

Beam Hardening Correction of Multi-Material Objects

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Abstract

In this paper we present a method for reducing beam hardening artifacts in Computed Tomography (CT) images. Due to the polychromatic characteristics of common X-ray tubes attenuation does not increase linearly with penetrated material thickness. This leads to dark streaks, blurring and so called cupping artifacts. Additionally, form errors hinder dimensional evaluation. In CT images of objects made of several materials with significant different attenuation characteristics these effects are even more distinct. The method described in this paper allows the correction of beam hardening artifacts in multi-material objects. Knowledge of the impinging X-ray spectrum or the materials absorption characteristics is not necessary. The method works iterative and without any reference measurements. Specimens of several material combinations were tested with CT and beam hardening corrected with the proposed algorithm.

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. The penetrating quality of the X-rays allows analyzing interior object. The CT reconstruction algorithm is based on the assumption that a particular volume element attenuates all X-rays in the same way regardless of projection angle or propagation path length. Therefore, the linear attenuation coefficient μ changes non-linearly. 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 in the early 1970s. In order 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 by means of various estimation algorithms [1-10]. The characteristic line can be determined by performing a reference measurement with a step wedge made of the same material as the specimen itself. Alternatively, the characteristic line can be determined out of the reconstructed CT image [6]. Afterwards, the artifact reduced CT image can be reconstructed using the generated characteristic line. This method will only be applicable, if the tested object is made of 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 an approximated material distribution. 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, 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 ρ , 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 $\mu(\rho, Z, E)$. This physical effect of attenuation is described by Beer's law, which is in case of a mono-energetic X-ray spectrum:

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

Theoretically, emitted photons can reach an energy between $E_{min} > 0$ eV and $E_{max} = U_b \cdot e$ where U_b is the maximum X-ray tube voltage and 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 $S(E) \cdot D(E)$ can be understood as a weighting factor $W(E)$ for each present energy and results in the following expression.

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

with

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

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

2.2 Proposed Correction Algorithm

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. For that purpose, the reconstructed CT image has to be segmented into all present N_m materials. We used a modified IsoData algorithm [11] for segmentation. 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. By performing a multi dimensional regression on that data a functional relation between propagation path lengths in each material and measured intensity can be found. Using this information allows computing 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 is iterative and charted in figure 1. A corrected X-ray projection can be computed using the following expression:

$$I_c = I_u + I_0 e^{-R_m(\mu, x)} - I_0 e^{-R_p(\mu, x)}, \quad (4)$$

with

$$R_m = \sum_{m=1}^{N_m} \int_{X_m} \mu_m(\rho, Z, E) dx, \quad (5)$$

$$R_p = \sum_{m=1}^{N_m} \ln \int_{E_{min}}^{E_{max}} W(E) e^{\int_{X_m} \mu_m(\rho, Z, E) dx_m} dE \quad (6)$$

The unknown ray sums R_m and R_p 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].

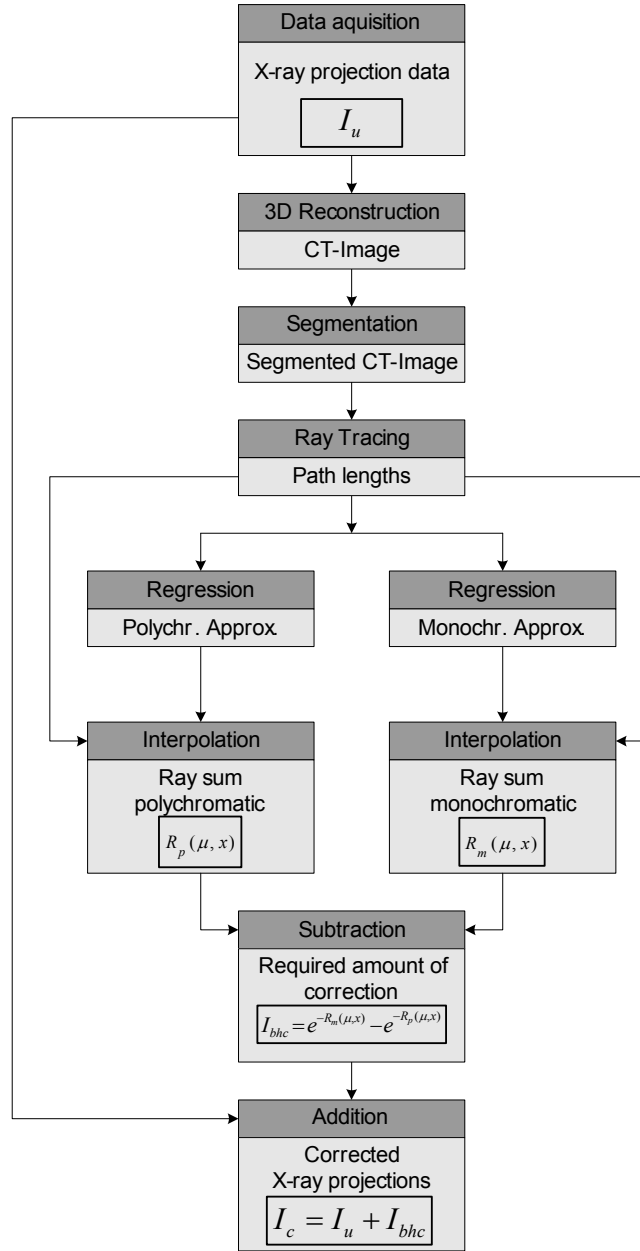


Figure 1: Flow chart of the proposed beam hardening correction method.

3. Results

In order to test the presented method we made measurements of a test specimen. This specimen is an aluminum cylinder with five drillings. Each can be filled with a steel pin. Several combinations were tested with the measurement parameters in table 1. After reconstructing the object a global threshold was applied to the data in order to perform segmentation. Two material sections were segmented. The algorithm described above allows computing the required amount of correction for each projection by subtracting mono-energetic and poly-energetic reprojections. As shown in figure 3(a), a reconstruction after only one iteration leads to an almost artifact-free CT image. Dark streaks and cupping are completely. The dark spots next to the pin are removed as well, beside a thin dark edge which represents an air gap between pin and hole.

	Parameter	Value
Trajectory	SDD (Source Detector Distance)	835 mm
	SOD (Source Object Distance)	285 mm
	Angular samples / 360°	800
Source	Voltage	220 kV
	Current	100 μ A
	Filter	500 μ m Copper
Detector	Type	flat panel
	Number of Pixels X,Y	1024
	Pixel Distance X,Y	0,2 mm
	Exposure Time	1 s
Object	Material 1	Aluminum
	Material 2	Steel
	Diameter	50 mm

Table 1: Measurement parameters.

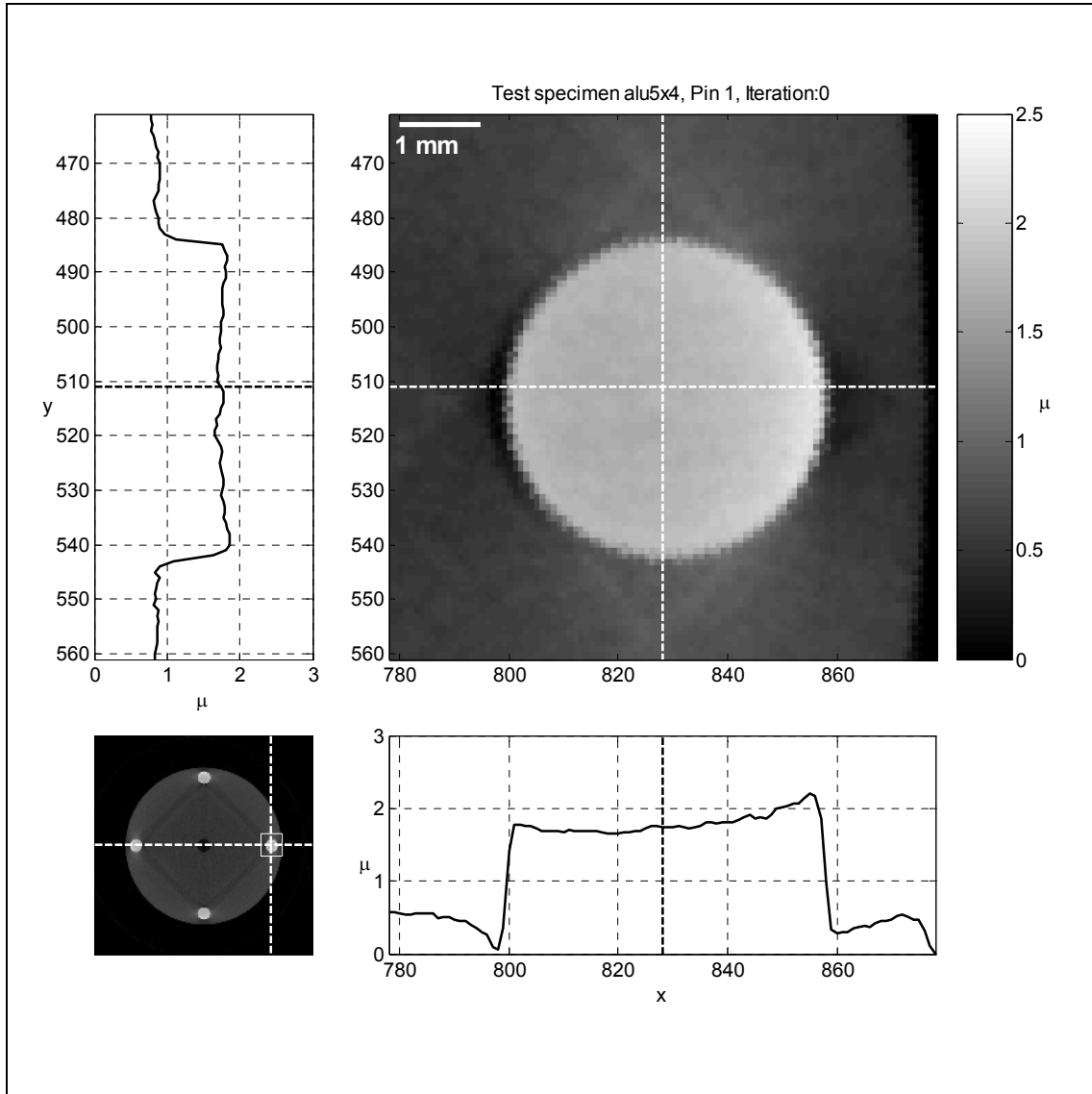


Figure 2: Part of the central slice of the measured specimen. The whole slice is shown to the lower left. Dark streaks can be found between the pins. The line profiles show the cupping artifact within the steel pins and some dark spots next to the pin.

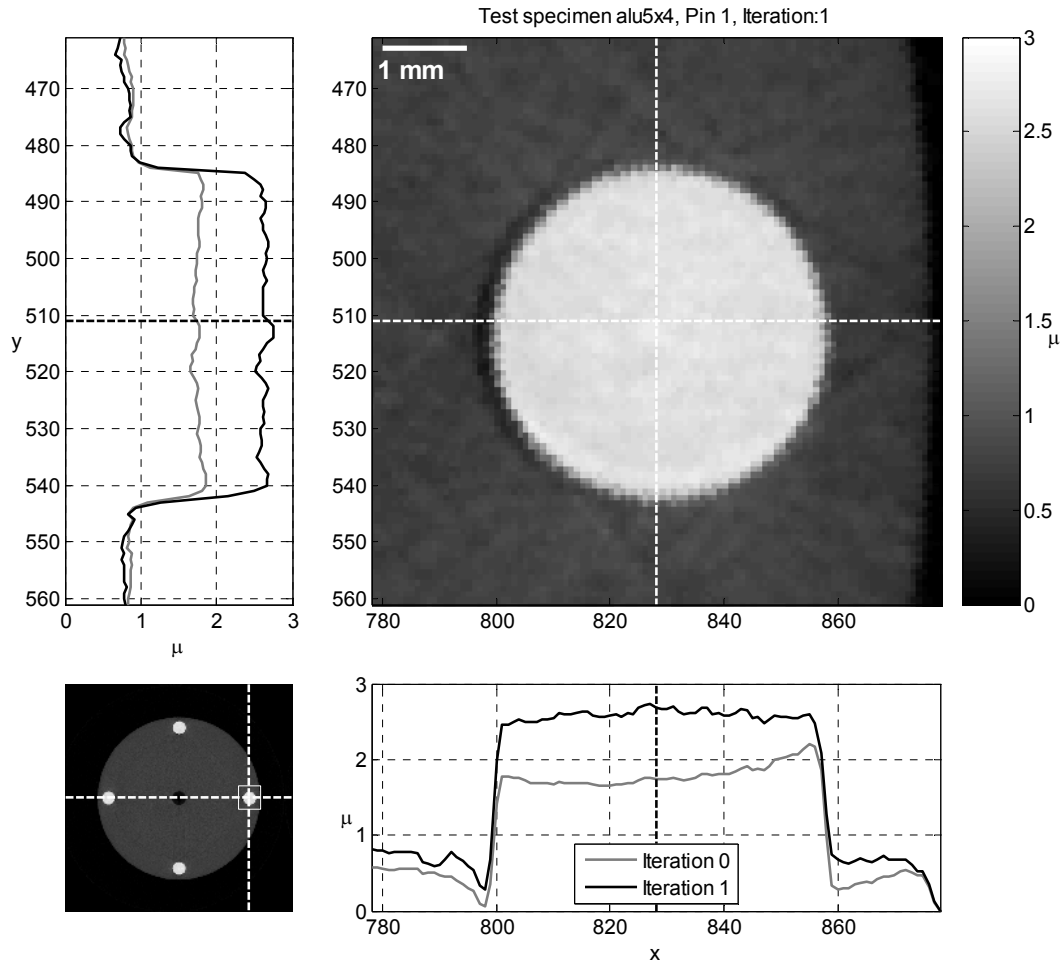


Figure 3 a): Part of the central slice of the measured specimen with applied correction algorithm. The whole slice is shown to the lower left. The dark streaks are removed. The line profiles show that the cupping artifact within the steel pins is removed as well. The dark spots next to the pin vanished beside a dark edge which represents an air gap between pin and hole.

4. Conclusion

In this paper a beam hardening correction for CT images of multi-material objects is described. 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 or material characteristics is needed.

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