Novel x-ray source for dual-energy subtraction angiography*

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ABSTRACT

In angiography practice an iodate contrast medium is injected in patient vessels with catheters. The absorption of x-rays raises immediately after the iodine K-edge energy (33.17 keV). In digital subtraction angiography, two images are used, acquired before and after the injection of the contrast medium, respectively. The vessels morphology results from the difference of images so obtained. This technique involves a non-negligible risk of morbidity or mortality, due to high concentration of injected contrast agent. We are investigating a new source which produces two thin parallel quasi-monochromatic beams - having peak energies centered before and after the iodine K-edge energy, respectively - by using a conventional x-ray tube and a highly oriented pyrolytic graphite mosaic crystal. The polychromatic x-rays incident on the crystal are monochromatized by Bragg diffraction and splitted in two thin parallel beams, by means of a collimating system. These two beams impinge on the phantom simulating patient vessels and are detected with solid-state array detectors. The image results as difference between the remaining intensities of two beams. We report a preliminary study of the new technique performed both with theoretical simulations and experimental measurements. Results of computer simulation give information about characteristics as size and quality of the quasi-monochromatic beams, that should be considered in detail to design a system dedicated to the clinical practice. Experimental measurements have been performed on a small-field detector in order to shows the enhancement of image contrast obtained with the application of the new technique.

Keywords: digital subtraction angiography, dual energy angiography, tungsten anode x-ray tube, dichromatic x-ray beams, Bragg diffraction, mosaic crystal

1. INTRODUCTION

Angiography is one of the most invasive diagnostic techniques both for the iodate contrast medium required and for x-ray exposures of long duration. For instance, in a typical cardiac angiography the contrast medium, with a concentration of 300-370 mg/ml of iodine, is injected at high speed by a long catheter fitted in the femural artery. To manage the catheter up to the heart, a long exposure time - several minutes of fluoroscopy - is required, and afterwards a sequence of radiological frames is acquired during the injection. For pediatric cases, the concentration of iodine and exposure time can increase (reaching 370 mg/ml of I and 20 minutes or more) because of the smaller vessel diameter, resulting in a total dose of the order of 1 Gy (but up to 5 Gy have been measured).[1] If the catheterization was performed on the venous side of the circulation system, through the arm or neck, the procedure would be less invasive but the contrast medium would be much more diluted so the imaging would require higher exposures.[2]

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The application of dual-energy subtraction angiography technique with synchrotron radiation in which intravenous injection of the contrast agent is performed, has obtained quality images with a considerable reduction of contrast medium concentration and lower exposure, i.e. a reduction of the involved risk.[3–8] To transfer the radiological potential of the synchrotron radiation to a clinical diagnostic imaging a development of new sources, compact and less expensive, is desirable.

We are investigating a new source which produces two thin and parallel quasi-monochromatic beams, having peak energies centered under and above the iodine K-edge energy, respectively. By using a conventional x-ray tube and a mosaic crystal, polychromatic x-rays are monochromatized by Bragg diffraction and splitted in two beams, by means of a collimating system. These two beams impinge on the phantom simulating patient vessels and are detected with solid-state array detectors. The image results as difference between the remaining intensities of two beams.

The work presents a preliminary study of this new technique. The first part of the contribution will present a computer simulation of the new source, which shows expected size and energy resolution of the source. The second part of the work will present an experimental study of the capabilities of the dual-energy subtraction technique with quasi-monochromatic beams, performed with a small-field detector.

2. THEORETICAL APPROACH

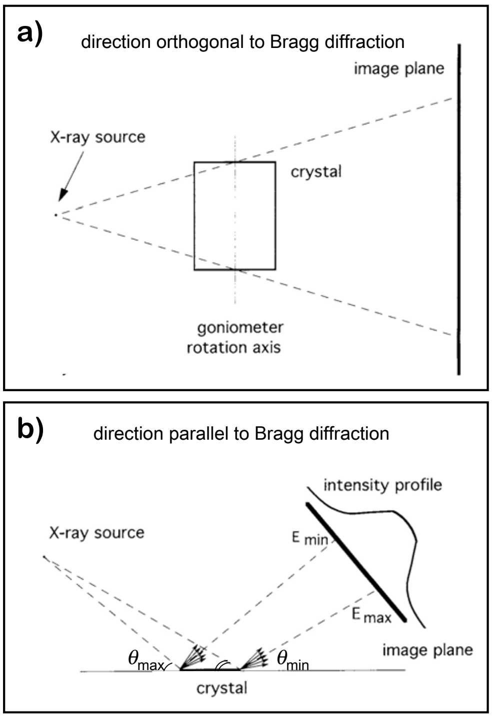

Figure 1. Schematic of Bragg diffraction of a divergent polychromatic x-ray beam from a mosaic crystal.

We have produced quasi-monochromatic x-ray beams via Bragg diffraction on pyrolytic graphite mosaic crystals.[9, 10] It has been demonstrated that mosaic crystals provide an excellent choice as monochromators for applications in which a high photon flux is required, as a medical imaging.[11]

The size of the quasi-monochromatic beam depends on crystal dimensions, Bragg angle, source-crystal and crystal-image plane distances, as shown in figure 1. The size along the diffraction plane depends also on the energy spread E_{max}-E_{min} (see figure 1b), where the photon energy E which satisfies the Bragg diffraction law is determined by the well known formula

$$E_B = \frac{n\,h\,c}{2\,d\,\sin\theta_B} \tag{1}$$

where d is the distance of the lattice planes, $n = 1, 2, 3, \ldots$ is the diffraction order, h is the Plank constant, c is the light speed in vacuum, and θ_B is the Bragg angle. In more detail we observe that when a polychromatic and divergent x-ray beam impinges on a mosaic crystal, the diffracted beam presents an energy gradient in the plane parallel to the direction of Bragg diffraction. This is due to the divergence of incident beam, i.e. photons impinge upon the crystal with different angles depending on their emission direction from the source. In the situation schematically depicted in figure 1b photons reaching the crystal on the right side, with an incidence angle $< \theta_B$, corresponding in equation 1 at an energy $E > E_B$. In a similar way, x-rays impinging on the left side of the crystal will be diffracted at energies lower than E_B. By applying this argument for each photons coming from the source we obtain that, on the image plane, the mean energy of the diffracted beam ranging from E_{min} on the left to E_{max} at the right, i.e. the field presents an energy gradient along the direction parallel to the Bragg diffraction.

Table 1: Main characteristics of the simulated quasi-monochromatic beams.

	beam size FWHM (mm)	mean energy (keV)	energy resolution (keV)	energy resolution (%)
I peak	4.1	35.6	3.9	10.8
II peak	4.2	31.1	2.8	9.0

3. COMPUTER SIMULATION

In order to estimate the characteristics of the source, in terms of quality, size and separation of the diffracted beams, computer simulations with the software SHADOW have been first performed.[12] SHADOW is a software package that is designed to study the propagation of a photon beam through an optical system, composed by a source and a set of optical elements, such as mirrors, slits, crystals, and screens placed in sequential order. The software is optimized to simulate synchrotron radiations sources, but the definition of source with whatever geometry is possible. A Monte Carlo method generates the x-rays produced by the simulated source, and a complete setting of the characteristics of the beam is possible (spatial type, the angle distribution and energy distribution of photons).

The x-ray tube characteristics used in simulation were those of a typical radiography source: square focal spot (0.5×0.5 mm^2 of size), and distribution of photons over an angle of 17.0 degrees. Moreover the maximum voltage applied to the tube was set to 65 kV, so as to maximize photon flux leaving out the photons of second diffraction order from the beam. The simulated optical system included also a highly oriented pyrolytic graphite mosaic crystal having the same characteristics of the crystal used in experiments with our facility: mosaic spread of 0.26 degrees, thickness of 0.1 cm and surface area of 2.8×6.0 cm^2. It was placed at 130 mm from the source, whereas the crystal-to-image plane distance was set to 600 mm. Since the Monte Carlo method generates at most 25000 photons each run, in order to have sensible results, the size of the diffracted beam on the image plane was limited to 10 mm along the direction orthogonal to the diffraction plane. In this way the obtained results allowed us a reliable study of the quasi-monochromatic beam in the direction parallel to the Bragg diffraction plane.

Results of the simulation are shown in figure 2. The quasi-monochromatic beam has a rectangular shape with a size of 10×20 mm^2 (figure 2a). The intensity profile obtained in the direction orthogonal to the Bragg diffraction plane shows a constant trend (2b), whereas in the parallel one the curve has a gaussian-like shape, with a calculated FWHM of 11 mm (2c). In addition, from figure 2d we observe along this direction the energy gradient discussed in the previous section. The energy profile show a gaussian trend, centered at 33.4 keV with a FWHM of 7.18 keV, corresponding to an energy resolution of 21.4%.

A second simulation was performed by maintaining the same geometrical set-up and by putting at the center of the image plane a beam stopper 4 mm-wide. Results are reported in figure 3. Two laminar and parallel quasi-monochromatic beams are obtained, separated both spatially and energetically. Table 1 reports the calculated characteristics of the beams. Energy profiles of the two beams have gaussian-like shape, and mean energy of 35.6 keV and 31.1 keV, respectively. Apart from mean energy, the two beams present similar characteristics: beam size differ only on 2%, and the percentage energy resolutions are of the same order of magnitude. Simulation results mean that, together with an appropriate geometrical set-up and a dedicated collimating system, quasi-monochromatic x-ray obtained by Bragg diffraction on mosaic crystal may constitute an ideal source for dual-energy subtraction angiography. In addition these results give important indications about the geometrical set-up which should be used to design a system dedicated to a clinical practice of this technique.

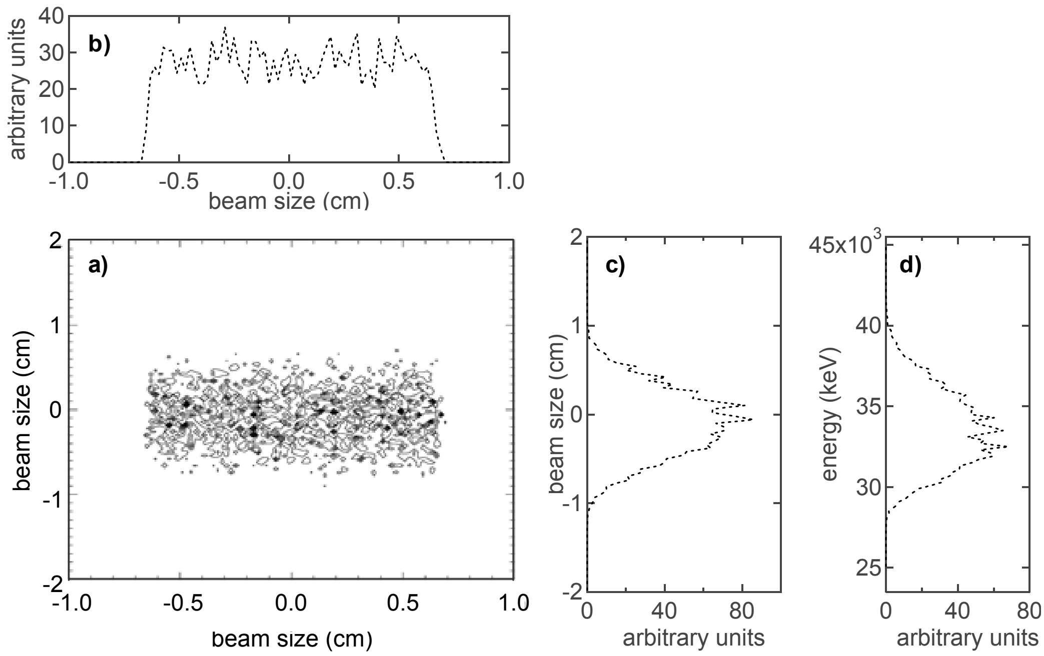

Figure 2. Results of the computer simulation of a quasi-monochromatic beam with a nominal mean energy of 33.17 keV obtained via Bragg diffraction with a x-ray tube and a pyrolytic graphite mosaic crystal: a) bidimensional image; b) intensity profile obtained along the direction orthogonal to the diffraction plane; c) intensity profile obtained along the direction parallel to the diffraction plane; d) energy profile obtained along the direction of the diffraction plane.

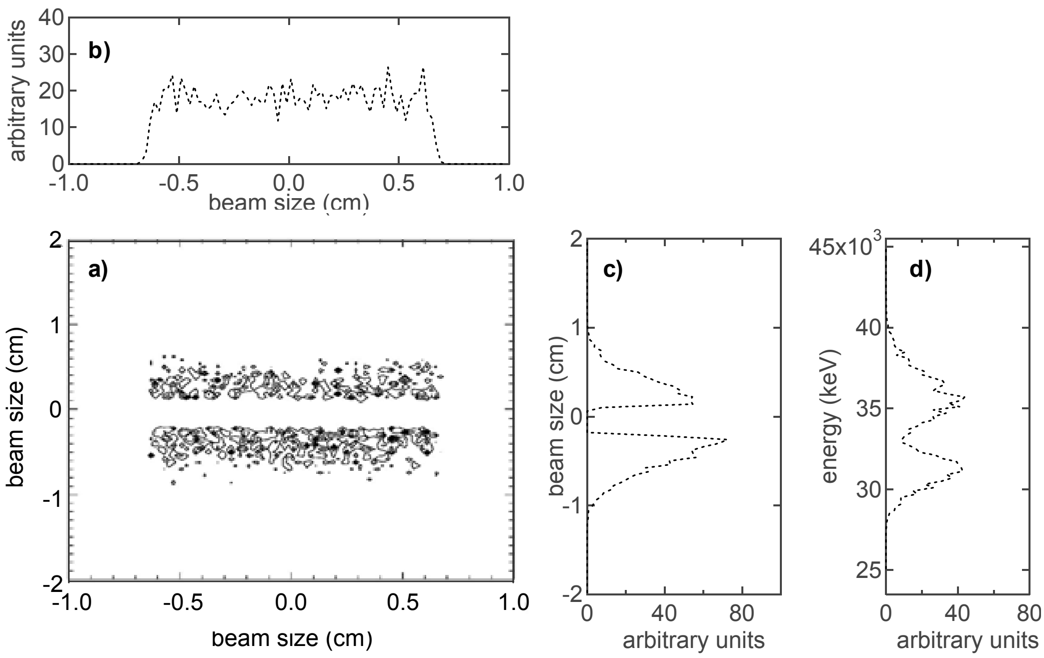

Figure 3. Results of the computer simulation of a quasi-monochromatic beam with a nominal mean energy of 33.17 keV obtained via Bragg diffraction with a x-ray tube and a pyrolytic graphite mosaic crystal, and with a beam stopper 4 mm-wide placed at the centre of the beam: a) bidimensional image; b) intensity profile obtained along the direction orthogonal to the diffraction plane; c) intensity profile obtained along the direction parallel to the diffraction plane; d) energy profile obtained along the direction of the diffraction plane.

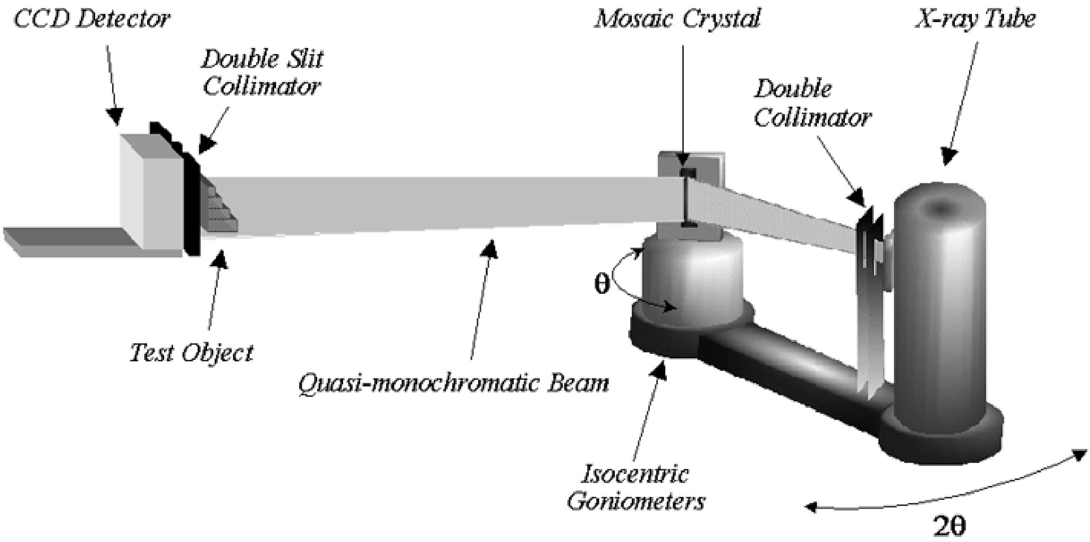

Figure 4. Sketch of the experimental apparatus. X-rays produced by a tungsten anode x-ray tube are diffracted by the mosaic crystal. A CCD detector is used to record the image of the phantom.

4. EXPERIMENTAL

The imaging system is schematically depicted in figure 4. The photon source consists of a W-anode X-ray tube, operating at 50 kVp. The X-ray tube is mounted on a goniometer so that the desidered Bragg angle can be selected. A double lead collimator is placed downstream of the tube so as to match the incident X-ray beam to the crystal size.

The monochromator, placed at 250 mm from the x-ray tube focus, is a highly oriented pyrolytic graphite crystal (HOPG) supplied by Optigraph (Optigraph Ltd., Moscow, Russia). It has a measured mosaic spread of (0.26 $\pm$ 0.1) degrees, a thickness of 0.1 cm and a surface area of 2.8 $\times$ 6.0 cm^2. A lead beam stopper is placed between the monochromator and the image plane to stop the direct beam coming from the x-ray tube

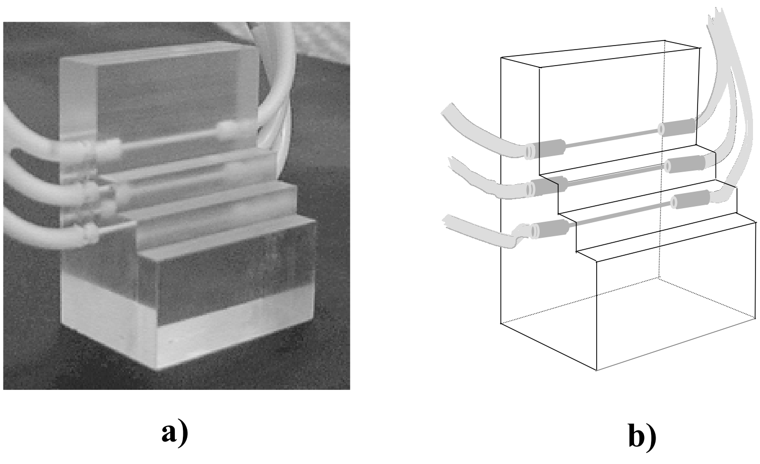

Figure 5. Step wedge plexiglas phantom, containing three cylindrical cavities filled with the iodate contrast agent: a) photograph of the test object; b) schematical representation.

and transmitted through the crystals.

As a test object we used a plexiglas step wedge phantom (see figure 5), 40 mm-high and 30 mm-wide, and with a thickness ranging from 10 mm to 45 mm. Three cylindrical cavities, having 1 mm of diameter have been drilled, and by means of lateral catheters they have been filled with iodate contrast medium, whose concentration was 370 mg/ml.

The digital detector was placed at 900 mm from the crystal. It is based on a phosphor coated CCD[13,14] which is obtained by direct deposition of a Gd_2O_2S:Eu powder (100 μm thick) onto the detector surface. The CCD is a grade 5 05-20 inverted mode device manufactured by EEV Ltd. (Chelmsford, UK), it has a pixel pitch of 22.5 μm, and 770 $\times$ 1152 pixels, with a useful surface of 17.3 $\times$ 25.9 mm^2.

Images have been acquired with the test object placed in contact with the detector window. A pixel binning was applied to each image, so as to obtain useful pixel size of 45 μm.

5. RESULTS AND DISCUSSION

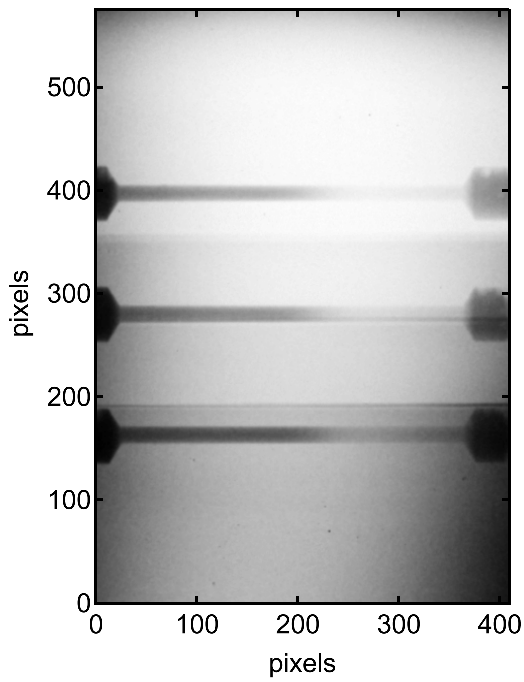

Figure 6. Complete image of the test object obtained with the quasi-monochromatic beam at a Bragg energy of 33.17 keV.

The image of the test object obtained with the quasi-monochromatic x-ray beam tuned at 33.17 keV is reported in figure 6. Exposure conditions were 50 kVp and 375 mAs. We observe that the cavities containing the iodate agent give a very high contrast only on the left side of the image, where the photon energy is higher than the iodine K-edge energy, while they are almost not detectable on the right side. This result demonstrates the existence, on the image plane, of a precise correspondence between energy and position of diffracted photons, thus producing the energy gradient discussed in the previous sections. In the image is also present a vertical gradient due to the attenuation characteristics of the step wedge phantom.

To obtain with a single exposure two separated images of the test object, with photons having mean energy under and above the iodine K-edge, respectively, a mask has been placed between phantom and digital detector. The mask consisted in a lead foil in which two identical slit have been carved. Each slit was 18 mm-high and 4.5 mm-wide, and they were separated by a 4.5 mm-wide obstructive slab. Position and size of the slits were set so as to obtain on the image plane two separated beam, identical in shape and size but energetically separated, with mean energy under and above the iodine K-edge, respectively.

Resulting images are shown in figures 7 and 8, together with their mean vertical profiles. Table 5 reports for each cavity of the two images, the minimum gray level, the mean gray level measured on the background, and the difference on these two values (i.e. the detail contrast). We observe that in the high energy image the measured contrast of the details is about four times higher of those measured on the low energy image.

The hybrid image obtained as a difference of the previous two in shown in figure 9. We observe the absence of the gradient due to the attenuation characteristics of the step wedge phantom which was present in the primary images, while the contrast generated by the iodate solution is very high. As a consequence of these two effects, the detail visibility is very improved in the final image. This result, together with the theoretical one obtained

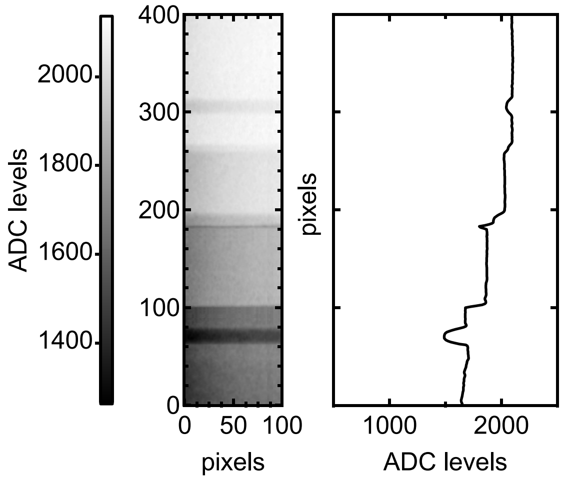

Figure 7. On the left: 100 × 400 pixels image of the test object obtained with the low energy side of the diffracted beam (E < 33.17 keV). On the right: mean intensity profile.

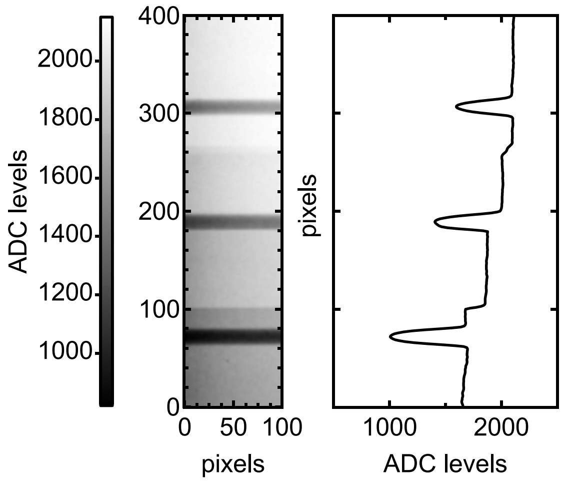

Figure 8. On the left: 100 × 400 pixels image of the test object obtained with the high energy side of the diffracted beam (E > 33.17 keV). On the right: mean intensity profile.

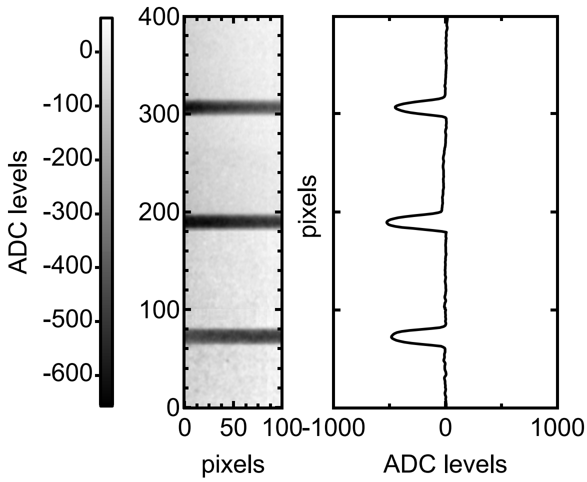

Figure 9. On the left: 100 × 400 pixels image of the test object obtained as a difference of the high and low energy images. On the right: mean intensity profile.

Table 2: Measured optical densities and contrasts for each detail of the images aquired at low and high energy.

image	cavity	min. gray level	mean gray level	Δ gray level
low energy	1	2013	2098	85
	2	1802	1916	114
	3	1488	1676	188
high energy	1	1757	2095	338
	2	1404	1874	470
	3	938	1692	754

with the computer simulation, is encouraging for the application of the dual-energy subtraction angiography using quasi-monochromatic beams, showing that the technique could lead to a reduction of contrast medium concentration and dose delivered to the patient.

At the moment works are in progress to build a large field source having size and fluxes conform to the clinical practice, and to develop a couple of linear digital detectors, whose characteristics (as size and efficiency) are optimized to work with the dichromatic source. The new system, composed by source and detector will allow us to perform test in realistic conditions.

6. CONCLUSION

A preliminary study of a new compact source for dual-energy subtraction angiography has been presented. Computer simulations performed with the computer software SHADOW have shown that quasi-monochromatic x-ray beams obtained via Bragg diffraction on mosaic crystal, together with an appropriate collimating system are able to produce two thin parallel quasi-monochromatic beams, having peak energies centered under and before the iodine K-edge energy, respectively. Experimental tests performed with a small-field digital detector show that the use of this new technique provides an enhancement of image contrast, and cancels the signal not due to the presence of the iodate medium. Thus, it could lead to a reduction of contrast medium concentration and dose delivered to the patient. Works are in progress to build a large field dichromatic source, that will allow us to obtain beams having size and fluxes conform to the clinical practice.

7. ACKNOWLEDGMENTS

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