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Simulation of scanner- and patient-specific low-dose CT imaging from existing CT images

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ABSTRACT

Purpose: Simulating low-dose Computed Tomography (CT) facilitates in-silico studies into the required dose for a diagnostic task. Conventionally, low-dose CT images are created by adding noise to the projection data. However, in practice the raw data is often simply not available. This paper presents a new method for simulating patient-specific, low-dose CT images without the need of the original projection data.

Methods: The low-dose CT simulation method included the following: (1) computation of a virtual sinogram from a high dose CT image through a radon transform; (2) simulation of a 'reduced'-dose sinogram with appropriate amounts of noise; (3) subtraction of the high-dose virtual sinogram from the reduced-dose sinogram; (4) reconstruction of a noise volume via filtered back-projection; (5) addition of the noise image to the original high-dose image. The required scanner-specific parameters, such as the apodization window, bowtie filter, the X-ray tube output parameter (reflecting the photon flux) and the detector read-out noise, were retrieved from calibration images of a water cylinder. The low-dose simulation method was evaluated by comparing the noise characteristics in simulated images with experimentally acquired data.

Results: The models used to recover the scanner-specific parameters fitted accurately to the calibration data, and the values of the parameters were comparable to values reported in literature. Finally, the simulated low-dose images accurately reproduced the noise characteristics in experimentally acquired low-dose-volumes.

Conclusion: The developed methods truthfully simulate low-dose CT imaging for a specific scanner and reconstruction using filtered backprojection. The scanner-specific parameters can be estimated from calibration data.

1. Introduction

Computed tomography (CT) has established itself as one of the most important medical imaging modalities [1]. In fact, the number of CT examinations is still increasing [2]. An important disadvantage of CT, however, is the exposure to ionizing radiation that is inherent to the technique [1]. Accordingly, it is common practice to keep the radiation dose as low as reasonable achievable (ALARA). Unfortunately, lowering the dose yields a lower signal-to-noise ratio and thus a poorer image quality which may hamper subsequent diagnosis. Optimization of the dose/quality trade-off is a far from trivial problem as one cannot simply expose subjects to a range of radiation doses for ethical reasons. Alternatively, measurements on anthropomorphic phantoms allow real low dose measurements [3,4]. However, such phantoms may not capture the large variability in structures that can be encountered in real life. Therefore, a lower-dose CT image is usually simulated by adding noise to the underlying projection data, i.e. the sinogram [5–11]. Subsequently, the lower-dose image is reconstructed from these noisy projections using the scanner's software. However, this approach is not always achievable in practice as the projection data are often simply not available. This paper studies a method to generate low-dose CT images based on existing image data. Therefore, we introduce new methodology to determine key system parameters such as the reconstruction kernel, bowtie filter, the X-ray tube output and the read-out noise by a simple calibration procedure.

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These system parameters determine the noise properties of the simulated low dose CT-images. Furthermore, retrospective investigation of the influence of low-dose imaging might be permitted if one could generate such data directly from existing images.

1.1. Related work

Mayo et al. [9] and Frush et al. [10] were among the first to simulate low-dose CT images. They added Gaussian noise to the projection data, after which the images were generated by means of the scanner's reconstruction software. Any such approach assumes that the number of photons hitting the detector is large. However, when only a low number of photons is detected, the properties of the noise in the sinograms become much more complex. Then, the readout noise becomes significant and the measured signal is best described by compound Poisson statistics [12–14]. Still, many low-dose CT-simulators have merely added Gaussian noise to the raw projection data [8,15,16,7]. Zabic et al. [17] extended the noise model to correctly reflect the noise (co)variances under photon-starvation conditions and appropriately simulate detector noise artifacts. Furthermore, Wang et al. combined the raw data acquired at two tube-voltages, which allowed also simulating adjustments in the tube-voltage [16]. Similarly, Wang et al. [18] present a method for generating simulated low-dose cone-beam CT (CBCT) preview images. Essentially, correlated noise is injected into the original projections after which images are reconstructed using both conventional filtered backprojection (FBP) and an iterative, model-based image reconstruction method (MBIR).

Simultaneously, the need for meaningful characterization of image noise beyond that offered by pixel standard deviation became increasingly important [10,8,7,19]. Boedeker et al. [20] and Faulkner et al. [21] proposed to use the NPS and the noise equivalent quanta (NEQ) to describe the noise properties in CT images, whereas Joemai et al. [7] used the NPS and variance to validate their low-dose CT model. Mieville et al. [22] investigated the spatial dependency and non-stationarity of the NPS. Verdun et al. [23] provide a review on image quality characterization and the dependency of the NPS and standard deviation on several scanner parameters.

The work that was done to describe the NPS of CT images also yielded techniques to estimate the reconstruction kernel. This proved very valuable information, since manufacturers are often reluctant to disclose the kernels. Other scanner-specific parameters, such as the bowtie filter and the readout noise, were derived from the projection data [8,14,12]. To the best of our knowledge the bow tie filter was never derived from actual image data.

In case projection data of the scanner is not available an approach based on simulated projection data from existing image reconstructions can be used to simulate low dose CT-scans. Initially, Wang et al. [24] and Kim and Kim [25] presented preliminary work on simulating low-dose CT scans from the reconstructed images. Wang et al. aimed to develop a simulation technique based on image data such that it produced similar results as a method using the original projection data. Kim and Kim [26] presented a comprehensive, image-based framework for reduced-dose CT simulation. The key characteristics of the CT system are estimated in this work based on several measurements of a tapered, cylindrical phantom: the reconstruction filter, noise parameters and the photon flux of the X-ray tube. Subsequently, reduced dose CT noise images are generated from a synthesized sinogram. The noise equivalent quanta (NEQ) is a key parameter that is used to determine the system parameters. Essentially, it reflects the (squared) SNR in a CT image, measured from the noise image of a uniform object. Kim and Kim adopt a linear relation between NEQ per detector element and the NEQ per image to specify the amount of noise that has to be added. This relation was derived (amongst others) by Wagner [27] and Hanson [28] assuming that the attenuation at the varying projection angles is uniform.

1.2. Objective

This paper presents a new framework to simulate lower-dose CT imaging from existing CT images without using the original projection data. We take a different approach to image-based low dose CT simulation compared to Kim et al. [26]. The most important additional value compared to their work is that our approach enables estimation of all scanner-specific parameters directly from the calibration scans without requiring technical information provided by the manufacturer. In particular the estimation of the bowtie filter directly from the measurements is an important novelty of our work. Another difference is that our method for estimating the system parameters relies on the variance in signal intensity reflecting the noise level. While doing so we do not need to assume that the noise properties of the projections are uniform. Additionally, Kim used a small region of interest in the center (where the noise properties are uniform) of a tapered phantom to estimate the photon flux and the read-out noise. Instead, we can use the complete phantom to estimate the system parameters. As such, a larger region of the image is involved which should improve the precision of the estimation.

The paper is organized as follows. Section 2 describes the materials and methods; Section 2.1 describes the CT-examinations, Section 2.2, the actual low-dose simulation method and Section 2.3. Subsequently, Section Section 2.3 goes into how several system parameters can be estimated from CT images. The outcome is discussed in Section 4.

2. Material and methods

2.1. Materials

CT images of a water cylinder 34 cm in diameter and an anthropomorphic pelvic phantom were acquired on a Philips Brilliance 64 CT scanner at the Academic Medical Center in Amsterdam, The Netherlands. A modified CT colon protocol was used, since the intended application is CT colonography. The modifications only concerned the tube current, which was adjusted to control the dose level and the acquisition mode, which was sequential for the water cylinder (i.e. imaging the exact same plane) and the pelvic phantom. Table 1 list the parameter settings.

CT images of the water cylinder were used to estimate the unknown, scanner-specific parameters (see Section 2.3). Here, the settings listed under 'Calibration/Training' (Table 1) were used. Subsequently, separate images of the water cylinder and images of the pelvic phantom were used to validate the low-dose simulation model (settings listed under 'Test'). Therefore, simulated and measured noise characteristics were compared by means of the pixel variances and the NPS.

2.2. Lower-dose CT simulator

In our simulation method we first create a virtual sinogram from a high-dose CT image, which is processed to yield one corresponding to a lower dose. Subsequently, the high-dose virtual sinogram is subtracted from the lower-dose sinogram. The resulting noise sinogram is used to reconstruct a noise volume via filtered back-projection. Addition of the noise volume to the original high-dose image results in the lower-dose image.

Fig. 1 presents an overview of the low-dose CT simulation steps;