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Preliminary evidence of shallow expiration breath hold (SEBH) superior to deep-inspiration breath hold (DIBH) for treating abdominal cancer

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ABSTRACT

Purpose: To demonstrate whether natural-respiration breath hold (NRBH) should be used to freeze organ motion rather than deep-inspiration breath hold (DIBH) in abdominal cancer treatment, as NRBH should be more reproducible and retain organ normal size, shape, and position without forced organ compression/expansion.

Methods: The clinical free-breathing (FB) and DIBH (x2) CT images of 42 liver cancer patients were analyzed, focusing on liver changes in volume, shape, and position. A deep-learning automatic segmentation tool was applied to contour major organs, and a deformable image registration (DIR) was applied to calculate the Jacobian determinants (J) of the FB-to-DIBH deformable vector field (DVF), estimating tissue compression (J<1.0) and expansion (J>1.0). Fiducial markers were identified in fifteen patients to assess DIBH reproducibility. Statistical analysis of the comparison data was conducted to show the diversity of these measured parameters. Additionally, MRI images of six volunteers at DIBH and NEBH were acquired and analyzed under a prospective 4DMRI protocol, and the reproducibility of diaphragmatic position was assessed.

Results: Diversified liver volume, shape, and position changes were observed among the 42 patients, including wide DIBH compression (22 patients) and expansion (20 patients) distributions, while the body and lung volumes were observed to be 100% and 95%, respectively. Liver volume was unchanged (ΔV=-1.0%±1.8%) in 19, increased (ΔV=19.2%±15.1%) in 8, and decreased (ΔV=-6.4%±2.1%) in 12 patients. The liver fiducial reproducibility between DIBHs was 4.4±3.2 mm among the 15 patients. In contrast, the NRBH diaphragm reproducibility in 6 subjects was 1.7±1.5 mm at full exhalation and 1.3±1.6 mm at full inhalation within free breathing range.

Conclusion: The preliminary results demonstrate that NRBH is more reproducible and easier to achieve than DIBH, without causing diverse tissue compression/expansions that may introduce unpredictable impacts on treatment uncertainties. The NRBH appears to be a favorable solution to freeze abdominal organ motion during radiotherapy treatments.

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INTRODUCTION

- Deep-inspiration breath-hold (DIBH) is used to freeze organ motion in abdominal radiotherapy, aiming for organs at risk (OAR) sparing, similar to techniques used for lung and breast cancer (1).
- However, DIBH involves forced breathing using the diaphragm, intercostal, and abdominal muscles, which causes complex tissue deformation (2).
- It remains unclear whether DIBH provides consistent OAR volume enlargement, increased tumor-OAR separation, or better positioning reproducibility compared to free-breathing (FB).

METHODS AND MATERIALS

- A retrospective study analyzed 42 patients treated for liver or pancreatic cancer.
- Simulation computed tomography (CT) scans were acquired in FB and two repeated DIBHs.
- Deep-learning-based auto-segmentation was used to consistently contour the liver, kidneys, and lungs.
- Deformable image registration (DIR) was performed to calculate Jacobian determinants (J) to assess tissue compression (J < 1.0) or expansion (J > 1.0) from FB to DIBH, as shown in an example in figure 1.
- The study evaluated volume changes and the positioning reproducibility of the diaphragm and internal mid-liver fiducials between the two DIBHs.

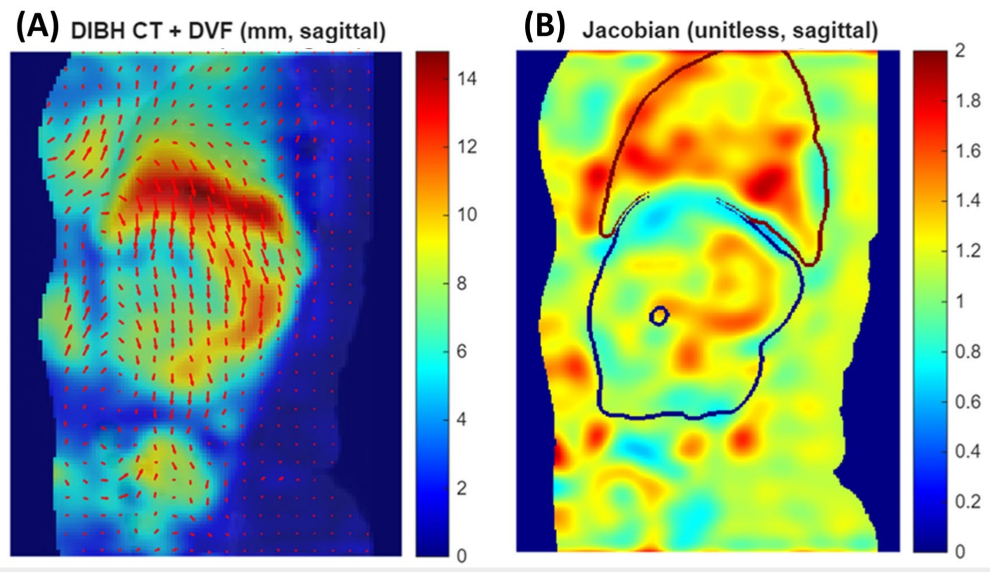

Figure 1. An example of the deformable vector field (DVR) (A) and Jacobian determinants (B) in the sagittal view of a patient. (A) Both color-coded and vector views are shown, and (B) the color-coded Jacobian [Green-Yellow-Red ($\bar{J}$ >1.0): expansion, Cyan-Blue ($\bar{J}$ <1.0): compression] and overlaid body, lung, and liver contours.

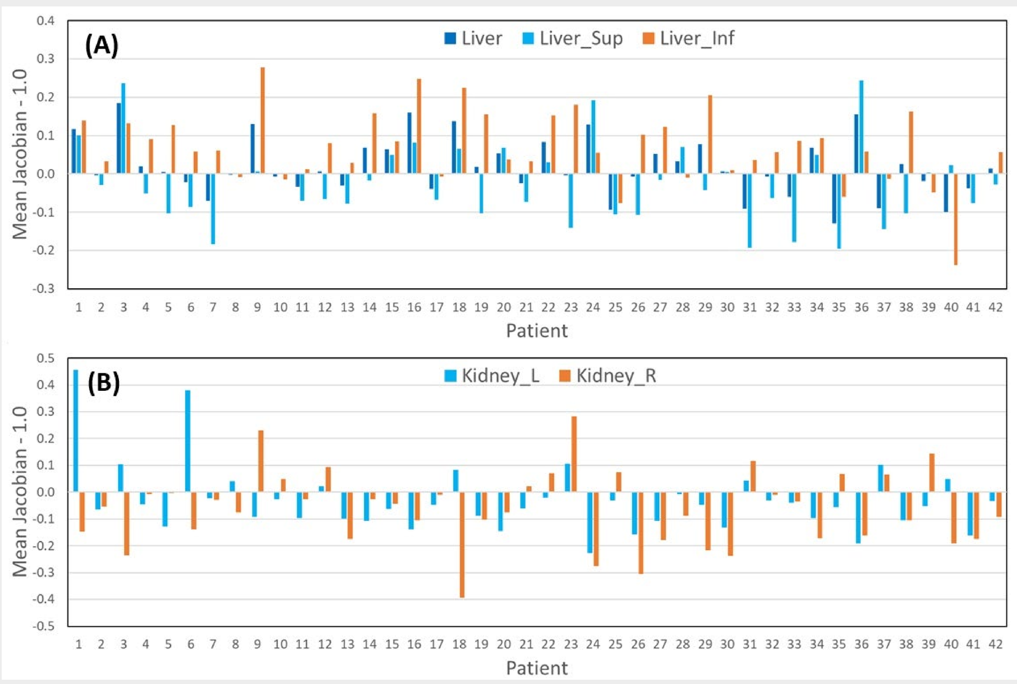

Figure 2. Diverse spread of the compression ($\bar{J}$ <1.0, below the x-axis) and expansion ($\bar{J}$ >1.0, above the x-axis) among 42 patients in their liver and its superior and inferior components (A), and both left and right kidneys (B).

RESULTS

- Tissue Deformation: From FB to DIBH, the liver compressed in 22 patients and expanded in 20 patients.
- Location Dependency: Compression is location-dependent; the superior half of the liver compressed in 26 patients, while the inferior half compressed in only 10 patients, as shown in figure 2.
- Volume Changes: Liver volume decreased by ΔV = -6.4 ± 2.1% in 14 patients, had little change in 19 patients, and increased by ΔV = 19.2 ± 15.1% in 9 patients. 25 patients experienced consistent compression in both kidneys, 4 experienced consistent expansion, and 13 experienced opposite compression/expansion between the left and right kidneys.
- Reproducibility: The positioning error for internal fiducials between DIBHs was Δd = 4.4 ± 3.2 mm, which was higher than the error for the diaphragm. The positioning error of the diaphragm between two DIBHs was Δ = 4.0 ± 6.2 mm, which reduces to Δ = 2.8 ± 2.8 mm when excluding two major outliers (Δ = 21.0 mm and Δ = 36.0 mm), as shown in figure 4.

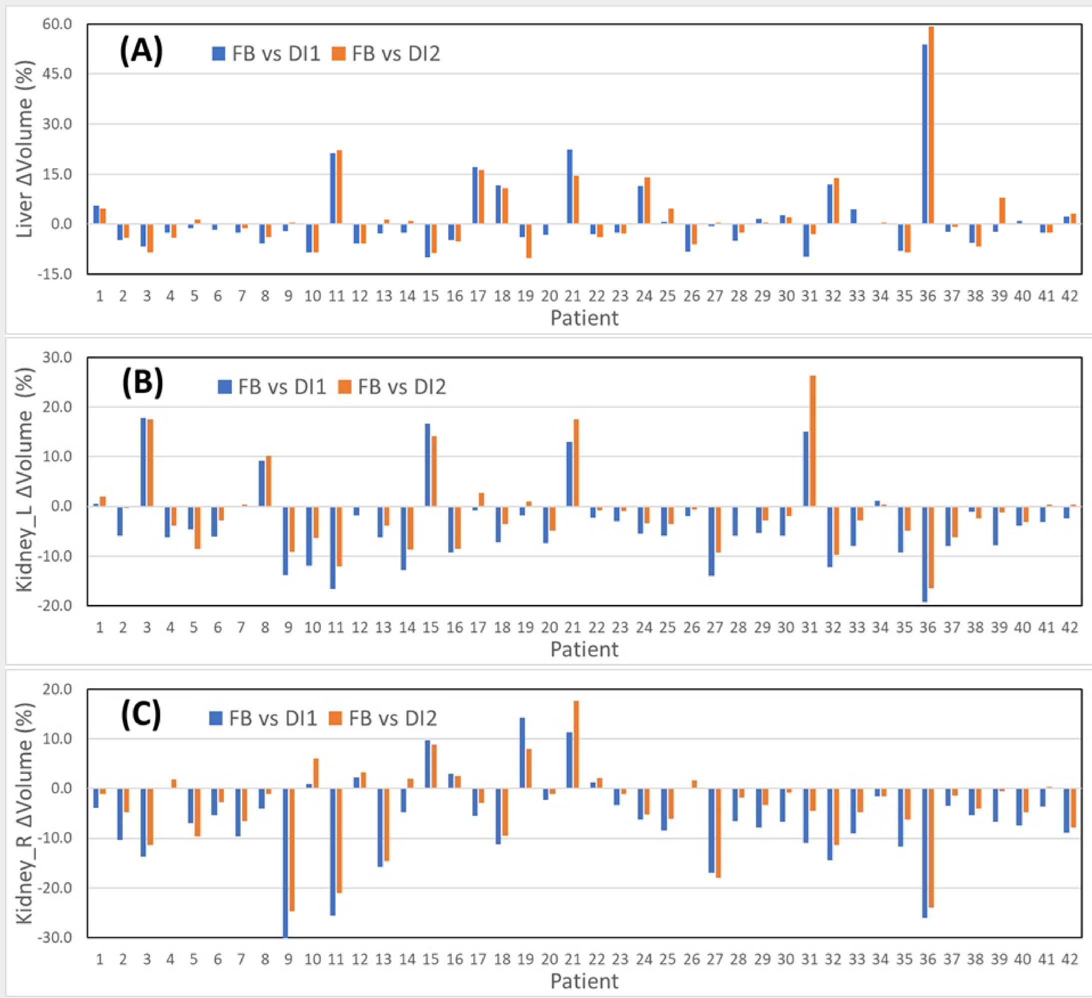

Figure 3. Relative volume changes (%) from FB to DIBHs (DI1 and DI2) in the liver (A), left kidney (B), and right kidney (C). The liver volume changes seem evenly spread among increase, little change, and decrease, but the kidney volume decreases are found in most of the patients.

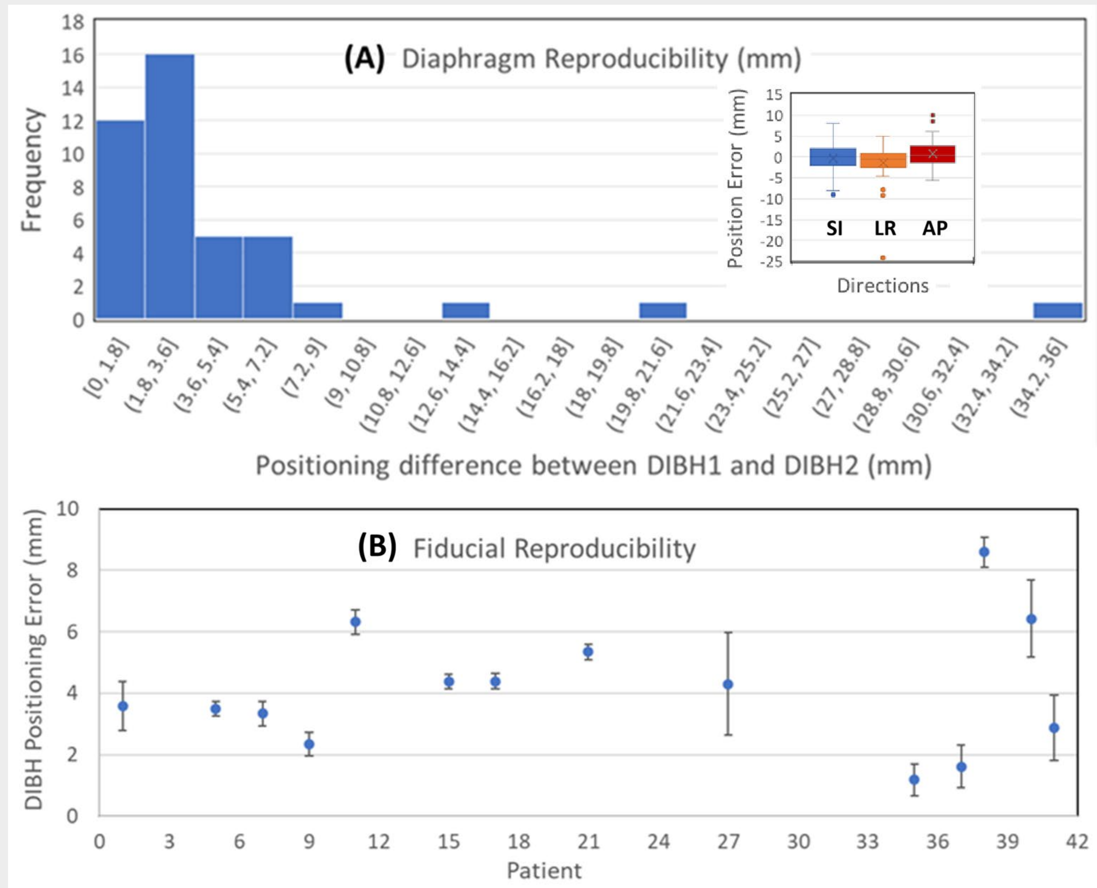

Figure 4. The absolute errors in positioning reproducibility of the liver between DIBHs: (A) the histogram of the absolute error for the diaphragm in 42 patients, and (B) the absolute distance errors of 2-3 mid-liver fiducials per patient in 14 patients. The insert in (A) is the positioning error of the liver bounding box between DIBHs in the superior-inferior (SI, Δd=-0.3±3.2mm), left-right (LR, Δ=-1.4±4.5mm), and anterior-posterior (AP, Δ=0.8±3.4mm) directions.

DISCUSSION

- DIBH forces complex, patient-specific, and location-dependent organ motions and deformations in the abdomen.
- The forceful diaphragm push likely causes body fluids (like blood and urine) to flow out of the organs, contributing to the observed volume decreases in the liver and kidneys.
- Because DIBH is an active, forced process rather than a natural passive one, it introduces higher positioning uncertainty, especially for internal targets where tissue deformation is greater than at the diaphragm.
- Contrary to expectations, DIBH does not provide consistent OAR enlargement or tumor-OAR separation for abdominal cancers. In addition, Because the motion range of DIBH is much greater than that of free breathing, DIBH may result in higher setup errors compared to a shallow-breathing breath-hold.

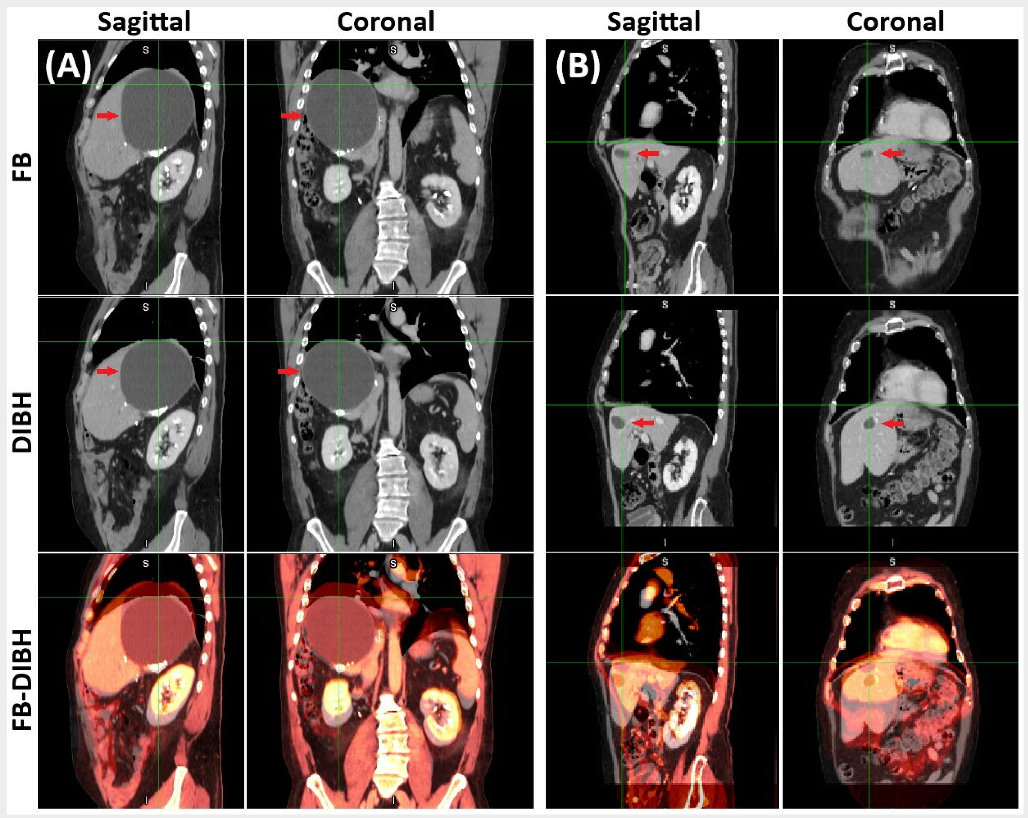

Figure 5. Demonstration of shape changes of liquid-filled dilomas (red arrows) in two cancer patients from FB (first row) to DIBH (second row). The fused FB-DIBH images are shown in the third row. (A) A large liver diloma changes its shape from a vertical oval (FB) to a circle (DIBH), showing compression in the superior-inferior (SI) direction due to diaphragmatic push, and (B) a small liver diloma changes from a flat shape to a round shape, showing expansion in the SI direction with little diaphragm displacement but substantial belly motion in the anterior-posterior direction.

CONCLUSIONS

- DIBH introduces diverse abdominal compression and expansion, unpredictable volume changes, and high setup uncertainties.
- The technique fails to provide consistent OAR sparing.
- Applying DIBH to freeze respiratory motion is unnecessary for abdominal cancer treatments; natural-respiratory breath-hold warrants further investigation as a potentially more reproducible alternative.

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