Method for Dual High Energy X-ray Imaging with Flat Panel Detectors

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Abstract
Dual-energy X-ray imaging in the keV range is a well-known technique e.g. used in baggage scanning. It requires two measurements at different energies and/or detector efficiencies and allows displaying material properties as the effective atomic number and mass density. The method thus provides the information allowing identifying illicit materials such as explosives and contraband or high-Z material used for shielding of radioactive or fissile material. Baggage scanners typically operate with 160 kVp X-ray sources, providing photons of energies between approximately 10 keV and 160 keV. For large objects as complete cars or sea freight containers for example, much higher photon energies are required to penetrate the object, i.e. in the range of a few MeV. The keV-dual-energy imaging exploits the energy dependence of the attenuation due to photo-electric and Compton effects. MeV-dual-energy imaging relies on pair production and Compton effect, which is more challenging since the energy dependence differs less between these effects. Due to the higher proportion of scattered radiation and the lower efficiency of flat panels, usually line detectors combined with a heavily collimated fan beam are used. However flat panel detectors offer a higher resolution and cover a two-dimensional area which allows for shorter scan times. We employed a method using a ratio of the intensities in both images of different X-ray energies, and could show that materials differing in Z can be distinguished. We introduce the principles of the method and present first measurements from our 9 MV linear accelerator (LINAC) test facility.

Keywords: dual energy, high energy, MeV, X-ray, imaging, Linac

1. Introduction

Dual Energy X-ray imaging in the keV range is an established technique in both security and medical imaging. A well-known application is the non-intrusive scanning of the carry-on baggage at airports. It allows the identification of effective atomic numbers and densities of the materials under examination and thus can indicate high-Z material used for shielding of radioactive or fissile material or other banned materials such as explosives and contraband. Baggage scanners typically operate with 160 kVp x-ray sources, providing photons of energies between approximately 10 keV and 160 keV. If an object as large as a sea freight container or a complete car needs to be scanned, much higher photon energies are required to penetrate the object, i.e. in the range of few MeV. The keV-dual-energy imaging exploits the energy dependence of the attenuation due to photo-electric and Compton Effect. MeV-dual-energy imaging relies on pair production and Compton Effect, which is more challenging since the energy dependence differs less between these effects. Due to higher proportion of scattered radiation and the lower efficiency of flat panels, usually line detectors combined with a heavily collimated fan beam have been used. While this is advantageous for very large objects, flat panel detectors allow faster 2D data acquisition for small and medium sized objects.

As mentioned above, the keV-range dual energy techniques exploit the energy dependence of photo-electric effect and Compton scattering. While the change in cross section for Compton scattering is marginal over a wide range and the cross section for photo-electric absorption is decreasing approximately as the inverse cube of the Energy (E^-3), i.e. it gets negligibly small at higher energies. However at energies above 1.022 MeV pair production can occur with an
increasing cross section at increasing photon energies. As the energy dependence of the attenuation due to pair production and Compton scattering is smaller than between photoelectric effect and Compton scattering, it is more challenging to apply a dual energy technique in the MeV range.

The total mass attenuation coefficient is proportional to the sum of the cross section of all effects contributing to the attenuation process. Figure 1 shows a log-log plot of the total mass attenuation coefficient for carbon, iron and lead over the photon energy range from 10 keV to 10 MeV. With atomic numbers Z being 6, 26 and 82 respectively, these example materials cover the relevant range of atomic numbers very well. At lower energies, i.e. 25 keV for carbon, 120 keV for iron and 600 keV for lead, photoelectric absorption dominates. At medium energies, Compton scattering with its slowly decreasing cross section contributes most. At higher energies, i.e. 28 MeV for carbon, 10 MeV for iron and 5 MeV for lead, pair production in the nuclear field eventually becomes the dominating factor of the attenuation. Figure 1 also shows that the attenuation coefficient differs very little for light materials (in this case carbon and iron) for energies between 300 keV and 3 MeV and therefore this part cannot contribute to the dual energy method. Unfortunately this energy range accounts for a large part of the spectrum of a typical MeV Linac source spectrum.

![Figure 1. Mass attenuation coefficient for selected materials between 10 keV and 10 MeV](image)

2. Methods

The signal of a detector working in energy integrating regime is

\[ I = \int \exp \left( - \sum_i \mu_i(E)d_i \right) I(E) D(E) E dE \]

where \( I(E) \) is the incident X-ray spectrum, \( D(E) \) the detector efficiency, \( \mu_i(E) \) the mass attenuation coefficient of material \( i \), and \( d_i \) the thickness of the respective material. The distinction between different materials is based on the differences of the attenuation.
coefficients. But, as the above equation shows, the attenuation coefficient is not accessible directly.

To retrieve information on the type of material a combination of two measurements of the object with different incident source spectra and/or detector efficiencies needs to be done. These two imaging situations will be called low and high energy (LE and HE). The ratio of the logarithmized HE and LE (Q-values) plotted images over the intensity of the unchanged intensity yields a characteristic line for each material:

$$Q = \frac{\log I_{LE}}{\log I_{HE}}$$

For a given detector efficiency and source spectra, this value can be calculated for materials with known attenuation coefficient. The so called Q-plots (see Fig. 2) are element specific; at least for an interval of atomic numbers, i.e. multiple groups of elements can be distinguished. Its performance is strongly impacted by the filtering of the incident spectra.

![Q-plot 6 MV / 9 MV](image.png)

Figure 2. Q-plot for a selection of materials for areal densities from 1 to 200 g/cm\(^2\) in steps of 1 g/cm\(^2\). The right end of the curve corresponds to 1 g/cm\(^2\) the left end to 200 g/cm\(^2\).

Using such a set of curves, every pixel can be associated not only with an intensity value (brightness) but also a type of material (effective atomic number). In the example of Figure 2 the Q-values are calculated for a pencil beam geometry neglecting the scattered radiation. The low and mid-Z materials can be separated, while tungsten and lead show very similar Q-values for most areal densities.

3. First measurements and preliminary results

The first measurements were done using a linear accelerator (Linac) with tungsten target and voltages up to 9 MV as an x-ray source. The detector is a flat panel Perkin Elmer XRD 1640 AL1 with 0.4 mm pixel pitch. Figure 3 shows an image of a lead step wedge with thicknesses.
from 14.4 mm to 5.4 mm in steps of 1.8 mm (from left to right) using a 5 MV; the second energy for the dual energy measurement was 9 MV. Furthermore an Aluminum step wedge with thicknesses from 40 mm to 100 mm in steps of 20 mm was used. The resulting Q-plot for the aluminum and lead step wedges can be seen in Figure 4.

Figure 3 Image of a lead step wedge imaged with the flat panel detector using a 5 MV spectrum from the Linac.

Figure 4. Q-plot of the aluminium and lead step wedge measurement imaged with the flat panel detector at 5 and 9 MeV.
Figure 4 shows that these two materials can be separated clearly over the considered thicknesses/intensities. We expect at least four Z-intervals (intervals of atomic numbers) to be distinguishable.

4. Conclusion

We introduced a method for dual energy imaging in the MeV range. Despite expected problems due to the low efficiency of the flat panel detector and large amounts of scattered radiation due to cone beam acquisition geometry, first results indicate the method is still applicable.

Flat panel detectors have very high (sub-millimeter) resolution compared to line detectors typically used in high energy X-ray imaging (approximately 5 mm). 2-D data acquisition allows faster scans, as it utilizes a larger part of the radiation field of the source. Assignment of colors corresponding to atomic number as in keV-dual energy is also feasible to generate colorized images to help the inspecting personnel to identify defined materials. Based on these features of flat panel detectors and dual energy capabilities, new areas of deployment arise.