Measuring the wobble of radiation field centers during gantry rotation and collimator movement on a linear accelerator

Weiliang Du[a] and Song Gao
Department of Radiation Physics, The University of Texas MD Anderson Cancer Center, Houston, Texas, 77030

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Purpose: The isocenter accuracy of a linear accelerator is often assessed with star-shot films. This approach is limited in its ability to quantify three dimensional wobble of radiation field centers (RFCs). The authors report a Winston–Lutz based method to measure the 3D wobble of RFCs during gantry rotation, collimator rotation, and collimator field size change.
Methods: A stationary ball-bearing phantom was imaged using multileaf collimator-shaped radiation fields at various gantry angles, collimator angles, and field sizes. The center of the ball-bearing served as a reference point, to which all RFCs were localized using a computer algorithm with subpixel accuracy. Then, the gantry rotation isocenter and the collimator rotation axis were derived from the coordinates of these RFCs. Finally, the deviation or wobble of the individual RFC from the derived isocenter or rotation axis was quantified.
Results: The results showed that the RFCs were stable as the field size of the multileaf collimator was varied. The wobble of RFCs depended on the gantry angle and the collimator angle and was reproducible, indicating that the mechanical imperfections of the linac were mostly systematic and quantifiable. It was found that the 3D wobble of RFCs during gantry rotation was reduced after compensating for a constant misalignment of the multileaf collimator.
Conclusions: The 3D wobble of RFCs can be measured with submillimeter precision using the proposed method. This method provides a useful tool for checking and adjusting the radiation isocenter tightness of a linac.
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Key words: radiation isocenter, wobble, stereotactic radiosurgery, Winston–Lutz

I. INTRODUCTION

Mechanical imperfection of a medical linear accelerator is one of the major sources of uncertainty in radiation treatments. Possible causes for mechanical imperfection include gantry sag due to gravity, age of the machine bearing system, and misalignment of collimation components. Ideally, the gantry and the collimator should move or rotate around a fixed point, i.e., the isocenter. In reality, the centers of the delivered radiation fields do not intersect at a single point as the gantry and collimator move. To account for this effect, one must localize a radiation isocenter at the averaged center of these radiation field centers (RFCs). The "wobble" of the RFCs around the radiation isocenter is characterized by a bounding sphere or isocenter sphere, which is defined by the minimum diameter needed to contain all the RFCs. For a linac used for stereotactic treatments, a submillimeter diameter of the isocenter sphere is highly desired.[1]

Numerous studies have attempted to localize the radiation isocenter and quantify its size. A classic technique is the star-shot technique using radiographic films.[2–4] The wobble of RFCs is measured by exposing on a piece of film to narrow radiation fields while the gantry or the collimator is rotated. The film-based approach is two-dimensional in nature; therefore, the method is insufficient for quantification of 3D wobble. For example, the wobble along the gantry rotation axis is not captured in a gantry star-shot film. In addition, it is difficult to correlate the gantry rotation axis and collimator rotation axis using this method because the gantry star-shot and the collimator star-shot cannot be obtained on a single piece of film without moving the phantom or the film. Another classic technique to localize the radiation isocenter is the Winston–Lutz (WL) test.[5–7] In this test, a metal ball-bearing (BB) is placed near the radiation isocenter and exposed to symmetric radiation fields at multiple gantry angles. Then, the BB is moved iteratively until the center of the BB best coincides with all the RFCs. The WL test is widely used in stereotactic radiosurgery for localizing the radiation isocenter and calibrating in-room lasers and imaging systems.[8,9]

In this study, we applied the WL method, without moving the BB,[7,8] to the quantification of the isocenter accuracy of a linac. This is an interesting issue because modern radiation therapy relies more and more on the mechanical accuracy of the treatment machines, as exemplified by cranial and body stereotactic radiation therapy.

II. METHODS AND MATERIALS

While the method can be applied to any linacs, the measurements were done on a Varian Trilogy linac (Varian Medical Systems, Palo Alto, CA) equipped with a Millennium multileaf collimator (MLC) and an electronic portal imaging device (EPID). The phantom used in this study has been described elsewhere.[8,10] In brief, a BB of 6.5 mm in diameter was placed near the isocenter using room lasers. The BB was exposed to MLC-shaped radiation fields, and images were acquired using the EPID. Three types of machine movements that affected the radiation production were studied: field size change, gantry rotation, and collimator rotation. During the measurements, the BB remained stationary, thus serving as a reference point in the 3D space.

The images were analyzed in two coordinate systems. The first was the u-v 2D coordinate system defined relative to the EPID. The v dimension was parallel to the gantry rotation axis and u was other dimension on the EPID. This coordinate system would rotate as the gantry was rotated. The second was the x-y-z 3D coordinate system that was independent of any machine motion. The x, y, and z represented the lateral, vertical, and longitudinal dimensions of the linac, respectively. The orientations of the two coordinate systems were illustrated previously.[8,10] Specifically, when the gantry was at 0° (Varian IEC 601-2-1 scale) the u-v coordinates were identical to the x-z coordinates.

To study the effect of changing field sizes, we employed 14 MLC fields of various sizes (from 2×2 cm^2 to 20×20 cm^2) with the gantry and collimator fixed at 0°. For each MLC field, the RFC was localized in the EPID image using a Hough transform method.[11]

To study the RFC wobble during gantry rotation, we sampled the 360° gantry rotation at 10° intervals. The MLC field size was fixed at 10×10 cm^2 and the collimator at 0°. At each gantry angle, a radiation central ray (i.e., a line passing through the radiation source and the RFC on the imager panel) was localized. Then the isocenter was determined by finding the point in the x-y-z space that had the shortest distances to these rays.[8] This isocenter point is herein referred to as the gantry rotation isocenter.

The collimator rotation was studied at 10° intervals, with a fixed 10×10 cm^2 MLC field size and 0° gantry angle. At each collimator angle, an RFC was localized as a point in the EPID image, i.e., in the x-z plane. Then the collimator rotation axis was identified as the point in the x-z plane that had the shortest distances to all RFC points at different collimator angles. Since the gantry was fixed at 0°, the collimator rotation axis was actually a vertical line in the x-y-z space. Finally, we calculated the distance between the gantry rotation isocenter and the collimator rotation axis.

III. RESULTS AND DISCUSSION

For the linac in this study, the RFC was stable as the MLC field size was varied from 2×2 cm^2 to 20×20 cm^2. The range of the RFC variation was 0.09 and 0.12 mm in the u- and v-directions, respectively. The standard deviation was 0.026 mm (u) and 0.037 mm (v). The deviation of the 10×10 cm^2 RFC from the averaged RFC was 0.022 mm (u) and 0.019 mm (v). These numbers demonstrated excellent leaf position precision and reproducibility.

Figure 1 shows the RFC wobble during gantry counterclockwise (ccw, or decreasing gantry angle) rotation in one measurement. The calculated gantry rotation isocenter was at $x = 0.35$ mm, $y = -0.58$ mm, and $z = 0.20$ mm from the BB center. The maximum RFC wobble from this radiation isocenter was 0.58 mm (u) and 0.49 mm (v). The averaged RFC wobble was 0.40 mm (u) and 0.03 mm (v). The largest 3D RFC wobble was 0.67 mm, which made the diameter of the bounding sphere 1.34 mm. In Fig. 1(b), the size of the bounding sphere appears too large when compared to the magnitude of the RFC wobble because the wobble in the v-direction is not shown. The effect of gantry sag was most evident in the v-direction. The RFC moved by 0.92 mm in the negative v-direction (away from gantry) when the gantry was rotated from 340° to 170°. This pattern and magnitude of gantry sag are consistent with those reported in the literature.[4,7] In the u-direction, the RFC wobble was approximated with two components: a constant offset (about 0.4 mm) and an irregularly shaped variation.

The RFC wobble measurement was also made during gantry clockwise (cw) rotation. The calculated radiation

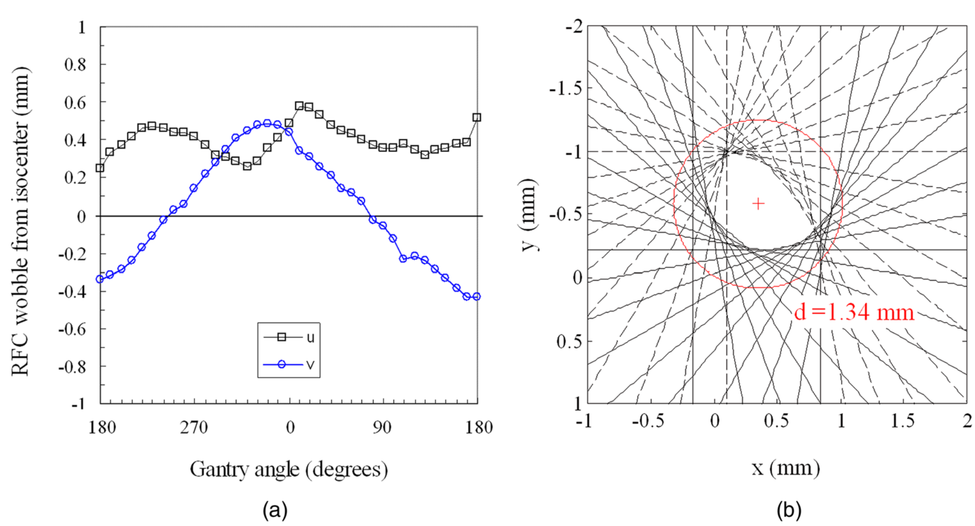

FIG. 1. (a) Measured RFC wobble during gantry ccw rotation. (b) Radiation central rays projected in the x-y plane. Solid lines indicate gantry angles from 180° to 0°; dashed lines indicate gantry angles from 360° to 180°. Also shown are the gantry rotation isocenter (+ symbol) and the bounding sphere (circle).

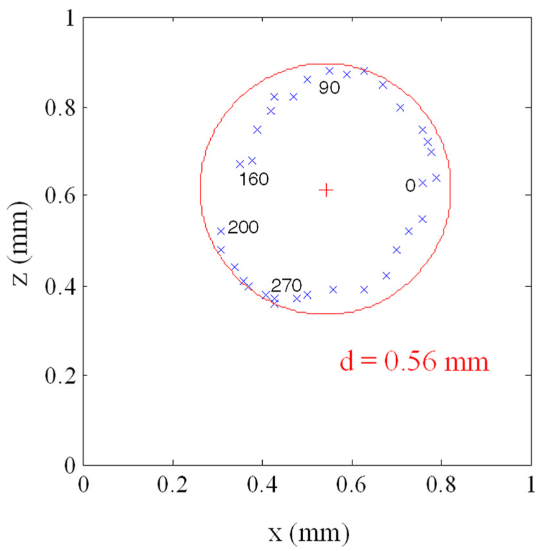

FIG. 2. Measured RFC (x symbol) wobble during collimator ccw rotation. The collimator rotation axis (+symbol) and the bounding circle are also shown.

isocenter was at $x = 0.26$ mm, $y = -0.55$ mm, and $z = 0.22$ mm from the BB center. The maximum RFC wobble from this radiation isocenter was 0.47 mm (u) and 0.46 mm (v). The averaged RFC wobble was 0.34 mm (u) and 0.00 mm (v). The diameter of the bounding sphere was 1.10 mm. The smaller wobble during cw (versus ccw) gantry rotation were verified in a repeat measurement (data not shown), although the cause of this finding is not clear.

The RFC wobble during collimator ccw rotation (viewed from the linac isocenter, or decreasing collimator angle) is illustrated in Fig. 2. The wobble was approximately ellipsoid and enclosed in a circle of 0.56 mm diameter. The calculated collimator rotation axis was at $x = 0.54$ mm and $z = 0.62$ mm from the BB center. The average and maximum values of the RFC wobble from the collimator rotation axis were 0.24 mm and 0.28 mm, respectively. During collimator cw rotation, the calculated collimator rotation axis was at $x = 0.51$ mm and $z = 0.60$ mm from the BB center. In this case, the

TABLE I. Errors in localizing the gantry rotation isocenter with different size samples of gantry angles.

		Error (mm)		
Sample size	Gantry angles	x	y	z
37	180-170-…-190-180	0.00	0.00	0.00
18	180-160-…-220-200	−0.02	−0.01	0.01
9	160-120-…-240-200	0.05	0.01	0.04
4	180-90-0-270	−0.01	−0.04	0.01
3	90-0-270	0.49	−0.01	0.12
2	90-0	0.49	0.36	0.19
2	0-270	0.49	−0.42	0.29

average and maximum values of the RFC wobble were 0.23 and 0.27 mm, respectively.

The averaged gantry cc and ccw rotation isocenter was at $x = 0.30$ mm, $y = -0.57$ mm, and $z = 0.21$ mm from the BB center. The averaged collimator rotation axis was at $x = 0.53$ mm, $z = 0.61$ mm from the BB center. Thus, the gantry rotation isocenter was at $x = -0.23$ mm, $z = -0.40$ mm, or a distance of 0.46 mm from the collimator rotation axis.

Table I shows the effect of the number of gantry angle samples on the accuracy of localizing the gantry rotation isocenter. The original 37 samples under gantry ccw rotation were used as a fully sampled data set. Using only two or three samples, the errors were relatively large because of the missing information (e.g., the RFC location at gantry angle 180°). Using four or more samples, the error was reduced to below 0.1 mm. This result is useful for selecting the number of gantry angles during the QA process of linac-based radiosurgery.

Because the RFC wobble during gantry rotation had a constant component (i.e., the 0.4 mm deviation in Fig. 1), on an ad hoc basis, we investigated a first-order strategy to compensate for this effect. We edited the MLC file manually so that the leaves were offset by −0.4 mm in the u-direction. Figure 3 shows the RFC wobble during gantry ccw rotation with and without the manual MLC offset. The measurements

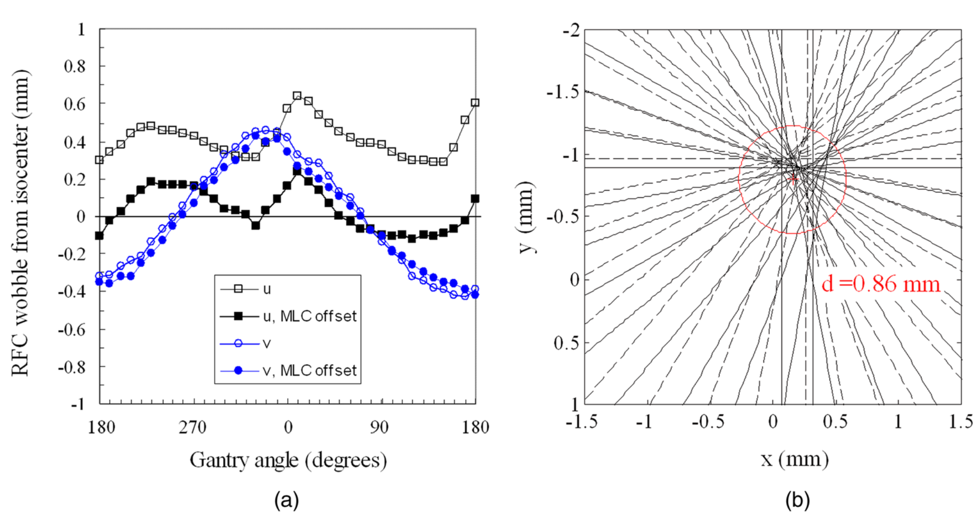

FIG. 3. (a) Measured RFC wobble during gantry ccw rotation, without (open symbols) or with (solid symbols) a manual MLC leaf offset in the u-direction. (b) Radiation central rays projected in the x-y plane, with the manual MLC offset.

were done 2 months after those in Fig. 1. Without the MLC offset, the results were similar to those in Fig. 1. The maximum RFC wobble from the gantry rotation isocenter was 0.64 mm (u) and 0.46 mm (v), and the largest 3D RFC wobble was 0.72 mm, making the diameter of the isocenter sphere 1.44 mm. With the −0.4 mm MLC offset, the maximum RFC wobble was 0.24 mm (u) and 0.43 mm (v), and the largest 3D RFC wobble was 0.43 mm, making the isocenter sphere smaller at 0.86 mm in diameter. The two gantry rotation isocenters, determined with and without the manual MLC offset, were essentially at the same location (different by 0.1 mm numerically). In other words, a constant lateral misalignment of the collimator does not change the radiation isocenter location, but indeed increases the wobble of RFCs.

This simple strategy reduced RFC wobble only in the u-direction (Fig. 3). We did not address the nonconstant component of the RFC wobble, nor did we attempt to reduce the wobble in the v-direction. As a result, the size of the isocenter sphere with the manual MLC offset is dominated by the v-component of the RFC wobble. Nonetheless, the reduction in the size of the isocenter sphere from approximately 1.4 mm to 0.9 mm may be significant because precision within 1 mm is a traditional threshold to discriminate stereotactic treatment machines from nonstereotactic machines.

The quantitative results from this study were obtained on only one linac; however, the presented methodology is applicable to any linacs equipped with an EPID. The phantom and its setup are simple: it is essentially a BB placed near the isocenter. The images need to be analyzed with subpixel accuracy, which is proved feasible by several authors.[11,12]

IV. CONCLUSIONS

We have developed a WL method to quantify the RFC wobble during gantry and collimator movements. The RFC wobble is highly reproducible and thus can be used as a robust indicator of the mechanical performance of a linac. Compared with the star-shot technique, the proposed method is advantageous in its ability to measure the 3D distance between the gantry rotation isocenter and the collimator rotation axis. We have also demonstrated that the gantry rotation isocenter sphere can be reduced by compensating for a constant MLC misalignment. More research is warranted to further reduce the RFC wobble by employing a gantry angle-specific correction strategy.

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[a]Author to whom correspondence should be addressed. Electronic mail: wdu@mdanderson.org; Telephone: 713 745 7054.

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