A Novel Patient-Specific Gating Method to Maximize Duty Cycle in Pancreatic Tumors

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PURPOSE

- Current mainstream MR-Linac gating strategies gate treatment either at end-exhalation or at the mid-position of the respiratory cycle.
- The effectiveness of these approaches varies with tumor motion amplitude, breathing waveform shape, and PTV margin, and neither is always optimal for duty cycle.
- The Elekta Comprehensive Motion Management (CMM) system enables real-time, high-temporal-resolution monitoring of tumor motion on an MR-Linac.
- Using histogram-based analysis of tumor positional variations, we propose a patient-specific gating strategy designed to maximize the duty cycle
- This study compares the patient-specific optimal gating position with standard exhale and 10-phase mid-position gating.
- The goal is to provide a practical framework for clinical gating selection, including guidance for making the best possible decision when the optimal strategy cannot be implemented.

MATERIALS & METHODS

- Fifteen pancreatic cancer patients treated on an MR-Linac with CMM were analyzed.
- Tumor positions were extracted from CMM log files for every treatment fraction.
  - Baseline drift was estimated using a low-pass filter and subtracted from the motion traces, which were then recentered to the midpoint between the respiratory peaks and valley.
- All fractions were combined to generate a tumor-position distribution over the full treatment course.
  - Motion in the x and y directions was small and adequately covered by a 2–3 mm margin, so analysis focused on the superior–inferior (z) direction.
  - Position histograms were constructed, and gating margins from 1 to 8 mm were evaluated.
- For each margin, the gating window was swept across the histogram, and the cumulative proportion of data points within the window was defined as the duty cycle.
- Duty cycles were calculated by sweeping the margin center across the histogram to identify the position of maximum duty cycle. The window position that produced the maximum duty cycle was identified.
- Three gating positions were compared: (1) the patient-specific optimal position, defined as the position with the maximum duty cycle; (2) the mid-position derived from a 10-phase respiratory cycle; and (3) the end-exhalation position, represented by the 40%–60% respiratory phases.

RESULTS

- Tumor motion amplitude ranged from 5.5 to 13.7 mm (mean 9.2 ± 2.2 mm) across the 15-patient cohort.
- Figure 1 shows a representative drift-corrected tumor-position trace for a single treatment fraction and the corresponding position histogram generated over the full treatment course.

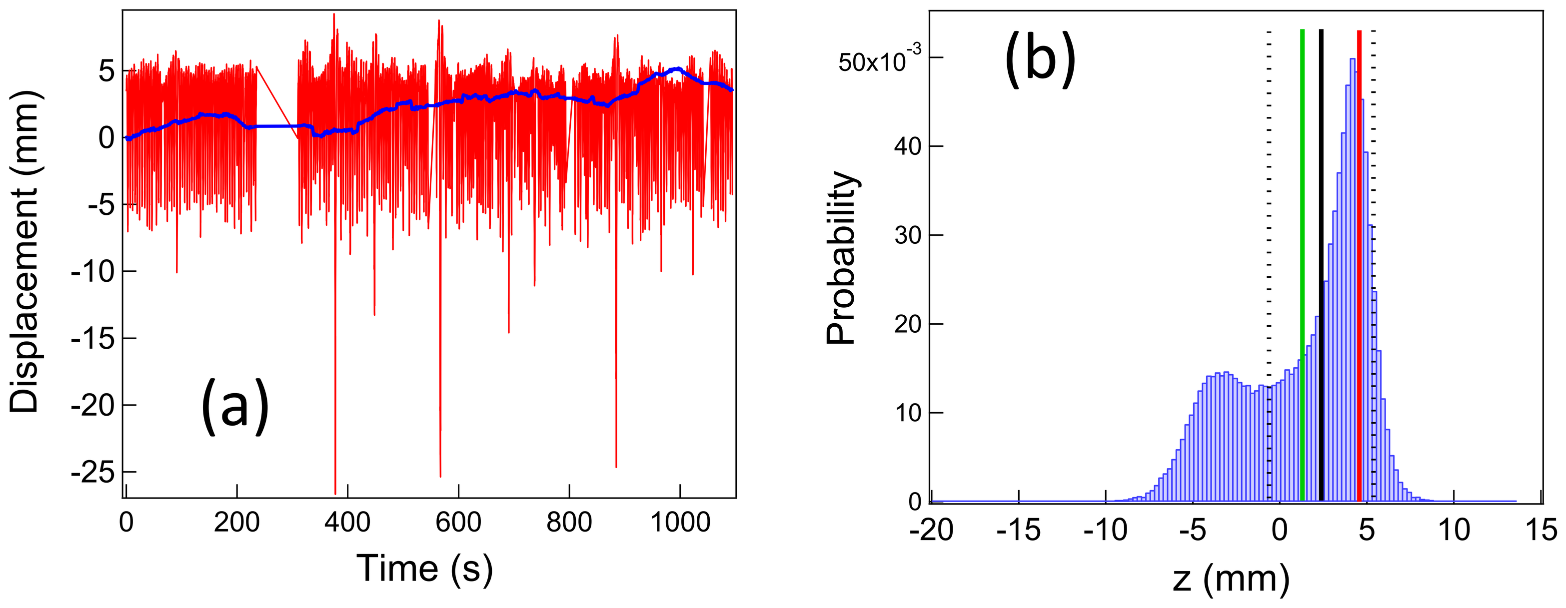

Figure 1. Representative tumor-motion and gating analysis. (a) Tumor-position trace in the z direction for a single treatment fraction after baseline-drift correction (red), with the removed baseline drift (blue). (b) Position histogram generated from all treatment fractions. For a ±3 mm gating margin, the green, red, and black lines indicate the 10-phase mid-position (1.3 mm), end-exhalation position (4.6 mm), and patient-specific optimal position (2.4 mm), respectively. The dashed lines indicate the gating margin centered on the optimal position.

- For this patient, the 10-phase mid-position and end-exhalation gating positions yielded duty cycles of 52% and 58%, respectively, whereas the patient-specific optimal position achieved a duty cycle of 67% with a ±3 mm gating margin.
- Figure 2 illustrates how the patient-specific optimal gating position varies with the gating margin.

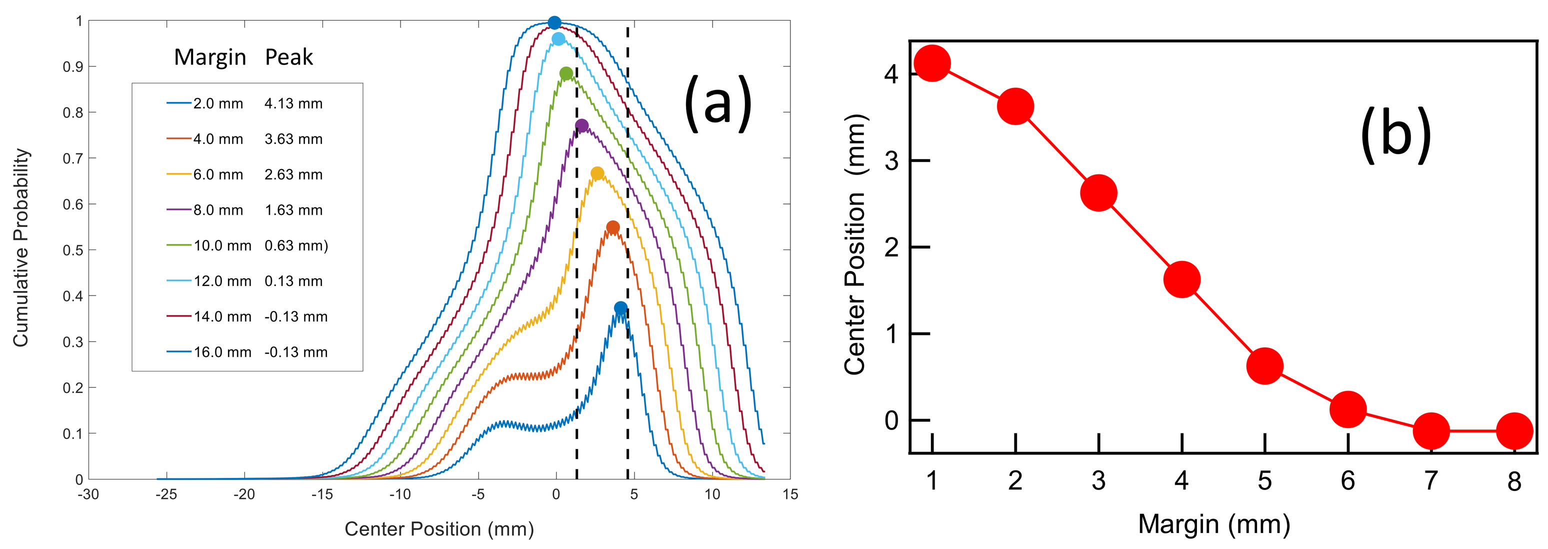

Figure 2. Effect of gating margin on the optimal gating position. (a) Duty cycle as a function of gating-center position for different margins; each peak identifies the optimal position. Dashed lines indicate the 10-phase mid-position and end-exhalation position. (b) Optimal gating position as a function of gating margin.

- Starting at small margins, the optimal position closely matches the end-exhalation position. As the margin increases, it shifts toward the 10-phase mid-position, passes it at approximately 9 mm, and eventually stabilizes near the center of respiratory oscillation.
- Figure 3 shows duty cycle as a function of margin for the three gating strategies in this patient. As expected by design, the patient-specific optimal strategy achieved the highest duty cycle across all evaluated margins.

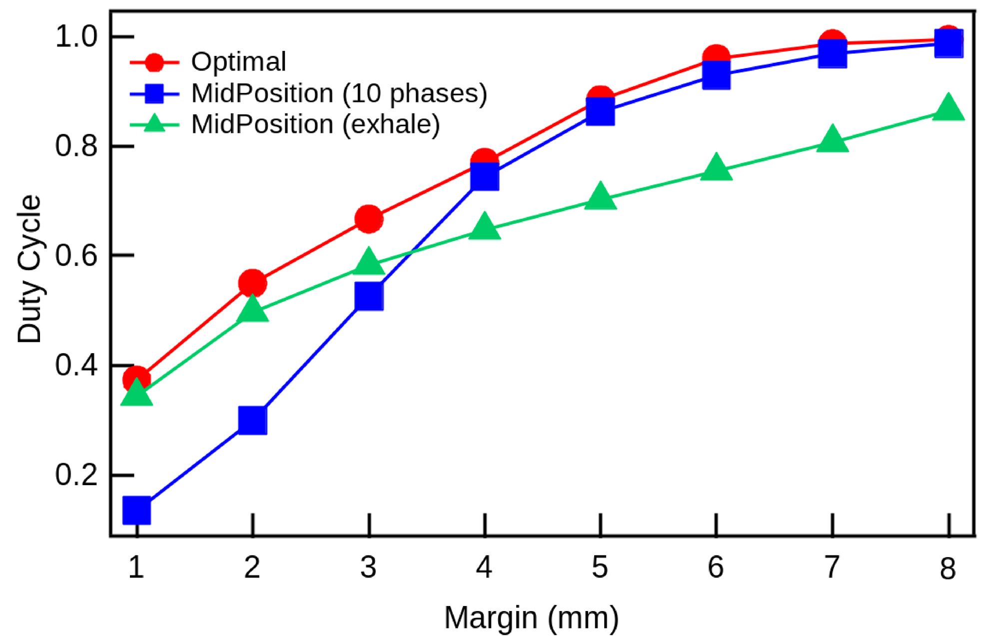

Figure 3. Duty cycle as a function of gating margin for the patient-specific optimal, 10-phase mid-position, and end-exhalation gating strategies.

- The end-exhalation and 10-phase mid-position curves intersected at a margin of 3.4 mm; below this threshold, end-exhalation gating was closer to optimal, whereas above it, the 10-phase mid-position was more favorable.
- Within the clinically relevant 2–4 mm margin range, the optimal position showed the greatest advantage, with an average duty-cycle improvement of 13% ± 4% across the cohort.
- Figure 4 summarizes the intersection margins between the end-exhalation and 10-phase mid-position duty-cycle curves across the cohort. The median intersection margin was 2.84 mm, and for margins greater than 4 mm, the 10-phase mid-position strategy yielded a higher duty cycle for all patients.

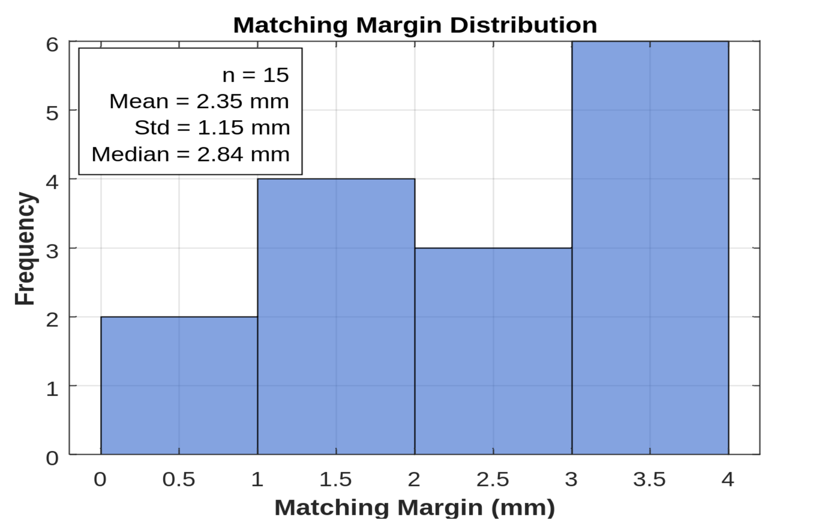

Figure 4. Distribution of the intersection margin between the end-exhalation and 10-phase mid-position duty-cycle curves across the 15-patient cohort.

CONCLUSIONS

- Histogram-based analysis enables patient-specific optimal gating positions to be determined from individual respiratory patterns and the selected gating or PTV margin, and can be applied across different gating platforms.
- When the optimal strategy is not available, end-exhalation and 10-phase mid-position gating may serve as practical clinical alternatives, depending on the margin used.

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