Simulation of CT metal artefacts

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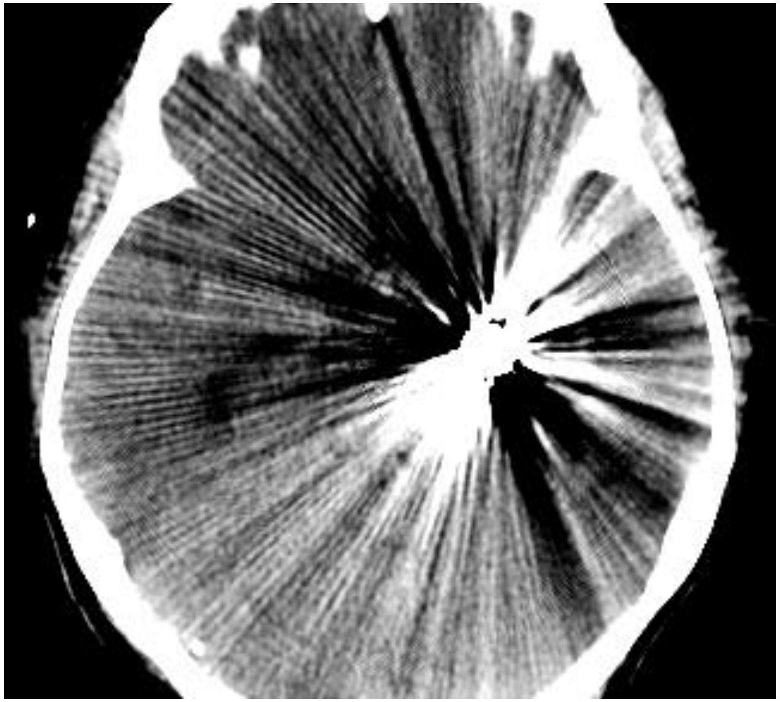
Clinical project final presentation

Examples of metal artefacts in CT

- The human body usually does not contain any metal objects
  - many medical **implants** are composed of metal
    - Artificial hip bones
    - dental fillings
    - Pacemakers
    - intramedullary rods
    - Screws
    - Needles
    - Trocars
    - etc.

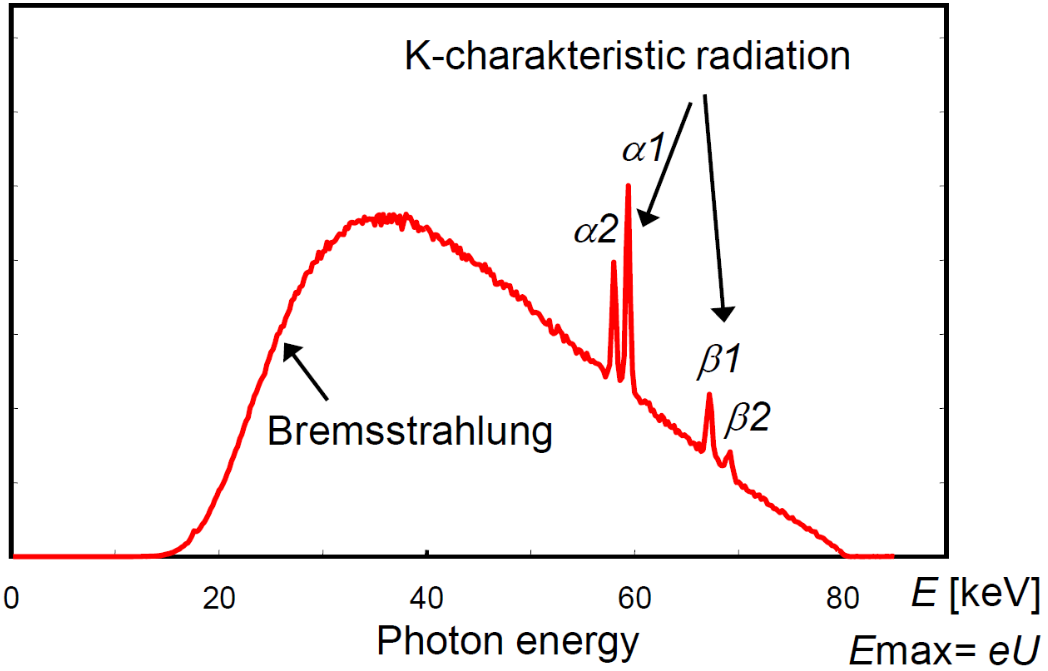


- artefacts usually consist of **dark stripes** between metal objects **with light, pinstriped lines** covering the surrounding tissue

Fundamentals of X-Ray physics

Generation of X-Ray radiation

- to generate X-Ray radiation an **X-Ray tube** is used
- consists of a cathode and a rotating (tungsten) anode
- electrons from the cathode hit the anode
  - Bremsstrahlung
  - Characteristic emission lines
- Both effects together result in the total **emission spectrum** of the X-Ray source



Fundamentals of X-Ray physics

Attenuation of X-Ray photons: Lambert-Beer's Law

- Usually all physical mechanisms that lead to the attenuation of radiation intensity behind a *homogeneous object* are summed up in a *single attenuation coefficient* µ
- In this simple model the total attenuation of a monochromatic X-Ray beam after passing a distance of through an object can be calculated as
$$I(\eta + \Delta\eta) = I(\eta) - \mu(\eta)I(\eta)\Delta\eta$$
- By reordering and taking the limit this leads to
$$\lim_{\eta \to 0} \frac{I(\eta + \Delta\eta) - I(\eta)}{\Delta\eta} = \frac{\Delta I}{\Delta\eta} = -\mu(\eta)I(\eta)$$
- Solving this ordinary linear and homogeneous, firstorder differential equation with constant coefficients this gives
$$I(\eta) = I_0 e^{-\mu\eta}$$

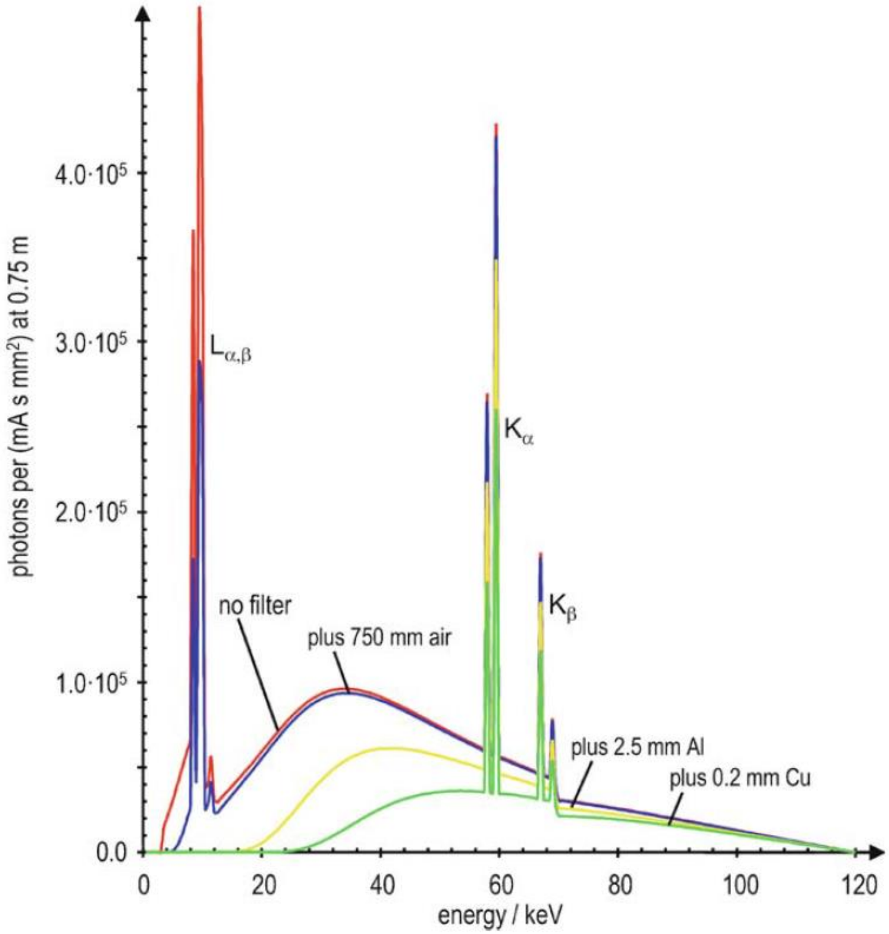
Fundamentals of X-Ray physics

Beam hardening

- *Colloquially*, X-ray is known to have the property of effectively penetrating material.

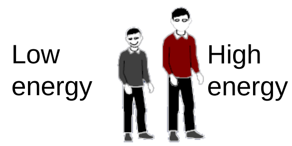
- But radiation attenuation is not only dependent on **path length**
  - but is a function of the specific, **wavelength-dependent** interaction between X-ray and the material concerned.

- Lambert-Beer's Law is a simplification
  - it does not take **beam hardening** into account



Fundamentals of X-Ray physics

Beam hardening



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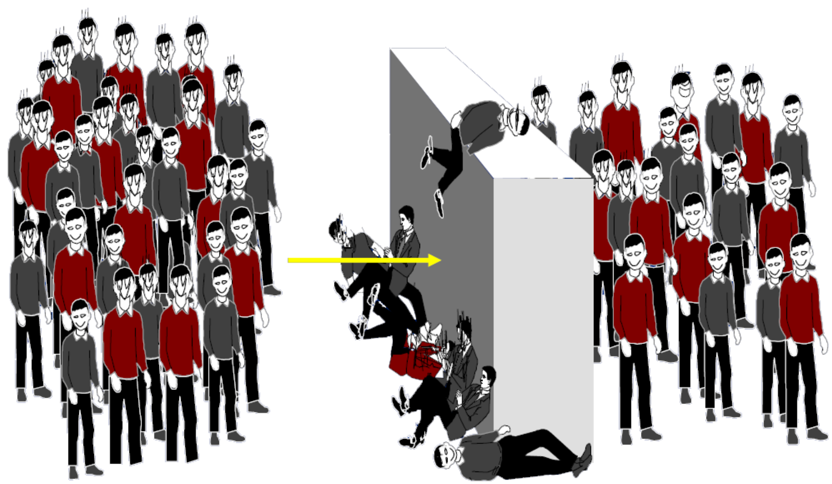


Ratio 40/24

Ratio 20/18

Fundamentals of X-Ray physics

Beam hardening

- Taking energy dependence into account this leads to

$$I(s) = \int_{0}^{E_{\max}} I_0(E)\, e^{-\int_0^s \mu(\eta,E)\,\mathrm{d}\eta}\, \mathrm{d}E$$

- If a beam is completely attenuated this is called **photon starvation**
- behind a thick metal object the system detects an *infinitely high attenuation*
- Filtered backprojection does not cope with these inconsistencies
  - lines through the object are encountered with extremely high numerical values, which spread across the entire image and are not compensated for by any other projection direction

Simulation of CT

Forward Projection

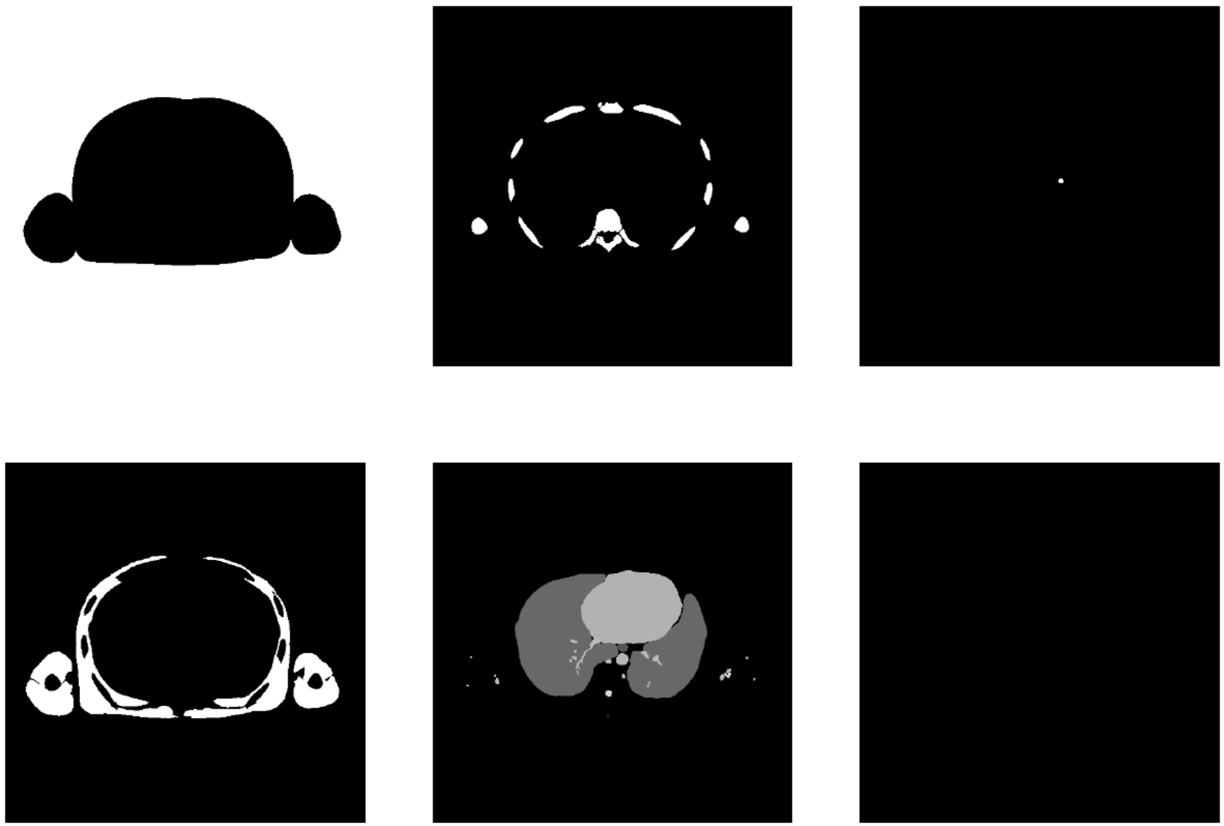
- Forward projection is essentially a Radon Transform
  - With some special conditionals to simulate physical effects not present in the mathematical model
- For this simulation parallel beam geometry was chosen
  - Equivalent to fan beam geometry
- Simulation of
  - Attenuation according to Lambert-Beer's Law modified to take energy dependence into account
  - X-Ray tube spectra at different voltages
  - Polychromaticy by several monochromatic runs
- Complete forward projection can be formulated as

$$\sum_{p \in P} \sum_{en \in E} \sum_{d \in D} \sum_{l \in L} I_0 \cdot e^{-\sum_{\eta \in M} \mu(\eta, x, y, en)}$$

$$\text{with } x = l \cdot \sin(p) + d \cdot \cos(p)\,, y = -l \cdot \cos(p) + d \cdot \sin(p)$$

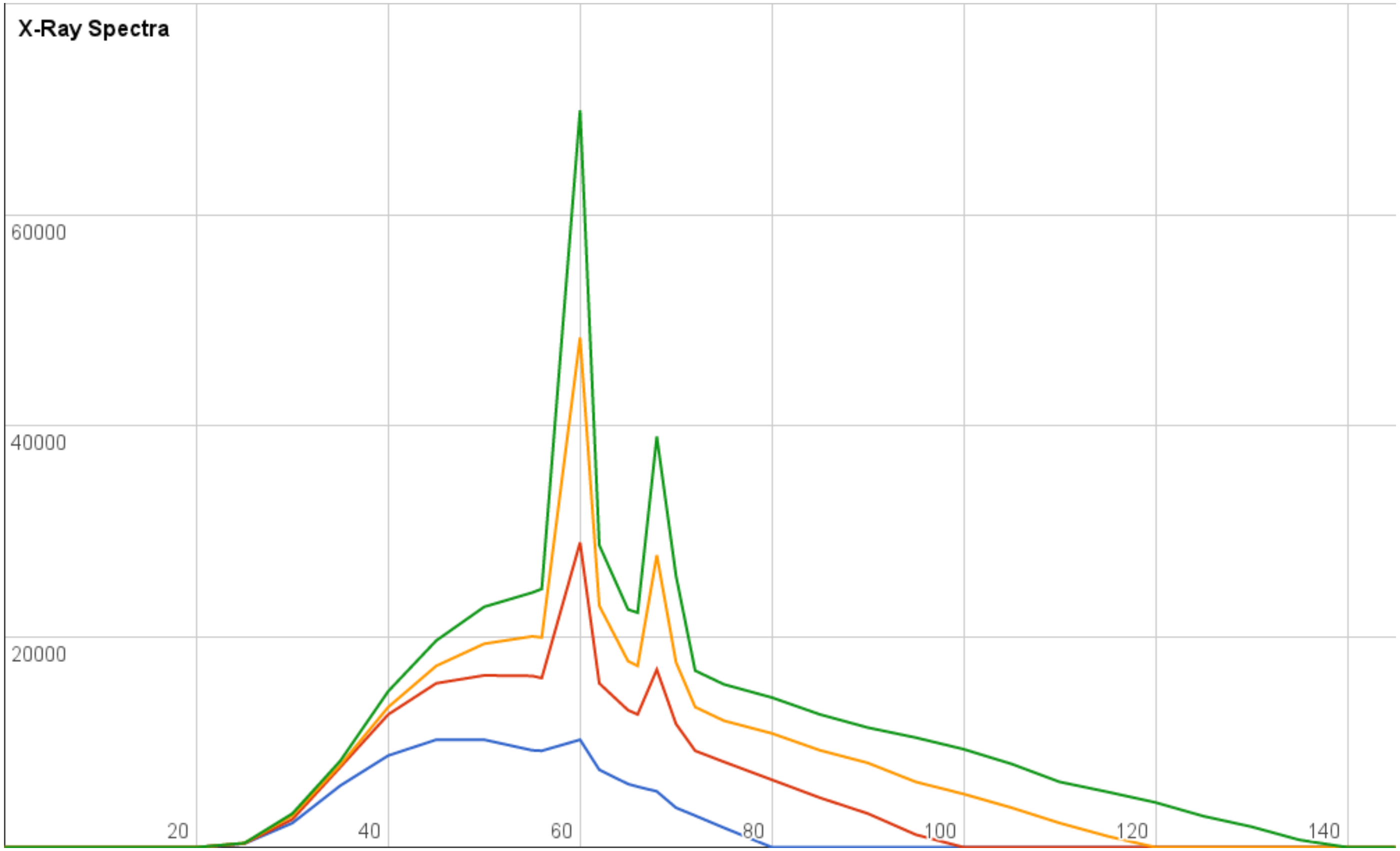
Simulation of CT

Segmented CT slice



Simulation of CT

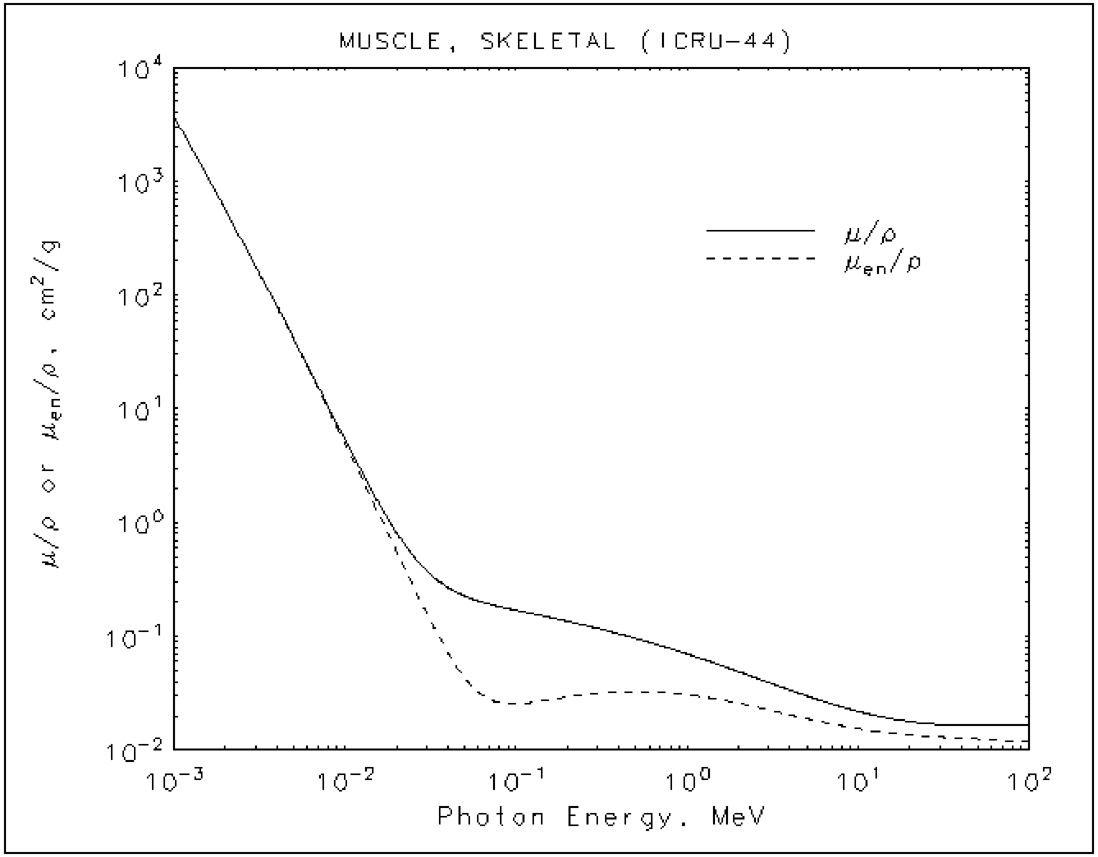
Lookup tables for X-Ray spectra



Sampled from:
J. Anthony Seibert. X-ray imaging physics for nuclear medicine technologists. part 1: Basic principles of x-ray production. J. Nucl. Med. Technol., 32 no. 3,:139–147, 2004.

Simulation of CT

Lookup tables for attenuation coefficients



Tables by:
S. M. Seltzer J. H. Hubbell. Tables of x-ray mass attenuation coefficients and mass energy-absorption coefficients from 1 kev to 20 mev for elements z = 1 to 92 and 48 additional substances of dosimetric interest, May 1996.

Simulation of CT

Configuration file

```
pathToSlice=slices/Segmentation2
pathToOutputReconstruction=outData.pgm
pathToOutputSinogram=simulatedSinogram.pgm
pathToXRaySpectra=Data/XRaySpectra
minEnergy=20
maxEnergy=140
energyLevels=8
numberOfProjectionAngles=64
numberOfThreads=4
tubeEnergy=140
detectorThreshold=100
attenuationMultiplicator=10
```

Simulation of CT

Miscellaneous parts of the simulator

- Out paradigm was not to rely on any third party libraries
  - So some more code had to be implemented…
- Own logger (inspired by loggers like log4j)
  - Different loglevels: `ALL > TRACE > DEBUG > INFO > WARN > ERR > FATAL > OFF`
  - Heavily relies on macros to guarantee no major impact on performance
  - Outputs loglevel, source code file, function, line and message. In “verbose mode”
  - Can also write output to file
- Image reading and writing
  - portable graymap format `.pgm` (Portable Anymap or Netpbm format)
  - One of the easiest image formats
    - Super short header followed by color values in ASCII separated by whitespaces

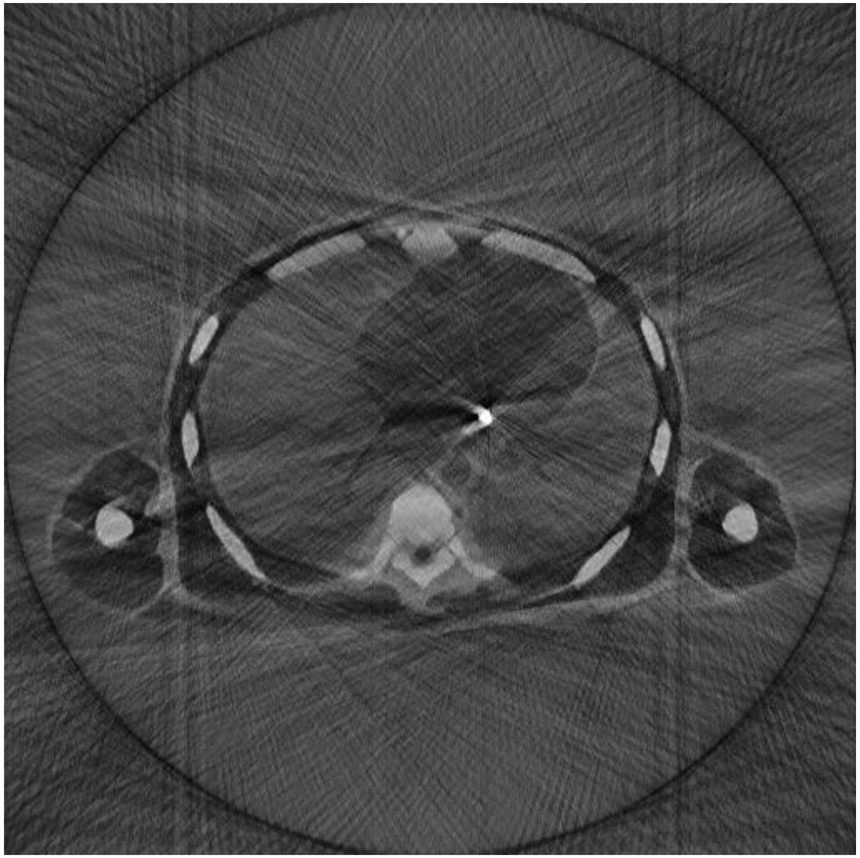
Results

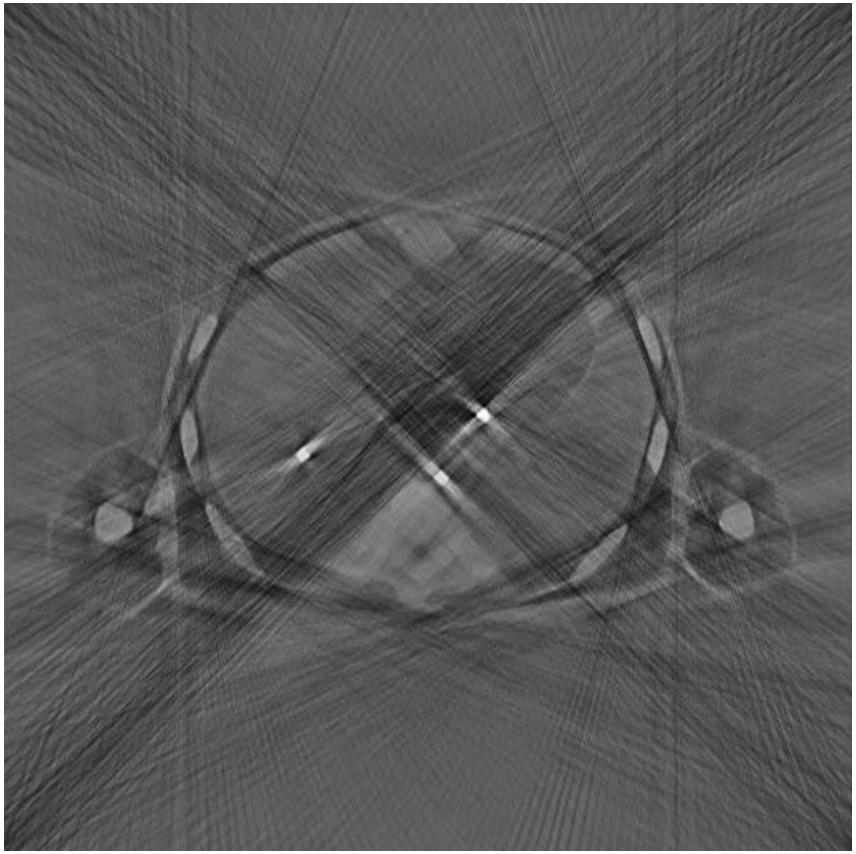
- Images take long to compute (5-60 minutes on my laptop)
- CPU speed and number of threads/cores is the limiting factor
- Computation speed is direct proportional to
  - Number of projections
  - Number of energy levels

- Computation speed is indirect proportional to the number of threads

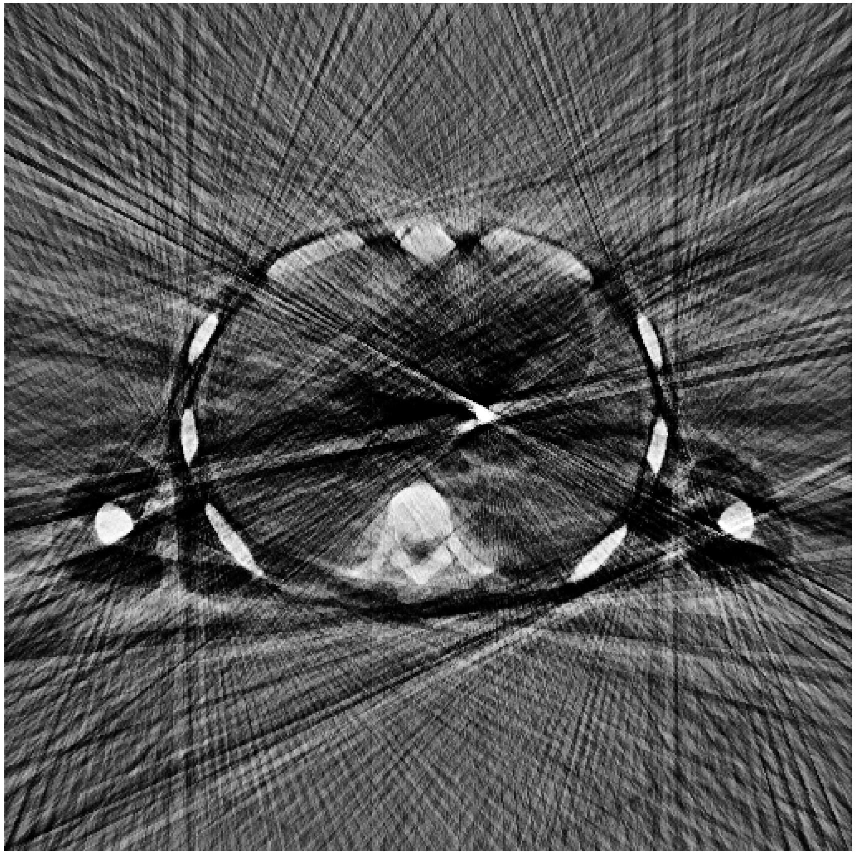
- We think that simulation of the CT would be a good candidate for the calculation on the graphics card
  - All rays from all projections can be run in parallel, no dependencies on each other
  - Current simulator is written in C, a port to CUDA-C should be possible with reasonable amount of work

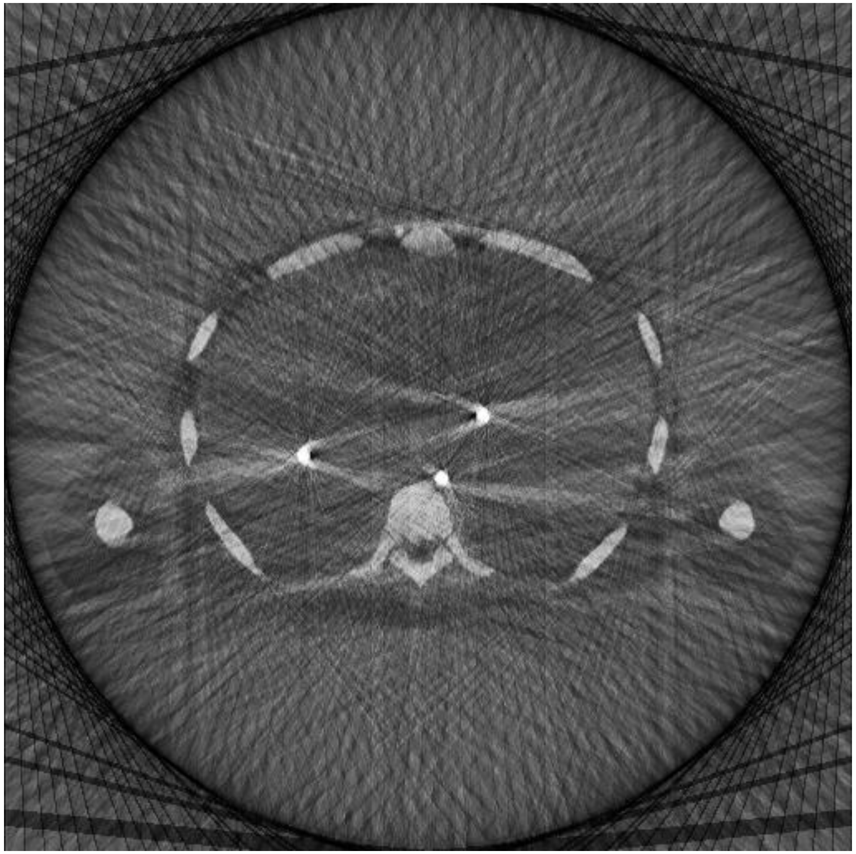
Results





Results





Future Work

More easily implementable CT artefacts

- Ring artefacts
  - Caused by miscalibrated detector
  - Multiply/Add intensity value by random numbers at the end of the ray
- Poisson Noise
  - Caused by discrete particle nature of light at low X-Ray doses
  - Modify relative photon count at the start of the ray
- Motion artefacts
  - Caused by the patient moving during the scan
  - Merge sinograms from two or more simulation runs