Estimation of Bowtie Filter Attenuation from Reconstructed CT Images

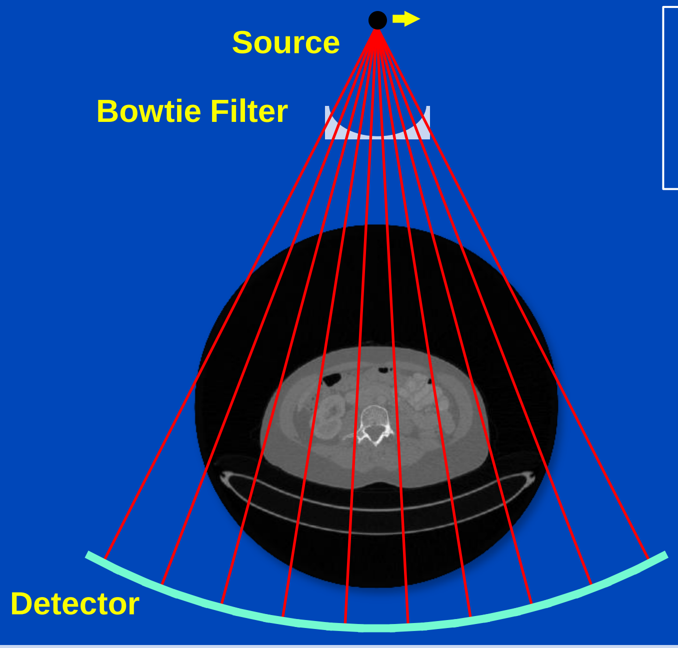
Joscha Maier, Stefan Sawall, and Marc Kachelrieß

German Cancer Research Center (DKFZ), Heidelberg, Germany

DEUTSCHES KREBSFORSCHUNGSZENTRUM IN DER HELMHOLTZ-GEMEINSCHAFT

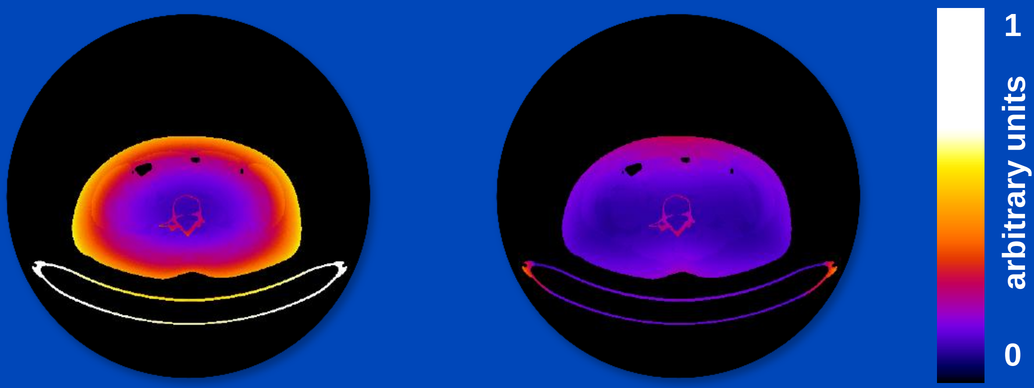
Motivation

- Commercial CT-scanners are usually equipped with a bowtie filter in order to optimize the patient dose distribution.
- Monte-Carlo dose calculations or statistical reconstruction algorithms require exact knowledge of the bowtie filter.
- The shape as well as the composition of the bowtie filter is usually not disclosed by the CT vendors.



Patient dose distribution of a circular scan without bowtie filter

Patient dose distribution of a circular scan with bowtie filter



Motivation

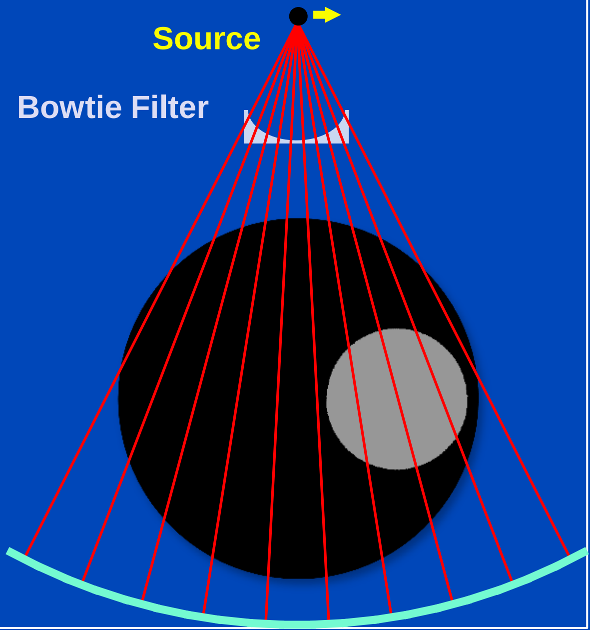
- Prior Work
  - Analysis of rawdata of a scan with empty gantry[1]
    → Rawdata not generally available
  - Measurement of bow tie profiles using real-time dosimeter[2]
    → Additional hardware required
  - Measurement of bow tie profiles using radiochromic film[3]
    → Additional hardware required
- Proposed Approach
  - In all cases the reconstructed CT images are available to the user
  - Variance distribution of reconstructed CT images contain information on the bowtie filter shape.
  - Analysis of the variance of reconstructed CT images of a calibrated object allows the estimation of the bowtie filter.

[1] B. R. Whiting et al., "*Properties of preprocessed sinogram data in x-ray computed tomography*," Med. Phys. 33(9), 3290 – 3303 (2006).
[2] B. R. Whiting et al., "*Measurement of bow tie profiles in CT scanners using a real-time dosimeter*," Med. Phys. 41(10), 101915-1 – 101915-7 (2014).
[3] B. R. Whiting et al., "*Measurement of bow tie profiles in CT scanners using radiochromic film*," Med. Phys. 42(6), 2908 – 2914 (2015).

Workflow

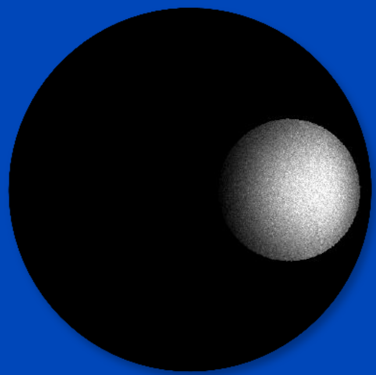
Reconstruction of N CT Scans of an object with known intersection lengths and attenuation

$$f_i = X^{-1} p_i$$



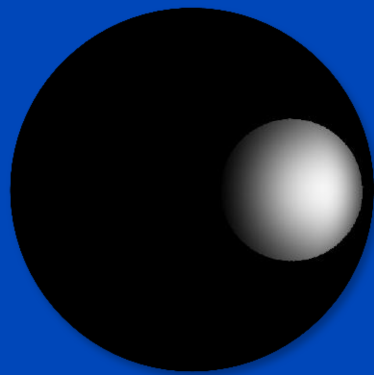
Calculation of the variance of the reconstructed images (clipped to object)

$$\sigma^2_{f,meas} = \frac{1}{N}\sum_{i=1}^{N}(f_i - \bar{f})^2.$$



Estimation of bowtie-filter attenuation such that the predicted variance fits the measured variance

$$e^{-\mu \cdot L_B} = \arg\min\left[\left(\sum(\sigma^2_{\text{f, sim}} - \sigma^2_{\text{f, meas}})\right)^2\right]$$

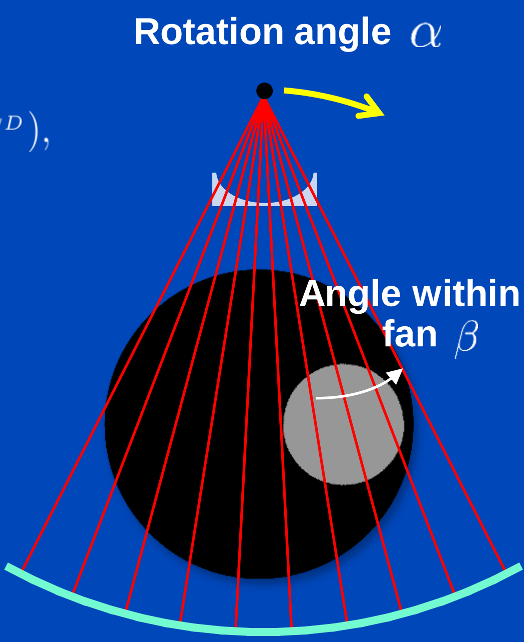


Estimation of Bowtie Filter Attenuation: Variance

- **Expectation value $n(E, \beta, \vartheta)$ of photons with energy E hitting an ideal detector element at position (β, ϑ) :**

$$n(E,\beta,\vartheta) = n_0(E) \cdot e^{-\mu_B(E)\cdot L_B(\beta)} \cdot e^{-\mu_O(E)\cdot L_O(\vartheta,\beta)} \cdot e^{-\mu_P(E)\cdot L_P} \cdot (1 - e^{-\mu_D(E)\cdot L_D}),$$

$$\begin{aligned}
\mu_B &= \text{Attenuation coefficient of the bowtie}\\
\mu_O &= \text{Attenuation coefficient of the object}\\
\mu_P &= \text{Attenuation coefficient of the prefilter}\\
\mu_P &= \text{Attenuation coefficient of the detector}\\
L_B &= \text{Intersection length through bowtie}\\
L_O &= \text{Intersection length through object}\\
L_P &= \text{Thickness of the prefilter}\\
L_D &= \text{Thickness of the detector}\\
n_0 &= \text{Photon spectrum}
\end{aligned}$$



- **Since photon matter interaction follow Poisson statistics the variance $\sigma_n^2(E, \beta, \vartheta)$ of incident photon numbers equals its expectation value: $\sigma_n^2(E, \beta, \vartheta) = n(E, \beta, \vartheta)$**

Estimation of Bowtie Filter Attenuation: Optimization

- **Calculating the propagation of the variance of the incident photons, the variance of the projection values $\sigma_p^2(\beta,\vartheta)$ is given by:**

$$\sigma_p^2(\beta,\vartheta) = \frac{\sum_E E^2 \sigma_n^2(E,\beta,\vartheta)}{\left[\sum_E E \sigma_n^2(E,\beta,\vartheta)\right]^2}$$

- **The images f are calculated from the projection data p using a filtered backprojection:**

$$f(x,y) = X^{-1} p(\beta,\vartheta)$$

- **Since the filtered backprojection is a linear operation, the image variance is given by:**

$$\sigma_{f,sim}^2(x,y) = (X^{-1} \circ X^{-1}) \sigma_p^2(\beta,\vartheta)$$

- **Finally, the bowtie filter attenuation $e^{-\mu(E)L(\beta)}$ can be estimated by minimizing the squared difference between predicted and measured variance:**

$$e^{-\mu(E)\cdot L_B(\beta)} = \underset{\mu(E),L(\beta)}{\arg\min} \left[\sum_{x,y} \left(\sigma_{\mathrm{f,\ sim}}^2(x,y) - \sigma_{\mathrm{f,\ meas}}^2(x,y) \right)^2 \right]$$

Estimation of Bowtie Filter Attenuation: Implementation

- The x-ray spectrum is approximated using a semi-empirical model of Tucker et al.
- If the material of the bowtie is known, tabulated attenuation coefficients are used. Otherwise, the attenuation coefficient can be estimated using a linear combination of two basis materials:

$$\mu_B(E) = c_1 \cdot \mu_1(E) + c_2 \cdot \mu_2(E)$$

- Estimation of the bowtie filter intersection lengths, which are assumed to be symmetric, at a given number of nodes $L[\beta_i]$. Determination of other intersection lengths by linear interpolation

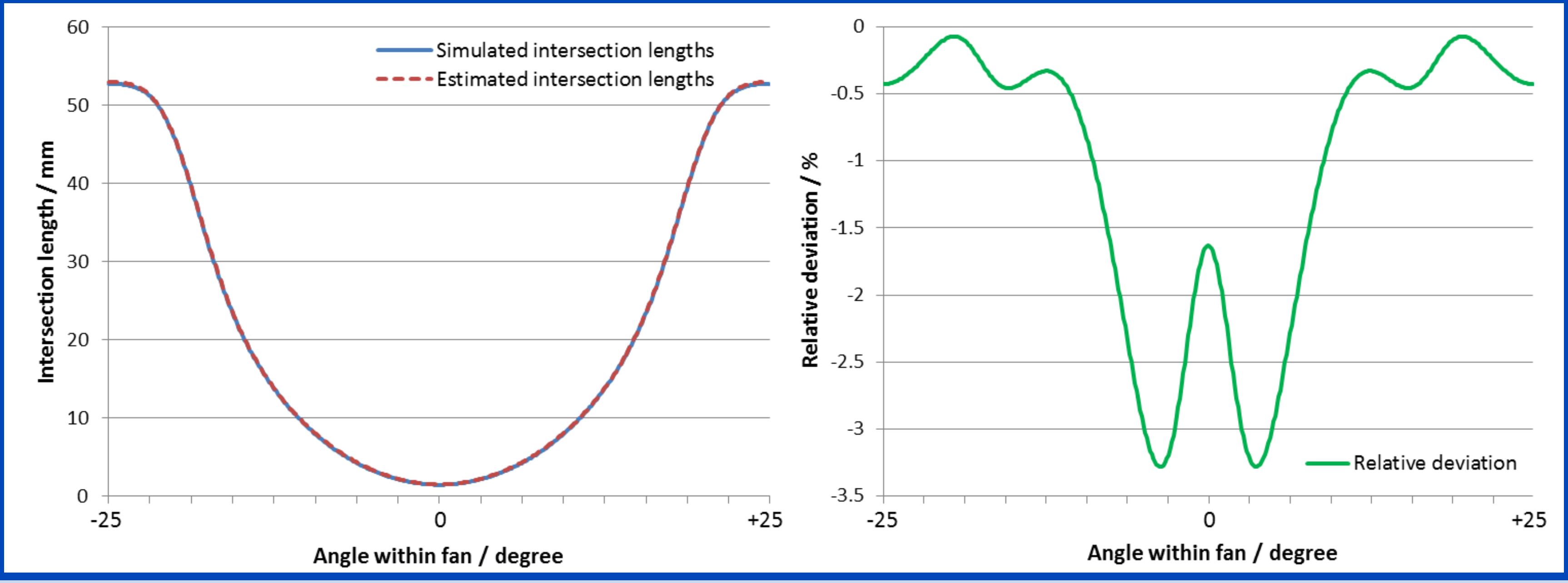
$$L_B(\beta) = w_i \cdot L[\beta_i] + (1 - w_i) \cdot L[\beta_{i+1}]$$

- Estimated parameters:

$$c_1,\ c_2, L[n_i], \text{intensity}$$

Results: Simulated Data

- A homogenous cylindrical PMMA phantom was used to simulate a 120 kV CT scan.
- A total number of 20 scans was simulated and 18 nodes were used for the estimation of bowtie filter intersection lengths.
- Simulated intersection lengths of a PTFE bowtie filter are compared to the estimated intersection lengths.



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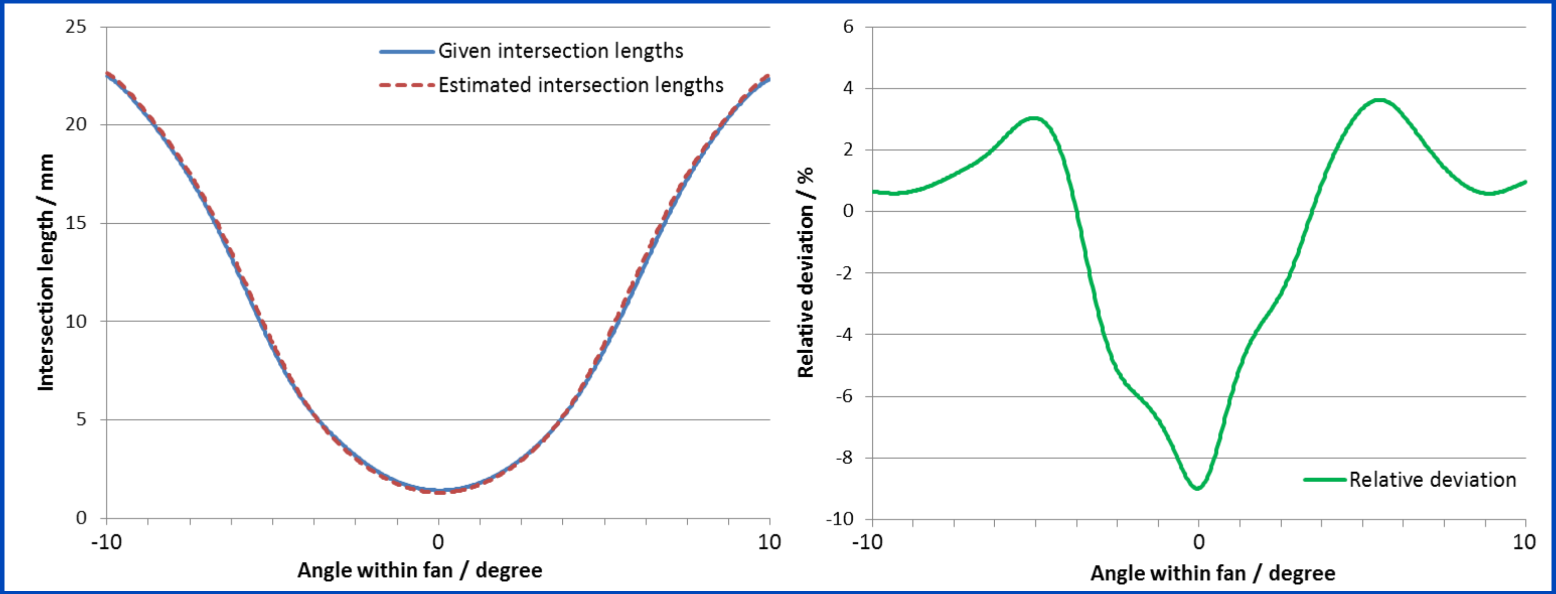
Results: Measured Data

- Measurements were conducted on a flat detector cone-beam CT with 20° fan angle at 120 kV, that is equipped with a known PTFE bowtie filter
- 20 Scans of a cylindrical PMMA phantom
- Given intersection lengths of the bowtie filter of the cone-beam system are compared to the estimated intersection lengths



Conclusion

- We proposed a novel approach to estimate bowtie filter attenuation from reconstructed CT images of calibrated objects.
- There is no need for special hardware except for a simple homogenous phantom.
- Simulations as well as measurements demonstrated that the proposed approach provides accurate attenuation curves with deviations less than 5 %.

Thank You!

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Conference Chair

Marc Kachelrieß, German Cancer Research Center (DKFZ), Heidelberg, Germany

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