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Construction of a phantom for dual energy CT quality assurance tests

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Acknowledgements

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- Thanks to Kirsten Hodgson and Laurence King for advice on dual energy testing in general

- CTUG presentation by Laurence King in 2021: “Dual energy CT image quality QC”

Contents

- Dual Energy CT – a very brief overview
  - with reference to the GE Apex CT scanner
- List of dual energy QA tests carried out at commissioning
  - including test object
- Construction of the in-house DECT QA phantom
- Measurements made using the DECT QA phantom: results and analysis

Single energy CT (SECT)

- Conventional single-energy CT (SECT) uses a polychromatic X-ray source to generate images based on linear X-ray attenuation
- For some beam energies, some materials have similar linear attenuation coefficients and hence CT numbers, making it difficult to differentiate between them
  - E.g. calcified plaques and iodine-containing blood

Dual energy CT (DECT)

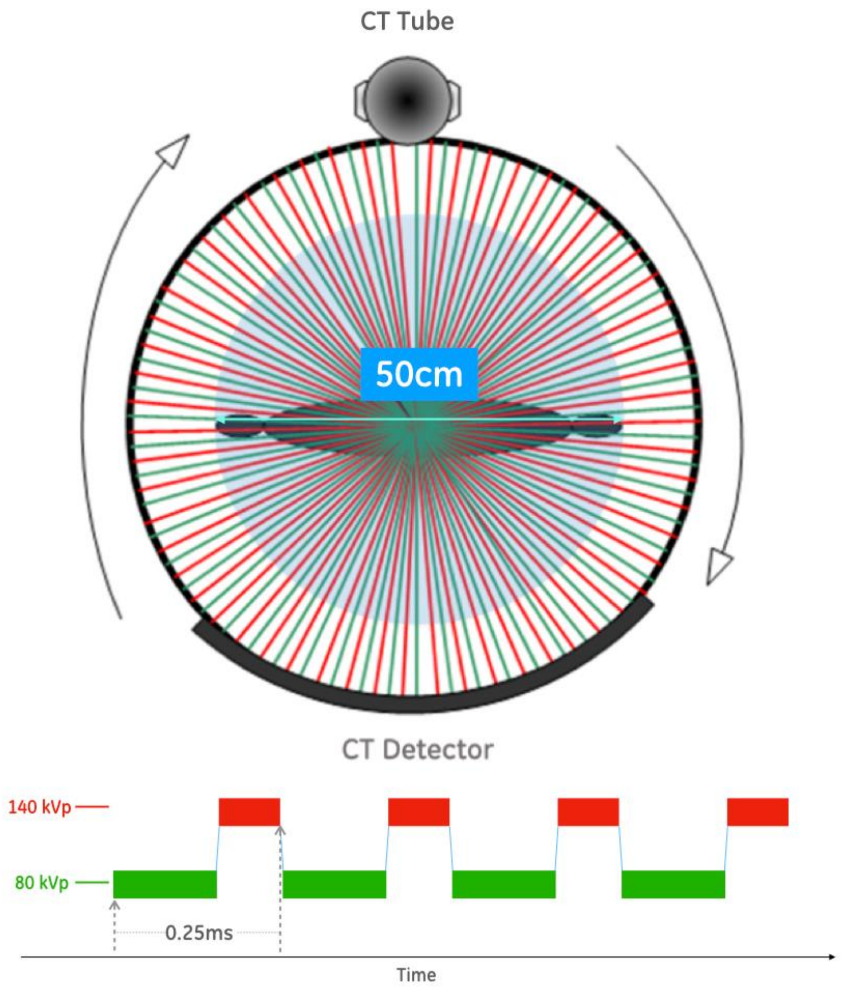
- Dual energy CT (DECT) acquires projection data at two different energy spectra
- Materials have unique attenuation profiles at different energy levels
  - Higher atomic numbers: larger differences in attenuation between high and low X-ray energies
- DECT uses this to differentiate and quantify material composition

Methods of acquiring dual energy datasets

- Rapid tube potential switching
- Multilayer detectors
- Dual x-ray sources

- The GE Apex uses fast kV switching
  - 80 and 140 kVp at sub-millisecond speed
  - minimises the impact of patient motion

GE – Rapidly switched kV



Examples of additional image sets reconstructed in DECT

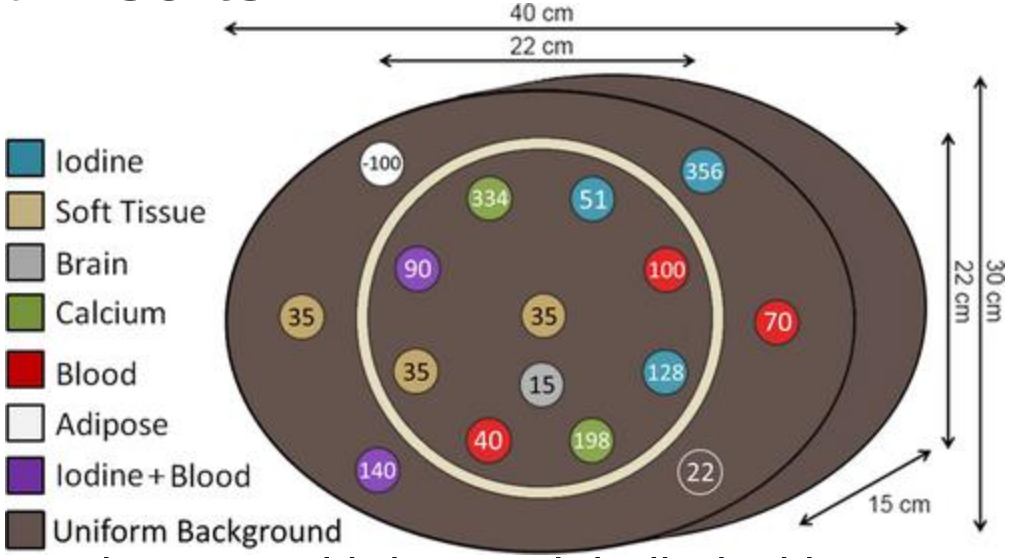
- Material Density Images
- Virtual monochromatic images
- Virtual Unenhanced images

DECT Commissioning Checks

- CTDIvol
  - Perspex CTDIvol phantom (as for SECT scans)
  - Able to do in service mode only
- CT number values and high contrast resolution
  - CatPHAN as for SECT scans
- CT number accuracy / uniformity / noise
  - GE water phantom
- Iodine quantification and CT number accuracy of virtual monochromatic images
  - In-house DECT QA phantom

Commercial phantom

- Gammex MECT phantom – contains several iodine inserts of different concentrations, plus additional inserts



Gammex phantom with inserts labelled with HU number

Constructing the DECT phantom in-house

- Main reference:

"Development of a dual-energy computed tomography quality control program: Characterization of scanner response and definition of relevant parameters for a fast-kVp switching dual-energy computed tomography system", J L Nute et al., Med. Phys. 45 (4), April 2018

  - Phantom described in this paper was the prototype for the Gammex MECT phantom

Components of DECT phantom

- 900 ml food container
  - contains background material: deionised water
- 5 x 65 ml inserts
  - Similar diameter to Gammex MECT phantom
  - Iodine concentrations 0.5, 2, 5, 10 and 15 mg I/mL
- 2 holders for the inserts – 3D printed in house
  - Notches in each to aid consistency in positioning

Components of DECT phantom

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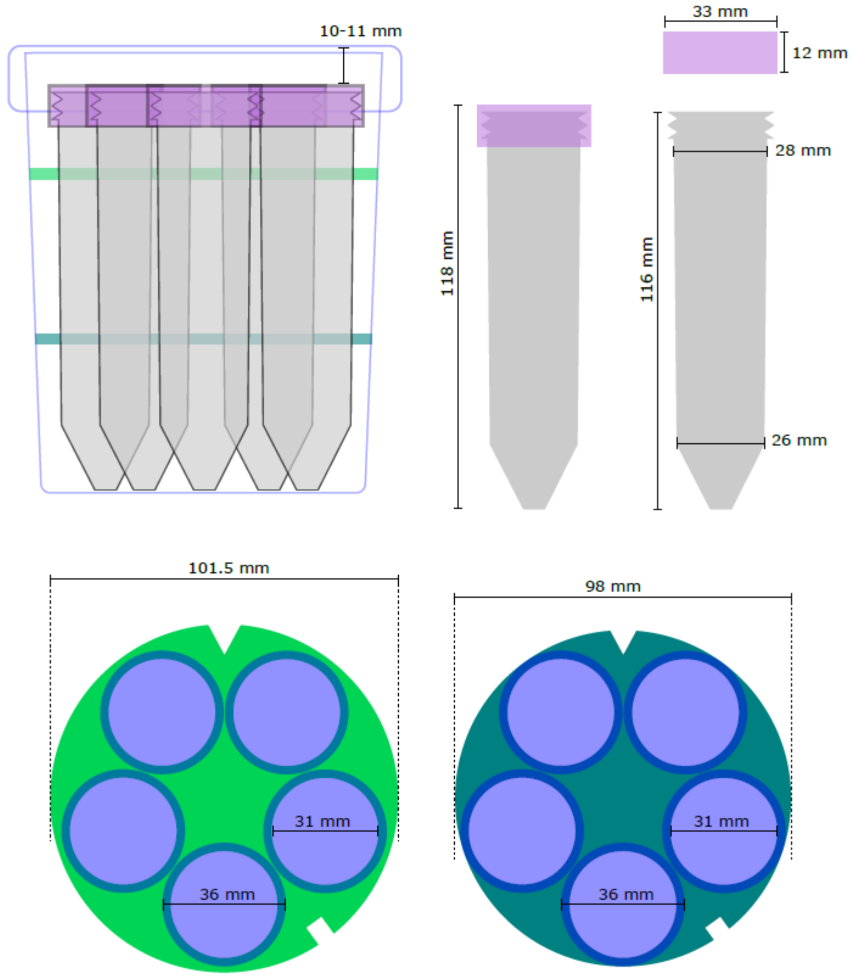

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Constructing the iodine inserts

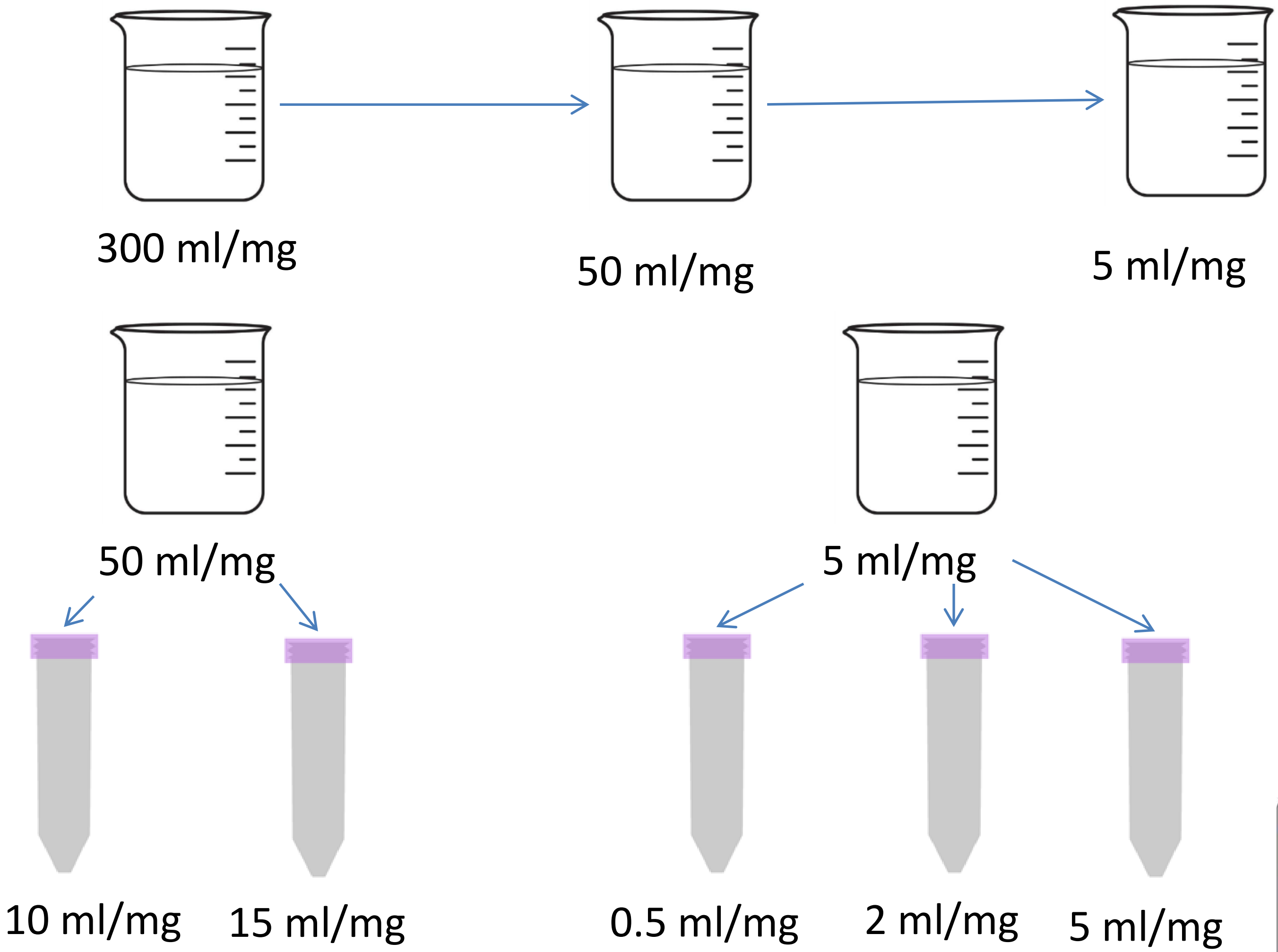
- Source of iodine: left over 'Omnipaque' iodine contrast agent (300 mg Iodine/ml)
  - All concentrations from now on refer to iodine concentrations

- Diluted with deionised water (from supermarket)

Measurement equipment

- Scales to measure water volume (ml)
  - measurement uncertainty: 0.05ml
- 2.5ml syringe to draw up iodine solution
  - measurement uncertainty on individual draws: 0.05ml

The Chemistry



A worked example

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- Relevant quantities:

Original concentration of iodine (c_1)	5 mg/ml
Final concentration of iodine (c_2)	0.5 mg/ml
Volume of 5 mg/ml iodine solution (v_1) needed to make the 0.5 mg/ml solution	What we needed to calculate
Final volume of 0.5 mg/ml iodine solution (v_2). This is the volume of each vial used for the inserts (+ a bit extra).	80 ml

- $v_1 \times c_1 = v_2 \times c_2$ (total mass of iodine stays the same)
- Therefore, the volume we needed to draw from the 5 mg/ml solution (v_1) = 80 x 0.5 / 5 = 8 ml
- And the additional amount of deionised water required (v_w) was 80 ml – 8 ml = 72 ml

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National Physical Laboratory, 2013. Good Practice Guide 11: A beginner's guide to uncertainty of measurement. https://www.npl.co.uk/gpgs/beginners-guide-measurement-uncertainty-gpg11
David Harvey, 2016. Analytical Chemistry 2.1 and Analytical Chemistry 2.1: Solution Manual. http://dpuadweb.depauw.edu/harvey_web/eTextProject/SMFiles/AC2.1SolnManual.pdf

Uncertainty analysis

- Relative uncertainties summed in quadrature for each dilution step
- Uncertainties propagated through each dilution step

- 0.5 mg/ml example:

Quantity	Value	Uncertainty (σ)	Uncertainty %
c_1 (starting concentration)	5 mg/ml	0.06 mg/ml (uncertainty from previous dilution)	1.23
v_1 (vol. of 5 mg/ml solution)	8 ml	$\sqrt{4 \times 0.05^2} =$ 0.1 ml (4 draws with the 2.5 ml syringe)	1.25
v_2 (vol. of 0.5 mg/ml solution)	80 ml	$\sqrt{0.1^2 + 0.05^2} =$ 0.1 ml (uncertainties in v_1 and water)	0.14
c_2 (final concentration)	0.5 mg/ml	0.01 mg/ml	1.76

National Physical Laboratory, 2013. Good Practice Guide 11: A beginner's guide to uncertainty of measurement. https://www.npl.co.uk/gpgs/beginners-guide-measurement-uncertainty-gpg11
David Harvey, 2016. Analytical Chemistry 2.1 and Analytical Chemistry 2.1: Solution Manual. http://dpuadweb.depauw.edu/harvey_web/eTextProject/SMFiles/AC2.1SolnManual.pdf

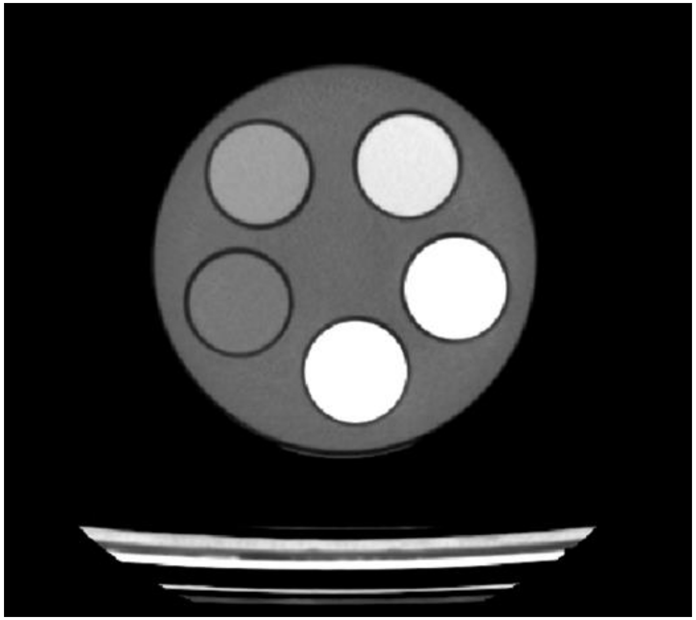
Summary of iodine insert concentrations with errors

Iodine concentration (mg/ml)	Uncertainty (mg/ml)
0.50	0.01
2.00	0.03
5.00	0.06
10.0	0.1
15.0	0.2

- Operator error not included in calculation of measurement uncertainties
  - Variation in repeat constructions required to measure

Using the phantom

- The DECT phantom was positioned horizontally on the CT couch
- Axial images were assessed



Acquisition settings

kV 1	kV 2	scan type	pitch	detector coverage (mm)	rotation speed (s)	mA	image thickness (mm)	SFOV	DFOV (cm)	CTDIvol (mGy)
80	140	helical	0.516	8x5	0.5	370	5	med body	22.7	18.81

Iodine quantification measurements

- Material density images were acquired
- ROIs were placed within the image of each iodine insert and the measured iodine concentrations (with standard deviations) were displayed
- These were then compared with the nominal values

Iodine quantification results

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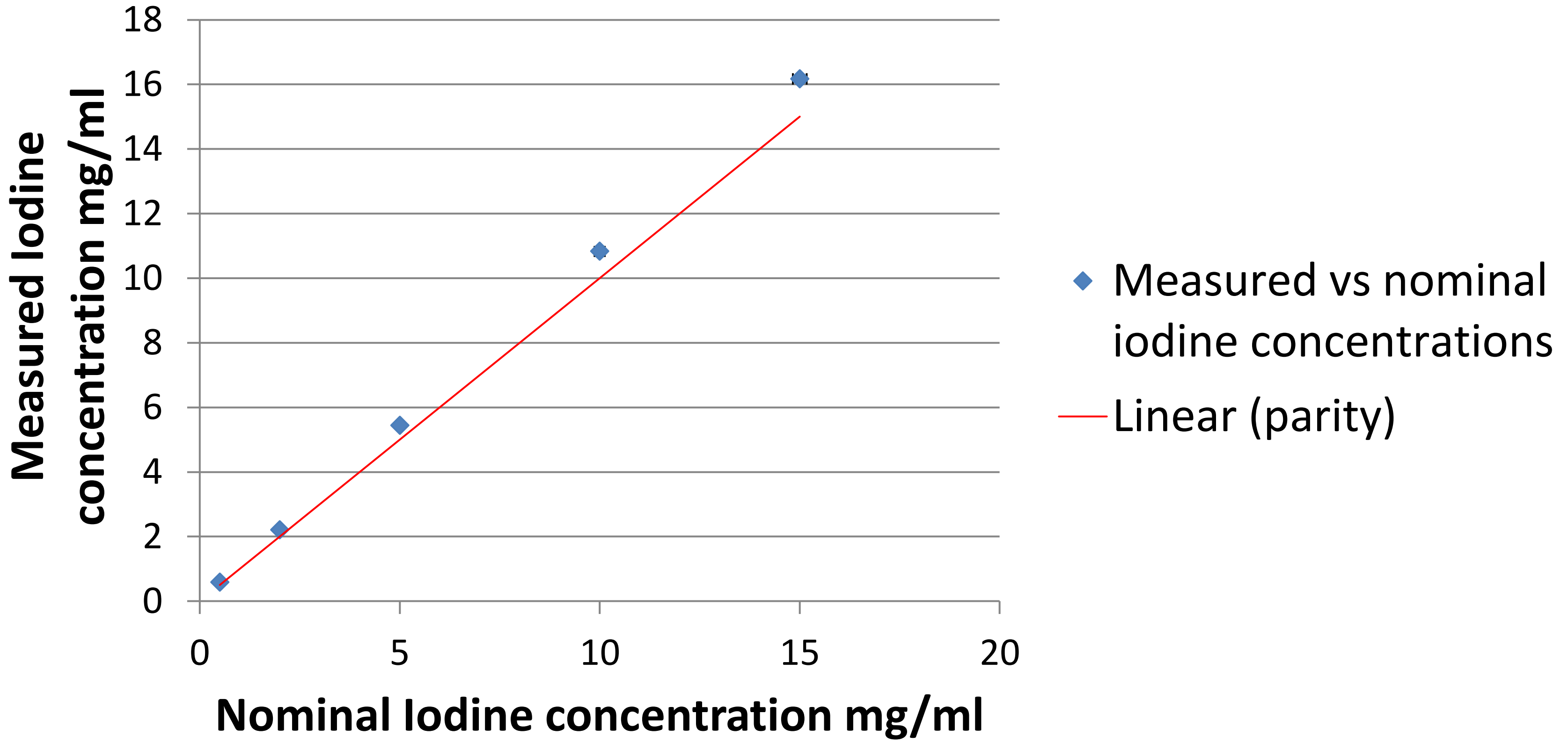

Iodine quantification results

nominal iodine concentration (mg/ml)	measured iodine concentration (mg/ml)	% difference measured to nominal iodine concentrations (%)	absolute difference measured to nominal iodine concentrations (mg/ml)
0.50 +/- 0.01	0.59 +/- 0.07	18	0.09
2.00 +/- 0.03	2.21 +/- 0.07	11	0.2
5.00 +/- 0.06	5.44 +/- 0.08	9	0.4
10.0 +/- 0.1	10.83 +/- 0.07	8	0.8
15.0 +/- 0.2	16.17 +/- 0.08	8	1.2

Iodine quantification tolerance suggested in Nute et al: > 10% or > 1 mg/ml (whichever greater)

GE Apex manual suggests a tolerance in measurements of material density of 10% or +/- 0.3 mg/ml (whichever greater)

CT number measurements for each virtual mono-energetic image

- Virtual mono-energetic images were generated
  - 40 to 140 keV
- ROIs were placed within the image of each iodine insert and the CT number and standard deviation were displayed
- These values were then compared with CT numbers derived using the National Institute of Standards and Technology (NIST) Standard Reference Database 126
  - The NIST database provides mass attenuation coefficients, from which Hounsfield units can then be calculated

CT number accuracy results

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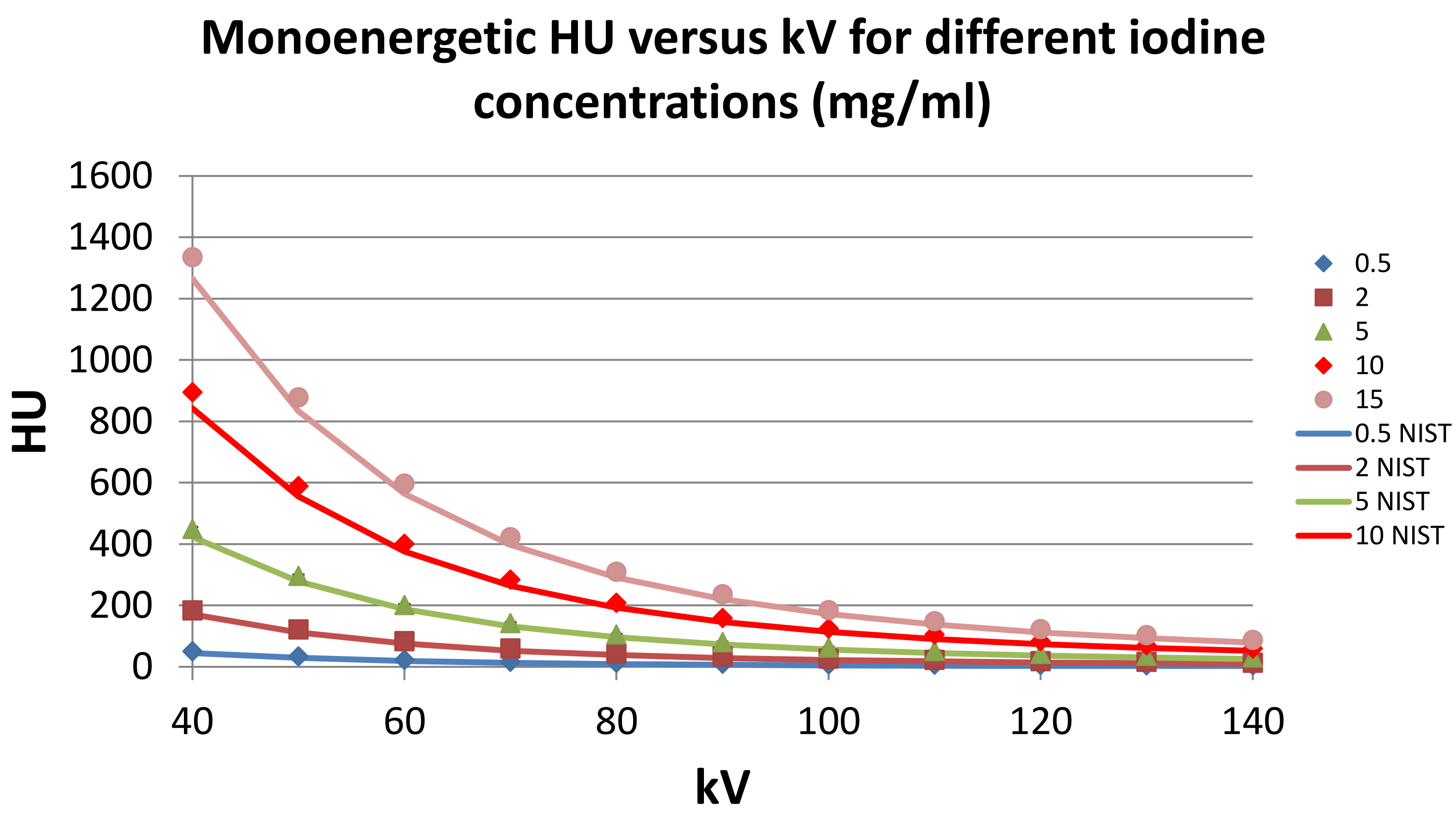

Data acquired at 18.8 mGy but not dose dependent

Difference between measured and nominal CT numbers (in HU)

	% difference measured to nominal CT numbers at each iodine concentration (%)				
kV	**0.5**	**2**	**5**	**10**	**15**
40	13	8	6	6	6
50	15	8	6	6	5
60	21	11	7	7	6
70	33	13	9	8	6
80	41	15	9	8	7
90	56	19	11	9	7
100	72	23	12	10	8
110	89	26	13	16	8
120	123	33	16	13	9
130	183	40	19	15	11
140	308	41	22	15	11

	Absolute difference measured to nominal CT numbers at each iodine concentration (HU)				
kV	**0.5**	**2**	**5**	**10**	**15**
40	6	13	27	53	70
50	4	10	18	34	45
60	4	8	14	26	33
70	4	7	11	20	25
80	4	6	9	16	19
90	4	6	8	14	16
100	3	5	7	11	13
110	3	5	6	14	11
120	3	5	6	10	11
130	3	5	6	9	10
140	4	4	6	8	9

Conclusions

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- Measurements made at commissioning demonstrated that the in-house phantom was a useful and cost effective additional tool for assessing the dual energy capability of a DECT scanner
- There was a linear relationship between measured and nominal iodine concentrations. Measured values were similar to nominal ones and within published tolerances
- CT numbers of virtual mono-energetic images plotted against keV showed a similar trend to National Institute of Standards and Technology (NIST)-derived nominal values

Further work

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- The calculated errors in nominal iodine concentrations are small. Calculations were based only on measurement errors (i.e. for the scales and syringe)
- For a more realistic approach, we will look to including operator error
  - By producing sets of verification vials and assessing consistency
- We note the errors quoted for CT numbers do not include any error in nominal iodine concentration – this will also affect the results and should be investigated

Further work

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- We understand that material density accuracy may be dose dependant. So would like to repeat the iodine quantification measurements at different doses
- Look at assessing the virtual unenhanced images
- Extend the investigation to other materials – e.g. calcium
- LOTS of reading!!