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Megavoltage cargo radiography with dual energy material decomposition

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ABSTRACT

Megavoltage (MV) radiography has important applications in imaging large cargos for detecting illicit materials. A useful feature of MV radiography is the possibility of decomposing and quantifying materials with different atomic numbers. This can be achieved by imaging cargo at two different X-ray energies, or dual energy (DE) radiography. The performance of both single energy and DE radiography depends on beam energy, beam filtration, radiation dose, object size, and object content. The purpose of this work was to perform comprehensive qualitative and quantitative investigations of the image quality in MV radiography depending on the above parameters. A digital phantom was designed including Fe background with thicknesses of 2cm, 6cm, and 18cm, and materials samples of Polyethylene, Fe, Pb, and U. The single energy images were generated at x-ray beam energies 3.5MV, 6MV, and 9MV. The DE material decomposed images were generated using interlaced low and high energy beams 3.5/6MV and 6/9MV. The X-ray beams were filtered by low-Z (Polyethylene) and high-Z (Pb) filters with variable thicknesses. The radiation output of the accelerator was kept constant for all beam energies. The image quality metrics was signal-to-noise ratio (SNR) of the particular sample over a particular background. It was found that the SNR depends on the above parameters in a complex way, but can be optimized by selecting a particular set of parameters. For some imaging setups increased filter thicknesses, while strongly absorbing the beams, increased the SNR of material decomposed images. Beam hardening due to polyenergetic x-ray spectra resulted in material decomposition errors, but this could be addressed using region of interest decomposition. It was shown that it is not feasible to separate the materials with close atomic numbers using the DE method. Particularly, Pb and U were difficult to decompose, at least at the dose levels allowed by radiation source and safety requirements.

1. Introduction

Projection X-ray imaging (radiography) has well-known applications in medicine, industry, security, and scientific research. In each of these areas certain requirements exist that determine the data acquisition methods, detection systems, X-ray energies, radiation dose, and imaging time. One important application of projection radiography is imaging cargos with large sizes for detecting illicit materials such as explosives, narcotics, nuclear materials, high density radiation shields, etc. These cargos may have sizes of up to a few metres in cross sections and average densities of about thousand kilogrammes per cubic metre. To image such a large object high energy X-ray beams with high penetration capabilities are required. X-rays with mega-electronvolt energies are appropriate for this purpose, and the corresponding imaging technique is called mega-voltage (MV) radiography.

Another useful feature of projection X-ray imaging is the possibility of separating and quantifying materials with different effective atomic numbers. In order to separate two materials from each other, two X-ray images of the object should be acquired at two different energies in a single image acquisition. This imaging method is called dual energy (DE) radiography. As in the case of single energy radiography, DE radiography also has various applications such as bone density and contrast measurements in medical imaging, and airport baggage inspection in security imaging. DE MV (DEMV) radiography has been investigated for cargo imaging [1–8] and several systems are now commercially available [9–13].

There are several conceptually different methods for acquiring DE radiography data. These include using (1) X-ray source and detector where the X-ray pulses are dynamically switched (interlaced) between two energies, (2) X-ray source and a two-layer detector where the detector layers can separate low and high energy X-ray photons, and (3) X-ray source with an energy-resolved photon counting detector that can split the X-ray spectrum into several parts and acquire multi-energy X-ray images in a single acquisition. Each of these methods has its advantages and limitations that determine its feasibility for cargo

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radiography. For DEMV cargo radiography, the method using a source with interlaced DE X-ray pulses has been shown as feasible [3,4,6,8], and corresponding X-ray sources are commercially available [12,14].

There are several difficulties when DEMV cargo radiography is acquired using X-ray beams with interlaced energies. One limitation is that the low and high energy X-rays are filtered by the same filter because both rays are emitted from the same source. Such filtration may not be optimal for separation of the energies of two beams. This problem is further complicated because the X-ray attenuations of the high-Z (atomic number) materials do not change monotonically as opposed to low-Z materials due to higher pair production cross section. The image quality of single energy radiography and material selective DE radiography depends on the types and thicknesses of the filter materials, background materials, and materials to be imaged. In this work, we have performed comprehensive simulation studies of single energy and DEMV radiography using (1) different beam filter materials including low- and high-Z materials, (2) different background thicknesses, (3) different material samples for imaging, (4) single energy radiography with different energy settings, and (5) DE radiography with different energy settings. The signal to noise ratio (SNR) of the images was used as image quality metrics while the radiation output of the source was kept constant for all image acquisitions. The complex nature of the dependence of SNR on beam energies, sample types, filter types, and background thicknesses was demonstrated quantitatively and qualitatively. In general, high-Z and low-Z filters materials showed similar performances, while the higher beam energies were more preferable, particularly for larger background thicknesses. Interestingly, for some imaging tasks, increasing filter thickness improved SNR in DE material decomposed images despite the fact that the thicker filter absorbed more X-rays and decreased photon statistics. Feasibility of decomposing high-Z materials such as Pb and U by DE radiography was also tested.

2. Methods and materials

2.1. Theory of the material decomposition

The physical principle of the material decomposition in X-ray imaging is based on differences of changing of the linear attenuation coefficients of materials with X-ray energies [15–20]. In general, an object including n known materials with different effective atomic numbers can be decomposed into components using n X-ray images acquired at different energies. The term "decomposition" here means determination of the unknown thicknesses of each of the n known materials included in the object. For simplicity, we assume that the object consists of two materials and is imaged at two X-ray energies that we call low and high energies E_L and E_H, respectively. The linear attenuation coefficients of the first component at low and high energies are μ_{1L} and μ_{1H}, respectively. Corresponding linear attenuation coefficients of the second component are μ_{2L} and μ_{2H}, respectively. We further assume that the X-ray beam includes N_{0L} and N_{0H} photons with energies E_L and E_H, respectively, and the thicknesses of the two components are t_1 and t_2, respectively. The low and high energy photon numbers in the beam passed through the object are $N_L = N_{0L}e^{-\mu_{1L}t_1-\mu_{2L}t_2}$ and $N_H = N_{0H}e^{-\mu_{1H}t_1-\mu_{2H}t_2}$, respectively. After log processing, the above expressions yield a system of linear equations with unknowns t_1 and t_2:

$$\begin{cases} \mu_{1L}t_1 + \mu_{2L}t_2 = \ln\dfrac{N_{0L}}{N_L} \\ \mu_{1H}t_1 + \mu_{2H}t_2 = \ln\dfrac{N_{0H}}{N_H} \end{cases}. \quad (1)$$

The above system can be resolved with respect to thicknesses t_1 and t_2 using the known linear attenuation coefficients and photon numbers. After cancelling out the thickness t_2 in the above system the expression for the thickness t_1 is:

$$t_1 = \frac{\mu_{2H}\ln\frac{N_{0L}}{N_L} - \mu_{2L}\ln\frac{N_{0H}}{N_H}}{\mu_{1L}\mu_{2H} - \mu_{2L}\mu_{1H}}. \quad (2)$$

The expression for the thickness t_2 can be found similarly. Also, the system of equations (1) can be extended to larger numbers of materials assuming that the images are acquired at the same numbers of energies. As can be seen from the expression (2), the thickness t_1 is undetermined if the condition

$$\frac{\mu_{1L}}{\mu_{2L}} = \frac{\mu_{1H}}{\mu_{2H}} \quad (3)$$

holds, which makes the denominator of (2) zero. Because the low and high energies E_L and E_H are independent, the expression (3) is equivalent to

$$\mu_1(E) = K\, x\, \mu_2(E) \quad (4)$$

for all energies E, where K is a constant. The expression (4) holds if the two materials have the same effective atomic numbers and mass attenuation coefficients. Therefore, two materials can be decomposed using DE method only if they have different effective atomic numbers and linearly independent mass attenuation coefficients.

Fig. 1a shows the dependence of the mass attenuation coefficients of several materials on photon energies, including low-Z (Polyethylene, H_2O), medium-Z (Al, Fe, Cu), and high-Z (Pb, U) materials. In the energy range of interest, 1–9 MeV, the mass-attenuation coefficients of low-Z and medium-Z materials monotonically decrease, while for high-Z materials such as Pb and U it has a minimum at around 3 MeV due to a higher pair production cross-section. Fig. 1b shows the relative mass-attenuation coefficients $(\mu/\rho)_f/(\mu/\rho)_k$ of the two materials f and k. Specifically, the relative mass-attenuation coefficients of Polyethylene/Fe, Al/Fe, Cu/Fe, W/Fe, Pb/Fe, H_2O/Polyethylene, and Pb/U are shown. As can be seen, for some material pairs, it is possible to select a particular low and high energy set from the 1–9 MeV range such that the expression (3) holds and decomposition is not possible.

For the material pairs with substantially different atomic numbers, it is possible to select low and high energy sets such that the expression (3) is far from equality, and decomposition is possible. However, for the material pairs with close atomic numbers such H_2O/Polyethylene and Pb/U, any low and high energy pair will result in approximate equality in the expression (3), and decomposition will not be particularly useful due to low SNR.

The above considerations and expressions (1)–(4) are correct for monoenergetic X-rays that are difficult to provide for cargo imaging applications, although some research in this area is ongoing [21]. For the polyenergetic X-rays used in practice, the X-ray beams are hardened as they pass through the materials. The average photon energies are increased and effective mass-attenuation coefficients are decreased depending on the material type and thicknesses. Therefore, the conditions (3) and (4) for the material decomposition become dependent on the thicknesses and types of the sample and background materials. In other words, when polyenergetic X-rays are used the coefficients in the system of equations (1) depend on background/sample thicknesses and types which may change for different areas of the object. Therefore, when polyenergetic X-rays are used, the decomposition should be performed separately for each particular area of interest of the object, which should not represent a problem when using dedicated computer software.

Notice that previous works on DE cargo imaging used material identification based on a different approach. Namely, the effective linear attenuation coefficients of the same material at low and high energies were determined and the relations of these two coefficients of the same material were tabulated and used to identify the unique material [3,5,8,22]. However, if the two or more materials in the object do overlap, the identified material will be an unknown mixture with certain effective atomic number that may not correctly identify a particular material. The DE energy material decomposition method used in the current work allows for complete separation and quantification of two materials, with the potential of multi-material decomposition using multiple energies.