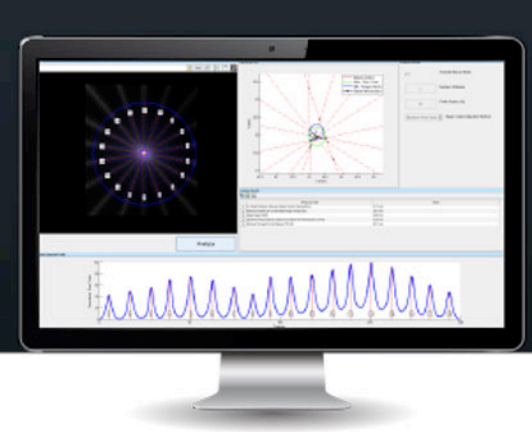

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TECHNICAL NOTE

MEDICAL PHYSICS

Technical note: Feasibility of gating for dynamic trajectory radiotherapy – Mechanical accuracy and dosimetric performance

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Abstract

Background: Dynamic trajectory radiotherapy (DTRT) extends state-of-the-art volumetric modulated arc therapy (VMAT) by dynamic table and collimator rotations during beam-on. The effects of intrafraction motion during DTRT delivery are unknown, especially regarding the possible interplay between patient and machine motion with additional dynamic axes.

Purpose: To experimentally assess the technical feasibility and quantify the mechanical and dosimetric accuracy of respiratory gating during DTRT delivery.

Methods: A DTRT and VMAT plan are created for a clinically motivated lung cancer case and delivered to a dosimetric motion phantom (MP) placed on the table of a TrueBeam system using Developer Mode. The MP reproduces four different 3D motion traces. Gating is triggered using an external marker block, placed on the MP. Mechanical accuracy and delivery time of the VMAT and DTRT deliveries with and without gating are extracted from the logfiles. Dosimetric performance is assessed by means of gamma evaluation (3% global/2 mm, 10% threshold).

Results: The DTRT and VMAT plans are successfully delivered with and without gating for all motion traces. Mechanical accuracy is similar for all experiments with deviations $<0.14°$ (gantry angle), $<0.15°$ (table angle), $<0.09°$ (collimator angle) and <0.08 mm (MLC leaf positions). For DTRT (VMAT), delivery times are 1.6–2.3 (1.6– 2.5) times longer with than without gating for all motion traces except one, where DTRT (VMAT) delivery is 5.0 (3.6) times longer due to a substantial uncorrected baseline drift affecting only DTRT delivery. Gamma passing rates with (without) gating for DTRT/VMAT were $\geq$96.7%/98.5% ($\leq$88.3%/84.8%). For one VMAT arc without gating it was 99.6%.

Conclusion: Gating is successfully applied during DTRT delivery on a TrueBeam system for the first time. Mechanical accuracy is similar for VMAT and DTRT deliveries with and without gating. Gating substantially improved dosimetric performance for DTRT and VMAT.

KEYWORDS
dynamic trajectory, gating, motion management

1 | INTRODUCTION

Intensity modulated radiotherapy (IMRT) and volumetric modulated arc therapy (VMAT) are considered state-of-the-art radiotherapy treatment techniques for external radiation therapy with C-arm linear accelerators (linacs). Building on the C-arm linacs potential to dynamically move multiple machine axes, previous studies demonstrated the potential of non-coplanar radiotherapy[1] to improve organ-at-risk (OAR) sparing and/or dose conformality to the target compared to coplanar techniques by avoiding OARs in the beam path.[2–6] Efficient non-coplanar delivery, such as in dynamic trajectory radiotherapy (DTRT[2]), can be obtained by combination of dynamic gantry and table rotation with intensity modulation, with or without dynamic collimator rotation.[7,8]

Regardless of the chosen treatment technique, respiratory motion in the thorax[9–13] and abdomen requires motion management to mitigate the degradation of the delivered dose distribution.[14] Motion management techniques include breath-hold, free-breathing gating, or MLC or couch tracking.[15]

Dedicated systems such as the CyberKnife (Accuray, Sunnyvale, CA, USA) or the discontinued VERO (Brainlab, Munich, Germany and Mitsubishi Heavy Industries, Tokyo, Japan) are specifically designed to make use of non-coplanar beam angles with dynamic tumor tracking for motion mitigation.[16,17] However, these systems are not as widely available as C-arm linacs where motion mitigation strategies such as gating are applied in clinical practice.[15] Free-breathing gating, however, imposes frequent beam-on/off switching, making it potentially more difficult to deliver for dynamic techniques.[18,19] To apply free-breathing gating for DTRT, several challenges and questions need to be answered:

- *Is the machine capable of applying free-breathing gating DTRT for realistic motion traces?*
- *Can the machine deliver the intended dynamic trajectory with sufficient mechanical accuracy despite gating events?*
- *What is the dosimetric accuracy of DTRT delivery with gating?*

The aim of this work is therefore to investigate the technical feasibility of gating during DTRT delivery, with additional dynamic table and collimator rotation compared to VMAT, and to evaluate mechanical accuracy, delivery time and dosimetric performance of DTRT delivery with and without gating. Mechanical accuracy and dosimetric performance for DTRT and VMAT deliveries with and without gating are compared for one case and four patient-recorded motion traces.

2 | MATERIALS AND METHODS

2.1 | Treatment planning and patient case

Free-breathing gating for DTRT is tested for a clinically motivated lung cancer case prescribed 60 Gy in 20 fractions to the median planning target volume (PTV). The target has a volume of 190 cm^3. The treatment planning process of Fix et al.[2] is followed to generate a DTRT treatment plan with dynamic gantry, table and collimator rotation during beam-on. The gantry-table path minimizes the target-OAR (heart and spinal cord) overlap in the beam's eye view. For collision prevention, an inhouse developed Blender[20] model of the motion phantom is used.[21] Dynamic collimator rotation minimizes field width in the leaf-travel direction. The obtained gantry-table-collimator path has 178 control points corresponding to a 2° gantry control point resolution and is duplicated by applying a 90° collimator angle offset on the second path. The DTRT treatment plan thus consists of two paths, each covering a full gantry rotation and a table rotation range of 56.4° (Figure 1a). The paths are imported into Eclipse (Varian Medical Systems, Palo Alto, CA, USA) using the Eclipse Scripting Application Programming Interface. For comparison, a VMAT plan with two partial arcs covering a total range of 195° gantry rotation each with collimator angles of 2° and 88° is created (Figure 1b). Both plans are optimized according to clinical standards using a research version of the Eclipse Photon Optimizer and the Analytical Anisotropic Algorithm (AAA) dose calculation algorithm v15.6. The two DTRT trajectories deliver 373 MU and 369 MU with mean dose rates of 299 and 291 MU/min and the two VMAT arcs, deliver 369 MU and 213 MU with nominal mean dose rates of 551, 313 MU/min. The resulting dose distributions conform to clinical standards and have been accepted by a clinician.

For each plan, a verification plan is created for a cylindrical polymethylmethacrylate (PMMA) motion phantom representing the Delta4+ (ScandiDos, Uppsala, Sweden) measurement device, and dose is recalculated on the motion phantom geometry (Figure 1c). For DTRT, a verification plan without table rotation is also created to distinguish the impact of potential table rotation errors. On this plan, dynamic gantry and collimator rotation and MLC movement is maintained.

2.2 | Respiratory motion

Gating is tested for four different breathing motion traces of lung tumors from a publicly available dataset recorded in patients,[22,23] denoted as: typical, high frequency, left right and baseline shifts, given after the predominant motion type. Each trace contains combined

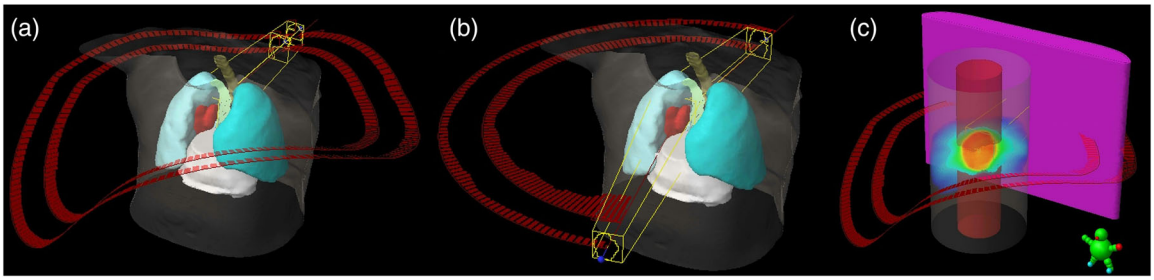

FIGURE 1 DTRT trajectories (a), VMAT arcs (b) and motion phantom with DTRT trajectories (c) for the lung cancer case. The PTV is shown in red, lungs in blue, spinal cord in yellow, oesophagus in green, heart in white and the body surface in translucent grey. The red bands indicate the beam incidences of the DTRT and VMAT plan respectively.

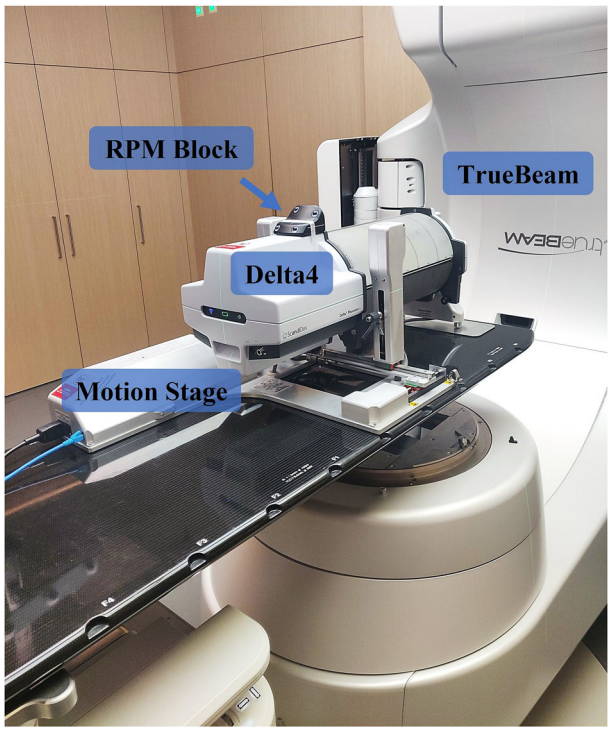

FIGURE 2 Experimental setup of motion stage, Delta4+ and RPM Marker Block on the treatment table.

motion in superior-inferior, anterior-posterior, and left-right directions. Gating is applied at end-exhale. The amplitude gating windows are selected on the main motion axis (either superior-inferior or anterior-posterior) with gating windows between 4 and 6 mm depending on the motion trace. For the typical motion trace, two gating windows (2 and 4 mm) are tested (Supplementary material S1).

2.3 | Experimental setup and plan delivery

The experimental setup is shown in Figure 2. For dosimetric verification, a Delta4+ motion phantom is used. It has two orthogonal planes of 1069 p-type silicon diodes with a resolution of 5 mm at isocenter. The Delta4+ motion phantom is positioned in the HexaMotion (ScandiDos) stage on the PerfectPitch 6-degree-of-freedom treatment table of the TrueBeam system (Varian). The motion stage can rigidly move the Delta4+ to reproduce the motion traces shown in the Supplementary material S1. Amplitude gating is triggered using the three-camera infrared-based Real-time Position Management respiratory gating system (RPM, Varian) with the marker block on top of the phantom (Figure 2).

The DTRT and VMAT plans are delivered at the machine with and without gating for all motion traces using Developer Mode. Developer Mode enables the delivery of experimental treatment techniques, by use of XML files which describe the plan. The gating latency of the TrueBeam system using the RPM signal has been recently reported to be 84 ms for beam-on and 44 ms for beam-off.[24] Delivery is started approximately ten seconds after the motion stage is set in motion. For each trajectory/arc, the motion trace is recycled until the MUs are fully delivered.

2.4 | Data analysis

2.4.1 | Mechanical accuracy

During delivery, motion along all mechanical axes is interpolated between controlpoints (every 2° gantry angle) by the TrueBeam supervisor and machine logfiles are collected to assess the mechanical accuracy as the deviation between actual and expected machine positions for gantry, table and collimator angle and moving MLC leaf positions in 20 ms intervals. Additionally, the MU delivery is assessed. Delivery time, duty cycle (DC) and beam-holds are extracted from the logfiles and compared for the deliveries with and without gating.

2.4.2 | Dosimetric accuracy

Dosimetric accuracy of the deliveries with and without gating is assessed using the Delta4+ motion phantom.

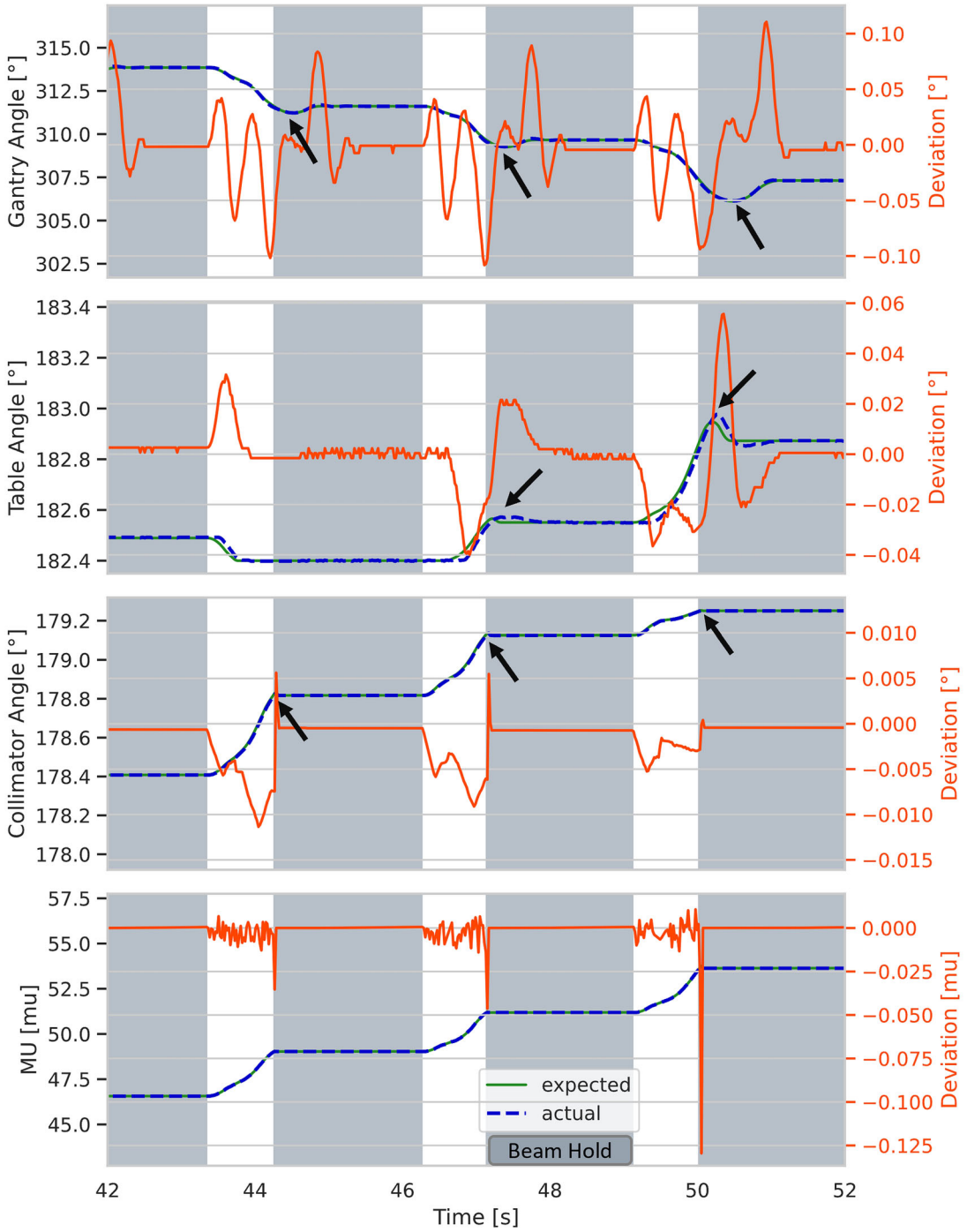

FIGURE 3 Zoom in on TrueBeam logfile of a gated DTRT delivery. The "overshoot" and "rotating back" is indicated by arrows during beam-hold (grey). The delivery is resumed when entering the gating window again.

For reference, dosimetric accuracy is also assessed in the static case (no motion, without gating) for VMAT and for DTRT with and without table rotation. Gamma passing rate (3% global/2 mm, 10% threshold) and dose difference are used for evaluation following the patient specific quality assurance criteria recommended for IMRT measurement-based verification QA[25] and MLC tracking.[26]

3 | RESULTS

Gating is successfully applied during DTRT and VMAT deliveries, with the gantry (VMAT and DTRT), table (DTRT) and collimator (DTRT) automatically rotating back during beam-hold and resuming motion at beam-on, that is, when entering the gating window (Figure 3). This correction is completed within <1 s. Maximal

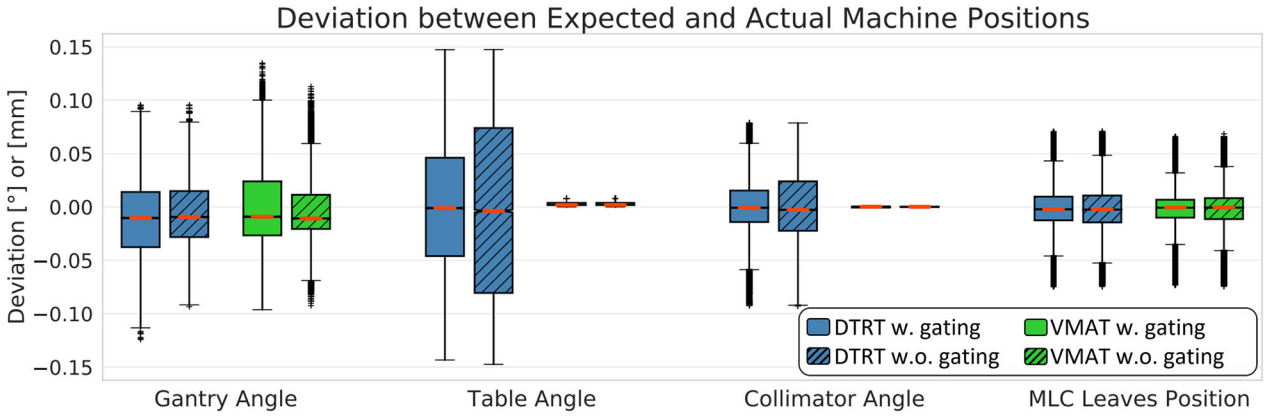

FIGURE 4 Deviation (expected-actual positions) in gantry, table and collimator angle and moving MLC leaf positions for DTRT (blue) and VMAT (green) delivery with (full) and without (dashed) gating. Deviations are only computed when the beam is on. The median is depicted in red, the notch defines the 95% confidence interval of the median, the box extends to the interquartile range (IQR, Q3-Q1), whiskers extend to the last (first) data point less (greater) than Q3+1.5*IQR(Q1-1.5*IQR). Outliers are marked with the plus sign.

overshooting due to gating-triggered beam-hold is <1.5° for the gantry (VMAT and DTRT) and <0.2° for the table and <0.02° for the collimator rotation. In the Supplementary material S2 a recording of a DTRT delivery with gating can be found. No loss of RPM signal is observed for the investigated case and motion traces and the RPM block is accurately tracked (Supplementary material S3). The gantry-table (GT) and gantry-collimator (GC) path for the DTRT delivery with and without gating during the "typical" motion trace agree within ±0.2° (Supplementary material S4).

3.1 | Mechanical accuracy

The mean root-mean-square (RMS) deviation between expected and actual position was below 0.1° for gantry, table and collimator rotation and 0.023 mm for moving leaf position for all deliveries.

The mechanical deviation distributions are shown in Figure 4. Greater variations (interquartile range) are observed for the deviations in table and collimator angle for DTRT deliveries without gating than for the deliveries with gating. Small systematic offsets for table/collimator angle observed in the delivery of the VMAT plans are not corrected, as they are within the precision limit of the machine component.

Delivery of the DTRT and VMAT plans takes 2.5 and 1.4 min without gating. Of note, total gantry angle ranges are 720° for DTRT and 390° for VMAT. The delivery time and number of beam-holds of the gated deliveries depend on the gating window and motion traces: For the selected gating windows the total delivery time increases for the gated DTRT (VMAT) delivery by a factor of 2.3 (2.0) for lung typical with a ±2 mm gating window and 3.4 (3.2) with a ±1 mm gating window, 1.6 (1.6) for predominantly left right and 2.3 (2.5) for baseline shift motion trace. This led likewise to a decrease in the DC for the gated DTRT (VMAT) deliveries to 43% (50%) for lung typical with a ±2 mm gating window and 29% (31%) with a ±1 mm gating window, 63% (63%) for predominantly left right and 43% (40%) for baseline shift motion trace. For the high frequency motion trace, delivery time is increased by a factor of 5.0 (3.6), DC 20%, for DTRT (VMAT) which corresponds to a DC of 20% (28%). This is because the VMAT delivery is completed before reaching a baseline drift in the motion trace which affects the duty cycle of the DTRT delivery (see Supplementary material S5). The number of beam-holds for DTRT (VMAT) deliveries are 173 (93) for lung typical with a ±1 mm gating window and 122 (54) with a ±2 mm gating window, 56 (31) for predominantly left right, 57 (38) for baseline shift, and 358 (112) for the high frequency motion trace.

3.2 | Dosimetric accuracy

Gamma passing rates are reported in Table 1 and Supplementary material S6. All gated deliveries achieve passing rates >95.0%, All deliveries without gating result in passing rates <88.3%, except for one arc of one VMAT plan where it was 99.6%. Gamma passing rates for the deliveries on static phantom are above 99.5% for static table plans and above 98.7% for DTRT deliveries. Figure 5 shows the Delta4+ measurement on one of the two orthogonal planes with dose profiles for the DTRT delivery with and without gating with the lung typical motion.

4 | DISCUSSION

Free-breathing gating is successfully applied during delivery of a DTRT treatment plan for the first time, demonstrating its technical feasibility for this highly

TABLE 1 Dosimetric performance.

Motion Trace	T1	T2	V1	V2
Typical				
Gating ±1 mm	**99.5**	**99.7**	**99.0**	**99.6**
Gating ±2 mm	**99.5**	**97.1**	**99.3**	**99.8**
No Gating	88.3	84.3	77.0	**99.6**
High frequency				
Gating +1/−3 mm	**99.7**	**97.9**	**98.5**	**99.8**
No Gating	55.4	48.6	55.3	50.6
Baseline shift				
Gating ±3 mm	**99.2**	**97.4**	**98.7**	**98.8**
No Gating	84.3	82.1	72.8	76.9
Pred. left right				
Gating ±2 mm	**96.7**	**98.0**	**99.3**	**99.1**
No Gating	79.3	85.3	84.8	76.2
No motion				
No Gating	**99.7**	**98.7**	**100**	**100**
No motion				
Static table	**100**	**99.5**	**NA**	**NA**

Gamma passing rates [%] (3% global dose difference/2 mm distance, 10% threshold) for the DTRT (T1: first DTRT trajectory, T2: second DTRT trajectory) and the VMAT (V1: first VMAT arc, V2: second VMAT arc) deliveries with and without gating for the different motion traces. Values above 95% are indicated in bold.

complex and dynamic treatment technique on a standard C-arm linear accelerator.

For the investigated case and motion traces, the mechanical accuracy of the TrueBeam system delivering a DTRT treatment plan gated by the RPM signal is within sub-mm and sub-degree accuracy, similar to VMAT. When the beam is held, the positions of certain machine components (such as gantry angle) may overshoot the planned value. The machine, however, automatically corrects for these overshoots during the beam hold within the physical machine limits (including adaptation of the expected machine positions). The machine waits to resume delivery as soon as all machine components are in the correct positions and the signal of the RPM indicates that the target is within the gating window. Similar deviations between gantry angle or MLC leaf positions are observed between the VMAT and the DTRT deliveries, indicating that the addition of dynamic table and collimator rotation does not influence the accuracy of these common dynamic axes. The observed deviations are similar compared to previous logfile analyses.[3,27,28] For DTRT, it is worth noting, that the spread in the deviations of table and collimator angle are lower with gating than without gating. This is probably because the mechanical axes have time to go back to the expected position at the beam hold and to accelerate when the beam is turned on again and MU output is ramping-up. It has been observed that for continuous delivery, table and collimator rotation tend to slightly lag behind,[3] whereas with gated delivery, lag can be eliminated at each gating event. It has to be noted that this mechanical accuracy evaluation is based on logfiles. These logfiles are not independent from the treatment machine and accurate calibration and routine QA are essential[29] and performed at our institute.

Dosimetric measurements for DTRT and VMAT showed that gating partially restores the planned dose distribution for common respiratory motion traces. Residual motion during beam-on depends on the gating window with a trade-off between residual motion and delivery time. In addition, the gating window is defined for one direction of motion and substantial, uncorrelated, motion in the other axes is still possible and will not trigger a beam hold. Despite these effects, deliveries with gating had high dosimetric accuracy with gamma passing rates >96.7%.

DTRT is currently a research technique and not available for patient treatments. However, only commercially available and adequate[30] equipment, widely employed during clinical PSQA, is used for the motion experiments. It is important to test the treatment machine capability to apply gating for real motion traces to test the technique for clinical practice.[31,32] As in previous studies on motion management system performance,[23,33] we used four different motion traces that are representative of common lung motion types.[22,23] No loss of RPM signal is observed for the investigated case and motion traces, despite the non-coplanar table positions during DTRT.

The dosimetric benefit of gating is directly related to the gating window and motion trace, which in turn influence DC and thus the delivery time. In clinical practice, the selection of the gating window and the PTV margins would be based on balancing accurate tumor targeting, DC and PTV margins, considering the inherent uncertainty of correlating the surface motion to the actual tumor motion. The total delivery time without gating for DTRT and VMAT is 2.5 min and 1.4 min respectively, with VMAT having slightly more than half the gantry angle range of the DTRT plan. With exception of the lung high frequency motion trace, delivery time increased by up to a factor of 2.5 for the gated deliveries (VMAT and DTRT), similar to the results of Chin et al.[19] For the lung high frequency motion trace, the delivery time increased by a factor of 5.0 for DTRT delivery with gating compared to delivery without gating due to an uncorrected baseline drift. For this motion trace, gating enabled dosimetric accuracy similar to the other motion traces for both treatment techniques. Without gating, dosimetric accuracy is substantially lower to approximately 50% gamma passing rate. This shows the need to monitor the motion during delivery and adapt in case of baseline drift. A potential solution would be to interrupt treatment and apply set-up correction as proposed in other gating studies.[34]

Our results show that motion mitigation, for example, free-breathing gating, is needed to ensure that the favorable dose distributions achievable with DTRT[2,3] are accurately delivered to the patient in treatment sites affected by breathing motion. In these cases, PSQA can

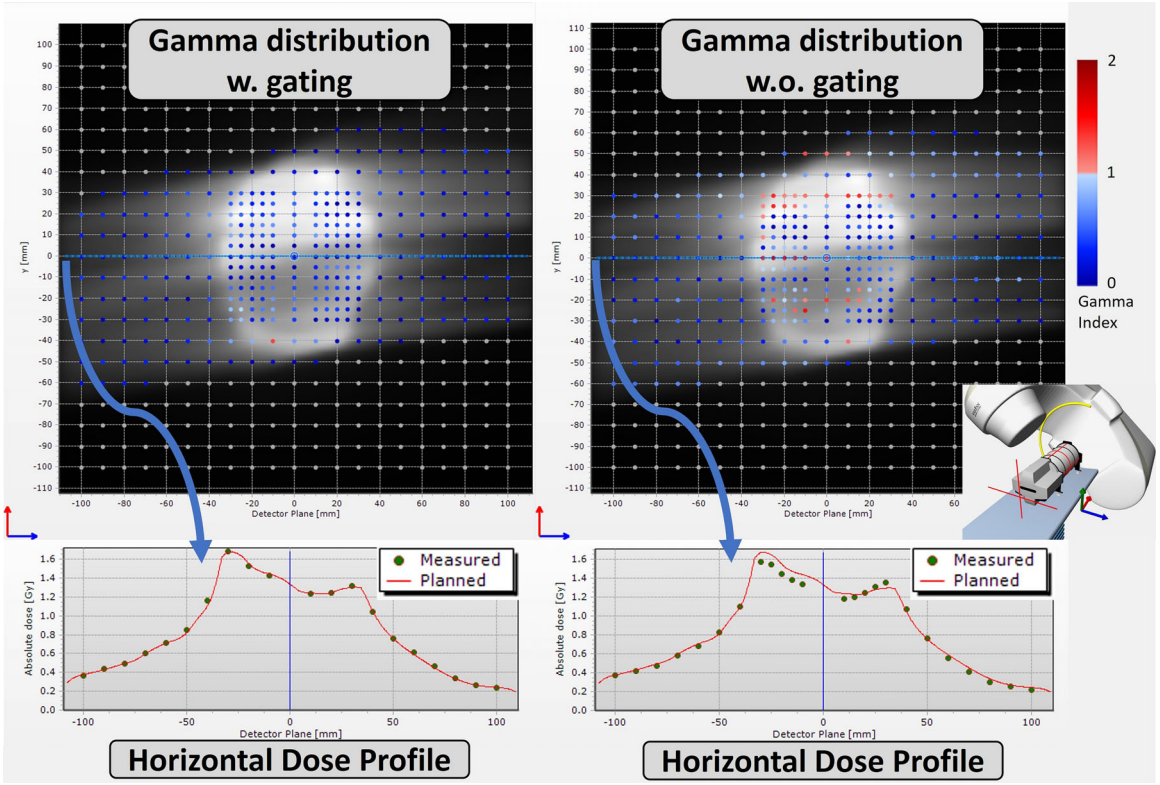

FIGURE 5 Gamma maps (top) and profiles (bottom) for DTRT delivery on the lung typical motion trace with (left) and without (right) gating. Red points indicate diode positions, where the delivery fails gamma analysis (gamma >1).

also be performed with realistic motion traces or using the motion recorded at 4DCT using the experimental setup proposed in this study.

5 | CONCLUSION

In this work, the technical feasibility of gating for DTRT on a TrueBeam is successfully demonstrated for the first time. The mechanical accuracy in terms of gantry, table and collimator angle and MLC leaf position is similar with and without gating and to VMAT delivery for the investigated case and motion traces. Comparable to VMAT, gating substantially improves the dosimetric plan quality, at the cost of increased delivery time.

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CONFLICT OF INTEREST STATEMENT

The authors have no relevant conflicts of interest to disclose.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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