

**PhD Thesis title:** 'Experimental Dosimetry and Simulation of Computed Tomography Radiation Exposure: Approaches for Dose Reduction'

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#### **ABSTRACT:**

Computed Tomography (CT) is a powerful imaging modality with ever new clinical applications and still increasing use in general diagnostic radiology and nowadays also in the staging, treatment planning and follow-up of cancer. Some of the advantages of CT leading to the increasing frequency of CT examinations are the wide availability of the technique, its fastness and its power to generate cross-sectional images of human body anatomy with very high spatial resolution. This trend is further boosted by technical improvements of CT opening opportunities for new diagnostic applications. As CT requires ionizing radiation (X-rays), the growing frequency in the use of CT examinations has simultaneously increased its contribution to patients' radiation exposure. Various methods have already been developed to reduce radiation exposure caused by CT and still the development of new strategies of radiation dose reduction is required for further reducing exposure burden. In view of this necessity, the overall goal of this thesis was to investigate the effect of optimizing beam-shaping filtration performance with regard to the efficient use of ionizing radiation and the potential dose savings associated.

In order to achieve the main aim of this research, accurate empirical models of static beam-shaping filtration currently used in commercially available CT systems have been derived on the basis of spectral measurements using Compton spectroscopy across the fan beam of a CT system. These empirical models and their evaluation by means of Monte Carlo (MC) simulation of a virtual spectroscopy system in combination with a spectral reconstruction process are presented. The MC technique has been chosen as a method of validation because it generates "experimental" radiation exposure without need for a scanner system, for complicated phantom setups, and for radiation exposure to either humans or animals. In addition, a virtually unlimited number of experiments can be conducted, and the method has been widely accepted to be a way to generate accurate dose calculations.

Since beam-shaping filtration currently available in CT systems is static during examinations, a novel dynamic beam-shaping filter that adapts to any kind of elliptical subject shape as a function of CT projection and fan angle has been developed in order to improve current filtration. The concept of this dynamic adaptive filtration has been tested by means of MC simulation of transmission profiles through a set of beam-shaping filter and a corresponding homogeneous elliptical phantom.

For accomplishing the main goal of the thesis an approach for radiation exposure evaluation based on MC simulation of CT was developed and optimized in order to simulate statistically reliable maps of radiation dose absorbed in subjects of arbitrary shape within a reasonable time. Comprehensive tests have been conducted to jointly validate this computational dosimetric tool and the corresponding dose map reconstruction process in terms of the expected accuracy of the results and execution times. To answer the central question of this thesis, CT-MC dosimetry simulations were carried out in order to evaluate the effect of the concept of dynamic adaptive beam-shaping filtration newly developed within this thesis' research in comparison with the dose reduction achievable by static beam-shaping filtration currently used in CT.

The "fast" CT-MC simulations described above were used to simulate CT acquisitions in angular steps of  $10^\circ$  without, with a static, and with a dynamic adaptive beam-shaping filtration model in order to calculate the total absorbed radiation dose in a standard phantom, i.e. a homogeneous elliptical water phantom with a major axis of 32 cm, a minor axis of 25 cm and a thickness of 15 cm.

The results of a direct comparison of measured and simulated filtered X-ray spectra indicate that the spectra match very well, with a correlation of 1 for small fan angles (below  $4^\circ$ ) and an average correlation of 0.996 for the whole field-of-view (FOV), and higher correlation factors at the border of the FOV for a simplified monoenergetic empirical model of filter attenuation than for a polyenergetic model. The overall accuracy of the polyenergetic and monoenergetic filter models was estimated by computing the average root-mean square (RMS) difference and the polyenergetic model was more accurate up to fan angles of  $12^\circ$ , but for larger fan angles the monoenergetic model has the highest accuracy.

Average RMS difference between measured spectra and those simulated using the monoenergetic model is 0.37%. For the polyenergetic model this difference is 0.39%, indicating that the measured spectra are reproduced with high accuracy for both models.

The dosimetric tool developed for accomplishing the main goal of the thesis allows for reconstruction of simulated total dose maps within subjects of elliptical cross-section with an RMS differences below 1.4% using simulations for only one-quadrant resulting in a reduction of 68.3% of CPU simulation time. Furthermore, a concept of virtual filtration reduces the simulation time per projection by an additional 10.79% while still achieving an RMS accuracy of 0.6% compared to a full simulation including modeling of "real" beam-shaping filtration.

Regarding signal homogenization the performance of dynamic adaptive beam-shaping filtration fully lives up to expectation in as much as the attenuation becomes constant throughout the complete FOV, i.e. independent of fan angle, for all projection angles.

The dose distribution within elliptical subjects using this dynamically adapted beam-shaping filtration was more uniform than with static beam-shaping filtration, and if automatic exposure control (AEC) is included a totally uniform distribution of absorbed dose can be expected by employing the dynamic filter concept proposed and developed within the course of this thesis. Results of the simulations also allow concluding that an additional reduction of absorbed radiation dose by 15% can be achieved by dynamically adapted beam-shaping filtration. Replacing static by

dynamic filtration allows relative patient skin dose reductions of around 23% in the antero-posterior (a.p.) projection and 40% in the lateral projection.

In summary, the new dynamic adaptive beam-shaping filtration allows to reduce and homogenize absorbed radiation dose distribution and has a potential for saving an additional 15% absorbed radiation dose compared to the beam-shaping filtration currently used in CT. Therefore, one can conclude that static beam-shaping filter geometry should be re-evaluated in favor of a dynamic adaptive beam-shaping filtration concept such as developed and evaluated here in order to reduce patients' (skin) dose. To this end, further work will be needed for assessing the effects of photon statistics redistribution on image quality (noise) when dynamic adaptive CT beam-shaping filtration is applied in future.

#### **Thesis-related publications:**

**L.S. Veloza**, H.U. Kauczor, W. Stiller, "Monte Carlo modeling of a computed tomography bowtie filter using measurements of unattenuated X-ray spectra: comparison of measurements with geant4 simulation", Biomed. Tech. 55(S1), 159-162 (2010).

W. Stiller, **S. Veloza**, H.U. Kauczor, "Attenuation-based dynamic CT beam-shaping filtration in dependence of fan and projection angle: Evaluation of a new method for radiation exposure reduction by Monte-Carlo simulation of spatial dose distribution", Nuclear Science Symposium Conference Record IEEE: 2625-2632 (2012).

**S. Veloza**, H.U. Kauczor, W. Stiller: Compton scattering spectroscopy for determining filtration of a clinical computed tomography system. Accepted for publication in: Proceedings of Science PoS(XLASNPA2013)033, 2014.