NHS
Royal United Hospitals Bath
NHS Foundation Trust

Experiences of TCM testing

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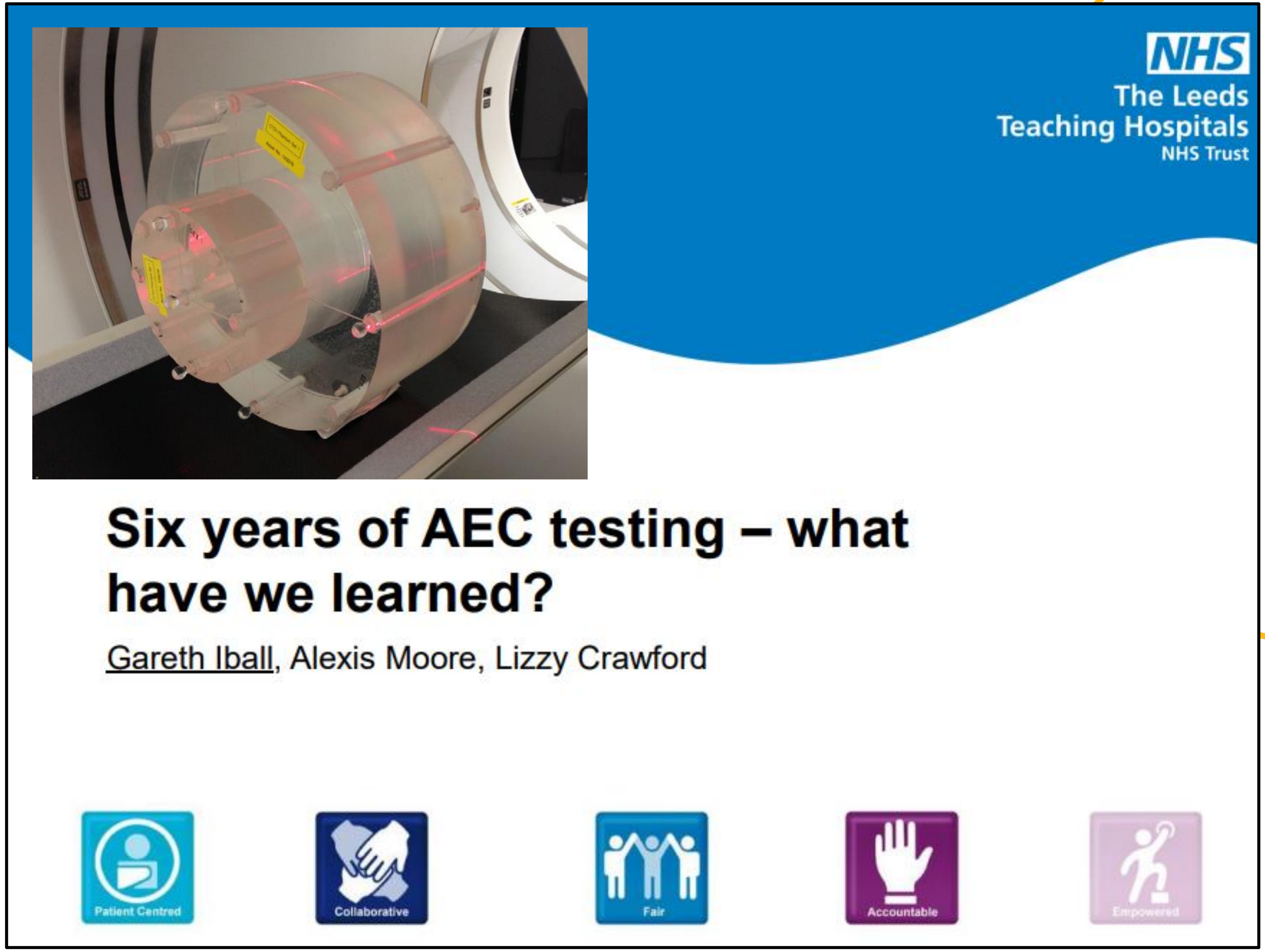
The RUH, where you matter

Inspiration from…

- 2018 CTUG meeting presentation by Gareth Iball on CT AEC testing:
- Recommended remedial limits of: scan $CTDI_{VOL}$ ± 15% from baseline noise ± 10 % from baseline.
- But mainly: just do it!
- https://doi.org/10.1120/jacmp.v17i4.6165

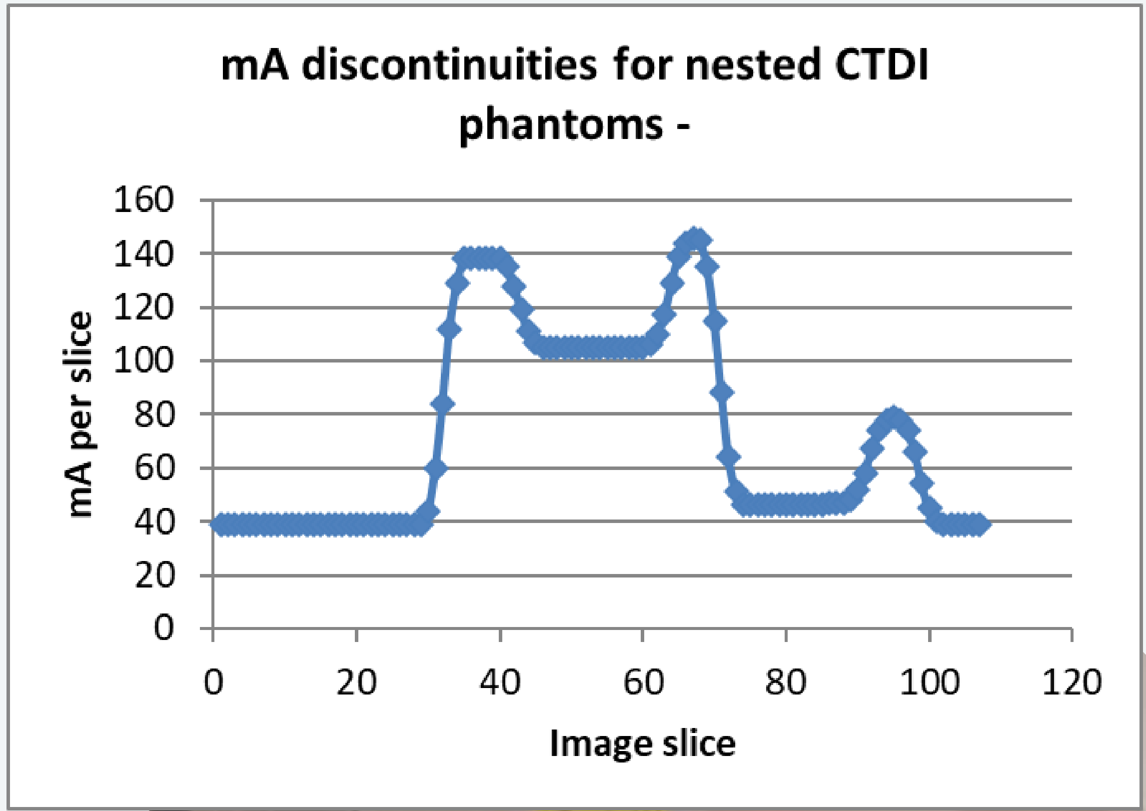
JOURNAL OF APPLIED CLINICAL MEDICAL PHYSICS

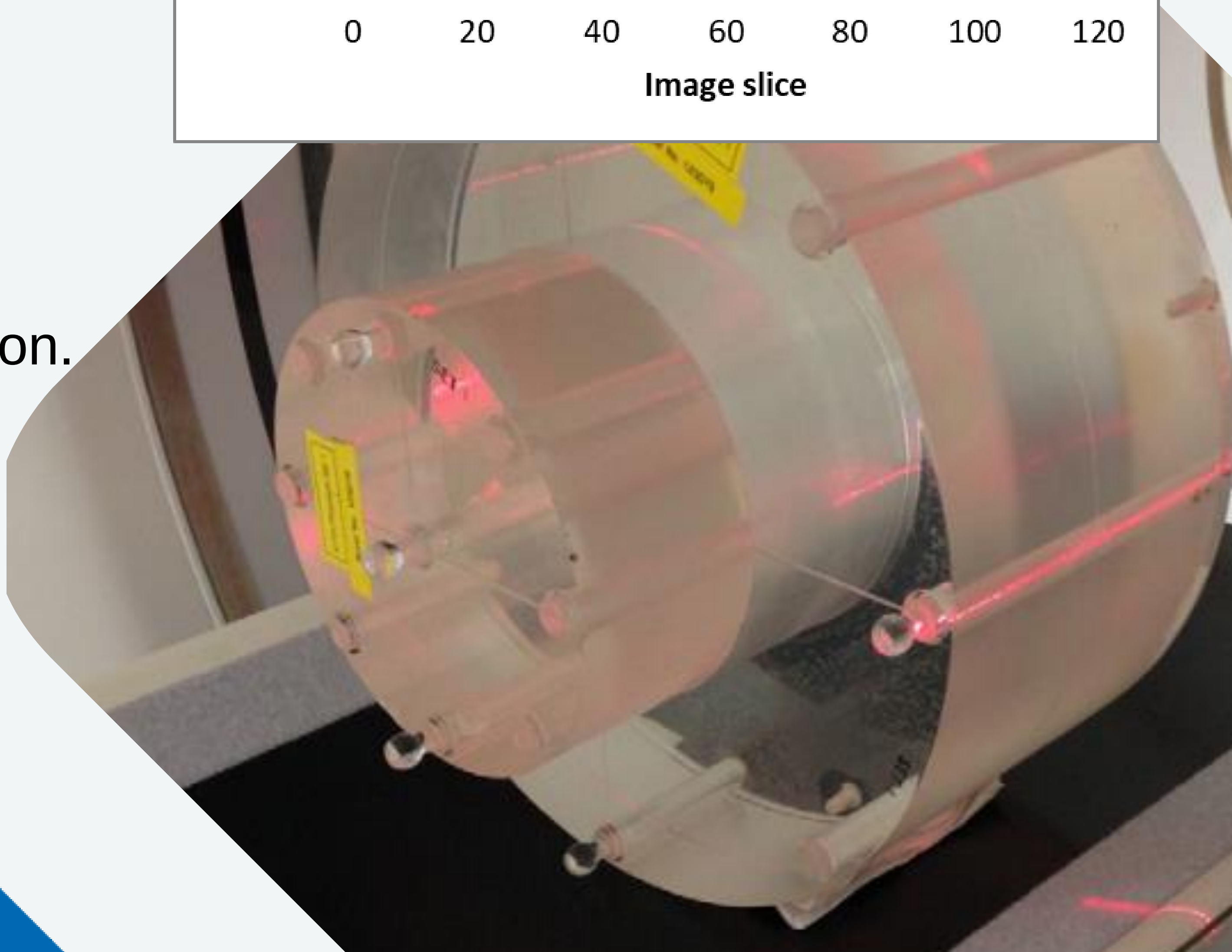


RUH Bath CT TCM QA in 2020

- CT TCM testing had been in place since 2013 ☺
- Nested CTDI phantom
- Scan average $CTDI_{VOL}$ and DLP compared against previous results: but no quantitative tolerances.
- Performed every three years on each scanner.

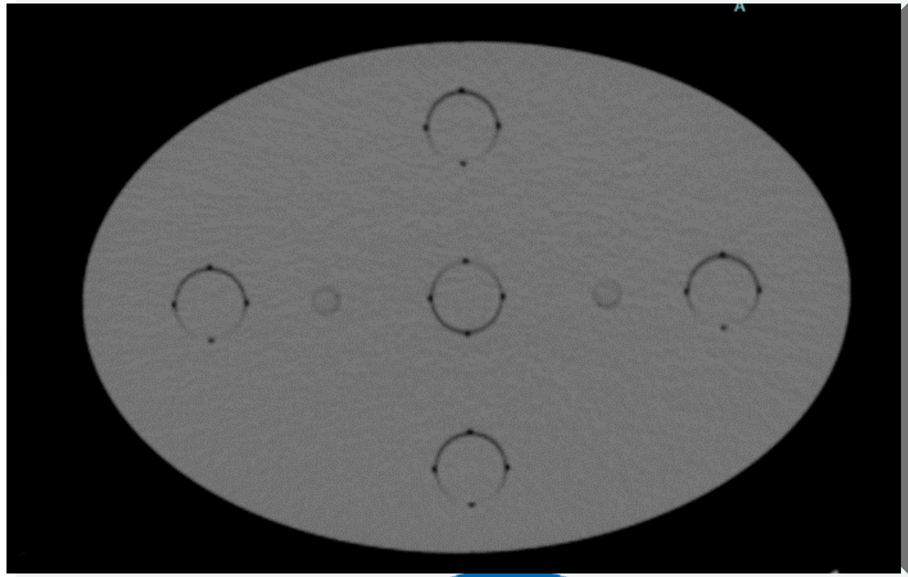
- Only three attenuation steps in phantom
  - 16 cm diameter; 32 cm diameter; annular section.
- Sharp discontinuities between phantom sections
- Fine as a constancy check – if phantom set-up and scan parameters are reproducible.
  - QA protocols must be set up identically and saved on each scanner!

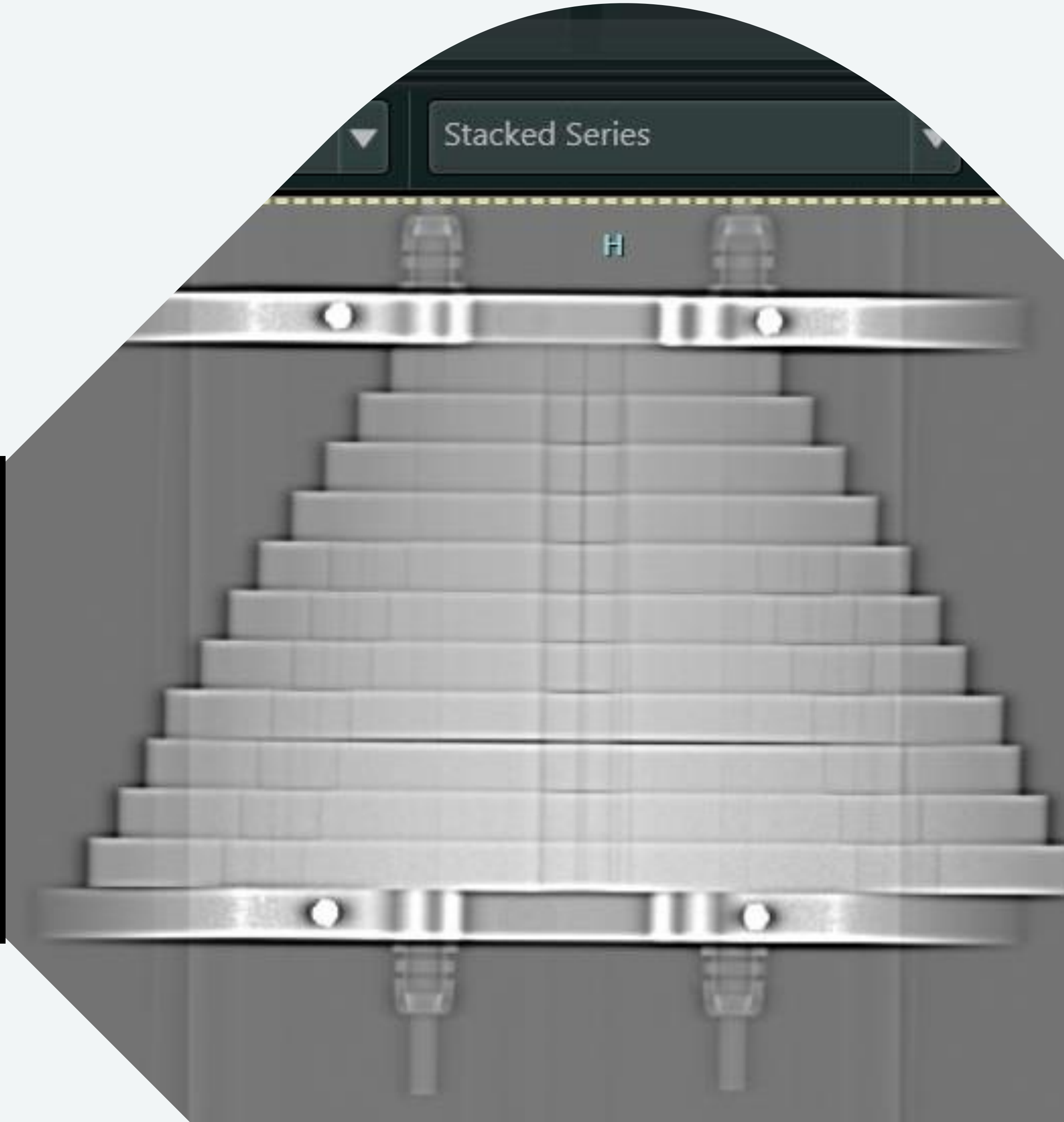




Next step…

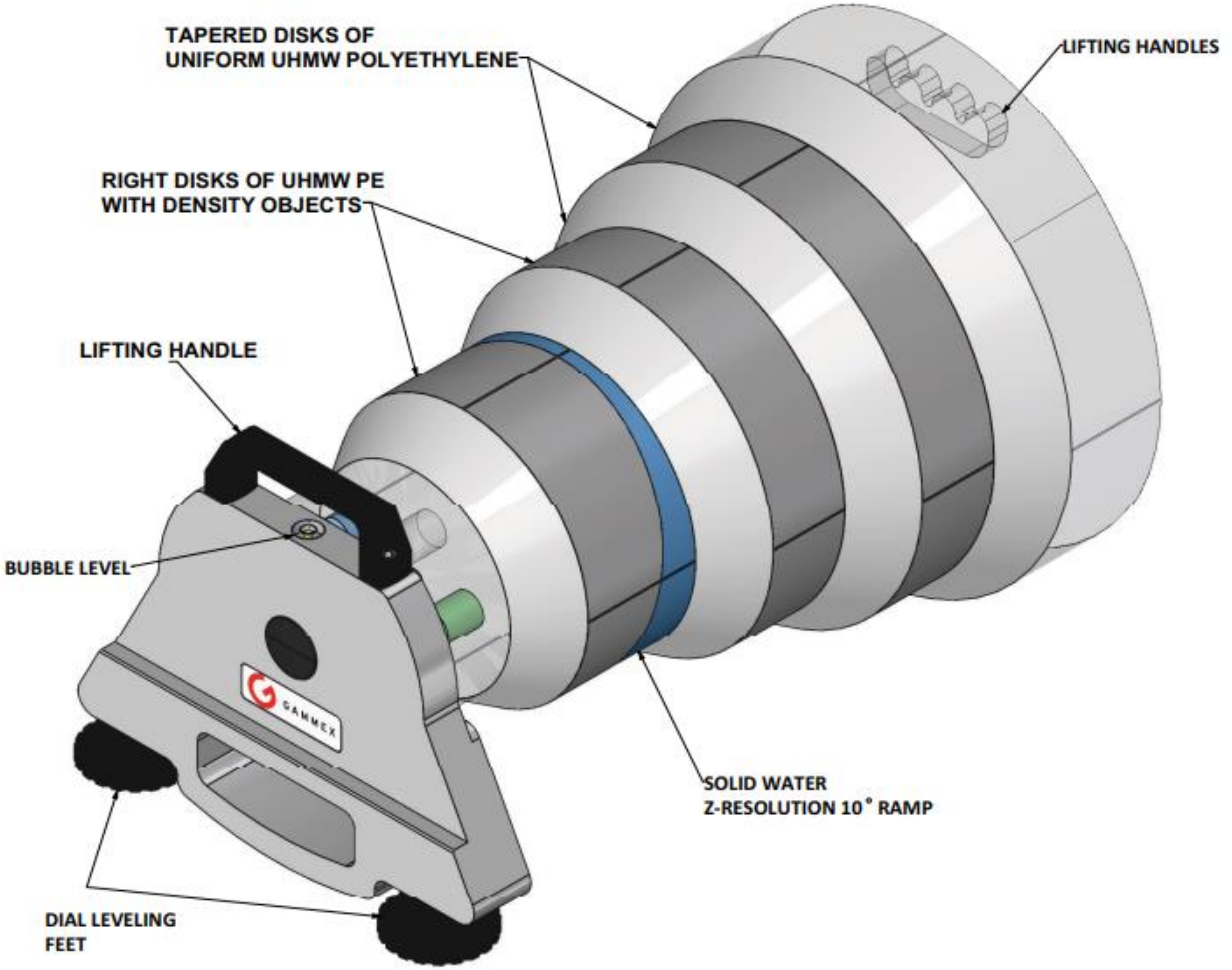
- ❑ Pre-2020: RUH Bath obtained a Leeds test object “CT AEC 25”
- ❑ 275 mm long (not including endplates)
- ❑ 11 × 25 mm-thick elliptical segments
- ❑ QA protocol not developed further at this point.
- ❑ This phantom was not used routinely.





2020: New phantom

- Mercury phantom obtained as part of DClinSci project looking at advanced image quality metrics.
- Advertised as appropriate for TCM tests.
- Approx 520 mm long. Five cylindrical sections joined by ramped sections – no discontinuous changes in phantom diameter.
- Each cylinder section has 5 contrast inserts
- 30 kg in weight!



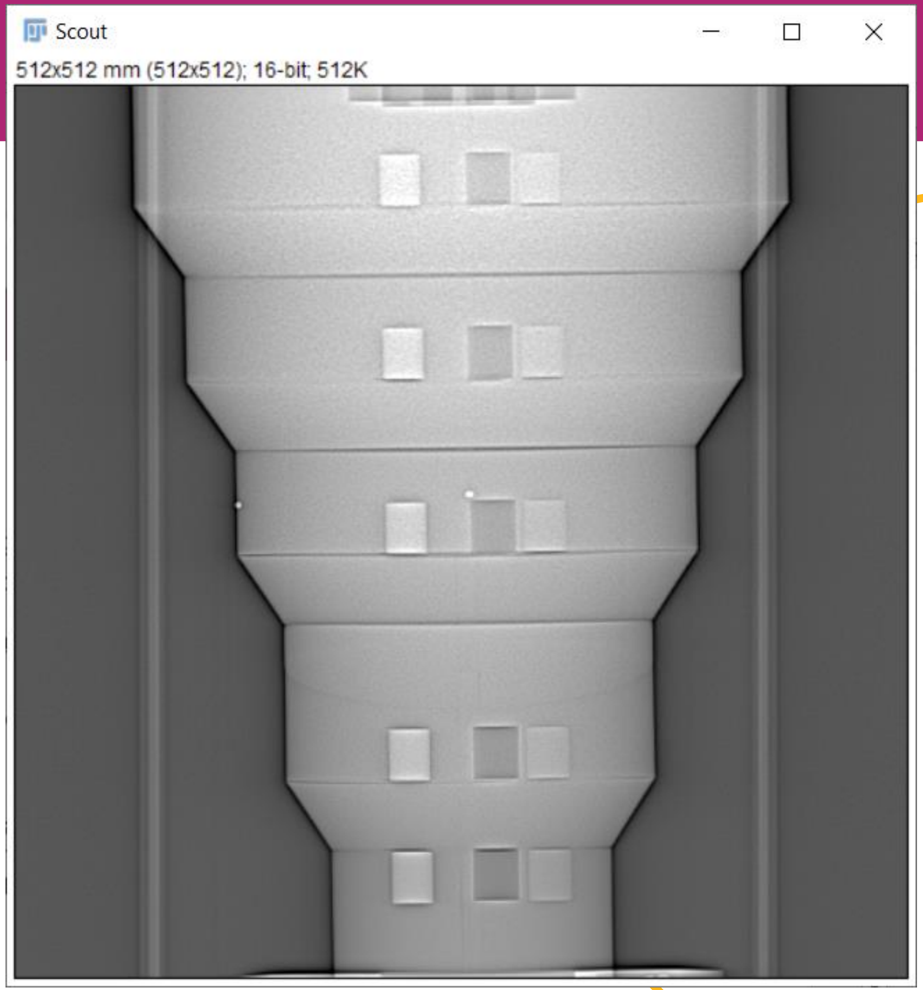
Cylinder section	1	2	3	4	5
Physical diameter (cm)	16	21	26	31	36
Water Equivalent Diameter (cm)	15.3	20.1	25.0	29.7	34.4

Phantom summary

- Disclaimer: other phantoms are available!

Phantom	Cross-section profile	Water-equivalent Diameters (cm)	Discrete step changes in WED?
Nested CTDI phantoms	Cylindrical	17, 34 and 29.4 [head; full body; body annulus]	Yes, large
Leeds test object	Elliptical	11 steps between 15 and 37 cm	Yes, small
Mercury phantom	Cylindrical	15.3, 20.1, 25, 29.7, 34.4 – **with continuous values inbetween**.	None

Current Bath TCM protocol



- SPR of phantom – avoiding discontinuities at either end (512 mm)
- SPR(s) should be performed the same way each time – e.g. 12 o'clock only; or 12 followed by 9'clock, etc.
  - We do whatever is most commonly performed in clinical use on each scanner (i.e. one on Siemens scanners; two on GE).

- Phantom scanned helically using identical 500 mm scan ranges at two or more different dose levels.
- Dose levels determined by protocol Noise Index / Quality reference mAs, SD, etc.
  - e.g. Siemens scanners: scan series are based on default Thorax and Abdomen scans at quality reference mAs of 66 and 147 mAs respectively.

TCM test protocol tips

- **Routine QA - we want the mA to modulate as freely as possible!**
- Don’t use mA caps, choose dose levels that will avoid minimum or maximum tube mA being reached for your phantom.
  - Do a pre-scan check using the displayed mA table / mA chart on the scanner interface
- Don’t scan too fast – we want the tube current to be able to adapt to changes in phantom size.

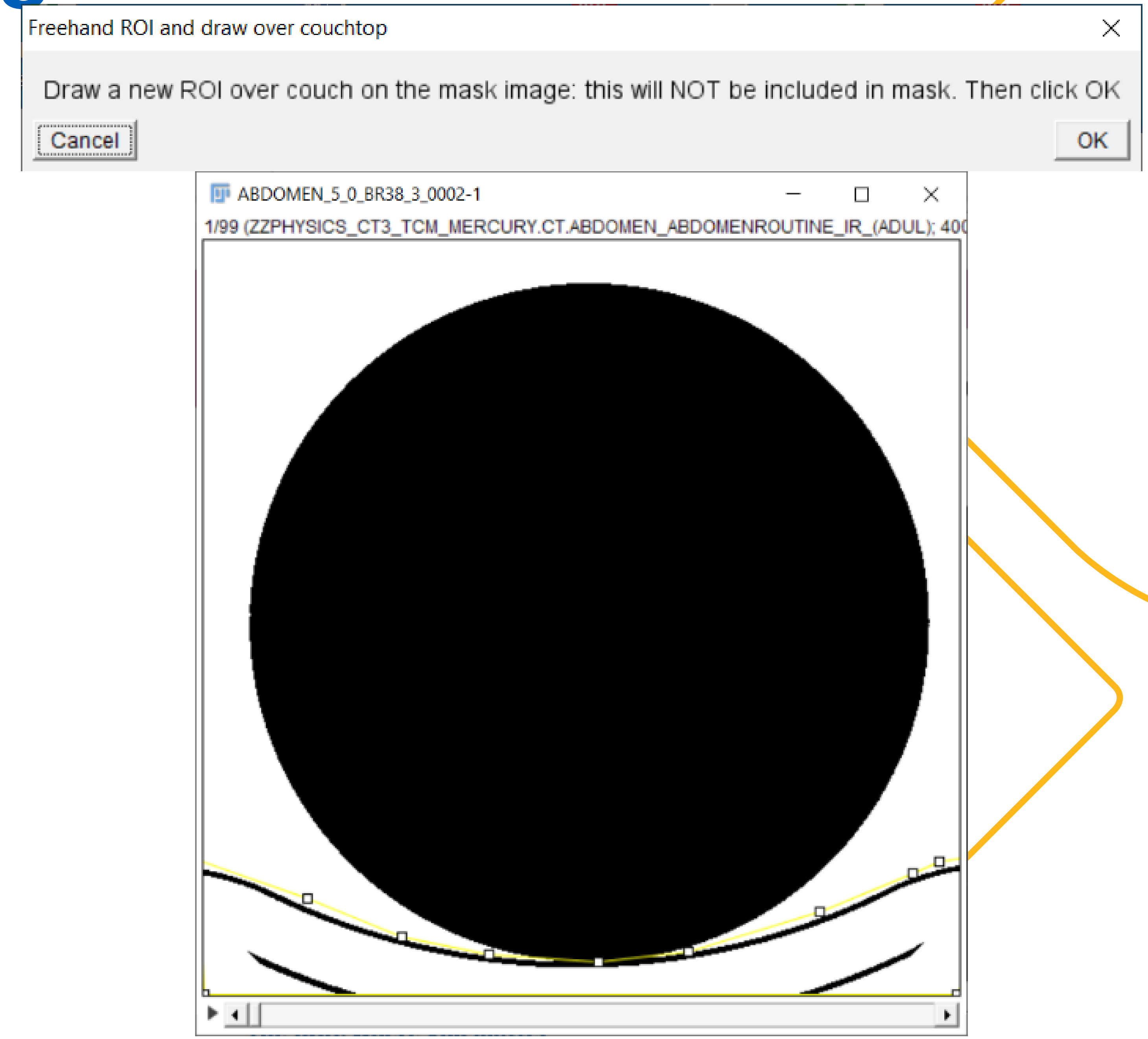
- When characterising the CT system at **commissioning** – break the above rules!
  - E.g. determine how modulation is inhibited by fast scan times / high pitch values
  - E.g. at what water equivalent diameter is modulation inhibited by tube current limits?
- This will be informative when it comes to clinical scan optimisation

Bath analysis of TCM QA images

- Reconstruct images at 5 mm slice thickness – giving us 100 images.
- Use a standard body kernel, medium IR strength (as used clinically)
- Reconstructed field of view always set at 400 mm to ensure entire phantom fits in FOV
  - The maximum Mercury phantom physical diameter is 36 cm

- Export images and perform automated analysis in ImageJ:
  - Manually positioned ROI for noise measurement; manual ROI to remove couch top from image mask in order to calculate Water Equivalent Diameter of just the phantom.
  - The plug-in interrogates DICOM tags for scan parameters in each image, too.

Analysis of TCM test images



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Analysis of TCM test images

- The analysis results file includes the following from each image slice:
  - Water Equivalent Diameter

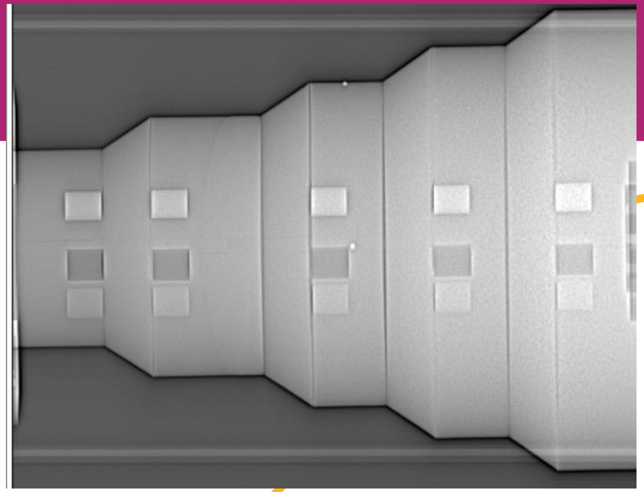
$$WED = 2 \times \sqrt{\left(\frac{\overline{HU}}{1000} + 1\right) \times \frac{A}{\pi}}$$

  - Image Noise in the analysis ROI
  - From DICOM tags: series number, image number, kV, rotation time, tube mA, pitch, slice thickness, recon kernel, and $CTDI_{VOL}$ if optional DICOM tag (0018,9345) is populated**
  - **Effective mAs** calculated from DICOM pitch, rotation time and mA:

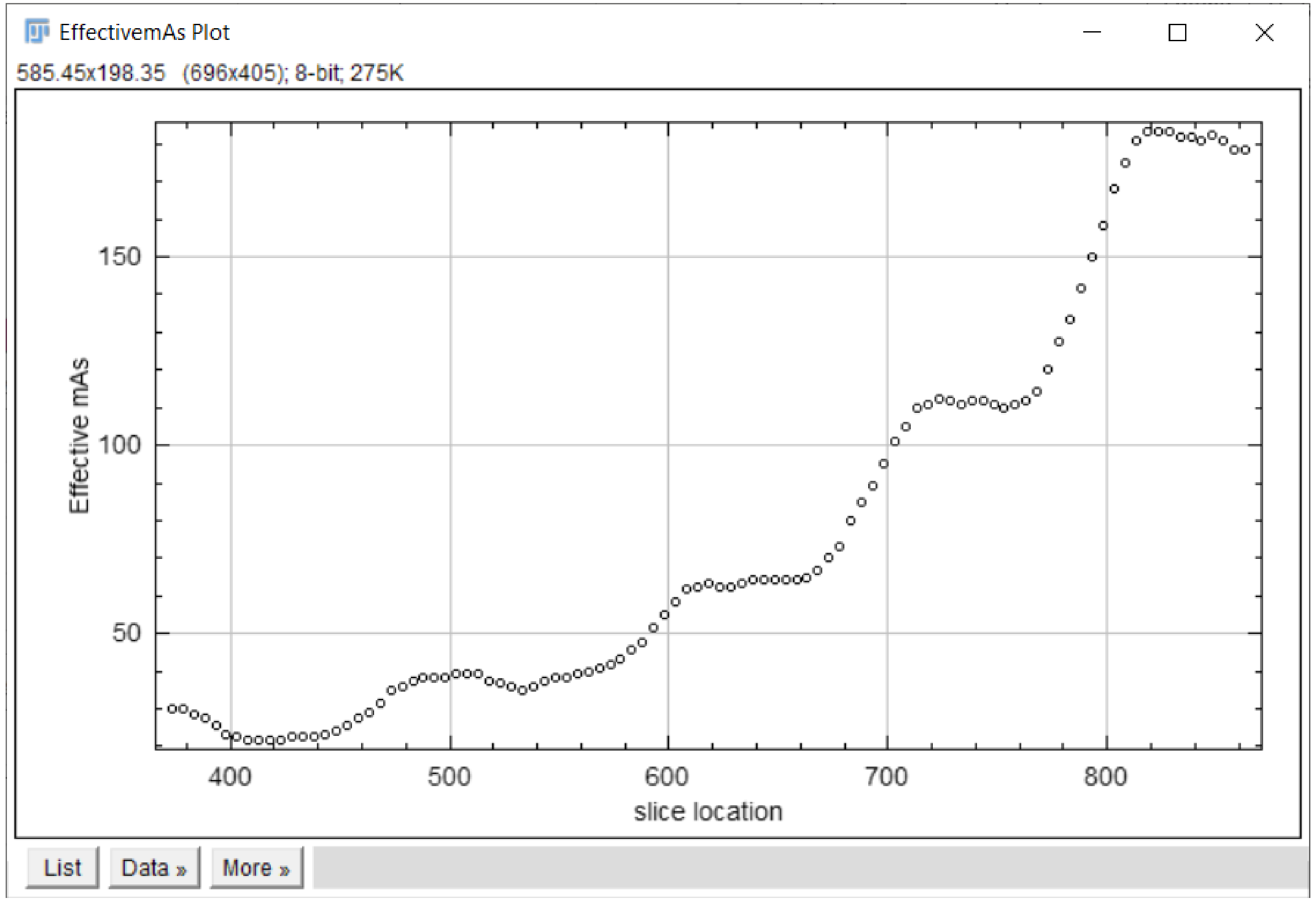
$$Effective\, mAs = tube\, mA \times rot\, time \div pitch$$

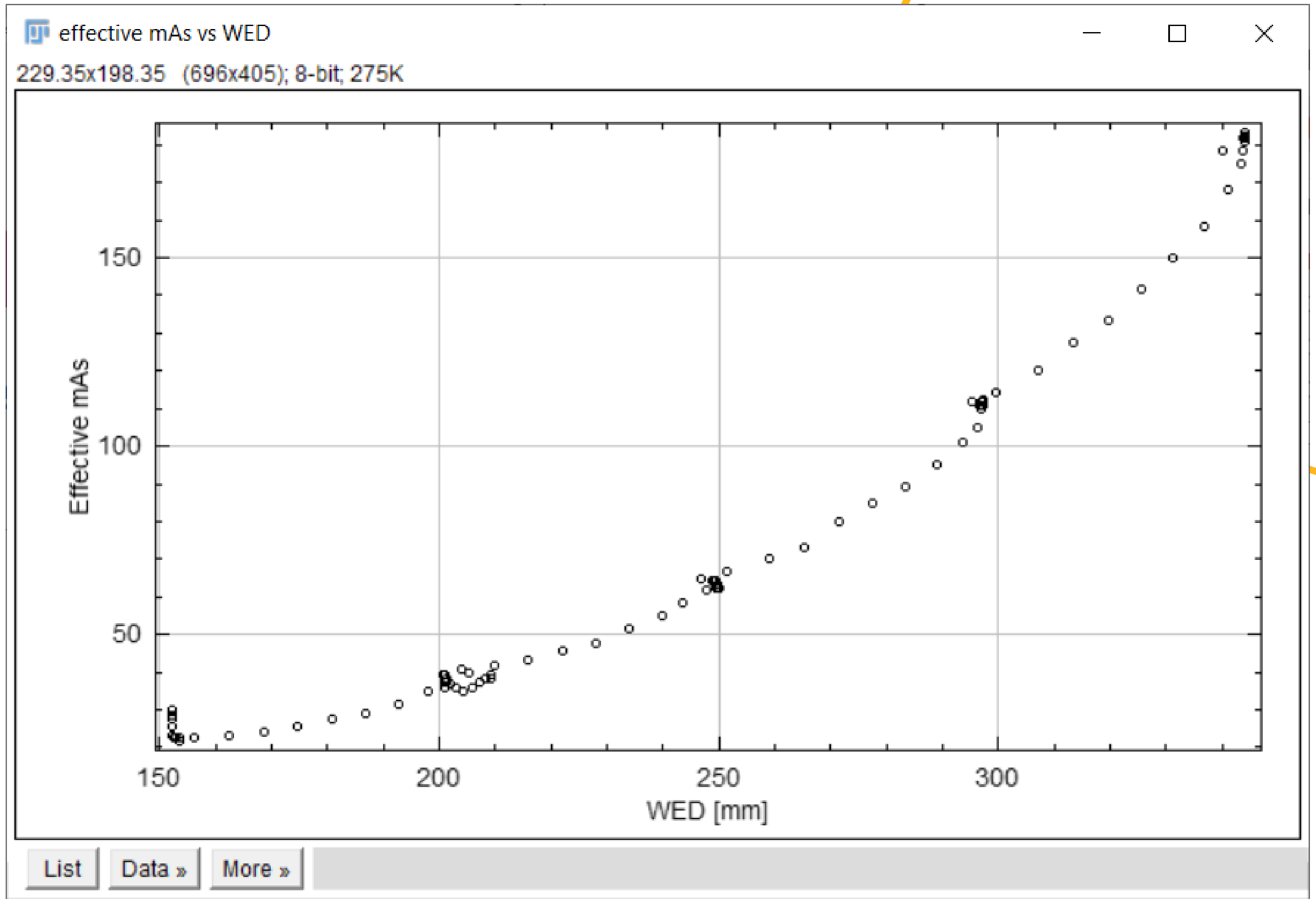
** N.B. our GE scanners do not populate the optional DICOM tag (0018,9345); our Canon scanner returns the scan average $CTDI_{VOL}$ in this tag for every image in a series. Instead, we manually calculate it from effective mAs and commissioning $CTDI_{VOL}$ per mAs.

Analysis output - plots



- Plots of effective mAs versus (left) couch position; and (right) versus phantom WED





AAPM recommendations

- AAPM report 233 published in early 2019 recommends:

3.1 Tube Current Modulation

3.1.1 Objective

To characterize the tube current modulation (TCM) in terms of tube current and image noise as a function of attenuation.

- Characterisation as a **function of attenuation** is key, therefore the more sizes (Water Equivalent Diameters) your TCM phantom has, the better.

Analysis completed in spreadsheet

- Scan conditions and displayed $CTDI_{VOL}$ and DLP are recorded, output csv pasted into sheet to generate charts.

Scan series (2):

Go to top of

Protocol name	Phys_RoutineTCM (Adult)			
Body region	Thorax	(if applicable)		
kV	120			
Total collimation	38.4	mm		
Scan pitch	1.2			
quality reference mAs	66			
upper mA cap	N/A	lower mA cap	N/A	
recon kernel	Bf37_3			

Care kV off
Care Dose on
Single topogram AP/PA

	displayed	baseline	% change
series average CTDIvol:	3.04	3.1	-2.33
series total DLP:	159.0	166.2	-4.32

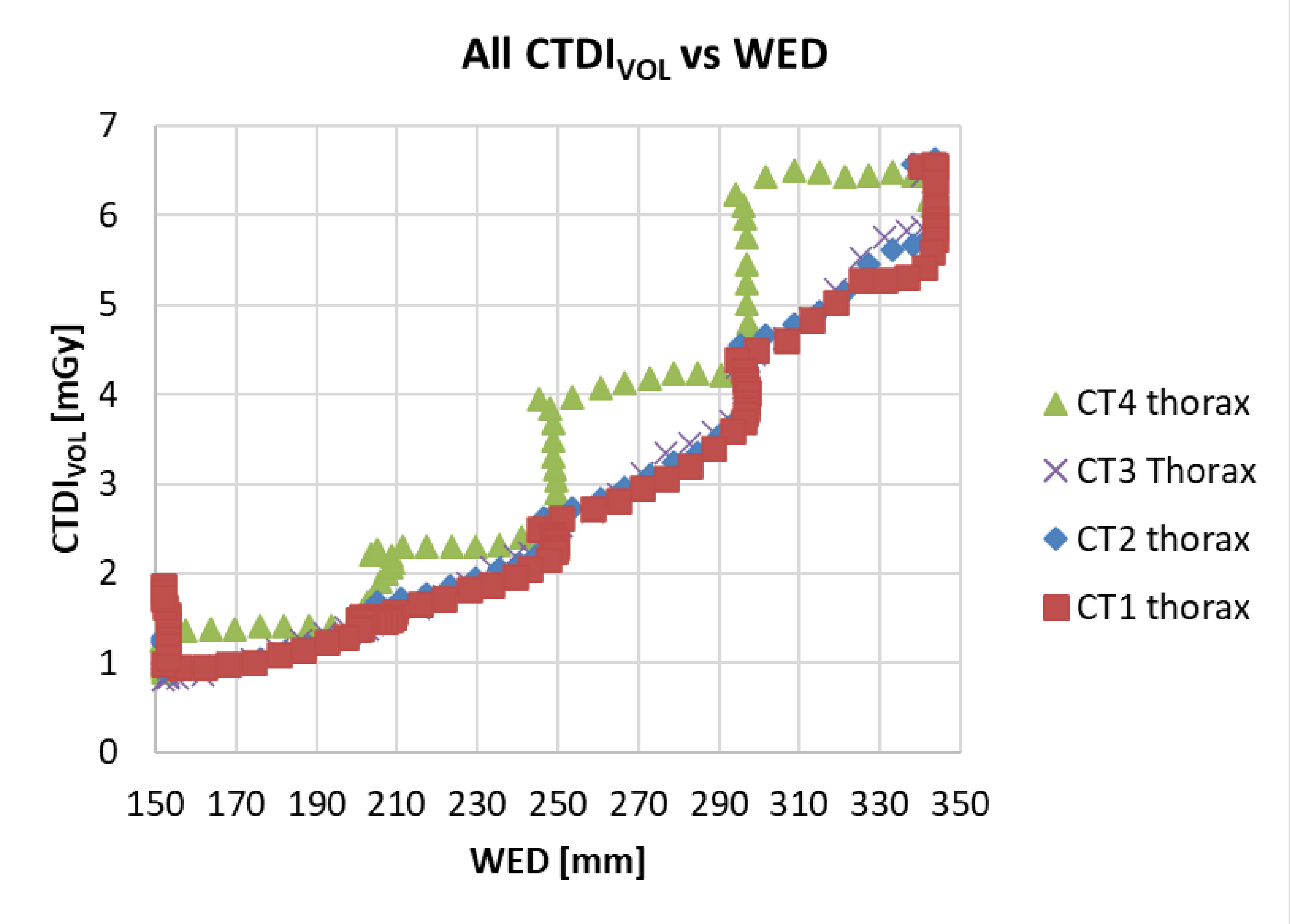
suggested tolerances: ± 15% [local limit]

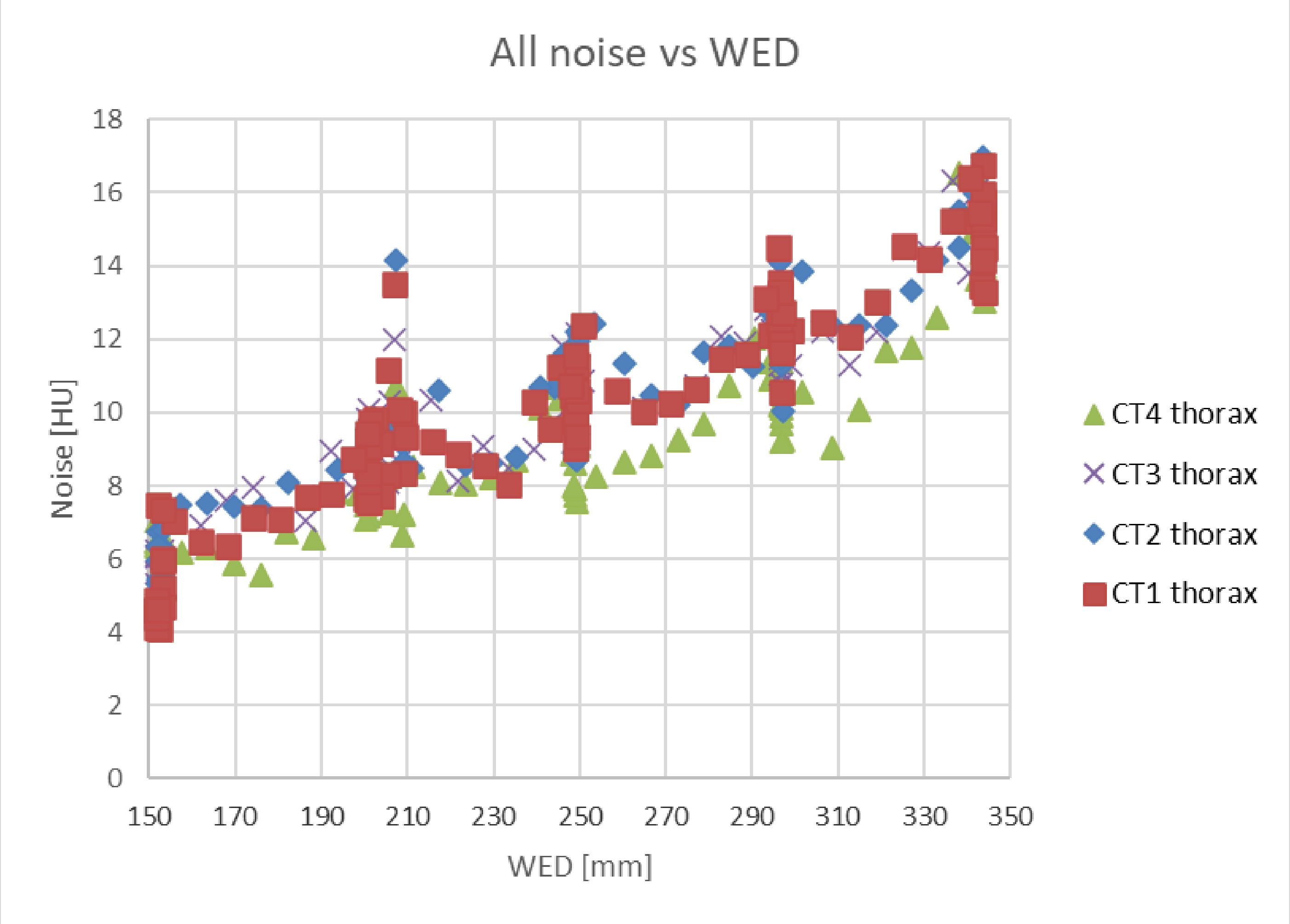
Analysis Results (2):

	Series_number	Image_number	Slice_location	kV	RotTime	Pitch	TubeCurrent	EffectivemAs	CTDIvol	Recon_kernel	SliceThick	ROInoise	WED
1	3	1	-8.5	120	500	1.2	234	97.5	6.57825	Bf37f\3	5	15.488	338.279
2	3	2	-13.5	120	500	1.2	235	97.917	6.60636	Bf37f\3	5	15.261	343.191
3	3	3	-18.5	120	500	1.2	236	98.333	6.63447	Bf37f\3	5	14.952	343.744
4	3	4	-23.5	120	500	1.2	231	96.25	6.49391	Bf37f\3	5	16.959	343.776
5	3	5	-28.5	120	500	1.2	221	92.083	6.21279	Bf37f\3	5	15.43	343.815
6	3	6	-33.5	120	500	1.2	216	90	6.07223	Bf37f\3	5	15.709	343.856
7	3	7	-38.5	120	500	1.2	215	89.583	6.04412	Bf37f\3	5	13.851	343.81
8	3	8	-43.5	120	500	1.2	215	89.583	6.04412	Bf37f\3	5	14.413	344.178

Results – four scanners same vendor

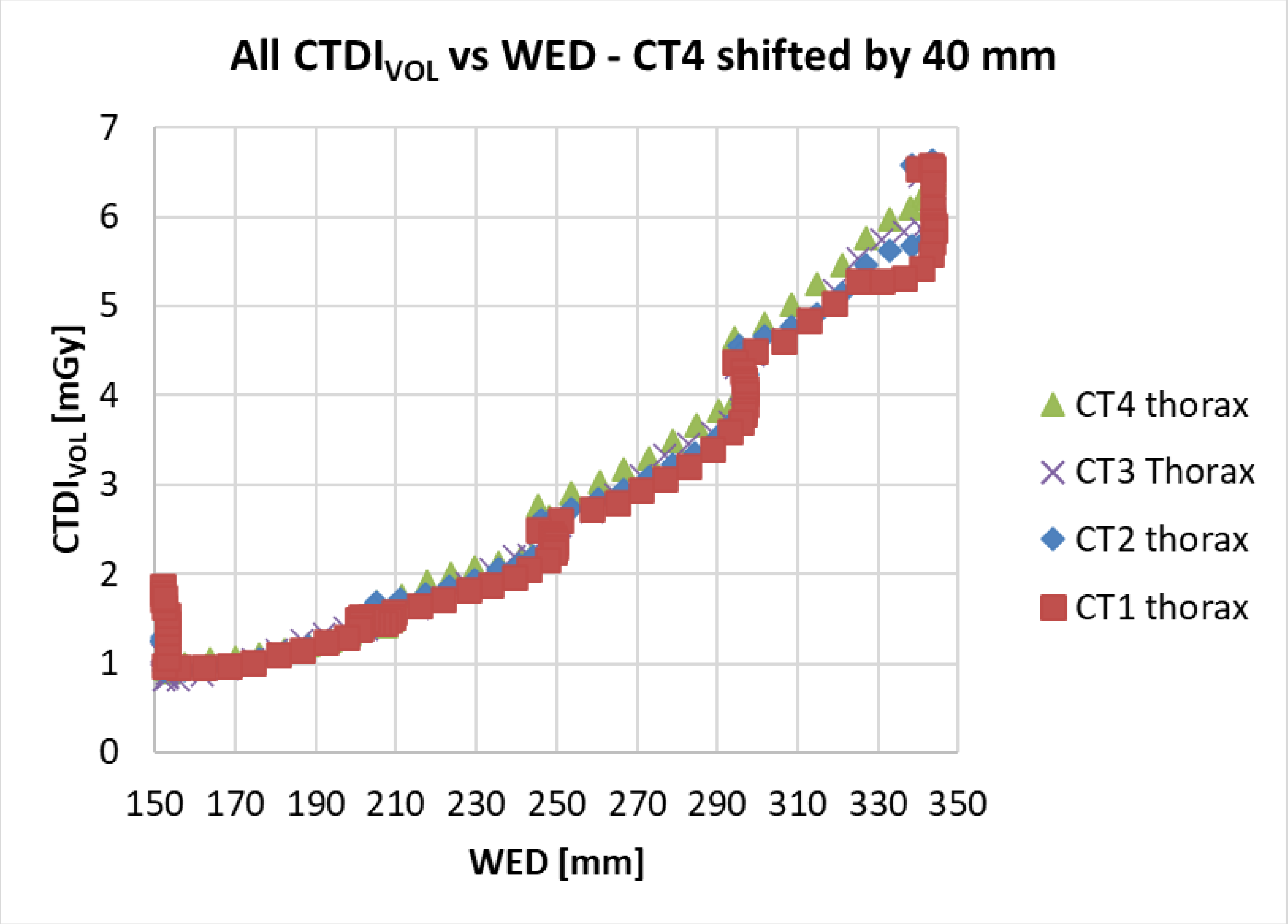
- 4 scanners of the same vendor – plots for comparison





Results – four scanners from the same vendor

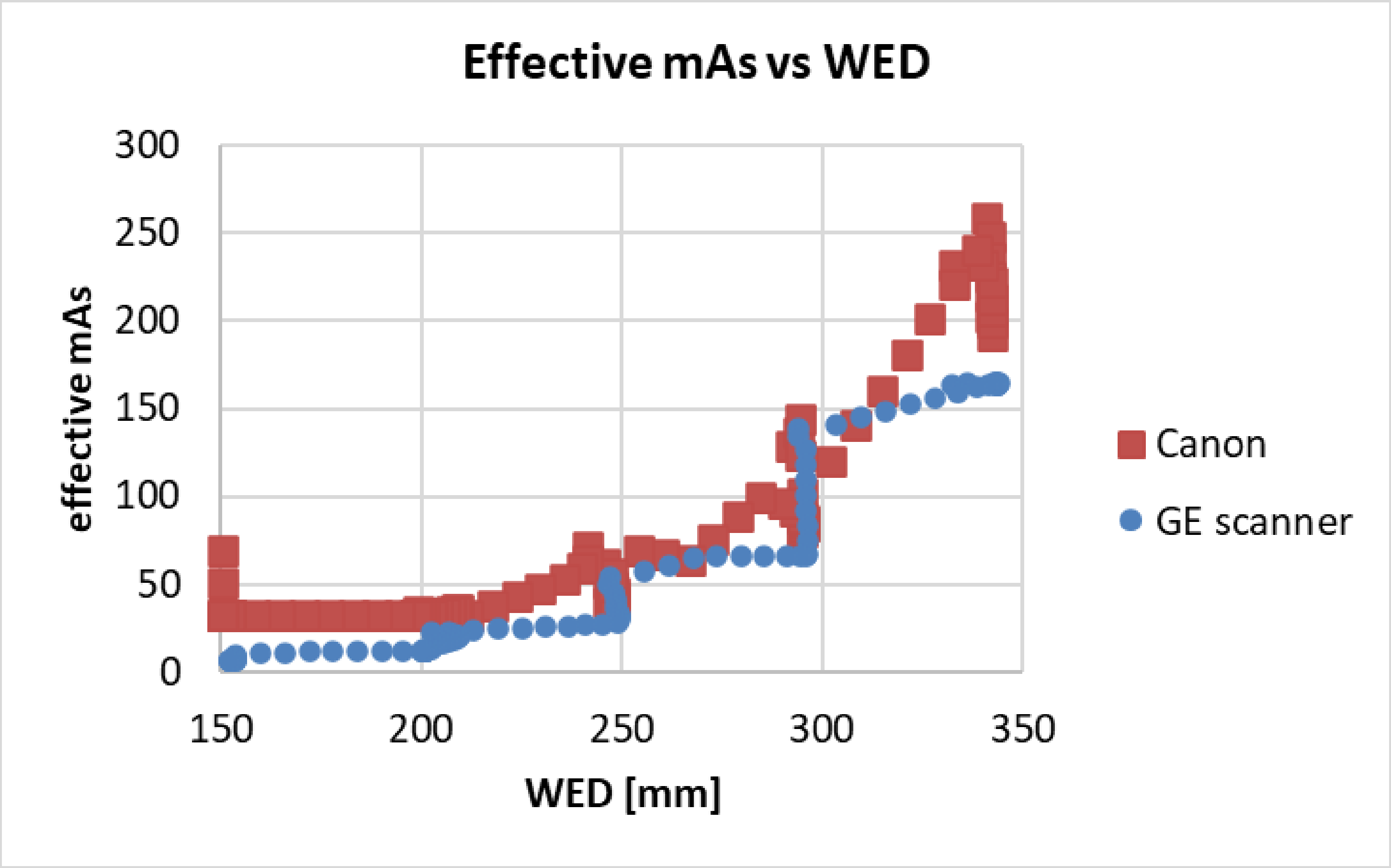
- CT4 – the only scanner where the phantom was scanned in the other direction to others (small to large diameter rather than large to small)!
- Interestingly – replot with this scanner data offset by approx. distance of N×T detector coverage:

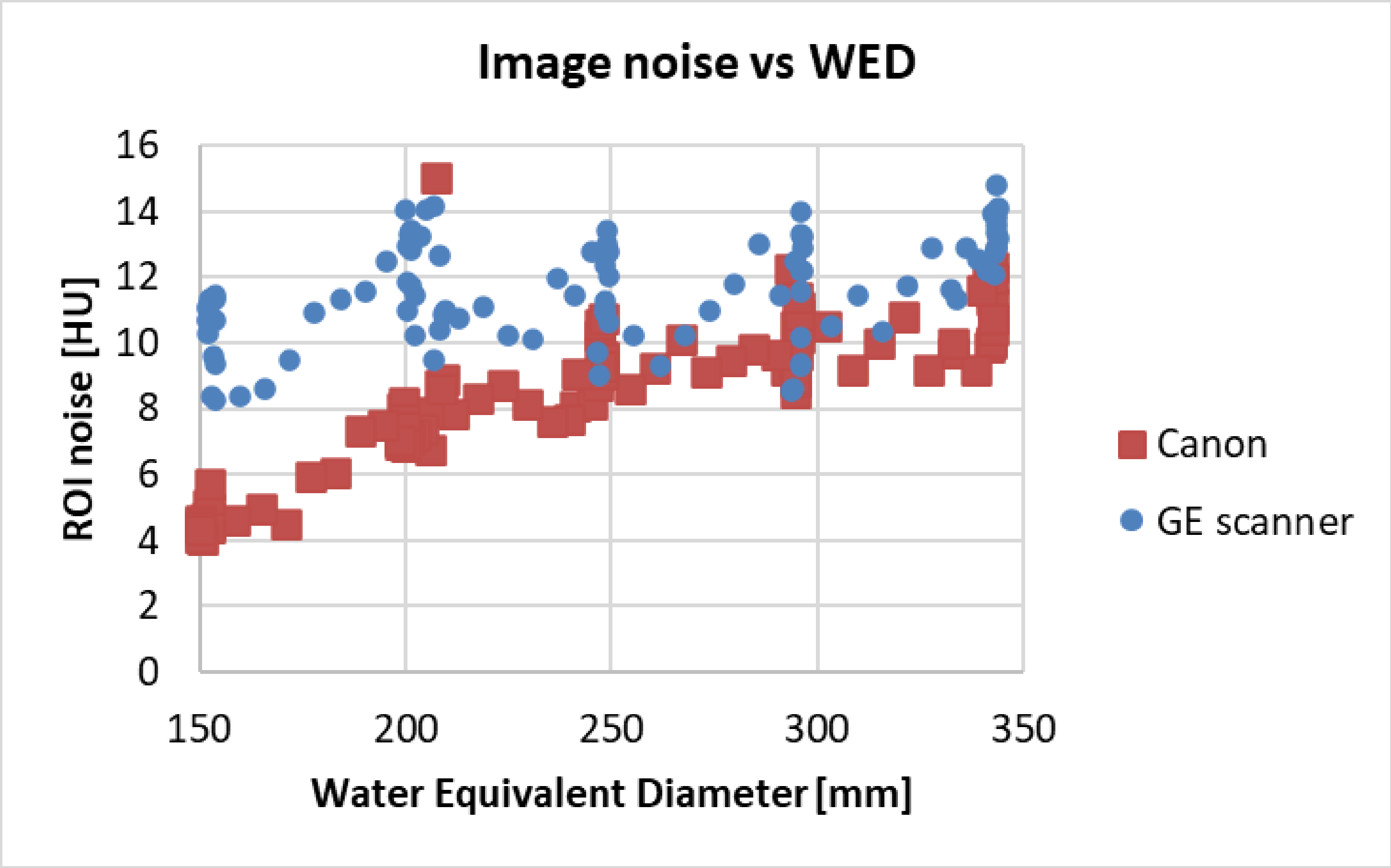


Scan DLP % difference from mean:	CT1	CT2	CT3	CT4
Abdomen	-3.1	-1.6	-7.9	12.6
Thorax	-4.6	-4.3	-8.5	**17.5**

Results - Two other scanners with constant-noise TCM strategies

- Confirms that noise is maintained, except where mA caps are reached (minimum, in this case)





PAUSE and CHECK

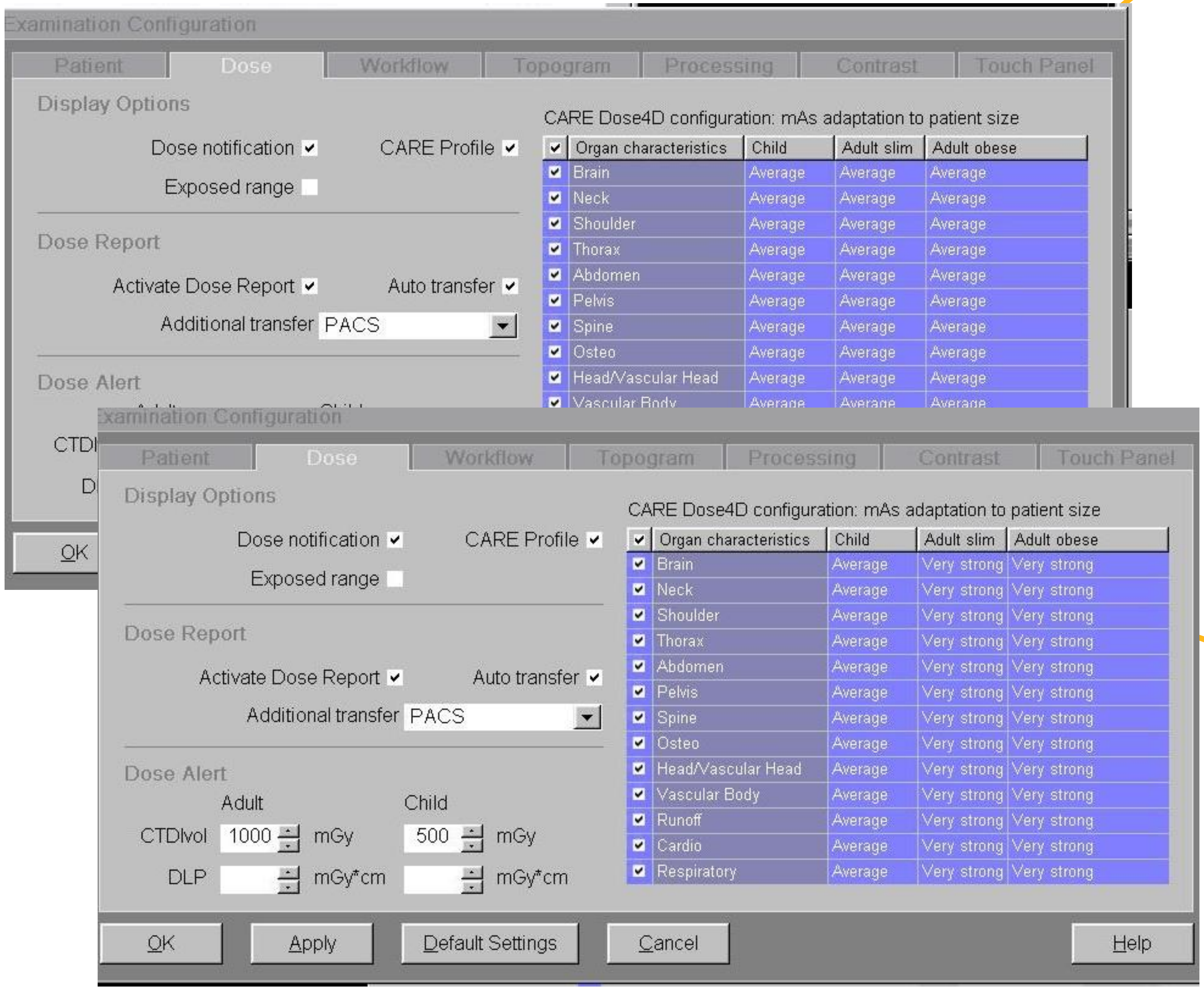
- ❑ Tests so far - great for TCM functionality and consistency checks.
- ❑ But why should we *routinely* test TCM response?
- ❑ We are looking for changes in performance.
- ❑ Annual checks not appropriate for detecting changes to individual clinical protocols
  - ❑ Far too many to test!
  - ❑ A robust system of protocol control should be in place for clinical protocols.
  - ❑ Unexpected clinical protocol changes should be picked up by clinical users
    - ❑ Image quality; comparison against Local DRLs, etc.
  - ❑ Or else by dose audit

- ❑ Instead, routinely, we are concerned about global scanner changes in TCM settings.

Sensitivity to change in TCM response

- Individual and batch protocol changes are password-protected on our diagnostic CT scanners

- **Scanner tube current modulation strength settings are not**



Sensitivity to change in TCM response

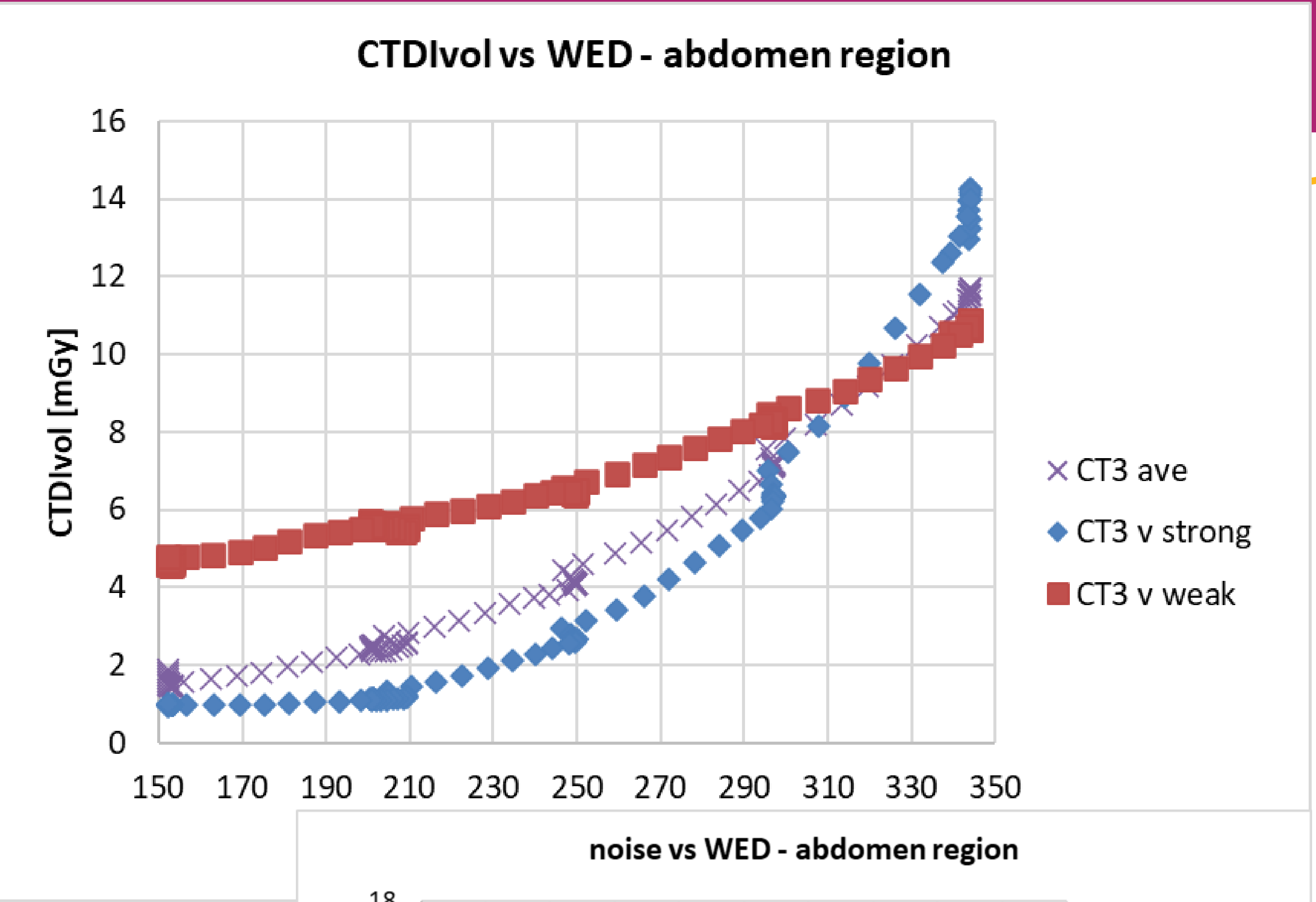
- Phantom scanned at AVERAGE, VERY WEAK and VERY STRONG tube current modulation strengths, 120 kV, pitch 0.6, Quality reference mAs at 147 mAs (based on default CT abdomen).

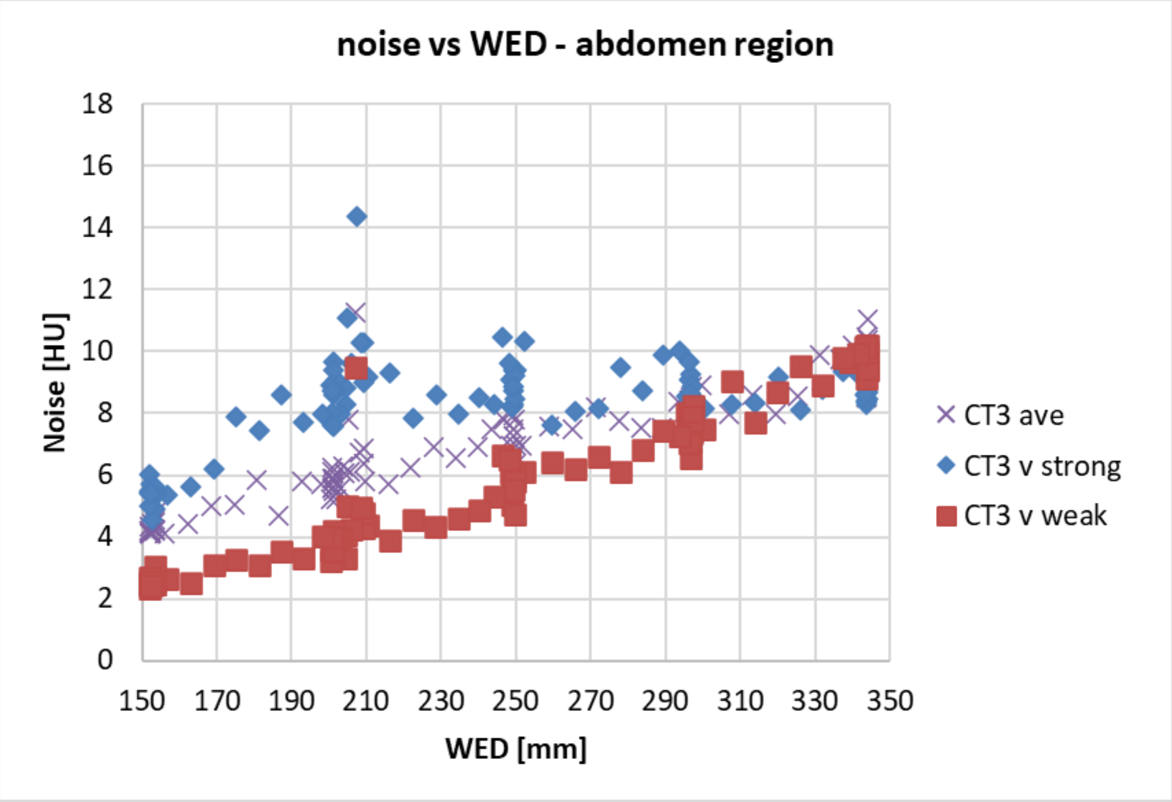
Strength setting	Average scan $CTDI_{VOL}$ [mGy]	% change from baseline	Scan DLP [mGycm]	% change from baseline
AVERAGE / AVERAGE	4.96	0 %	253.0	0%

Sensitivity to change in TCM response

- ❑ Why didn't we detect the change from AVERAGE to V STRONG modulation response in average $CTDI_{VOL}$ and DLP?

- ❑ At the stronger TCM response, the minimum mA was reached for phantom diameters below approx. 200 mm – no further modulation possible.
- ❑ The decrease in $CTDI_{VOL}$ for smaller phantom diameters was also partially offset by an increase in $CTDI_{VOL}$ for larger phantom diameters.

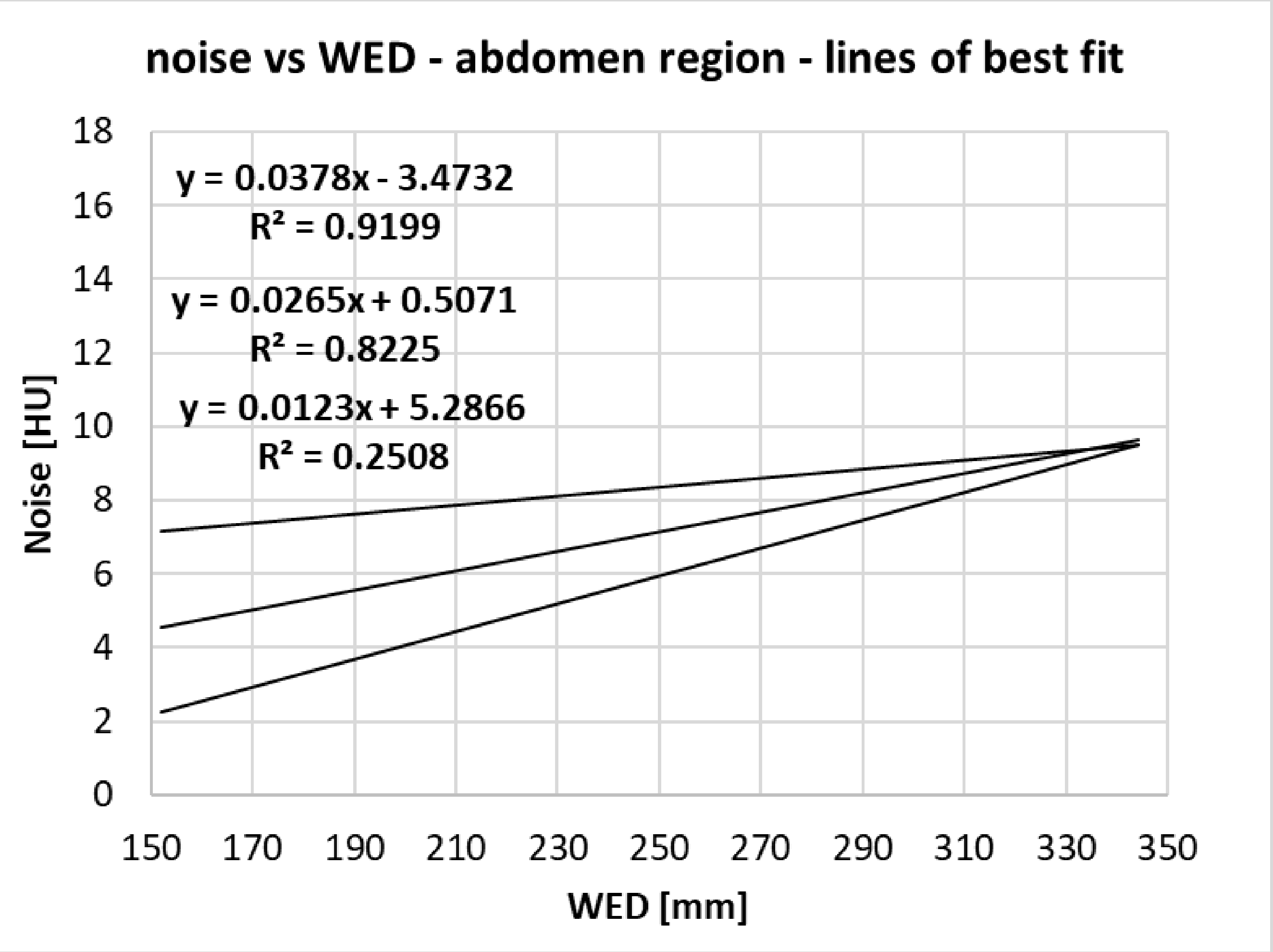


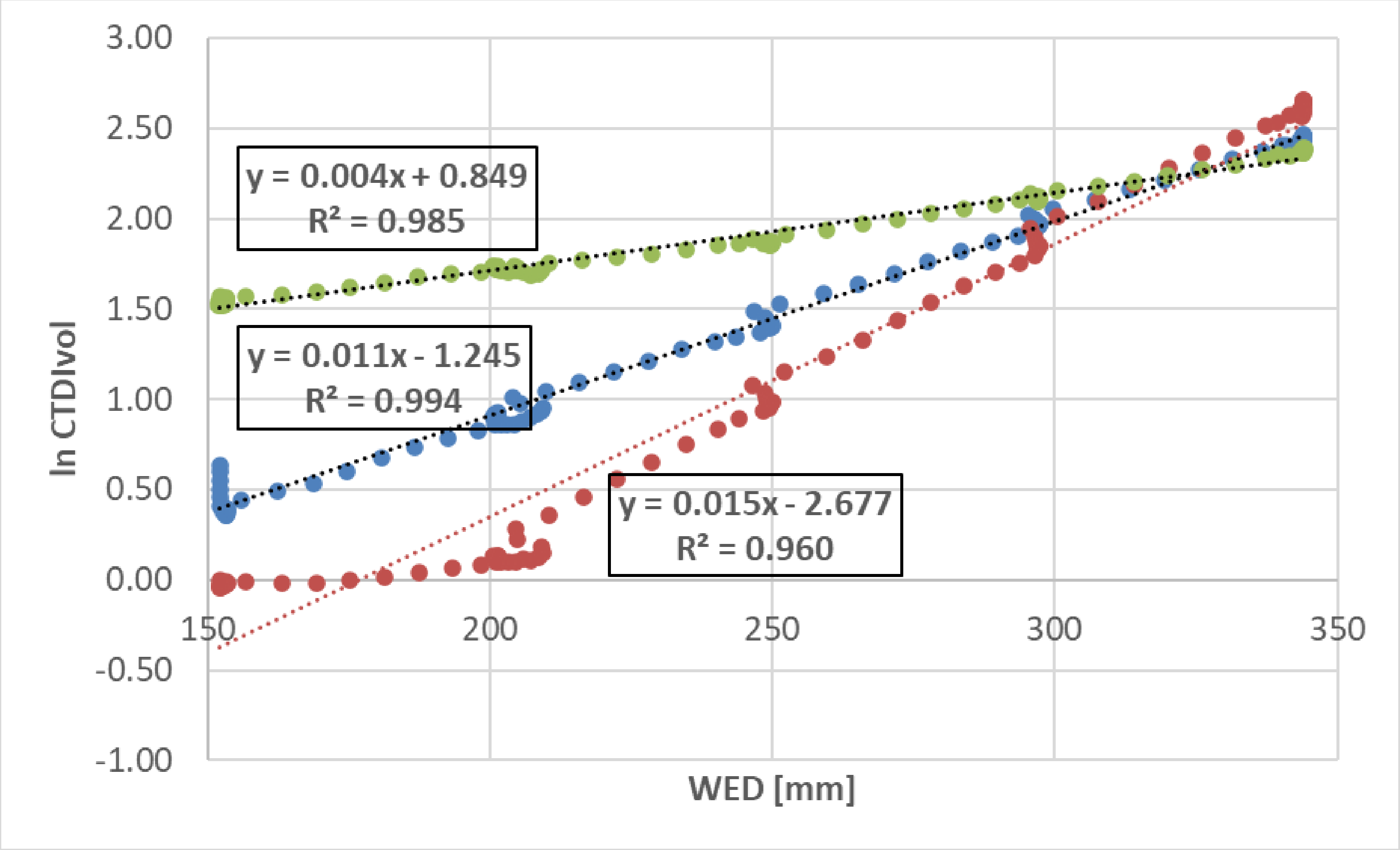


The RUH, where you matter

Sensitivity to change in TCM response

- Instead – look at the **gradient** of response curves - **recommended by AAPM 233**





Sensitivity to change in TCM response

- Instead – look at the **gradient** of response curves - **recommended by AAPM 233**

Strength setting	Gradient (noise vs WED)	% change from baseline	Gradient (ln $CTDI_{VOL}$ vs WED)	% change from baseline
AVERAGE / AVERAGE	0.0265	0 %	0.011	0 %

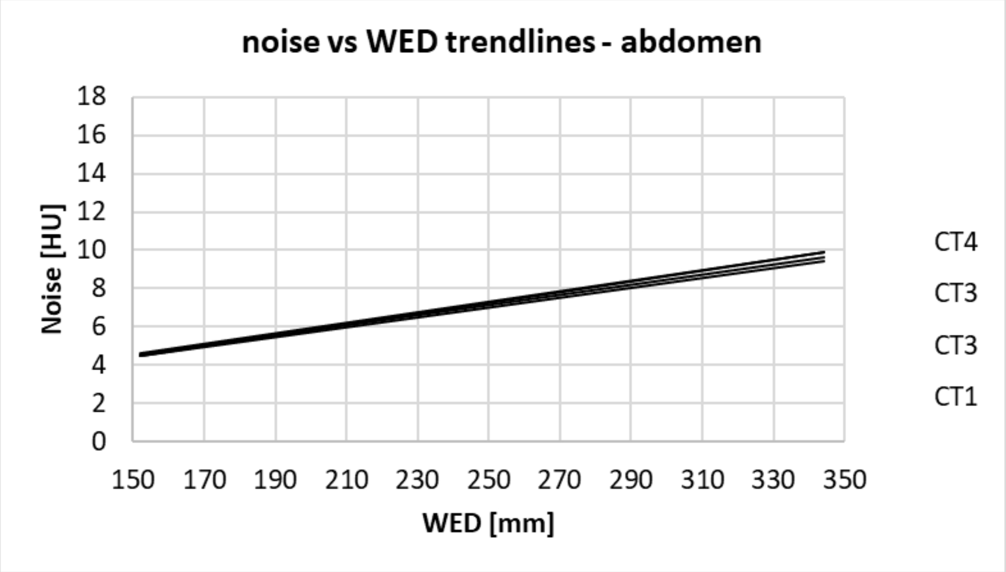
3.1.7 Recommended Performance Metrics

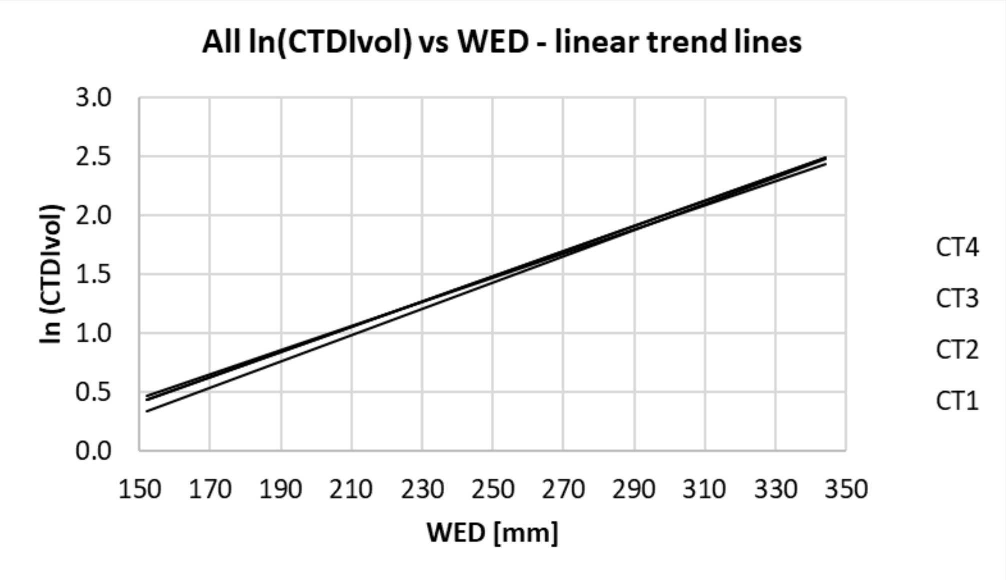
- Slope α and the correlation coefficient (R_{mA}) of $\ln(\mathrm{mA}) = \alpha(d_w)+\beta$ relationship (g_{mA}), for a given phantom
- Slope s and the correlation coefficient (R_n) of $n=s(d_w)+t$ relationship (g_n), for a given phantom

Reproducibility of TCM response for same vendor:

- Gradients of four scanners, same vendor, at same settings, match to within ± 10%:

Scanner	Gradient (noise vs WED)	R^2 value	Gradient (ln $CTDI_{VOL}$ vs WED)	R^2 value
CT1	0.0281	0.915	0.0102	0.979
CT2	0.0272	0.921	0.0107	0.995
CT3	0.0265	0.907	0.0108	0.997
CT4	0.0255	0.922	0.0110	0.984





Sensitivity to change in TCM response

- The gradients of noise vs WED and ln($CTDI_{VOL}$) vs WED are straightforward to add to our analysis spreadsheets.
- For these to be assessed our phantom needs a range of WEDs.
- The Mercury phantom provides a continuous range of WEDs from 15 to 35 cm.

Scan series (1):

Protocol name	PHYSICS_RoutineTCM		
Body region	abdomen	(if applicable)	
kV	120		
Total collimation	38.4	mm	
Scan pitch	0.6		
quality reference mAs	147		
upper mA cap	N/A	lower mA cap	N/A
recon kernel	Br38_3		

Add any other comments on scan technique or variation in scan parameters here: e.g. number and orientation of topograms; dose reduction settings; etc

VERY STRONG TCM response
baselines - AVERAGE TCM response strength

	displayed	baseline	% change
series average CTDIvol:	4.53	4.96	-8.67
series total DLP:	231.2	253.0	-8.62

suggested tolerances: ± 15% [local limit]

AAPM analysis:	slope	baselines	% change	correlation
Ln CTDIvol versus WED	0.0151	0.0108	40.45	0.9798
Noise versus WED	0.0123	0.0265	-53.64	0.5008

Analysis Results (1):

Series_number	Image_number	Slice_location	kV	RotTime	Pitch	TubeCurrent	EffectivemAs	CTDIvol	Recon_kernel	SliceThick	ROInoise	WED
2	1	-10.4	120	500	0.6	247	205.833	12.5968	Br38f\3	5	9.732	339.38
2	2	-15.4	120	500	0.6	250	208.333	12.9605	Br38f\3	5	8.378	343.698
2	3	-20.4	120	500	0.6	255	212.5	13.2453	Br38f\3	5	8.637	343.925

Characterising TCM response – a story

Background

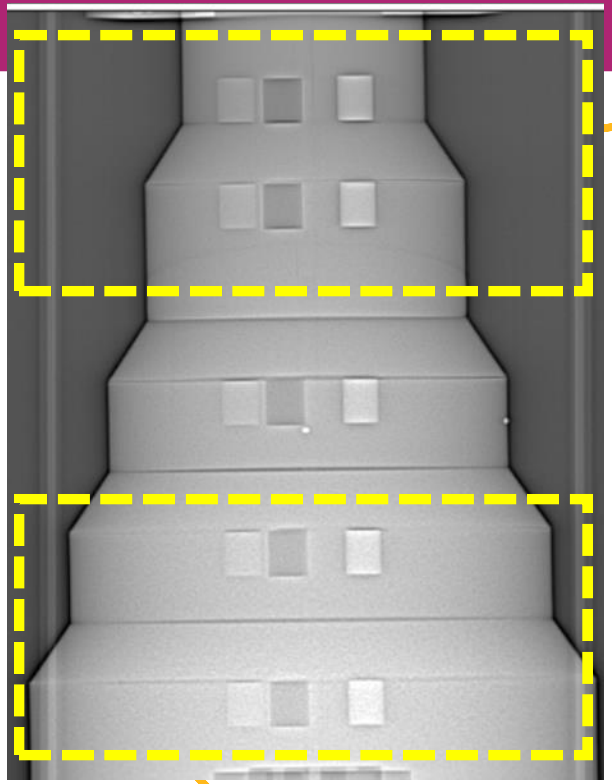
- New SPECT-CT system install during COVID lockdowns in 2020.
- CT component is a third-party manufacturer bolt-on to the SPECT system
- Very little prior information from the vendor or manufacturer on TCM strategy, not described in scanner user manuals.
  - Constant noise strategy? Constant image quality strategy? Unknown.

- kV set in protocol; prescribed tube current controlled via “effective mAs” parameter
- After performing scan projection radiograph, the user can view a mA modulation chart plotted against SPR image – clearly shows modulation as a function of attenuation.

Initial scans

- Single scan of phantom of varying diameter demonstrated modulation of tube current against phantom diameter
- Varying the effective mAs parameter gave proportional changes in delivered DLP and series-average $CTDI_{VOL}$
- So far so good. But…

Further scanning



- Scanning **just** the small diameters of the phantom – or **just** the large diameters of the phantom – gave the same scan average $CTDI_{VOL}$ and DLP.
  - For **both** ranges, the mA modulated from approx. minimum to maximum.
- All clinical scans with TCM enabled gave the same scan average effective mAs – regardless of overall patient size.
- The mA modulates within anatomy, but seems not to take into account overall patient size.
- Images, data, queries sent to vendor – we were told that this was the correct and intended function of this feature.

Outcome

- We would have taken a lot longer to come to this realisation if we didn't have a decent TCM test protocol, or if we did not have appropriate phantoms.
- Vendor not at fault – system operating as they expected. Just not as we expected! We did not have sufficient information to know this.
- Having a test protocol and appropriate phantoms enables us to characterise the functionality of these systems
- Clinically: most scanning on this system is performed for attenuation correction and localisation: highest diagnostic quality not required. Weight-based mA prescriptions introduced for other exams.

Conclusions

Conclusions

- Should we be testing TCM response?
- YES – it informs us how these systems work, enables appropriate optimisation advice, and we've confirmed our tests are sensitive to global changes in TCM settings.
- At RUH Bath our strategy will be to test using absolute values AND the gradient of noise and $CTDI_{VOL}$ response curves – Local tolerances on the latter yet to be defined.

Test	Test automatic exposure control
Commissioning	YES
Major software change	YES
Routinely	Infrequently – every three years currently

- Implementation in progress: pending on documentation updates within our Quality System!