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Automating quality assurance of digital linear accelerators using a radioluminescent phosphor coated phantom and optical imaging

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Abstract

Purpose—To develop a novel strategy to automate the predominantly manual process of mechanical and geometric tests in routine quality assurance (QA) of digital linear accelerator (LINAC).

Methods—The autonomous QA system consists of three parts: (1) a customized phantom coated with radioluminescent material; (2) an optical imaging system capable of visualizing the incidence of the radiation beam, light field or lasers on the phantom; and (3) software to process the captured signals. The radioluminescent phantom, which enables visualization of the radiation beam on the same surface as the light field and lasers, was placed on the couch and imaged while a predefined treatment plan was delivered from the LINAC. The captured images were then processed to self-calibrate the system and perform measurements for evaluating light field/radiation coincidence, jaw position indicators, cross-hair centering, treatment couch position indicators and localizing laser alignment. System accuracy was probed by intentionally introducing errors and by comparing with current practice. The accuracy of self-calibration was evaluated by examining measurement repeatability under fixed and variable phantom setups.

Results—The integrated system was able to automatically collect, analyze and report the results for all tests. The average difference between introduced and measured errors was 0.13 mm. The system was shown to be consistent with current techniques. Measurement variability increased slightly from 0.1 mm to 0.2 mm when the phantom setup was varied, but no significant difference in the mean measurement value was detected. Total measurement time was less than 10 minutes for all tests as a result of automation.

Conclusions—The integrated QA system succeeded in autonomously performing mechanical alignment tests specified by TG-142. The system's unique features of a phosphor-coated phantom and fully automated, operator independent self-calibration offer the potential to streamline the QA process for modern LINACs.

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1. INTRODUCTION

Success of external beam radiation therapy treatments critically depends on the proper function of linear accelerators (LINACs). AAPM TG-142 highlights the importance of routine quality assurance (QA) of LINACs and provides comprehensive descriptions of a series of important tests to be performed at regular intervals (Klein et al. 2009). In practice, however, many tests are manual in nature and require multiple instances of data collection and analysis. With recent advances in LINAC technology and increasing use of SBRT and other image-guided radiation therapy procedures, both the number and complexity of required checks continue to expand (Solberg et al. 2012). This leads to an urgent clinical need for streamlined and automated methods for completing QA tests.

The need for tools to automate QA tests is perhaps best captured by an illustrative example. TG-142 specifies a simple test to examine the congruence of the LINAC light field and radiation field. While methods exist for completing such a test, all of them require a user to manually mark the light field on a piece of film or align a phantom to the light field. A radiation field is then delivered and the film is examined to compare the field edges and center of both the light and radiation fields. Alternatively, an image of the phantom is captured on an on-board electronic portal imaging devices (EPID) and analyzed with dedicated software (Polak et al. 2013; Njeh et al. 2012). The time required to complete the setup and testing for a single field using these methods ranges from 14–40 minutes (Polak et al. 2013). A survey of radiation therapy clinics found that on average, clinics spent 19.5 hours per month performing and analyzing quality assurance measurements (Palmer et al. 2012). Given the time consuming nature of these test, there have been several recent studies proposing various methods to streamline or automate various QA tests, many of which take advantage of the EPID and specialized phantoms (Mao et al. 2008; Schreiber et al. 2009; Rowshanfarzad et al. 2014). Shandiz et al. also proposed a method for examining distance and gantry angle with a camera and phantom (Shandiz et al. 2015). While these studies represent advances in the space, none have demonstrated an ability to fully automate a series of tests including light fields, lasers and radiation fields.

The purpose of this study was to develop a novel strategy to automate the routine mechanical and geometric tests in QA of digital LINACs. Practically, two essential components must be in place in order to automate these tests: (1) programmable station to station movement of the LINAC under testing (Xing & Li 2014); and (2) streamlined, preferably real-time, data collection and analysis for all intended tests at a specified station point. The former capability is made possible by newly available digital LINACs while the latter is the focus of this work. In the following we present a novel method of visualizing the entrance of radiation beams at the phantom surface, applying techniques for measuring radiation fields, light fields and lasers and completing the data processing required for a number of QA tests specified in TG-142. System self-calibration and experimental validation will also be described in detail. This work builds upon our previous work in developing a real-time beam visualization system for monitoring external beam radiotherapy (Jenkins et al. 2015).

2. MATERIALS AND METHODS

The proposed system consisted of a radioluminescent phantom, an optical imaging system, and image processing software for autonomously completing the TG-142 QA tests listed in the first column of Table 2. A custom phantom that enables coincident visualization of radiation beams, light fields and lasers with a single imaging system was fabricated using a 3D printer (MakerBot Industries LLC., Brooklyn, NY). The phantom was coated with a thin layer of a mixture of Gd₂O₂S:Tb and PDMS⁹. This coating produces visible light when exposed to ionizing radiation, thereby enabling visualization of radiation beams incident on the phantom. The phantom is 12.5 cm on each side, containing several 2.4 mm steel balls that act as fiducials. The couch was moved to a predetermined location and the phantom was placed such that a 10×10 cm light field was visible on its anterior surface.

A 1280 × 960 pixel CMOS digital camera (BlackFly, Point Grey Research, Inc., Richmond, BC) was attached to the LINAC accessory tray and imaged the anterior surface of the phantom (Figure 1). The camera was equipped with a 5mm f/2.5 lens (Edmund Optics Inc., Barrington, NJ). Key images were identified using a motion detection algorithm and saved to the hard drive for further analysis.

Each image was treated as a 2D array of integers with the origin at the top left of the image and pixel locations denoted by their row and column number. Self-calibration was completed by transforming the pixels corresponding to the phantom face into a calibrated image space in which the phantom was aligned, centered and each pixel represented 0.1 mm. The transformation was determined as the linear transform that transforms the locations of the four fiducials in the image to their aligned locations within the calibrated image space, effectively compensating for any variation in phantom placement. The calibrated images were then analyzed to identify the locations of salient features such as field edges, cross-hairs and lasers.

An XML file containing instructions for machine motions, couch motions and radiation beams required for performing the desired tests was prepared and delivered on a TrueBeam STx LINAC (Varian Medical Systems, Palo Alto, CA). All radiation fields were delivered at 6MV and 600 MU/min.

The accuracy of system self-calibration was evaluated by performing ten measurements of light/radiation field alignment and light field cross-hair alignment with a single phantom setup and comparing the results with six measurements each taken with a unique phantom setup. Light/radiation field alignment was defined as the distance between the edge of the light field and the edge of the radiation field. For symmetric fields the difference between the width and height of the respective fields was reported. The distance between the geometric centers of the respective fields was also reported. This distance is divided into orthogonal components aligned with the lateral (x) and longitudinal (y) directions in the treatment space. For the purposes of our system we defined the edge of a field as the location where the intensity becomes greater than half of the maximum intensity. Light field to cross-hair alignment was defined as the distance between the geometric center of the light field and the center of the cross-hairs.

Additional tests implemented on the system include jaw position indicators, cross-hair centering, couch position indicators and laser localization. The accuracy of jaw position indicators was assessed by comparing the field size indicated on the console, or in our case provided to the machine as part of the treatment plan, and the actual size of the field. Cross-hair centering measured the distance between the center of the cross-hairs and the geometric center of a delivered radiation field. Cross-hair walkout, reported as part of cross-hair centering, was defined as the smallest circle circumscribed by the locations of the cross-hairs during a 270° rotation of the collimator. Laser localization examined the distance between the center of the laser cross-hairs and the center of the light field cross-hairs.

System performance was evaluated by intentionally introducing several displacements into the XML file to simulate 1–2mm misalignments. The full test routine was repeated six times on a single day and compared with results obtained with commercially available QA tools as outlined below.

An FC-2 phantom (Standard Imaging, Middleton, WI) was placed on the treatment couch at 100 cm SSD. The jaws are adjusted to align the edges of the light field with lines etched on the surface of the phantom. A separate card was then placed on top of the phantom and aligned to the light field cross-hairs. An image of the phantom was then acquired using the on-board MV imager and processed with PIPSPRO software (Standard Imaging) to determine the distance between the centers of the light field, radiation field and the light field cross-hairs. The size of the radiation field was calculated and compared to the size of the etchings on the phantom. Jaw position indicators were tested by placing the Iso-Align tool (Civco, Orange City, IA) on the couch and aligning it to the light field cross hairs. The jaws were adjusted until the edges of the light field are aligned with etchings on the surface of the tool and the jaw position indicators were noted. Cross-hair walkout was evaluated by rotating the collimator and noting the distance traversed by the cross-hair center on the phantom. Laser localization was evaluated by comparing the distance between the centers of the lasers to the light field cross-hairs using the 1 mm grid lines etched on the surface of the Iso-Align tool. Couch position indicators were tested by placing a ruler on the couch, moving a specified distance and comparing the distance moved along the ruler with the difference in couch position indicators.

3. RESULTS

An example of the self-calibration and image processing results are shown in Figure 2. A video file containing the camera feed from a set of QA tests is also included in the supplemental materials. The measurements in table 1 show that measurement variation increased slightly when the phantom was setup differently for each measurement, but that no significant shift in results occurred. Intentionally introduced misalignments were identified correctly with an average error of 0.13 mm between the introduced and measured displacement. Table 2 summarizes the comparison of the system with current clinical QA techniques. The values obtained are generally in excellent agreement and all are within the tolerance specified by TG-142. The standard deviation for the six measurements performed by the autonomous system is also reported. These uncertainties are on the order of 0.1 mm.

When a 1.0 mm shift was introduced to the X1 collimator for a baseline 10×10 cm field, the system detected a 1.4 mm shift. This shift is expected to result in a 0.5 mm shift in the locations of the optical alignment and imaging systems. The measured shift was 0.67 ± 0.06 mm. Perturbations in individual collimator positions were measured with an average error of 0.13 mm.

Total time for setup, plan delivery, image processing, and report generation was approximately 10 minutes. Actual plan delivery time was approximately 60 seconds for all tests listed in Table 2.

4. DISCUSSION

Current QA techniques for mechanical alignment are time-consuming, tedious and require manual user input. As a step toward improving this process an autonomous measurement system was designed to perform these tasks with minimal user intervention. The system was shown to autonomously image and measure radiation fields, light fields and lasers, and self-calibrate in order to compensate for variation in phantom setup.

In the raw images acquired from the camera, each pixel represents 0.28 mm on the surface of the phantom. Prior to analysis, these images are transformed to an image space wherein each pixel represents 0.10 mm. While the initial resolution of the camera limits the smallest feature that the system is capable of analyzing, all of the features used for performing the measurements presented span at least eight pixels in the original images. Many features, such as field edges, appear as a gradient across ten or more pixels. By implementing sub-pixel methods in locating these features in the transformed image, resolutions exceeding those of the original image can be achieved. This is supported by the fact that variations in measurements across multiple independent setups was on the order of 0.10 mm (Table 1). This suggests that uncertainties due to camera resolution and image processing would be expected to be of this same magnitude.

The uncertainties observed in the measurements presented in Table 2 are similarly on the order 0.1 mm. These tests have a tolerance of one or two millimeters, hence an uncertainty that is an order of magnitude less than this enables variations to be identified and tracked over time prior to having a test fail. The invariance to phantom setup is important because it removes an additional source of error. Polak et al. found that using film, operators could vary by 0.5 to 0.75 mm in their measurements while using automated software dramatically reduced this variation (Polak et al. 2013).

The tests currently implemented within the autonomous system would typically require more than an hour for a physicist to complete using current techniques. The 10 minutes required for setup, execution and cleanup of the autonomous system present the opportunity for significant time savings. Much of this time savings is realized by the fact that only one phantom setup is required for completion of all tests. The setup is further simplified by the self-calibration capabilities of the system. This reduces the time, complexity and equipment necessary for completing the tests.

The focus of this paper is on presenting the principle of operation of the autonomous system; therefore, only a small set of tests was demonstrated. Given the rich data made available by directly visualizing the radiation beam and all in-room optical systems, the system can easily be extended to perform additional measurements such as collimator, gantry and couch walkout, imager alignment, MLC leaf location and speed, etc. The flexibility of the system also enables any of these tests to be performed at multiple gantry angles and during dynamic LINAC motions.

One common concern for QA tools is durability. The system presented in this work was intended as a proof-of-concept system, and therefore the materials used to fabricate the phantom were selected in part for ease of fabrication rather than durability. However, the materials used are generally acceptable for use in high radiation environments. For example, Gd₂O₂S is commonly employed in x-ray environments despite having been shown to have a moderate increase in light output with accumulated dose (Tremis et al. 2001). PDMS is also known to be stable under doses on the order of 100's of kGy (Lazurkin & Ushakov 1958). It is known that CMOS cameras will experience image degradation following exposure to radiation. While no such degradation was noted in the cameras used throughout this study, further work will be necessary to fully investigate the usable lifetime of both the phantom and camera used in the system.

5. CONCLUSIONS

A strategy for automating TG-142 mechanical alignment measurements has been developed and a proof-of-concept system has demonstrated the ability to autonomously perform several mechanical QA tests from TG 142. The system was shown to be accurate with uncertainties on the order of 0.1 mm and to be independent of setup, thereby enabling fully operator independent data collection. Given the potential for reduced variation in measurements, reduced time for test completion, and simplification of QA procedures, the development of autonomous systems present an attractive option for future LINAC QA procedures.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Figure 1.
Example setup showing the camera mounted to the LINAC and the phantom placed on the treatment couch.

Figure 2.

Image processing example. Example of self-calibration and processing for images of a light field (left) lasers (center) and radiation field (right). Original images (top) are transformed and analyzed (bottom). Field edges (green), center (blue) and cross-hair location (red) are shown.

Table 1

Self-calibration assessment. Mean and standard deviations for light field to cross-hair and light/radiation field coincidence measurements made with a single setup vs a unique phantom setup for each measurement.

Measurement	Single Phantom Setup		Varied Phantom Setup	
	Light field cross-hair coincidence (mm)	Light/radiation field coincidence (mm)	Light field cross hair coincidence (mm)	Light/radiation field coincidence (mm)
Center Shift X	-0.16 ± 0.03	0.21 ± 0.03	-0.10 ± 0.05	0.17 ± 0.06
Center Shift Y	-0.80 ± 0.03	0.61 ± 0.06	-0.86 ± 0.09	0.60 ± 0.16
X1 Difference		-0.19 ± 0.06		-0.19 ± 0.12
X2 Difference		0.60 ± 0.05		0.53 ± 0.06
Y1 Difference		0.99 ± 0.05		0.87 ± 0.11
Y2 Difference		0.24 ± 0.11		0.32 ± 0.25

Table 2

System results compared to existing methods. Summary of tests performed by the autonomous system (mean $\pm$ standard deviation) and comparison to current QA techniques (shown in italics).

Light field/Radiation Alignment	Symmetric beams	Center Shift X (mm)	Center Shift Y (mm)	Width Difference (mm)	Height Difference (mm)
Auto	5 $\times$ 5 cm	-0.02 $\pm$ 0.05	0.68 $\pm$ 0.11	-0.58 $\pm$ 0.05	-0.59 $\pm$ 0.09
Auto	10 $\times$ 10 cm	-0.21 $\pm$ 0.07	0.96 $\pm$ 0.12	-0.63 $\pm$ 0.15	-0.94 $\pm$ 0.31
<i>FC-2</i>	<i>15 $\times$ 15 cm</i>	<i>-0.19</i>	<i>0.40</i>	<i>-0.30</i>	<i>0.00</i>
	Asymmetric beams	Difference in position (mm)			
	(X1, X2, Y1, Y2)	X1	X2	Y1	Y2
Auto	(-3, 4, -3, 4) (cm)	0.23 $\pm$ 0.03	-0.39 $\pm$ 0.05	-0.26 $\pm$ 0.06	-0.95 $\pm$ 0.07
Jaw position indicators	Symmetric beams	Width Difference (mm)	Height Difference (mm)		
	5 $\times$ 5 cm	-0.76 $\pm$ 0.02	-1.73 $\pm$ 0.06		
	10 $\times$ 10 cm	-0.46 $\pm$ 0.16	-1.71 $\pm$ 0.19		
	<i>5 $\times$ 5 cm</i>	<i>0.0</i>	<i>-2.0</i>		
	<i>10 $\times$ 10 cm</i>	<i>0.0</i>	<i>-2.0</i>		
	Asymmetric beams	Difference in position (mm)			
	(X1, X2, Y1, Y2)	X1	X2	Y1	Y2
Auto	(-3, 4, -3, 4) (cm)	0.06 $\pm$ 0.06	0.80 $\pm$ 0.03	1.40 $\pm$ 0.16	0.63 $\pm$ 0.21
<i>Iso-align</i>	<i>(-5, 2.5, -5, -2.5) (cm)</i>	<i>0.0</i>	<i>1.0</i>	<i>1.0</i>	<i>1.0</i>
Cross-Hair Centering	Center Shift X (mm)	Center Shift Y (mm)	Walkout (mm)		
	-0.35 $\pm$ 0.03	0.77 $\pm$ 0.01	0.87 $\pm$ 0.12		
	<i>-0.25</i>	<i>0.67</i>	<i>0.5</i>		
Couch Position	Shifts (Lat., Long.) (mm)	Lat. (mm)	Long. (mm)		
	(30, 30)	30.17 $\pm$ 0.25	30.22 $\pm$ 0.15		
	<i>(200, 300)</i>	<i>200.3</i>	<i>300.4</i>		
Laser Localization (relative to cross hairs)	Center Shift X (mm)	Center Shift Y (mm)			
	0.19 $\pm$.30	-0.26 $\pm$ 0.13			
	<i>0.25</i>	<i>-0.25</i>			