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Referenceless Beam Hardening Correction in 3D Computed Tomography Images of Multi-Material Objects

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Abstract

We propose a new method to reduce the effects of non-linearities such as beam hardening in Computed Tomography (CT) images. Due to the polychromatic characteristics of X-ray sources the ratio of attenuated and incoming intensity is not exactly exponential with the material thickness. Within CT images this leads to artifacts like cupping, streaks and blurring. Especially in multi-material objects with highly different attenuation characteristics these effects are even more complex. The method described in this paper allows the correction of beam hardening artifacts in multi-material objects. The presented approach does not require any estimate or knowledge of the incident X-ray spectrum nor of material characteristics like mass density or absorption coefficients. The method uses the original projection images and works without any reference measurements. Several specimens of miscellaneous material combinations were measured with CT. Afterwards, the artifact correction was applied to show the efficiency of the proposed method.

Keywords: CT, NDT, X-Ray, artifacts, beam hardening

1. Introduction

Computed Tomography (CT) is an imaging method used to generate three-dimensional images from a series of two-dimensional X-ray projections. Due to the penetrating quality of the X-rays it is possible to analyze interior object structures. The CT reconstruction algorithm is based on the assumption that a particular volume element attenuates all X-rays in the same way independent of the projection angle or propagation path length. Therefore, the linear attenuation coefficient $\boldsymbol{\mu}$ changes non-linearly along the propagation path. Hence, the reconstructed image of the specimen seems to have changing densities depending on the location in the volume. This effect is called beam hardening and induces several artifacts like cupping and dark streaks between regions of high mass density [1-10].

A vast amount of correction approaches has been proposed since the computed tomography was introduced in the early 1970s. To give a short review on beam hardening corrections, two common methods are presented subsequently. The technique called Linearization is based on the estimation of the relation between a propagated path length within the specimen and an according measured weakened intensity Preprint submitted to Elsevier 3 January 2008 by means of various estimation algorithms [1-10]. The characteristic line can be determined by performing a reference measurement of a step wedge. Alternatively, the characteristic line can be determined out of the reconstructed CT image itself [ref]. Afterwards, the artifact reduced CT image can be reconstructed using the generated characteristic line. This method is only applicable if the tested object is made of only one material.

Another common beam hardening correction method is based on the use of reprojections. Unlike X-ray projections reprojections are computed X-ray images based on the material distribution within a CT image. However, previous knowledge about the used energy spectrum and all present materials is necessary. Due to the fact that this technique was conceived for medical CT systems, this previous knowledge is normally existent. In industrial CT applications this information is unavailable in most cases and doesn't allow a beam hardening correction.

The scope of this paper is the presentation of a method which allows performing a beam hardening correction on CT images of multi-material objects without any knowledge about the used X-ray spectrum and present materials.

2. Method

2.1 Analyzing the Problem

While propagating through matter, X-rays with an incoming intensity I_0 are attenuated according to the specimen material characteristics. These characteristics are the mass density $\boldsymbol{\rho}$, the atomic number **Z**, the used photon energy **E** and the length of the propagation path **x**. All material and energy dependencies are expressed by the linear attenuation coefficient $\boldsymbol{\mu(\rho,Z,E)}$. This physical effect of attenuation is described by Beer's law, which is in case of a mono-energetic X-ray spectrum:

$$I_{mono} = I_0 e^{-\int_X \mu(\rho,Z,E)dx} \tag{1}$$

Theoretically, emitted photons can reach an energy between $\boldsymbol{E_{min} > 0}$ **eV** and $\boldsymbol{E_{max} = U_b \cdot e}$, where $\boldsymbol{U_b}$ is the maximum X-ray tube voltage and $\boldsymbol{e}$ the elementary charge. Additionally the number of emitted photons per energy level is not constant. Therefore, each photon is part of a polychromatic X-ray spectrum ***S(E)***. Furthermore the used detector system has an energy dependent efficiency ***D(E)***. Both energy dependencies cannot be obtained separately. Therefore their product ***S(E)·D(E)*** can be understood as a weighting factor ***W(E)*** for each present energy and results in the following expression.

$$I_{poly} = I_0 \int_{E_{\min}}^{E_{\max}} W(E)\, e^{-\int_X \mu(\rho,Z,E)dx} dE \tag{2}$$

with

$$\int_{E_{\min}}^{E_{\max}} S(E) \cdot D(E)\, dE = \int_{E_{\min}}^{E_{\max}} W(E)\, dE = 1 \tag{3}$$

The difference of equation 1 and 2 equals the required amount of correction. Therefore, an uncorrected intensity $\boldsymbol{I_u}$ results in a beam hardening corrected intensity $\boldsymbol{I_c}$ by adding this intensity difference. Hence, $\boldsymbol{I_c}$ can be used to compute an artifact-free CT image. The problem is to estimate $\boldsymbol{I_{mono}}$ and $\boldsymbol{I_{poly}}$ without any knowledge of the energy dependencies or the material characteristics.

2.2 The proposed Correction Approach

The correction method proposed here is based on the reprojection approach. Basically, the mono-energetic and poly-energetic reprojections have to be computed using previous knowledge of material characteristics as well as the used energy spectrum $W(E)$. The approach described here, doesn't require this information since it can be obtained out of the reconstructed CT image itself. For that purpose, the reconstructed CT image has to be segmented into all present N_m materials. A simple global threshold algorithm is convenient in most cases. Afterwards, a ray tracing algorithm is used to compute the propagation path lengths of the X-rays within the different material sections for each detector pixel. Now, it is possible to form a relation between propagation path lengths in each material and measured intensity. Using this information allows to compute mono-energetic and poly-energetic reprojections for each angular sample. The difference of both reprojections equals the required amount of correction. The whole correction process has an iterative nature and is charted in figure 1.

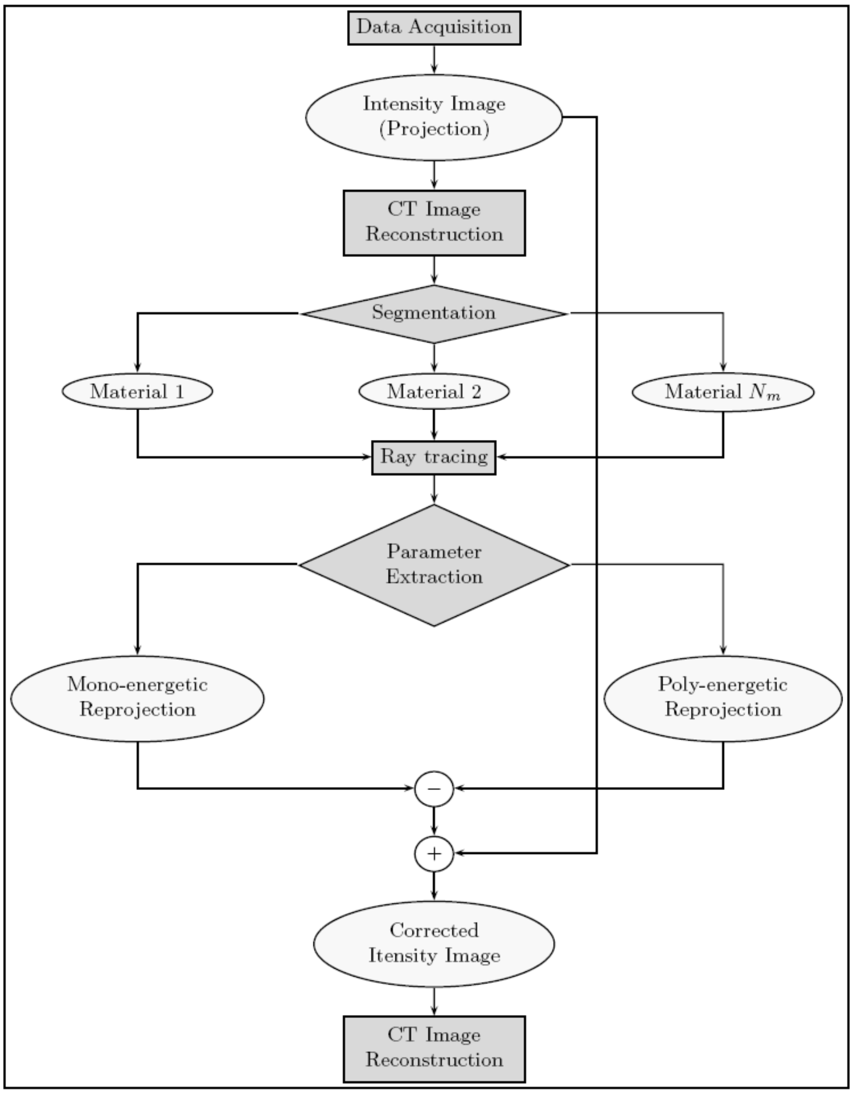

Figure 1: Flow chart of the proposed beam hardening correction method.

A corrected X-ray projection can be computed using the following expression:

$$I_c = I_u + I_0\, e^{-R_{mono}(\mu,x)} - I_0\, e^{-R_{poly}(\mu,x)}, \tag{4}$$

with

$$R_{mono}(x_1 \dots x_m, \mu_1 \dots \mu_m) = \sum_{m=1}^{N_m} \int_{X_m} \mu_m(\rho, Z, E)\, dx, \tag{5}$$

$$R_{poly}(x_1 \dots x_m, \mu_1 \dots \mu_m) = \sum_{m=1}^{N_m} \ln \int_{E_{min}}^{E_{max}} W(E)\, e^{\int_{X_m} \mu_m(\rho,Z,E)\, dx_m}\, dE \tag{6}$$

The unknown parameters $\boldsymbol{R_{mono}}$ and $\boldsymbol{R_{poly}}$ can be approximated by a regression method based on radial basis functions using the measured intensity images and the previously computed propagation path lengths [7].

3. Results

In order to test to presented method without any influence of disturbance variables like noise, we simulated a virtual test object with help of the analytic simulation tool Scorpius-XLab®. We used approximated parallel beam geometry with high source detector and source object distances, to avoid any cone beam artifacts. Additionally we didn’t simulate any pre-filtering beside the X-ray tube window. All simulation parameters are listed in table 1.

	Parameter	Value
Trajectory	SDD (Source Detector Distance)	10 m
	SOD (Source Object Distance)	5 m
	Angular samples / 360°	400
Source	Voltage	200 kV
	Current	1 mA
	Anode angle	0,175 rad
	Filter	0,7 mm Beryllium
Detector	Type	flat panel
	Number of Pixels X,Y	512
	Pixel Distance X,Y	0,4 mm
	Fill Factor	0,7
	Exposure Time	1 s
Object	Material 1	Aluminum
	Material 2	Acrylic glass
	Diameter	5 cm

Table 1: Simulation parameters.

The simulated object has the shape of the Yin and Yang Symbol. After reconstructing the object a global threshold was applied to the data in order to perform segmentation. Two material sections ware segmented.

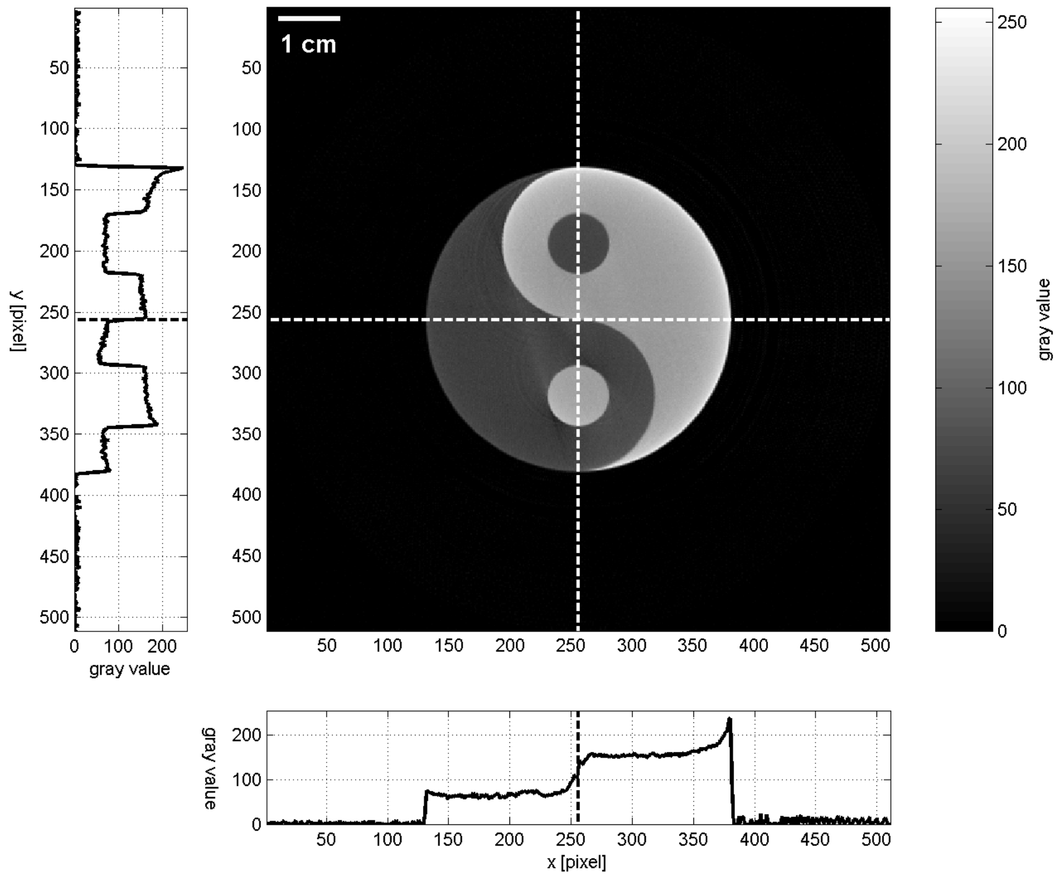

Figure 2: Central slice of simulated object Yin and Yang and corresponding line profiles.

Using the algorithm described above it is possible to compute the required amount of correction for each projection by subtracting a mono-energetic and a poly-energetic reprojection. As shown in figure 2(a), a final reconstruction leads to an almost artifact-free CT image.

The difference of corrected and uncorrected CT image is shown in figure 2(b). Darker gray values indicate decreased gray values. Especially the dark outer edge of the aluminum section shows that a bigger amount of correction was necessary to remove the cupping. In general, object region made of same material appear homogeneous.

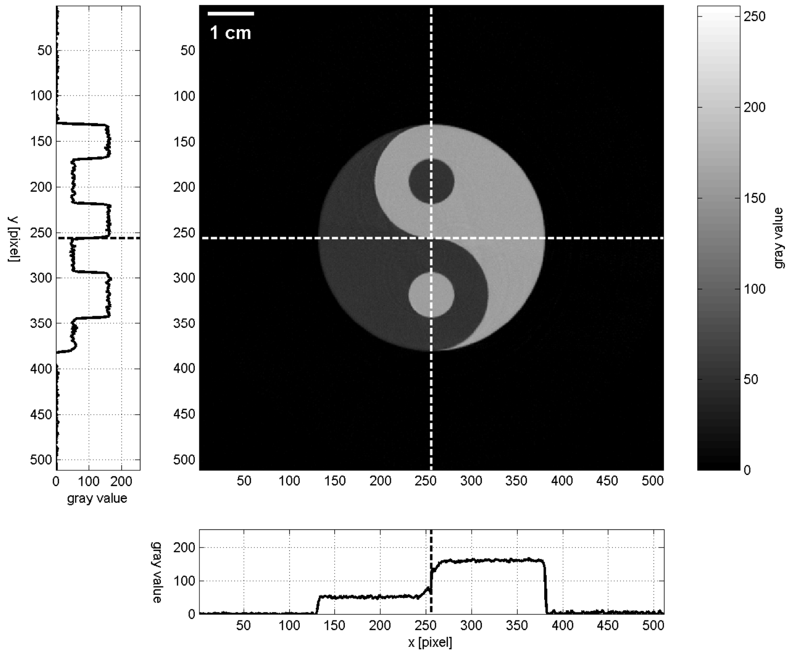

Figure 3 a): Central slice of beam hardening corrected object and corresponding line profiles.

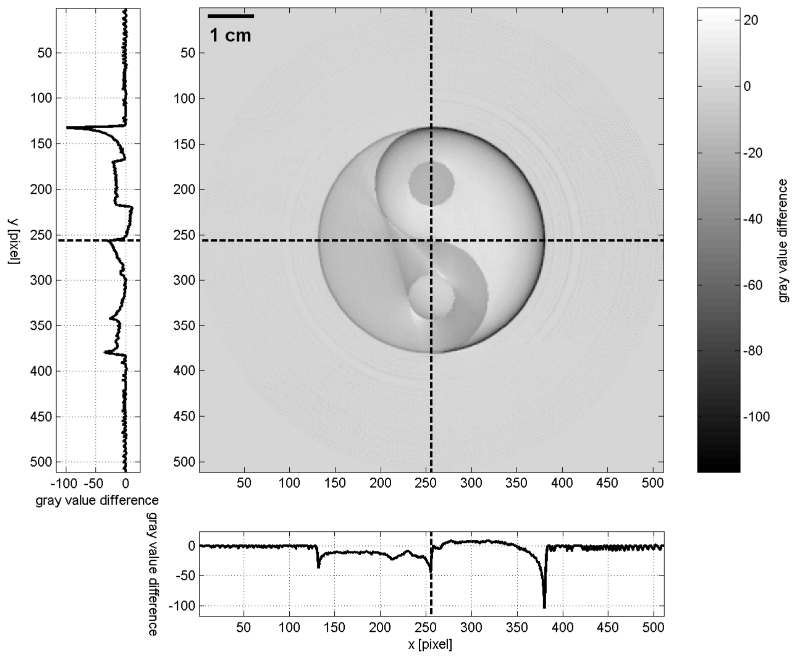

Figure 3 b): Central slice of difference of beam hardening corrected and uncorrected object.

4. Conclusion

This paper introduces a method to perform a beam hardening correction on CT images of multi-material objects. It is based on the reprojection technique. Theoretically, it is possible to perform a beam hardening correction on CT images measured with any CT system. No reference measurements are required. That means no a priori information about energy distribution, trajectory of the measurement system or material characteristics are needed.

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