Polyenergetic Data Acquisition Using a Video-Scintillator Detector for Scanned Proton Beams

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Introduction

Among the current methods of radiotherapy, scanned proton-beam therapy offers high dose conformity and minimal dose to critical structures, in part because of the high degrees of freedom present in multienergy, intensity-modulated particle therapy. In contrast to conventional electron linear accelerators, where a few-to-several energies are typically commissioned, proton accelerators often provide a continuous or quasicontinuous option of beam energy incident on the patient. Thus, measurement tasks can easily amplify to accommodate the multitude of energies that may be used for treatment. Deciding the exact number of energies that should be measured for proton beam commissioning and ongoing beam-quality testing is not straightforward. The development of new measurement systems that enable fast data acquisition for proton therapy are, therefore, desirable.

The "video-scintillator detector" appears to be one such system, which may allow breakthroughs in data acquisition speed for scanned proton-beam therapy. These systems were proposed for use in proton therapy nearly 2 decades ago [1, 2] and continually refined since then [3–5]. Essentially the systems consist of a scintillating screen contained in a light-tight box and viewed by a digital camera, often by means of mirrors to avoid radiation exposure to the camera. Commercial systems following this simple design have also been released by a handful of companies. However, because of the novelty of the detector, continued software development is needed, and in-house software tools are useful to interact with the data.

The purpose of this work was to describe methods for acquiring scintillator video-mode data for scanned proton beams and to describe methods for automatic sorting and analysis of data. In our approach, video frame rates were chosen based on the timing characteristics of our proton accelerator. Digital camera gain and beam exposures were optimized to minimize noise and avoid saturation. Finally, data from different proton energies were automatically sorted from the acquired videos and analyzed as needed for commissioning of our proton treatment-planning system.

Materials and Methods

Our group is currently commissioning a superconducting proton cyclotron and beamline built by Varian Medical Systems (Palo Alto, California) at the Maryland Proton Treatment Center (Baltimore, Maryland). The system can deliver active-scanning proton beams to any of 5 treatment rooms (4 having rotational gantries) at energies ranging continuously from 70 MeV to 245 MeV. Energy is modulated far from the treatment rooms using a carbon-wedge degrader with a linear drive, followed by a magnetic-dipole energy selector. Coarse energy modulation is also possible using plastic slab degraders (called range shifters) inserted in the nozzle near the patient, mainly to allow the treatment of superficial tumors. The proton focal spot size in air ranges from approximately 8 to 45 mm
full-width-at-half-maximum (fwhm) at isocenter, depending on energy and the presence of range shifters, and also varies with gantry angle because of beam asymmetries, which propagate differently through the magnetic fields at different gantry angles. The spot size also changes along the beam central axis after exiting the nozzle because of the competing processes of magnetic focusing and elastic scattering of protons in air and nozzle components. Measurement of the proton spot size in air under these conditions is one of the core tasks needed to commission the beam model for most proton treatment-planning systems.

To measure these data, we chose to use a video-scintillator detector to measure proton fluence profiles in air at different positions along the beam axis, at different gantry angles, and with different range shifters present in the proton-treatment nozzle. Our rationale for choosing this detector was that, compared with film, the detector provides immediate digital feedback and there is no need to enter the treatment room between irradiations, and, compared with small-volume ionization chambers, the scintillating screen offers much-faster data acquisition of spatial distributions than motor-driven ionization-chamber measurements provide. We used the Lynx detector system (IBA Dosimetry, Schwarzenbruck, Germany) with its software package Lynx 2D. A schematic of our experimental setup is shown in Figure 1.

Using this detector-software package, data can be acquired in either “still mode” or “video mode.” Still mode captures a single 2-dimensional (2D) image from the scintillation screen for an image size of $30 \times 30$ cm$^2$, with pixel size of $0.5 \times 0.5$ mm$^2$; signals are optimized to avoid noise and saturation by adjusting the exposure time, the camera aperture, and the number of protons delivered during the exposure. Video mode captures the same spatial resolution but offers sequential imaging with variable frame rates and frame durations. In video mode, a “gain” setting can be adjusted to control noise and saturation, but measured signal magnitudes are slightly more difficult to directly control than in still mode: For very short frame durations, with comparably longer proton “spot” irradiation times, the proton current becomes the dominant aspect of signal control, which is problematic for polyenergetic fields, in which constant proton current is not guaranteed from the accelerator; on the other hand, for relatively longer frame durations, with comparably shorter proton spot irradiation time, the number of protons per spot becomes the dominant aspect of signal control, which can be adjusted in the treatment plan file (i.e., the irradiation scheme file). However, using the longer frame time, there remains the possibility that a single proton spot can occur over the transition between video frames, spilling signal into adjacent frames. To minimize that, the (dead) time between adjacent frames should be minimized. Finally, we exploited one unique characteristic of our proton accelerator to aid with the summation of proton data spilled across adjacent frames. Namely, our accelerator always produces a pause of approximately 1 s between energies, when magnetic fields are reset for the changing energy, and the frame duration was set to half of the pause time (0.5 s). This ensured that there would always be at least one empty frame in the video between different proton energies. Furthermore, the pause time between proton spots having the same energy is approximately 50 $\mu$s, which implies that, with our frame timing, there would never be a blank frame between images arising from the same proton energy. Thus, we were able to use simple logic tests to combine images resulting from the same proton energy and to separate data resulting from different proton energies. Figure 2 shows an overview of this concept.

Based on the above rationale, we chose the following settings for the Lynx 2D control software of the video-scintillator detector: frame rate, 1.875 frames/s; duration, 266.7 s (manually terminated after irradiations complete); gain, 2.0; iris, 60; and frame duration, 532 ms. After acquiring the videos, the data were saved as DICOM images. We developed software in MATLAB Version R2015a with its Image Processing Toolbox (MathWorks, Natick, Massachusetts) to read the data, discard empty frames, combine adjacent frames having the same proton energy, find the center of mass of spots, extract profiles, and
to determine fwhm in x- and y-directions. The flow of the code is as follows. Each video frame was imported into a 2D array. The 2D arrays were projected (integrated) to 1-dimensional arrays for x and y to allow finding the center of the mass in x and y. At the center of the mass, 1-dimensional profiles were extracted and analyzed to find the fwhm. To determine whether a frame contained beam data, we used a logic test with 2 conditions: (1) the center of mass was within 20 mm of the detector center (appropriate for measuring protons aimed at the center), and (2) the fwhm fell in the range of 5 mm to 100 mm. These criteria were adequate to reject frames containing only noise (speckle) for all of our measurements, which we verified visually and by counting the number of isoenergy frames found by the code. If 2 or more adjacent frames containing beam data were found, those frames were summed into a single frame representing a single proton energy before analysis (Figure 2). If frames having beam data were separated by 1, or more, empty (noise) frames, those frames were considered to arise from different proton energies and were analyzed independently. Extracted profiles were written to text files in a format suitable for the treatment-planning system beam model.

To understand the sensitivity of our measured data to variables in data acquisition, we first compared proton spot fluence profiles measured in air using the video-scintillator detector against radiochromic film measurements (Gafchromic EBT3, Ashland, Covington, Kentucky). Films were scanned after irradiation using an Epson Perfection V750 Pro flatbed scanner (Seiko Epson Corp, Suwa, Nagano, Japan). Then, to understand possible dose-rate effects, we repeated measurements using the video-scintillator detector at both a “conventional” proton dose rate of 60 000 monitor units/min, which is approximately 3 billion protons/s, and a high-dose rate (HDR) of 600 000 monitor units/min. In addition, we briefly investigated variation in the determined fwhm values of spot profiles as a function of signal amplitude over the range of the camera bit depth of 210 (or 1024).

Results

Overall, the detector system, polyenergetic irradiation, and video-mode workflow allowed us to measure proton spot fluence profiles in air at least 10 times faster than that using a still-mode workflow. This estimate arises considering we wished to measure 20 discrete proton energies, the beam preparation time was approximately 2 minutes, whether or not multiple energies were included in a plan, and the beam delivery time was < 1 second for a single-energy plan and < 1 minute for a multienergy plan. In many instances depending on stability of the cyclotron and beamline, beam preparation times exceeded 2 minutes, which leads to an even greater advantage for polyenergetic measurements using video mode.

Figure 3 shows an example of data captured in 1 frame of the video along with its extracted x and y profiles. The camera uses 10 bits/pixel; thus, profiles were visually inspected to ensure that data values did not exceed roughly 95% of the maximum value of 1024, at which saturation would occur. Optimization of the signal amplitude for all energies was performed in an iterative manner by adjusting the number of protons per spot (ie, the number of monitor units per spot) individually for each energy in the treatment delivery file.

Figure 4 shows our analysis of spot fwhm at isocenter for all energies for the different range shifter configurations of our system. The complete set of data points for a given range shifter option is acquired in a single irradiation.

Regarding sensitivity, Figure 5 shows a comparison of video-scintillator-measured spot-intensity profiles compared with film measurements and also shows the results of the dose-rate study for a 240 MeV proton beam. Corresponding to that figure, we found fwhm x to be 10.4 mm by video-scintillator and 10.8 mm by film, a 5% difference; fwhm y was 9.4 mm by video-scintillator and 9.9 mm by film, a 3% difference. We found the scintillator to be minimally sensitive to dose rate in the range...
tested. Our HDR test showed < 1% change in the measured fwhm values compared with the conventional dose-rate measurement. Of the possible range of measured signal amplitudes of 0 to 1024, we studied signals in the range of 30 to 850 and found a variation of 5%, likely attributable to noise in the low signals. In the range of signal amplitude of 100 to 700, we found variation of up to 2% in the determined fwhm from signal amplitude.

Figure 3. An example of data captured for a video single frame. The x and y profiles were extracted at the spot center of mass, indicated by the crosshair. All profiles were inspected visually to ensure peaks fell at an intensity of < 1000 (red horizontal dashed line) to avoid saturation effects.

Figure 4. Proton spot full-width-at-half-maximum (fwhm) in air at the isocenter as a function of the energy for no range shifter (red circles), 22.8-mmH2O range shifter (orange squares), 34.2-mmH2O range shifter (blue diamonds), and 57.0-mmH2O range shifter (green triangles). In our workflow, this data set would likely require multiple days to acquire using still-mode acquisition but required < 1 day using video-mode acquisition. Error bars on the points with no range shifter represents the standard deviation of the spot width as a function of gantry angle, measured in 30° increments from 0° to 330°.
Discussion

We found that a video-scintillator detector can support an efficient workflow for collecting proton-beam data at multiple energies and appears to be an attractive option for scanned proton-beam commissioning. The factor 10 savings in time likely not only apply to the commissioning process but also to ongoing quality-control measures for the proton beam. The methods proposed are general and can likely be extended to measure scanned proton fields in more complex configurations than spots on the central axis. One future clinical application might be the measurement of patient-specific treatment fields and verification of fluence distributions for individual proton energy layers against those planned before treatment.

One limitation of the method in its present form is that the logic tests used to discriminate data from different energies would likely fail for synchrotrons because pauses could also occur during single proton-energy irradiations. However, one can envision future solutions, perhaps involving a priori knowledge of expected signal magnitudes or perhaps introducing "marker" signals into the irradiation files (e.g., deliver a proton spot to the corner of the detector each time an isoenergy layer is completed). Another limitation of the method is that data collection is restricted to 2D planes. That limitation has been addressed by other researchers developing 3D volumetric scintillating systems [6, 7], for example, a tank filled with liquid scintillator monitored by multiple video cameras, which allows simultaneous measurement of depth-dose and off-axis–dose data; however, such a system is not commercially available yet. Another group reported the use of a variable-filling water column positioned upstream of the scintillating screen, which should allow fast data collection of proton distributions after traversing multiple thicknesses of water [8]. Another limitation of this system is that the detector dead time between acquired video frames can result in a missing signal from the measured data set. This requires that data sets be checked to ensure the number of proton spots detected matches the number of proton spots delivered. Furthermore, this presents a hurdle for absolute-dosimetry measurements using such a system.

Conclusion

We reported detailed methods for acquiring measurements of polyenergetic proton fields using a commercially available video-scintillator detector. We explained technical details that may be used to automatically sort and analyze data. Works such as this may collectively streamline work burdens at particle-therapy centers and open avenues for proton experimental studies in shorter times.

ADDITIONAL INFORMATION AND DECLARATIONS

Conflicts of interest: The authors have no conflicts of interest to disclose.

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