

Development of a novel airbag system of abdominal compression for reducing respiratory motion: preliminary results in healthy volunteers

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ABSTRACT

This study used cine-magnetic resonance imaging (cine-MRI) to evaluate the safety and efficacy of a novel airbag system combined with a shell-type body fixation system in reducing respiratory motion in normal volunteers. The airbag system consists of a six-sided polygon inflatable airbag, a same shape plate, a stiff air supply tube, an air-supply pump and a digital pressure load cell monitor. Piezoelectric sensors were installed in the plate to detect compression pressure load changes; pressure load data were transferred to the digital pressure load cell monitor through Bluetooth. Five volunteers underwent cine-MRI with and without airbag compression to detect differences in the respiratory motion of the organs. The volunteers' physiologic signs were stable during the experiment. The maximum inspiration pressure load was 4.48 ± 0.86 kgf (range, 4.00–6.00 kgf), while the minimum expiration pressure load was 3.69 ± 0.95 kgf (range, 2.8–5.3 kgf). Under airbag compression, the right diaphragm movement was reduced from 19.50 ± 6.43 mm to 9.60 ± 3.61 mm ($P < 0.05$) in the coronal plane and 23.12 ± 6.30 mm to 11.00 ± 3.69 mm ($P < 0.05$) in the sagittal plane. The left diaphragm, pancreas and liver in the coronal plane and the right kidney and liver in the sagittal plane also showed significant movement reduction. This novel airbag abdominal compression system was found to be safe during the experiment and successful in the reduction of internal organ respiratory motion and promises to be a convenient and efficient tool for clinical radiotherapy.

Keywords: airbag system; abdominal compression; organ motion; radiotherapy

INTRODUCTION

Radiotherapy has become more and more precision-oriented with the widespread use of modern external beam radiotherapy techniques including intensity-modulated radiotherapy (IMRT). IMRT techniques facilitate improved conformity and reduced exposure to surrounding normal tissues. For locally advanced non-small cell carcinoma (NSCLC), the use of IMRT was clearly associated with lower rates of severe pneumonitis in the NRG Oncology RTOG 0617 randomized clinical trial [1]. In addition, the National Cancer Center Network guidelines recommend IMRT or volumetric modulated arc therapy (VMAT) over 3D conformal radiotherapy for locally advanced NSCLC [2].

It has been well acknowledged that IMRT or VMAT is subject to increased uncertainties for moving targets [3, 4]. In particular, the

'interplay effect' is known as the potential deterioration in dose distribution due to the movement of targets under intensity-modulated radiation beams, resulting in either under- or overdosing of targets and/or critical organs. If the target's motion could be limited, the increase in radiation fractions would cause the interplay effect to average out such that it could be ignored dosimetrically. In other words, motion management strategies such as gating, tracking and abdominal compression are critical for reducing the dosimetric uncertainties derived from the interplay effect.

Abdominal compression is a simple way of respiratory motion control, and various abdominal compression devices have been used to control respiratory motion [5]. Typically, an adjustable compression plate is used to restrict the patient's diaphragm motion and hence the depth of breathing. The efficacy of a compression plate for reducing the

motion of tumors of the lower lung lobe and liver has been established [6]. However, there are few compression devices that can measure or monitor compression pressure before and/or during radiotherapy to help doctors and technicians keep track of changes in patients' respiratory status [7]. We have developed a novel airbag system combined with a thermoplastic shell immobilization device that allows abdominal compression and tracks patients' respiratory waveform in real-time, furthermore combined with breath-holding under compression. This study aimed to evaluate the safety and efficacy of this airbag system in normal volunteers using cine-magnetic resonance imaging (cine-MRI).

METHODS AND MATERIALS

Airbag system

We have developed a novel airbag system for abdominal compression in cooperation with Engineering System Co., Ltd (Matsumoto, Japan), to obtain effective abdominal compression and to monitor the compression pressure load during fixation with the thermoplastic body shell. The schematic view of the airbag system is shown in Fig. 1a. The system consists of a six-sided polygon inflatable airbag, a same shape fixation plate, an air supply tube, an air-supply pump and a digital pressure load cell monitor. The airbag is made of elastic nylon and polyurethane laminate. The shape of the airbag's six-sided polygon consists of a trapezoidal and a rectangle which can produce efficient abdominal compression in the epigastric. A same shape positioning fixation plate is attached to the airbag. When full of air, the airbag's maximum width was about 7 cm (Fig. 1b). This width was sufficient for abdominal compression when using the thermoplastic shell. The air supply tube connecting the air supply to the airbag was selected to be stiff enough that it would not be crushed by the shell and/or abdominal wall. Piezoelectric sensors were installed in the positioning plate to detect the compression pressure load. The data were transmitted via Bluetooth from a transmitter to a dedicated tablet terminal that could display a waveform showing the airbag's pressure load changes in real-time (Fig. 2).

Volunteers

The safety and efficacy of the airbag compression system were evaluated in healthy volunteers. Five male volunteers were included in this study. Their median age was 32 years (range 26–58 years). All volunteers gave their informed consent before the investigation began, after being provided with a detailed explanation of the scope and methods to be used. Each volunteer was asked not to arrive to the imaging sessions with a full stomach. Volunteers were instructed to breathe normally during the examination. This study was approved by the Institutional Review Board of our university.

Fixation

Each volunteer was fixed with a thermoplastic shell, and an abdominal airbag compression system was placed between the shell and the upper abdomen (Fig. 3). Pneumatic pressure load was increased up until the volunteer felt discomfort in the condition without supplemental oxygen and the data of airbag pressure load was recorded for the future imaging session. A finger pulse oximeter sensor was placed to check

the changes in pulse rate and oxygen saturation during abdominal compression for 20 min. All procedures to measure the pressure load were performed on a dockable table.

MRI

After the fixation procedure is completed, the volunteers will move to the MRI room and complete the fixation operation again outside the MRI room. The pneumatic pressure load was set according to the recorded, then measuring devices were removed from the airbag without changing the pressure load, and cine-MRI scans were performed on each volunteer. The scans were performed with a 3.0-T system (Discovery MR750w, GE Healthcare, Waukesha, WI, USA) using a single-slice segmented True-FISP cine sequence (repetition time/echo time of 85 msec/1000–1300 msec). To detect the respiratory motion of the organs, real-time cine images (5-mm slice thickness) were acquired every second for 30 seconds on the mid-liver sagittal and then coronal planes in volunteers with and without abdominal compression. An image data acquisition matrix of 320×224 was used with a rectangular field of view of 250 mm, which resulted in a pixel size of 0.98×0.98 mm.

Evaluation

After the acquisition of images from the cine datasets, the sets were compared using Image J software (National Institutes of Health, USA). We checked all 30 respiratory images of each set and picked out the maximum inhalation and exhalation images and the difference between these two images as the maximum respiratory movement. The diaphragm, liver, kidney and pancreas were identified based on the soft-tissue contours (Fig. 4a and b). The movement points recorded were the superior margins of the left diaphragm, the right diaphragm, the right kidney and the body of the pancreas in either plane and the inferior margins of the right liver lobe in the coronal plane and the left liver lobe in the sagittal plane. The difference in motion of each organ with and without abdominal compression was compared by paired t-test in SPSS 24 (SPSS Inc., Chicago, IL, USA). P values < 0.05 were considered to indicate statistically significant differences.

RESULTS

Abdominal compression under the use of body shell

It was possible to pump air into the airbag without the air supply tube being crushed by the shell and abdominal wall in all volunteers. Simultaneously, the airbag's pressure load could be measured through the piezoelectric sensor and transmitted to the display. The airbag continued to be inflated until the volunteer felt uncomfortable, at which point the pumping was stopped. The abdominal compression pressure load changed according to the respiration phase as a wave shape (Fig. 2). At the maximum inspiration, the median pressure load \pm standard deviation (SD) was 4.48 ± 0.86 kgf (range, 4.00–6.00 kgf). At the end of the expiration, the pressure load decreased to a median low of 3.69 ± 0.95 kgf (range, 2.8–5.3 kgf).

Tolerability

All volunteers underwent abdominal compression for at least 20 minutes and showed no signs of physiologic stress. Under

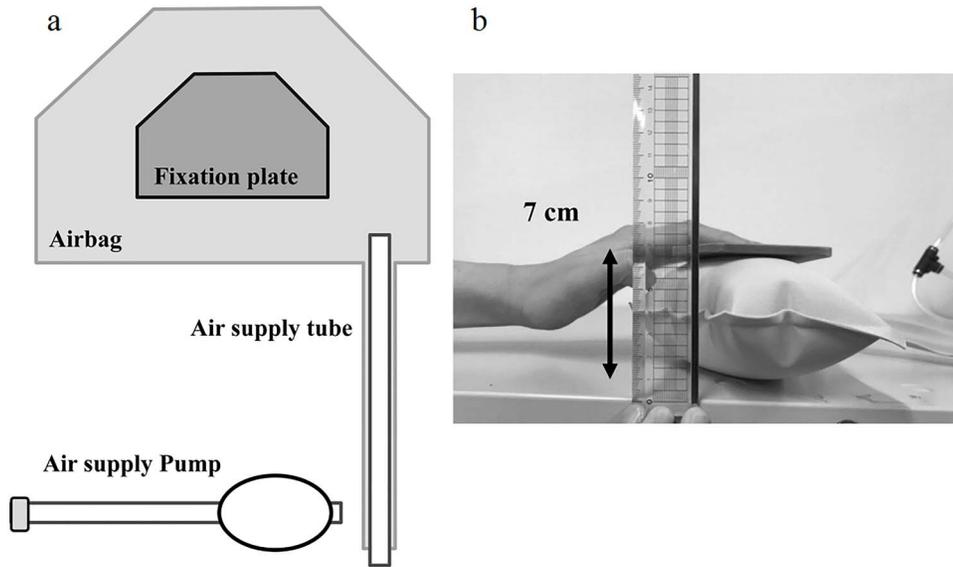


Fig. 1. Airbag system. (a) Schematic design of the airbag and pump; (b) The nylon airbag's maximum width is 7 cm.

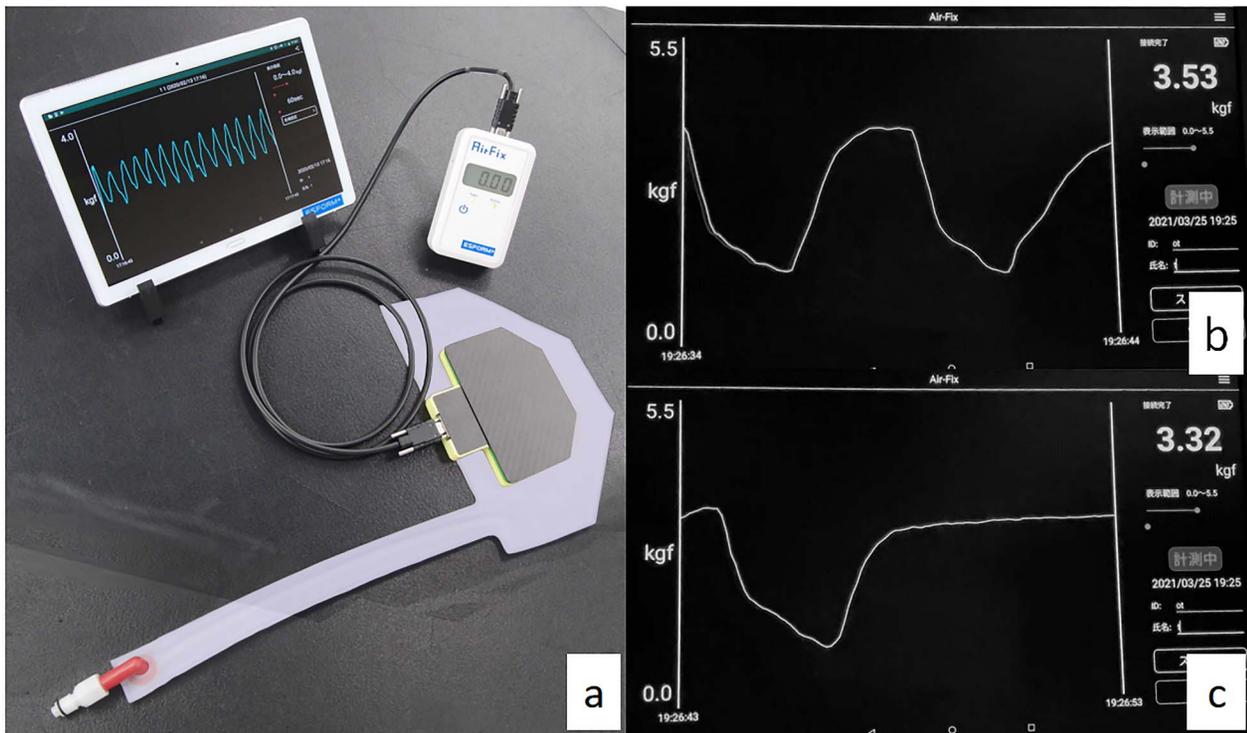


Fig. 2. Photo of the whole airbag system and screen display. (a) The device of airbag and digital monitor; (b) Waveform of free breath; (c.) Waveform of breath-holding.

continuous observation, the heart rate and peripheral oxygen saturation (SpO₂) levels were no different from those without abdominal compression (Table 3). All volunteers felt the airbag compression was acceptable.

Cine-MRI

The real-time cine-MRI sequences demonstrated that the airbag system for abdominal compression successfully suppressed the respiratory motion of abdominal organs in all five volunteers. In the

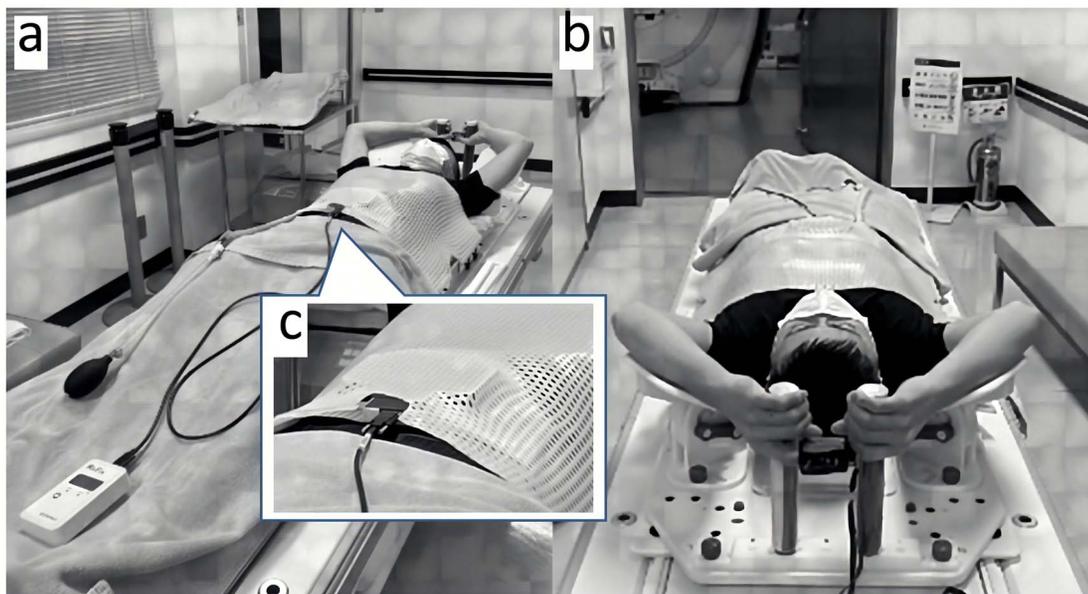


Fig. 3. Volunteer setup: a volunteer lies down in a supine position with the airbag compression system. (a) Inferior-superior photo of volunteer; (b) Superior-inferior photo of volunteer; (c.) Detail photo of airbag and thermoplastic shell on abdomen.

Table 1. Internal organ movement with and without airbag compression

Plane	Organ	w /AC vs w/o AC Mean \pm SD(mm)(P value)
Coronal Plane	Right Diaphragm	9.60 \pm 3.61 vs 19.50 \pm 6.43 (0.002)
	Left Diaphragm	10.16 \pm 4.12 vs 16.65 \pm 5.18(0.001)
	Pancreas	9.67 \pm 2.89 vs 14.52 \pm 3.27(0.014)
	Liver	9.31 \pm 3.03 vs 20.54 \pm 6.65(0.016)
Sagittal Plane	Right Diaphragm	11.00 \pm 3.69 vs 23.12 \pm 6.30(0.003)
	Right kidney	8.63 \pm 1.49 vs 15.27 \pm 5.12(0.029)
	Liver	9.37 \pm 3.30 vs 26.25 \pm 10.60(0.010)

SD, standard deviation; w/o AC, without airbag compression; w /AC, with airbag compression

coronal plane, the right diaphragm, left diaphragm, pancreas and liver showed significantly less movement with airbag compression than without it (Table 1, Fig. 5a and b). A similar result appeared in the sagittal plane: namely, the right diaphragm, right kidney and liver motion were reduced with airbag compression compared to that without compression. The maximum movement reduction of the right diaphragm in the coronal and sagittal planes was 6.63–14.37 mm and 7.51–18.13 mm (Table 2).

DISCUSSION

In Japan, IMRT for lung tumors used to be performed mainly by helical tomotherapy, an IMRT-dedicated system, but recently, general linear accelerators using conventional fractionation regimens have been also applied to IMRT or VMAT for lung tumors as well as stereotactic radiation therapy. Even though IMRT has been found to be a good technique, numerous limitations have been identified for moving targets. The investigators at the Princess Margaret Hospital stated that IMRT

for gastric cancer was associated with reduced dose homogeneity and the potential for high-dose spots in the small bowel. They cautioned that there is a need for detailed information regarding organ motion in the upper abdomen and that implementation of breath-hold or gating techniques may be necessary prior to the adoption of IMRT in routine clinical practice [8].

Human breathing movements include chest breathing and abdominal breathing. These two breathing modes are always mixed, with approximately 2/3 of lung capacity deriving from the movement of the diaphragm (abdominal breathing) and 1/3 from the movement of the rib (chest breathing). In this study, a more comfortable and viewable abdominal breathing compression method for reducing internal organ motion was investigated. The use of our novel airbag system resulted in meaningful reduction of right diaphragm movement: from 19.50 \pm 6.43 mm without compression to 9.60 \pm 3.61 mm with compression in the coronal plane and from 23.12 \pm 6.30 mm to 11.00 \pm 3.69 mm in the sagittal plane. The maximum right diaphragm movement reduction in the coronal and sagittal planes was 14.37 mm

Table 2. Movement of diaphragm with and without airbag compression

Patient No.	Coronal Plane (mm)		Sagittal Plane (mm)	
	w /AC vs w/o AC	Reduction of displacement	w /AC vs w/o AC	Reduction of displacement
1	9.30 vs 17.27	7.97	13.12 vs 31.25	18.13
2	7.97 vs 17.94	9.97	6.88 vs 21.25	14.37
3	9.14 vs 19.69	10.55	9.37 vs 16.88	7.51
4	15.63 vs 30	14.37	16.25 vs 28.12	11.87
5	5.98 vs 12.61	6.63	9.37 vs 18.12	8.75

w/o AC, without airbag compression; w /AC, with airbag compression

Table 3. Physiologic signs before airbag compression and after airbag compression

Volunteer No.	Heart rate (beat per minute)		Peripheral oxygen saturation (%)	
	Before airbag compression	After airbag compression	Before airbag compression	After airbag compression
1	60	64	97	98
2	65	67	97	98
3	68	70	99	99
4	72	76	99	99
5	86	73	97	99

and 18.13 mm, respectively. Significant movement reduction was also seen in the left diaphragm, pancreas and liver in the coronal plane and the right kidney and liver in the sagittal plane. Here we just evaluated respiratory motion in the superior–inferior (SI) direction on the cine-MRI scan of volunteers. The use of a body-fixed shell restricts chest motion in the right–left (RL) and anterior–posterior (AP) directions. Strydhorst et al. reported that the thermoplastic shell can effectively reduce respiratory motion of the chest wall, especially for in the AP direction to less than 2 mm [9]. Several researchers reported that by using the thermoplastic shell fixation the mean lesion movement in the RL and AP directions was less than 2.5 mm [10, 11]. These results indicate that our new airbag abdominal compression technique detailed above provides meaningful benefits in terms of reduction of internal organ motion while monitoring pressure load generated at the abdomen at the same time.

The volunteers could easily tolerate the pressure load generated by the airbag. At the same time, the airbag's pressure load was displayed on the monitor and recorded. All volunteers could also hold their breath under airbag pressuring, whether it was inhalation or exhalation breath-holding (Fig. 2). This technology will be used to monitor the breathing rate of radiotherapy patients during abdominal compression, providing physicians and technicians with visual and quantifiable data on breathing during radiotherapy. Then, one of the merits of monitoring the airbag's pressure is to detect the status of breath-holding (Fig. 2c), which will be evaluated in the near future. Previous studies have only combined thermoplastic shells with abdominal compression or thermoplastic shells with breath-hold, this system is the first to integrate all three. We have combined thermoplastic shell, abdominal compression and breath-hold technology in the hope of obtaining maximum breath movement control in the future.

This present study had some limitations including the relatively small number of volunteers. We evaluated the 30 respiratory images acquired in 30 seconds and choose the maximum inhalation and exhalation phase. Because of the limitation of our MRI imaging, it is very difficult to track respiration synchronously. Another limitation is we only studied the intrafraction respiratory motion control. It has been reported that abdominal compression may increase interfraction variation in tumor position and affect the local control of lung lesion stereotactic body radiation therapy (SBRT) [12, 13], one reason for which may be interfraction breathing unstable from abdominal compression. To address these issues, in the future we will examine the intrafraction and interfraction relationship of pressure load data and respiratory motion (organs and tumor lesions) on 4D-CT scans to assure the tracking effect of this system.

In subjects with healthy lungs, the abdominal compression-induced ventilation volume decrease can be compensated for by an increased respiratory rate. However, it should be noted that it is necessary to monitor oxygen saturation in patients with pulmonary dysfunction. Furthermore, this system is contraindicated in patients with huge liver tumors or abdominal aneurysms. Caution should be also taken in the cases of abdominal wall hernias, inguinal hernias and other conditions that contraindicate the application of high abdominal pressure load.

CONCLUSION

IMRT for lung cancer is expected to be more widespread in Japan in the future. To ensure dose conformity, it would be clinically beneficial to have a system that facilitates convenient and efficient abdominal compression during lung IMRT. We have developed an airbag system with a body-fixed shell and an abdominal airbag for this purpose, which

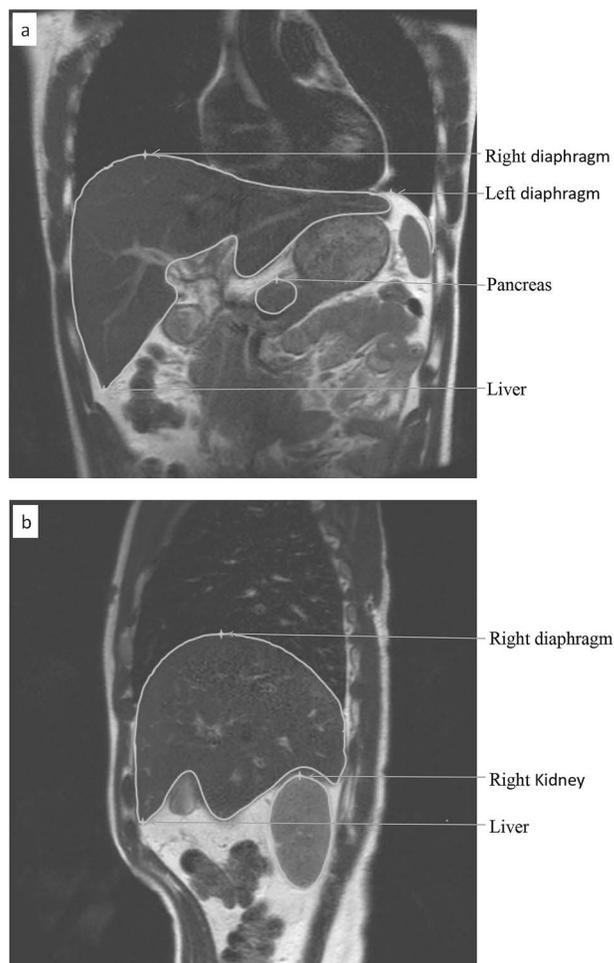


Fig. 4. Example of MRI scan generation results. (a) Coronal scan and measurement point of right diaphragm, left diaphragm, pancreas and liver; (b) Sagittal scan and measurement point of right diaphragm, right kidney and liver.

demonstrated significant organ motion reduction and high tolerability in healthy volunteers while monitoring respiratory motion waveform. In the future, we plan to verify the actual clinical use of this system using both linear accelerators and tomotherapy.

SUPPLEMENTARY MATERIAL

Supplementary material is available at *RADRES Journal* online.

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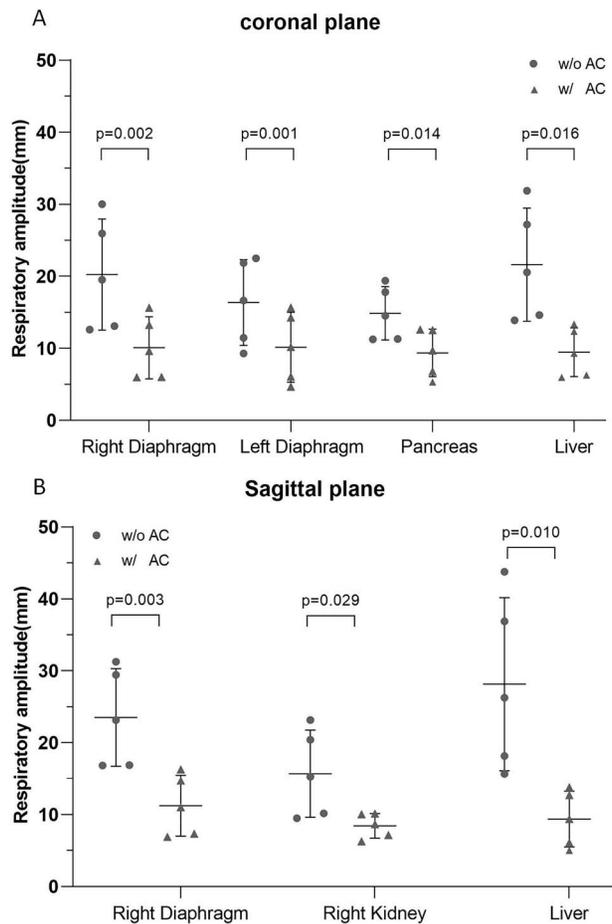


Fig. 5. The internal organ movement difference without and with airbag compression. (a) Right diaphragm, left diaphragm, pancreas and liver in coronal plane; (b) Right diaphragm, right kidney and liver in sagittal plane.

CONFLICT OF INTEREST

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

REFERENCES

1. Chun SG, Hu C, Choy H et al. Impact of intensity-modulated radiation therapy technique for locally advanced non-small-cell lung cancer: a secondary analysis of the NRG oncology RTOG 0617 randomized clinical trial. *J Clin Oncol* 2017;35:56.
2. National Comprehensive Cancer Network. *Non-small cell lung cancer* (version 7.2021) (29 October 2021, date last accessed).
3. Edvardsson A, Nordström F, Ceberg C et al. Motion induced interplay effects for VMAT radiotherapy. *Phys Med Biol* 2018;63. <https://doi.org/10.1088/1361-6560/aab957>.
4. Inoue T, Widder J, van Dijk LV et al. Limited impact of setup and range uncertainties, breathing motion, and interplay effects

- in robustly optimized intensity modulated proton therapy for stage III non-small cell lung cancer. *Int J Radiat Oncol Biol Phys* 2016;96:661–9.
5. Van Gelder R, Wong S, Le A et al. Experience with an abdominal compression band for radiotherapy of upper abdominal tumours. *J Med Rad Sci* 2018;65:48–54.
 6. Heinzerling JH, Anderson JF, Papiez L et al. Four-dimensional computed tomography scan analysis of tumor and organ motion at varying levels of abdominal compression during stereotactic treatment of lung and liver. *Int J Radiat Oncol Biol Phys* 2008;70:1571–8.
 7. Raphael JC, Varghese MK, Gopu PG et al. Effectiveness of abdominal compression in reducing internal target motion during conformal radiotherapy for carcinoma stomach—A pilot study. *Indian J Cancer* 2018;55:382–389. <https://doi.org/10.4103/ijc.IJC>.
 8. Ringash J, Perkins G, Brierley J et al. IMRT for adjuvant radiation in gastric cancer: a preferred plan? *Int J Radiat Oncol Biol Phys* 2005;63:732–8.
 9. Strydhorst J H, Caudrelier J M, Clark B G et al. Evaluation of a thermoplastic immobilization system for breast and chest wall radiation therapy[J]. *Med Dosim*, 2011;36:81–84.
 10. Shimohigashi Y, Toya R, Saito T et al. Tumor motion changes in stereotactic body radiotherapy for liver tumors: an evaluation based on four-dimensional cone-beam computed tomography and fiducial markers. *Radiat Oncol* 2017;12:61. <https://doi.org/10.1186/s13014-017-0799-7>.
 11. Jiang B, Dai J, Zhang Y et al. Comparison of setup error using different reference images: a phantom and lung cancer patients study. *Med Dosim* 2012;37:47–52.
 12. Mampuya WA, Matsuo Y, Ueki N et al. The impact of abdominal compression on outcome in patients treated with stereotactic body radiotherapy for primary lung cancer. *J Radiat Res* 2014;55:934–9.
 13. Mampuya WA, Nakamura M, Matsuo Y et al. Interfraction variation in lung tumor position with abdominal compression during stereotactic body radiotherapy[J]. *Med Phys* 2013;40:91718. <https://doi.org/10.1118/1.4819940>.