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Use of XR-QA2 radiochromic films for quantitative imaging of a synchrotron radiation beam

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ABSTRACT: In the framework of an ongoing project, promoted by INFN, at the SYRMEP beamline of the ELETTRA synchrotron radiation facility (Trieste, Italy) for phase-contrast breast X-ray computed tomography, the assessment of the dose to the breast is one of the issues, requiring the determination of the distribution of X-ray incident photon fluence. This work investigates the use of XR-QA2 radiochromic films for quantitative imaging of the synchrotron radiation (SR) beam. XR-QA2 films were irradiated in a plane transverse to the beam axis, with a monochromatic beam of energy of 28, 35, 38 or 40 keV. The response of the radiochromic film was calibrated in terms of average air kerma measured with an ionization chamber. The net reflectance of the exposed film was then converted to photon fluence per unit air kerma ($mm^{-2}mGy^{-1}$). The SR beam profile was acquired also with a scintillator (GOS) based, fiber optic coupled CCD camera as well as with a scintillator based flat panel detector. Horizontal and vertical line profiles acquired with the radiochromic films show the 2D distribution of the beam intensity, with variations in the order of 15–20% in the horizontal direction. The response of the radiochromic film is comparable to that of the other imaging detectors, within less than 5% variation.

KEYWORDS: Beam-line instrumentation (beam position and profile monitors; beam-intensity monitors; bunch length monitors); Dosimetry concepts and apparatus; Instrumentation for synchrotron radiation accelerators

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Contents

1 Introduction

This experimental study has been performed within the project SYRMA-CT, supported by INFN (Italy). SYRMA-CT is a pilot study at the SYRMEP beamline of the ELETTRA synchrotron radiation (SR), facility in Trieste, Italy [1, 2], for producing the first in-line phase-contrast Computed Tomography (CT) scan of the female breast with monochromatic synchrotron radiation (~ 40 keV). The setup will include a single photon counting CdTe imaging detector [3]. The assessment of the radiation dose to the breast is one of the critical issues in this context [4]. The dosimetric protocol will be based on the evaluation of the Mean Glandular Dose (MGD), the dose metric used in X-ray mammography. The MGD for a CT scan will be calculated as the product of the measured air kerma (at the isocenter of the scanner) for the normalized dose coefficient (DgN_{CT}). This will require the recalculation via Monte Carlo (MC) simulations, for the case of the SR beam, of the DgN_{CT} coefficients estimated by Boone et al. [5] for cone beam CT dedicated to the breast based on an X-ray tube source.

SR breast CT adopts peculiar irradiation geometry, with a monochromatic, collimated laminar beam; the specification of the spatially resolved X-ray beam fluence (photons/mm^2) enters as an input to the MC simulation, in order to calculate the resulting dose distribution in the breast. Hence, the experimental assessment of the beam distribution in a plane transverse to the beam propagation direction is a specific dosimetry task in the SYRMA-CT project. While variations in the vertical direction are mainly due to the beam collimation system, additional variations of the beam profile in the horizontal direction might be expected, in case of misalignments or local defects in the beam optics (the monochromator crystal), beam instability, presence of scatter from collimator slits, etc. However, the determination of the absolute beam fluence in 2D of the SR beam is not a straightforward procedure when using spatially integrating detectors.

This work investigates the use of XR-QA2 radiochromic films — designed for quality control in diagnostic radiology [6] — for quantitative imaging of the SR beam. In particular, radiochromic films will be used to obtain, on a periodic basis, the 2D distribution of the photon fluence at isocenter of the breast CT scan, in a plane orthogonal to the beam axis. This will permit the calculation of the appropriate DgN_{CT} coefficients in the actual conditions of the CT scans, as regards the 2D beam intensity.

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Radiochromic films have been used in the past for dose verification purposes with synchrotron-produced monochromatic X-ray beams [7]. Use of radiochromic films was also reported for dosimetry of synchrotron microbeam radiation therapy [8]. The goal of the present method is to determine the photon fluence per unit area over the whole transverse surface of the SR beam, after calibration with an ionization chamber in terms of air kerma.

2 Materials and methods

The Gafchromic^{TM} XR-QA2 film (Ashland, NY, U.S.A.) is a reflective-type film with an asymmetric geometrical structure, composed of one active layer of 25 μm thickness separated by an adhesive layer of 20 μm, sandwiched between two 97-μm thick polyester layers, one with an orange colour on the front and the other with a white colour on the back. By specifications, the film is sensitive in the dose range 1–200 mGy and energy range 20–200 keV. Pieces of film ($200 \times 30\,mm^2$) were cut from a single sheet (lot #A10071003A) and irradiated in a plane transverse to the beam axis. The front orange layer of the film was facing the X-ray beam. Measurements were performed at the SYRMEP (SYnchrotron Radiation for MEdical Physics) beamline at the ELETTRA facility [1, 2]. A monochromatic, laminar beam of transverse size $170 \times 3.94\,mm^2$ ($H \times V$) and photon energy of 28, 35, 38 or 40 keV, irradiated the film at a distance of about 23 m from the source. The beam cross section was defined by a slits system. During the measurements, the electron energy was 2.4 GeV and the ring current was 160 mA. The response of radiochromic film was calibrated in terms of average air kerma, K_{air} (mGy), measured with a calibrated ionization chamber (Radcal 10X6-3CT connected to the dosimeter Radcal AccuPro, Radcal Corp., Monrovia, CA, U.S.A.). The 100-mm long chamber was positioned along the vertical direction at the centre of the beam (figure 1a), so that its 3-cm^3 sensitive volume was covered only partially by the SR beam. Hence, its reading was scaled by a factor $100/L$, where L (mm) is the vertical height of the beam at the position of the chamber, as determined by the vertical collimation of the beam. This correction is intended to provide an air kerma averaged along the vertical direction (determined by the central height of the

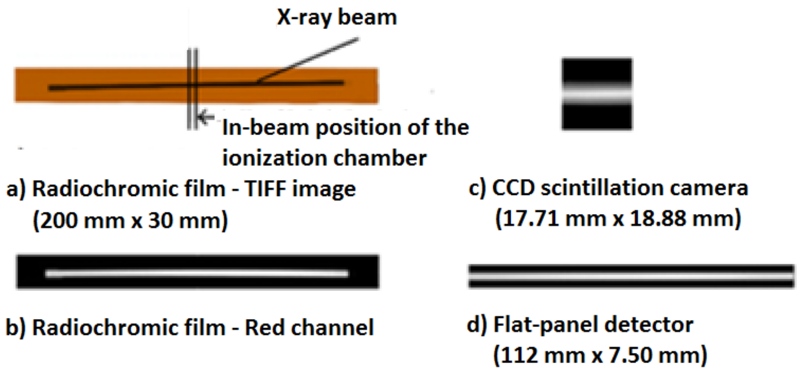

Figure 1. a) Raw colour image of the SR beam (photon energy = 28 keV) acquired with the radiochromic film; the position is indicated where the ionization chamber was placed for air kerma measurements. b) The red channel of the raw image of the radiochromic film. c) Image of the SR beam acquired with the scintillator based CCD camera. d) Image acquired with the flat panel detector. The white zones in the middle of images 1b), 1c), 1d) correspond to the irradiated area.

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beam), as well as along a horizontal beam span of 9 mm (determined by the diameter of the CT ionization chamber). This value of air kerma was taken as the reference value for normalization of the radiochromic film response.

The calibration process was performed at each beam energy (28, 35, 38 and 40 keV). For each calibration curve (air kerma vs. net reflectance), eleven $50 \times 50\,\text{mm}^2$ pieces of film were irradiated in air obtaining a dataset of eleven air kerma values ranging from 1 to 25 mGy (figure 2). This irradiation was performed by translating the film across the beam along the vertical direction, at a constant speed, thus obtaining a uniform film exposure. This procedure allowed to average the vertical beam profile and to obtain a sufficiently wide area for film digitization and analysis [7]. Films were digitized in reflectance mode using a flatbed scanner (Epson 750V Pro, EPSON Scan readout software) with an image resolution of 150 dpi in 48 bit RGB mode and saved as tagged image file format (TIFF) files. The 16-bit red channel of the RGB image was used for the film processing. Following Menegotti et al. [9], in order to obtain stable values from the scanned image each scan was repeated five times consecutively and only the last one was analysed. The analysis was performed by using the open software ImageJ (National Institutes of Health, Bethesda, MD, U.S.A.). Following Tomic et al. [10], the film response was evaluated, at each beam energy E (keV), in terms of net reflectance, netΔR. Its value (mean pixel value $\pm$ std. dev.) in a Region Of Interest (ROI) of $10 \times 10\,\text{mm}^2$ was plotted versus the air kerma, K_{air}, and a function of the form

$$K_{\text{air}} = a + b \left[\frac{\text{net}\Delta R}{\ln(\text{net}\Delta R)} \right] \tag{2.1}$$

was fitted to the data using the data analysis software Origin 5 (OriginLab Corporation, Northampton, MA) with a and b as fitting parameters. The netΔR was then converted to photon fluence ϕ (mm^{-2}), using the relationship between K_{air} (mGy) and ϕ, given by

$$K_{\text{air}} = c \cdot \phi \cdot E \cdot \frac{\mu_{\text{en}}}{\rho} \tag{2.2}$$

where μ_{en}/ρ (cm^2/g) is the mass energy absorption coefficient of air at photon energy E (keV) and where c ($= 1.6 \times 10^{-8}$) is a scaling factor. Here μ_{en}/ρ (cm^2/g) is used instead of μ_{tr}/ρ (cm^2/g) since for low Z materials in this energy range the two coefficients are virtually identical [11]. This permits to express quantitatively the calibrated pixel value of the radiochromic image of the SR beam, normalized to air kerma, in $\text{mm}^{-2}\ \text{mGy}^{-1}$.

The SR beam profile was acquired also with a CMOS flat panel detector (Hamamatsu, model C7942CA-02) featuring a 50 μm pitch and a 150-μm thick CsI:Tl scintillator, as well as with a scintillator based CCD camera having a field of view of $17.71 \times 11.88\,\text{mm}^2$. It is a water cooled CCD camera by Photonic Science (Millham, East Sussex, U.K.), model VHR, 4008×2672 pixel full frame, used in 4×4 binning mode resulting in a pixel size of 18 μm by side, coupled to a $3\,\text{mg/cm}^2$ Gadolinium Oxysulphide (GOS) scintillator placed on a fiber optic taper. This camera was used to analyse the 2D intensity distribution at the center of the 170-mm wide SR beam. The CCD camera response was not uniform in the horizontal and vertical directions, due to the optical coupling between the phosphor layer and the CCD chip. The image acquired with the CCD detector was corrected for the flat field acquired with a uniform illumination with a 40 kV X-ray tube beam. Then, the horizontal beam profiles obtained with the three modalities (radiochromic film, CCD

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camera and flat panel) were compared (at 28 keV). For beam energies of 35, 38 and 40 keV only the radiochromic and CCD images have been acquired.

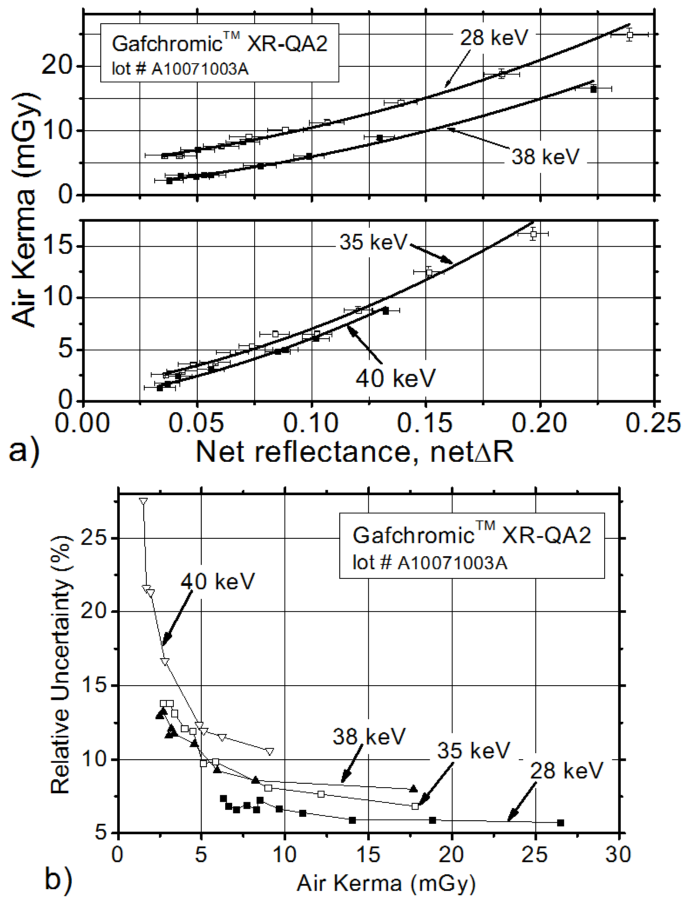

Figure 2. a) XR-QA2 radiochromic film calibration curves (at 28, 35, 38 and 40 keV) and b) corresponding uncertainties, calculated via error propagation as std. dev./ measured value, according to ref. [10].

3 Results and discussion

Figure 1a shows the raw image of the SR beam acquired with a piece of radiochromic film ($200 \times 30\,\text{mm}^2$), and the SR beam image acquired with scintillator-based CCD camera ($17.71 \times 11.88\,\text{mm}^2$) (figure 1c). The red channel of the image acquired with the radiochromic film (figure 1b) was calibrated in terms of photon fluence per unit air kerma at the beam centre, where the ionization chamber was placed during the air kerma measurements. Calibration curves obtained at the various energies are shown in figure 2a, at all energies, while corresponding experimental uncertainties (obtained via error propagation) are shown in figure 2b: at all energies, they decrease to less than 10% for air kerma values above 10 mGy. Figure 2a evidences the necessity to perform a separate calibration at each photon energy.

Figure 3 shows the horizontal and vertical profiles evaluated from the radiochromic images in a rectangular ROI of size $176.6 \times 0.68\,\text{mm}^2$ and $22.69 \times 8.97\,\text{mm}^2$ for the horizontal and vertical direction, respectively, across the beam centre. The beam uniformity at 28 keV, in terms of percent variation from the peak value of the line profile, is over 20% (in the horizontal direction) and 37% (in the vertical direction) as observed in figure 3. Interestingly, as shown in the inset in figure 3b, the vertical profile of the radiochromic image of the beam shows a beam halo, whose signal is up to two orders of magnitude less intense than the main peak intensity.

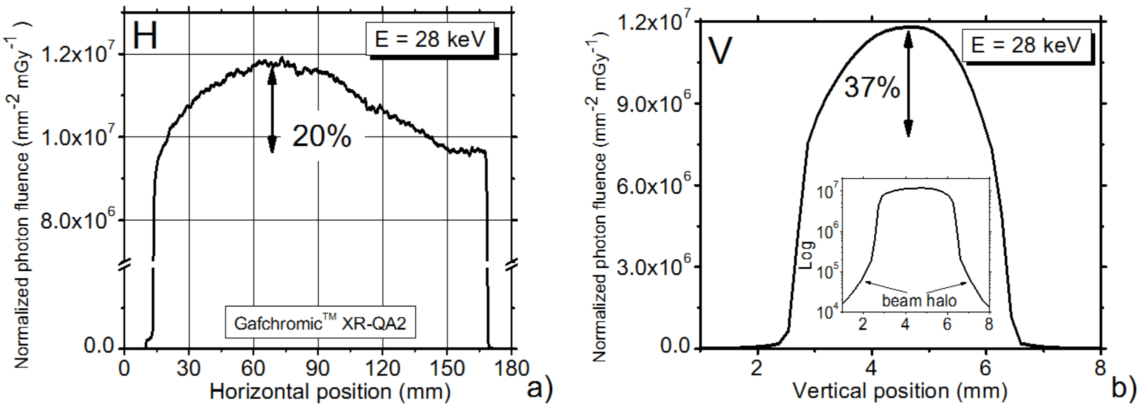

Figure 3. a) Horizontal (H) and b) vertical (V) profiles of the SR beam at 28 keV, obtained from the image of the radiochromic film. In (a) the line profile was averaged along the vertical direction. Maximum variation of 20% (H) and 37% (V) were observed, with respect to the peak value. The inset in (b), in log scale, highlights a low-intensity scatter signal at the periphery of the beam.

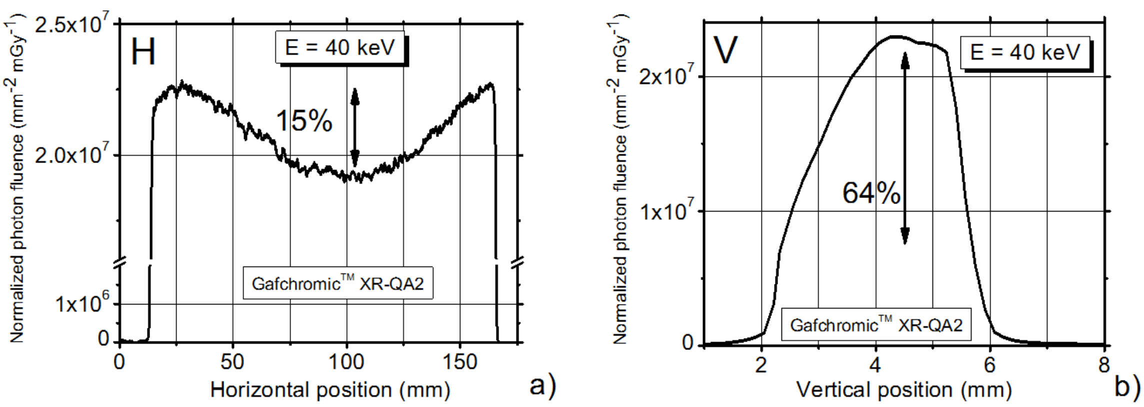

Figure 4. a) Horizontal and b) vertical average profiles of the SR beam at 40 keV, obtained from the radiochromic image. Maximum variations of 15% (H) and 64% (V) were observed.

The beam line profiles obtained with radiochromic imaging at 40 keV are shown in figure 4; in this case the maximum non-uniformity of the beam was 15% along the horizontal direction. The variation of about 64% of the beam profile in the vertical direction is attributed to the misalignment of the slits system with the peak. Figure 5 shows the comparison of the horizontal beam profiles obtained with the three modalities (radiochromic film, CCD camera and flat panel detector). The profiles were evaluated in rectangular ROI of size $17.71 \times 0.59\,\text{mm}^2$ (at 28 keV, figure 5a, and at 40 keV, figure 5b, respectively) and ROI of size $100 \times 0.59\,\text{mm}^2$ at 28 keV in figure 5c. The CCD and flat panel profiles were scaled in order to have the same average value as the normalized profile

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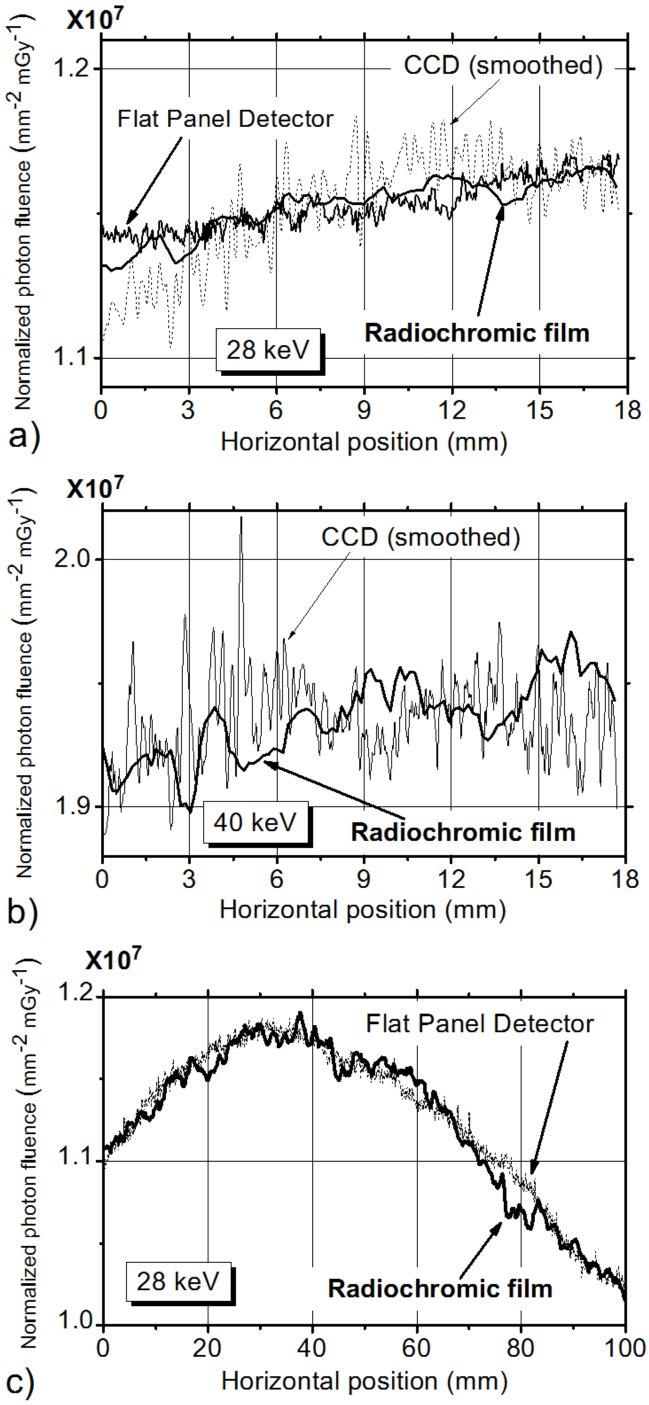

Figure 5. The average horizontal line profiles along a ROI of size $17.71 \times 0.59\,\mathrm{mm}^2$ of the image of the beam acquired with the radiochromic film, with a CCD detector and with the flat panel detector, at a) 28 keV, b) 40 keV. c) The average horizontal line profiles along a ROI of size $100 \times 0.59\,\mathrm{mm}^2$ of the image of the beam acquired at 28 keV with the radiochromic film and with the flat panel detector. Profiles were scaled vertically in order to have the same average value as the average line profile acquired with the calibrated radiochromic film. The response of the radiochromic film is comparable to that of the other imaging detectors, within less than 5% difference. The image for the flat panel detector at 40 keV was not available.

acquired with the radiochromic film. Moreover, given the higher spatial sampling of the CCD detector (1411 pixels per inch) with respect to the radiochromic image (150 dpi scan), the profile corresponding to the CCD detector was smoothed by a 10 point second order polynomial moving average digital filter.

The relative variation [(max-min)/mean] of the normalized photon fluence obtained with radiochromic film over the 18-mm wide SR beam (figures 5a and 5b) was about 3% for all profiles, well within the statistical uncertainties evaluated for the radiochromic dose measurements (6% at 28 keV). The difference in the response of the radiochromic film with that of the other imaging detectors was less than 5%. The comparison of the horizontal profiles — acquired with the radiochromic film and with the flat panel detector over the 100-mm wide SR beam at 28 keV (figure 5c) — shows once again a difference in the response of less than 5%.

A set of exposures (figure 6a) was made by inserting thin foils of pure aluminium (from 1 mm up to 5-mm thick) consecutively in the beam, which determined an increasing attenuation of the beam intensity. From the average value of the calibrated response of the film in a ROI centred on each Al foil of varying thickness (figure 6b), an attenuation curve was derived (figure 6c). The half value layer (HVL) evaluated from the exponential fit of the data points was 1.75 ± 0.15 mm Al: at the given beam energy (28 keV) the calculated HVL is 1.9 mm Al ($\mu_{\mathrm{Al}} = 1.351\ \mathrm{g/cm^2}$, from XMuDat [12]), a reasonable agreement.

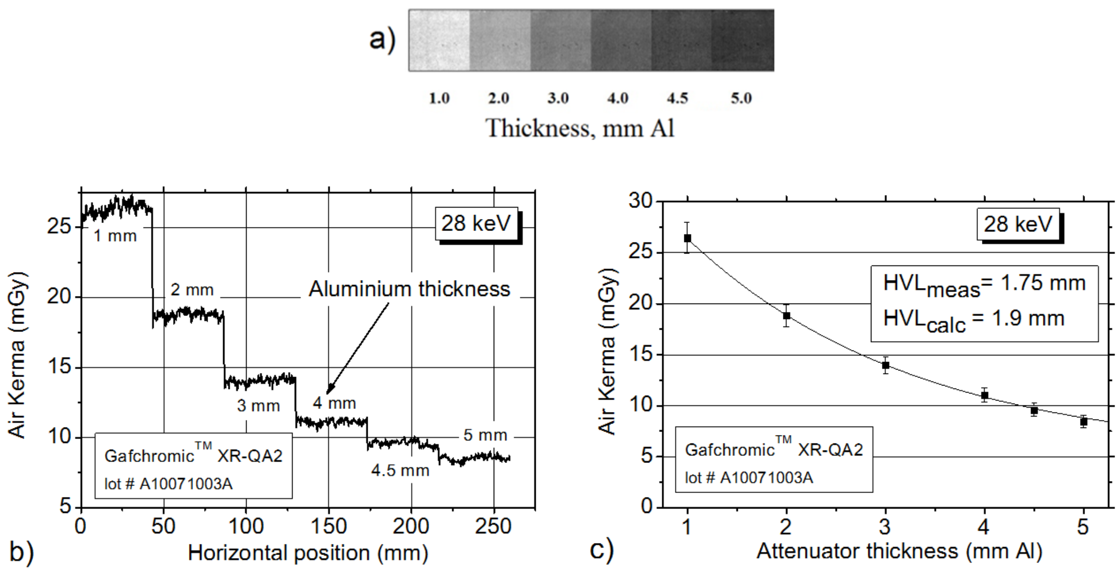

Figure 6. a) Composite image of six radiochromic film pieces exposed to the SR beam at 28 keV attenuated by varying thicknesses of Al foils. b) Average line profile of the calibrated film response in (a). c) Attenuation curve from the data in (b) (data points shown as mean ± std. dev. in a ROI), along with an exponential fit (continuous line). Measured and calculated HVL values (mm Al) are also indicated.

4 Conclusions

The images of the SR beam produced with the Gafchromic™ XR-QA2 films have been calibrated in terms of air kerma free-in-air, using a standard 100-mm-long CT ion chamber. Once expressed

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in units of photons mm^{-2}mGy^{-1}, the radiochromic film provides the 2D distribution of the beam intensity in a plane transverse to the beam axis in terms of photon fluence per unit air kerma. The radiochromic films show beam intensity variations which were down to four orders of magnitude lower than the maximum beam intensity. Observed variations of the beam intensity were from 15% to 64% over the whole beam, but beam intensities over two orders of magnitude lower than the maximum intensity were detected. The comparison with images acquired with a CCD scintillator camera and with a flat panel detector shows that the performance of the film is comparable within 5%, but the film is expected to provide an unsaturated response in a larger range of air kerma values. Moreover, the radiochromic film may have a larger sensitive area than CCD or flat panel detectors and it does not require any flat field correction, but it requires an offline processing.

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