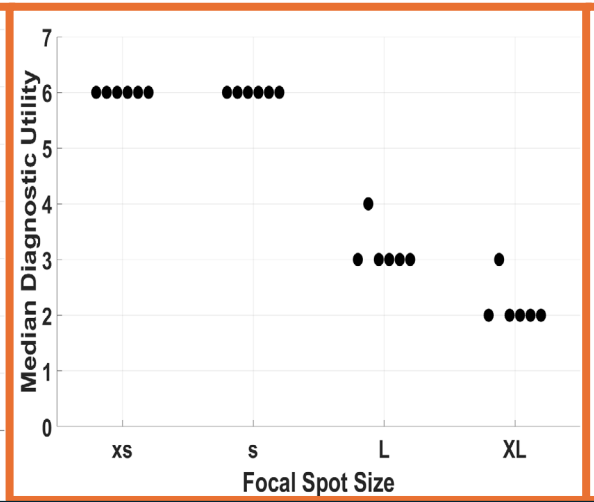
Radiologists are complaining that routine abdomen–pelvis CT images from a photon-counting detector CT are too blurry/smooth. The scan was reconstructed with a Br76 sharp kernel and Quantum Iterative Reconstruction (QIR) Strength 3 in a patient with BMI 60, effective mAs 335, and CTDIvol 38 mGy.

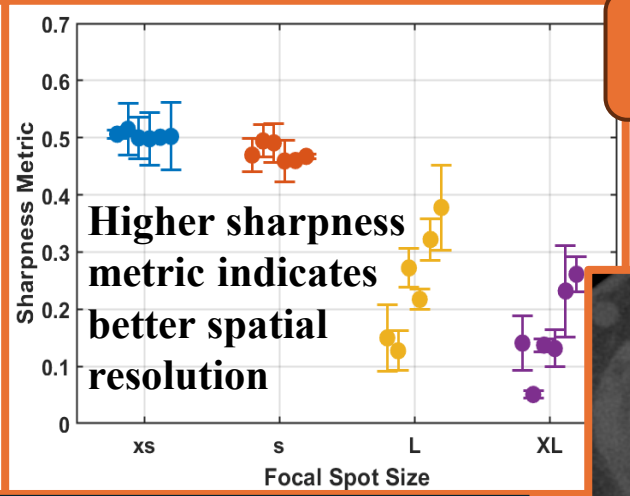
How to achieve high spatial resolution Recon?

- Sharp kernel, Br76 √
- Small focal spot, usually not available for a 38 mGy scan
- Reconstruction matrix size. For a body size RFOV and 512 matrix size, this becomes the limiting factor. Even 1024 may not be sufficient

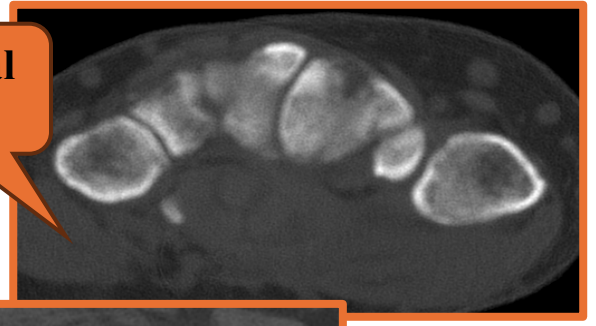
Focal spot titration



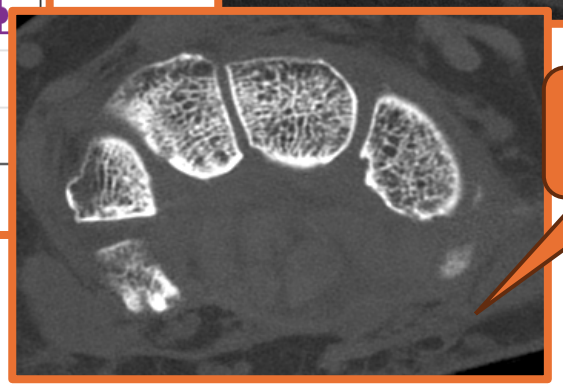




Higher sharpness metric indicates better spatial resolution



XL focal spot



XS focal spot

Both sharpness metric and reader score for spatial resolution and diagnostic utility decrease with increasing focal spot size.

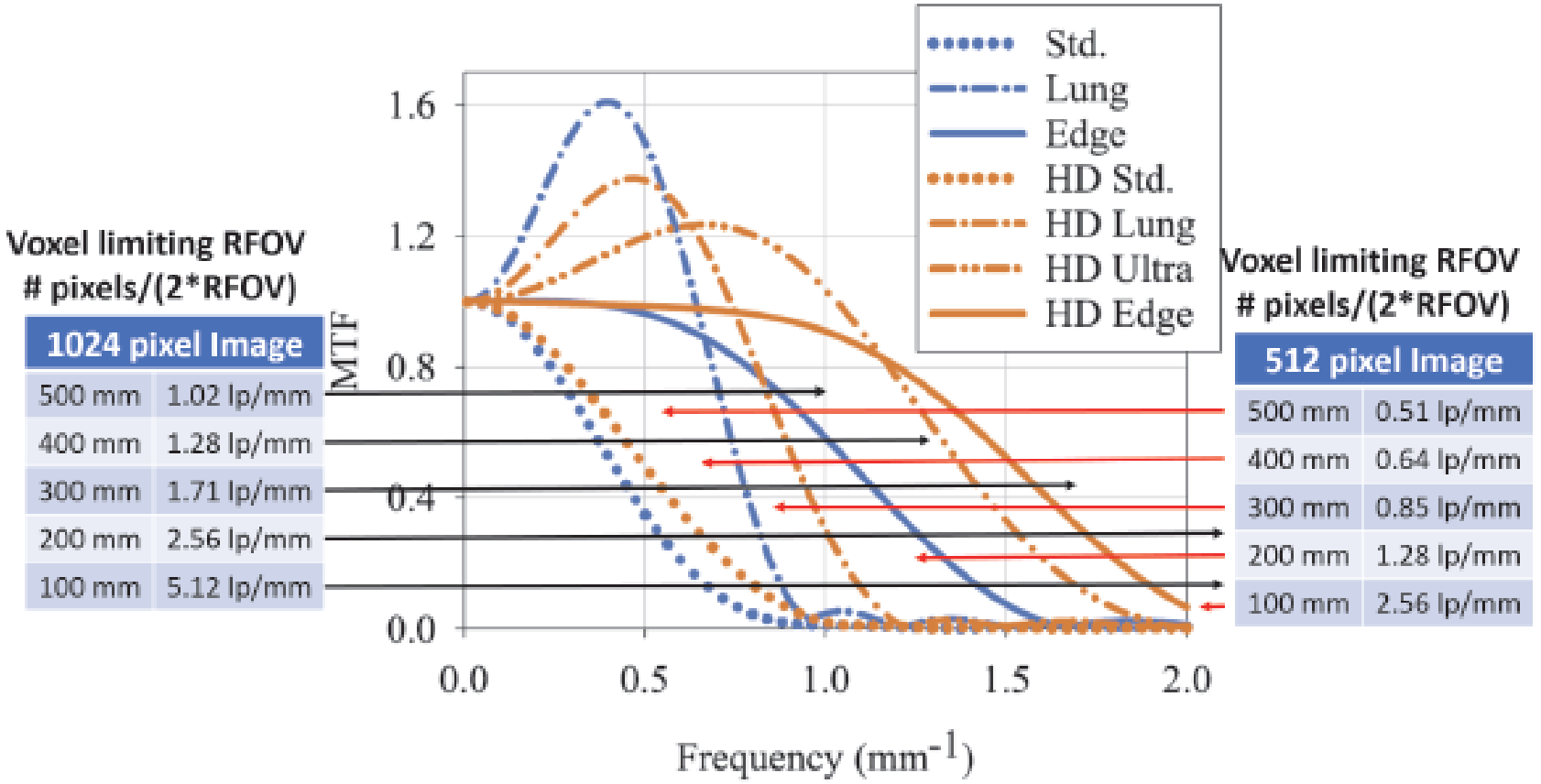


Figure 5.17 Using a "high resolution" kernel does not always translate into high resolution in the final reconstructed image. Resolution in the final image will only reflect the "high resolution" characteristics of the kernel if you use a small enough RFOV or enough pixels to support the needed resolution. This is demonstrated in this figure. The equation shown in the figure relates the amount of blurring due to voxel averaging to the number of pixels across the RFOV. The arrows denote where resolution will be limited for each RFOV size for 1024 and 512 options. Std. and HD Std. are soft tissue kernels, lung/HD lung/HD Ultra are edge enhancing kernels, Edge and HD Edge are high resolution kernels. All kernels, even the soft tissue kernels, are limited in resolution by large RFOV, albeit using a large RFOV has a much higher impact on higher resolution kernels relative to soft tissue kernels. (Figure adapted from a slide created by Dr. Robert Bujila, Karolinska University Hospital, Stockholm Sweden.)

PROBLEM #7

Submitted by Joseph Wishart, UW

Our emergency department radiologists are complaining of delays between image acquisition and population of studies in PACS for our Photon-Counting CT Scanner. This is most significant for our Panscan protocol which is comprised of a non-contrast Head, followed by a CTA of the Head and Neck, sometimes followed by a venous runoff CAP acquisition. Depending on the exact scanning details and networking status, these take up to an hour to populate in our PACS system. Radiologists want spectral data available which requires using the QuantumPlus scanning mode. We have an offline reconstruction workstation (SyngoVia) and can also perform limited reconstructions on the acquisition workstation but are limited by patient throughput.

Comments

- Matrix size 1024 or 512?
- Slice interval
- Spectral series
- Reformat trick

Randy Ruhs—CT Supervisor—INOVA Health System (Inova Fairfax hospital—Virginia)

PROBLEM: Body Radiologists have all body protocols in triplicate; <30, 30-65, >65 (cancer). The noise index are no more than 1.5 between routine exams and 3 for multiphase studies. After scanning a cadaver with the same start, end, coordinates, and DFOV on the same machine there is an approximate variance of dose between the <30 and the >65 of 50%. I clearly see the dose savings, yet my question is can the human eye detect the special resolution difference of 27 and 20, or 13 and 17? We are an extremely busy department.

Routine Abdomen Pelvis

	<30	30-65	>65
VCT	9	18.6	15
Rev	15.4	15.1,	12.2

Three Phase Liver

VCT WO	20	20	17
VCT ART	18.6	15	15
VCT VEN	17	13	13
REV WO	16.3	16.3	13.8
REV ART	15.1	12.2	10.6
REV VEN	15.1	12.2	10.6

$$D \propto \frac{1}{NI^2}$$

Table 7.4 Table showing how small changes in NI values modulate the dose. The values in the table are percent changes in CT scanner output ($CTDI_{vol}$ or DLP) as a function of starting NI value and incremental changes in NI. The addition or subtraction of different increments of NI values (increments of [0.1, 0.5, 1.0, 5.0, –0.1, –0.5, –1, –5] are shown here) modulate the dose differently depending on the starting value of the NI.

NI Change	1	2	3	4	5	6	7	8	9	10	11	12	13	14
0.1	–21.0%	–10.3%	–6.8%	–5.1%	–4.0%	–3.4%	–2.9%	–2.5%	–2.2%	–2.0%	–1.8%	–1.7%	–1.5%	–1.4%
0.5	–125.0%	–56.3%	–36.1%	–26.6%	–21.0%	–17.4%	–14.8%	–12.9%	–11.4%	–10.3%	–9.3%	–8.5%	–7.8%	–7.3%
1.0	–300.0%	–125.0%	–77.8%	–56.3%	–44.0%	–36.1%	–30.6%	–26.6%	–23.5%	–21.0%	–19.0%	–17.4%	–16.0%	–14.8%
5.0	–3500.0%	–1125.0%	–611.1%	–406.3%	–300.0%	–236.1%	–193.9%	–164.1%	–142.0%	–125.0%	–111.6%	–100.7%	–91.7%	–84.2%
–0.1	19.0%	9.8%	6.6%	4.9%	4.0%	3.3%	2.8%	2.5%	2.2%	2.0%	1.8%	1.7%	.5%	1.4%
–0.5	75.0%	43.8%	30.6%	23.4%	19.0%	16.0%	13.8%	12.1%	10.8%	9.8%	8.9%	8.2%	7.5%	7.0%
–1.0	NaN	75.0%	55.6%	43.8%	36.0%	30.6%	26.5%	23.4%	21.0%	19.0%	17.4%	16.0%	14.8%	13.8%
–5.0	NaN	NaN	NaN	NaN	NaN	97.2%	91.8%	85.9%	80.2%	75.0%	70.2%	66.0%	62.1%	8.7%
NI Change	**15**	**16**	**17**	**18**	**19**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**
0.1	–1.3%	–1.3%	–1.2%	–1.1%	–1.1%	–1.0%	–0.8%	–0.7%	–0.6%	–0.5%	–0.4%	–0.4%	–0.4%	–0.3%
0.5	–6.8%	–6.3%	–6.0%	–5.6%	–5.3%	–5.1%	–4.0%	–3.4%	–2.9%	–2.5%	–2.2%	–2.0%	–1.8%	–1.7%
1.0	–13.8%	–12.9%	–12.1%	–11.4%	–10.8%	–10.3%	–8.2%	–6.8%	–5.8%	–5.1%	–4.5%	–4.0%	–3.7%	–3.4%
5.0	–77.8%	–72.3%	–67.5%	–63.3%	–59.6%	–56.3%	–44.0%	–36.1%	–30.6%	–26.6%	–23.5%	–21.0%	–19.0%	–17.4%
–0.1	1.3%	1.2%	1.2%	1.1%	1.0%	1.0%	0.8%	0.7%	0.6%	0.5%	0.4%	0.4%	0.4%	0.3%
–0.5	6.6%	6.2%	5.8%	5.5%	5.2%	4.9%	4.0%	3.3%	2.8%	2.5%	2.2%	2.0%	1.8%	1.7%
–1.0	12.9%	12.1%	11.4%	10.8%	10.2%	9.8%	7.8%	6.6%	5.6%	4.9%	4.4%	4.0%	3.6%	3.3%
–5.0	55.6%	52.7%	50.2%	47.8%	45.7%	43.8%	36.0%	30.6%	26.5%	23.4%	21.0%	19.0%	17.4%	16.0%