Imaging Characterization of a Multi-Energy CT with Quasi-Monochromatic X-ray source

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A new multi-energy computer tomographic system for small animals was developed – and is now operative – with a quasi-monochromatic X-ray source. The system brings together two important features: the possibility to scan small animal with quasi-monochromatic X-ray beams and the possibility to select a multiple energy algorithm for the imaging reconstruction. The medical imaging with monochromatic beams is in fact the new frontier of X-ray systems since it allows a new way to visualize selectively different tissues by injecting contrast medium but also without using it. Indeed, an Alvarez and Macovsky like algorithm can enhance the sensitivity of the imaging system to a contrast medium provided with a K-shell binding energy sufficiently high (for example, the iodine has a K-edge at 33.2 keV and the measured sensitivity enhancement is of about 10 times). Moreover, using monochromatic X-ray beams with different energies, it is possible to measure, point-by-point, the tissue density, the electron density and the effective atomic number, exalting the physical-chemical information of tissues. These data are all available with a patient scanning using two (or better three) quasi-monochromatic X-ray beams centred at different energies. However, with a new reconstruction algorithm based on three different energy beams, the so-called projection artefact (due to not homogeneous density of the background) can be corrected, making the tissues separation and the visualization of very low concentration of contrast medium available.
Our multi-energy CT, with this new reconstruction algorithm, was developed to study, on small animals, the possibility to introduce a new method for the earlier diagnosis of the tumour, by exalting the precancerous tissue changes as, for example, the neo-angiogenesis. Aim of this work is to discuss the imaging proprieties of the quasi-monochromatic CT, using both the images of dedicated phantom and in-vivo images of small animals.

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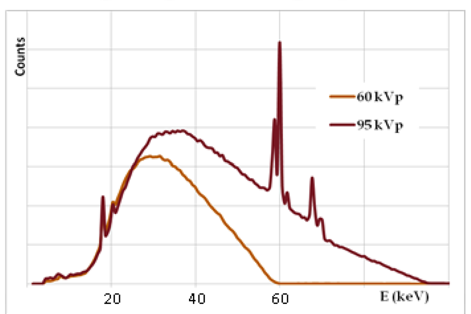
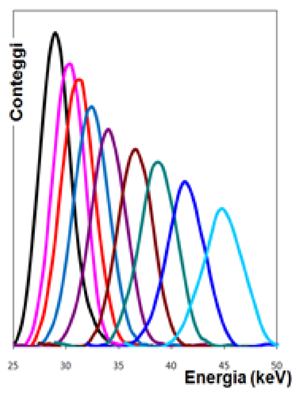
Introduction and state of the art

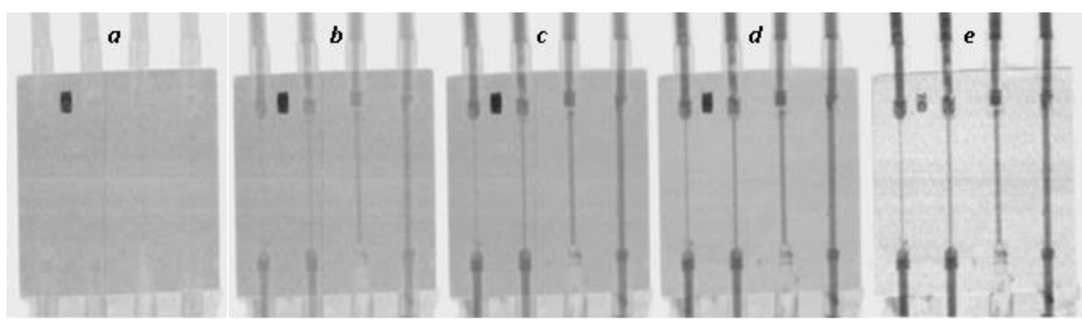
The tomograph was entirely developed at the Departement of Physics of the University of Bologna and performs an innovative technology of radiology imaging using quasi-monochromatic X-rays beams [1]. Unfortunately, it is not yet available a source of monochromatic radiation sufficiently intense to replace the X-ray tube in all clinical applications. Many studies have been carried out in this sense [2], [3], [4], Leaving glimpse of the possibility of reaching a useful results in reasonable times.
Using the algorithm of Alvarez-Makowsky [5], two different energies are used to separate the contributions of different tissues to the formation of the image.



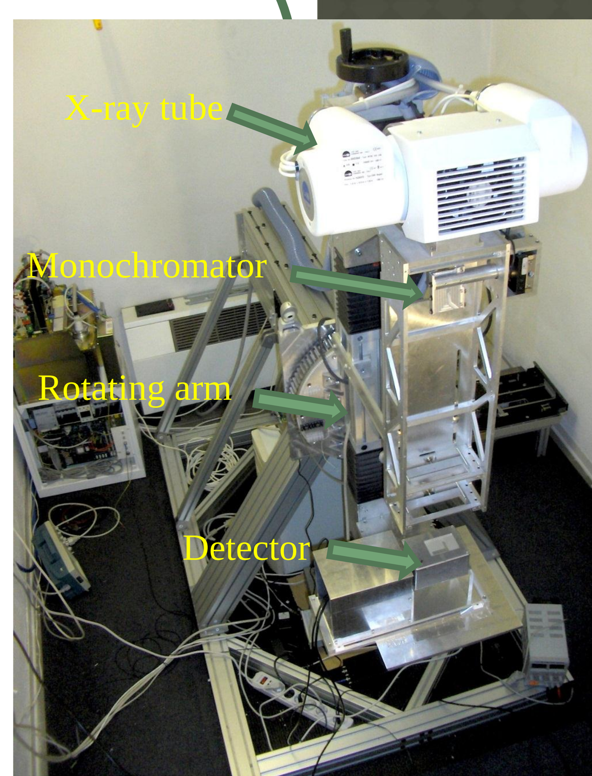
Two energy beams of radiation emitted from an X-ray tube, fed by 60 kv and 95 kV (top).



For comparison we can see some of the spectra generated by quasi-monochromatic tomograph (left).



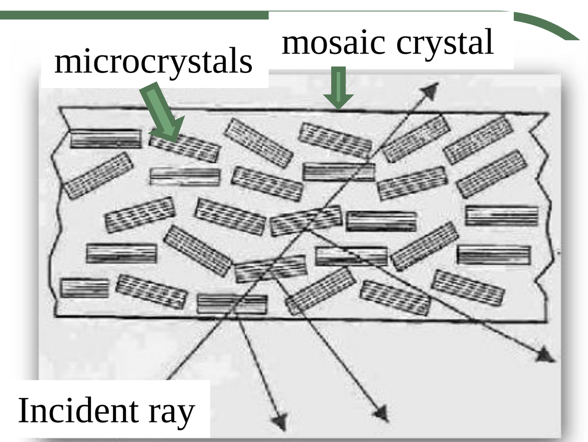
Alvarez-Makowsky algorithm. Epoxy resin phantom with vessels of different sizes in which flow a iodinate contrast medium. (a) weighing water; (b) to (d) weightings intermediate; (e) weighing iodine. The concentration of iodine used here is equal to 30 mg/ml (less than a tenth of that normally used in the angiography).

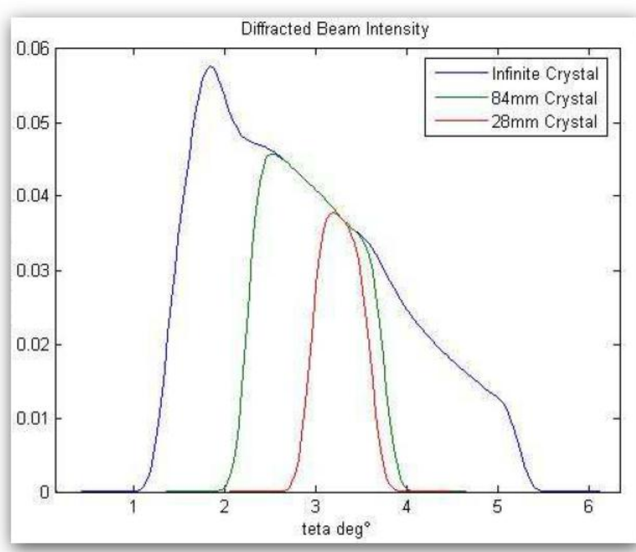


Recent developments have led to the use of the multi-energy technique for the reconstruction of atomic number effective and of the chemical composition of the tissue under examination: starting from the classic approach of Alvarez and Macovski, one can derive an explicit expression for the Z_{eff} of a tissue as a function of the relative radiographic reflex R, obtained from the ratio of the logarithmic attenuation of two monoenergetic beams with different energies.

The monochromator and the detector

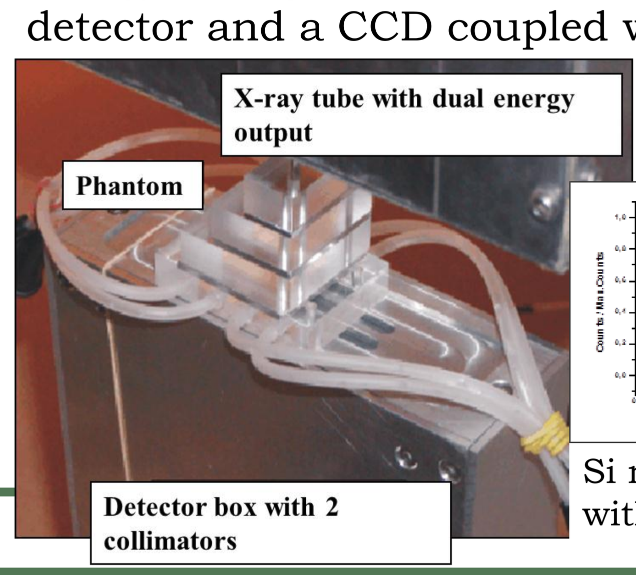
The diffracting target is a higly oriented pyrolitic graphyte crystal (HOPG) that allows a high reflectivity also for the higher orders of diffraction.

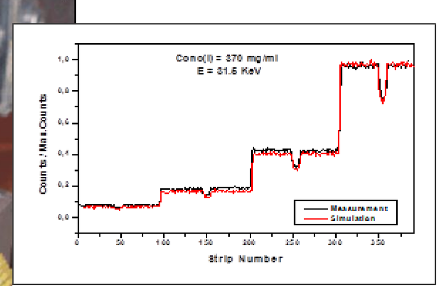




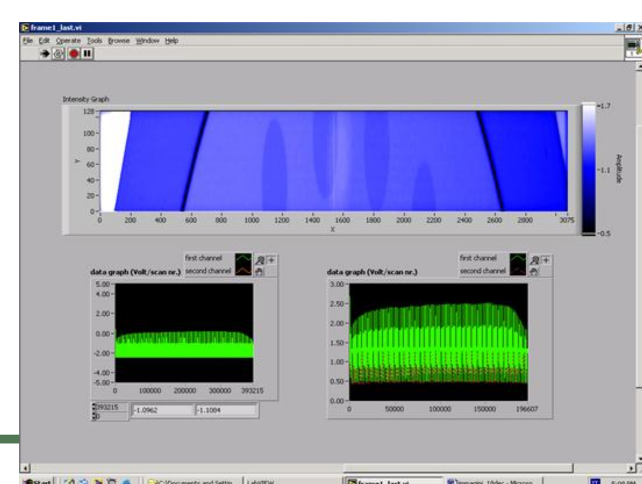
Diffracted beam intensity for the HOPG target and an input beam of 120 kVp.

Different kind of detector was developed for the different applications of the multi-energy tomograph: a couple of Hamamatsu linear CCD with FOS, a Si microstrip detector and a CCD coupled with CsI(Tl) microneedle scintillator by 45° mirror.





Si microstrip detector with dinamic phantom

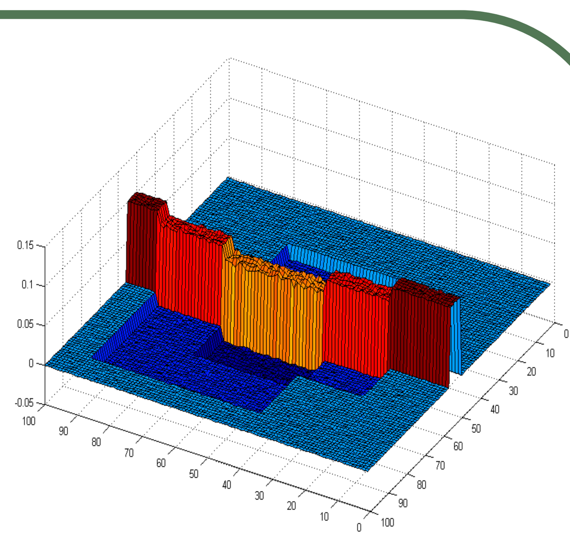


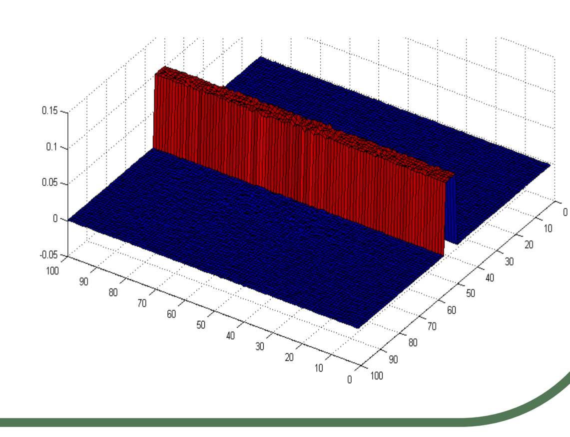
Control software developed for the Hamamatsu linear CCD with FOS.

The triple-energy radiography reconstructs the contrast medium mass-thickness

Triple-energy radiography is an important technique, able to provide accurate estimations about the investigated materials. These information are determined by acquiring images of the analyzed object at three different energies. The triple-energy algorithm is here applied to reconstruct quantitatively the distribution of a contrast medium (Iodine) into the sample. The technique permits to remove completely the background signal from the image: the result is an image that contains only the signal of the Iodine. With respect to dual-energy techniques, the use of three energies is essential when the background has an inhomogeneous composition. For instance, if the background contains soft tissue and a layer of bone, the dual energy reconstructed signal of Iodine is significantly distorted. Adding the third energy, the projection errors are drastically reduced, and the accuracy of the signal much increased also to low concentration of Iodine. Hence, the removal of the projection error enables the quantitative imaging of Iodine. If we take the logarithm of the transmitted to incident photon flux ratio $T = \ln(N/N0)$, for the same sample at three different energies, we can generalize the Beer-Lambert attenuation law to the case of multiple beams. We can write:

$$\begin{pmatrix} T(1) \\ T(2) \\ T(3) \end{pmatrix} = -\begin{pmatrix} \hat{\mu}_{mdc}(1) & \hat{\mu}_1(1) & \hat{\mu}_2(1) \\ \hat{\mu}_{mdc}(2) & \hat{\mu}_1(2) & \hat{\mu}_2(2) \\ \hat{\mu}_{mdc}(3) & \hat{\mu}_1(3) & \hat{\mu}_2(3) \end{pmatrix} \begin{pmatrix} L_{mdc} \\ L_1 \\ L_2 \end{pmatrix} \quad \text{or} \quad \vec{T} = A\vec{L}$$





Where T is the collection of the logarithmic attenuation of the three beams, L is the set of mass thicknesses (product of density and thickness) of the basis materials, and A is a 3×3 matrix whose elements are $\mu_i(k)$, namely the mass-attenuation coefficients of the i-th material at the k-th energy. Solving the system for L, we obtain the image of Iodine L contrast medium, and the background projection over the two basis materials $L1$ and $L2$:

$$\vec{L} = A^{-1}\vec{T}$$

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2011 IEEE Nuclear Science Symposium and Medical Imaging Conference
Workshop On Room-Temperature Semiconductor X-Ray And Gamma-Ray Detectors
23-29 October 2011, Valencia, Spain