Bow-tie wobble artifact: Effect of source assembly motion on cone-beam CT

Dandan Zheng, John C. Ford, and Jun Lu

Department of Radiation Oncology, Virginia Commonwealth University, Richmond, Virginia 23298

Dimitrios Lazos

Department of Radiation Oncology, Beth Israel Medical Center, New York, New York 10003

Geoffrey D. Hugo, Damodar Pokhrel, Lisha Zhang, and Jeffrey F. Williamson

Department of Radiation Oncology, Virginia Commonwealth University, Richmond, Virginia 23298

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Purpose: To investigate the cause of a bow-tie wobble artifact (BWA) discovered on Varian OBI CBCT images and to develop practical correction strategies.

Method and Materials: The dependence of the BWA on phantom geometry, phantom position, specific system, and reconstruction algorithm was investigated. Simulations were conducted to study the dependence of the BWA on scatter and beam hardening corrections. Geometric calibration was performed to rule out other gantry-angle dependent mechanical non-idealities as BWA causes. Air scans were acquired with ball-bearing markers to study the motions of the x-ray head assembly as functions of gantry angle. Based on measurements, we developed hypothesis regarding the BWA cause. Simulations were performed to validate our hypothesis. Two correction strategies were implemented: a measurement-based method, which acquires gantry-dependent normalization projections (NPs); and a model-based method that involves numerically shifting the single-angle NP to compensate for the previously-measured bow-tie-filter (BTF) motion.

Results: The BWA has a diameter of ~ 15 cm, is centered at the isocenter, and is reproducible independent of phantom, position, system, reconstruction, and standard corrections, but only when the BTF is used. Measurements identified a 2D sinusoidal gantry-angle-dependent motion of the x-ray head assembly, and it was the BTF motion (>3 mm amplitude projected onto the detector) resulting an intensity mismatch between the all-angle CBCT projections and a single-angle NP that caused the BWA. Both correction strategies were demonstrated effective.

Conclusions: A geometric mismatch between the BTF modulation patterns on CBCT projections and on the NP causes the BWA. The BTF wobble requires additional degrees of freedom in CBCT geometric calibration to characterize. © 2011 American Association of Physicists in Medicine. [DOI: 10.1118/1.3582944]

Key words: cone-beam computed tomography, geometric calibration, bow-tie-filter, image artifact, image-guidance radiation therapy

I. INTRODUCTION

Image quality is an important aspect for the linear-accelerator (LINAC)-integrated kilovoltage (kV) and cone-beam computed tomography (CBCT) systems whose usage has seen rapid growth in contemporary image-guided radiation therapy (IGRT).^{1–3} Our study investigated a CBCT image artifact that pertains to two important technical aspects of CBCT: geometric calibration and use of bow-tie-filters (BTFs). Geometric calibration is essential both for safeguarding CBCT image quality and localization accuracy in the LINAC spatial coordinate system. Many methods and phantoms have been developed for geometric calibration, defined as estimation of a set of parameters that describes the system geometry.^{4–9} The use of BTFs improves dynamic range, reduces patient dose, mitigates cupping artifact, and improves the image quality.^{10–13}

Our study addresses the interplay of CBCT system geometric calibration and the BTF regarding a bow-tie wobble artifact (BWA). This artifact was observed on clinical CBCT

images acquired on Varian On-Board ImagerTM (OBI) machines (Varian Medical Systems, Inc., Palo Alto, CA), and was most visible on images of homogeneous phantoms [see Figs. 1(a)–(c)]. This paper reports our investigations on the cause and correction strategies for the BWA.

II. METHODS AND MATERIALS

II.A. CBCT system and reconstruction algorithms

The LINAC-integrated CBCT system under investigation in our study was the Varian On-Board ImagerTM (OBI) CBCT system (Varian Medical Systems, Inc., Palo Alto, CA) with detailed system description reported in references.¹⁴ For the most part of our study, one OBI system was used. However, images were also acquired on two other OBI systems to investigate whether the observed BWA was systematic across machines. On all three systems, software version OBI 1.3 was used when data were acquired. Under this version, about 610 projections were acquired over 360°

FIG. 1. CBCT images of (a) a patient thorax, (b) a cylindrical water phantom centered in the FOV, and (c) an off-centered water phantom. (a) and (b) were reconstructed with our in-house software, and (c) was reconstructed with vendor software.

rotation. The manufacturer's reconstruction software uses projections of cylindrical scatter phantoms acquired at a single gantry angle for normalizing CBCT projections.¹⁴ In addition to images reconstructed by using the manufacturer-supplied reconstruction software, CBCT projection sets were also processed and reconstructed with our in-house Feldkamp–Davis–Kress (FDK) (Ref. 15) software. We applied our in-house reconstruction to first investigate whether the artifact was reconstruction-algorithm-dependent, and to subsequently allow us the flexibility of studying the interplay between projection preprocessing and other possible causative factors. An in-house preprocessing software was used to correct the projections for flat-panel detector low-frequency drop, scatter, and beam hardening artifacts.^{16,17} The presence of the BWA was tested with and without each of these individual corrections applied. For normalization, air projections with BTF modulation acquired at a single gantry angle were used to normalize the CBCT projections. We also altered the gantry angle at which the single gantry angle air projections were acquired, to study the dependence of the BWA on the gantry angle at which the normalization projections were acquired.

II.B. Geometric calibration

After initial testing, we hypothesized that the BWA was caused by gantry-angle dependent geometric instability of the OBI system and was linked to the BTF. We therefore applied the geometric calibration technique described by Cho *et al.*⁴ to quantify the stability of the imaging geometry. This technique characterizes system geometry in terms of nine parameters detailed in the original paper, and, to our

knowledge, provides the most complete system described to date for quantifying single circular-orbit CBCT scanning geometry.

II.C. Bow-tie filter wobble measurements and analyses

Because the stability of the BTF is not considered in geometric calibration, yet it is crucial in our hypothesis, additional measurements were performed using air scans with the BTF, with radiopaque markers attached to the BTF and other head assembly components.

The first batch of air scans were acquired with the full-fan BTF in the beam path but no additional markers affixed to source housing components. Each projection image shows the BTF modulation pattern projected onto the FPD. The origin of the FPD coordinate system was defined at the inferior-right most corner pixel of the FPD. The U and V are detector reference coordinates in the directions normal and parallel to gantry axis, respectively. The symmetric axis of the BTF on each projection was identified, which enabled the U -axis translation and the rotation of the BTF axis to be evaluated as functions of gantry angle.

Because the BTF modulation analysis described above can only detect filter shifts in the direction parallel to the filter thickness gradient and cannot detect filter shifts in the orthogonal direction if no rotation is involved, additional batches of air scans were acquired with three spherical radiopaque markers (BBs) attached to the BTF. By measuring the BB centroids on each projection, the two-dimensional motion of the BTF (both U and V motions) with gantry rotation could be studied. By comparing the motion tracks of individual centroids of these three BBs, we can analyze the components of the BTF motion in both translation and in-plane rotation. Because determining what other mechanical parts of the source assembly move with the BTF and studying the movement patterns are crucial for stabilizing the components and eliminating the motions, we also studied the motion trajectory of other key source assembly components (U - and V -axis collimator blades, x-ray tube exit window, and transparent plastic cover), using additional air-scan acquisitions performed with three BBs affixed to these components. In the analyses, the BB centroids were automatically detected on the projections, and the projected BB centroid locations (U , V) in the detector plane were plotted as functions of gantry angle. We presuppose that the rotation of the BTF in the U , V plane is negligible and therefore does not contribute to the BWA. Because the BTF thickness is only variant along the U direction, therefore only the BTF motion with nonzero U axis projections can result in BTF modulation change with gantry angle variation. The fitted sinusoidal model of BTF U translation as described by

$$\Delta U(\theta) = A \sin(\omega\theta + B) \quad (1)$$

was applied in the computer simulation studies and in the BWA correction, where A , B , and ω are the model parameters and θ is gantry angle.

II.D OBI imaging chain simulation

To isolate possible BWA causes and to study them separately, we created a computer model of the OBI CBCT system. Because it has been shown that insufficient scatter and beam hardening correction can exhibit circular band artifact on CBCT images somewhat similar to the observed BWA except for the asymmetric shading,¹⁷ we also included corrections for these effects in both simulation and experiments. Effects such as flat-panel detector low-frequency drop, scatter, and beam hardening were individually introduced¹⁶ into the simulation to study whether any of these effects contributed to the BWA. The imaging system geometry flex parameters as characterized by the Cho geometric calibration were also introduced to the simulation to evaluate the contributions of these parameters to the BWA. The effect of the BTF motion on the BWA was assessed as follows. Full projections of the cylindrical water phantom used in experiment were computed assuming no BTF motion. Then, the sinusoidal BTF translation model in Eq. (1) derived from our measurements was introduced into the simulation. Images were reconstructed from the various synthetic data sets allowing the impact on image-quality of the following scenarios to be compared: (a) ideally rigid system with and without the BTF, (b) ideally rigid system including only modeled motion of the BTF, and (c) actual OBI geometry as characterized by Cho gantry angle-dependent beam geometry with and without the BTF motion.

II.E Correction strategies

Based on our hypothesis regarding the cause of the BWA, we implemented two alternative flood-field correction strategies.

Strategy 1 is mathematically described by

$$A(U, V, \theta) = -\ln \left[\frac{PP(U, V, \theta)}{NP_{\text{air}}(U, V, \theta)} \right] \quad (2)$$

Here U, V is the location on the detector array in the detector reference frame, θ denotes gantry angle, A denotes attenuation sinogram, PP denotes the patient/phantom projection, and NP_{air} denotes the in-air normalization projection. This strategy is a measurement-based correction strategy in which in-air normalization projections, $NP_{\text{air}}(U, V, \theta)$, with the BTF in place, are acquired as a function of gantry angle θ . These gantry-angle specific flood-field images are used to normal-

ize scan subject projections, $PP(U, V, \theta)$, at the corresponding gantry angles.

Strategy 2 is mathematically described by

$$A(U, V, \theta) = -\ln \left[\frac{PP(U, V, \theta)}{NP_{\text{air}}(U - \delta(\theta), V, \theta_0)} \right] \quad (3)$$

Strategy 2 is a model-based correction strategy in which a single-angle normalization projection at θ_0 is acquired, but is translated according to the modeled sinusoidal BTF motion following equation (1), prior to normalizing each phantom projection. Here $\delta(\theta)$ denotes the U translation, where $\delta(\theta_0) = 0$. The BTF motion along detector V direction is not used in this method, since the BTF thickness is invariant along this direction. The single-angle in-air normalization projection was averaged over multiple exposures (around 200 frames) to reduce image noise.

For the Varian reconstruction using the scatter phantom normalization projection, a straightforward adaptation of strategy 1 can be applied. Use of the scatter phantom normalization projection prevents a direct adaptation of strategy 2, because the BTF attenuation is gantry-angle-dependent while the scatter phantom attenuation is not.

III. RESULTS

III.A BWA characteristics

The BWA was present on full-fan images reconstructed both by the vendor's and our in-house reconstructor. The BWA was observed only with the BTF in place. With the full-fan BTF, the BWA appeared on the images as a circular band about 7.5 cm in radius centered on the isocenter. The location of the BWA and its asymmetric illumination pattern were consistent independent of phantom placement, OBI system, and gantry rotation direction. When the gantry angle at which the single-angle normalization projections were acquired was altered, the BWA asymmetric illumination pattern was also altered with corresponding bowtie modulation mismatch change.

III.B Geometric calibration

The geometric calibration analysis demonstrated small but measurable deviations from the ideal geometry as listed in Table I. Incorporating the system nonidealities into our

TABLE I. System description of one OBI system in our clinic following Cho *et al.* geometric calibration.

	Description	Mean	sd
η (deg)	Detector yaw	-0.015	0.056
θ (deg)	Detector pitch	-0.16	0.097
ϕ (deg)	Detector roll	-0.15	0.063
U_{off} (mm)	Detector piercing point offset from the panel center; normal to gantry axis	0.21	0.10
V_{off} (mm)	Detector piercing point offset from the panel center; parallel to gantry axis	1.38	0.24
DAD (mm)	Detector-to-isocenter distance	499.88	0.28
SID (mm)	Source-to-isocenter distance	999.50	0.24
Y_s^i (mm)	Source out-of-rotation-plane excursion	0.00032	0.013
Gantry dev (deg)	Gantry-angle deviation from the nominal gantry angle	-0.14	0.036
F_{magn}	Magnification factor	1.50	0.00035

FIG. 2. Full-fan BTF symmetry axis shifts along U axis (perpendicular to gantry axis) as a function of gantry angle.

forward projection model, did not generate a BWA on the cylindrical water phantom.

III.C Bow-tie-filter wobble analyses

Analysis of the full-fan BTF projection profiles demonstrated that its symmetry axis was parallel to the detector V axis within 0.1 degree, which supported our assumption that the rotation of the BTF in the U , V plane was a negligible contributor to the BWA. However, a U -axis translation (normal to gantry axis) with a quite large peak-to-peak magnitude over 3 mm in the detector plane is evident (Fig. 2). Sinusoidal fitting of the U -direction translation of the BTF projection profile axis is described as follows:

$$\Delta BT_U[\text{mm}] = -1.900 \times \cos(0.992 \times \theta[\text{radian}] + 1.022) \quad (4)$$

Because the source and detector motion corrections derived from the geometric calibration had negligible effect on the observed BTF profile shifts, we conclude that the shifts reflect the motion of the BTF itself. The nominal distance from the x-ray source to the exit window from the manufacturer is 14.8 cm. Taking into account the BTF thickness and magnification, the U -axis translation at the BTF level was magnified about 10 times in the detector plane. Thus, the identified U -direction motion has peak-to-peak magnitude of about 0.38 mm in the BTF plane. From the air scan with radiopaque BB markers attached to the x-ray head cage window, the motion was identified as a two-dimension translation along both detector U and V directions as shown in Fig. 3 as the relative shifts of all 3 BBs at each gantry angle about their individual mean positions averaged over all gantry angles, demonstrating approximate sinusoidal trajectories as functions of gantry angle along both directions. The motion tracks of the three BBs revealed high coincidence, and further supported our assumption that there was negligible in-plane rotation of the BTF. All investigated x-ray head assembly component exhibited a similar motion pattern, while also demonstrated some

FIG. 3. The relative 2D trajectories of all three BBs on the detector superimposed with one another, with the 3 BB markers attached to the x-ray head cage window.

in-coincidence. Figure 4(a) shows a superposition of the average motions of three representative tube head components illustrated in a schematic drawing in Fig. 4(b), with the average referring to average motion of the three BBs in each investigation as functions of gantry angle. From the motion tracks we observed that along the detector V direction, the motion was more uniform among different components; and along U , the motion was similar in motion pattern but slightly different in magnitudes for different components. The circled regions on the BB motion track of the BTF (component #3 in Fig. 4) exhibited the same discontinuity as shown in Fig. 3 with direct BTF motion analysis. Of all three investigated OBI systems, the one illustrated by Figs. 3 and 4 demonstrated clear discontinuities; the second exhibited smaller effects at different angles, while the third exhibited purely continuous behavior. For a given machine, the effects were reproducible. These discontinuities may be due to sudden gravity-induced BTF translations that are superposed on the overall smooth motions of the tube head motion track.

FIG. 4. (a) Superimposed average BB motion trajectories of some representative x-ray head assembly components as illustrated in (b). (b) The three levels of the x-ray head assembly the BBs were set to: (1) at the x-ray tube exit window, (2) at the U blades, and (3) at the back surface of the BTF.

FIG. 5. Images of the cylindrical water phantom before and after the BWA correction. (a) Simulated images incorporating the modeled BTF motion, (b) simulated images incorporating BTF motion but reconstructed following a translational correction to $NP(U,V,\theta_0)$ projection for each angle Eq. (3), (c) experimental images before BWA correction, (d) experimental images with measurement-based correction [angle-dependent normalization scans Eq. (2)], (e) experimental images with the model-based correction [the NP translation strategy Eq. (3)], (f) central profiles on the images (c)–(e).

III.D Computer simulation results

Images reconstructed from synthetic projections based on the actual OBI geometry as characterized by the Cho gantry-angle dependent beam geometry did not show the BWA, indicating that none of the parameters contributed to the BWA. On the other hand, simulation from the data model including the simple 1D BTF translation model clearly exhibited the artifact, whether with the actual beam geometry included or assuming ideal beam geometry. Accurate corrections for effects such as scatter and beam hardening in the synthetic data without the BTF motion generated images free of the BWA, while the BWA was evident when the BTF motion was included. This clearly ruled out the possibility that inadequate corrections of such effects contributed to the BWA. The simulation results validated our hypothesis that the BWA was caused by the mismatching BTF modulation profiles due to the BTF wobble. The wobble was found to be 2D, but only the 1D motion along U in

which BTF thickness is variant is responsible for the BWA.

III.E Analyses of reconstructed images

As in Fig. 5, both correction methods were effective in mitigating the BWA on both simulated [Figs. 5(a) and 5(b)] and experimentally acquired datasets [Figs. 5(c)–5(e)]. Note that for simulated cases, the two correction methods were mathematically identical, because the same motion model was used to generate the gantry-angle-dependent normalization projections and to translate a single-angle normalization projection, and because noise was not simulated. Figure 5(f) shows the central profiles on the experimental images, Figs. 5(c)–5(e) before and after the two alternative corrections, showing that the BWA artifact is reduced by 53% for gantry-angle dependent flood fields and by 71% for mathematically corrected flood-field normalization using data collected at a single gantry angle.

IV. DISCUSSION

The BWA was also noted and reported by another group.¹⁸ They attributed the BWA to the partial rotation scan because their images with full rotation scan did not have the BWA present. Because the location of the BWA also coincided with the interface of their imaged phantom, they also indicated that the BWA could be related to the interface of two different density materials. In light of our findings, neither of these factors can explain the formation of the BWA in the general case. Regarding the first hypothesized cause, we established that the BWA was present in both full and partial rotation scans with the full-fan BTF. The reason that the BWA did not appear in their full rotation scan was due to the coincidence that their scan used the half-fan BTF rather than the symmetric full-fan BTF. Regarding the second hypothesized cause, the appearance of BWA on the images of our homogeneous water phantom clearly showed that its formation did not depend on density gradients in the scanned object. We use Fig. 6 to show BTF thickness, $T(U)$ and filter thickness gradient, $dT(U)/dU$, as functions of pixel index, U , for the full-fan BTF used in the OBI system. It demonstrates that the regions of interest exhibiting BWA coincide with the regions of largest $dT(U)/dU$. Therefore, we can conclude that the appearance and location of the BWA depends on the BTF thickness gradient. It appears most strongly where this $dT(U)/dU$ achieves its maximum value, where a small lateral shift of the modulation pattern can produce a relatively large mismatch between the NP and PP. Due to the more gradual thickness filter gradient of the half-fan BTF, on extended FOV images acquired with the half-fan data acquisition mode the BWA are significantly mitigated.

After our paper was submitted to Medical Physics on September 09, 2010, a paper submitted by Giles *et al.* on September 21, 2010 also addresses in detail the BWA on Varian CBCT systems.¹⁹ Like our paper, they also identified the cause of BWA as the mismatch between the BTF profile on the PP and the NP. However, in their work they showed in simulation that three deviations from an ideal geometry could have caused the mismatch but did not identify which

one was the true cause in the case. Using a different methodology and performing a full geometric calibration, our study complements their work by ruling out the other possible causes and definitively establishing the BTF wobble as the cause of the mismatch. In addition, our study also studied the mechanical motion of the system in more depth, and developed alternative correction strategies for the BWA. Our study discovered that the BWA was caused by the geometric mismatch between the BTF modulation patterns in the CBCT projections versus those in the normalization projection. The mismatch in turn results from a geometric wobble of the BTF during gantry rotation. Similar mechanical motion trajectories affect other components of the x-ray head assembly we investigated and are independent of the focal spot motion trajectory. Therefore imaging artifacts commonly associated with an uncorrected source wobble are not observed. Careful geometric calibration of our OBI system geometry according to the method by Cho *et al.*, revealed small deviations from the ideal beam geometry that could not account for BWA formation. To our knowledge, Cho *et al.* method describes the most complete single circular orbit CBCT beam geometry model available in the literature. Thus, we propose extending this model to describe the potentially independent motion trajectory of the beam-modulating BTF. The BTF is an integral part of all modern commercial CT scanners. Independent filter motion has been shown to be a possibility for such systems and to cause significant deterioration of image quality if not accurately corrected for.

In our study, both simulation and experimentally acquired data demonstrate that correction strategies proposed by our work significantly mitigate BWAs. Residual BWA is due mostly to detector-pixel-dependent beam hardening and scatter corrections that assume a geometrically static BTF modulation pattern according to the nominal filter design, instead of taking into account the measured BTF motion, while in reality the BTF motion changes the registration of the modulation pattern with the patient geometry, altering the attenuation line integral corresponding to large thickness gradient rays, thereby altering beam hardening and scatter corrections. Compared with the model-based strategy, the measurement-based strategy showed an increased noise level on the reconstructed images because each normalization projection is a single frame instead of the multiple-frame-average used in single-gantry-angle acquisition [at noise level of 1.92% versus 1.43% for the example shown in Figs. 5(d) and 5(e)]. On the other hand, for the model-based strategy, although the identified wobble can be fairly well-modeled with the sinusoidal curves, discontinuities in the sinusoidal motion trajectory also cause residual errors. Such singularities present a challenge even for the measurement-based strategy because the exact gantry angle match between the PPs and NPs cannot be achieved mechanically with the current hardware and software systems. The ultimate solution would be for the manufacturer to eliminate the x-ray assembly motion or to use BTFs designed with gradual modulation changes.

FIG. 6. Along-ray filtration thickness plot of the full-fan BTF with its slope in relative units superimposed. The regions shaded in red show the portions of the filter corresponding to the BWA on reconstructed images.

V. CONCLUSIONS

We have studied the characteristics of a bow-tie wobble artifact unique to images acquired on the Varian OBI CBCT image acquired with a full-fan BTF in place. We have demonstrated the cause of the artifact to be a spatial mismatch of the BTF modulation patterns on the single-angle normalization projection and those on the multiple-angle phantom/patient projections from which images are reconstructed. The BTF modulation pattern change over gantry angle, in turn, was found to be due to a mechanical 2D wobble of the kV x-ray head assembly as the gantry rotates about the isocenter. The source position or focal spot, however, exhibits minimal motion over gantry angle.

Because the motion of the BTF is not part of geometric calibration techniques, additional tests are needed to fully characterize the system geometry. Such calibration and/or better mechanical stability of the BTF can then generate near BWA-free images.

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^{a)}Author to whom correspondence should be addressed. Telephone: (804) 628-0661; Electronic mail: dzheng@mcvh-vcu.edu

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