



Technical note

Feasibility study of utilizing XRV-124 scintillation detector for quality assurance of spot profile in pencil beam scanning proton therapy

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ABSTRACT

Purpose: The purpose of the current study is to (i) investigate the feasibility of utilizing the XRV-124 – a cone-shaped scintillation detector – to measure the spot size and spot position in pencil beam scanning proton therapy, and (ii) compare the spot sizes acquired by the XRV-124 with that of the widely used Lynx detector.

Methods: Spot position was tested by delivering a map of 30 spots at different locations to the XRV-124. Spot position test included energies 70–210 MeV. Spot size measurements were performed at the isocenter using the XRV-124 and Lynx detectors for a total of 32 energies (70–225 MeV at an increment of 5 MeV) at four cardinal gantry angles.

Results: The position (X, Y, and Z) of the radiation isocenter was within ± 0.3 mm. For spots placed on the horizontal (X) and longitudinal (Y) axes of the spot map, both the X and Y locations of the spots were within ± 0.5 mm. The spots placed diagonally in the map showed a higher deviation (± 0.9 mm). In evaluating spot sizes acquired using the XRV-124 vs. Lynx, the results from the XRV were found to be slightly higher but within 0.2 mm for energies ≥ 130 MeV and within 0.4 mm for energies < 130 MeV.

Conclusions: It is feasible to utilize the XRV-124 to perform the quality assurance of position and size of a pencil proton beam around the radiation isocenter but within the usable XRV-124 cone area.

1. Introduction

Spot scanning proton therapy provides more conformal target dose distributions compared to the uniform scanning and double-scattering proton beam delivery techniques. [1,2] However, an unwarranted change in spot size and spot position can affect the quality of treatment beam delivery and patient treatment plan [3]. Therefore, the size and position of a pencil proton beam are measured as a part of quality assurance (QA) program [2].

Several commercial detectors are available to measure the spot size and position of a pencil proton beam. The Lynx (IBA Dosimetry, Schwarzenbruck, Germany) – a gadolinium-based scintillation detector – has been utilized by several authors to measure the spot size and position [4–8]. The MatriXX-PT (IBA Dosimetry, Schwarzenbruck, Germany) and Daily-QA3 (DQA-3) device (Sun Nuclear Inc., Melbourne, FL, USA) have been used in conjunction with in-house phantoms and software to measure the spot profiles [9–11]. A radiochromic film (Ashland Advanced Materials, Bridgewater NJ; Type: EBT3) is a high-resolution detector that can be used to measure the spot size and

position of a pencil proton beam [12].

The XRV-124 (Logos Systems Int'l, Scotts Valley, CA) is a cone-shaped scintillation detector, which requires BeamWorks software (Logos Systems Int'l, Scotts Valley, CA) to acquire and analyze the images. The XRV-124 provides the real-time proton and X-ray 3D beam vector and profile capture over 360° of rotation. Prior studies have characterized the XRV-124 to measure the centrality of the X-ray beam [13,14] and proton beam [15]. Since the XRV-124 can provide the centrality and profile of a pencil proton beam, the detector can potentially be used as an alternative QA device to measure the size and position of a pencil beam. Recently, Cai et al. [15] utilized the XRV-124 to perform QA of certain parameters for the spot scanning – also referred as pencil beam scanning (PBS) – proton therapy. As a part of PBS QA, Cai et al. [15] measured in-air spot sizes using XRV-124 and compared the XRV-124 results with the spot sizes acquired using MatriXX detector. However, positions of spots at various locations within XRV-124 was not addressed in the publication [15].

The purpose of our study is to investigate the feasibility of utilizing the XRV-124 to measure a spot profile in PBS proton therapy. This study

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differs from previous studies [8,13,15] on the XRV-124 in two important aspects: i) position of pencil proton beam is measured at thirty different locations using XRV-124, whereas previous studies [8,13,15] did not address the spot position measurements at different locations within the XRV-124, and ii) although Cai et al. [15] compared the in-air spot sizes from XRV-124 vs. MatriXX (detector spacing of 7.6 mm), to the best of our knowledge, our study is the first one to compare the in-air spot sizes acquired by the XRV-124 with that from the Lynx detector (0.5 mm resolution), which is most commonly used QA detector for the spot size and position measurements as shown in numerous publications [4–8,12,16–19]. The in-air one sigma spot size (hereafter simply referred as spot size) comparison between the XRV-124 vs. Lynx demonstrates the feasibility of utilizing the XRV-124 with an efficient setup of the detector to measure the spot size as a part of routine (weekly and monthly) QA. Additionally, limitations of both the XRV-124 and Lynx detectors are presented.

2. Materials and methods

2.1. Detectors

The XRV-124 [Fig. 1] is composed of an imaging cone laminated with $Gd_2O_2S:Tb$ screen that is sensitive to proton and X-ray beams. The device is coupled with the sensitive charge-coupled device (CCD) camera that can be connected to the controlling computer via the USB interface. The resolution of the CCD using BeamWorksPlus software is 1280×960 pixels, whereas the BeamWorksPlus software runs at 640×480 pixels (binned from 1280×960 pixels). [14] The cone has a 140 mm long field of view over 360° , whereas width of the cone varies from 30 mm to 60 mm. [14] The XRV-124 also includes the probe that can hold a fiducial (2.54 mm in diameter) on the central axis of the imaging cone. In the current study, the distance from the end of the imaging cone to the reference hole (isocenter) was set to 145 mm. For more details on the technical and operational aspects of the XRV-124, the readers are advised to refer to the XRV-124 manual [14] and

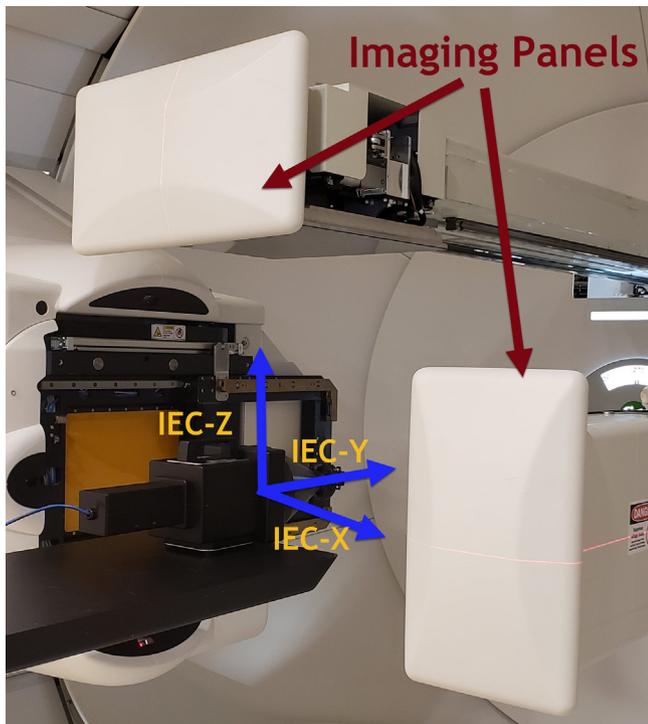


Fig. 1. (Left) An example of couch-top setup of the XRV-124; (Right) kV X-ray panels are extended for the image acquisition of the XRV-124 prior to beam delivery.

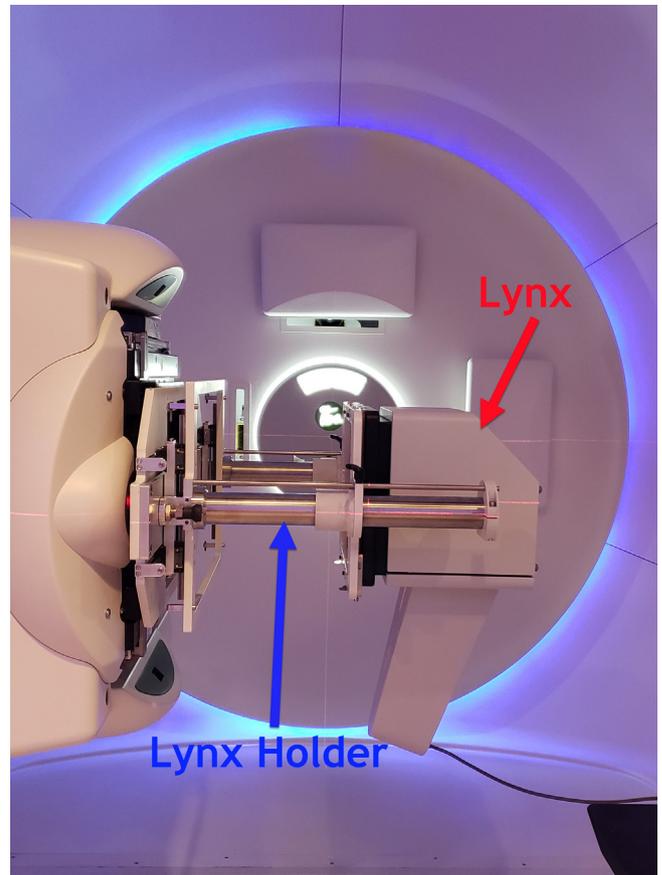


Fig. 2. Lynx detector is mounted to the gantry-head for spot profile acquisition.

published studies [13,15]. In brief, as the proton beam passes through the imaging cone, it creates two spots of light that the CCD camera digitizes. For the XRV-124, the proton beam is delivered in bursts so that the beam duration spans several camera frames of 0.05 s each [14]. The integration of several beam images allows to improve the signal to noise ratio of the image yielding a more precise measurement [14]. The controlling computer in conjunction with the BeamWorks converts the digitized information into vector and profile that can provide the position and direction of the proton beam.

The Lynx detector [Fig. 2] includes a gadolinium-based scintillating screen (0.4 mm thickness). The Lynx has dimensions of $36 \times 37 \times 60$ cm with an active surface area of 300×300 mm² (600×600 pixels) and effective spatial resolution of 0.5 mm. As the proton beam strikes the scintillating screen, light photons are created. This is followed by the reflection of the light to the photodiodes of a CCD camera. The detector signal from the CCD camera is then digitalized. A detailed characterization of the Lynx can be found in a publication by Russo et al. [4].

2.2. Experiment design

Our proton center has a ProteusPLUS (Ion Beam Applications, Louvain-la-Neuve, Belgium) proton therapy system with a PBS dedicated nozzle. Currently, adaPT-Deliver (v.11.0.3) and adaPT-Insight (v.2.1.0d) are used for beam delivery and imaging (kV–kV X-ray and kV-CBCT), respectively. For more details on the ProteusPLUS PBS proton therapy system, readers are advised to refer to published literature [7,16,20].

The current study included spot position and size measurements. The XRV-124 was scanned using a Siemens computed tomography (CT) Scanner with a 1 mm slice thickness. The CT images of the XRV-124 are used to generate the digitally reconstructed radiography (DRR) images

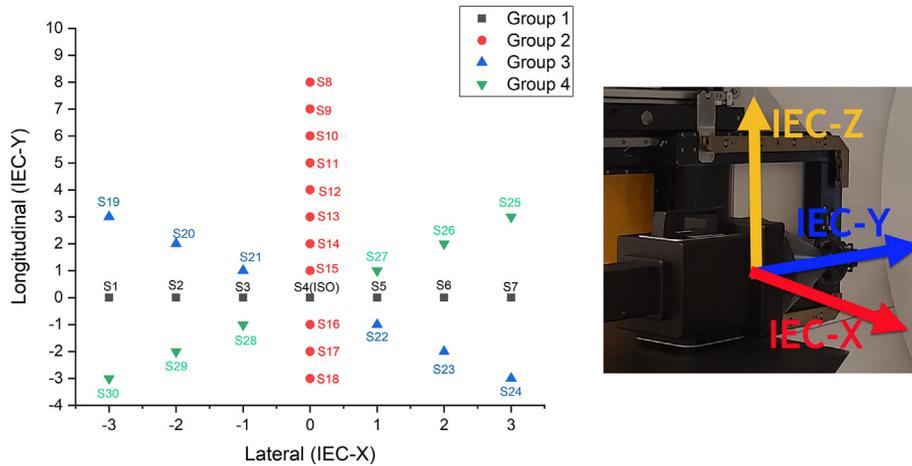


Fig. 3. (Left) A map of 30 spots to evaluate spot positions using the XRV-124. Spot 4 is at the isocenter. The planned vertical (IEC-Z) location of all 30 spots in this study is zero; (Right) IEC coordinate system with respect to XRV-124 setup is illustrated.

within the IBA system. The DRR images are then registered to the acquired portal kV X-ray images prior to beam delivery.

For spot position measurements, a map of 30 spots at different locations within the XRV-124 cone surface was generated. Fig. 3 shows the spot position map used in the current study. The positions of group 1 spots were evaluated at a distance up to 3 cm from the isocenter ($X = 0$, $Y = 0$, and $Z = 0$) in both lateral directions ($\pm X$). Similarly, for the spot positions in the longitudinal directions (group 2), the Y location was varied (+8 cm (superior) to -3 cm (inferior)) from the isocenter. A total of 8 proton fields were created for energies ranging from 70 MeV to 210 MeV at an increment of 20 MeV. For a given proton field, the energies of all 30 spots remained the same.

Spot size measurements are performed using a proton field of 32 energy layers. Specifically, the layers were consisted of energies ranging from 70 MeV to 225 MeV at an increment of 5 MeV, and each layer consisted of a single spot at the isocenter. The monitor units (MU) of spots of different energies were optimized to avoid having a measured spot profile with a flat top.

2.3. Setup and measurement

Fig. 1 shows the example of the couch-top setup of the XRV-124 displaying IEC co-ordinate system. In the current study, the positions IEC-X, IEC-Y, and IEC-Z denote the lateral, longitudinal, and vertical directions, respectively. Prior to proton beam delivery, the XRV-124 was imaged with kV X-rays, and center of the fiducial was aligned with the imaging isocenter. This was further verified by registering the acquired portal kV X-ray images to the DRR images of the XRV-124. The kV X-ray imaging alignment was followed by the delivery of a treatment field to the XRV-124. Specifically, the spot position measurements were performed at the gantry angle 0° , whereas the spot sizes were measured at the gantry angles 0° , 90° , 180° , and 270° . For both the spot position and spot size measurements, the XRV-124 was operated in a movie mode. The BeamWorks software (version 2.31) was used to acquire and analyze the XRV images. The software provides the centricity of the spot in X, Y, and Z axes as well as the width of the spot. Additionally, the displacement (d) of the spot from the planned target location was calculated using Eq. (1).

$$D = \sqrt{[\Delta_x]^2 + [\Delta_y]^2 + [\Delta_z]^2} \quad (1)$$

where

$$\Delta_x = M_x - T_x; \Delta_y = M_y - T_y; \Delta_z = M_z - T_z$$

M_x , M_y , and M_z = measured locations in the lateral, longitudinal and vertical directions, respectively;

T_x , T_y , and T_z = planned target locations in the lateral, longitudinal and vertical directions, respectively; (Note that planned T_z is zero for all spots in the current stud)

Fig. 2 shows the gantry-mounted setup of the Lynx on a Proteus-PLUS PBS system. In order to compare the data from the XRV-124, spot size measurements were repeated using Lynx at the gantry angles 0° , 90° , 180° , and 270° . The Lynx-plugin in within myQA software (IBA Dosimetry, Schwarzenbruck, Germany) was used for the spot profile acquisition and data analysis. Spot size is defined as the FWHM divided by 2.355, where FWHM is full width at half maximum of a single-spot profile modeled by a Gaussian function.

3. Results

The difference in spot positions between the measured (XRV-124) and planned values for various energies (70–210 MeV) are illustrated in Fig. 4. A total of 30 spots are divided into four groups (1, 2, 3, and 4) based on their arrangement in the spot map as shown in Fig. 3. The location (X, Y, and Z) of the radiation isocenter (spot 4) was within ± 0.3 mm. For group 1, the X, Y, and Z locations of the spots deviated from the planned values by -0.4 mm to 0.5 mm. For group 2, the X, Y, and Z locations of the spots deviated from the planned values by -0.5 mm to 0.4 mm. The range of spot positions deviation from the planned locations was slightly higher for groups 3 and 4. The difference in the X, Y, and Z locations ranged from -0.7 mm to 0.4 for group 3 and from -0.9 mm to 0.5 mm for group 4.

The results of spot size analysis/measurements are illustrated in Figs. 5 and 6. Overall, the XRV-124 produced slightly higher spot size compared to the Lynx for the energies and gantry angles selected in the current study. The average difference in spot size was 0.2 mm (range, 0 – 0.3 mm) for gantry angle 0° , 0.2 mm (range, 0.1 – 0.3 mm) for gantry angle 90° , 0.2 mm (range, 0.1 – 0.4 mm) for gantry angle 180° , and 0.2 mm (range, 0.1 – 0.3 mm) for gantry angle 270° .

4. Discussion

The complexity in PBS beam delivery system possess QA challenges in many centers. [21] We have investigated the feasibility of utilizing XRV-124 as an alternative QA equipment to measure the spot size and spot positions in PBS proton therapy. The current study included the spot positions measurements for a total of 30 spots within the active volume of the XRV-124. Additionally, the spot size was measured for several energies at four cardinal gantry angles, and the spot sizes from the XRV-124 were compared with that from the the Lynx. Although the

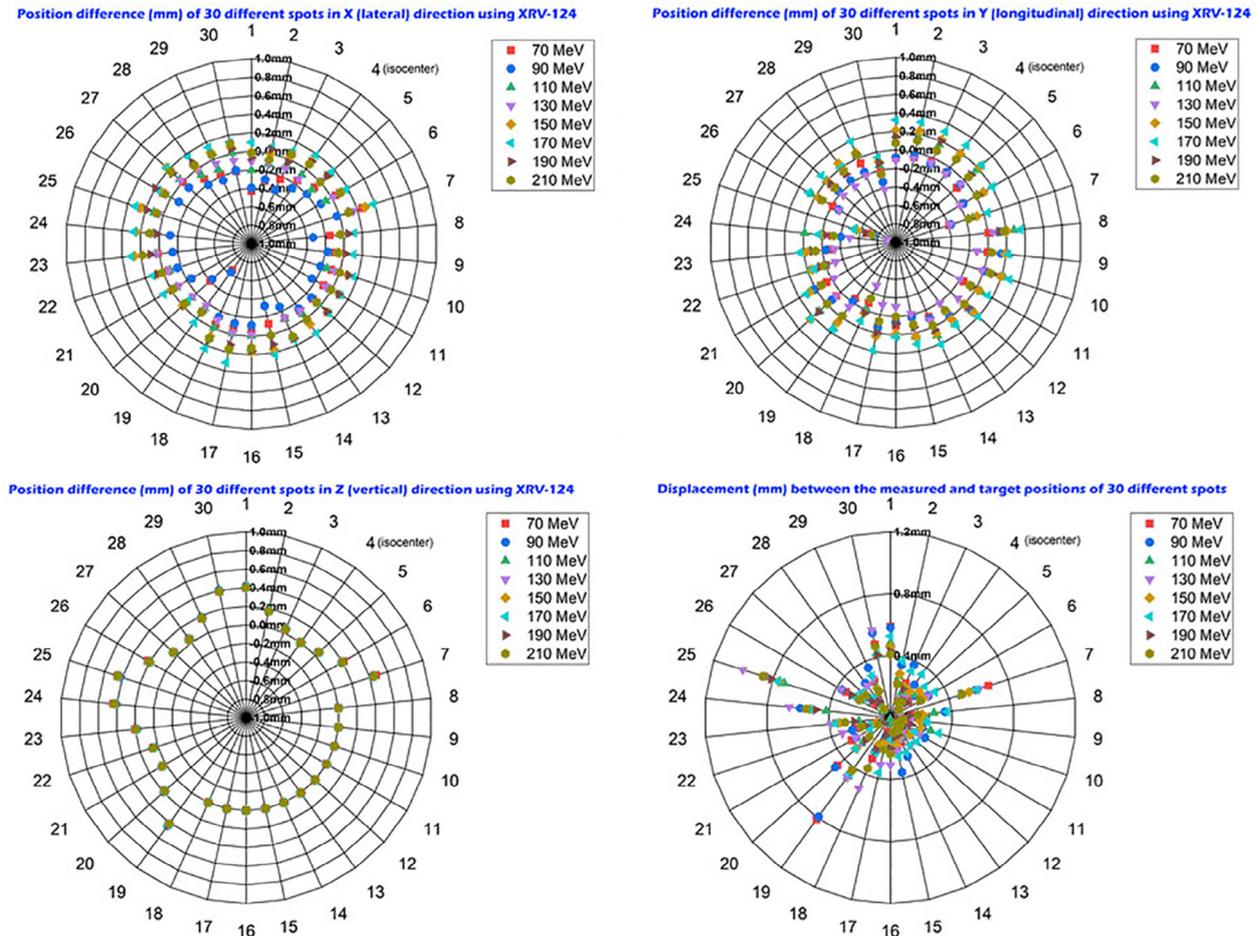


Fig. 4. Spot position differences in the lateral (top left plot), longitudinal (top right plot), and vertical (bottom left plot) directions for 30 different spots of energies 70–210 MeV. The displacement of measured spots from their target locations is shown in the bottom right plot. The displacement of spot from the target location is defined in Eq. (1).

XRV-124 is predominantly used to measure the radiation isocentricity at different beam angles, the current study demonstrates that the XRV-124 can be utilized to perform additional important PBS QA tests such as spot position and spot size.

In order to measure the spot position using the XRV-124, a spot map was generated by varying X and Y locations of the spots. Since the XRV-124 is cone-shaped and does not have a large surface area to accommodate the measurements at a greater distance from the central axis of the cone, the measurement region within the cone surface was investigated. For group 1 spots, although the expected difference in Y and Z locations was zero, the absolute difference was found to be up to 0.4 mm in the Y direction and up to 0.5 mm in the Z direction. For group 2 spots, the expected difference in the X and Z locations was zero, and the absolute deviation was up to 0.2 mm in the X direction and 0 in the Z direction. These results from group 1 and group 2 spots suggest that the variation in X (lateral) location within the XRV-124 has a higher impact on the Z (vertical) location than the variation in Y (longitudinal) location. This may be attributed to distortion from the lateral cone surface, which has a steeper curvature than the longitudinal cone surface.

For the diagonal spots (groups 3 and 4), both the X and Y locations were varied from -3 cm to $+3$ cm, and the planned Z location was zero. The results showed that the variation in the Z direction was found to be higher (up to 0.5 mm) as the spot was placed further diagonally from the isocenter in the XY plane. Overall, the deviation in the X, Y and Z positions of all 30 spots were found to be within ± 1 mm of the planned values. These measurements were repeated five times. The

repeatability was found to be within ± 0.05 mm for the spot position measurements.

The bottom right plot in Fig. 4 illustrates the displacement of 30 spots of various energies from the planned location. Prior studies [4–8] on the spot positions have focused on measuring the deviation of the spot in the 2D plane perpendicular to the beam direction. The XRV-124 provides the ability to measure the absolute position of the pencil beam in 3D space yielding spot position difference in the lateral, longitudinal and vertical directions. The current study included the kV X-ray imaging of the XRV-124 prior to beam delivery. The kV X-ray imaging was performed to ensure the alignment of the treatment field isocenter with the imaging isocenter. If the spots are placed at various off-isocenter locations within the XRV-124 cone surface, the registration of acquired XRV-124 images to the reference images must be accurate to reduce any misalignment (translational and rotational) of the device. A combination of robust indexing of the XRV-124 on the couch-top and pre-defined coordinates of the 6D robotic couch could further eliminate setup errors.

In evaluating spot size of XRV-124 vs. Lynx, the results from the XRV were found to be slightly higher but within 0.2 mm for energies ≥ 130 MeV and within 0.4 mm for energies < 130 MeV. These results suggest that higher energies have a better spot size agreement between the XRV-124 and Lynx than the lower energies. Nevertheless, the difference is within the Lynx detector resolution of 0.5 mm. One of the benefits of using the XRV-124 for the QA of spot size measurement is the easy setup on the couch-top [Fig. 1] eliminating the need of mounting the detector to the gantry head such as in the case of our

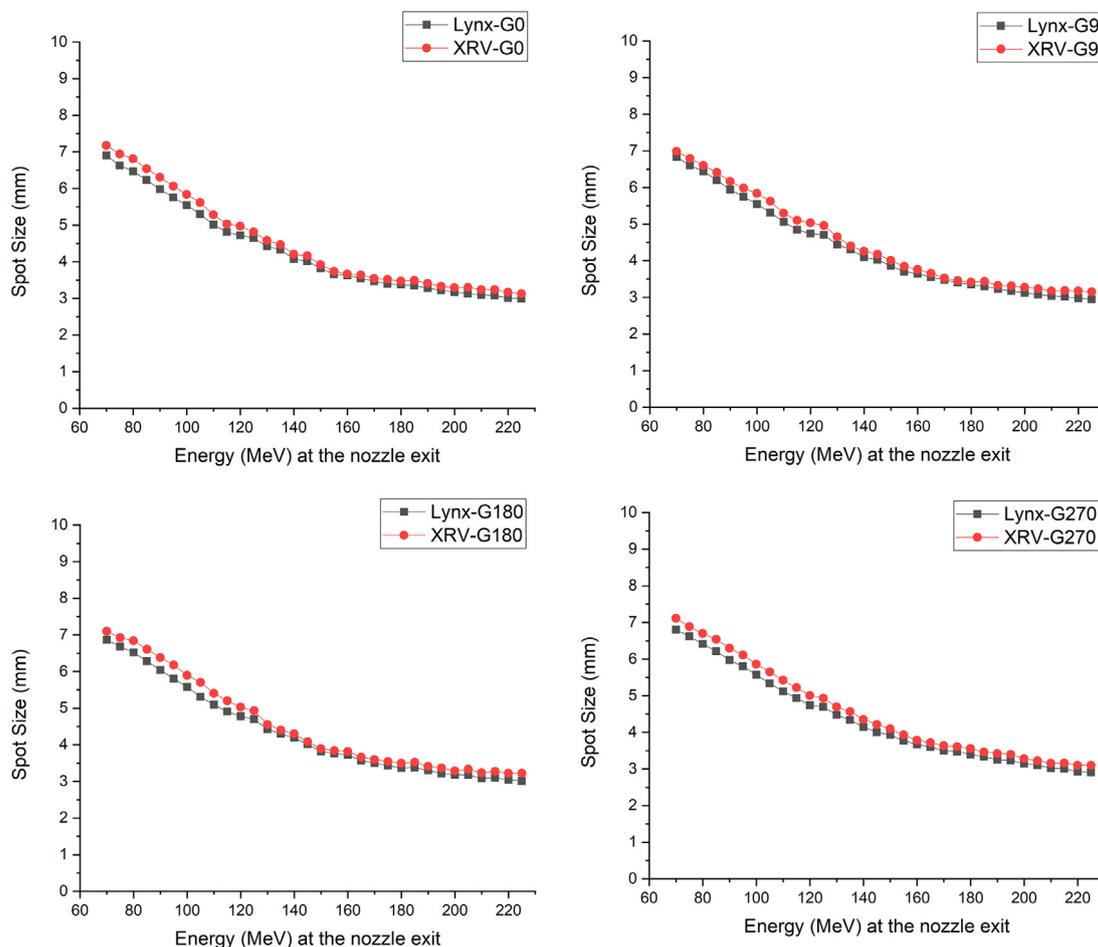


Fig. 5. Spot size measured by the XRV-124 and Lynx for energies ranging from 70 MeV to 225 MeV (at an increment of 5 MeV) at gantry angles 0°, 90°, 180°, and 270°.

current Lynx setup [Fig. 2] to measure spot profile at different gantry angles. However, the smaller effective area of the cone limits the spot size measurements outside the cone area (140 mm over 360° with a width of 30 mm–60 mm). Hence, the XRV-124 cannot replace the Lynx to measure spot profile at off-axis points, and the Lynx is more suitable than the XRV-124 to measure spot profile for the proton treatment planning system (TPS) commissioning. However, if the goal of spot profile QA is to evaluate around the radiation isocenter but within the usable cone area of the XRV-124, it can be an easy and effective alternative option to measure the spot positions and sizes as a part of

routine (weekly and monthly) QA.

5. Conclusion

It is feasible to utilize the XRV-124 to perform the QA of position and size of a pencil proton beam around the radiation isocenter but within the usable XRV-124 cone area. The results from our study show that the spot size from the XRV-124 measurements agreed with that from the Lynx within 0.2 mm for energies ≥ 130 MeV and within 0.4 mm for energies < 130 MeV.

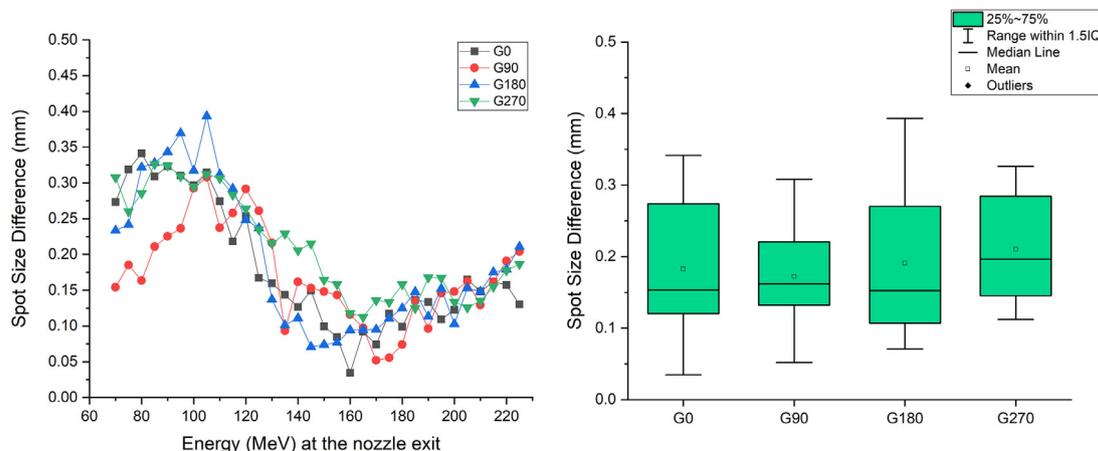


Fig. 6. Difference in spot size results measured by the XRV-124 and Lynx detectors at the gantry angles 0°, 90°, 180°, and 270°.

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Conflict of interest

Authors do not have any relevant conflict of interest to disclose.

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