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Scientific Article

Audiovisual biofeedback guided breath-hold improves lung tumor position reproducibility and volume consistency

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Abstract

Purpose: Respiratory variation can increase the variability of tumor position and volume, accounting for larger treatment margins and longer treatment times. Audiovisual biofeedback as a breath-hold technique could be used to improve the reproducibility of lung tumor positions at inhalation and exhalation for the radiation therapy of mobile lung tumors. This study aimed to assess the impact of audiovisual biofeedback breath-hold (AVBH) on interfraction lung tumor position reproducibility and volume consistency for respiratory-gated lung cancer radiation therapy.

Methods: Lung tumor position and volume were investigated in 9 patients with lung cancer who underwent a breath-hold training session with AVBH before 2 magnetic resonance imaging (MRI) sessions. During the first MRI session (before treatment), inhalation and exhalation breath-hold 3-dimensional MRI scans with conventional breath-hold (CBH) using audio instructions alone and AVBH were acquired. The second MRI session (midtreatment) was repeated within 6 weeks after the first session. Gross tumor volumes (GTVs) were contoured on each dataset. CBH and AVBH were compared in terms of tumor position reproducibility as assessed by GTV centroid position

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Conflicts of interest: Paul Keall is an inventor on U.S. patent 7,955,270, which is related to audiovisual biofeedback. Paul Keall, Sean Pollock, Ricky O'Brien, and Kuldeep Makhija are founders of a company (Respiratory Innovations) that aims to disseminate a cost-effective breathing guidance solution.

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and position range (defined as the distance of GTV centroid position between inhalation and exhalation) and tumor volume consistency as assessed by GTV between inhalation and exhalation.
Results: Compared with CBH, AVBH improved the reproducibility of interfraction GTV centroid position by 46% ($P = .009$) from 8.8 mm to 4.8 mm and GTV position range by 69% ($P = .052$) from 7.4 mm to 2.3 mm. Compared with CBH, AVBH also improved the consistency of intrafraction GTVs by 70% ($P = .023$) from 7.8 cm^3 to 2.5 cm^3.
Conclusions: This study demonstrated that audiovisual biofeedback can be used to improve the reproducibility and consistency of breath-hold lung tumor position and volume, respectively. These results may provide a pathway to achieve more accurate lung cancer radiation treatment in addition to improving various medical imaging and treatments by using breath-hold procedures.
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Introduction

Breath-hold techniques are frequently used to immobilize respiratory-induced tumor motion, leading to the reduction of respiratory-related motion artifacts in medical imaging and clinically meaningful tumor positions and shapes in respiratory-gated radiation treatment.[1-8] In addition, the immobilization of lung tumors[1] can reduce phase or time shift between surrogates (ie, abdomen, chest, and diaphragm) and tumors[9] and system latency between tumor positioning and gating.[10] Immobilizing the tumor position is advantageous in reducing treatment margins and treatment delivery time.[6,11]

Several breath-hold strategies have been studied and practiced to maintain the same level of breathing in repeated breath-holds. Deep inspiration breath-hold has improved the reproducibility of intra- and interfraction target positions compared with free-breathing.[2,3] Conventional breath-hold (inhalation and exhalation positions of free breathing) using the audio instructions of a computed tomography (CT) scanner (automated “breathe in”, “breathe out”, and “hold your breath” commands) reduced the variation of exhalation diaphragm positions compared with free-breathing.[1] An active breathing coordinator (ABC) forcibly suspends patient breathing without automated verbal or audio instruction at predetermined positions of lung volume. ABC has been demonstrated to improve intrafraction tumor position reproducibility but still needs to improve a large variation of interfraction tumor positions >5 mm.[4,5] A quasi-breath-hold using consecutive short breath-holds (3, 5, or 7 seconds) has demonstrated equivalent or less motion variation while improving breath-hold efficiency.[7,8] Visual biofeedback techniques have also reduced the uncertainty of target position by improving the reproducibility of abdominal and chest wall and pancreatic tumor positions using voluntary breath-hold techniques.[3,7,8,12,13] However, lung tumor position reproducibility and volume consistency using audiovisual guidance for inhalation and exhalation breath-holds for precise lung cancer radiation therapy has not been studied.

Audiovisual (AV) biofeedback[14-20] is an interactive breathing guidance system that has been employed to improve inhalation and exhalation breath-hold reproducibility.[21] AV biofeedback consists of (1) monitoring the respiratory motion of patients’ abdomens using a real-time position management (RPM) system (Varian Medical Systems, Palo Alto, CA) to form a personalized and customized guiding wave, (2) displaying their present breathing position and the guiding wave on a visual screen that patients can see, and (3) allowing patients to control their breathing by following the guiding wave and holding their breath at the inhalation and exhalation positions of the guiding wave when instructed.

Previous AV breath-hold (AVBH) results from healthy volunteers have demonstrated that the reproducibility of intrafractional abdominal positions was improved during inhalation and exhalation breath-holds and intrafraction image intensity variation was reduced across multiple breath-holds.[21] However, previous AVBH investigations recruited healthy volunteers, so the impact of AVBH on tumor position and volume for patients with lung cancer has not been examined.

In this study, we introduced a novel approach for AVBH for patients with lung cancer that involved a breath-hold training session to obtain a customized guiding wave for each patient and used the inhalation and exhalation breath-hold positions over 2 MRI sessions.[22] This study was the first to investigate the impact of AVBH on lung tumor position reproducibility and volume consistency and used the direct measurement of gross tumor volume (GTV) from breath-hold high-resolution 3-dimensional MRI scans.

Methods and materials

Patients

Eleven patients who underwent external beam radiation therapy from April 2013 to June 2015 consented to enrollment in an ethics-approved protocol. The patients

Table 1 Patient and disease characteristics

Patient No.	Sex (F/M)	Age (y)	Height (cm)	Weight (kg)	Stage	PS	Location	Glasses	Gy/Fx	Hearing Aid	Breath-hold (s)
1	F	62	170	80	IIIA	0	RUL	Yes	60/30	No	16
2	F	61	158	72	IIA	1	RUL	Yes	60/30	No	16
3	F	66	165	66	IIIB	1	LUL	Yes	40/15	No	16
4	F	26	170	70	IIIA	1	LUL	No	50/20	No	16
5	M	72	175	114	IIA	1	RLL	No	60/30	No	22
6	M	54	170	84	IIIA	0	LUL	No	60/30	No	16
7	M	55	180	69	IIIB	1	RUL	No	60/30	No	17
8	M	79	168	80	IB	1	RUL	No	60/30	Yes	16
9	M	68	160	76	IIIA	1	LUL	Yes	50/20	No	17

Fx, fraction; LUL, left upper lobe; PS, Eastern Cooperative Oncology Group performance status; RLL, right lower lobe; RUL, right upper lobe.

met the following eligibility criteria: 1) had non-small-cell and small-cell stage I-IIIB lung cancer of any histology to be treated using radiation treatment; 2) were ≥18 years old; 3) were any sex or ethnicity; 4) were not pregnant or mentally impaired; and 5) had no surgical clips, surgery metal-ware, or pacemakers. The study comprised a breath-hold training session and 2 MRI sessions on different dates (pre- and midtreatment). The breath-hold training session was scheduled on the same day as the first MRI session, and the second MRI session occurred within 3 to 6 weeks later, depending on the duration of the radiation treatment. The 9 patients with lung cancer who completed the training and both MRI sessions are described in Table 1. Two patients were excluded because they withdrew from the study before their second MRI session. Patients received a prescription dose of 40 to 60 Gy for primary lung cancer or metastatic lung cancer at the isocenter in 15 to 30 fractions.

AVBH training session

Before the MRI sessions, individual patients in the head-first supine position participated in a breath-hold training session (no imaging performed) to allow them to become comfortable with AVBH guidance. The breath-hold training session included the acquisition of a breathing wave (ie, an average of 10 respiratory cycles) and inhalation and exhalation breath-hold practices. Once inhalation and exhalation breath-hold positions were determined at the peak and trough of the guiding wave, patients were guided by AVBH and practiced breath-holds (first inhalation and second exhalation), as shown in Figure 1 (red line). Inhalation and exhalation breath-hold practices were repeated 2 to 3 times with verbal instruction from radiographers for approximately 15 minutes until the patients were comfortable with AVBH. After each breath-hold practice and on the basis of a consult with the patient, the inhalation and exhalation positions were set for the subsequent MRI sessions.

The workflow of AVBH is as follows: (1) monitor breathing motion of patient's abdomen using RPM and build a guiding wave (calculated from the average of 10 breathing cycles in a Fourier Series fit)[17] shown in Figure 1 (blue line); (2) display real-time breathing position and the guiding wave on the patient's screen; (3) patients control their breathing to follow the guiding wave; and (4) patients hold their breath at inhalation and exhalation breath-hold positions by following the verbal instructions of radiographers.

For the MRI setup of AVBH, patients were positioned with an optical marker block on their abdomen to monitor their breathing motion. Visual display goggles were used for an AVBH training session, and a head-mounted mirror overlooking an MRI-compatible projection screen was used (Fig 1) for both MRI sessions. The gray marker block on the screen represented the patients' actual breathing position, and the red line indicated the desired inhalation and exhalation breath-hold positions. To minimize the change of inhalation and exhalation breath-hold positions across a training session and 2 MRI sessions, the RPM camera was placed on the patient's abdomen at the same height from the ground and distance from the RPM marker, and the visual guidance of inhalation and exhalation was formed with individual breathing patterns for a consistent displacement (ie, amplitude in millimeters).

Magnetic resonance imaging with AVBH

Breath-hold 3-dimensional MRI scans were acquired with a 3 Tesla MRI (Skyra, Siemens Healthcare, Erlangen, Germany) and in the head-first supine position. For the breath-hold 3-dimensional MRI scans, a volumetric interpolated breath-hold examination of a magnetic resonance pulse sequence was used to acquire 160 slices per 3-dimensional MRI scan with individual breath-hold durations between 16 and 22 seconds (Table 1). Typical MRI scan parameters were repetition time (TR)/echo time (TE) = 2.24/0.88 ms, bandwidth = 710 Hz, flip angle = 9°, field of view = 368 × 380 mm^2, slice thickness = 1.2 mm, pixel size = 1.2 × 1.2 mm^2, and image matrix = 310 × 320. For patient 5 (Table 1), TR/TE = 2.14/0.83 ms,

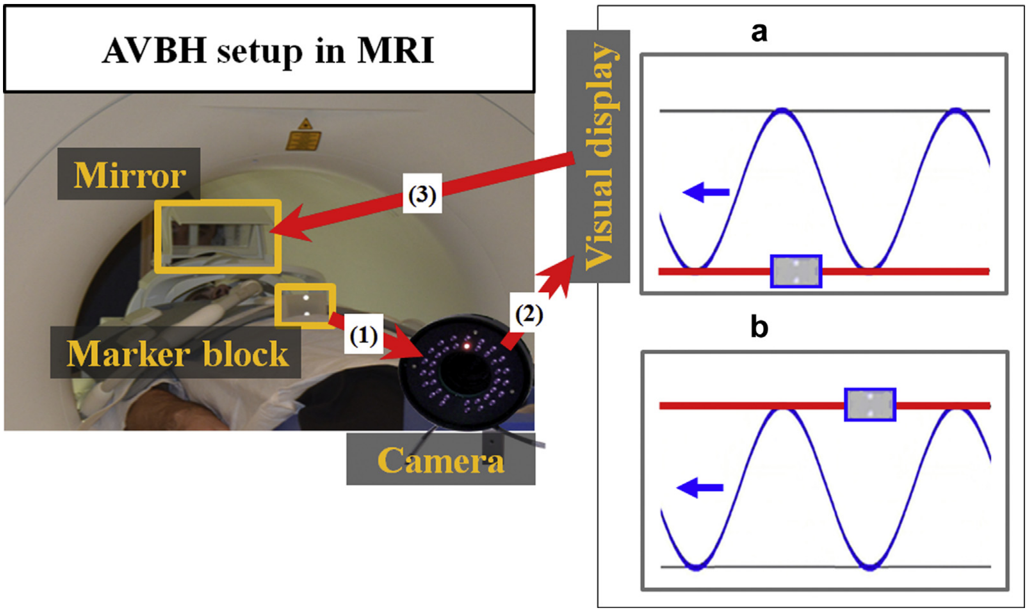

Figure 1 The MRI setup of AVBH. (a) Exhalation and (b) inhalation breath-hold positions (red line) of the guiding wave (blue line) for two MRI sessions.

field of view = 435 × 450 mm^2, and pixel size = 1.4 × 1.4 mm^2 due to the large field of view that was required.

In the first MRI session (before treatment), 3-dimensional inhalation and exhalation breath-hold MRI scans with (1) CBH and (2) AVBH were acquired. The second MRI session (midtreatment) was repeated within 6 weeks of the first MRI session. Audio instructions (MRI; 3T Siemens Skyra) in CBH (ie, "breathe in", "breathe out", and "hold your breath" or "breathe out", "breathe in", and "hold your breath") and verbal instructions (from radiographers) in AVBH were used. For the verbal instructions, radiographers continuously monitored the patient's breathing trace on an MRI-compatible projection screen that displayed the real-time breathing position and guiding wave. The radiographers verbally provided (1) the exhalation breath-hold instructions once the patient's breath reached the inhalation position ("breathe out", "breathe in", and "breathe out and hold your breath") and (2) the inhalation breath-hold instructions once the patient's breathing reached the exhalation position ("breathe in", "breathe out", and "breathe in and hold your breath").

Eight datasets per patient (2 image datasets [inhalation and exhalation] × 2 breath-hold types [CBH and AVBH]) were obtained from 2 MRI sessions. In total, 72 breath-hold datasets were obtained from 9 patients with lung cancer.

Lung tumor delineation

The GTV of 72 breath-hold datasets was delineated by a radiation oncologist using the Eclipse Treatment Planning System (Varian Medical Systems, Palo Alto, CA). Rigid registration based on spinal vertebral anatomy was performed between 2 MRI sessions. In this study, 2 rigid registrations were included per patient: (1) the exhalation dataset of the first MRI session with CBH to the exhalation dataset of the second MRI session with CBH and (2) the exhalation dataset of the first MRI session with AVBH to the exhalation dataset of the second breath-hold MRI session with AVBH. During the rigid registration, the first and second datasets were used for the fixed and moving datasets, respectively. Exhalation datasets were used for the rigid registrations because they were obtained at the beginning of the breath-hold image acquisition with CBH and AVBH.

Breath-hold lung tumor position and volume

The impact of AVBH on breath-hold lung tumors, compared with FB, was investigated using (1) interfraction tumor position reproducibility across the first (S1) and second (S2) MRI sessions in the GTV centroid position and GTV position range, defined as the distance between inhalation and exhalation GTV centroids; and (2) intrafraction tumor volume consistency between inhalation and exhalation GTVs in each MRI session was also investigated. For example, tumor positon and volume can be consistent when breath-hold is performed at the same respiratory level. The interfraction tumor position reproducibility along each direction (left–right [LR], anterior–posterior [AP], and superior–inferior [SI]) was calculated with the following equations and in 3-

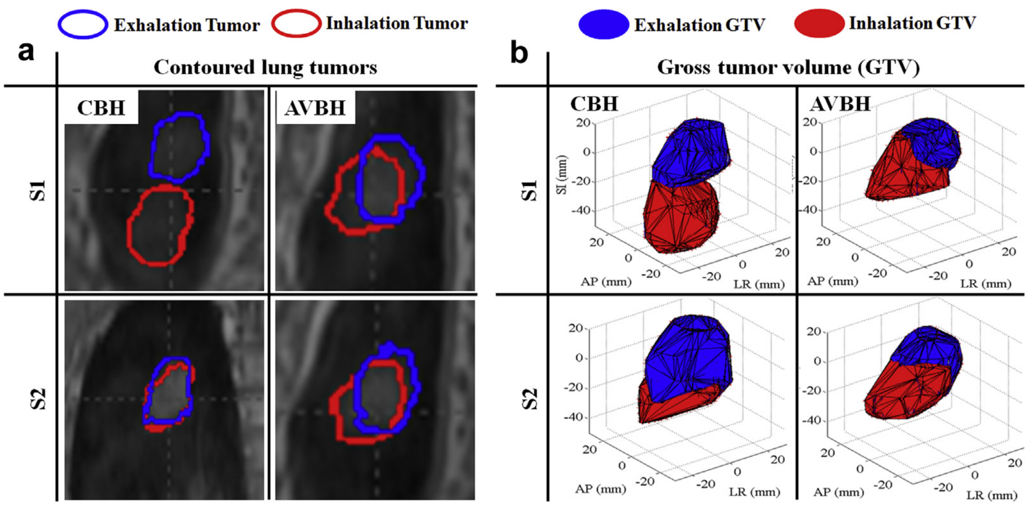

Figure 2 Lung tumors during CBH (top) and AVBH (bottom). (a) Contoured inhalation and exhalation breath-hold lung tumors, (b) corresponding inhalation and exhalation GTVs. S1: the first MRI session, S2: the second MRI session.

dimensional vector with 3-dimensional Euclidean distance:

$$The\ difference\ of\ GTV\ centroid\ position = GTV^{S1}_{CENTROID} - GTV^{S2}_{CENTROID}$$

For the calculation of intrafraction tumor volume consistency, the following equation was used:

$$The\ difference\ of\ GTV = {}_{INHALE}GTV - {}_{EXHALE}GTV$$

Quantitative statistical comparisons between CBH and AVBH were determined from the root mean square (RMS) along each direction and the 3-dimensional vector using the Wilcoxon signed rank test to evaluate the interfraction GTV centroid position and position range reproducibility and intrafraction GTV consistency.

Results

Figure 2 shows images of inhalation and exhalation lung tumors taken during breath-hold with CBH and AVBH across 2 MRI sessions.

In Table 2, compared with CBH, the reproducibility of interfraction GTV centroid position with AVBH was improved by 46% (P = .009) from 8.8 mm (the RMS average of each direction) to 4.8 mm and by 45% (P = .001) from 15.2 mm to 8.3 mm (the RMS of the 3-dimensional vector). A difference in GTV centroid position >10 mm was seen in 7 of 18 GTVs across 5 patients with CBH and only 2 of 18 GTVs with AVBH in 1 patient. For both CBH and AVBH, the largest difference in GTV centroid position was found in the SI, followed by the AP and LR. In terms of inhalation and exhalation GTV centroid positions, the difference in the exhalation GTV centroid position with CBH was 12.8 mm (the RMS average of each direction); it was 17.3 mm for the inhalation GTV centroid position. For AVBH, the differences in exhalation and inhalation GTV centroid positions were 8.3 mm and 8.2 mm, respectively, which corresponds to an improvement in reproducibility of 35% and 52%, respectively, compared with CBH.

In Table 3, compared with CBH, the reproducibility of the interfraction GTV position range with AVBH was improved by 69% (P = .052) from 7.4 mm (the RMS average of each direction) to 2.3 mm and by 68% (P = .289) from 12.8 mm to 4.0 mm (the RMS of 3-dimensional vector). The difference in GTV position range varied between −15.1 mm and 21.9 mm with CBH, and it was between −5.4 mm and 2.9 mm for AVBH. The GTV position range in the AP had the smallest difference for AVBH but was 4 times smaller than the AP position range with CBH. The difference in GTV position range was smaller with AVBH compared with CBH except for patients 4 and 9, for whom the position range was comparable or slightly larger.

In Table 4, compared with CBH, the consistency of intrafraction GTV with AVBH improved by 70% (P = .023) from 7.8 cm^3 (CBH) to 2.5 cm^3 (AVBH). Inhalation GTV with CBH was 4.5 cm^3 larger than exhalation GTV (57.9 cm^3 and 62.4 cm^3, respectively), but inhalation and exhalation GTVs with AVBH in RMS were almost identical at 60.8 cm^3 and 60.7 cm^3, respectively. In addition, the decrease in GTV between pre- and midtreatment was similarly noted, with 20.4 cm^3 (P = .001) in CBH and 20.3 cm^3 (P < .001) in AVBH. However, inhalation and exhalation GTVs were only identical in *S1* (69.7 cm^3 and 69.3 cm^3) and *S2* (50.3 cm^3 and 50.4 cm^3) with AVBH but varied in *S1* (65.2 cm^3 and 71.9 cm^3) and *S2* (49.5 cm^3 and 51.2 cm^3) with CBH.

Table 2 Difference in GTV centroid position with CBH and AVBH from 72 breath-hold datasets across 2 MRI sessions

Patient No.	The GTV centroid position difference (mm), $GTV^{S1}_{CENTROID} - GTV^{S2}_{CENTROID}$								
	CBH					AVBH			
	BHP	LR	AP	SI	3-dimensional Vector	LR	AP	SI	3-dimensional Vector
1	E	−3.5	1.4	−3.3	5.0	2.5	4.8	3.9	6.6
	I	−1.5	14.0	11.1	18.0	2.3	4.9	5.1	7.4
2	E	1.3	−3.2	−6.9	7.7	3.7	2.6	−5.0	6.7
	I	0.5	−2.7	−5.1	5.8	0.7	3.2	−5.7	6.6
3	E	−9.7	−2.6	9.9	14.1	−3.1	−4.7	9.5	11.1
	I	−7.5	−11.4	6.2	15.0	−3.2	−3.4	6.4	7.9
4	E	−2.7	0.0	3.7	4.6	−1.0	−0.6	7.2	7.3
	I	−2.7	5.6	6.6	9.0	−1.4	−0.6	1.9	2.5
5	E	5.9	−0.8	−6.2	8.6	2.7	−1.8	−0.2	3.3
	I	0.6	−4.2	−27.8	28.1	1.8	−1.2	1.1	2.5
6	E	6.0	3.0	7.4	10.0	5.0	4.2	2.7	7.1
	I	10.3	11.6	10.3	18.6	4.1	3.8	2.5	6.2
7	E	−4.5	4.3	−0.4	6.2	0.7	0.6	1.7	2.0
	I	−6.1	2.5	−0.3	6.6	−0.8	2.8	1.2	3.1
8	E	−0.2	2.2	−0.4	2.3	1.2	1.6	0.6	2.0
	I	−1.5	−9.5	4.1	10.4	1.7	1.9	0.6	2.6
9	E	0.6	−2.6	−2.2	3.5	1.4	0.0	−1.5	2.1
	I	−0.5	−6.4	1.2	6.5	2.4	2.8	2.1	4.3
RMS		4.8	6.3	8.8	11.8	2.5	3.0	4.2	5.7

3-dimensional vector, $\sqrt{LR^2 + AP^2 + SI^2}$; AP, anterior-posterior; AVBH, audiovisual biofeedback breath-hold; BHP, breath-hold positions; CBH, conventional breath-hold; E, Exhalation; GTV, gross tumor volume; I, inhalation; LR, left–right; MRI, magnetic resonance imaging; RMS, root mean square; SI, superior–inferior.

Discussion

Patient setup,[23] medical imaging, and radiation treatment[4,6] often require the immobilization of lung tumors to avoid respiratory-related motion. In this study, we introduced AVBH, which uses the same breath-hold positions in a breath-hold training session and 2 MRI sessions to investigate lung tumor position and volume. Using AVBH, we demonstrated the improvement of lung tumor position reproducibility and volume consistency using GTV directly measured from inhalation and exhalation 3-dimensional MRI.

During radiation therapy, lung tumor displacement and baseline shift may lead to a failure of local tumor control.[24] Previous studies have demonstrated that inhalation lung tumor position can vary by 3.6 mm, 3.5 mm, and 5.1 mm (for LR, AP, and SI, respectively) in ABC CT scans taken pre- and midtreatment.[4] The lung tumor position of exhalation respiratory-gated CT scans (pre- and end-treatment) varied by 5.1 mm in 3-dimensional vectors,[25] and the center-of-mass position of lung tumor meausred in 4-dimensional CT scans (pre- and mid-treatment) varied by 5.8 mm, 6.5mm, and 7.8 mm (for LR, AP, and SI, respectively). This study demonstrated that the improvement of breath-hold lung tumor position reproducibility with AVBH (2.4 mm, 4.3 mm, and 4.6 mm) is less than that in previous studies but similar to or greater than that with CBH (4.2 mm, 6.5 mm, and 9.0 mm).

Practical and effective use of breath-hold techniques requires a breath-hold training session for patient comfort,[26] composed of a series of breath-holds at inhalation and exhalation positions and customized to the patient's breath-hold level. Thus, AVBH with individual breath-hold training allows patients to understand where and how to hold their breath. Consequently, AVBH can improve inhalation and exhalation lung tumor position reproducibility and volume consistency. In addition to the previous report finding up to 40% shrinkage during the course of radiation treatment,[27-29] this study found a similar shrinkage of GTVs with AVBH between pretreatment and midtreatment (inhalation, 27.8%; exhalation, 27.2%), but shrinkage significantly varied with CBH (inhalation, 24.1%; exhalation, 28.9%) due to the variation in breath-hold positions. Our results indicate that accurate lung tumor position and volume with AVBH can be observed at the same level of respiration during the course of radiation treatment.[26]

To guide breath-hold positions, this study used RPM signals (1-dimensional abdominal movement) acquired from the RPM camera, which was placed at the same height and distance, and breath-hold tumor positions were controlled by the same level of respiratory motion across a breath-hold training session and 2 MRI sessions. The use of a 1-dimensional external signal to maintain an internal breath-hold is a limitation of this study. Various internal and external respiratory signals as an input to

Table 3 Difference in GTV position range across 2 MRI sessions

	The GTV position range difference (mm), $({}_{EXHALE}GTV^{S1}_{CENTROID} - {}_{INHALE}GTV^{S1}_{CENTROID}) - ({}_{EXHALE}GTV^{S2}_{CENTROID} - {}_{INHALE}GTV^{S2}_{CENTROID})$							
	CBH				AVBH			
	LR	AP	SI	3-dimensional vector	LR	AP	SI	3-dimensional vector
1	−1.9	−12.0	−14.5	18.9	0.2	−0.1	−1.2	1.2
2	0.8	−0.5	−1.7	2.0	3.1	−0.6	0.8	3.2
3	−2.2	8.8	3.7	9.8	0.0	−1.3	3.1	3.4
4	−0.1	−5.6	−2.8	6.2	0.4	0.0	5.3	5.3
5	5.3	3.8	21.6	22.6	0.9	−0.6	−1.3	1.7
6	−4.3	−8.6	−2.9	10.0	0.8	0.4	0.2	0.9
7	1.6	1.8	−0.1	2.4	1.5	−2.2	0.6	2.7
8	1.4	11.7	−4.5	12.6	−0.6	−0.3	−0.1	0.6
9	1.1	3.7	−3.4	5.2	−1.0	−2.9	−3.5	4.7
RMS	2.6	7.4	9.1	12.0	1.3	1.3	2.5	3.1

3-dimensional vector, $\sqrt{LR^2 + AP^2 + SI^2}$; AP, anterior–posterior; AVBH, audiovisual biofeedback breath-hold; CBH, conventional breath-hold; GTV, gross tumor volume; LR, left–right; MRI, magnetic resonance imaging; RMS, root mean square; SI, superior–inferior.

AVBH can be used for tumor motion management in the thoracic and abdominal regions[13] to immobilize target motion during medical imaging and respiratory-gated radiation treatment, which could lead to the reduction of tumor motion margins and therefore the corresponding dose to the lung and heart.[6,30] Inhalation and exhalation MRI is an effective technique to determine lung tumor position and volume information for patient setup and treatment planning.[10,31]

AVBH can be used as a conventional breath-hold technique for a consistent tumor position. In addition, the acquisition of 4-dimensional MRI scans is still a challenge, so AVBH could be used for (1) 2 respiratory-gating windows with a dual quasi-breath-hold technique[8]; (2) a measure of 4-dimensional tumor motion by using inhalation and exhalation breath-hold data and evaluating tumor motion range as measured with 4-dimensional CT[32]; and (3) real-time 4-dimensional tumor motion

Table 4 Difference in GTV as a measure of residual motion at inhalation versus exhalation position for CBH versus AVBH. A negative value indicates that GTV was larger in the inhalation GTV and a positive value indicates that it was smaller

Patient No.	Sessions	Gross tumor volume (cm^3)					
		CBH			AVBH		
		Exhale	Inhale	Exhale − Inhale	Exhale	Inhale	Exhale − Inhale
1	S1	23.9	18.7	5.3	22.1	20.6	1.4
	S2	14.4	16.3	−2.0	15.5	14.1	1.4
2	S1	68.7	79.3	−10.5	80.0	83.9	−3.8
	S2	62.1	66.7	−4.6	61.4	64.3	−2.9
3	S1	16.7	17.7	−1.0	20.3	20.0	0.3
	S2	3.5	4.6	−1.1	9.7	8.6	1.2
4	S1	18.6	16.6	2.0	16.9	16.1	0.7
	S2	9.6	9.6	0.0	9.1	9.1	0.0
5	S1	19.8	16.5	3.3	19.9	19.3	0.6
	S2	18.8	24.4	−5.5	18.1	17.7	0.4
6	S1	74.2	69.2	5.0	71.5	75.3	−3.9
	S2	58.9	58.9	0.0	57.5	57.7	−0.2
7	S1	131.0	159.5	−28.6	146.0	138.6	7.4
	S2	100.8	102.9	−2.1	103.9	103.0	0.9
8	S1	78.3	73.5	4.8	79.1	82.3	−3.2
	S2	45.6	46.4	−0.8	44.6	46.2	−1.6
9	S1	56.3	57.8	−1.5	55.6	55.7	−0.1
	S2	42.6	44.2	−1.6	46.6	45.0	1.6
RMS		57.9	62.4	7.8	60.8	60.6	2.5

AVBH, audiovisual biofeedback breath-hold; CBH, conventional breath-hold; GTV, gross tumor volume; RMS, root mean square.

using 3-dimensional breath-hold data as a reference in conjunction with 2-dimensional cine-MRI.[33]

The present study has several limitations: (1) most lung tumors were located in the upper-lobe; (2) the interfraction changes were determined using only 2 MRI sessions (pretreatment and midtreatment); and (3) the AVBH method used only RPM (1-dimensional abdominal movement) as the wave guide. Lung tumors were contoured by a physician, so interobservation errors could arise and rigid registration based on bony anatomy could be improved by deformable image registration for considering tumor shape and form changes due to tumor shrinkage or growth between 2 MRI sessions.

AVBH is a voluntary breath-hold method that requires patient cooperation. To minimize variability dependent on patient cooperation, this study provided a breath-hold training session for 15 minutes before 2 MRI sessions. However, a breath-hold training session may need to be individually customized for a consistent GTV range across all patients. A further limitation is that CBH was performed before AVBH for each patient, which could potentially introduce bias. Future studies will include investigations of (1) the direct impact of the breath-hold training session on MRI sessions, (2) a comparison of AVBH with respiratory-gated[19] and free-breathing across medical imaging modalities, and (3) the significant impact of tumor location on the effectiveness of AVBH.

Conclusions

This study was the first to assess the impact of audiovisual biofeedback on breath-hold lung tumor position and volume in MRI. AVBH resulted in an improvement of interfraction tumor position reproducibility across 2 MRI sessions by 4.0 mm (46%) along each direction and 6.9 mm (45%) in 3-dimensional vector and an improvement in intrafraction tumor volume consistency by 5.3 cm^3 (70%) in each MRI session. These results demonstrate that AVBH can facilitate reproducible lung tumor breath-hold position and consistent volume and could be a desirable technique for medical imaging and radiation therapy procedures.

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