K-edge subtraction X-ray imaging with a pixellated spectroscopic detector

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Summary

- Hyperspectral imaging
- K-edge subtraction X-ray imaging for mammography
  - Methods
  - Results so far
  - Open problems
  - Perspectives

What is hyperspectral imaging?

- Any imaging technique allowing to retrieve a spectrum of the radiation detected
- Spectral information can be used for
  - Scatter rejection
  - Dual energy techniques
  - Non-conventional techniques (diffraction, fluorescence)
  - Nuclear Medicine
- So far, hyperspectral X-ray imaging methods have been limited due to the limited availability of pixellated spectroscopic detectors
  - Scanning methods are time consuming
- Recent technological developments are making hyperspectral imaging a reality

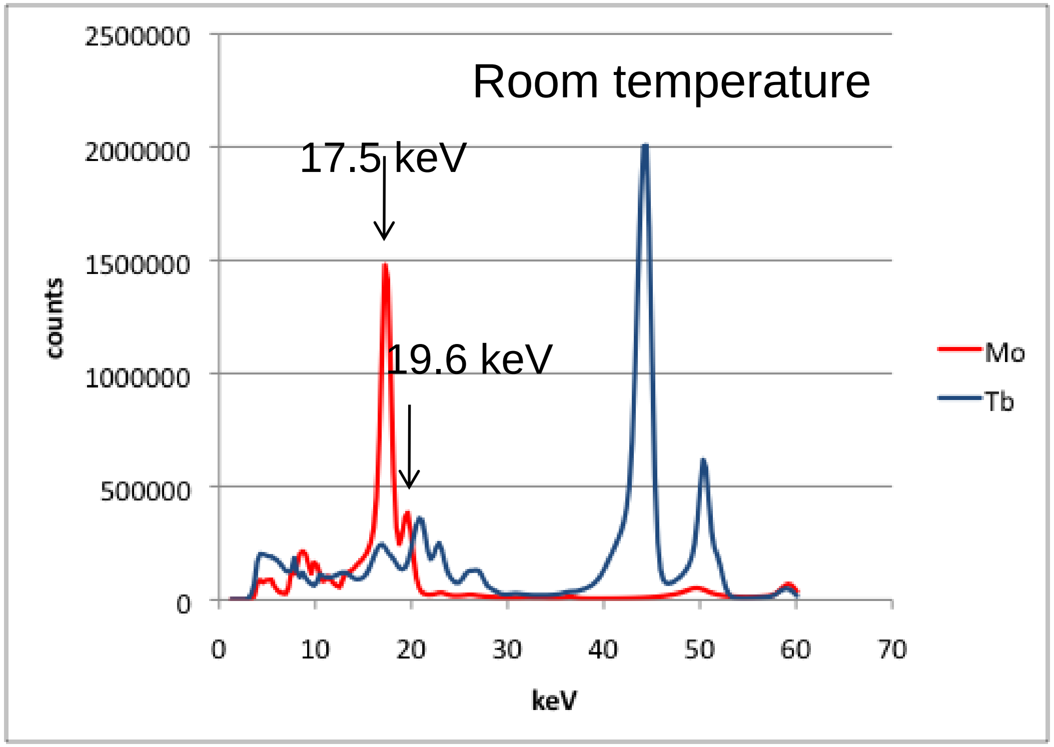
In the beginning was HPGe…

- HPGe has excellent energy resolution (<0.5 keV @ 60 keV)
- BUT:
  - Very expensive
  - Needs cooling → bulky and not suitable for in-field applications
  - Very few examples of position-sensitive devices

- HEXITEC collaboration (EPSRC funded):
  - Collaboration between STFC (Rutherford Appleton Labs), Universities of Manchester, Surrey, Durham, Royal Surrey County Hospital
  - Development of pixellated room temperature spectroscopic detectors (CdTe, CZT)
  - Now in its translational phase

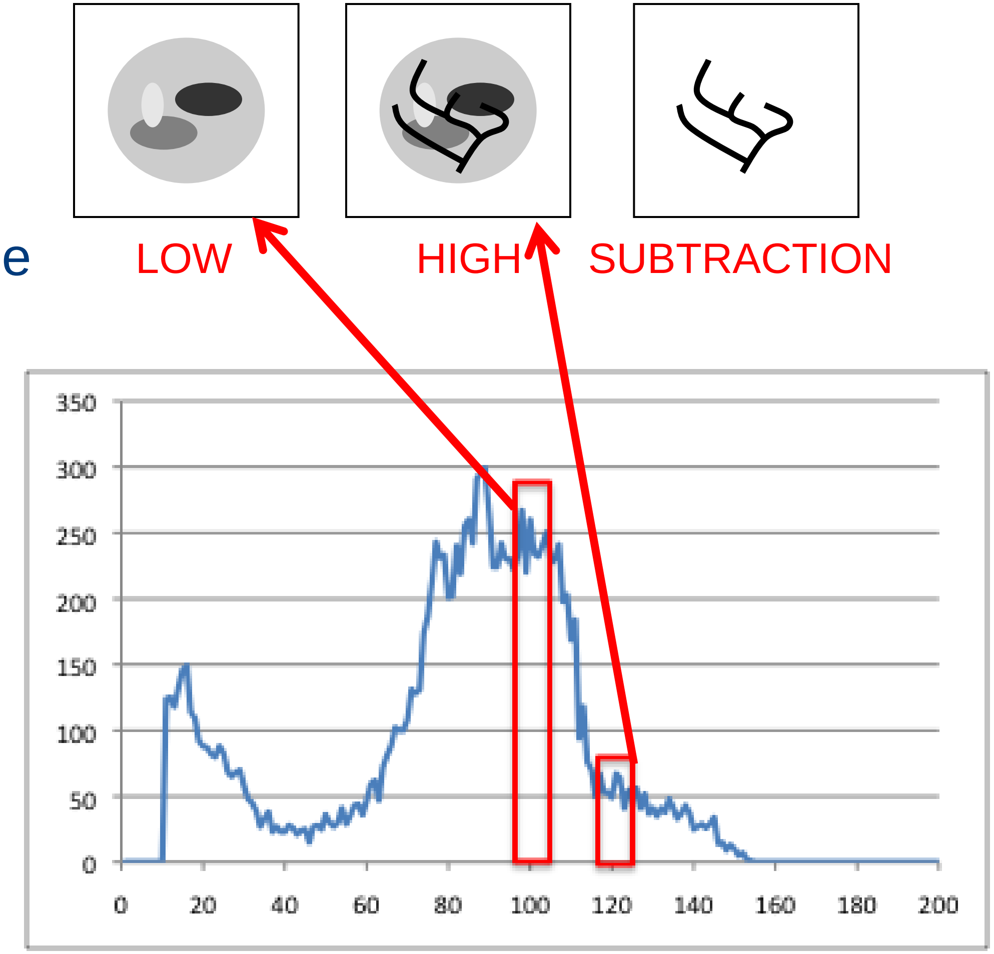
HEXITEC characteristics

- Currently using room temperature/sub-room temperature CdTe sensors
- Current sensors 80x80 pixels, 250 µm pitch, 1 mm thick
  - Tiled arrays of 2 x 2 sensors are under development
- Operated at -500V



K-edge subtraction imaging

- Typically used for angiography/angiogenesis studies
- Two images are acquired with energies above and below the K-edge of a contrast agent
- Combination and subtraction of the two removes the background
- Problems with conventional KES
  - Increased dose (two images!)
  - Image registration (the patient moves between the two images)
- This is removed with a spectroscopic detector:
  - The images above and below the K-edge are obtained by integrating the spectrum in appropriate ranges



Iodine KES with HEXITEC

- Aim: study of angiogenesis around breast tumours
- Different concentrations of Niopam® are used
  - Iodine-based contrast agent
- Iodine K-edge: 33.2 keV

  → Higher energy spectra than in conventional mammography

  W anode, 3 mm Al filtration, 45-50 kVp
- Plus single-photon counting detector
  - Intrinsically low noise

→ Significant dose reduction compared to conventional mammography!

The simplest approach: logarithmic subtraction

- The assumption is that the attenuation coefficient of the background materials does not vary strongly on the two sides of the K-edge

→ by subtracting the logarithm of the image below the K-edge from the logarithm of the image above the K-edge the background is removed

$$
\begin{aligned}
S(i,j) &= \ln\left(I^0_{high} / I_{high}(i,j)\right) - \ln\left(I^0_{low} / I_{low}(i,j)\right) \\
&= \mu^I_{high} x_I + \mu^{bg}_{high} x_{bg} - \left(\mu^I_{low} x_I + \mu^{bg}_{low} x_{bg}\right) \\
&\approx \left(\mu^I_{high} - \mu^I_{low}\right) x_I
\end{aligned}
$$

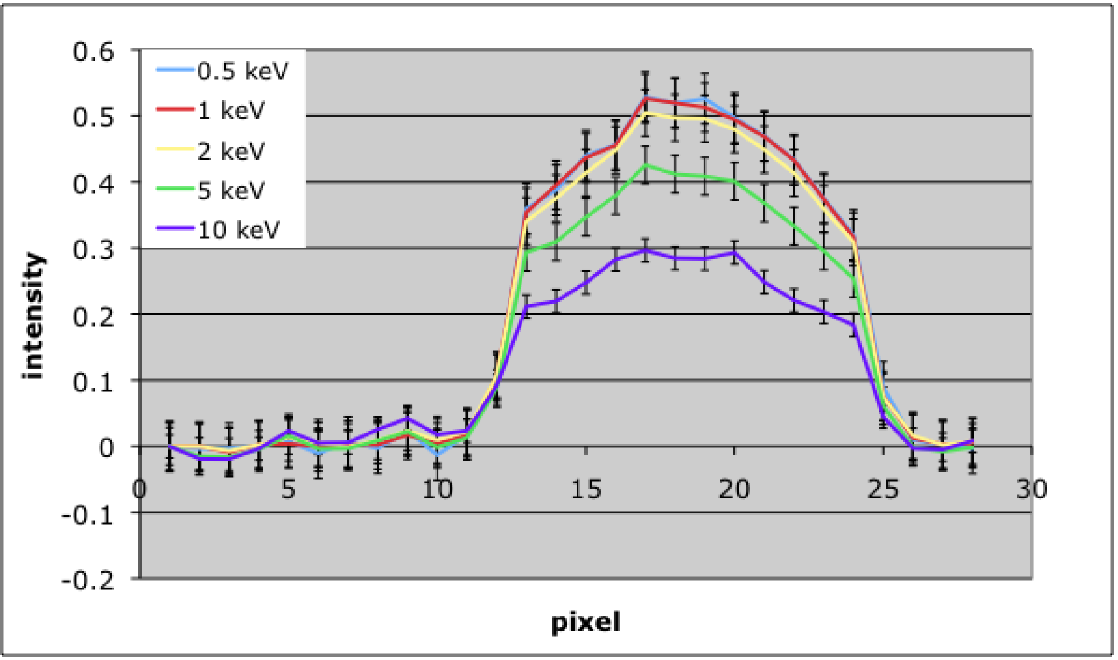
- Problems:
  - Only works if $\Delta\mu^{bg}$ is negligible across the K-edge
  - Maximum if $\Delta\mu^{I}$ is maximum

    Integration bands must be close to each other
  - Poor background removal if wide bands are chosen

Finding the optimum integration ranges

- 3 mm tube filled with undiluted Niopam 150 (150 µg/ml I)
- The optimum integration ranges for the images above and below the K-edge result from a trade-off
  - Wide range → high statistics, BUT low contrast + high structural noise

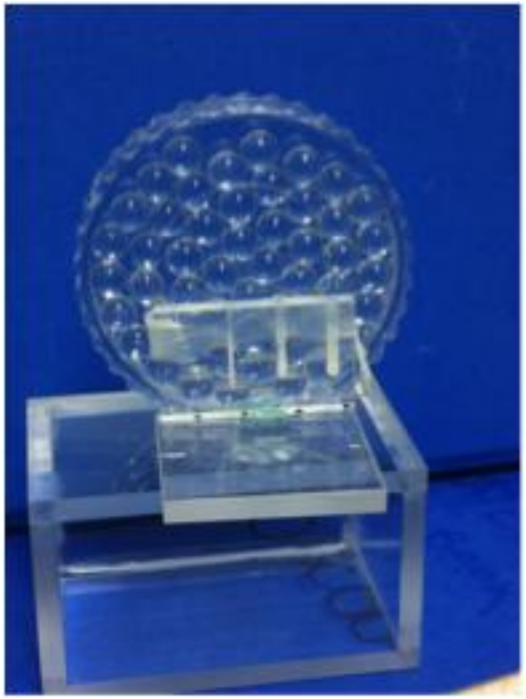
    The drop in transmission between the two sides of the K-edge is not fully exploited
  - Narrow range → high contrast, BUT poor statistics/high noise
- Investigated via contrast-to-noise ratio; CNR = (I - Ib)/σ



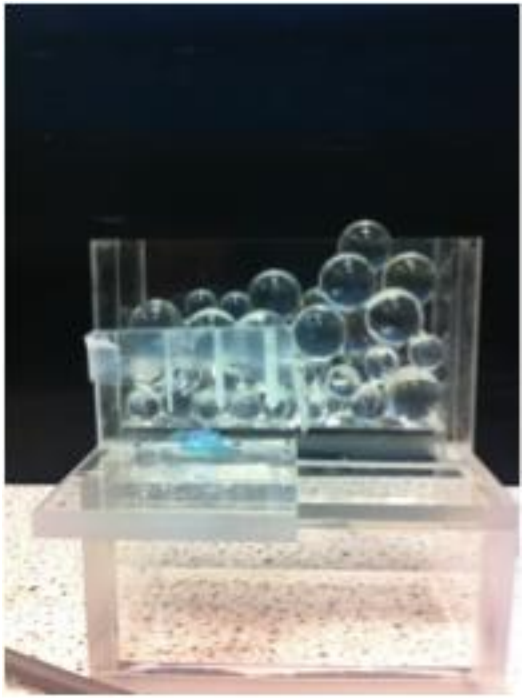
Width (keV)	CNR
0.5	48
1	76
2	55
5	32
10	14

Complex test objects

- “non uniform background” phantoms to verify the effectiveness of subtraction algorithms
- Images taken with a W-anode tube, 2 mm filtration, 45 kVp, 7μA
  - Entrance dose ~270 μGy



“single layer phantom”
1 cm thick



“multi-layer phantom”
4 cm thick

Initial K-edge studies

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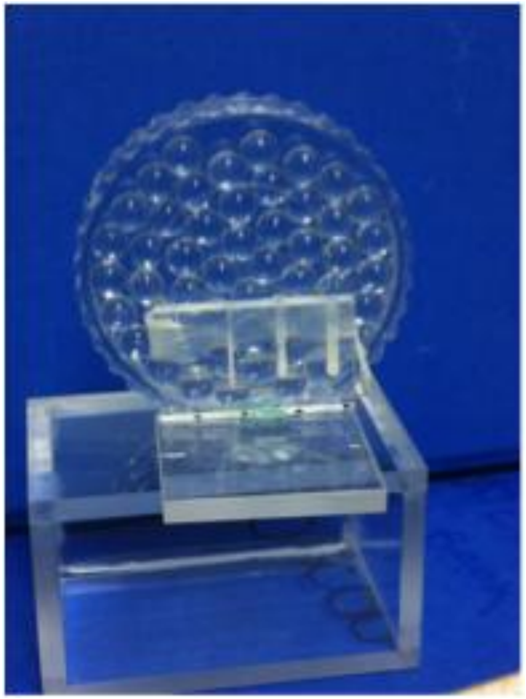

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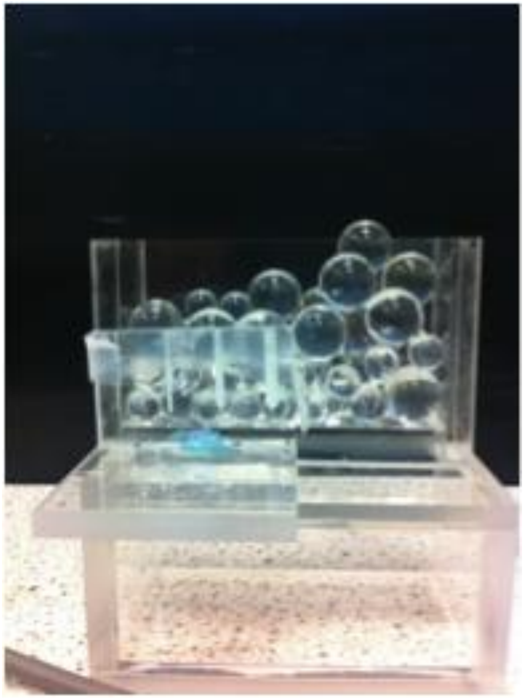


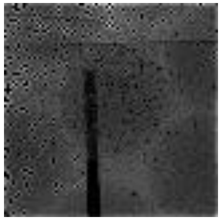
“multi-layer phantom”
4 cm thick

Results – logarithmic subtraction

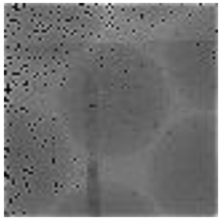
“one layer” phantom

“multilayer” phantom

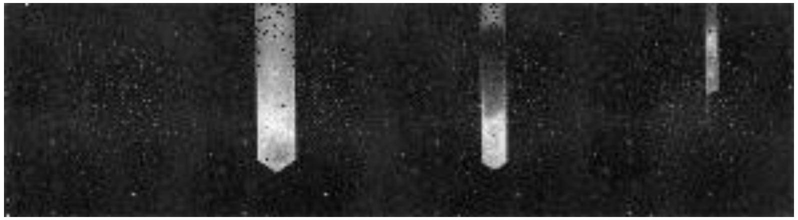
Above K-edge



Below K-edge



Subtracted

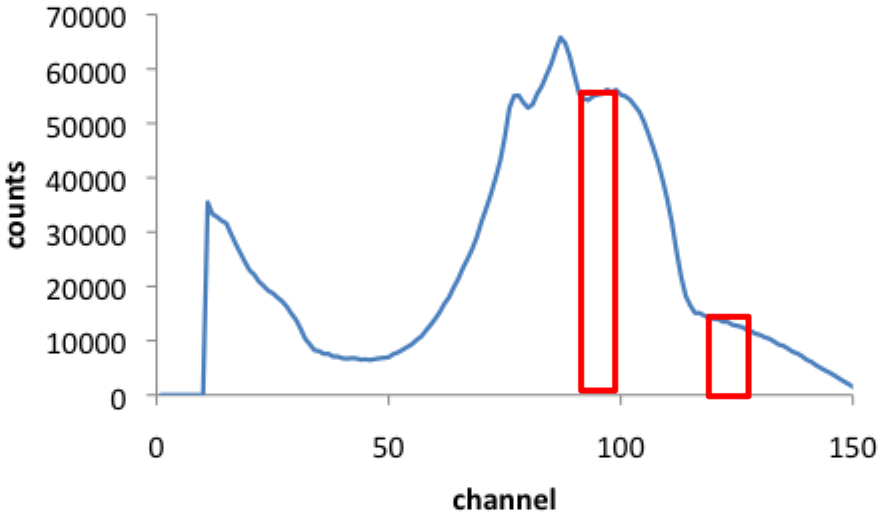


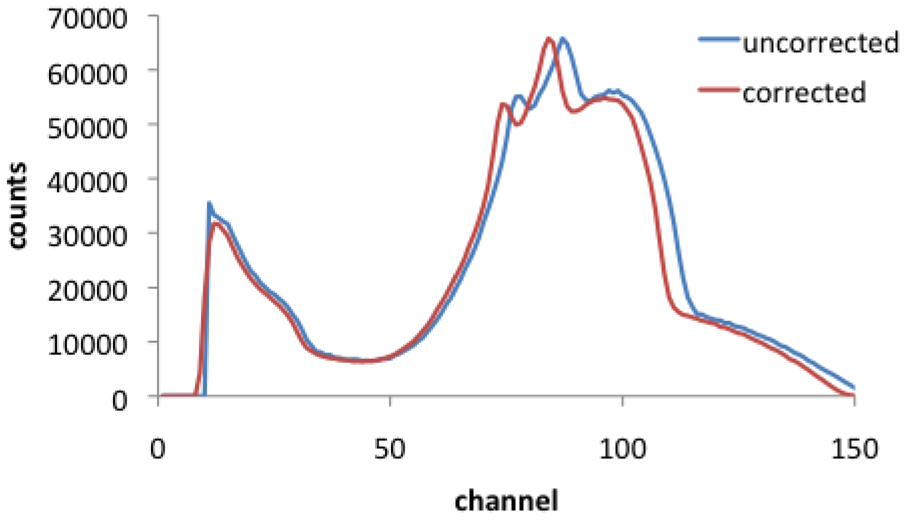
Limited background removal:
Outside linear regime

Increasing contrast and improving background subtraction

- When different pixel gain is not taken into account, conservative integration ranges need to be chosen

- The problem is removed by interpolating the spectra for all calibrated pixels so that peaks/K-edges coincide

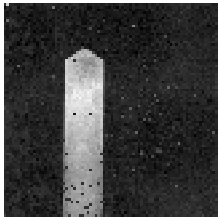




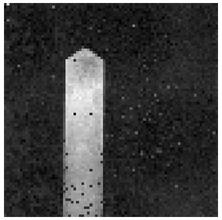
Results – optimised calibration

- The procedure allows the choice of integration bands closer to the physical K-edge of contrast agent
  - Higher intrinsic contrast
  - Lower noise due to improved background removal

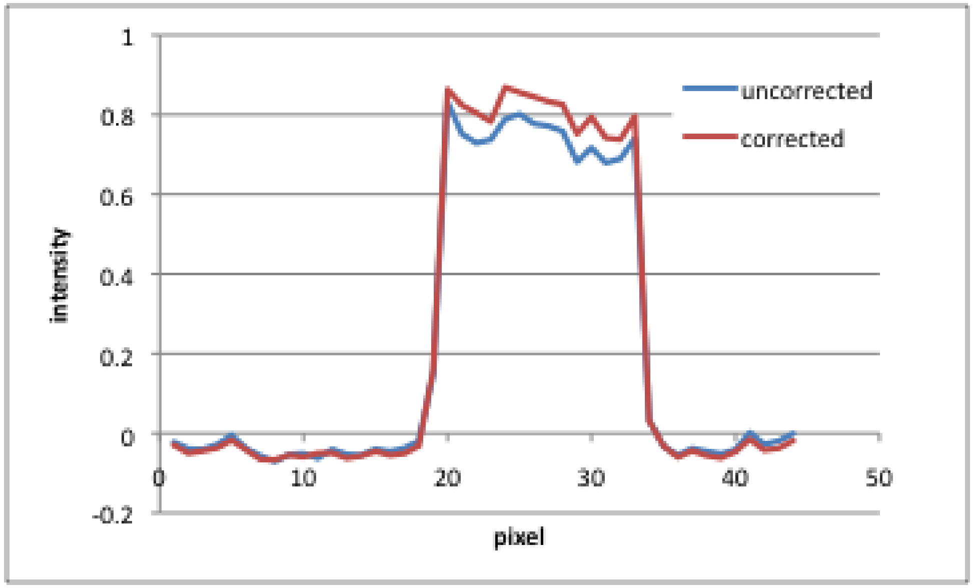
non corrected



corrected



Width (keV)	**CNR – uncorr**	**CNR – corr**
1.2	31	54
2	26	41
3	31	36



“Dual energy algorithm” (Lehmann 1981)

- Any image pixel is seen as a vector
- The vector is projected onto a basis {iodine component, water component} and the two projections are retrieved separately, giving rise to a “iodine equivalent” image and a “water equivalent” image

$$\begin{cases} \ln(I_0/I)_{low} = \left(\frac{\mu}{\rho}\right)^{I}_{low} (\rho x)_I + \left(\frac{\mu}{\rho}\right)^{water}_{low} (\rho x)_{water} \\ \ln(I_0/I)_{high} = \left(\frac{\mu}{\rho}\right)^{I}_{high} (\rho x)_I + \left(\frac{\mu}{\rho}\right)^{water}_{high} (\rho x)_{water} \end{cases}$$

- Allows quantitative information (μx)
- No pre-assumptions on the position and width of integration bands
  - Proved much more effective than log-subtraction on conventional KES

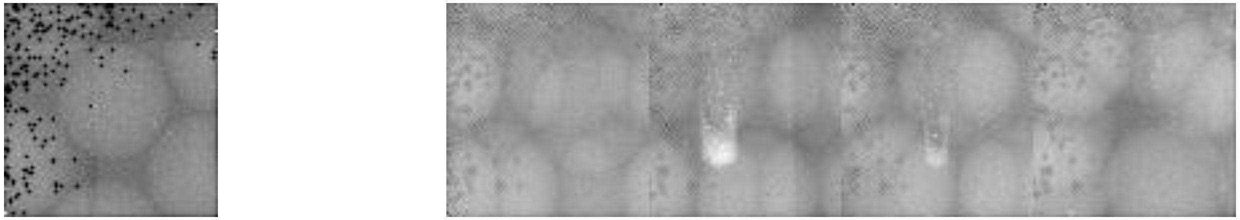
Results – Dual energy algorithm (2 keV)

- Background removal is improved!
- Increased CNR (more uniform background)

Log subtracted

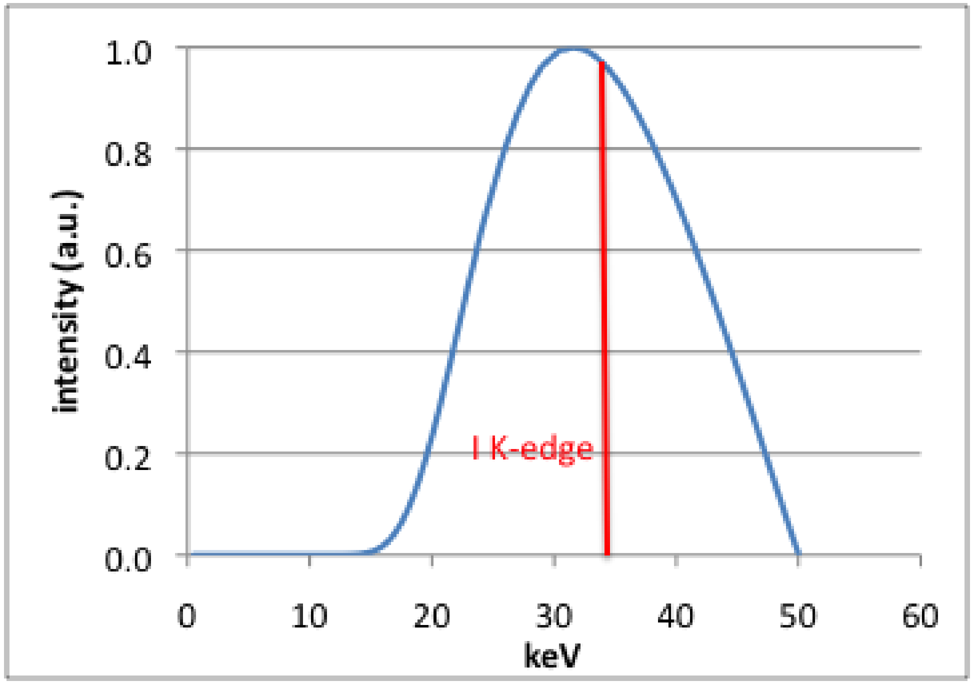
Iodine projection

Water projection

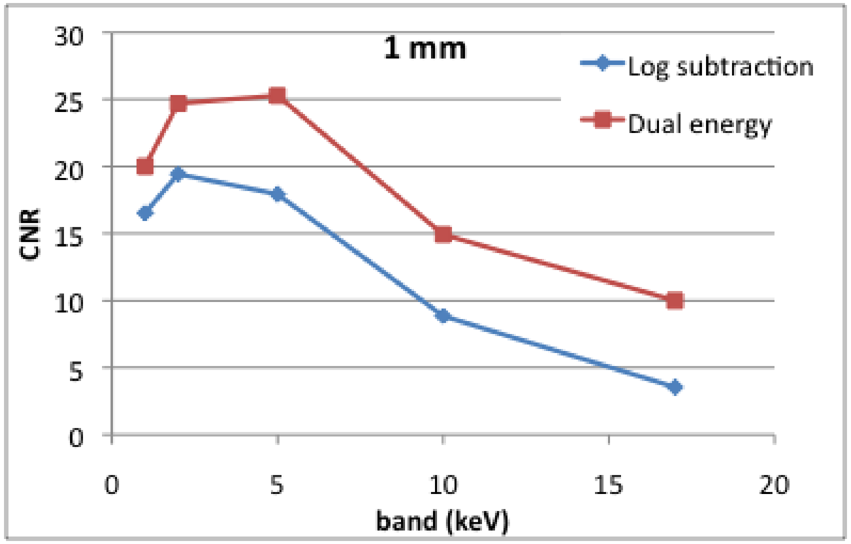


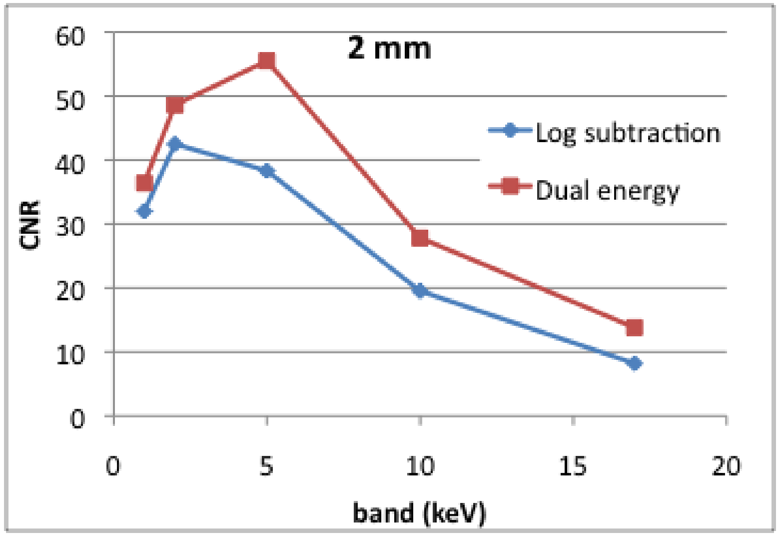
Dual energy optimisation

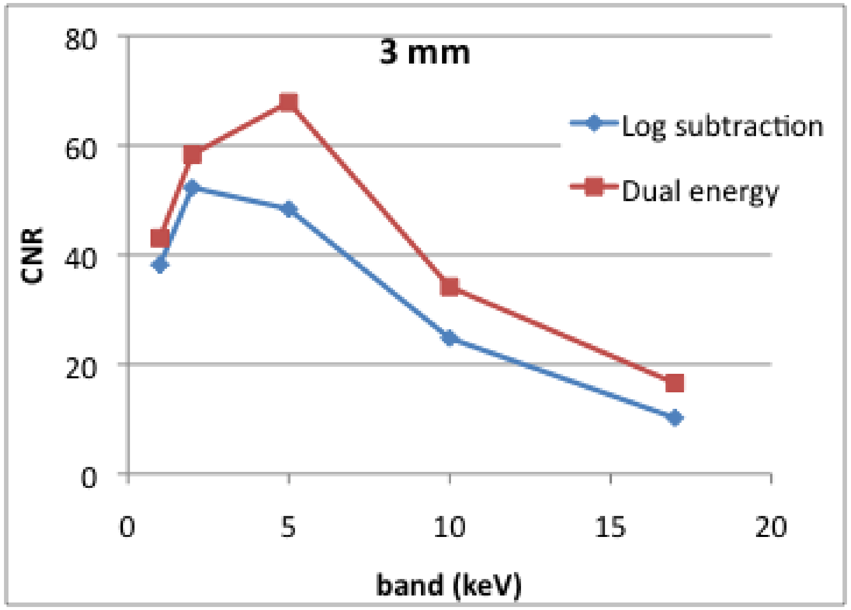
- "Breast equivalent" test object (Perspex spheres + oil)
- 50 kVp, 3 mm Al (mean energy 33 keV)
- 2 µA, 9 min acquisitions → entrance air dose 75 µGy



Dual energy optimisation - II

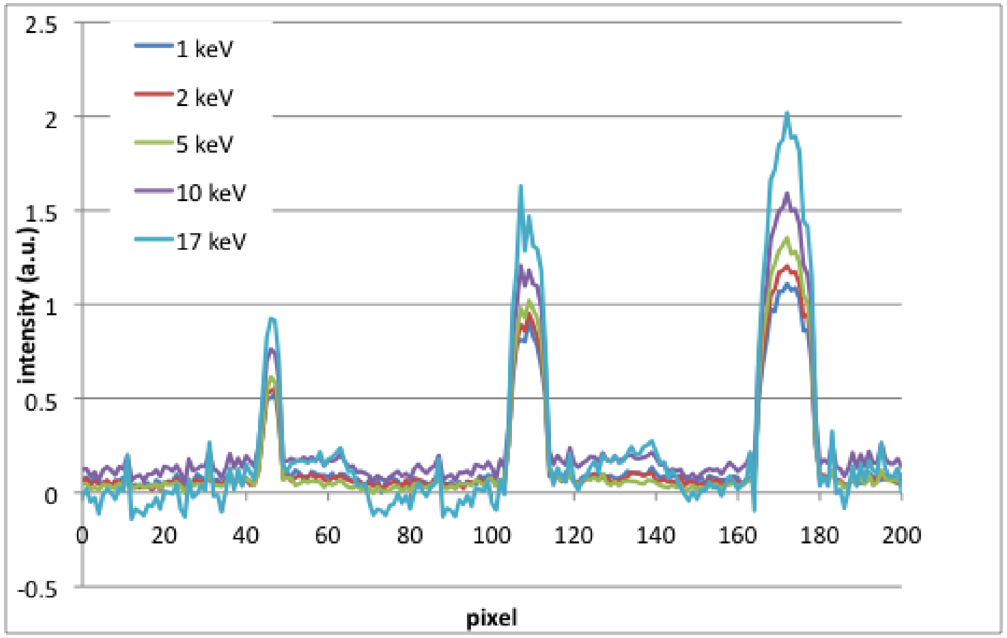




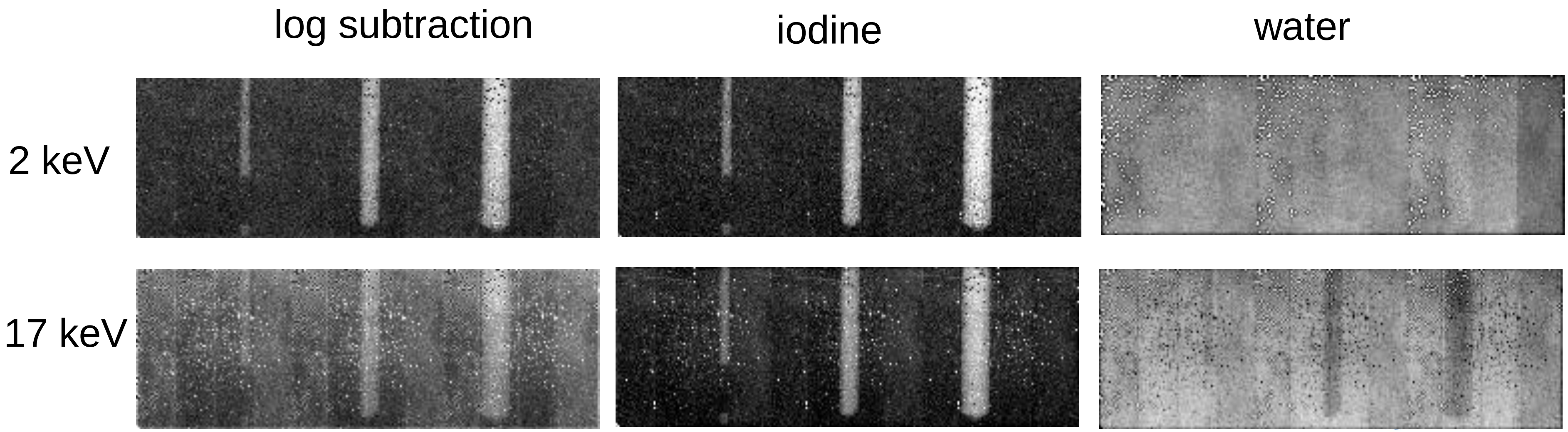


- CNR reaches a maximum at wider band than with log subtraction
  - Better background removal →lower structural noise

Iodine vs water

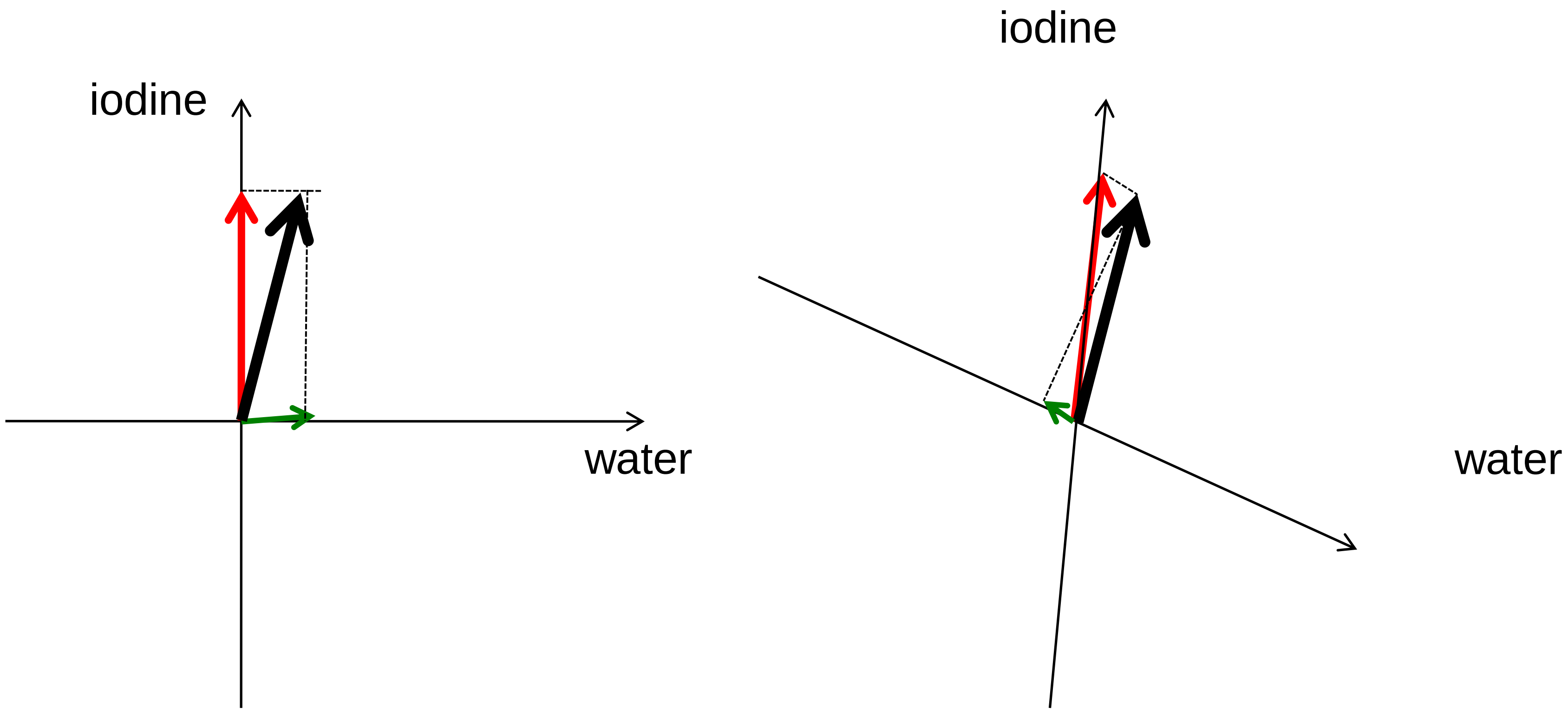


- Unlike with the log-subtraction algorithm, contrast increases when increasing the bandwidth (but structural noise increases, too)



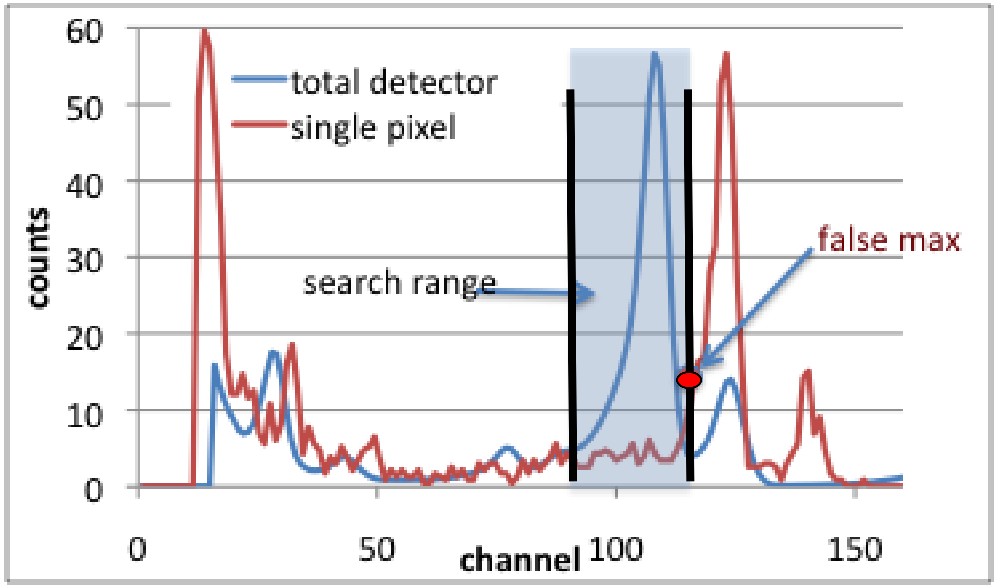
What is going on?

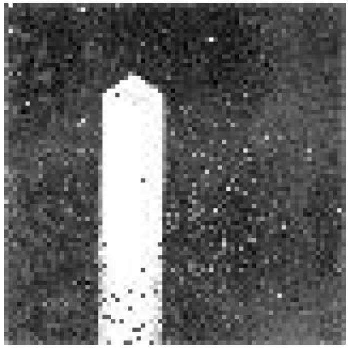
- The two base vectors are no longer orthogonal
- A more accurate treatment will involve changing the system of linear equations for dual energy into a system of integrals



Open problems - calibration

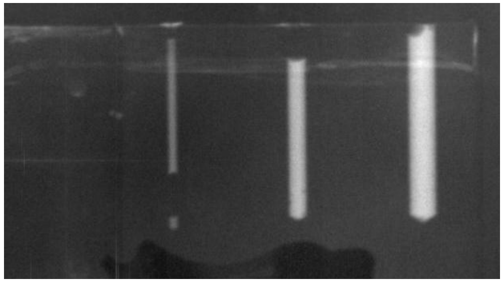
- The energy calibration of an 80x80 array must be done automatically
- Typically, the user selects a range for peak search using the spectrum averaged on all pixels
- This may cause a problem with pixels with gain significantly off-average → speckles





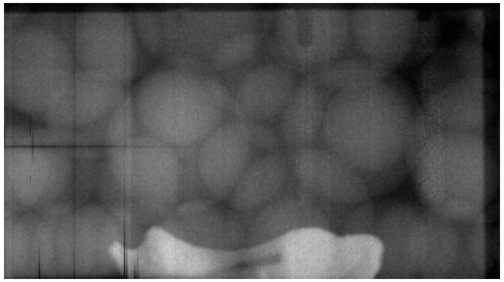
Comparison with conventional imaging

- Pairs of spectra were chosen with average energies below and above the K-edge of iodine, respectively
- CNR was calculated to identify the optimum pair of spectra
  - Low: W anode, 45 kVp, 250 µm Tin filter
  - High: W anode, 50 kVp, 12.5 mm Al filter



iodine

Tube Ø (mm)	CNR – HEXITEC	CNR – conventional
1	25	15
2	55	40
3	68	62



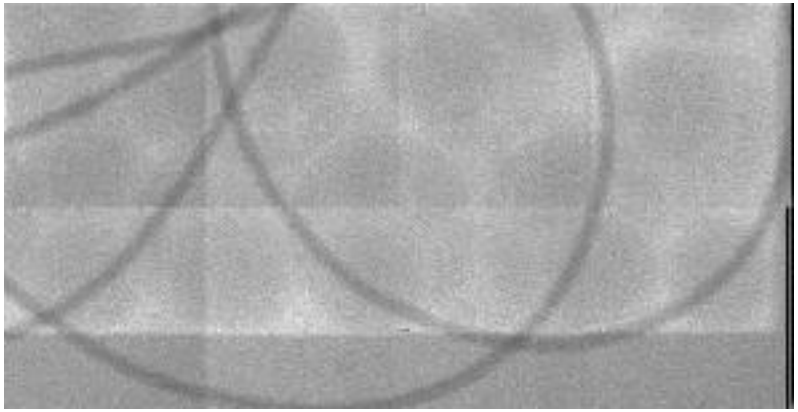
water

Entrance dose
Conventional 1.2 mGy
HEXITEC 75 µGy

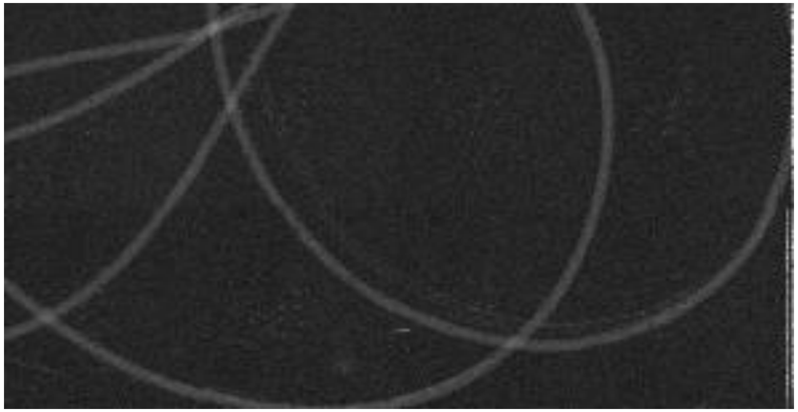
A large test object

- Mean glandular dose 0.5 mGy (in conventional mammography 1.5 mGy/image)

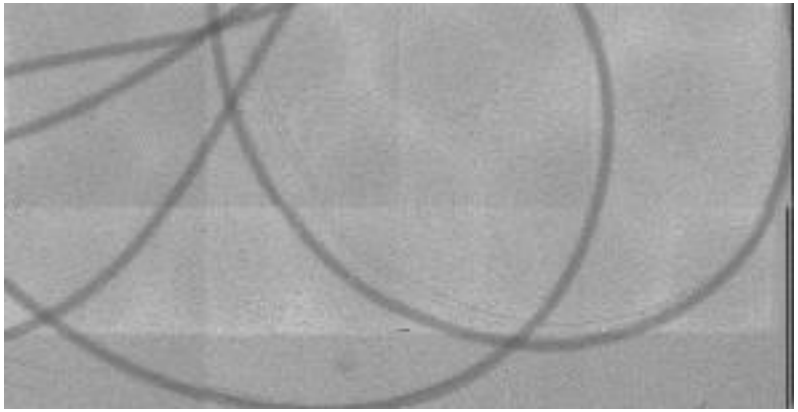
LOW



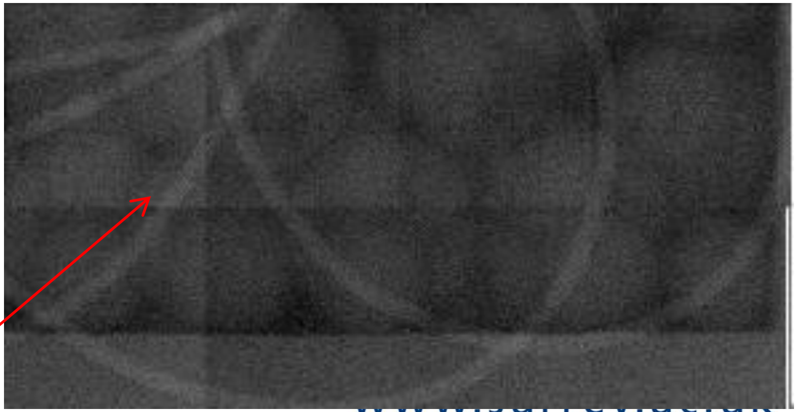
IODINE



HIGH

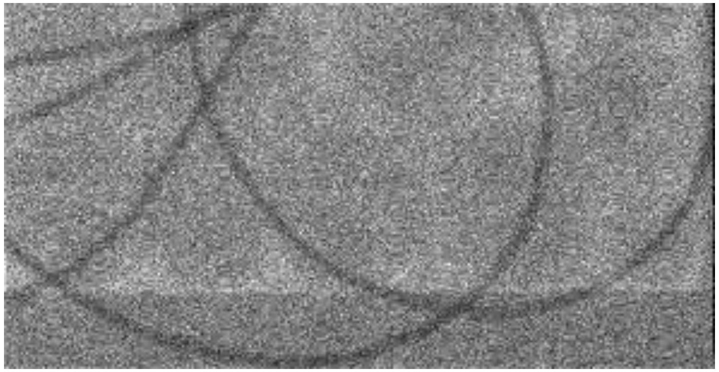


WATER

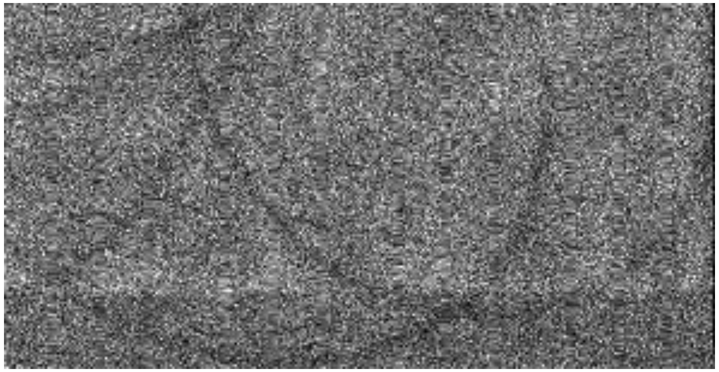


Tube + water component of solution

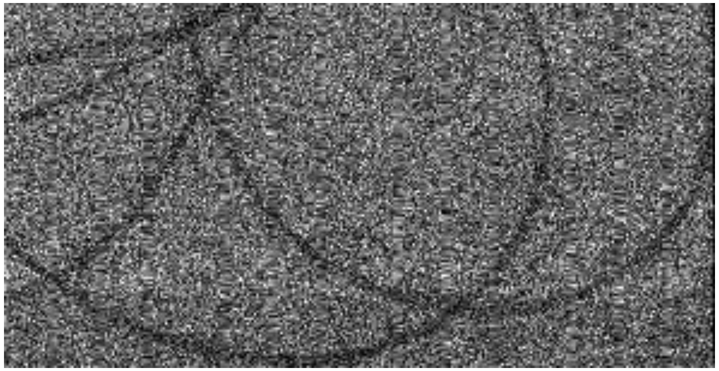
Very low dose – MGD 1.5 μGy



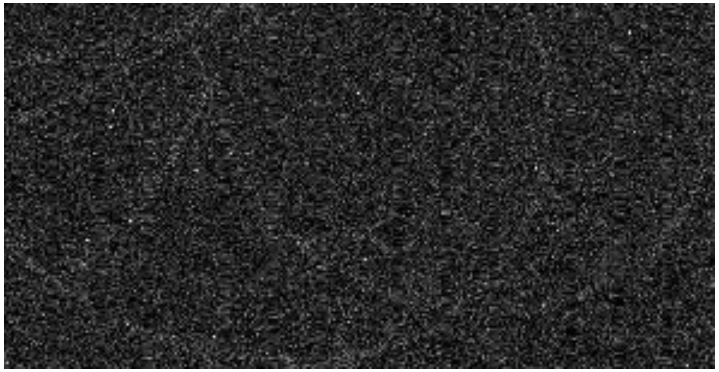
Full spectrum



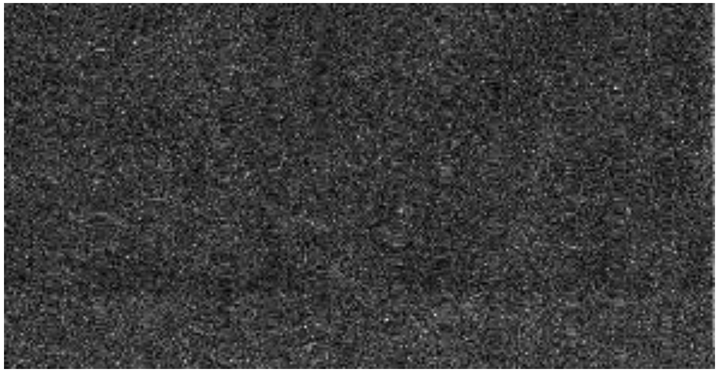
low



high



iodine



water

Conclusions

- A pixellated spectroscopic CdTe detector has proven effective in one-shot K-edge subtraction imaging around the Iodine K-edge
  - Dose 15 times lower than conventional imaging with comparable image quality
  - The optimum energy band to be integrated results from a trade-off between signal and noise (statistical and structural)
- Open problems:
  - Limited linearity (to be addressed with a systematic study on pulse shaping parameters)
  - Pixel gain spread
- Future work
  - Improving spatial resolution (sub-pixel) with charge-sharing algorithms
  - Design of a “dynamic” test object for uptake-washout measurements
  - New contrast agents

    Gold nanoparticles?

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