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Spectral micro-CT for simultaneous gold and iodine detection, and multi-material identification

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Abstract: Multiple energy bin spectral micro-CT (SμCT) is an advanced imaging technique that allows multi-material decomposition according to their specific absorption patterns at a sub-100 µm scale. Typically, iodine is the preferred CT contrast agent for cardiovascular imaging, while gold nanoparticles have gained attention in recent years owing to their high absorption properties, biocompatibility and ability to target tumors.

In this work, we demonstrate the potential for multi-material decomposition through SμCT imaging of a test sample at the PEPI lab of INFN Trieste. The sample, consisting of gold, iodine, calcium, and water, was imaged using a Pixirad1/PixieIII chromatic detector with multiple energy thresholds and a wide spectrum (100 kV) produced by a micro-focus X-ray tube. The results demonstrate the simultaneous detection and separation of the four materials at a spatial scale of 35 µm, suggesting the potential of this technique in improving material detectability and quantification in a range of pre-clinical applications, including cardiovascular and oncologic imaging.

Keywords: Computerized Tomography (CT) and Computed Radiography (CR); Image reconstruction in medical imaging; Medical-image reconstruction methods and algorithms, computer-aided software; X-ray detectors

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2024 JINST 19 C04023

Contents

2024 JINST 19 C04023

1 Introduction

Spectral-micro-computed tomography (SμCT) is an advanced imaging method that allows for the quantitative analysis of materials at a spatial scale below 100 µm. Differently from traditional CT, that considers the overall loss of intensity due to the attenuation of X-rays, SμCT selects photons in terms of their energy. In this way, the different absorption characteristics of the multiple components within the sample are exploited, allowing for their differentiation and quantification [1].

The use of high-atomic-number contrast agents in biomedical X-ray imaging enhances the visibility of target tissues or specific structures in the body. Contrast element attenuation has a distinct dependence on energy, characterized by sudden increases of absorption at specific energy levels (K-edges), making these elements suitable for spectral imaging purposes [2]. In this context, iodinated contrast media are the most commonly used in cardiovascular imaging [3], while gold nanoparticles are emerging as a CT contrast agent due to their high X-ray absorption, low toxicity, high biocompatibility, and their specificity in targeting tumors [4].

The present work reveals the capability of multi-material decomposition via SμCT imaging of a sample including iodine and gold, in addition to calcium (representing osseous tissues) and water (as a representation of soft tissues). The experiment was conducted at the PEPI (Photon-counting Edge-illumination Phase-contrast imaging) laboratory of INFN Trieste [5], using the Pixirad1/PixieIII chromatic detector [6].

2 Materials and methods

The imaging setup used for the experiment is composed by a Hamamatsu L10101 microfocus X-ray source, operated at 100kVp and 200 µA. The detector is the Pixirad-1/Pixie-III x-ray photon counting detector (XPCD) [6]. Both setup elements are shown in figure 1(a). The detector features a high-Z, 650 µm thick CdTe sensor and has a sensitive area consisting in a 512×402 matrix of square pixels at 62 µm pitch. A double energy threshold is applicable, enabling the discrimination of photons based on their energy.

The images were acquired through multiple acquisitions in 5 energy bins defined by the applied energy thresholds. These were chosen at 26, 33, 42, 70, and 92 keV (see figure 2(a)). A CT scan of the object, in a $(1.3 \times 1.8 \times 1.4)\,\mathrm{cm}^3$ volume, was acquired with 720 projections over 360 deg, for a total scan time of 75 minutes per energy bin. The sample consisted of three plastic cuvettes,

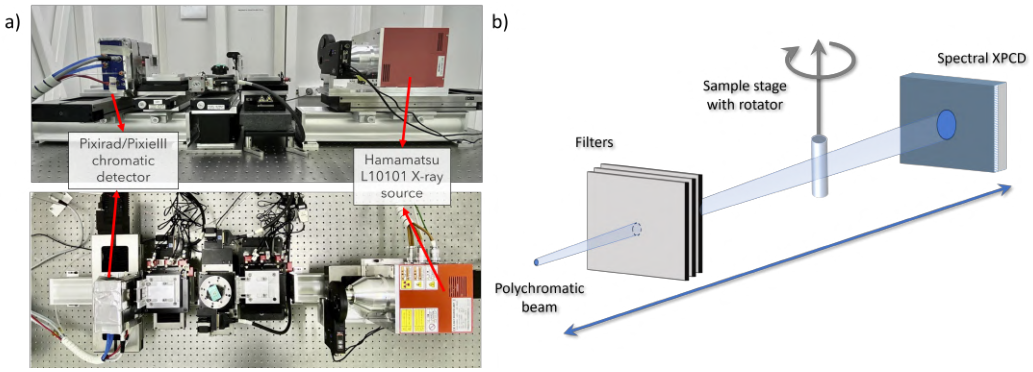

Figure 1. a) Photo of the experimental setup from the lateral and top point of views. In the photo, the detector and the X-ray source can be noticed. b) Schematic representation of the setup during acquisition.

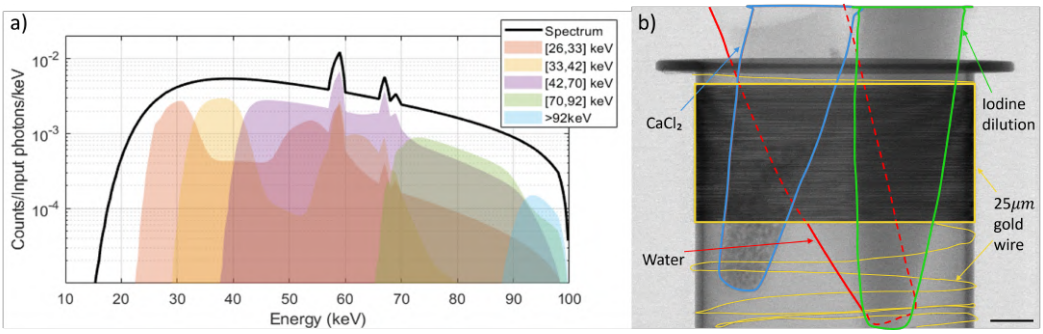

Figure 2. a) Simulated X-ray spectrum at 100 kVp voltage (black line). The energy thresholds were set at 26, 33, 42, 70, and 92 keV. These delimit the shaded regions, which correspond to the fraction of photons in each energy bin. b) X-ray projection of the sample composed of three plastic cuvettes, filled with water, a calcium salt and an iodine dilution respectively, all inserted in a spool of gold wire.

filled with water, a calcium salt ($CaCl_2$) and a 50 mg/mL iodine dilution, all inserted in a spool of 25 µm-thick gold wire, as visible in figure 2(b). The magnification factor was 1.8, reducing the effective voxel size down to 35 µm.

A detector-specific pre-processing procedure and an image-denoising technique [7] were applied to the projection images before tomographic reconstruction. The images were then processed through a material decomposition algorithm to obtain independent distributions of each chosen material. Assuming that the images are acquired in n energy bins, and that the sample is composed of m known materials, the system in eq. (2.1) (left) is obtained, where S_i are the logarithmized and flat-field corrected X-ray images, $\frac{\mu}{\rho}\Big|_i^j$ is the mass attenuation coefficient of the j-th material in the i-th bin, ρ is the density of the material, and t is its thickness. The inversion of the system, coupled with tomographic reconstruction, produces the ρ maps for each material. Each mass attenuation coefficient was integrated over the energy spectrum $w(E)_i$ and the detector energy response $D(E)_i$ in the specific bin (eq. (2.1) (right)) [8, 9].

$$S_i = \sum_{j=1}^{m} \frac{\mu}{\rho}\Big|_i^j \rho^j t^j \qquad \frac{\mu}{\rho}_i = \frac{\int_E D(E)_i\, w(E)\, \frac{\mu(E)}{\rho} dE}{\int_E D(E)_i\, w(E) dE} \tag{2.1}$$

2024 JINST 19 C04023

3 Results

A four-element material decomposition was applied to the reconstructed slices. Notably, the results demonstrate the successful separation of iodine, gold, calcium and water into four distinct maps, with minimal cross-contamination between channels, as shown in figure 3.

It is important to note that all decomposition images are quantitative, as indicated by the colour bars in figure 3. The density of the elements was determined by selecting a circular region of interest (ROI) inside each cuvette and by measuring its mean intensity. The uncertainty associated with each measurement was calculated as the standard deviation within the chosen ROI. Water and iodine inside the cuvettes are accurately quantified, with a relative error of 6.8 % for iodine and of 2 % for water. Measurement results are reported in table 1. However, the densities of calcium and gold could not be assessed as the actual density of calcium is unknown, as it was not diluted in water, and the gold wire diameter is smaller than the voxel size of the imaging system.

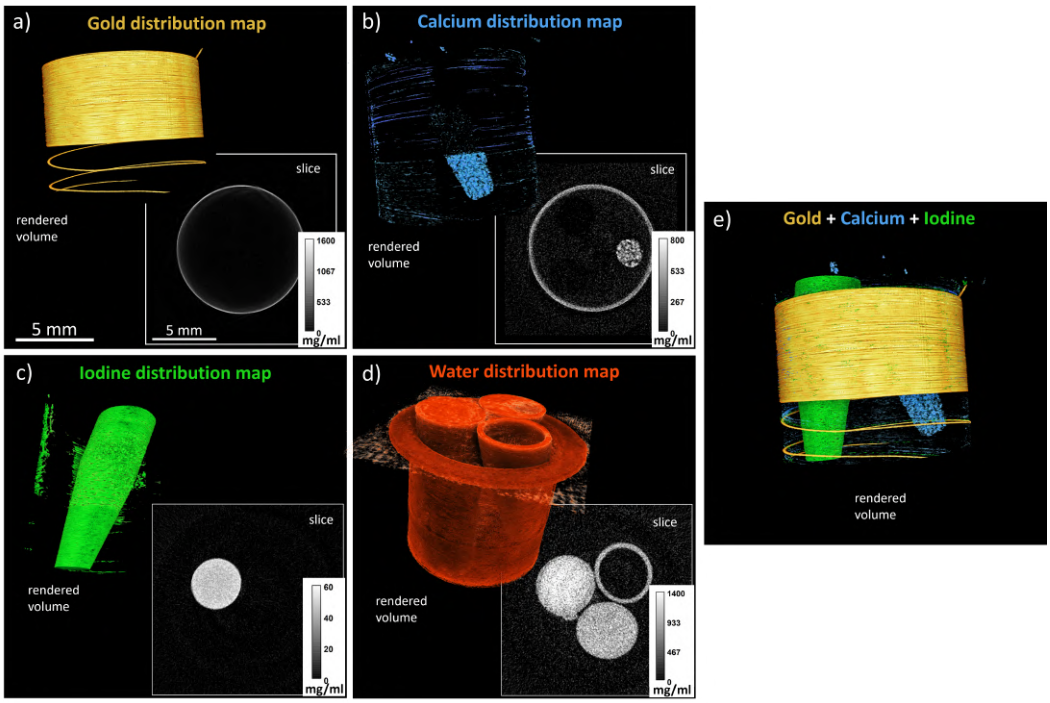

Figure 3. a), b), c), and d): 3D rendered volumes along with single tomographic slices of gold, calcium, iodine, and water decompositions, respectively. e) 3D rendered volume of gold, calcium and iodine together.

Table 1. Expected and measured densities of iodine and water inside the cuvettes.

	expected	measured
Iodine (mg/mL)	50	46.6 ± 1.3
Water (mg/mL)	1000	1020 ± 115

2024 JINST 19 C04023

4 Conclusions

The SμCT study, implemented at the PEPI laboratory of INFN Trieste, demonstrated the potential of this technique for simultaneous detection, separation, and quantification of multiple elements within an object, by exploiting their energy-dependent attenuation properties. By utilizing the Pixirad1/PixieIII chromatic detector and a wide spectrum (100 kV) generated by a micro-focus X-ray tube, the study effectively imaged and isolated gold, iodine, calcium, and water with a voxel size of 35 µm. Moreover, accurate quantification of iodine and water was achieved. The success of this study suggests the potential of this technique in improving material detectability and quantification in a range of pre-clinical applications, offering the possibility of imaging multiple processes simultaneously.

Acknowledgments

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2024 JINST 19 C04023