Quality assurance of carbon ion and proton beams: A feasibility study for using the 2D MatriXX detector

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Quality assurance of carbon ion and proton beams: a feasibility study for using the 2D MatriXX detector

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Purpose: The quality assurance (QA) procedures in particle therapy centers with active beam scanning make extensive use of films, which do not provide immediate results. The purpose of this work is to verify whether the 2D MatriXX detector by IBA Dosimetry has enough sensitivity to replace films in some of the measurements.

Methods: MatriXX is a commercial detector composed of 32×32 parallel plate ionization chambers designed for pre-treatment dose verification in conventional radiation therapy. The detector and GAFCHROMIC® films were exposed simultaneously to a 131.44 MeV proton and a 221.45 MeV/u carbon-ion therapeutic beam at the CNAO therapy center of Pavia – Italy, and the results were analyzed and compared.

Results: The sensitivity MatriXX on the beam position, beam width and field flatness was investigated. For the first two quantities, a method for correcting systematic uncertainties, dependent on the beam size, was developed allowing to achieve a position resolution equal to 230 μm for carbon ions and less than 100 μm for protons. The beam size and the field flatness measured using MatriXX were compared with the same quantities measured with the irradiated film, showing a good agreement.

Conclusions: The results indicate that a 2D detector such as MatriXX can be used to measure many parameters of a scanned ion beam quickly and precisely and suggest that the QA would benefit from a new protocol where the MatriXX detector is added to the existing systems.

Key words: Quality Assurance, Active Beam Scanning, Particle Therapy, MatriXX

Introduction

In radiation oncology, periodic verification of dosimetric data and radiation beam quality are required as part of quality assurance (QA) programs.[1, 2] The correct use of radiations for therapeutic purposes is ensured by focusing on the detection of any possible abnormal behavior which may lead to deviations from the prescribed dose larger than tolerances. Several detectors are used for the dosimetry of both conventional and charged particle beams. Among these are ionization chambers, radiographic films, diodes, and radiochromic films. Ionization chambers are the reference instrumentations for absolute dose calibration either in standard radiotherapy, which uses photon beams, either in charged particle therapy (CPT), which uses ion beams.[3] Film and diode measurements are also widely used with ion beams, although as the beam energy varies with depth, care must be taken to account for energy-dependent effects[3] especially if accurate quantitative measurements are required.

The most advanced clinical implementations of CPT are the modulated scanning techniques, for which thousands of pencil beams are aimed in a rapid 3D sequence of spots conformed to the tumor. The complexity of the technique has generated the need for a new class of QA systems that permit rapid and precise two-dimensional (2D) and possibly three-dimensional (3D) measurements. Most of the systems in use are based on single or arrays of ionization chambers and on films, which are certainly precise but suffer for lengthy procedures. Nichiporov et al.[4] examined the usefulness of multichannel detectors, while in many other studies[5-9], film dosimetry has been proposed to verify dose distributions and perform QA in proton therapy. Film dosimetry, shown to be highly precise, does not give immediate results because the procedures required for preparing, scanning, calibration, and off-line analysis are time-consuming. More recently, Y. Hara et al.[10] published a paper on application of radiochromic films in the heavy-ion beam QA which has been performed at HIMAC. In this paper they have verified the QA measurements using the EBT2 film by comparing the measurements with a reference ionization chamber and a fluorescent screen. It is shown that the results obtained with EBT2 were in good agreement with those obtained with the reference detector. This result confirms that the film can be used as a part of QA procedures for therapeutic scanned carbon-ion beams.

Since several years, detectors made of 2D-arrays of ionization chambers are commercially available, examples being the OCTAVIUS Detector 729 XDR (PTW Freiburg, Germany) and the MatriXX (IBA Dosimetry, Schwarzenbruck, Germany). They are mainly designed for intensity-modulated radiotherapy (IMRT) QA, and in fact several investigators[11-13] have assessed their adequacy for QA in conventional radiotherapy with photons, electrons, and in IMRT. On the other hand, currently no specific instrument is commercially available for use in CPT.[14, 15]

Recently MatriXX has been shown to be an appropriate online device for machine QA checks of passive scattering[14] and spot scanning[16, 17] proton treatment facilities. At the University of Texas MD Anderson Cancer Center, the device has been proven to be accurate and fast for measuring the absolute dose, relative output factor, dose rate, flatness, and symmetry of the proton beams. Comparing the profiles, obtained using MatriXX, to films and to a 0.6 cc Farmer chamber in water, an excellent agreement, within 1%, has been reported. Furthermore at the Center of MD Anderson the feasibility of using MatriXX for quick and accurate verification of patient-specific proton-dose distribution has been examined.[15]

In the present study we have determined the performances of the 2D MatriXX detector for a set of measurements typically performed for QA of carbon ion beams. For completeness and comparison we have also studied the detector with proton beams. This study is preliminary to the design of a new QA procedure in CPT in which some of the operations are taken over by MatriXX measures. The work has been performed at CNAO (Centro Nazionale Adroterapia Oncologica, Pavia, Italy),[18] where the QA procedure is presently well established and based on Gafchromic films and a water phantom with a ionization chamber.[19]

Materials and Methods

At CNAO hadrontherapy center a synchrotron based on the PIMMS (Proton-Ion Medical Machine Study) design[20] is used to deliver both proton and carbon ion beams. Patient treatments started with protons in September 2011 and with carbon ions in November 2012.

A cycle of 4 to 5 s duration is the unit of operation of the accelerator and it is composed by the beam acceleration followed by the charged particles extraction, called spill. The duration of the spill is typically 1 s but can be extended up to two seconds if needed. During the inter-spill time, the machine is prepared for the next cycle by setting the beam elements for the desired beam. In addition to the selection of the beam species, beam particle's energy, beam flux and beam transverse size can be selected among predefined values.

The beam energy can be selected within a set of values between 120 MeV/u and 400 MeV/u for carbon ions and between 60 and 250 MeV for protons, corresponding to steps of particle range in water of approximately 1 mm, up to a maximum range of 27 cm. The accelerator can provide a maximum of 4×10^8 C^{+6} or 10^{10} protons per spill, leading to a maximum beam current on the patient of 0.38 nA and 1.6 nA respectively. Lower currents can be achieved either by increasing the spill duration or by reducing the particles injected in the accelerator using injection grids. Two nominal beam transverse sizes are available for carbon ions, corresponding to 6 and 10 mm full width at half maximum (FWHM), while for protons a single FWHM of 10 mm is used.[21] For this work, the carbon beam FWHM of 6 mm was selected in order to test the MatriXX detector with the most demanding beam conditions.

Typically, in the transverse plane the beam is scanned through a grid with a pitch, projected on a plane perpendicular to the beam and located at the isocenter, of 2 mm for carbon ions and 3 mm for protons, with an accuracy of ±0.1 mm.[18] The beam position and step size is controlled with two scanning magnets acting separately along horizontal (X) and vertical (Y) directions. By adjusting the currents in the magnets, the beam is deflected with the required precision. All these design parameters fulfill the clinical requests.

MatriXX[22] is a commercial two-dimensional matrix of ionization chambers designed for pre-treatment verification of 2D dose distribution and for routine QA of photon and electron beams in conventional radiotherapy and IMRT. The device includes 1020 cells resulting from a 32×32 matrix with four missing chambers at the corners. Each detector cell is a parallel plate vented cylindrical ionization chamber with a size of 4.5(Ø)×5(h) mm^2 and 0.08 cc sensitive volume, separated from the adjacent cells by 7.619 mm center-to-center distance. The active area is about 24.4×24.4 cm^2. The charge produced by the ionizing tracks crossing the sensitive volume, proportional to the dose, is measured and digitized by a charge to digital count converter.[23] Each count unit corresponds to 200 fC and the total number of counts is proportional to the dose deposited in each cell. At any given time all the counters can be latched by storing the contents in registers, thus providing a snapshot of the charges collected by the 1020 pixels. The data are then transferred to a PC via a standard Ethernet interface. The read out cycle for all the pixels may take a time as short as 500 µs. The performances of MatriXX in conventional radiotherapy have been discussed in several papers.[11-13, 23, 25]

The OmniPro-I'm*RT*® software program (IBA, Be[27]) was used to control, calibrate and acquire data with the MatriXX detector. Before the measurements, a procedure recommended by the manufacturer was followed which includes the hardware/software setup, a warm-up and a pre-irradiation of the detector. Ambient temperature and pressure were entered into the acquisition program to correct for air-density variation in the ion chambers. To equalize the gains of all the 1020 channels, the detector was irradiated with a broad uniform field. The gains were then stored in the MatriXX software, and applied to all subsequent measurements.

The program OmniPro-I'm*RT*® gives the possibility of acquiring consecutive snapshots at fixed time intervals, selected by the user, with MatriXX. For each snapshot any of the 1020 ionization chamber readings provide the absolute charge delivered in the corresponding time interval in terms of number of counts.

A single spot was irradiated in each spill. The entire beam cycle was monitored with MatriXX having set-up the data acquisition in order to acquire snapshots at time intervals of 500 ms. Given a spill length of approximately 1 s, the spill in general was split over three snapshots and the beam cycle (4 s) over 9 snapshots.

For each snapshot, the 1020 data were recorded and logged in a file. The final analysis was implemented using the NI LabVIEW[26] package. For most of the analyses, all snapshots related to a single spot were added off-line to have a single set of data for one irradiated spot.

The center of gravity coordinates (X_{cog}, Y_{cog}) of the spots were calculated using the formulae reported in the following:

$$X_{cog} = \frac{\sum S_{ij} \times X_{i,j}}{\sum S_{ij}}, \quad Y_{cog} = \frac{\sum S_{ij} \times Y_{i,j}}{\sum S_{ij}} \qquad (1)$$

where S_{ij} is the number of counts recorded in chamber (i,j) and summed over the snapshots acquired when the corresponding spot was irradiated. $(X_{i,j}, Y_{i,j})$ is the coordinates of the center of chamber (i,j), and sums run over all the MatriXX chambers.

The FWHM of the projections along X and Y is interpreted as the beam width along X and Y respectively, and was evaluated with the following relations:

$$X_{FWHM} = 2.355 \times \sqrt{\frac{\sum S_{ij}(X_{i,j} - X_{cog})^2}{\sum S_{ij}}}, \quad Y_{FWHM} = 2.355 \times \sqrt{\frac{\sum S_{ij}(Y_{i,j} - Y_{cog})^2}{\sum S_{ij}}} \qquad (2)$$

where the symbols have the same meaning as in Eq. 1.

Snapshots taken during the inter-spills, when no particles are extracted from the accelerator, were used to measure the electronics background level. We remark that the background level was found to be very small (< 1 ‰ of the maximum signal) and in this analysis has been neglected.

Due to the geometry of MatriXX, which has an active area not fully covered, only parts of the irradiation fields can be probed and the reconstructed beam position and width can be affected by systematic errors. To estimate such errors, related to the pitch and size of the MatriXX chambers and beam width, a simple Monte Carlo was developed. Referring to Figure 1, given the position (X, Y) of the beam central axis with respect to the center of the detector and the beam transverse shape, the fraction of charged particles crossing the chamber centered at $(X_{i,j}, Y_{i,j})$ and the corresponding collected charge is precisely determined. This was done by randomly generating a sufficiently large number of tracks. The study has been repeated for different positions of the beam axis to evaluate the fraction of charge collected by each chamber as a function of (X, Y). The data generated by the Monte Carlo simulation were used to

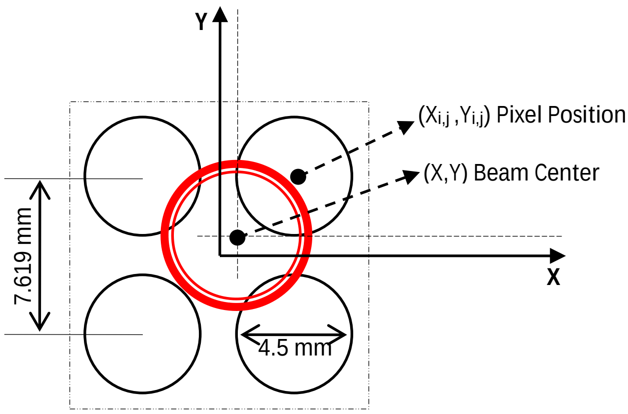

FIG. 1. Sketch of the Monte Carlo simulation. The red circle represents the FWHM of the beam. Only four central chambers of MatriXX are shown.

reconstruct the beam position and width using Eq. 1 and 2 and compared to the generated quantities. The systematic differences were tabulated to be used for later correction.

The measurements performed with MatriXX were compared to the measurements using the CNAO QA standard procedures. At CNAO, QA measurements[19] are currently done by using GAFCHROMIC® EBT film and a PTW Farmer® Ionization Chamber. GAFCHROMIC® EBT films, used to probe the field homogeneity, the beam FWHMs, and spot positions, are scanned using EPSON® scanner E1680-PRO (Epson America, Inc.).

Measurements and Results

The aim of this work is to explore whether ionization chamber arrays, specifically the MatriXX 2D detector, can be used for part of the QA procedure in CPT environment. For both carbon ion and proton beams we focused on three QA procedures: beam position measurement, beam width determination, and field dose uniformity.

MatriXX was placed perpendicular to the beam at the isocenter position by aligning the external reference marks of the chamber to the laser alignment system of the treatment room. The beam impinged on MatriXX after crossing the vacuum window and, with a good approximation, the ionization chambers were probing the plateau of the depth dose curve. Thus, the beam energy is expected to have little impact on the measurements described above. We chose arbitrarily a beam energy equal to 221.45 MeV/u for carbon ion and 131.44 MeV for proton beams.

When a uniform field was required, the scanning beam was steered across the detector in steps of 2 mm and 3 mm for carbon and proton beams respectively. These figures correspond to typical values used in patient treatments and ensure field homogeneity at the level of 1% or better.

Beam position measurement accuracy

The purpose of this measurement was to evaluate the accuracy of the MatriXX detector in measuring the position of a delivered spot. For this purpose the CNAO dose delivery system (DDS) was required to deliver a 7×7 grid of spots with a spacing of 26 mm for carbon and 30 mm for proton beams. The number of particles per spot was fixed to 3×10^7 carbon ions and 3×10^8 protons, and the total number of particles in a spot was typically reached in one single spill. The grid was obtained by a sequence of vertical sweeps of the beam where the current of the horizontal deflection magnet of the DDS was kept constant. The reconstructed spot positions of each vertical sweep were fitted to a straight line and the deviations were

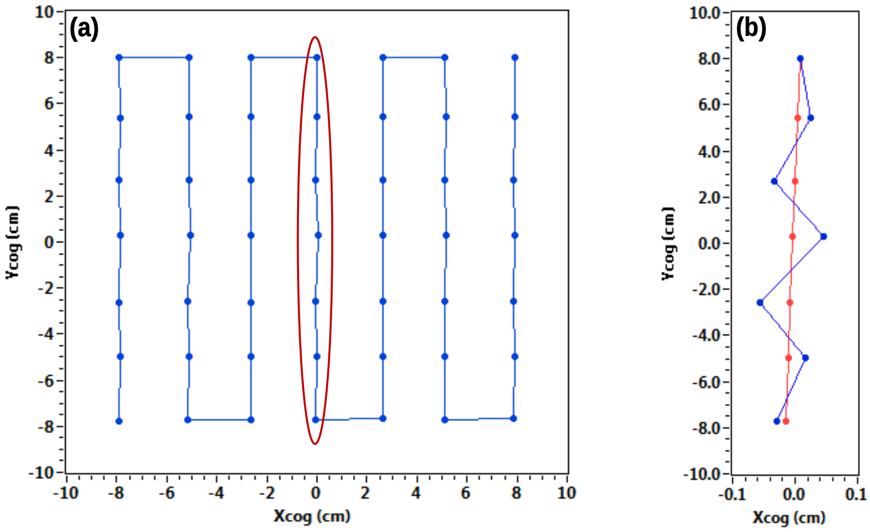

FIG. 2. a) Measured grid spot positions with the carbon ion beam. Blue points are the measurements and lines are added to indicate the spot sequence; b) blowup of the central column. The red line is the result of the fit.

used to estimate the position resolution. The rms was found to be as small as 13 µm, with a maximum deviation of 30 µm for protons, but substantially larger for carbon ions, 220 µm with a maximum deviation of 480 µm. This is due to the comparatively large pitch of the MatriXX grid with respect to the smaller beam FWHM of the carbon ion beam. For the carbon beam, Figure 2.a shows the pattern of the measured spot positions while Figure 2.b shows a blowup of the central column and the result of the fit. The full swing of the measurements is well contained within 480 µm.

We remark that the beam position deviations from the straight line accounts only for the statistical contribution to the measurement errors. There could be an additional systematic effect, common to all the spots in the same column, related to the fixed relative horizontal position of the beam spots with respect to the column of chambers. To explore this contribution we repeated the same spot delivery after a small rotation of MatriXX detector about the beam axis. Repeating the vertical scan the spots would now be located at different relative positions between adjacent columns of chambers.

For each of the two beam species, the 7 groups of 7 spots were fitted to straight lines imposing the same slope. The deviations of the measured positions from the fitted line have a magnitude similar to the untilted chamber for protons (rms of 14 µm with a maximum deviation of 25 µm), but appear to be larger for carbon ions (rms of 580 µm with a maximum deviation of 1.2 mm). This results suggest that the accuracy of the beam position measurements strongly depends on the beam FWHM, being very good for beams width FWHM of 10 mm or more, and barely within the required position accuracy (±1 mm) for narrower beams of FWHM ≈ 6 mm. The histograms of the deviations are shown in figure 3.a for carbon ion and in figure 3.b for proton beams.

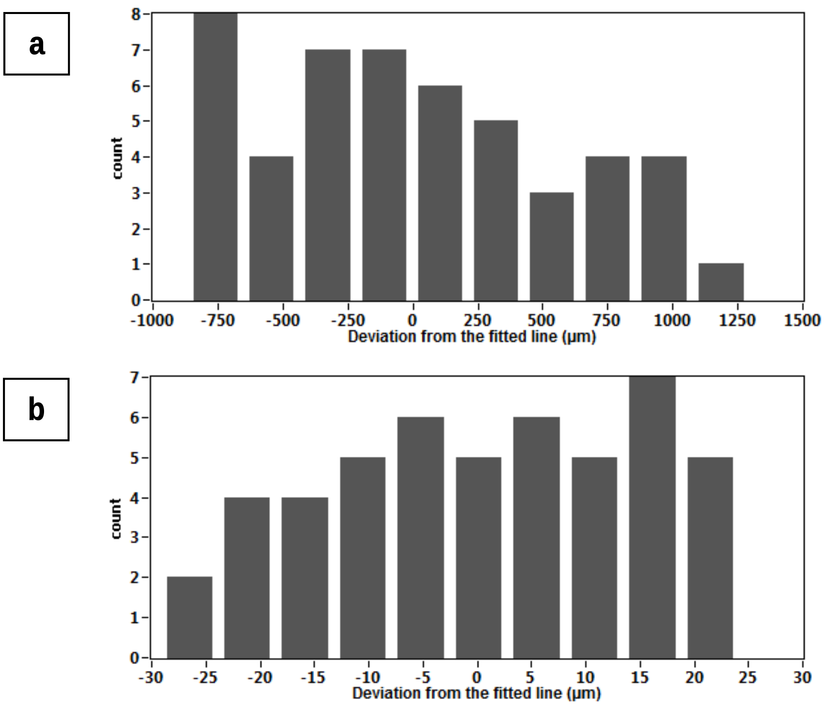

FIG. 3. Histogram of deviations from a straight line for a) carbon ion (FWHM = 6 mm) and b) proton beams (FWHM = 10 mm)

We investigated the systematic effects in the beam position measurement originated by the MatriXX chamber spacing and their dependence on the beam FWHM. For this purpose, the simulation described in the previous section was performed by generating a large number of beam positions (≈ 50×50) uniformly covering the square area defined by 4 adjacent chambers (see Fig. 1). The beam shape was described by a two dimensional Gaussian distribution with equal widths in both directions. From the simulation, the shifts along the X and Y directions, $S_x(X,Y,W)$ and $S_y(X,Y,W)$, between the reconstructed beam position and the generated one were recorded, for later use, as a function of X, Y and the beam FWHM W. The correction S_x (S_y) is found to depend on only on X (respectively Y). In addition, being the problem completely symmetrical in X and Y, we can write $S_x(X, W) = S_y(Y, W) = S$ for $X = Y$. As expected, S strongly depend on W. The S values are plotted for carbon ions, with $W = 6$ mm, in Fig. 4.a, and for protons, with $W = 10$ mm, in Fig. 4.b, as a function of the X position of the beam relative to the center of MatriXX (see Fig. 1). For a FWHM of 10 mm the shift is well confined within ±50 μm, while the smaller beam size induces a correction up to ±1 mm.

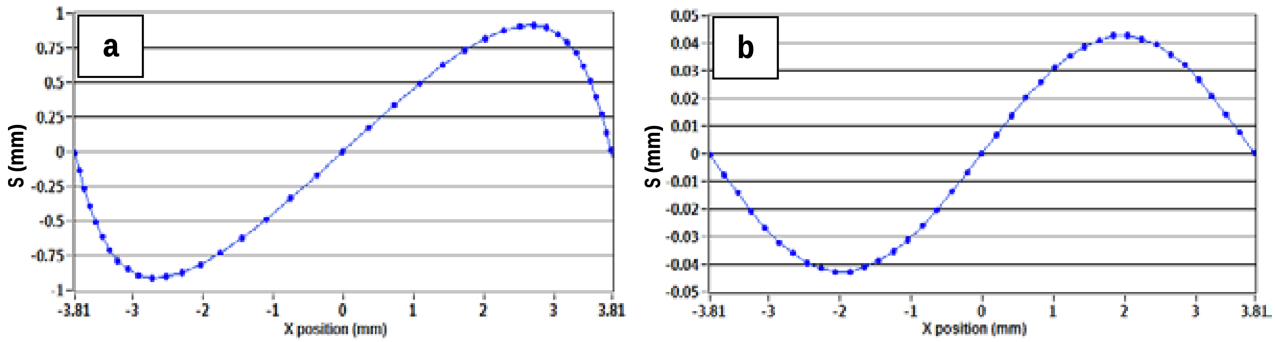

FIG. 4. Systematic deviations of the reconstructed from the generated beam centers as a function of the beam position. The beam position origin is set in the center of MatriXX. Being a periodic function of the position, a single cycle corresponding to the distance between the two central chambers is shown: a) is for carbon ion beam and b) is for proton beam

To improve the precision of the beam position measurement, we applied the shift corrections with the following equations:

$$X_{cog}^{corr} = X_{cog} + S(X_{cog}, W), \quad Y_{cog}^{corr} = Y_{cog} + S(Y_{cog}, W) \qquad (3)$$

To apply this correction, we assumed that the value of W is known from independent measurements. In Figure 5, we show the distributions of the deviations of the positions from the fitted lines for carbon ions and protons after the shift corrections of Eq. 3 have been applied. As expected, for carbon ion beams (Fig. 5.a) the improvement is noticeable, reducing the rms from 580 to 230 μm. For protons (Fig. 5.b), the improvement is almost negligible, reducing the rms from 14 μm to 8 μm.

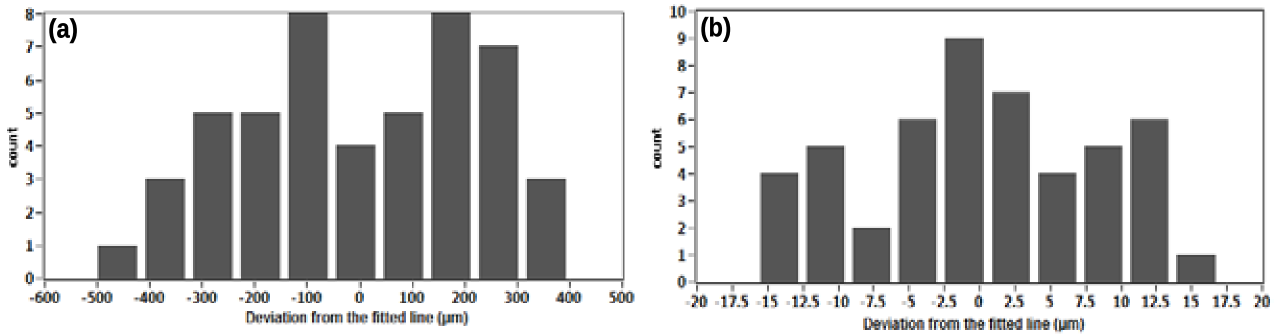

FIG. 5. Distribution of deviation from a straight line after corrections have been applied: a) is for carbon ion (FWHM = 6 mm) and b) is for proton beams (FWHM = 10 mm)

The effect of the corrections is particularly impressive when applied to a large sequence of 6 mm-FWHM beam spots for the delivery of a (6×6 cm^2) uniform square field with steps of 2 mm along X and Y directions. The scan was done by moving the beam vertically and, once swept a vertical line, by moving it horizontally by 2 mm. A spill could cover on average three vertical spots, thus the center of gravity gives the average positions of the three spots. In Figure 6.a we show the positions, as reconstructed with MatriXX with Eq. 1, and in Figure 6.b we show the same sequence after the corrections have been applied. The positions prior corrections are not as regular as the DDS provides. Once the positions have been corrected the inter-space between them becomes more regular.

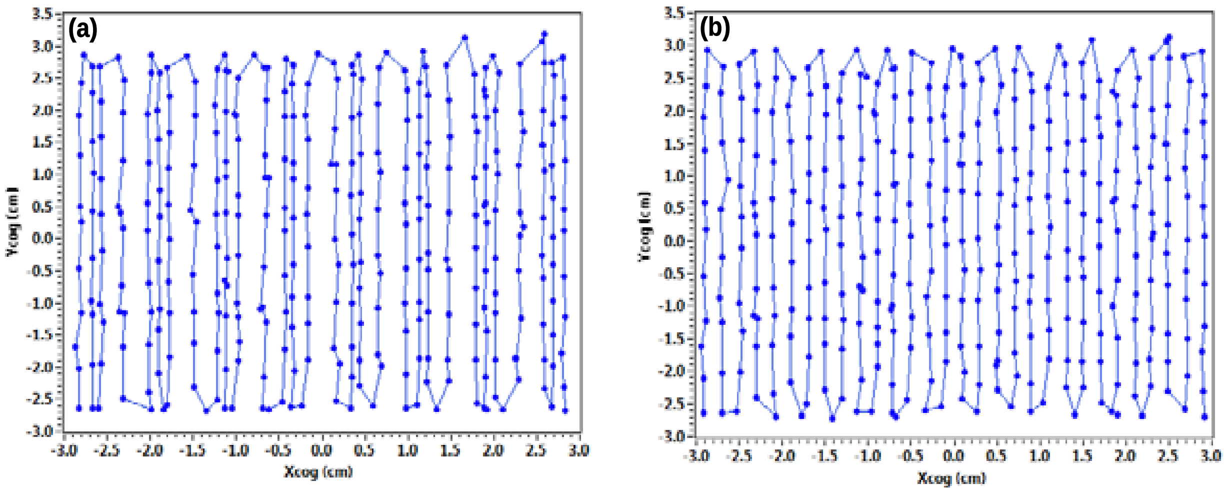

FIG. 6. Sequence of spots to deliver a square field of 6 cm × 6 cm. Figures show the positions reconstructed a) before and b) after corrections, explained in the text, have been applied.

Beam width determination

The measurement of the beam width along X and Y coordinates is a crucial part of the daily QA as a too narrow or too wide beam can affect the dose uniformity or the lateral dose fall-off. The FWHM of the beam transverse distribution is commonly used to describe the beam transverse size. Typically, a tolerance of ±1 mm is set to this quantity.

MatriXX and GAFCHROMIC® EBT3-1417 film (MediTron, Switzerland, Frauenfeld) were simultaneously exposed to a 3×3 grid of spots, 10 cm apart, 3×10^7 carbon ions each (see Fig. 7.); being smaller the transverse dimension of the beam tends to generate a larger systematic error. A typical horizontal projection of the gray levels of a spot measured with the film is shown in Fig. 8.

FIG. 7. Picture of the set-up, right after irradiation: beam spots are visible on the strips of Gafchromic films, which have been taped to the MatriXX surface.

While the vertical scale is arbitrary, the horizontal scale gives the position in mm. The average FWHM for carbon ion beams as measured from the film analysis are 6.5 ± 0.1 mm along X and 5.4 ± 0.1 mm along Y. The FWHM measured with MatriXX were found to be: X_{FWHM} = (7.3 ± 0.2) mm, Y_{FWHM} = (5.1 ± 0.4) mm, where Eq. 2 was used and the errors have been derived from the fluctuations of the 3×3 measurements. A similar approach of the one pursued to reduce the systematic errors for the position measurement was then applied. With the Monte Carlo simulation a correction to the measured width, dependent on the beam position, was applied to the raw measurements. After correction, the FWHM resulted to be (6.3 ± 0.1) mm along X and (5.7 ± 0.5) along Y. The agreement between film and MatriXX is within 0.3 mm, which is well below the ±1 mm limit required.

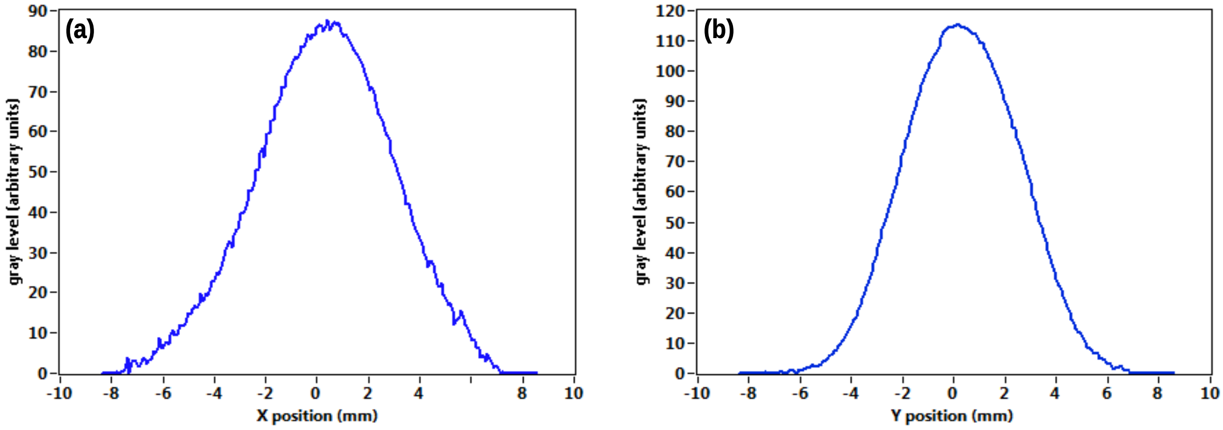

FIG. 8. a) Horizontal and b) vertical projection of the gray levels of a spot measured with the film.

Field dose uniformity

At CNAO, the dose uniformity level in a square field is part of the daily QA checks. It is currently done by irradiating a Gafchromic film with a square uniform field and by determining the dose flatness along the horizontal and vertical directions. We used MatriXX to perform the same check.

First, we investigated the uniformity of the gain of the MatriXX by delivering a 5×5 spot grid with 1.5×10^{10} protons/spot in steps of 35 mm, thus covering an area of 14×14 cm^2 where spots are fully contained in the active area of the detector. The DDS of CNAO is designed and calibrated to deliver particles with high precision, at the per mille level.[28] Therefore only negligible deviations in number of particles between different spots are expected. From the number of counts, integrated over all the MatriXX chambers for each spot, a relative standard deviation between spots equal to 0.36% and a maximum deviation of ±0.8% is observed, showing a good uniformity of the detector.

Later, MatriXX was exposed to a uniform 6×6 cm^2 square field with both carbon ion and proton beams. In the case of carbon ion beams, the dose profiles were simultaneously measured by positioning a Gafchromic film on the front surface of MatriXX. The profiles along X (Y) were obtained by considering a single row (column) of chambers of MatriXX positioned at the center of the field. For comparison, the sum of 20 rows (columns) of pixels of the film image located at the same position was considered. The results along X are shown in Figure 9.

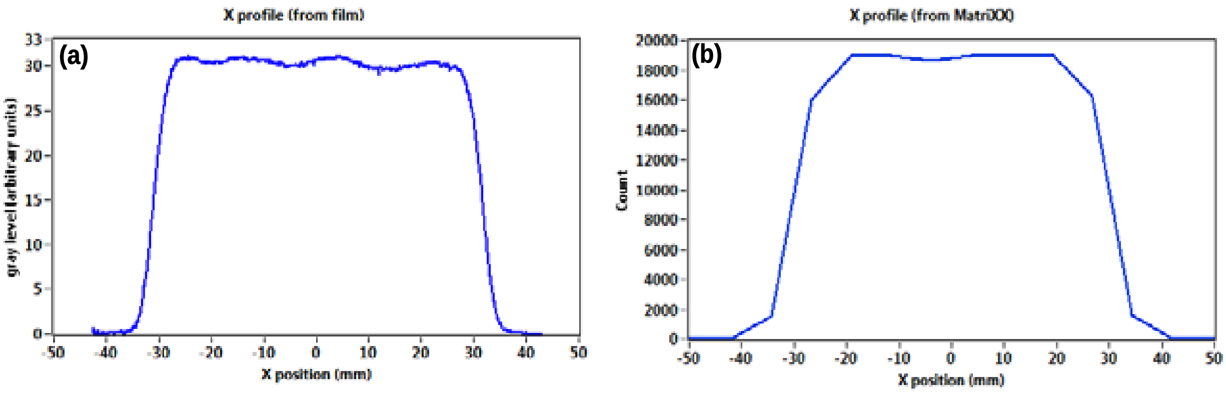

FIG. 9. Dose profiles of a 6×6 cm^2 square uniform field from a) film and b) MatriXX measurements. The irradiation has been obtained with a carbon ion beam.

The flatness was defined as

$$flatness = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \times 100 \qquad (4)$$

where I_{max} and I_{min} are the maximum and minimum values found in the dose plateau. This condition was ensured by considering only the measurements covering 80% of the central region of the plateau. The plateau is defined as the region where measurements are above 90% of the maximum. The tolerance of flatness used for the QA is set to ±3%. The measured carbon ion beam field flatness with MatriXX was found to be better than 2% in both directions, in agreement with the film measurements, 2.6% flatness in X and 2.3% flatness in Y. Similar results were obtained with protons, where the measured flatness was found to be 1.7% in X and 1.3% in Y directions.

Discussion

Quality assurance for CPT is a lengthy procedure that, in many centers, relies both on film measurement and on pinpoint ionization chambers. Many efforts have been devoted to reducing the length of the procedure without affecting the sensitivity.

Several years ago our group developed a 2D ionization chamber, commercially known as MatriXX, and more recently, designed and implemented the Dose Delivery System in use at CNAO. It is then being natural the match of both expertise to provide a feasibility study for the use of MatriXX in the QA of CPT. Indeed the same type of detector was investigated at MD Anderson with protons whilst, in this paper, we focus mainly on the carbon and in parallel we verify the results for proton beams.

In this context we show that precise beam position and fast 2D dose distribution information can be determined very quickly using the MatriXX detector. With a chamber pitch of 7.619 mm, MatriXX has a sampling grid that is much larger than a film. However it is well known from the literature that by measuring the beam tails in the transverse plane one can accurately derive the beam central position provided that the beam width is known. We remark that prior QA, or before a patient treatment for that matter, among the several settings of the machine, the beam width is one of the key parameters to be chosen, and this value is the one we need to know to apply reliably the corrections.

For this work we evaluated the corrections with a simple and quick simulation and the results were stored in a file as a function of the beam widths allowed by machine, both for carbon ion and proton beams. The pre-computed corrections were then applied for the measurement of both the beam position and width.

Once the corrections have been applied the precision of position and width is at the sub-millimeter level. In summary with this method one can derive online the beam position and verify the beam width.

For what concerns the verification of the flatness one has to differentiate between a local irregularity and global deviation. In the former, if the dimension of the irregular delivery area is smaller than the pitch then MatriXX can fail the detection. On the other hand a global deviation can be detected at the level of 2% or less. In fact, the results show that MatriXX is quick and accurate enough to be used to determine the dose flatness of the scanned ion beam.

The performance of the 2D MatriXX detector in accurately and quickly measuring the beam position, beam size, dose field uniformity and flatness shows that this 2D detector is a well suited device for quality assurance checks of spot scanning ion beam therapy.

Conclusions

From this study we conclude that a 2D detector (in this paper we investigated the case of MatriXX) can replace films in part of the QA procedures in CPT centers. While films require a lengthy procedure for preparing, scanning, and offline analysis and a single ionization chamber requires repetitive beam deliveries, a 2D detector can be used to measure many parameters of a scanned ion beam quickly and precisely. The results suggest that the QA would benefit from a new protocol where the MatriXX detector is added to the existing systems.

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