Influence of Scatter in X-ray Imaging and Scatter Correction Methods for Industrial Applications

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48.1 Artifacts from Scattered Radiation
Scattered photons are one of the main sources of image degradation in industrial X-ray computed tomography (CT) (see Section III, Chapter 32). The scattered radiation that reaches the detector represents an additional signal contribution that does not correspond to the classical model of straight line X-ray beam attenuation, described by the Beer–Lambert law. This means that the scattered radiation introduces high non-linearity in the CT scan. As a result, scattered radiation leads to a considerable blur in the measured X-ray images, which leads to a general loss of contrast in the radiographs as well as the reconstructed images. Since scattered photons add, by definition, spurious signals, their effects are generally similar to beam hardening artifacts. Moreover, the non-linearity introduced by scattered radiation adds to the image degrading effects beam hardening has on the measurement (Kasperl et al. 2003). This means scattered radiation enhances beam hardening artifacts such as cupping and streaking. Cupping artifacts can commonly be observed in large and uniform areas of an object. Instead of a homogeneous area, a reconstructed volume exhibits a non-uniform gray value distribution, where the attenuation values in the middle of the object are underestimated. Streaking artifacts mainly occur between high-contrast details in the object volume. They are caused mainly by photon starvation; however, beam hardening and scattered radiation add to the image degradation effect, leading to streak artifacts in the reconstructed images. Typically, these artifacts appear as dark streaks connecting the high-absorbing features with adjacent bright streaks.

Figure 48.1 shows the exemplary case of an X-ray CT measurement of an aluminum cylinder head exhibiting the aforementioned artifacts. It can be seen that streaks occur along directions with high attenuation. Moreover, in Figure 48.1, it can be seen that cupping introduces an artificial variability in the gray value of the reconstructed image for single material regions.

Scatter artifacts constitute a considerable problem in industrial CT. The general loss of contrast, as well as the cupping and the streaks, can impede the detection of defects. Particularly, dimensional measurements suffer from scattered radiation. The blurred edges in the reconstructed volume hinder an accurate surface detection, and thus, prevent the exact measurement of sizes and wall thicknesses.

48.2 Sources of Scattered Radiation

48.2.1 Physics of X-ray Scatter
X-rays travelling through matter can undergo several different physical interactions. These interactions can result in the scattering or the absorption of the incident photon. The four main interactions of X-rays in matter are the photoelectric effect, Rayleigh scattering, Compton scattering, and pair production (see Section I, Chapter 1). The quantitative occurrence of these effects depends on the energy of the incident photon as well as the atomic number of the material. This means that the relative importance of these physical interactions in a given X-ray CT scan depends on the spectrum of the X-ray beam as well as the material of the object under investigation.

Figure 48.2 shows that, while photoelectric absorption is dominant for X-ray energies below 100 kiloelectronvolt (keV), incoherent scattering in the form of Compton interactions dominates
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Pair production becomes relevant for photon energies above 1 megaelectronvolt (MeV). Moreover, it exceeds Compton Scattering as the dominant physical interaction for energies above 10 MeV.

At small X-ray energies, the photoelectric effect dominates over all other physical interactions. For a given material of atomic number $Z$ and an incident photon of energy $E$, the occurrence probability of the photoelectric effect is approximately proportional to:

$$P_{\text{photoelectric effect}} \propto \frac{Z^n}{E^{1.5}}, \quad \text{with } 4 \leq n \leq 5$$

**FIGURE 48.1** Measurement of an aluminum cylinder head under low and high scatter conditions showing the typical artifacts that scattered radiation introduces into the images. (a) Shows the aluminum cylinder head and one radiograph. (b) Scan and reconstruction parameters. The typical cupping and streaking artifacts can be seen in one reconstructed slice of the cylinder head in (c) corresponding to the horizontal line in (a). Low scatter conditions were achieved by slit collimation at the detector.

**FIGURE 48.2** Plot of the photon cross-sections for steel at various energies. The cross-section data for this plot were retrieved from the NIST photon cross-section database XCOM. It can be seen that, for low X-ray energies around 80 keV, the photoelectric effect, dominates over all other interactions. At energies of several hundred keV, for example at the 300 keV line, Compton scattering, is the main physical interaction process. At higher energies exceeding 1 MeV, pair production events can occur. However, the process of pair production, supersedes the Compton interaction as dominant interaction process only for energies above 10 MeV.
In a photoelectric interaction, the incident photon interacts with an electron that is bound to an atom. The energy of the photon will be fully absorbed in the process and, as a result, the electron will be kicked off the atom. This energy needed for the photoelectric effect to occur has to exceed the binding energy of the electron in the atom. The photoelectric effect leaves behind an ionized atom with a vacancy in one of its bound shells. This vacancy will subsequently be filled by an outer shell electron of the atom or a free electron in the material. During this process of rearrangement of the electron in the bound shells of the atom, excess energy will be radiated away in the form of characteristic X-rays.

The Compton interaction describes the inelastic scattering of a photon by an electron. In typical X-ray CT context, the electron involved in a Compton scattering event is typically a lightly bound electron of an atom. Compton interactions lead to the deflection of the incident photon, accompanied by a transfer of a part of the energy of the photon to the recoil electron. The transferred energy can vary over the whole range of the energy of the interacting photon. This, in turn, means that all scattering angles of the photon are possible. The shift in energy observed for the photon is dependent on the scattering angle. It is typically described by the photon’s wavelength shift, which is inversely proportional to its energy:

$$\Delta \lambda = \frac{(h/c)(1 - \cos(\theta))}{E}$$

The probability of the occurrence of a Compton scattering event is linearly proportional to the atomic number of the material. The angular distribution from Compton interactions is given by the Klein–Nishina formula. A plot of the angular distribution of Compton scattered photons with respect to their initial energy shows that Compton scattered radiation is highly forward directed for high-energy photons while the distribution is symmetric in the forward and backward directions for photons with very low energy. An exemplary case of angular distributions of Compton scattered photons at different energies can be seen in Figure 48.3.

In contrast to the Compton interaction, Rayleigh scattering can be described as an elastic scattering event, because the energy of the interacting photon doesn’t change. Rayleigh scattering angles are typically much smaller than Compton scattering angles. Rayleigh scattering mainly has to be considered in very low energy X-ray applications. At energies of several tens of keV, Rayleigh scattering dominates over all other X-ray scattering interactions.

In the presence of a nucleus or an electron, a photon can create a pair of an electron and its antiparticle, the positron. This interaction is called pair production. In order to create these two particles, the incident photon needs to have an energy that is at least twice the rest energy of the electron. As a result, pair production does not occur for photon energies below 1.022 MeV. The positron created in a pair production event will likely annihilate with a nearby electron. This will result in the creation of a pair of two photons, commonly known as annihilation radiation. The two photons will both have an energy of 0.511 MeV, corresponding to the rest mass of the electron. Moreover, the annihilation photons will be oppositely directed due to momentum conservation.

Bethe and Heitler (1934) were the first to derive the differential cross-section for the process of pair production. To date, several corrections have been added to the formula, such as the Coulomb Correction and a correction for screening, as well as radiative corrections. Generally, pair production can be described as increasing approximately with the square of the atomic number of the interacting matter and increasing with photon energy. Pair production dominates for energies above 10 MeV. From energies of 100 MeV on, the cross-section of pair production saturates, which means it can be characterized by a constant.

Besides the physical interactions involved in the scattering process, the order of scattering of incident photons at the detector is of importance when trying to mediate scatter artifacts. Figure 48.4 shows a sketch of a cone beam CT setup with single and multiple scattered photons. If a photon underwent only one scattering event on its way to the detector, it is considered as part of the single scattered radiation. Due to knowledge of the relative importance of all physical interactions as well as knowledge of the differential cross sections of the interactions, the impact of single scattered radiation can be estimated analytically. This will be presented in Section 48.3.2. Multiple scattered radiation is much more involved as it contains photons that underwent several scattering events, including scattering through different physical interactions. As a result, the amount and distribution of multiple scattered radiation are much harder to estimate. With increasing X-ray beam energies and increasing object sizes, the ratio of multiple to single scattered radiation will increase. This means that the impact of multiple scattered photons on the measured signal is of particular importance for high-energy X-ray CT measurements. Figure 48.5 shows the simulated distributions of single and multiple scattered photons for an aluminum step cylinder measured with a 450 keV X-ray source. The first
and higher order scatter was distinguished using a Monte Carlo simulation.

### 48.2.2 Sources of Scattering in an X-ray CT Setup

In a common CT system, three general sources of scattered radiation can be distinguished (Stritt et al. 2016b). First of all, the object itself is an obvious origin of scattered photons. As described previously, the scattering events are an essential part of X-ray interactions with matter. Moreover, besides the absorption of photons, scatter events are a part of the attenuation process which forms the basis of X-ray imaging. This means the object cannot be avoided as a source of scattered radiation in the image formation process. There are methods to reduce the impact of object scattered radiation in the measured signal. They will be described in the following sections. In addition to the object, other sources of scattering in the X-ray imaging process can be found. Particularly, components of the X-ray CT setup, such as mounts, shielding, and walls, can act as a second source of scattered radiation, which is known as the environmental scattered radiation. Especially, multiple scattered photons from CT-system components can reach the detector and thus lead to image degradation. Finally, the detector itself can be an origin of scattered radiation. Housing, entrance windows, and other detector components cannot be neglected in the investigation of scattered radiation in the X-ray signal (Stritt et al. 2016a).

These three sources of scattered radiation have a distinct distribution with respect to the measured X-ray signal. Figure 48.6 shows these distributions of scattered radiation for the exemplary setup introduced in Figure 48.4 with a steel step cylinder as the object. Object scattered radiation is highly dependent on the size and form of the sample. In contrast to the object scattered radiation, the scatter signal arising from peripheral equipment is much more isotropic and can generally be treated as a gray value dependent offset (Schütz et al. 2014). This is mainly due to the fact that environmental scattered radiation consists, to a large part, of multiple scattering events. The high order of scattering events out the contribution in the measured signal. The third source of scattered radiation, detector internal scattering, can be highly complex. It is not only dependent on the structure of the detector but also on the energy and angle of the incident photons. Detector internal scattering includes not only forward scattered radiation from the entrance window and collimation or shielding, but also backscattered photons from the housing and the detector base material. Due to the proximity of the detector components in the imager’s setup, scattered radiation can be essentially modeled as an image blur. This blur can be measured with traditional imaging performance measures, such as the modulation transfer function of the detector in a given X-ray setup.

### 48.3 Scatter Correction Methods

Scatter correction methods can be classified in three general categories. Firstly, scatter artifacts can be reduced by decreasing the

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**FIGURE 48.4** Sketch of an X-ray CT system with single and multiple scattered photons.

**FIGURE 48.5** Exemplary case of an aluminum step cylinder Monte Carlo simulation of X-ray scatter showing the difference between the distributions of single and multiple scattered photons.
impact of scattered radiation from system components. The concept of optimizing an X-ray CT system with respect to scattered radiation is described in the following Section 48.3.1. Another category of scatter correction methods is based on estimating the scatter signal in the measurement of offline corrections. This method can be either hardware based or depend on analytical estimations. Section 48.3.2 will discuss these methods and their respective merits in the field of X-ray scatter correction. Finally, the third category will examine X-ray simulations in the context of X-ray scatter correction in Section 48.3.3.

### 48.3.1 Scatter Reduction by System Design

The first concept of scatter reduction in X-ray images is based on the concept of system optimization. Scattered radiation can be reduced by a careful choice of system design parameters such as distances, materials, collimators, or filters.

First of all, a carefully chosen source collimation can hinder the unnecessary irradiation of system components by primary radiation, and thus it directly reduces scattered radiation from the environment. Specifically, the irradiation of shielding material at the detector can lead to unwanted scatter signals at the border of the X-ray images (Stritt et al. 2016b). Also, unnecessary irradiation of manipulator or detector mount can lead to unavoidably scattered radiation.

Similarly to source collimation, collimation at the detector can help reduce the overall scatter to primary ratio at the detector. The choice of detector collimation is certainly limited by the system geometry. In a fan-beam setup, detector collimation in the form of single collimated detector elements or slit collimation can reduce the amount of scattered radiation in the signal by cutting out photons that arrive at the detector in other angles than the primary beam (Stritt et al. 2014). Figure 48.7 shows the comparison of the result of a measurement of a cylinder head performed in both fan-beam and cone beam geometry. However, fan-beam systems are only able to scan objects slice-wise, thus increasing measurement time considerably.

The concept of detector collimation in fan-beam geometry can also be extended to cone beam setups. For flat panel detectors, detector collimation takes the form of anti-scatter grids. These grids work on the same principles as fan-beam detector collimators. They were first introduced as grating diaphragms by Bucky (1913). They are based on the fact that scattered photons reach the detector under a different angle than the primary beam. This means filtering out radiation with respect to its incident angle can reduce the amount of scattered radiation in the measured signal. An example of an anti-scatter grid can be seen in Figure 48.8. The success of an anti-scatter grid in a given X-ray CT setup is dependent on the correct choice of all parameters associated with these grids. Particularly, the anti-scatter grids are described by their geometrical properties, such as the height, the thickness as well as the grid ratio, but also by the material chosen for the grid (Chan and Doi 1982). Figure 48.9 shows a simulation study investigating the impact of an anti-scatter grid. It can be seen that the anti-scatter grid successfully reduces scattered radiation in the measurement. Anti-scatter grids typically pose the challenge of correct alignment of the grid with the primary beam. Moreover, the production of anti-scatter grids involves a trade-off between an accurate and high grid ratio as well as a thick and high-absorbing grid material.

Specifically, when using collimation in an X-ray CT setup, particularly collimation at the detector, a trade-off between the reduction of scattered radiation and signal strength has to be considered (Stritt et al. 2014). Especially, anti-scatter grids constitute a large loss in information in the radiograph. Moreover, for high energies and for high-resolution detectors, anti-scatter grids become impossible to design. High-resolution detectors would require a very fine anti-scatter grid so as not to reduce the resolution of the detector. High energies, however, would require very dense and large grids in order to filter out the scattered high-energy photons. Additionally, the precise alignment required for anti-scatter grids with the primary beam hinders a versatile X-ray CT setup as changes in the source to detector distance will prompt a necessary realignment of the grid.

A simpler method for reducing scattered radiation in the measured signal involves changing the distance of the X-ray CT system. First of all, a correct choice of the source to detector distance, matching the system geometry, is of importance, in order to avoid unnecessary scattered radiation from irradiated system components such as mounts or shielding (Stritt et al. 2016b). Additionally, increasing the distance between object and detector can help reduce the amount of scattered radiation in
the radiograph as well. This procedure is known as the air-gap method (Neitzel 1992). Particularly, a larger distance between an object and the detector will lead to a reduction of object scattered radiation at the detector. The air-gap method is based on the fact that scattered radiation will, to a large part, consist of X-rays that are directed under larger angles with respect to the primary beam. This means that a large travel distance between the origin of scattering—the object—and the detector will increase the probability of scattered radiation missing the detector. The air-gap method is mainly known in the field of medical X-ray imaging, but it can be shown to work in industrial CT as well (Stritt et al. 2016b). However, the maximum size of the air gap is limited by the object size, which makes it impractical for most applications. Moreover, given a typical CT inspection task, the distance between the object and the detector will naturally be chosen to be as big as possible to increase the magnification of the scan.

Another interesting method for reducing scattered radiation involves adding beam filtration to the X-ray source. As previously seen, the occurrence of the different physical interactions highly depends on the energy of the photons. Moreover, the energies of scattered X-ray photons will be lower than the energies of the incident photons due to the inelasticity of most of the scattering processes. This means that filtering out low energy photons from the initial spectrum of the beam will generally reduce the occurrence of scattering interactions in the measurement. Moreover, most X-ray CT setups nevertheless need filter material at the source in order to shape the beam. However, filtration has to be chosen with care, as it will reduce the overall flux of photons in the measurements, which will increase measurement time and can, in the worst case, dramatically increase the signal coming from electronic noise in the radiographs.
Another class of scatter correction methods is based on scatter estimation in combination with offline corrections of the measurement. Scatter estimation can either be hardware based or depend on analytical estimations of the scattered radiation in the X-ray images.

Hardware scatter estimation methods include the beam-shadow (Siewerdsen et al. 2006) and beam-stop methods (Peterzol et al. 2008, Schörner et al. 2011a) as well as the method of primary modulation of the X-ray beam (Schörner et al. 2011b). All of these approaches are based on the concept of measuring the amount of scattered radiation at distinct locations in the radiograph. The complete scatter signal will subsequently be computed through interpolation.

Dependent on the inherent X-ray CT system design, the X-ray beam shadow method becomes more or less viable. If the system design entails collimation that partially covers the active area of the detector, this region can be directly used for X-ray scatter estimation. The signal measured in the so-called collimator shadow (the regions behind the collimator that block the primary X-ray beam) can be associated with scattered radiation. An interpolation of this scatter contribution over the full image is able to estimate the full scatter signal in the radiograph (Siewerdsen et al. 2006). This beam-shadow measurement is, of course, only possible as long as there is a set of regions in the radiographs that is covered by a collimator. If the full field of view is necessary for a measurement, this method can no longer be applied.

The measurement of X-ray scatter by beam-stop array artificially introduces the X-ray scatter measurement points by placing a set of high-attenuating media in front of the detector. Typically, the beam-stop medium will be arranged in the form of a grid; this setup is called the beam-stop array. Similarly to the beam-shadow array, the X-ray scatter can also be measured by a beam-hole array (Schörner et al. 2011a). In a CT setup employing a beam-hole array, most of the primary beam is blocked by a sheet of high-attenuating material. The X-ray beam can only reach the detector through small holes in the sheet. In the same way as for the collimator-shadow method and the beam-stop array, the scatter for the projections is estimated from the signals measured at the regions of the detector where the primary signal is blocked.

Measurement of X-ray scatter by beam-stop array can be assumed to be more exact than the collimator-shadow method due to the better sampling of the scatter distribution in the radiograph. However the beam-stop array directly reduces the total information in the radiography. This can be mediated by performing two scans of the object, one with and one without the beam-stop or beam-hole array. The scatter for the projections is estimated from the signals measured at the regions of the detector where the primary signal is blocked.

![Fig 48.9](image-url) (a) Simulation of an aluminum cylinder with and without an anti-scatter grid, as shown in Figure 48.8. The profile plots in (b) and (c) show that the grid reduces scattered radiation by a factor of three.

**FIGURE 48.9**

(a) Simulation of an aluminum cylinder with and without an anti-scatter grid, as shown in Figure 48.8. The profile plots in (b) and (c) show that the grid reduces scattered radiation by a factor of three.
In contrast to the beam-shadow and beam-stop methods, in the method of scatter estimation by primary modulation, the grid placed in between the source and the object is not required to fully stop the beam (Schörner et al. 2011b). The grid introduces a modulation into the primary X-ray beam. By comparing the initial primary modulation with the primary modulation of the radiographs of the scan, the blurring introduced by scattered radiation can be estimated and a deconvolution can be applied.

In contrast to hardware based scatter estimation approaches, analytical scatter correction methods do not require a change of the system setup. Generally, analytical scatter correction methods rely on the fact that, in many cases, in industrial CT, the Compton scatter process dominates over all other physical interactions. This means that the scattered radiation can be estimated using the Klein–Nishina formula that describes the differential cross-section per unit solid angle of the Compton scattering event. With the help of these analytical calculations, scattered radiation is typically described by a point spread function dependent on specific measurement parameters, which is used to deconvolve the X-ray images (Boone and Seibert 1988, Wang et al. 2005). However, this approach of estimating the scatter signal in the measurement from analytical calculations is generally limited to single scattered radiation. For measurements where multiple scattered radiation constitutes a significant part of the scatter distribution, analytical estimations based on single scatter calculations will not be able to adequately estimate the scattered radiation in the measurement.

Other analytical scatter formulas assume a constant and homogeneous contribution of the scattered radiation to the radiographic image. The simplest case of these corrections would be the assumption of a constant scatter offset in the radiographic images which can be corrected by subtraction. More elaborate scatter corrections include a gray value dependency similar to the typical beam hardening correction formulas. Schütz et al. (2014) proposes a gray value dependent correction formula specifically designed to correct for the detrimental effects of environmental scatter:

\[ T_b = (I + T_b)T'_b - T_b \]

Here, \( T_b \) describes the environmental scatter corrected transmission value and \( T'_b \) the measured transmission. The correction term \( I_r/I_0 \) describes the relative strength of the environmental scatter \( I_r \) with respect to the flat field value \( I_0 \).

### 48.3.3 Scatter Simulation

A third class of scatter correction methods is based on the concept of scatter simulation. The X-ray simulations result in an equivalent simulated version of the X-ray image, with the difference that the simulation software can provide more information about the measured signal. This additional information enables the differentiation between primary and scattered radiation. As a result, the simulated scattered radiation can be subtracted from the X-ray measurements in order to correct for the additional signal introduced by the scattered photons.

There are several different options for X-ray imaging simulations. X-ray simulations can be deterministic, based on ray tracing or transfer matrices, or they fall under the large category of Monte Carlo simulations. Generally, the name Monte Carlo simulation describes a class of algorithms that are based on a stochastical procedure using repeated random sampling. For X-ray imaging applications, the term Monte Carlo simulation typically describes single particle tracking approaches that use the underlying physical cross-sections in order to simulate the photon paths and their interactions with matter in an X-ray CT setup. Monte Carlo simulations are useful in these cases because the underlying physical problem of X-ray transportation through the system with all X-ray interactions contains too many coupled degrees of freedom for it to be solved analytically. It can be assumed that the scatter estimation from Monte Carlo simulation is accurate as long as all simulation parameters, such as cross-sections, X-ray spectra as well as the simulated system components, the object, and its material, are known and correctly implemented. Despite their accuracy, Monte Carlo simulations are not used very often as a scatter correction method. This is due to their high computational effort, which is a result of the high photon statistics necessary for a valid simulation result.

Nevertheless, full simulations of X-ray systems have been performed several times in order to characterize and quantize the impact of scattered radiation (Miceli et al. 2007). However, these simulations are typically used for analysis purposes only. They serve the purpose of determining the details of scattered radiation for a specific X-ray system. Due to the high amount of information that can be retrieved in Monte Carlo simulations, these system simulations can help to optimize the entire CT-setup. A clear understanding of the impact of system components in a given X-ray CT system can help to amend a large part of the problem of scattered radiation (Schütz et al. 2013). Thereby, Monte Carlo simulations can help find an appropriate system re-design. Accordingly, full system Monte Carlo simulations can help identify optimal system and measurement parameters. Performing a set of simulations in order to test a large set of measurement parameters is arguably easier with a Monte Carlo simulation than the completion of all corresponding measurements. Regardless of that, the determination of optimal measurement parameters by system simulation will, in any case, reduce the necessary beam time for a measurement, which can be helpful if there is limited system access.

However, Monte Carlo simulations are not only helpful in designing and changing X-ray CT setups. Additionally, extensive simulation work can help in the development of correction procedures and algorithms. Most of these procedures rely on similarity of scattered distributions. They typically result in numerical approximations of the scatter contribution as a function of gray value and X-ray spectrum.

Aside from using pre-simulation work for the development of correction algorithms, some approaches for scatter correction in X-ray CT try to use Monte Carlo simulations directly and in an iterative way. In order to do this in a feasible fashion, most of these methods try to reduce the computational effort of the simulations to shorten computation time. Likewise, Monte Carlo simulations can be used to pre-simulate scatter kernels for different materials and material thicknesses. The scatter kernels can be used in order to deconvolve the measured projections.

Another approach involves using Monte Carlo simulations in a hybrid way (Thierry et al. 2009, Freud et al. 2005). Hybrid
Simulations typically incorporate elements of both deterministic and Monte Carlo simulations. Hybrid simulations are based on the fact that it is generally possible to analytically estimate the quantity of single scattering in the projections. This means the purpose of Monte Carlo simulations in a hybrid simulation is the estimation of the amount of multiple scattering in the measured signal. A comparison between a full Monte Carlo and a hybrid simulation of the scattered radiation of an aluminum step wedge can be seen in Figure 48.10.

Aside from hybrid simulations, the so-called forced detection technique (Thierry et al. 2007) can be used in order to optimize the computation time of Monte Carlo simulations. The forced detection algorithm drives the occurrence of specific physical interactions as well as their detection. As a consequence, the statistics of scattering events are increased but biased, which has to be corrected for in the analysis of the results. By increasing the probability of certain events, computation time can be accelerated significantly.

A general problem with the simulation of X-ray CT measurements is that all system components have to be known, including the shape and material composition of the object that is measured. This means that, ideally, a large amount of previous information about the object is available, which is not always possible. Direct simulations of an X-ray measurement can still be performed in the case of metrological applications where all geometrical and material information about the object is available. For unknown objects, the input for the simulation software has to either be estimated with similar primitives or approximated using a first rough reconstruction of the measurements, which can be corrected iteratively using several subsequent runs of the simulations.

48.4 Summary

This chapter presented the impact of scattered radiation on industrial X-ray CT. Artifacts introduced by scattered radiation in the reconstructed images were described, and the underlying physics at different energies and for different materials were discussed. Finally, three categories of scatter correction approaches were introduced and their respective merits were examined. It is noteworthy that these different scatter correction concepts are not mutually exclusive. Not only is it possible to combine several of the suggested techniques, it is even recommendable to use various scatter correction approaches, depending on the task at hand. While full system simulations can help in the design of an X-ray CT system optimized with respect to scattered radiation, analytical scatter estimation methods might be more suitable for day-to-day operations. Moreover, the applicability of the different techniques presented here is highly dependent on the energy of the X-ray source, as well as the shape, size, and material of the object under investigation. For a large set of similar objects, pre-simulated scatter corrections might work well for offline scatter corrections, while measurements with little pre-knowledge might require an operator to switch from cone beam to fan-beam geometry. In general, it is important to know the impact of scattered radiation in a given X-ray CT setup, in order to have an understanding of the amount of scattering at the measurement energies. With this knowledge, the optimal scatter correction method can be chosen.

REFERENCES


