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Commissioning and Robustness Evaluation of the Laser Sensor for Respiratory Gating in Carbon-Ion Therapy

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Introduction

- Respiratory monitoring in CIRT commonly relies on belt-based abdominal pressure sensors, but this method has practical drawbacks, including complex setup and calibration, discomfort from tight fixation, and interference with immobilization devices such as thermoplastic shells, especially in the prone position.
- We commissioned and rigorously evaluated the clinical applicability of the ANZAI laser respiratory gating system for carbon-ion radiotherapy.

Materials and Methods

1. Respiratory gating system (ANZAI laser sensor)

Figure 1. ANZAI laser-based respiratory gating system and clinical setup using a thermoplastic immobilization shell. (a) System configuration showing the laser sensor, sensor port, control personal computer (PC), and software interface. (b) Clinical setup of the laser sensor positioned above the shell for respiratory motion tracking. (c) Opening in the shell enabling unobstructed laser projection onto the patient's skin for accurate signal acquisition.

- An ANZAI laser-based gating system (AZ-733VI) was implemented and clinically commissioned for CIRT to provide accurate, non-contact respiratory monitoring and gated irradiation.

2. Laser-based respiratory monitoring with thermoplastic shell

- The shell is wrapped around the abdomen to ensure stability.
- However, this setup obstructs respiratory motion monitoring of the thoracic or abdominal surface. To overcome this limitation, a hole was created in the shell (Figures 1b and 1c).

3. Response (Delay) time measurement

- System delay was dissected into four distinct intervals: motion-to-waveform conversion, waveform-to-gating signal generation, gating-to-beam initiation, and signal-to-irradiation response.

4. Motion phantom

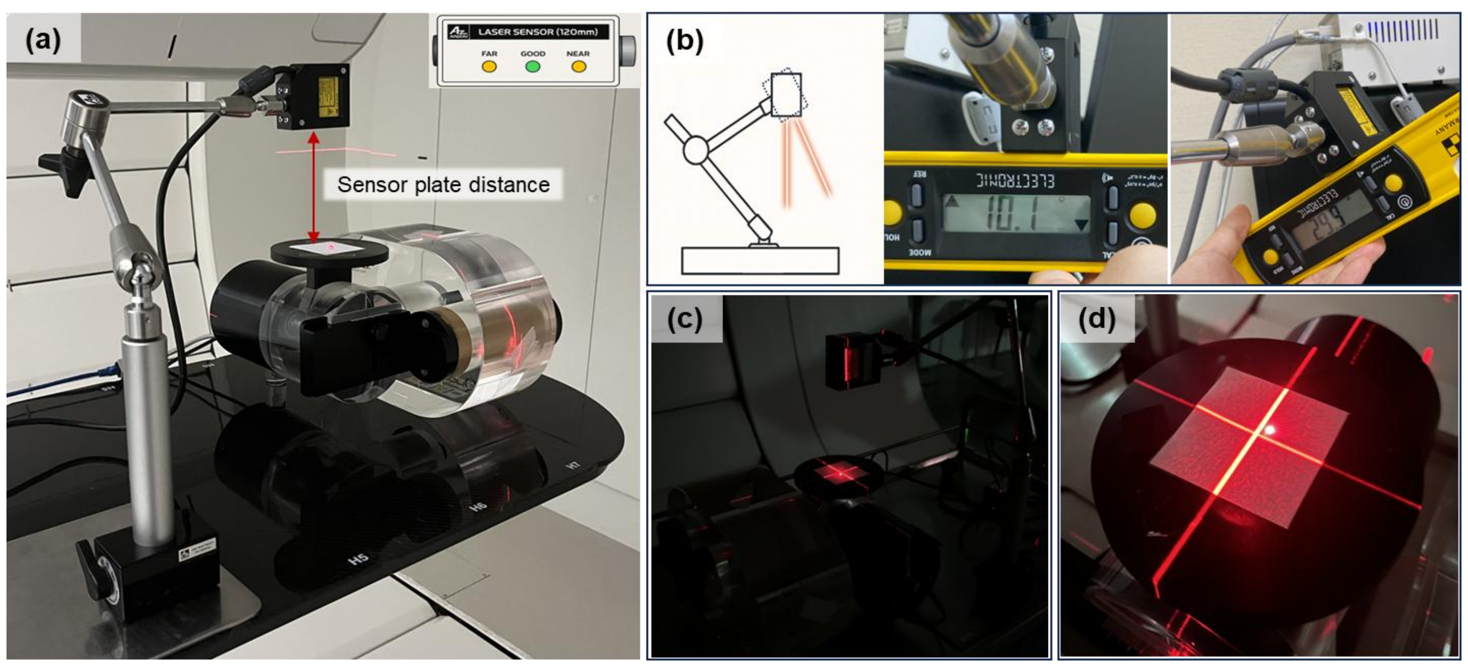

Figure 2. Motion phantom configuration for evaluating the accuracy and robustness of the ANZAI laser sensor system. (a) Setup for validating respiratory signal acquisition under varying breathing conditions, including changes in period, amplitude, baseline shift, and irregular phase patterns. (b) Quantitative assessment of measurement accuracy at nonperpendicular sensor angles. (c) Evaluation of laser signal stability under low-light (dark) conditions. (d) Assessment of signal interference caused by adjacent laser sources.

- A programmable motion phantom tested the tracking accuracy across multiple breathing conditions, including varying amplitudes, breathing cycles, and complex patterns involving baseline shifts and phase inconsistencies.
- Robustness tests involved variations in sensor-to-surface distance (9-17 cm), sensor orientation angles (0-45°), ambient lighting conditions, and interference from room alignment lasers.

5. Volunteer test

- Volunteer tests validated the correlation of external sensor signals with internal diaphragm movements acquired via 4DCT in supine and prone positions, alongside compatibility assessments with conventional belt sensors.

Results & Discussion

1. Measurement of system delay time

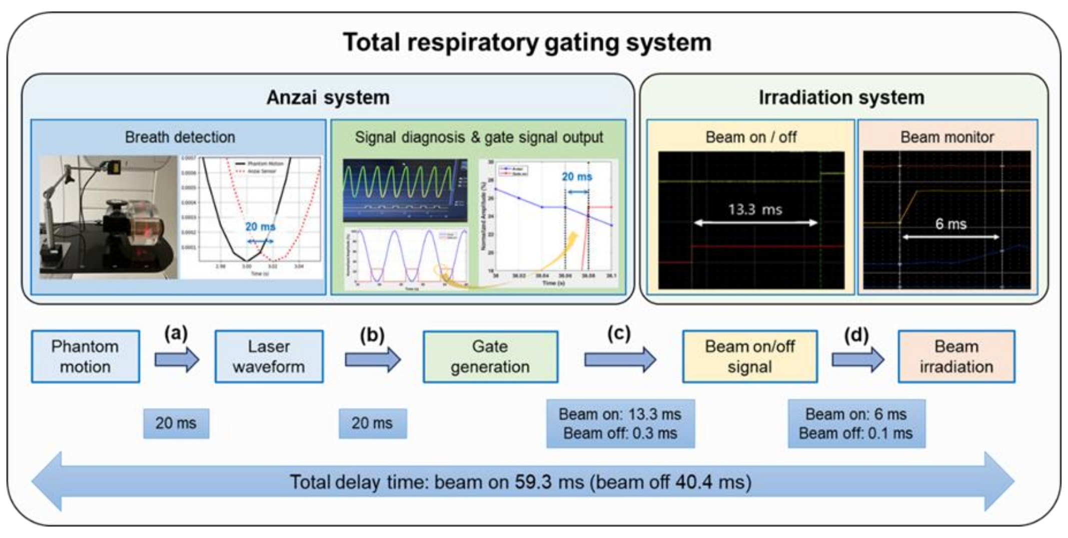

Figure 3. Schematic representation of delay time measurement. (a) Delay from phantom motion to waveform detection, (b) waveform to gate signal generation, (c) gate signal to beam-on/beam-off signal, (d) beam-on/beam-off signal to actual beam irradiation.

- Total system delays were measured as 59.3 ms (beam-on) and 40.4 ms (beam-off), comfortably meeting the recommended tolerance threshold of 100 ms by guidelines such as AAPM TG-142.

2. Validation of respiratory tracking accuracy with motion phantom

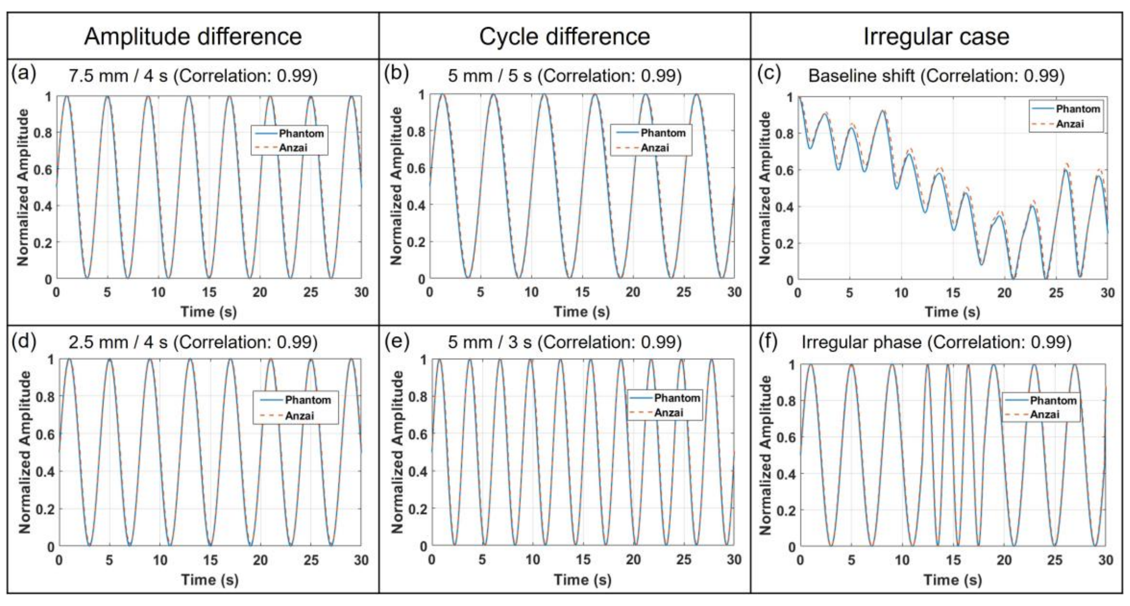

Figure 4. Reliability evaluation of the ANZAI laser sensor system using a programmable motion phantom. To evaluate the tracking accuracy of the sensor, respiratory motion signals were acquired under various conditions.

- Phantom studies indicated excellent tracking precision, consistently achieving cross-correlation coefficients above 0.99 across diverse respiratory conditions.

3. Evaluation of sensor robustness under geometric and environmental variations

- The sensor maintained robust signal stability within a 9-17 cm operational range and under dimmed lighting conditions.
- However, sensor orientations beyond 20° from perpendicular resulted in amplitude discrepancies, and interference from alignment lasers significantly degraded the signal quality.

4. Volunteer test

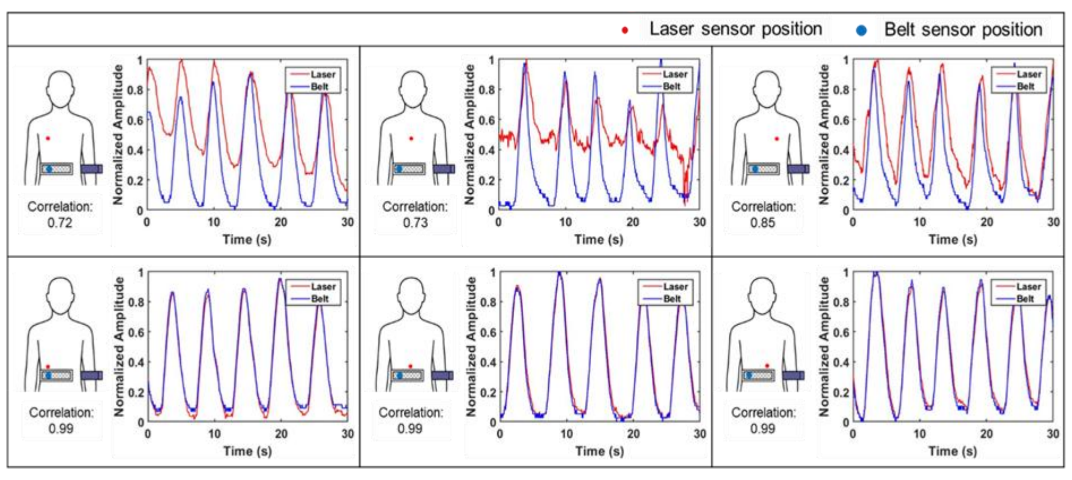

Figure 5. Comparison of respiratory signals acquired simultaneously by the laser sensor (red dots) and belt sensor (blue dots) placed at various positions on the torso.

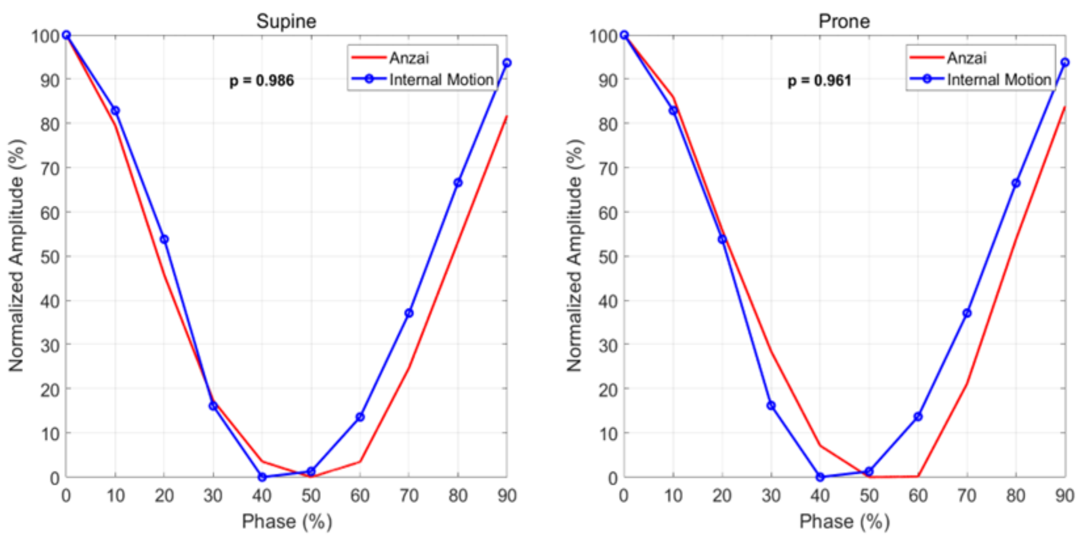

Figure 6. Comparison of ANZAI laser sensor signals and four-dimensional computed tomography-derived internal organ motion at different patient positions. Normalized amplitude curves are presented for supine (left) and prone (right) positions.

- Volunteer evaluations revealed strong correlations between external signals and internal diaphragm movements irrespective of positioning (supine or prone), confirming reliable system performance and excellent compatibility with belt-type respiratory sensors placed adjacently.

Conclusion

- The ANZAI laser-based gating system is clinically reliable, demonstrating high accuracy, robust signal stability, and acceptable system delays for carbon-ion radiotherapy.