# Metal streaking artifacts and dual-energy CT material extraction

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# Acknowledgements


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# Lecture outline

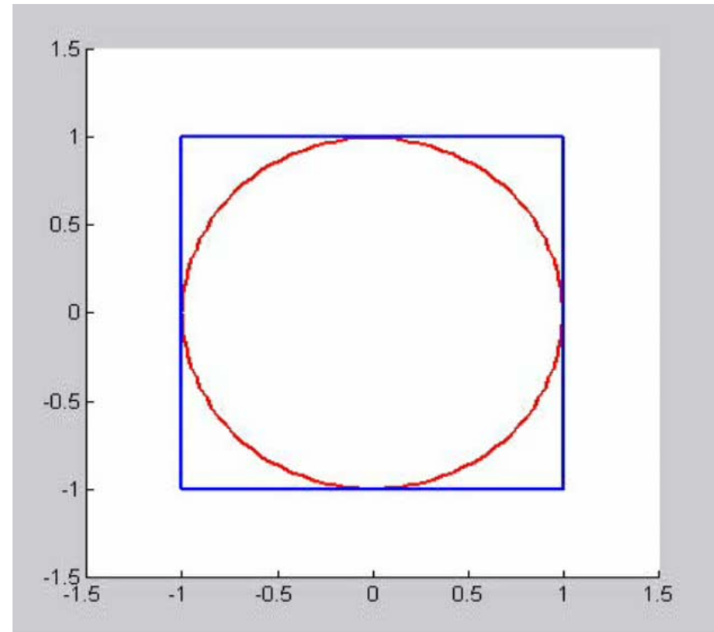
1. Monte Carlo method for radiation physics
2. Overview of CT principles
3. Metal streaking artifacts
   a) corrections
   b) causes
4. Dual-energy CT-based material extraction (DECT)
5. Metal streaking artifacts and DECT

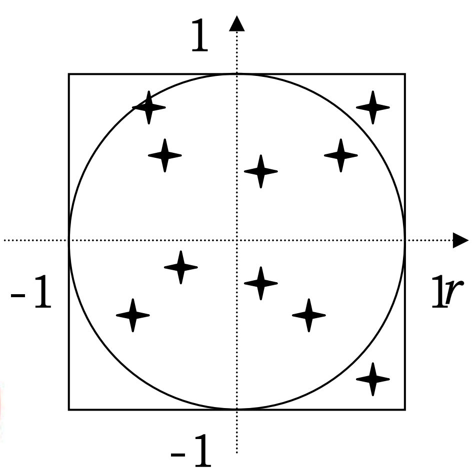
# 1. Monte Carlo method

- any method which solves a problem by generating suitable random numbers and observing that fraction of the numbers obeying some property or properties
- useful for obtaining numerical solutions to problems which are too complicated to solve analytically

# Example of a MC method

- evaluation of $\pi$
- $S_{\bigcirc} = \pi r^2$;
- $S_{\square} = (2r)^2$;
- $S_{\bigcirc} = \pi$; $S_{\square} = 4$;
- N random samples of x and y; $x,y \in (-1;1)$

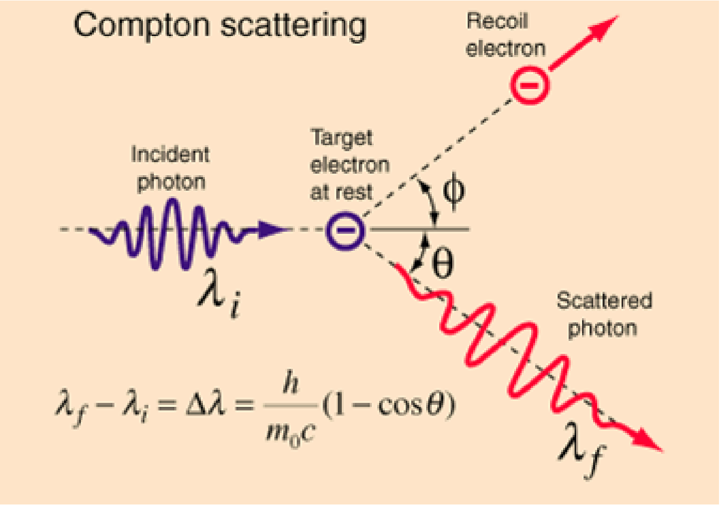


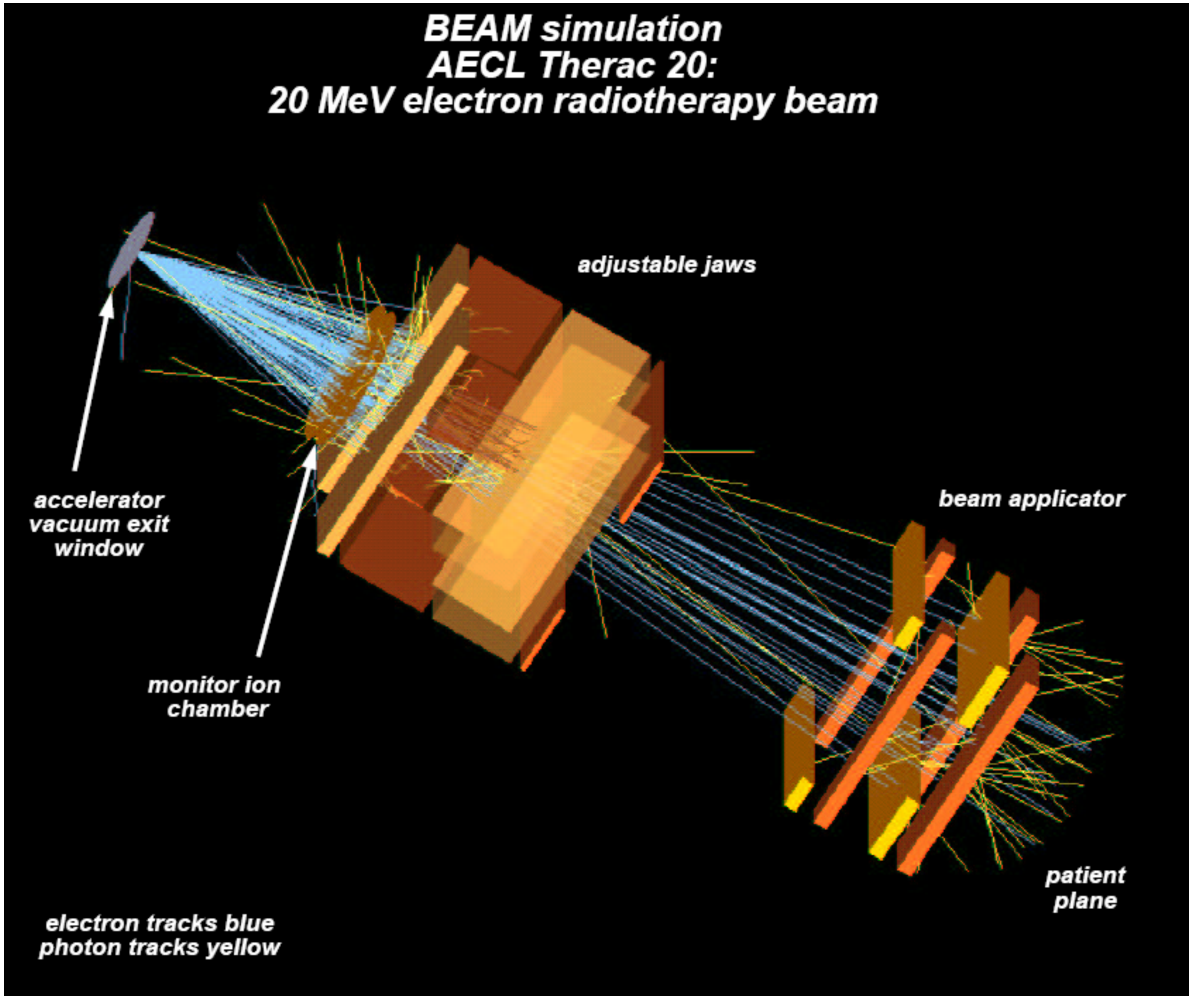

- number of samples in the circle: p
- $S_{\square} / S_{\bigcirc} = 4/\pi = N/p \Rightarrow \pi = 4*p/N$
- example: $\pi \approx 4*8/10 = 3.2$
- for $N \to \infty$ exact value of $\pi$

# Monte Carlo for particle transport

- photons and electrons are 'born' and their 'lives' are followed until they 'die'
- particle transport is pseudo-random
- certain laws for particle interactions apply – probability distributions are followed
- e.g.: Compton effect
- $\theta$ and $\lambda_f$ are related
- => sample $\theta$ from a prob. distribution, calculate $\lambda_f$



# Monte Carlo in radiotherapy and radiology (beam definition)



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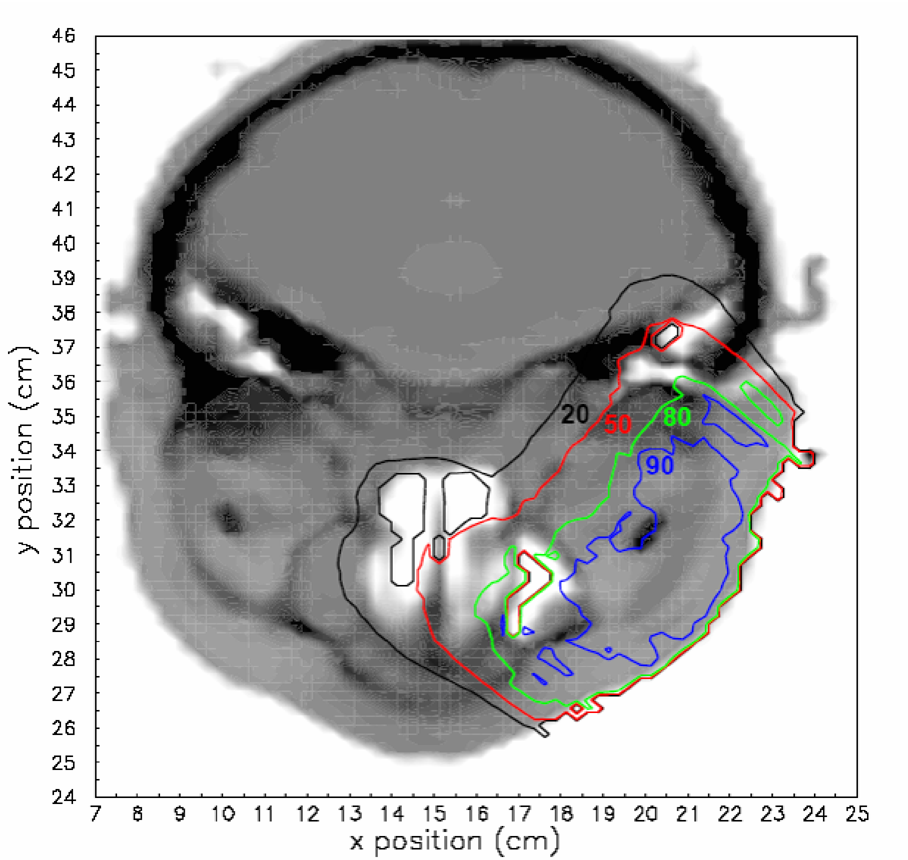
# Monte Carlo in radiotherapy and radiology (dose calculations)




- MC is potentially the most accurate method for assessment of dose delivered to patients during CT scanning (and radiotherapy)

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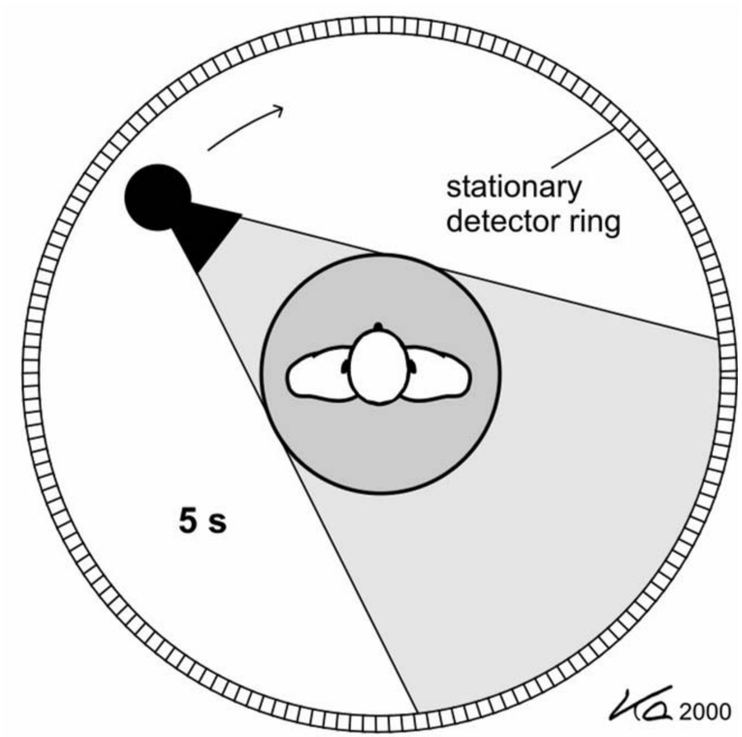
PROBLEMS of MC

- long computation time
- beam definition
- anatomy of patients

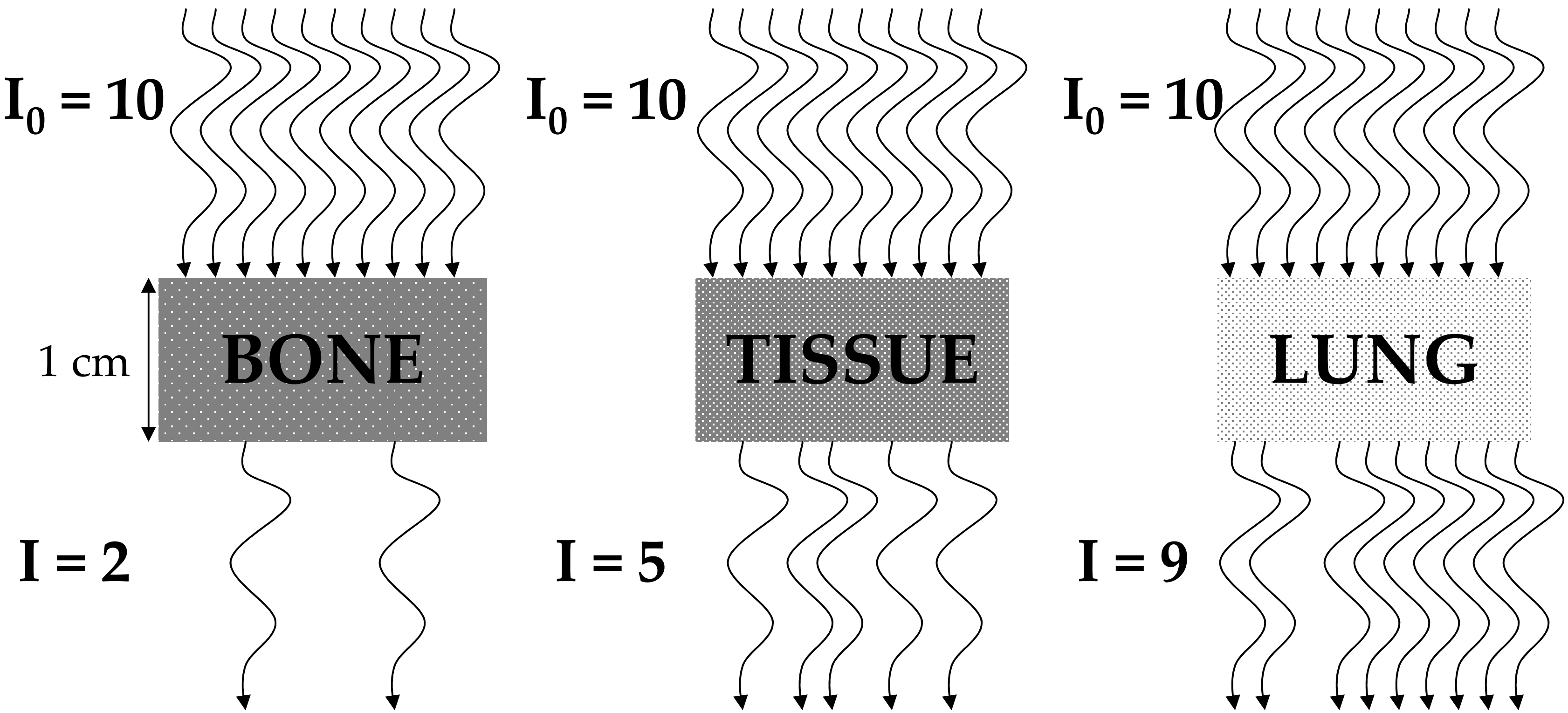
# 2. Computed Tomography (CT)




- x-ray tube rotates around the patient
- attenuation of the photon beam measured by a detector ring
- axial CT images reconstructed from a set of attenuation measurements

# Philips CT simulator

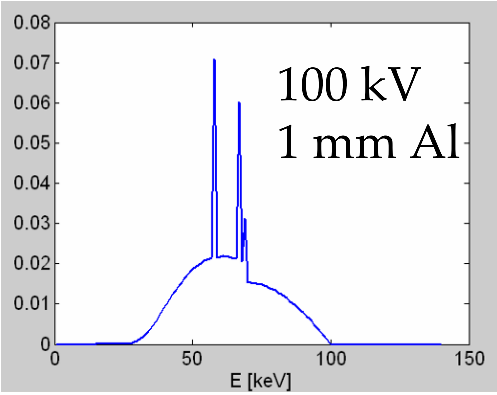
# Linear attenuation coefficient (μ)

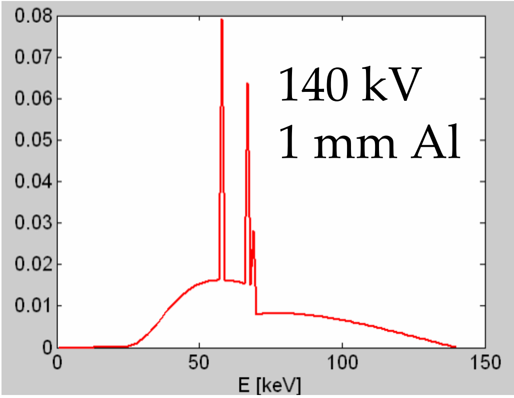


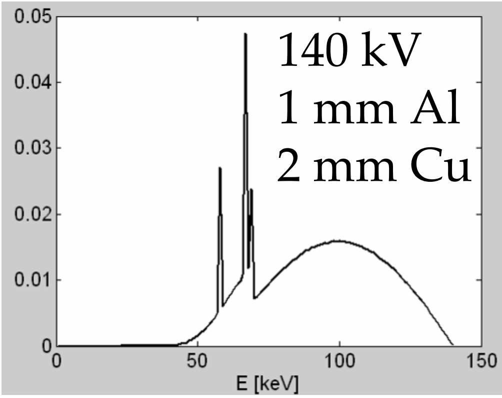

$\mu = 1.6\ cm^{-1}$ $\mu = 0.7\ cm^{-1}$ $\mu = 0.1\ cm^{-1}$

# CT x-ray beam

- is (unfortunately!) not monoenergetic
- x-ray tube emits a spectrum of photons that influences image quality and that can be modified by:
  - kV settings of the tube
  - added filtration

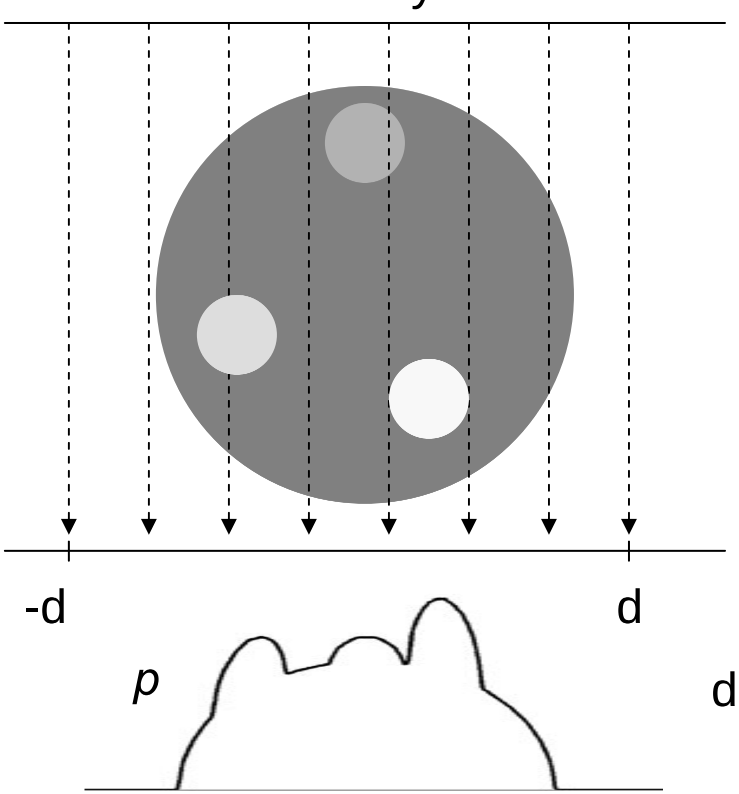


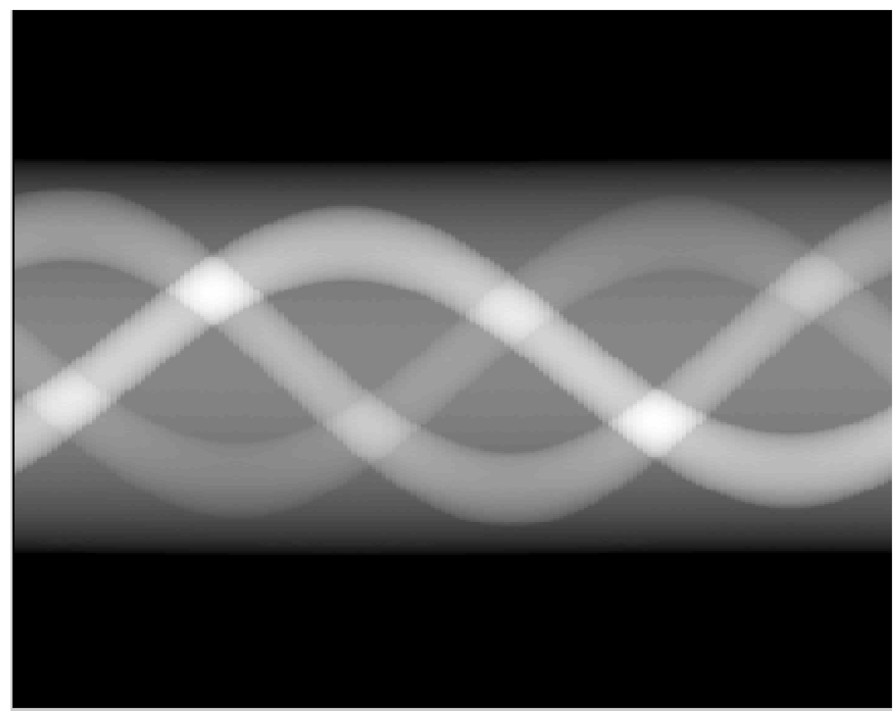



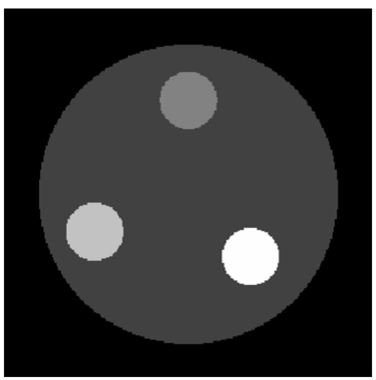
# 2D-projection data set - sinogram

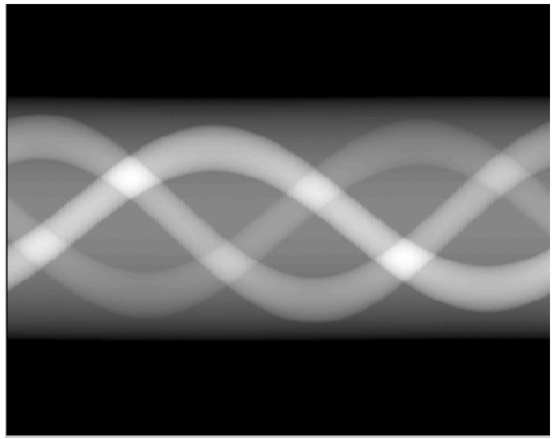
- projections $p = -\ln\left(\frac{I}{I_0}\right)$
- $I$, $I_0$ - intensities



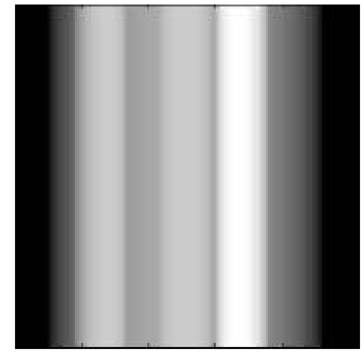



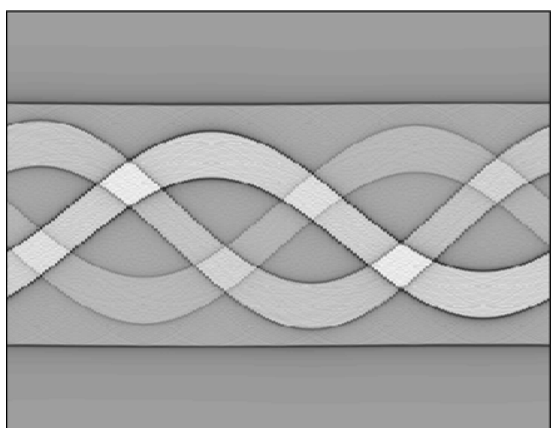
# Image reconstruction



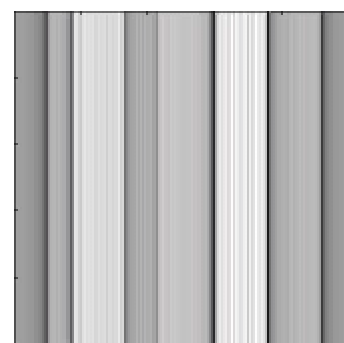


Simple back-projection





Filtered back-projection



**Filtered back-projection FBP**

# CT image

- displays CT numbers (or Hounsfield Units, HU)
- HU = $1000 \times (\mu/\mu_w - 1)$
- $\mu$ and $\mu_w$ are the linear attenuation coefficients of a material and water, respectively
- intensity of a beam at depth $x$ : $I = I_0 e^{-\mu x}$

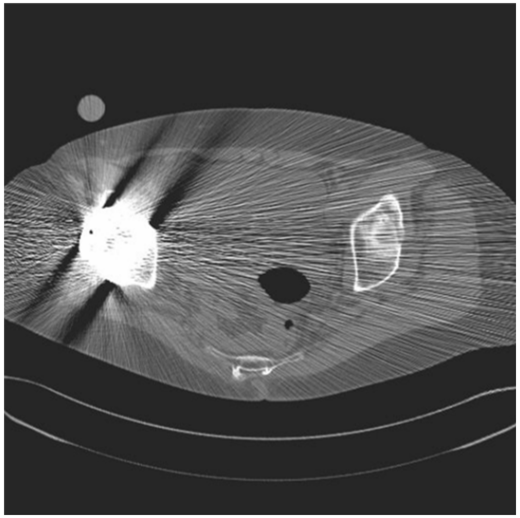
# 3. CT artifacts
# (“if a problem appears…”)

…image artifacts can be produced – they can cause misdiagnosis and errors in dose calculation

- physics based - result from the physical processes involved in the acquisition of CT data
- patient based - which are caused by factors such as patient motion or the presence of metallic materials in or on the patient
- scanner based - which result from imperfections in scanner function

# Metal streaking artifacts

- appear when a high Z, high density material (such as metal) is present in the patient body
- common for head and neck patients (dental work), occasionally for prostate patients (hip prostheses)
- severely degrade image quality

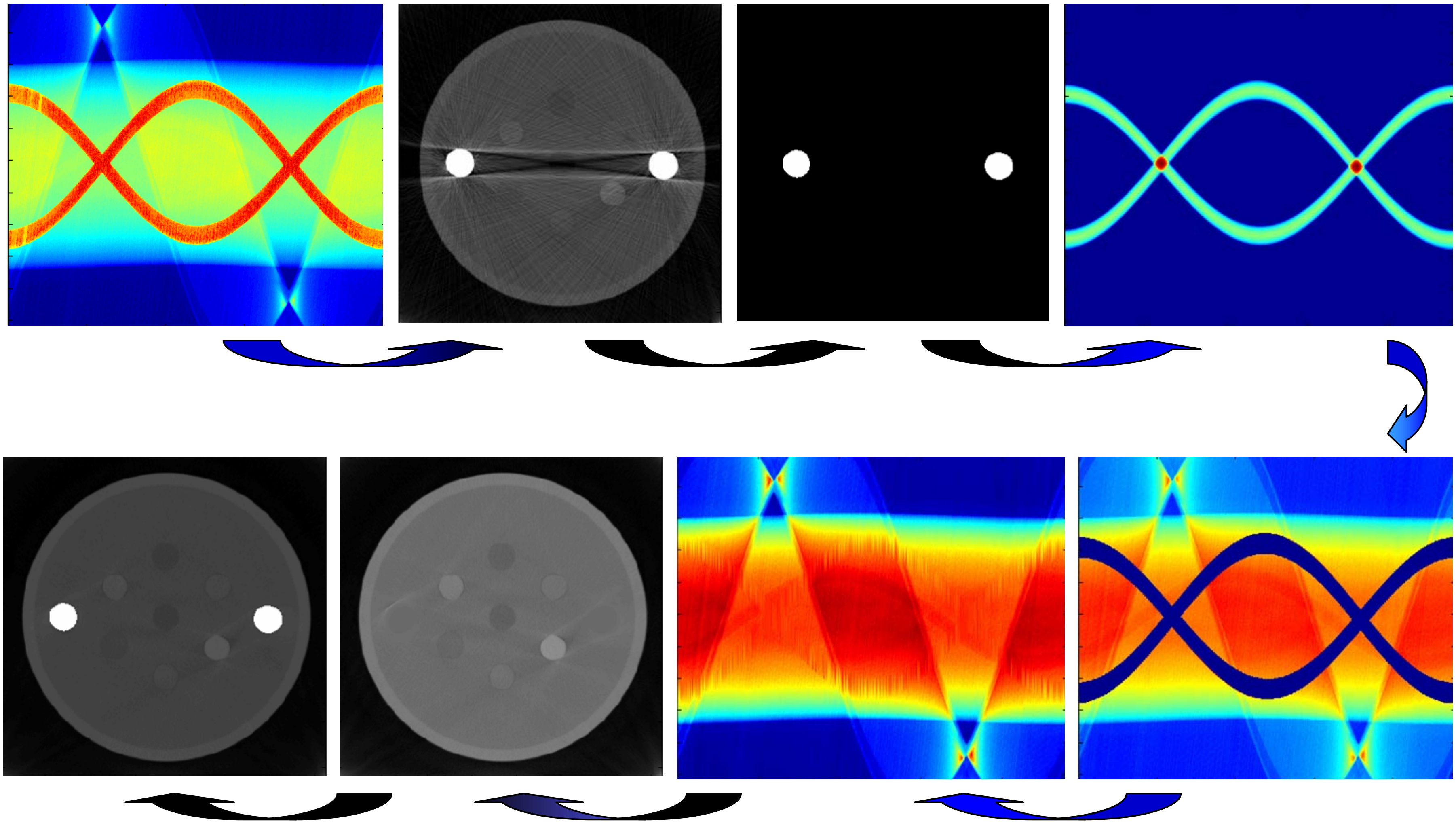


# 3a. Metal artifact correction

- reduction of metal artifacts is possible
- three main approaches exist - FBP on modified raw data (sinograms), iterative methods and filtering
- our work was done on the basis of FBP on modified raw data
- first done by Willi Kalender,

  a number modifications exist

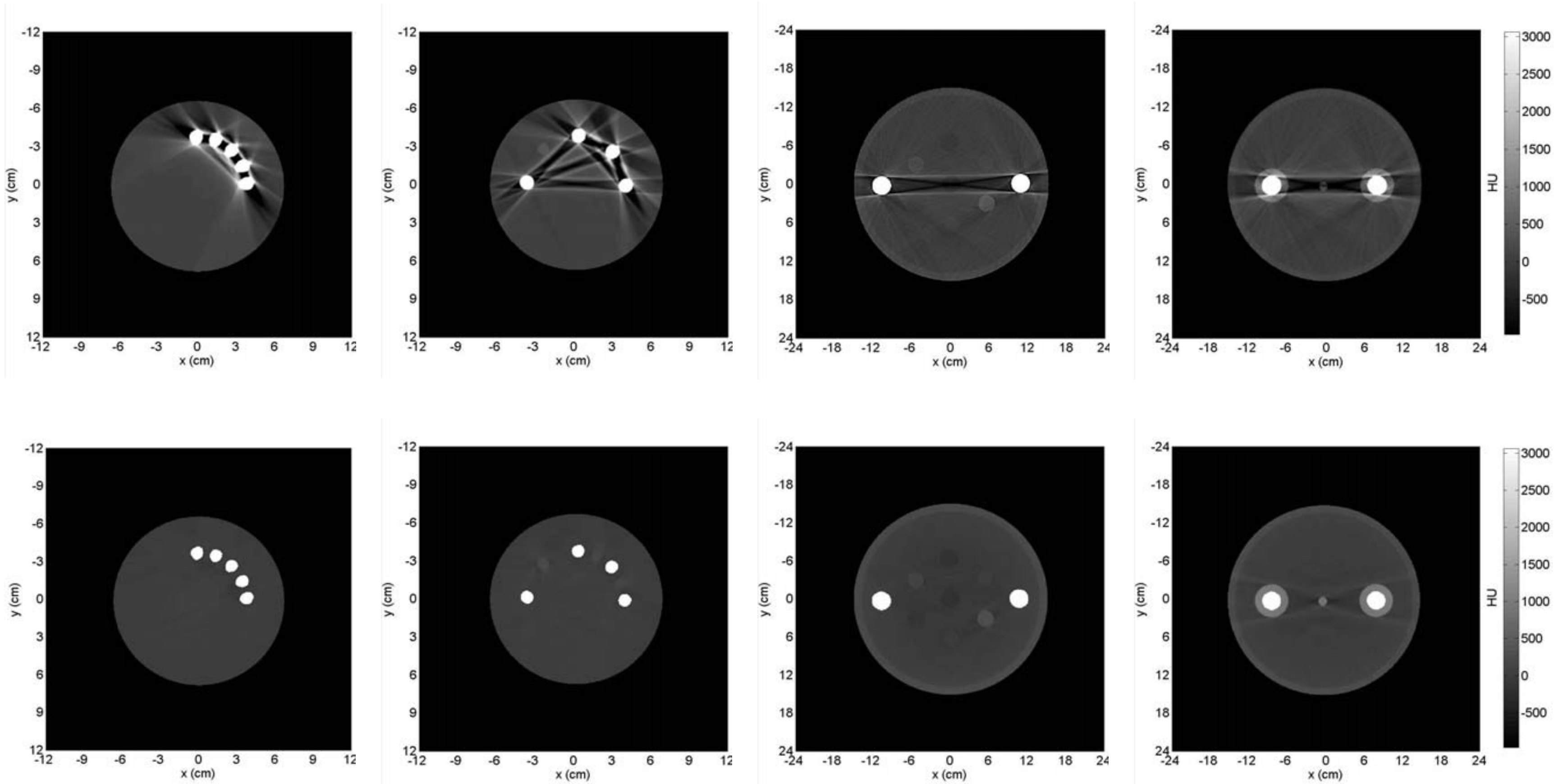
# Correction algorithm



# Correction results

original CT images

corrected images

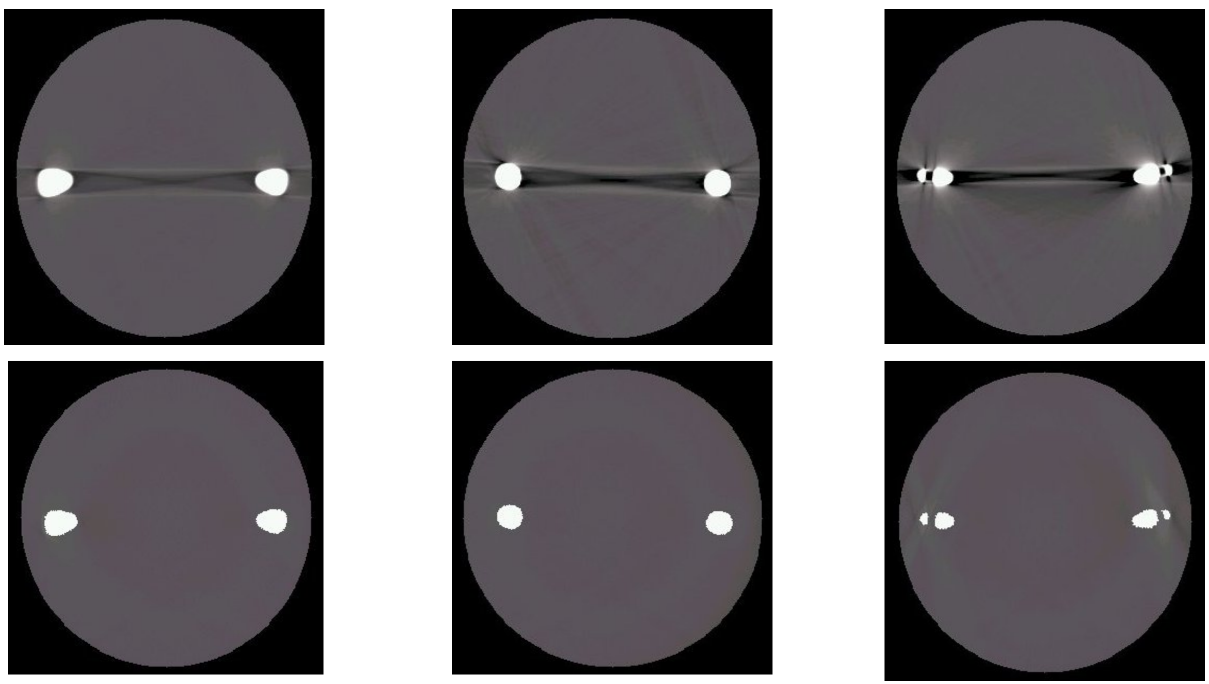



head phantoms

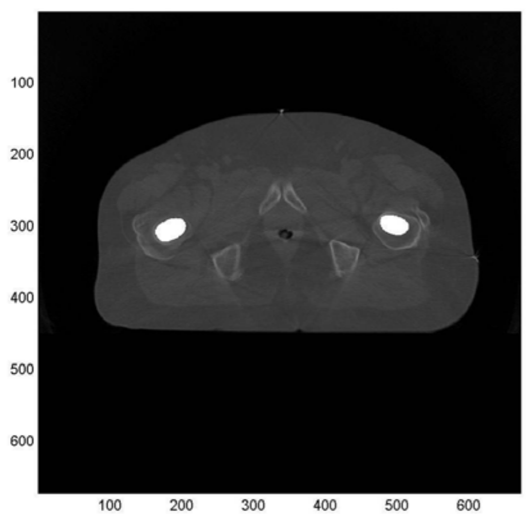
pelvic phantoms

# Different prosthesis materials

| Ti-alloy | Stainless steel | Co-Cr-Mo alloy |
| --- | --- | --- |
| $\rho=4.48\ gcm^{-3}$ | $\rho=6.45\ gcm^{-3}$ | $\rho=8.20\ gcm^{-3}$ |

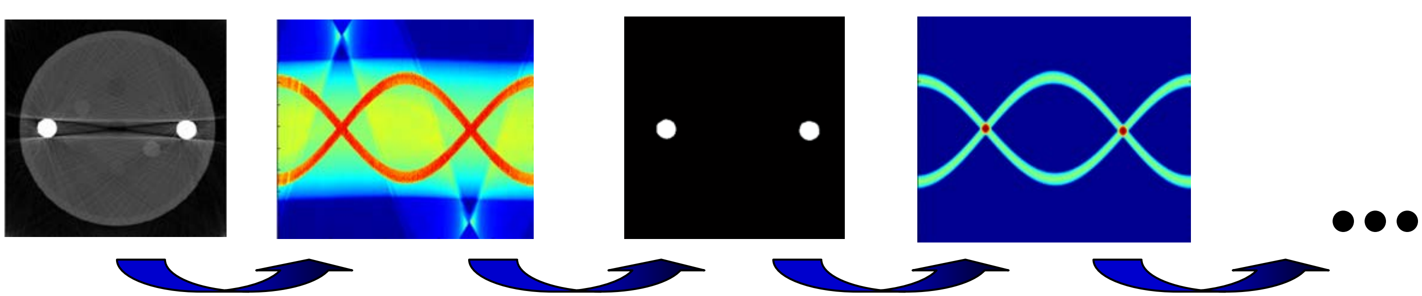


# Artifact reduction for a patient with hip prostheses

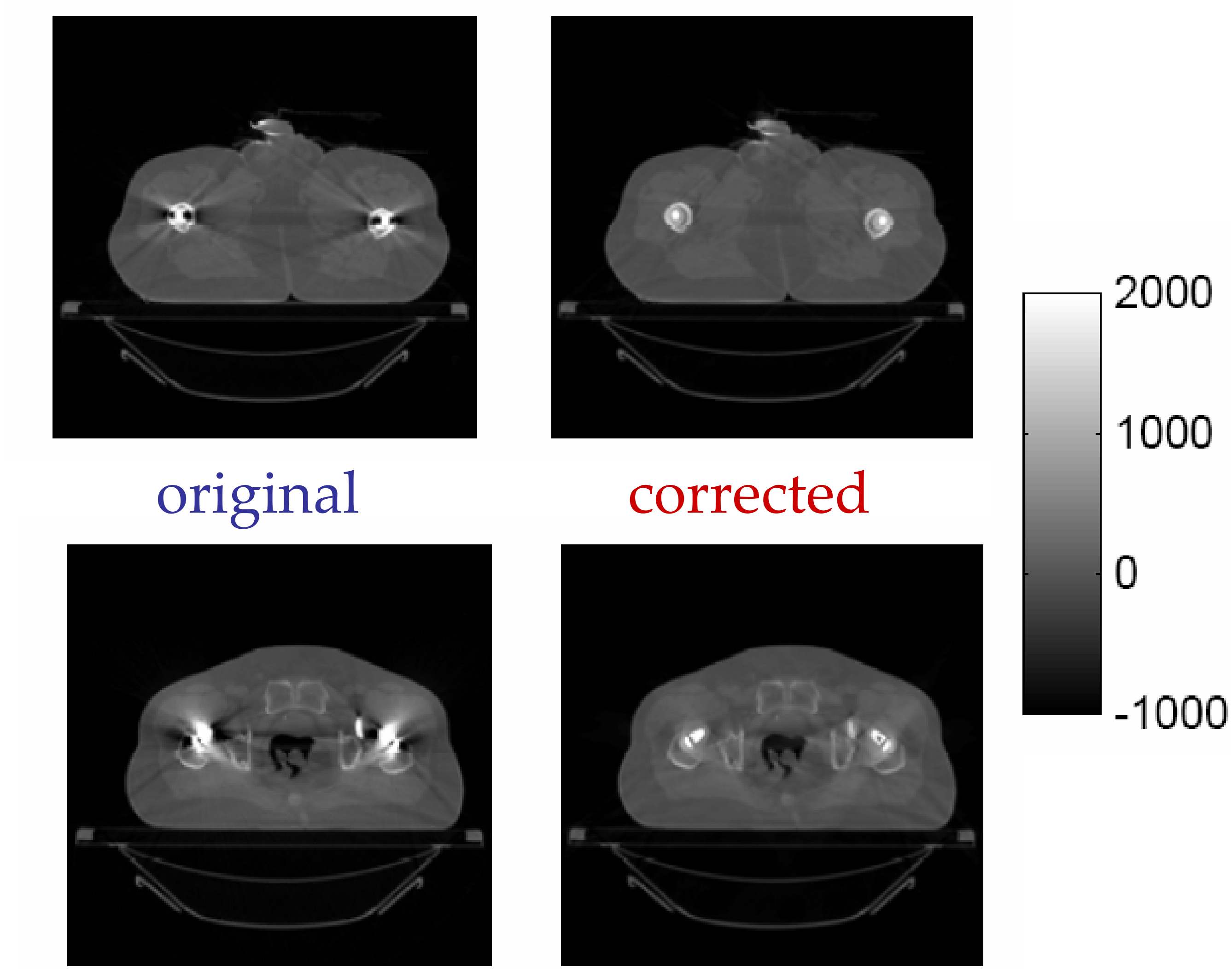



# If sinograms are not available

- artifact correction might start from original CT images
- sinograms are created from these images containing artifacts
- not ideal – such sinograms are already 'artifact corrupted'



# Artifact corrections based on original CT images



# CT artifact correction: conclusions

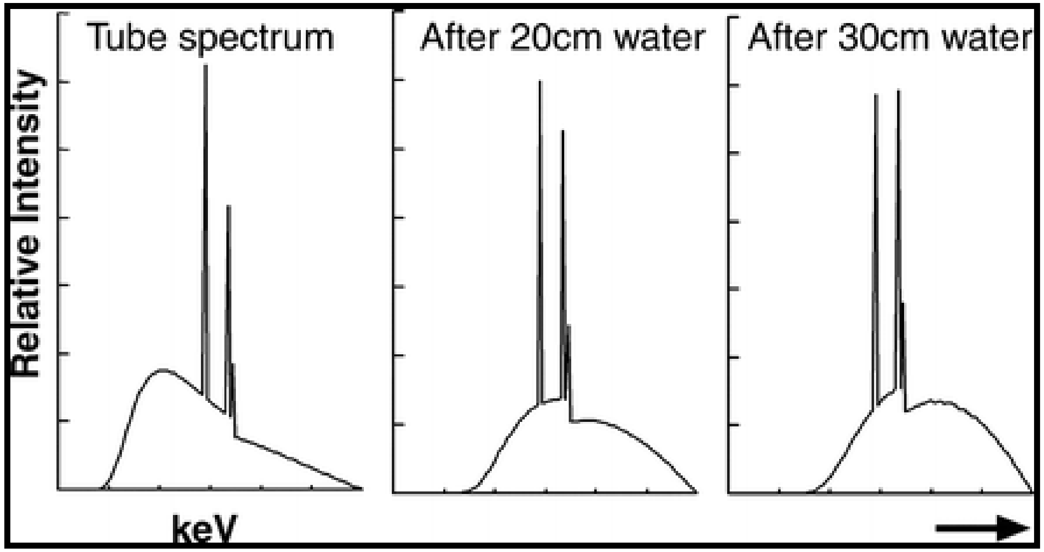
- sinogram interpolation correction algorithm for metal streaking artifacts caused by hip prostheses improves image quality and makes dose calculation more accurate
- metal streaking artifacts are significantly reduced for all three common hip prosthesis materials
- limitations: irregular shapes, new minor streaks created, results worse when sinograms are not available

# 3b. What is the cause of metal streaking artifacts?

- most of physicists believe it is photon starvation
- B. De Man and J. Williamson proved by mathematical simulation that it is the 'detector-model mismatch' including beam hardening, scatter, and noise that is the main cause to metal streaking artifacts
- we studied beam hardening and scatter

# Beam hardening

- low energy photons of a polyenergetic x-ray spectrum are attenuated more than those at higher energies
- mean energy of the spectrum increases as the beam passes through matter – the beam becomes harder and more penetrating




- it is then impossible to assign a single value of linear attenuation coefficient to a voxel

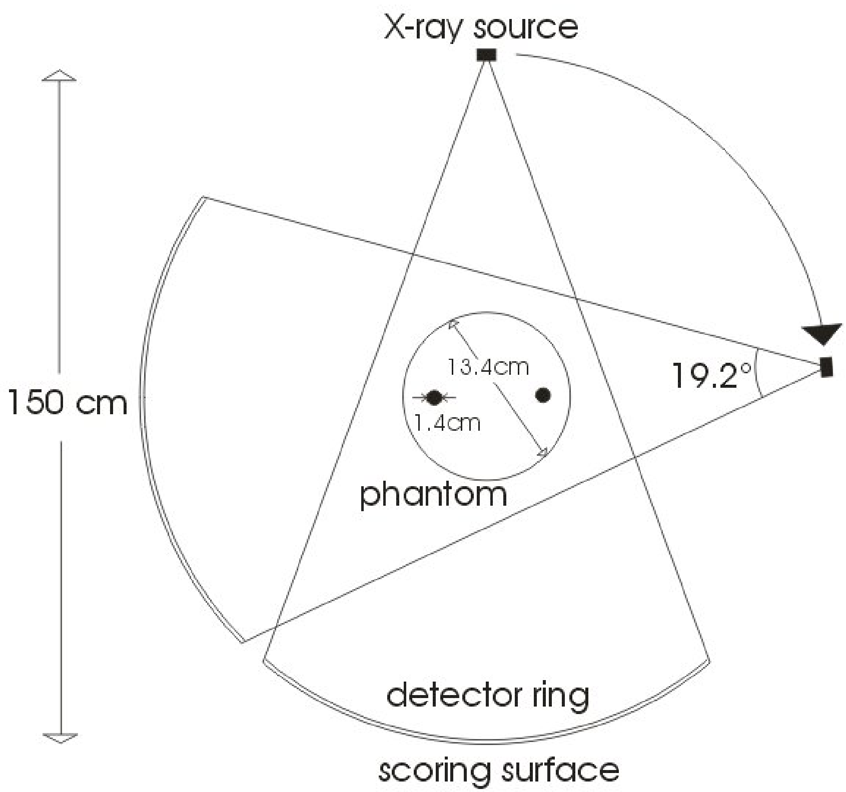
# Filtered back-projection assumes:

- monoenergetic beam
- primary beam (no scatter)
- no noise (detector response)

# Reality:

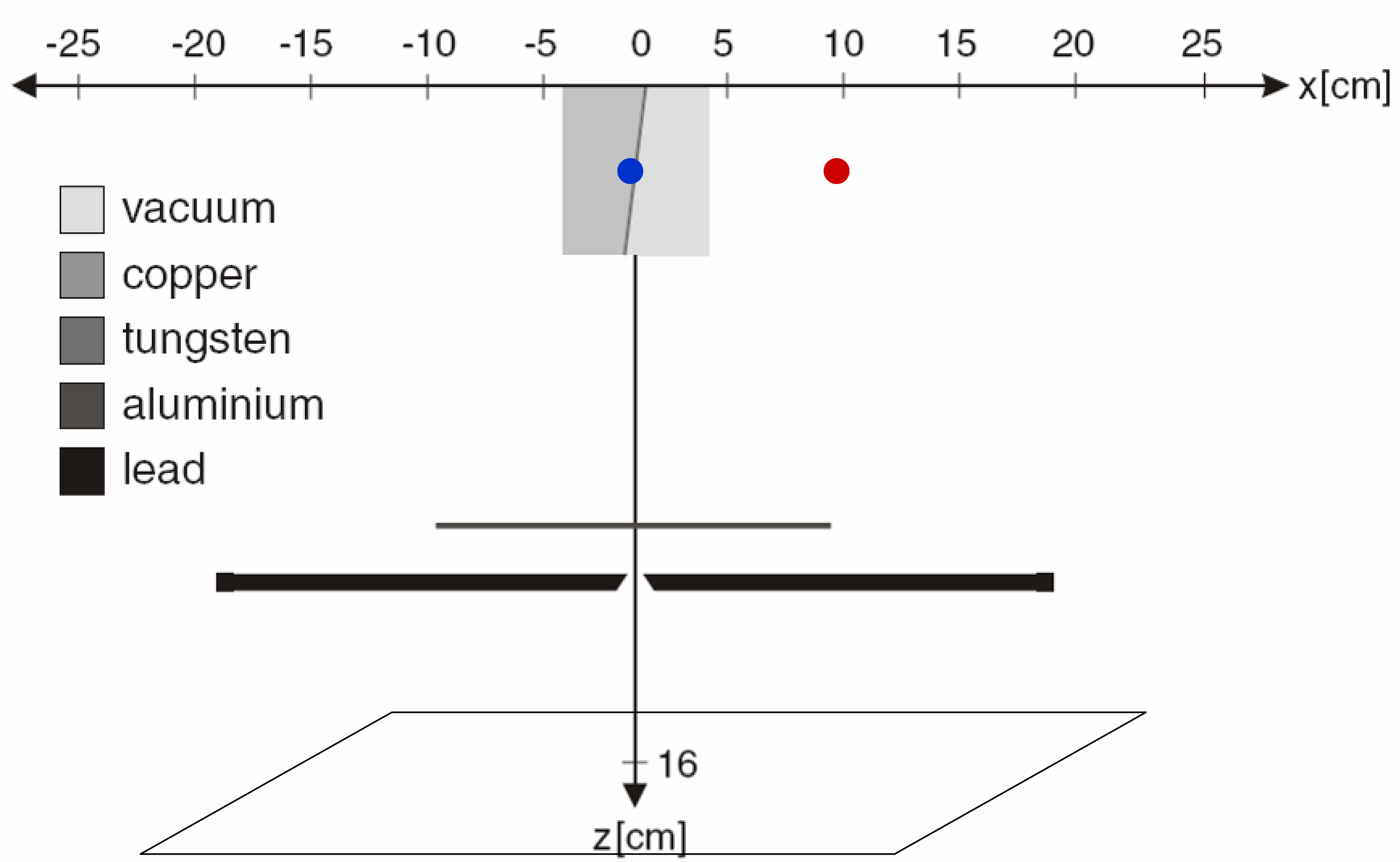
- x-ray tubes emit polyenergetic spectrum
- although anti-scatter grids are sometimes used, scattered photons reach the detector ring
- detectors have a certain level of noise

# Monte Carlo model for a CT scanner

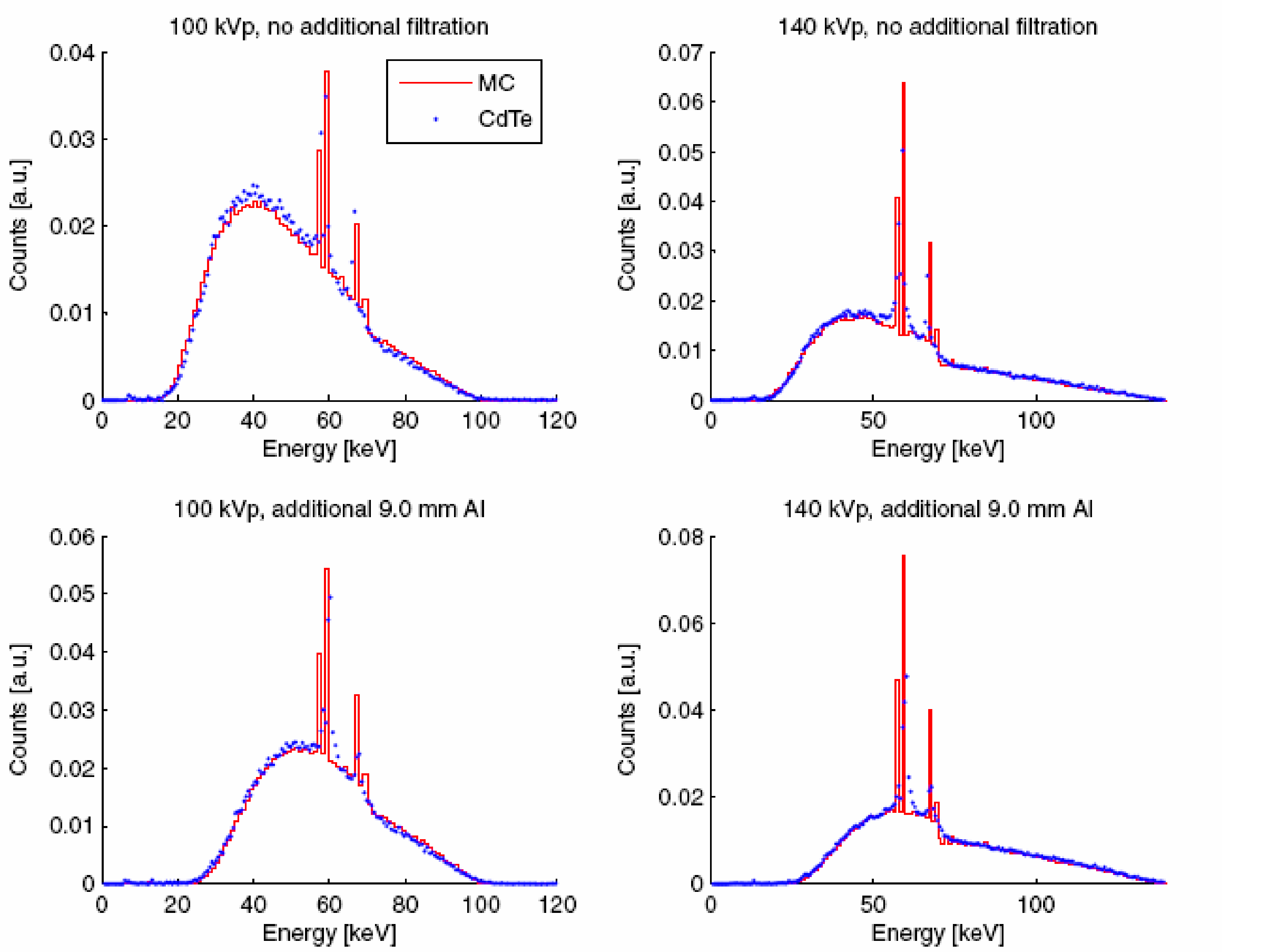



- modified DOSXYZnrc code
- X-ray source rotates 200 ° in 1° degree steps
- a monoenergetic and a polyenergetic spectrum to study beam hardening
- photon transport is simulated and scattered particles are labeled
- energy of all photons is deposited in the detector ring and two types of sinogram are produced
- a primary sinogram and a scatter sinogram
- the primary and the total sinograms are processed

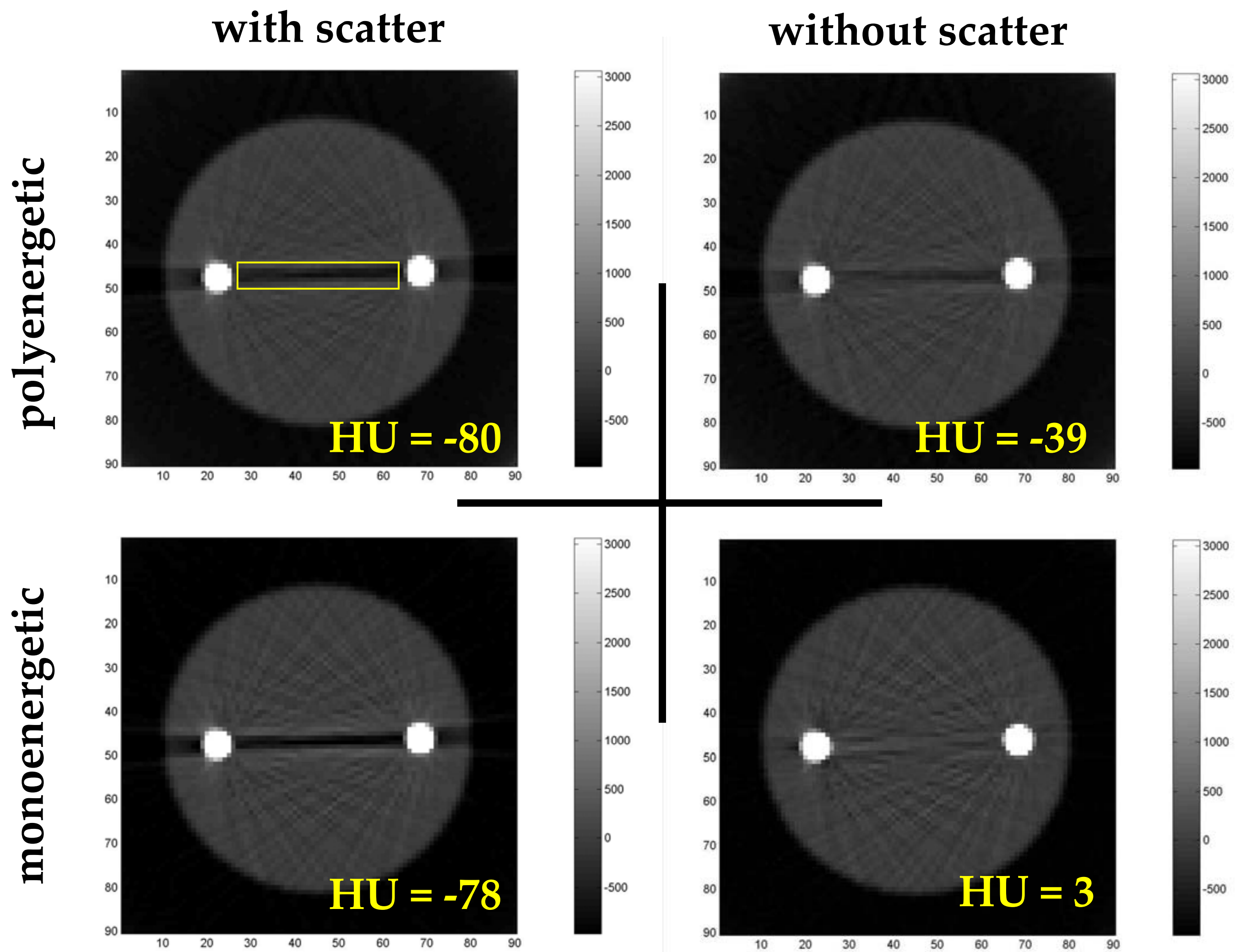
# X-ray tube simulations



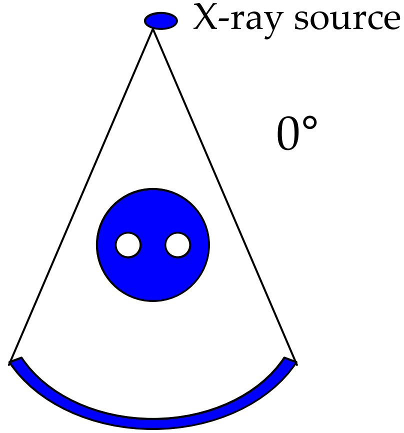
# CT x-ray tube simulation results

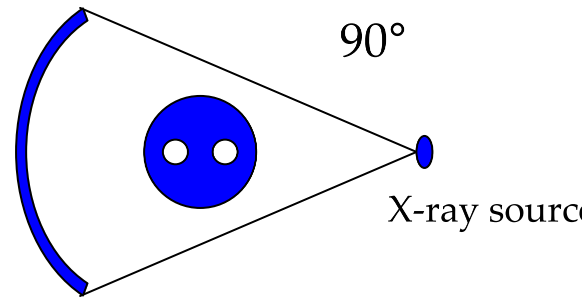


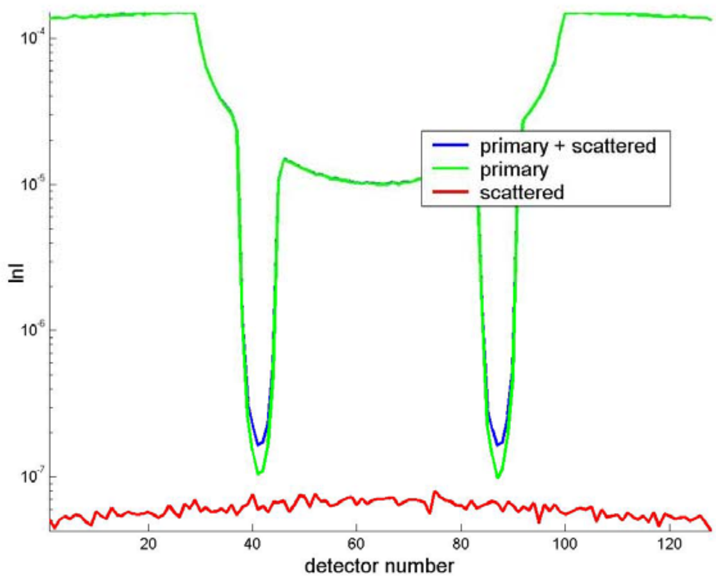
# Simulation results

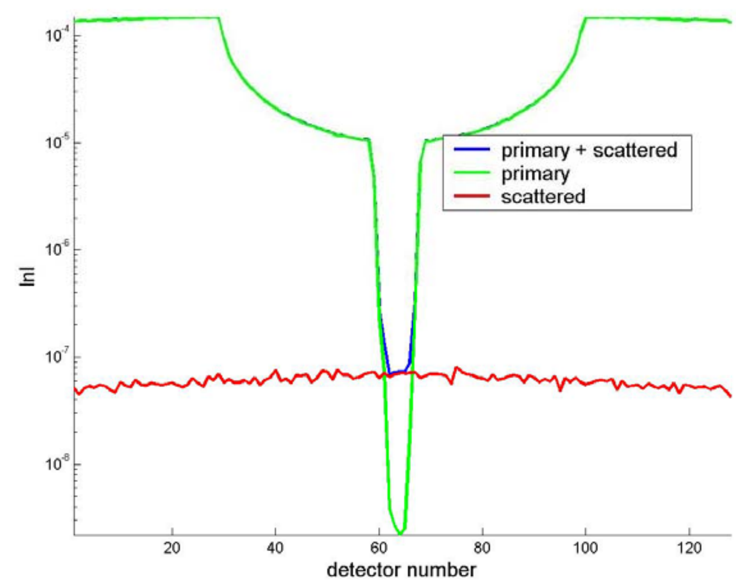


# Scatter - intensity profiles



# CT artifact causes: conclusions

- beam hardening has a minor effect on metal streaking artifacts compared to scatter
- contribution of scatter could be reduced by decreasing slice thickness
- images could be improved by adding filters to X-ray beam to narrow the polyenergetic spectrum as much as possible
- scatter was overestimated in our simulations (the anti-scatter grid not included)
- detector noise was not simulated

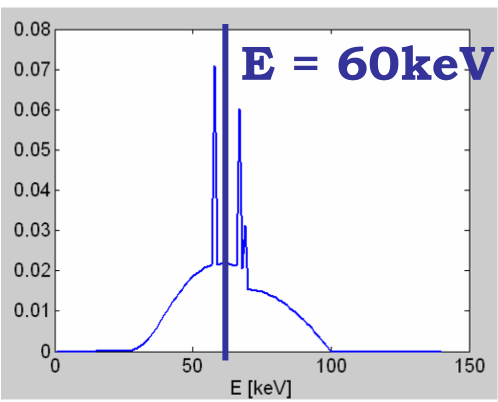
# 4. Dual-energy CT material extraction

- dual-energy material extraction (DECT) is based on
  - taking CT images at two tube voltages (100 kVp and 140 kVp)
  - parameterization of the linear attenuation coefficient
- results in electron density ($\rho_e$) and atomic number ($Z$) values of each voxel

$$Z^4 - \frac{\frac{\mu_2}{\mu_{2w}}\sum_i \omega_{2i}\left[Z_w^4 F(E_{2i},Z_w)+G(E_{2i},Z_w)\right]\sum_i \omega_{1i} G(E_{1i},Z) - \frac{\mu_1}{\mu_{1w}}\sum_i \omega_{1i}\left[Z_w^4 F(E_{1i},Z_w)+G(E_{1i},Z_w)\right]\sum_i \omega_{2i} G(E_{2i},Z)}{\frac{\mu_1}{\mu_{1w}}\sum_i \omega_{1i}\left[Z_w^4 F(E_{1i},Z_w)+G(E_{1i},Z_w)\right]\sum_i \omega_{2i} F(E_{2i},Z) - \frac{\mu_2}{\mu_{2w}}\sum_i \omega_{2i}\left[Z_w^4 F(E_{2i},Z_w)+G(E_{2i},Z_w)\right]\sum_i \omega_{1i} F(E_{1i},Z)} = 0$$

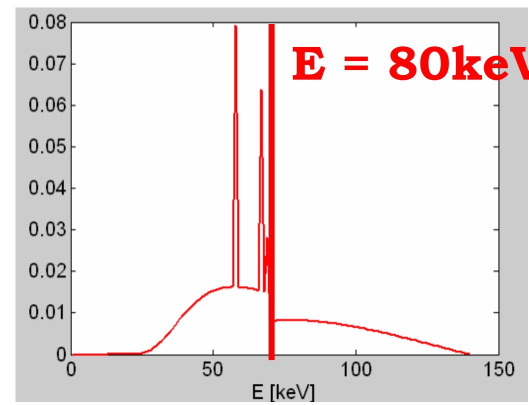
# DECT

- CT number of a material depends on $\rho_e$ and $Z$ of the material and the mean energy $E$ of the beam used for scanning: $\mu = f(Z, \rho_e, E)$




100 kVp

| kVp | 100 | 140 |
|---|---|---|
| lung | -703 | -704 |
| water | 0 | 0 |
| bone | 1399 | 1110 |




140 kVp

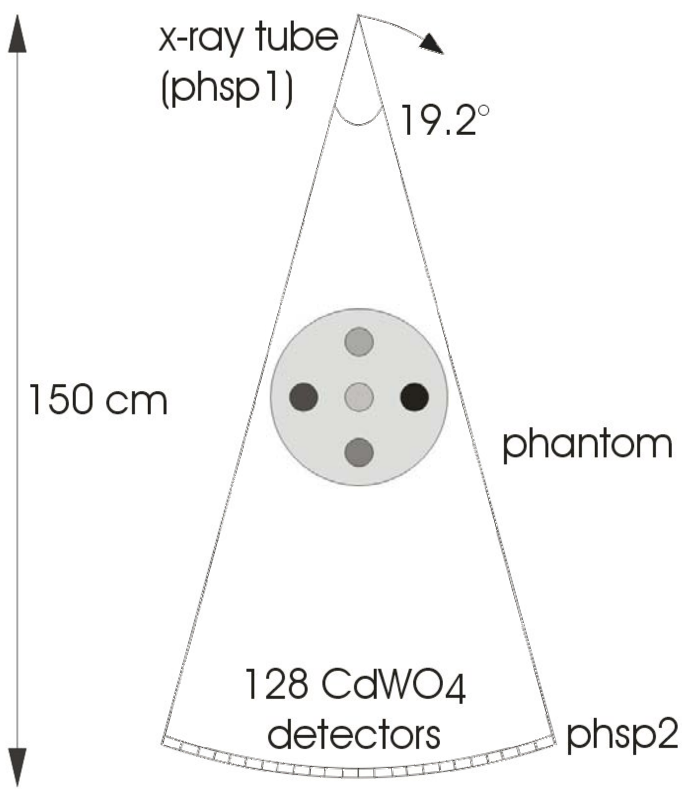
- knowing the two x-ray beams, comparison of the two scans leads to $Z$ and $\rho_e$ extraction

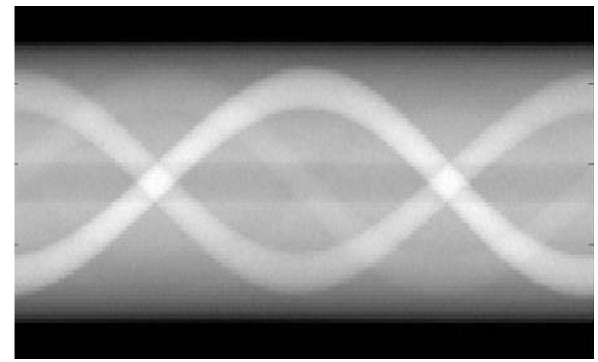
# Monte Carlo & measurements

- images of a cylindrical phantom with inserts at two energies produced by
  - Monte Carlo simulations
  - measurements using a CT scanner
- inserts - RMI electron density calibration materials
  - $Z \in (5.740,14.141)$
  - $\rho_e \in (0.292,1.692)$
- $Z$ and $\rho_e$ extracted from the images in Matlab
- calculated values compared to the true values

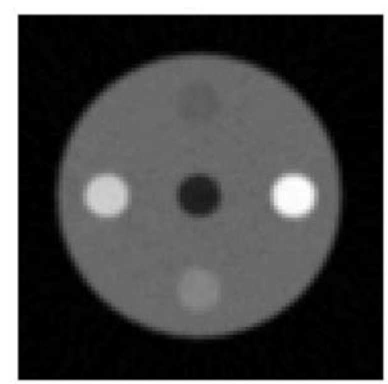
# Monte Carlo simulations

- Picker PQ5000
- EGSnrc/DOSXYZnrc code

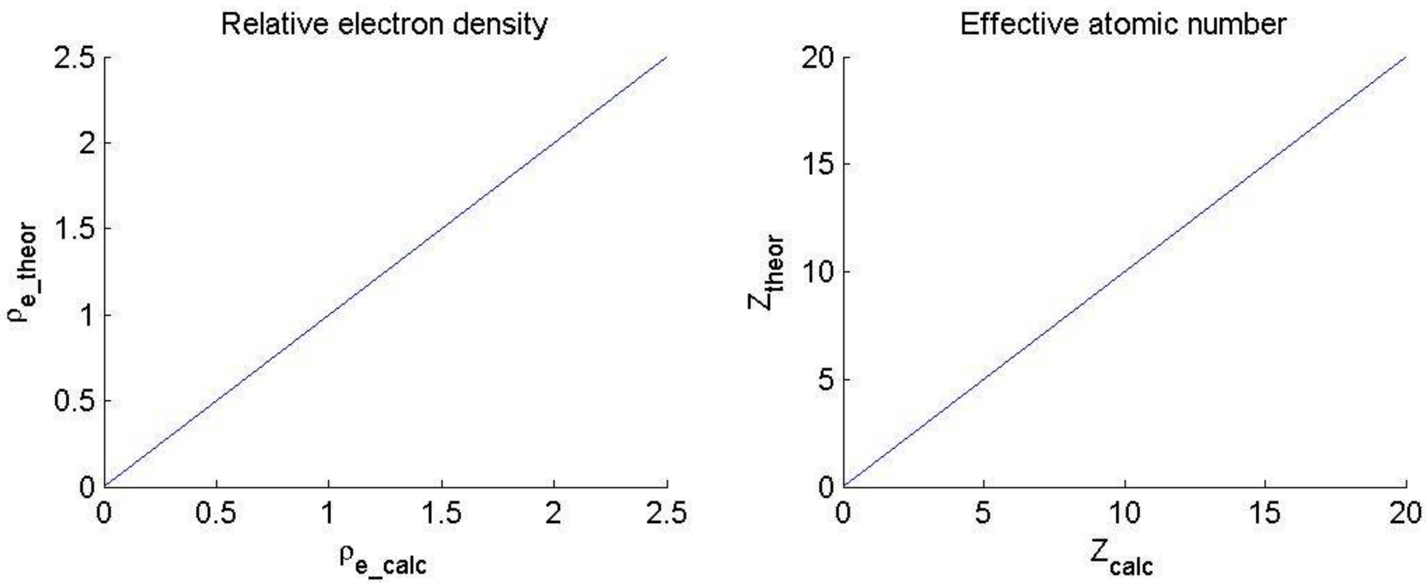


- soft spectrum
  100 and 140 kVp
- hard spectrum
  added 9mm Al filter
  100 and 140 kVp



# MC simulation results



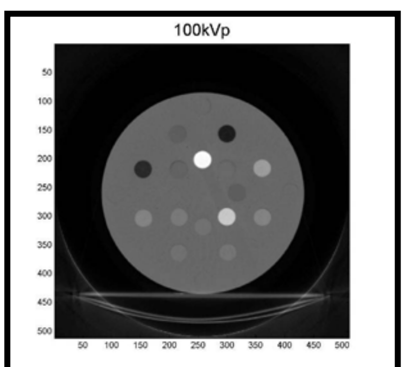

**SOFT SPECTRUM**

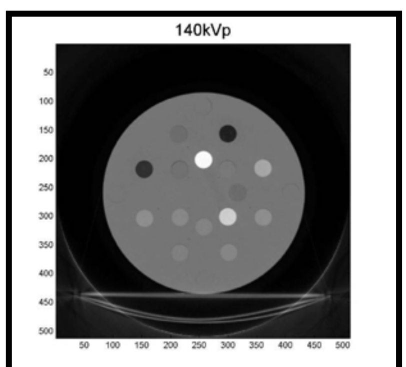
**HARD SPECTRUM**

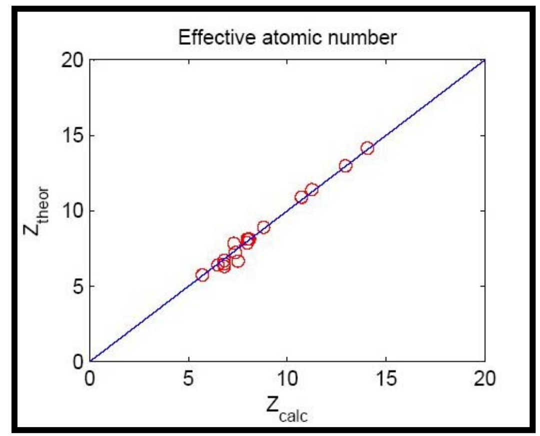
**In order to minimize beam hardening effects, hard spectra have to be used.**

# CT measurement results

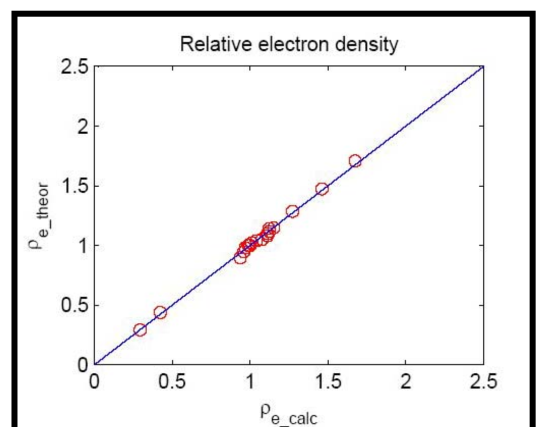
- solid water phantom with RMI cylindrical inserts, scans taken at 100 and 140 kVp with a 9 mm Al filter, $Z$ and $\rho_e$ extracted

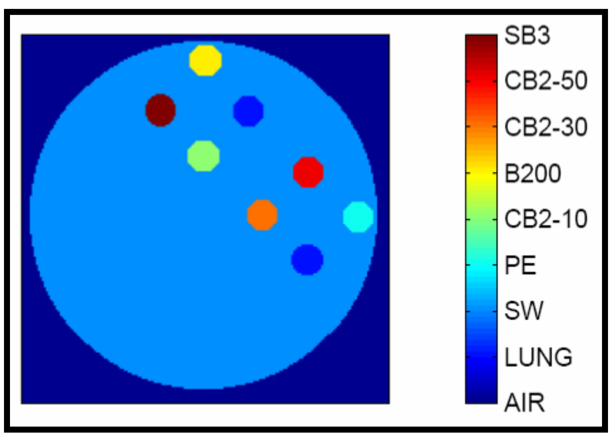




2.8 %

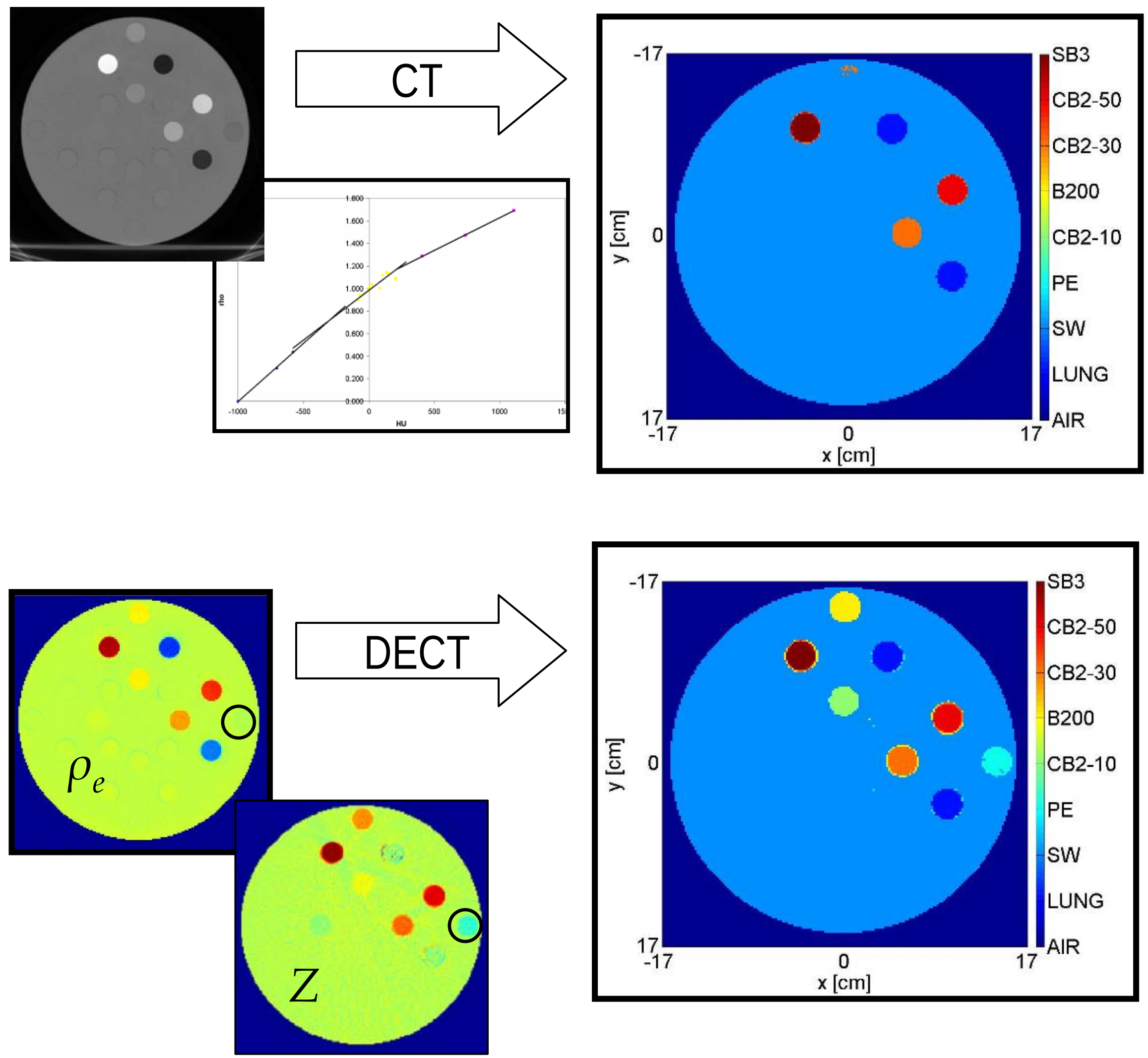



1.6 %

# Material segmentation using DECT




**exact geometry**



# Dual-energy CT: conclusions

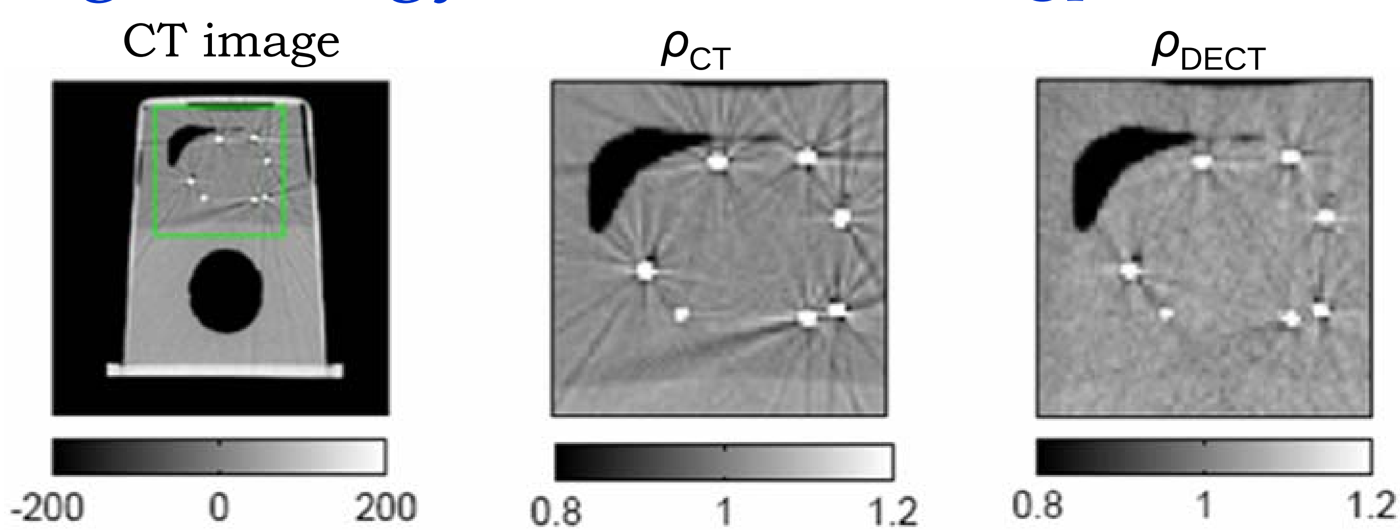
- in order to minimize beam hardening effects, dual-energy CT (DECT) should be done with hard beam
- DECT material extraction was successful for a set of tissue-equivalent materials with a wide range of densities and atomic numbers using 100 kVp and 140 kVp
- DECT works well on static phantoms with low image noise and makes material segmentation more accurate

# 5. DECT and metal streaking artifacts

- streaking artifact reduction between bone materials was observed during phantom studies (artifacts appear in both images)
- is DECT helpful for reduction of metal streaking artifacts?
- phantom studies were successful but what about patients?
  - high mAs values set for phantoms, cannot be done for patients due to dose limits – noise will be increased
  - effects of patient motion on DECT

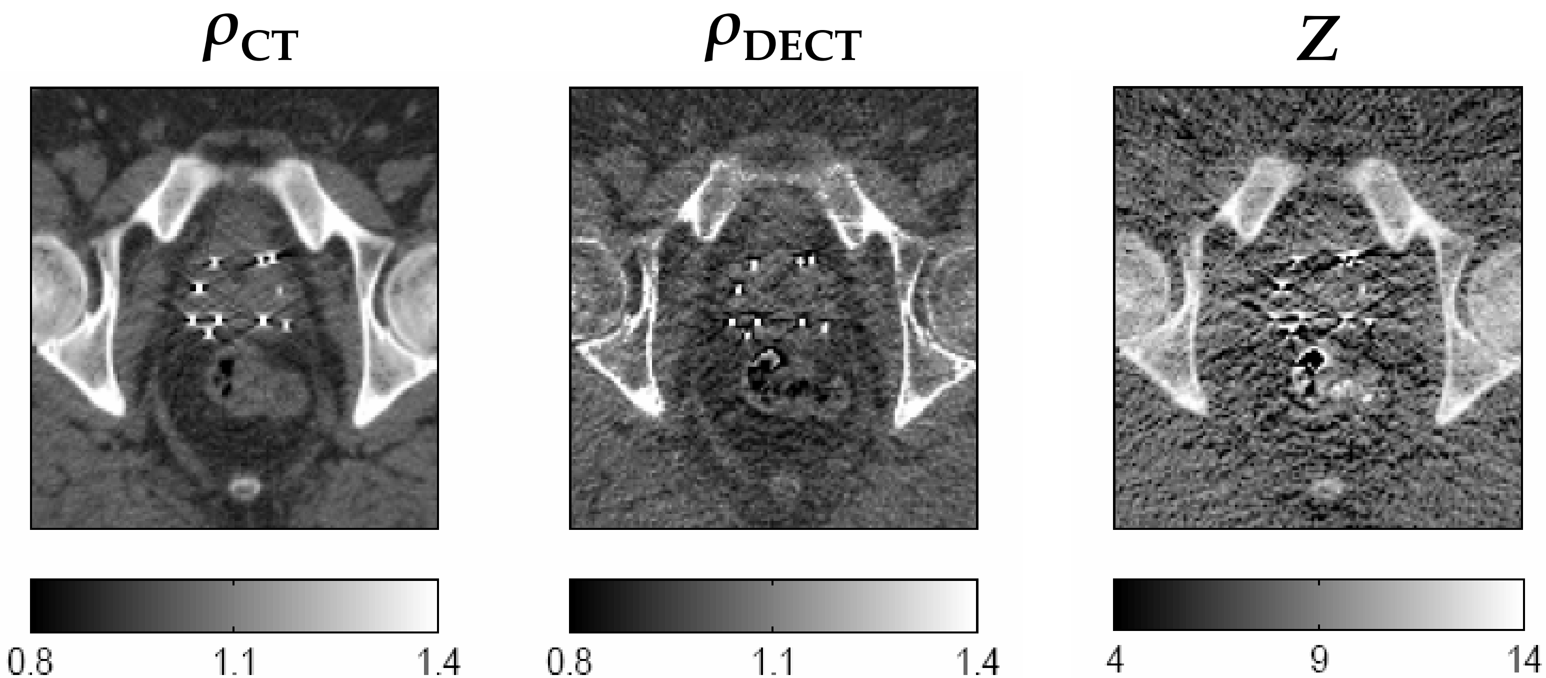
# Artifact reduction for brachytherapy seeds

- US prostate phantom with 45 seeds
- 100 kVp and 140 kVp scans on the AcQSim CT
- $\rho_e$ and Z extracted, $\rho_{DECT}$ compared to the single-energy CT method ($\rho_{CT}$)



# DECT for prostate patients with brachytherapy seeds

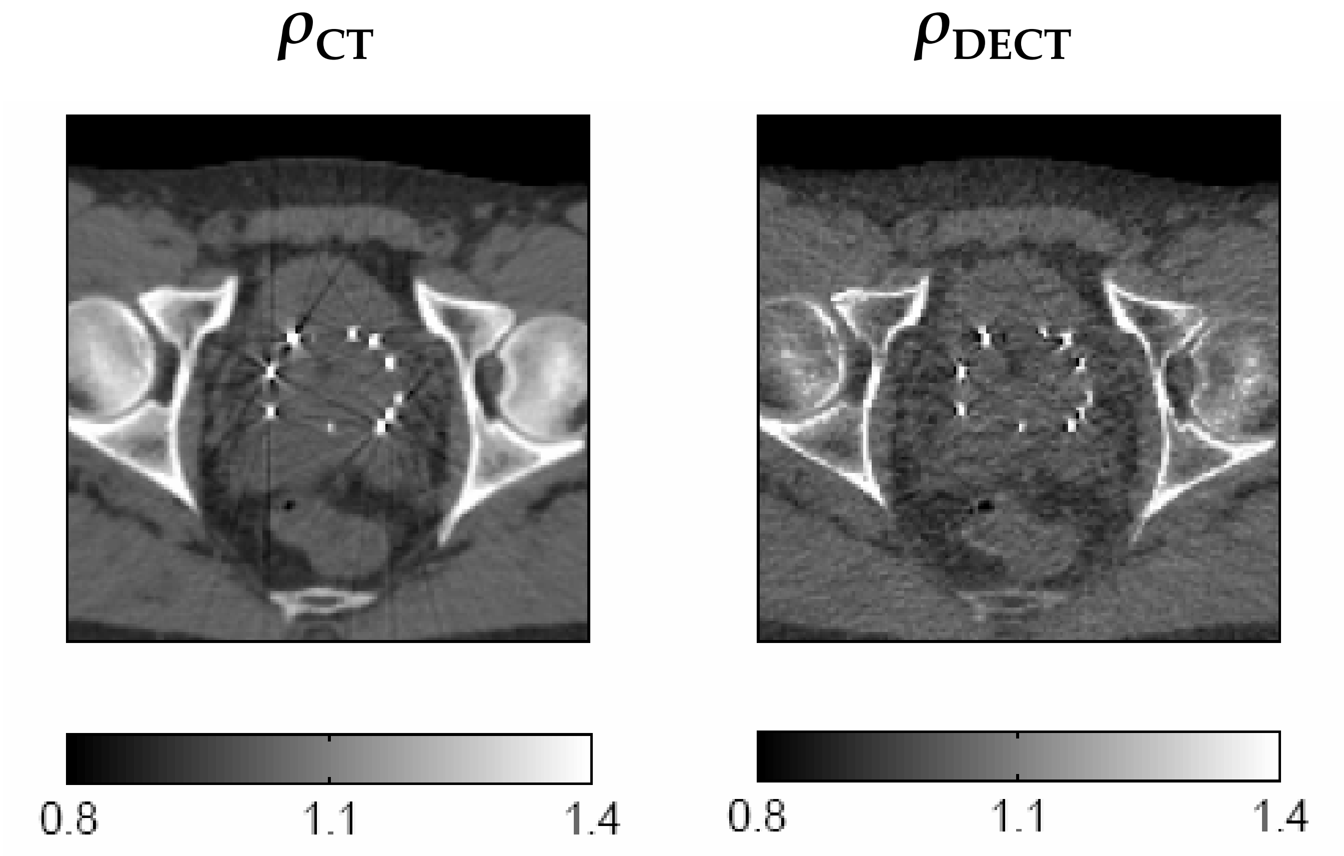
- 4 patients scanned at 90 kVp and 140 kVp on a Philips Brilliance CT scanner at CHUQ
- $\rho_{CT}$ derived from the RMI phantom calibration



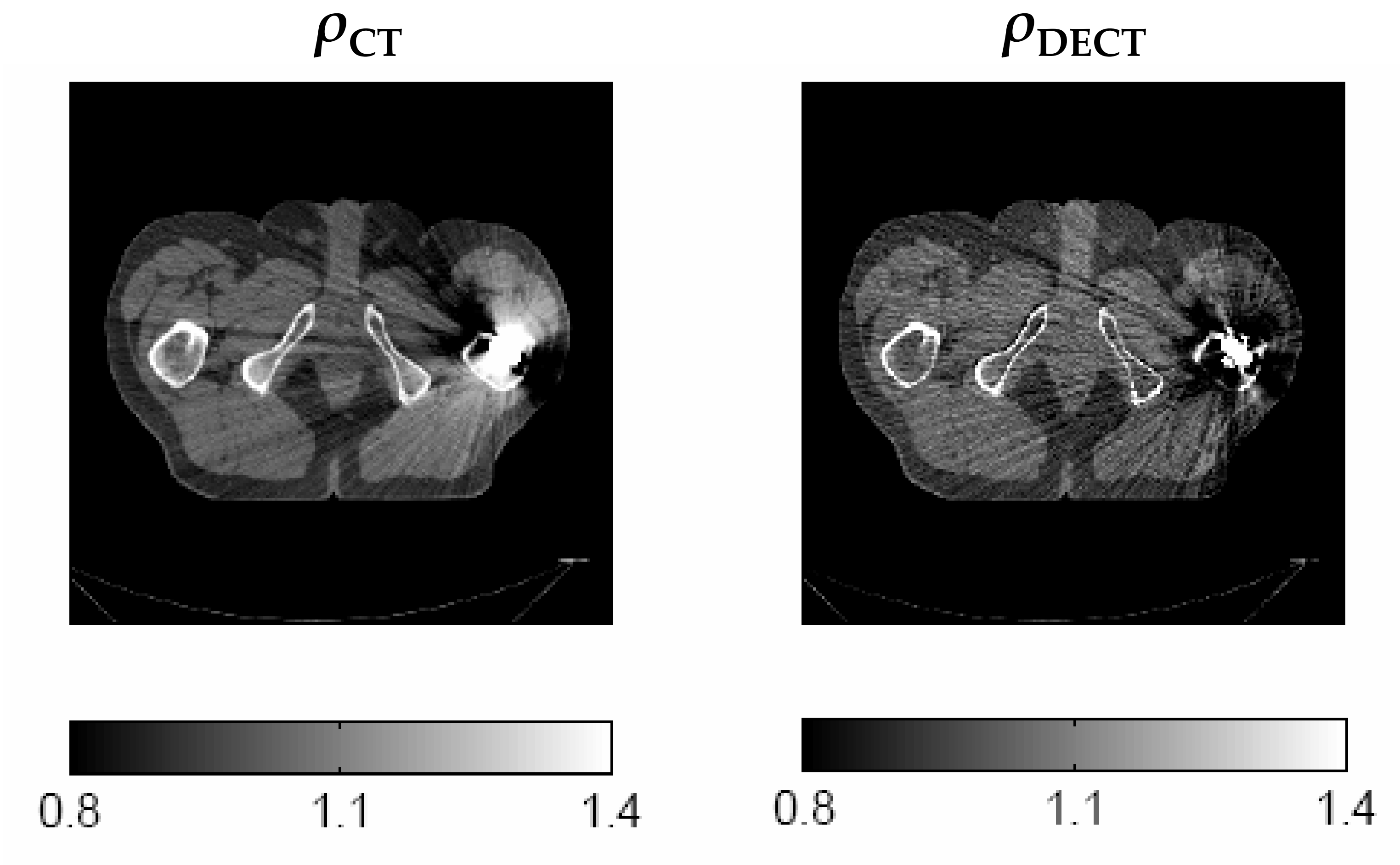

- image noise is a factor

# DECT for prostate patients with brachytherapy seeds

- changing the reconstruction filter…

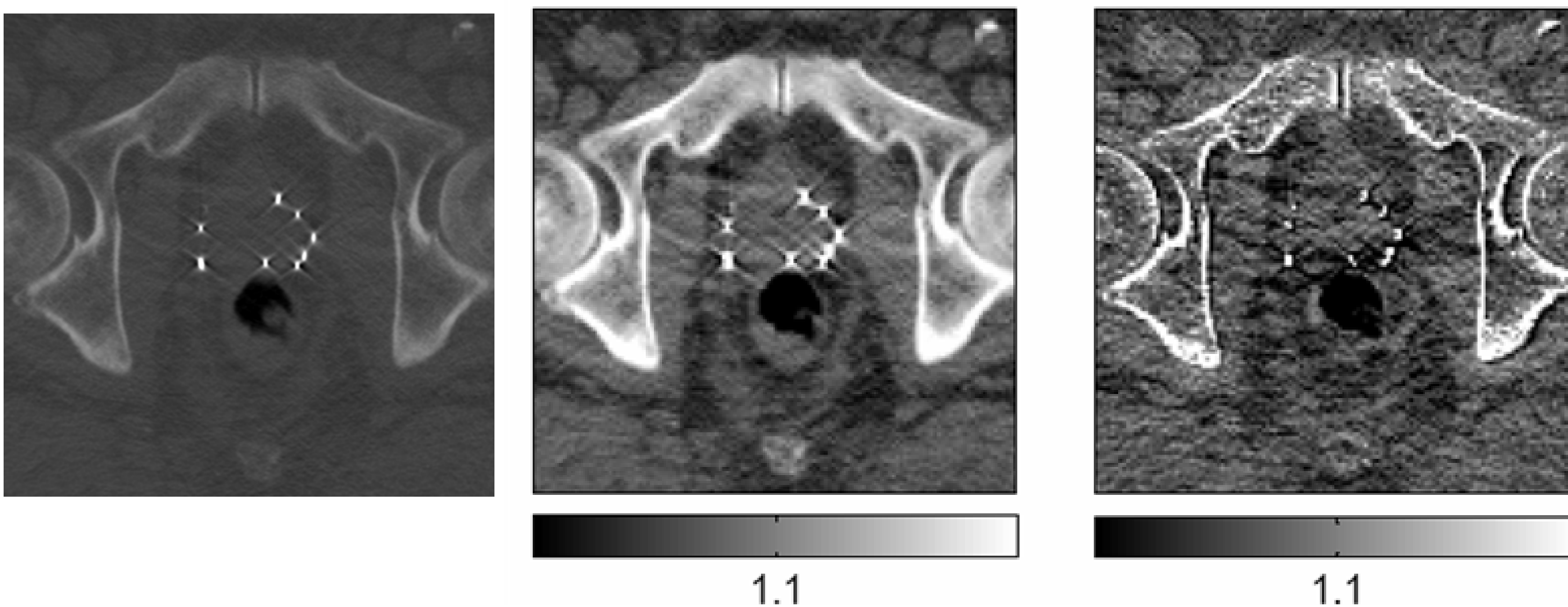


# DECT for a patient with a hip prosthesis




- is this an improvement?

# DECT for another prostate patient with brachytherapy seeds – image registration issue

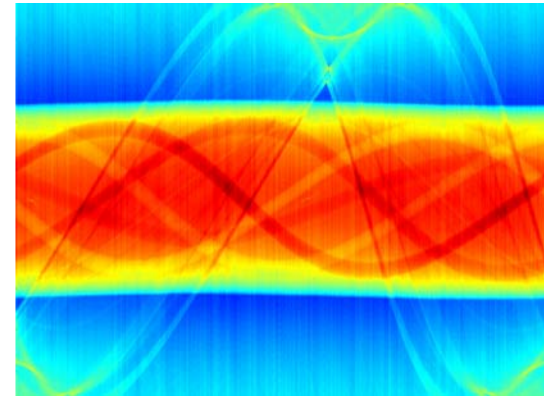


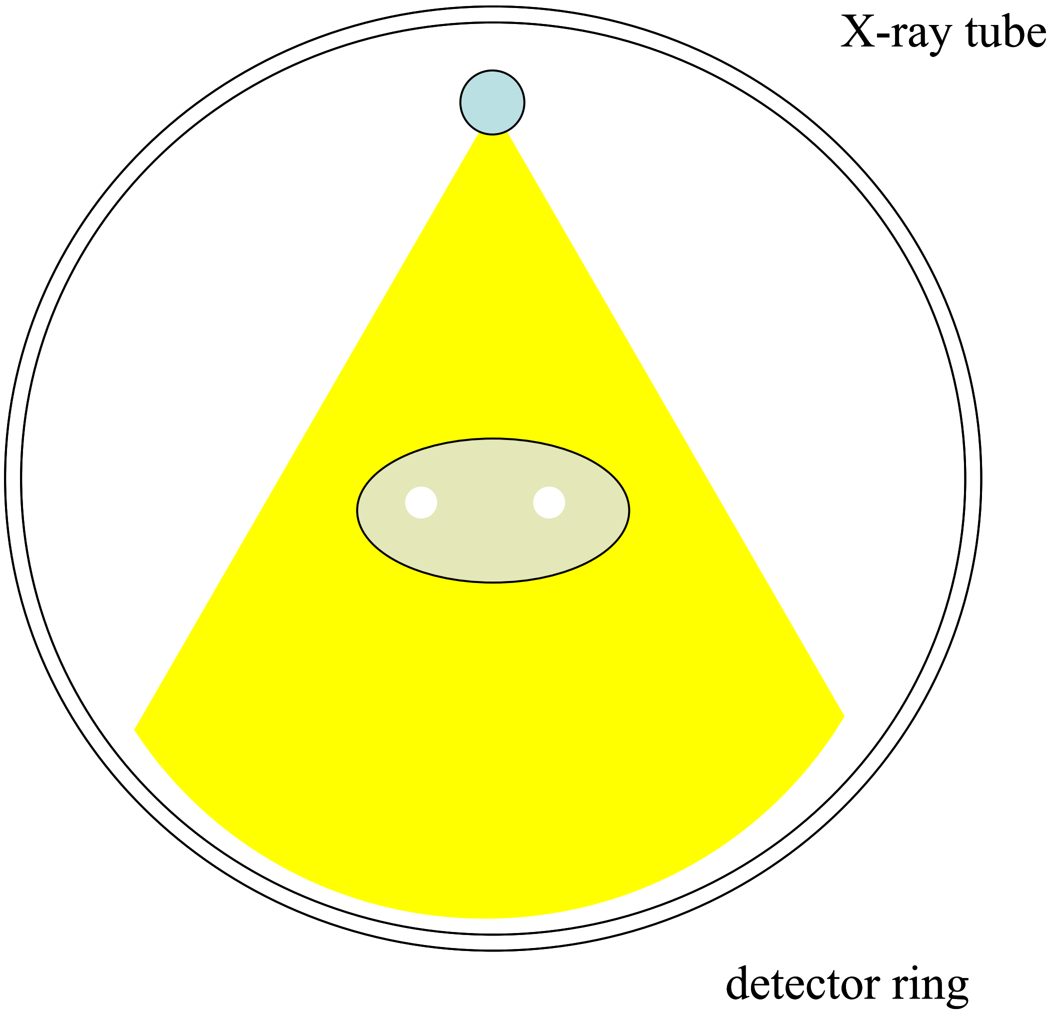

- patient motion is also an important issue for DECT

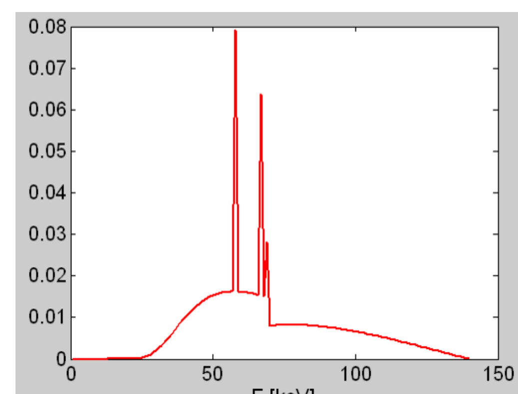
# Reduction of patient motion

- using a copper filter at 140 kVp
- the tube voltage is constant
- the filter moves in and out of the beam so two different x-ray beams are produced
- the output of the x-ray tube changes significantly with the filtration and the signal coming from the filtered beam can be distinguished from the unfiltered beam in the raw data file

# CT scanner




X-ray tube
detector ring


0.08
0.07
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0.02
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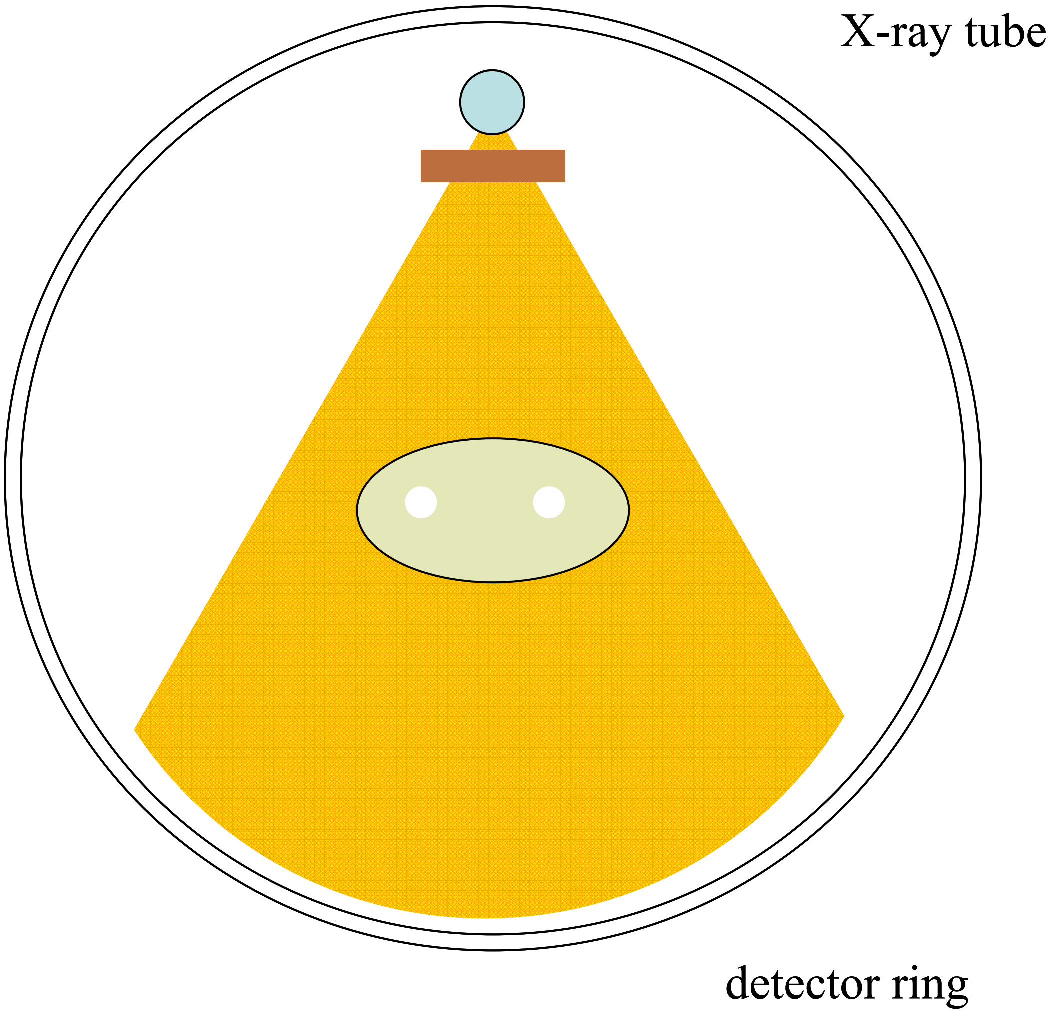
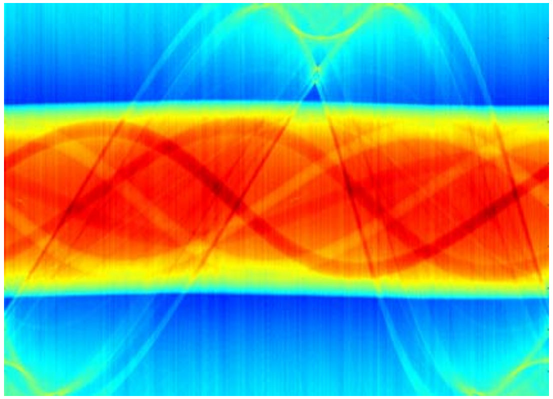
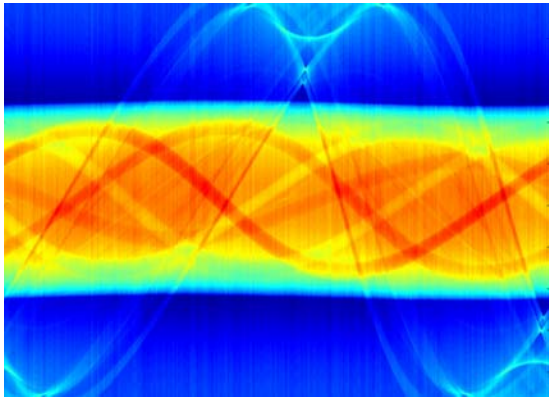
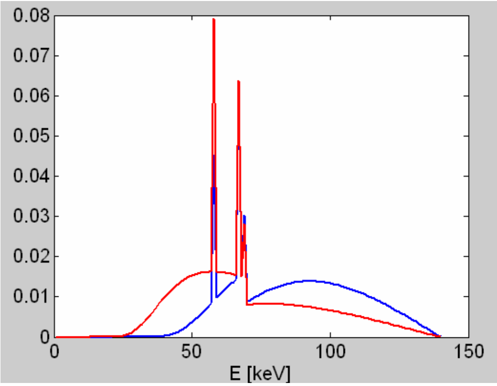
0
50
100
150
E [keV]

# CT scanner


X-ray tube
detector ring



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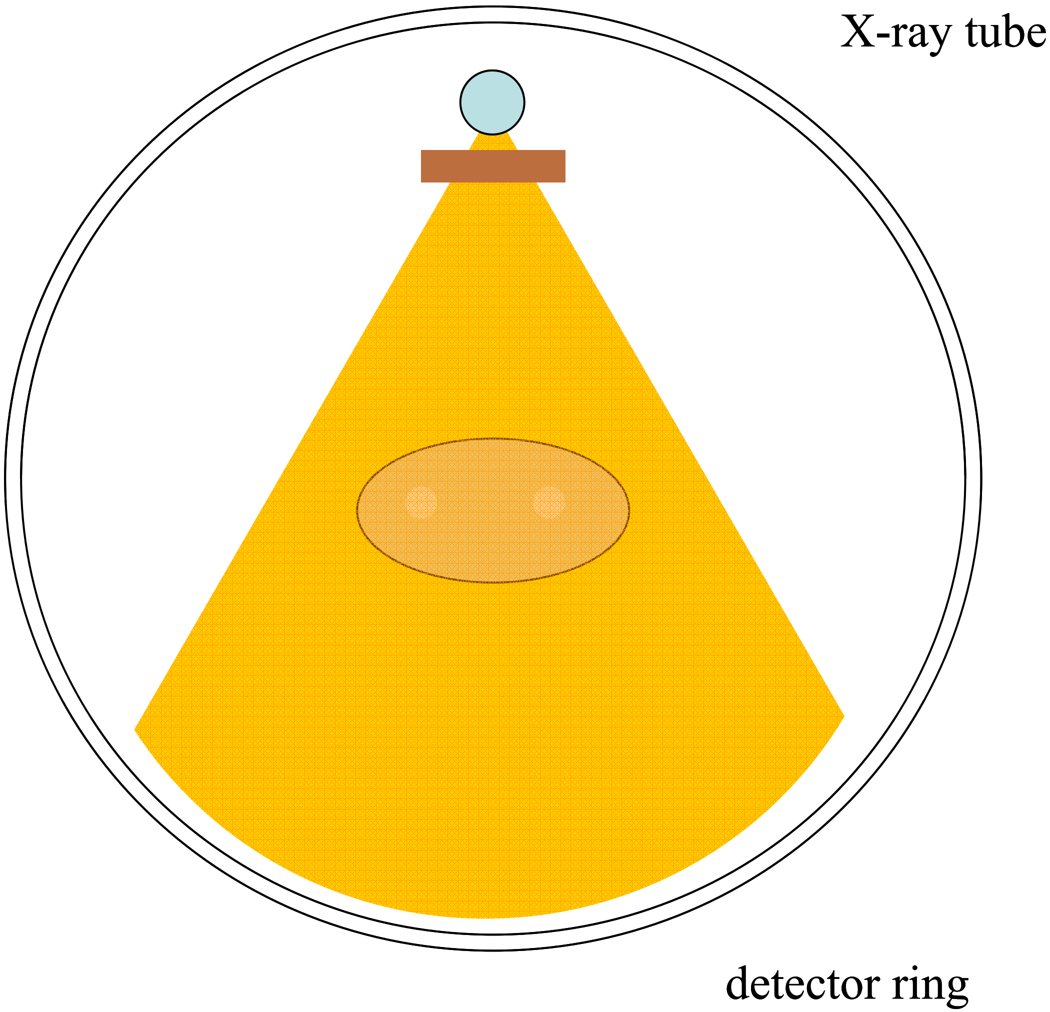
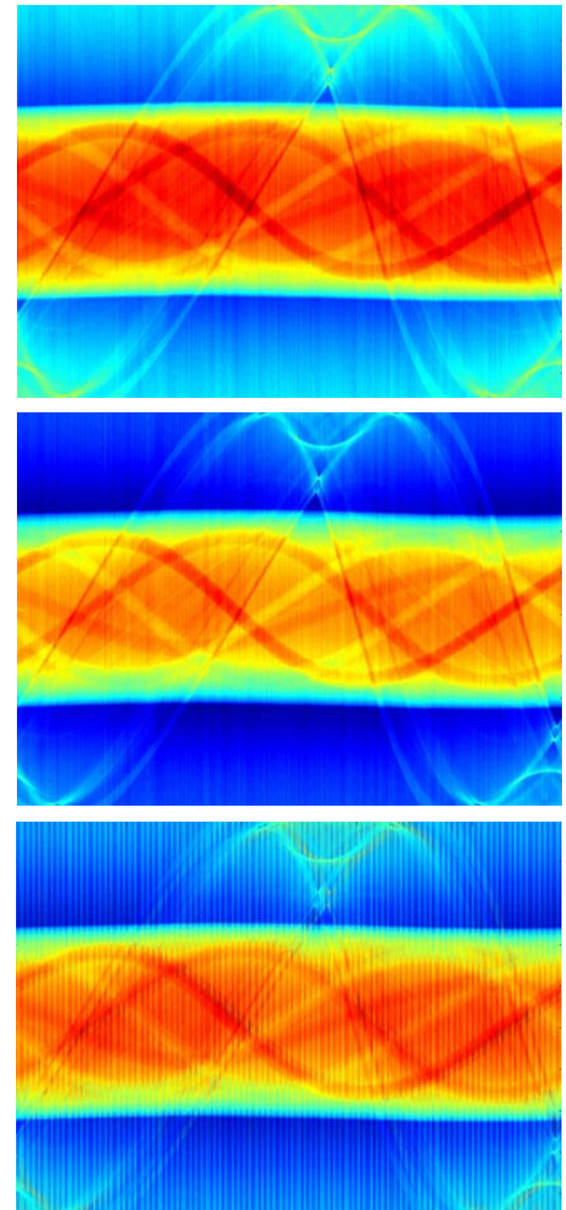
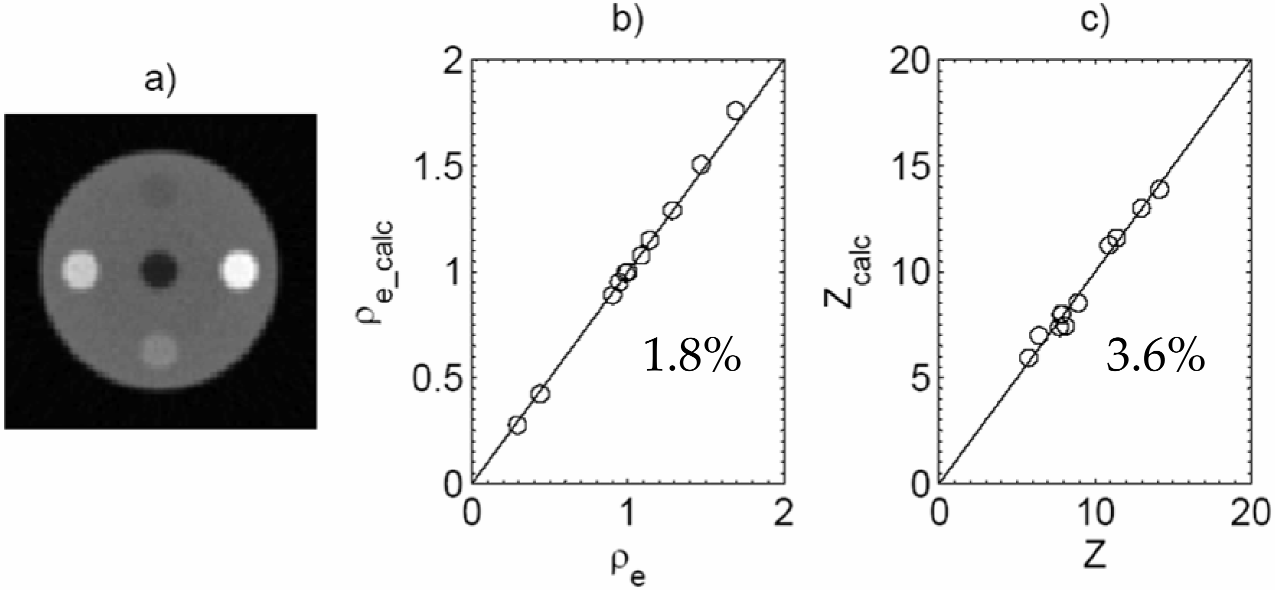
# CT scanner



# MC study of DECT with a 2 mm Cu filter

- 2 mm Cu filter and 140 kVp beam
- two separate MC simulations
- 10 tissue equivalent materials




- patient motion reduction using rotating filter might be possible

# DECT and metal artifacts: conclusions

- DECT has the potential to reduce streaking artifacts from brachytherapy seeds, as seen in the phantom and the patient study
- it might not be practical for reduction of artifacts caused by large metals (such as hip prostheses)
- the patient study has shown that image noise and patient motion significantly influence the accuracy of DECT
- solutions for reduction of image noise and patient motion were proposed

# Thank you!

Centre universitaire de santé McGill
McGill University Health Centre