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Quasi-breath-hold (QBH) Biofeedback in Gated 3D Thoracic MRI: Feasibility Study

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The aim of the study is to test a hypothesis that quasi-breath-hold (QBH) biofeedback improves the residual respiratory motion management in gated 3D thoracic MR imaging, reducing respiratory motion artifacts with insignificant acquisition time alteration. To test the hypothesis five healthy human subjects underwent two gated MR imaging studies based on a T2 weighted SPACE MR pulse sequence using a respiratory navigator of a 3T Siemens MRI: one under free breathing and the other under QBH biofeedback breathing. The QBH biofeedback system utilized the external marker position on the abdomen obtained with an RPM system (Real-time Position Management, Varian) to audio-visually guide a human subject for 2s breath-hold at 90% exhalation position in each respiratory cycle. The improvement in the upper liver breath-hold motion reproducibility within the gating window using the QBH biofeedback system has been assessed for a group of volunteers. We assessed the residual respiratory motion management within the gating window and respiratory motion artifacts in 3D thoracic MRI both with/without QBH biofeedback. In addition, the RMSE (root mean square error) of abdominal displacement has been investigated. The QBH biofeedback reduced the residual upper liver motion within the gating window during MR acquisitions (~6 minutes) compared to that for free breathing, resulting in the reduction of respiratory motion artifacts in lung and liver of gated 3D thoracic MR images. The abdominal motion reduction in the gated window was consistent with the residual motion reduction of the diaphragm with QBH biofeedback. Consequently, average RMSE (root mean square error) of abdominal displacement obtained from the RPM has been also reduced from 2.0 mm of free breathing to 0.7 mm of QBH biofeedback breathing over the entire cycle (67% reduction, p-value=0.02) and from 1.7 mm of free breathing to 0.7 mm of QBH biofeedback breathing in the gated window (58% reduction, p-value=0.14). The average baseline drift obtained using a linear fit was reduced from 5.5 mm/min with free breathing to 0.6 mm/min (89% reduction, p-value=0.017) with QBH biofeedback. The study demonstrated that the QBH biofeedback improved the upper liver breath-hold motion reproducibility during the gated 3D thoracic MR imaging. This system can provide clinically applicable motion management of the internal anatomy for gated medical imaging as well as gated radiotherapy.

Key Words: Gated 3D thoracic MRI, Quasi-breath-hold biofeedback, Respiratory motion management

Introduction

One of the most critical steps in the radiotherapy process is anatomic image acquisition. Obviously, any error induced during imaging such as motion artifacts in four-dimensional computed tomography (4DCT)[1,2] and Positron Emission Tomography (PET)[3] images is systematic and remains the same through the whole treatment process, resulting in adverse impact on clinical outcome.[4-6] For instance, incorrect target and healthy sur-

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rounding tissue delineation can be implemented in treatment planning due to these artifacts, leading to the irradiation of healthy surrounding tissues in addition to the tumor, which results in the increased risk of radiation-related toxicity.[4-6)]

Various respiratory motion-guidance systems using an external surrogate[7-12)] were developed in medical imaging and treatment procedures to improve respiratory motion management in clinical practice. In multiple breath-holds based Magnetic Resonance Imaging (MRI), an audio breath-hold prompt was used to improve coronary imaging[8)] and an MR-compatible active breathing control (ABC) system was applied to lung MRI.[13)] In addition, a respiratory biofeedback with an adaptive gating windowing was implemented in voluntary breathing guidance for thoracic aorta MR imaging. Breath-hold practice, however, often suffers from limited pulmonary function of the patient.[14)] On the other hand, the respiratory gating technique is frequently subject to non-negligible residual motion during acquisition[15)] and lengthened practice.

Recently, Park et al.[16)] proposed a hybrid technique combining free-breathing-based gating and multiple breath-holds called Quasi-breath-hold (QBH) biofeedback, and demonstrated its feasibility that the QBH biofeedback reduced phase-shift, residual motion, complexity, and patient's discomfort. However, the previous study has not been fully investigated in the feasibility of the QBH biofeedback in medical imaging. The current study is the first to investigate the feasibility of QBH biofeedback to demonstrate the residual motion management of the internal anatomy with gated 3D thoracic MRI. The specific aim of this study is to verify that QBH biofeedback would reduce respiratory motion artifacts in gated 3D thoracic MR imaging by reducing the residual respiratory motion in acquisition.

Materials and Methods

1. QBH biofeedback

The QBH biofeedback system was proposed to provide voluntary multiple breath-holds guidance in medical imaging and treatment practices.[16)] QBH is a respiratory biofeedback technique which utilizes a hybrid technique combining free-breathing-gating and breath-hold. In the current study, the QBH biofeedback system utilized real-time respiratory motion signals obtained from the real-time position management (RPM) system (Varian Medical Systems, Palo Alto, USA) consisting of an infrared camera and a marker block on the abdomen as shown in Fig. 1. The RPM system was combined with MR compatible audiovisual equipment including a projector, a semi-transparent screen and headphones. In addition, the QBH biofeedback system utilized an in-house developed software interfaced to the RPM system,[17)] including a multiple breath-holds maneuver to audio-visually guide a human subject for 2s breath-hold at 90% exhalation position in each respiratory cycle during gated 3D thoracic MR imaging. A patient-specific visual guiding wave, utilized for the QBH guidance, has been formulated from the patients' own breathing within the MRI magnet.

2. MRI studies with QBH biofeedback and residual motion assessment

The improvement in the upper liver breath-hold motion reproducibility within the gating window using the QBH biofeedback system has been assessed for a group of volunteers. Five healthy human subjects underwent two gated MR imaging studies: one under free breathing and the other under QBH biofeedback breathing (mean age: 43, range: 38～51). In the QBH biofeedback breathing session, the QBH biofeedback sys-

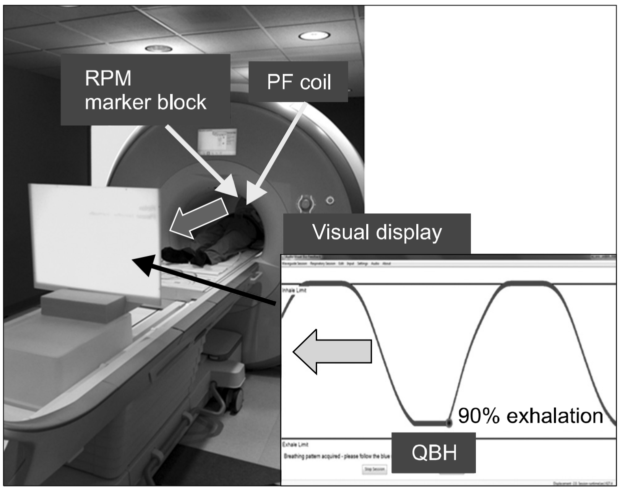

Fig. 1. QBH biofeedback system in 3 Tesla Siemens MRI consisting of the RPM system and audio-visual devices. The screen of the QBH biofeedback system shows a guiding wave (blue curve) and a marker position (red ball) in real time. 2s breath-hold at 90% exhalation position in respiratory cycle is shown.

tem has been combined with a gated 3D thoracic MRI acquisition with an upper dome scout navigator. The respiratory gated T2-weighted SPACE MR pulse sequence with an MR respiratory navigator of a 3T Siemens MRI has been employed for 3D thoracic imaging (range of acceptance gated position: ±4 mm and triggering position: 90% exhalation position). Typical MR imaging parameters were TR/TE=~4400/89 ms, FOV=380×380 mm^2, Pixel size: 1.19×1.19×4 mm^3 and image matrix=320×320×52.

The residual upper liver dome motion using the navigator signal has been qualitatively evaluated. In this study, the navigator utilized an additional MR pre-pulse to measure the position of the liver dome before obtaining image signal with imaging pulses thus, navigator signals were not obtained during image signal acquisition, resulting in discontinued information on liver dome displacement with time. Therefore, visual evaluation of liver dome displacement was made only during the navigator signal available. In the respiratory motion artifact analysis from the obtained gated 3D thoracic MR images, the region of interest (ROI) was selected on the liver since the left side of the chest showed considerable cardiac motion artifacts including signals from blood vessels and the heart. Qualitative analysis of respiratory motion artifacts with/without QBH biofeedback has been assessed. The residual respiratory motion management within the gating window has been evaluated using the synchronized respiratory signal obtained from the RPM system. The RMSE (root mean square error) of abdominal displacement in the gated window has been investigated in the phase domain and the RMSE in period was also computed from each waveform. The slope of the linear fit on the collected entire data has been investigated as a baseline drift.

Quantitative statistical comparison of RMSE in displacement and period from the different breathing conditions was performed using the paired Student's t-test (Microsoft Excel 2010, TTEST).

Results

Five healthy human subjects participated across ten MRI sessions including five free breathing and five QBH biofeedback sessions. The upper liver dome motion data from navigator signals, the abdominal motion data from the RPM system, and gated 3D thoracic MRI have been obtained simultaneously. However, continuous navigator signals were not acquired during image signal acquisition due to a current technical limitation.

1. Upper liver breath-hold motion management in the gating window

Fig. 2 shows 1D RF navigator signal of each subject that is basically the upper liver dome position according to time under (a) free breathing (FB) and (b) QBH. As can be easily seen, the liver dome, when compared to FB, remained at the

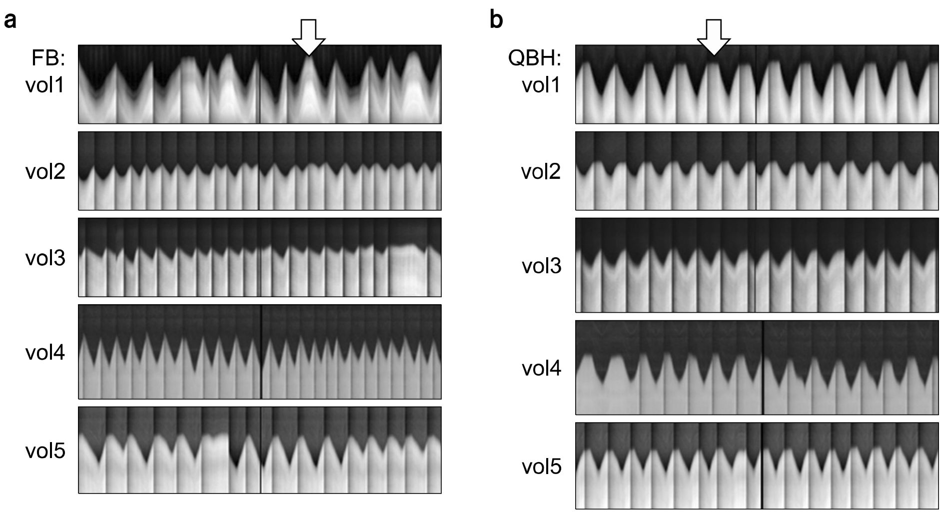

Fig. 2. Upper liver breath-hold motion obtained using the RF navigator pre-pulse with (a) FB and (b) QBH biofeedback breathing. The upper liver breath-hold motion reproducibility has been considerably improved at 90% exhalation using QBH biofeedback (arrow in (b)). Dark vertical lines indicate signal acquisition for MR images with a pause of the navigator.

designated position longer under QBH in vol 1, 2, 4 and 5, resulting in reduction of the residual motion within the gating window during MR acquisitions (arrows in Fig. 2). In addition, QBH biofeedback made the liver dome motion more reproducible through the entire session in both period and displacement aspect. In Fig. 2, each dark vertical line indicates a pause of the navigator during which imaging signal was obtained. More irregular pattern of the dark vertical lines with FB indicates unsuccessful signal acquisition in certain respiratory cycle. In contrast, the dark vertical lines under the QBH biofeedback are more regular and reproducible, implying successful signal acquisition in each respiratory cycle.

2. Respiratory motion artifact analysis in gated T2 weighted 3D thoracic MR images

Fig. 3 shows coronal images corresponding to the navigator sequence in Fig. 2 [(a) FB and (b) QBH]. Anatomical features such as the liver, heart and lung, were clearly observable in addition to the diaphragm in all sets of Fig. 3. The MR signal of the organs with a higher proton density is more prominent than that of the lungs. Corresponding to the reduced residual motion in the gating window in Fig. 2(a), the QBH biofeedback reduced respiratory motion artifacts in lungs and liver of 3D thoracic MR images (especially in vol1, vol3 and vol5), while the scan time with QBH biofeedback increased from 355±78 s with FB to 377±35 s due to repeated breath-holds. However, non-negligible cardiac motion artifacts such as blurring artifacts due to the signal from the blood vessels and the heart still can be seen in Fig. 3.

3. Residual motion and RMSE analysis in abdominal displacement

In Fig. 4, five sets of abdominal motion data obtained from the RPM with/without QBH biofeedback are shown. The abdominal motion with free breathing shows large variations in displacement, period and baseline. However, the variations have been significantly reduced by using the QBH biofeedback system. The results are significant reductions of RMSE in displacement due to QBH biofeedback from 2.0 mm of free breathing to 0.7 mm over the entire cycle (67% reduction, p-value: 0.02) and from 1.7 mm of free breathing to 0.7 mm in the gated window (58% reduction, p-value: 0.14). The aver-

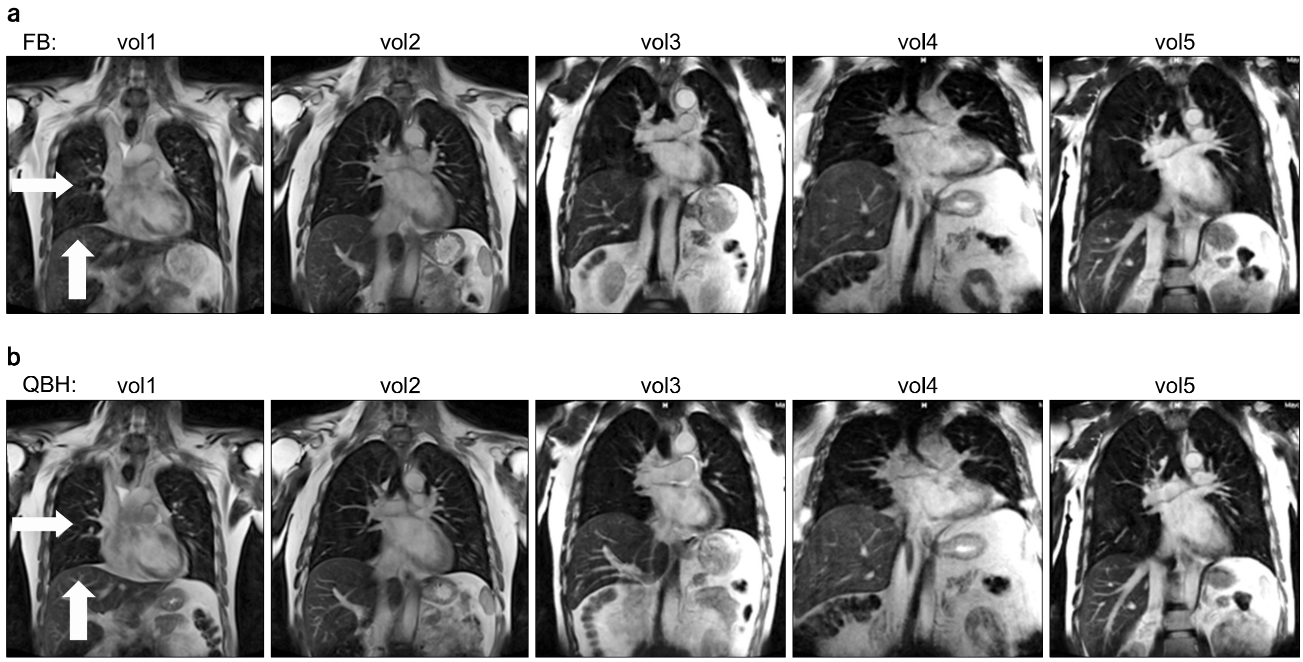

Fig. 3. Gated T2 weighted 3D thoracic MR images obtained with (a) FB and (b) QBH biofeedback breathing. Respiratory-related motion artifacts are shown distinctly in liver and lungs with free breathing [arrows in (a)]. The artifacts have been reduced by controlling residual motions within the gating window during acquisitions using QBH biofeedback [arrows in (b)].

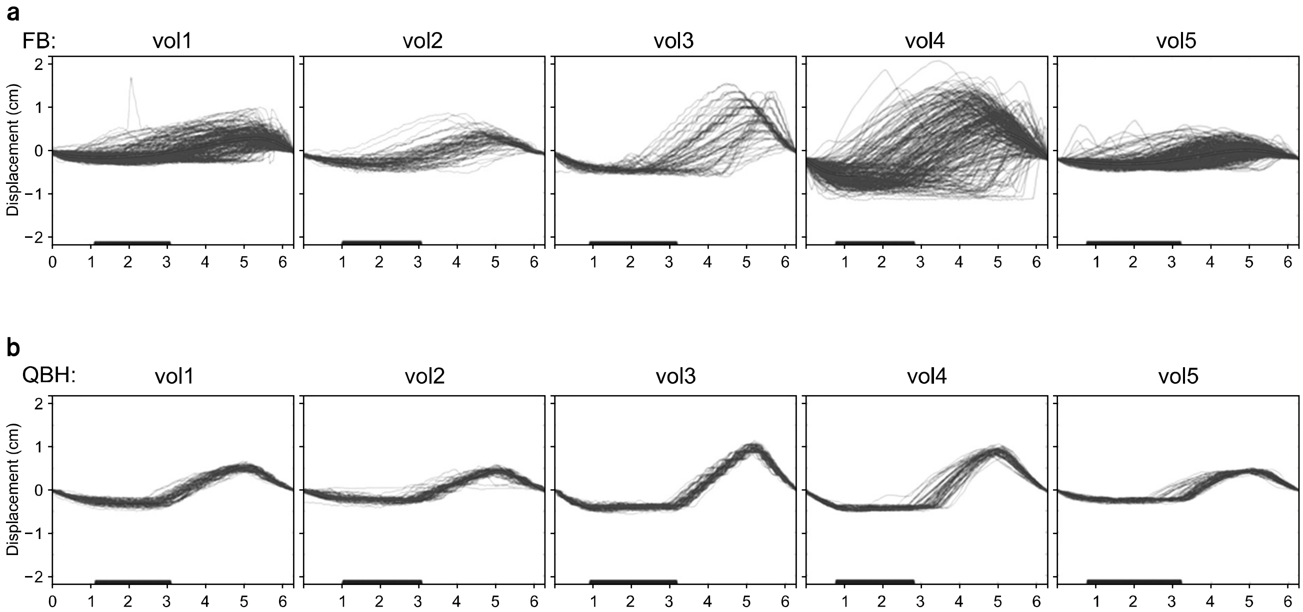

Fig. 4. Example of RMSE analysis in displacement with (a) FB and (b) QBH biofeedback. Average RMSE of abdominal displacement has been reduced from 1.7 mm of free breathing to 0.7 mm of QBH biofeedback within the gating window (bar on the bottom of each figure), providing more consistent breathing patterns.

age baseline drift obtained using a linear fit was reduced from 5.5 mm/min with free breathing to 0.6 mm/min (89% reduction) with QBH biofeedback (p-value=0.017). In addition, the average RMSE of the respiratory cycle length was reduced from 1.8 sec with free breathing to 0.3 sec (i.e., 83% reduction) with the implementation of QBH biofeedback, resulting in more consistent breathing patterns.

Discussion

In this study, the feasibility of QBH biofeedback to improve the residual motion management of the internal anatomy with gated 3D thoracic MRI was investigated for the first time. The need of MR imaging in radiotherapy is continuously increasing because of its non-ionizing radiation property and superior soft tissue contrast compared to CT imaging. However, current 3D thoracic MR imaging with a long scan time often suffers from respiratory motion artifacts such as blurring, causing non-diagnostic quality of MR images and needs to be improved.

The most advanced technique in routine clinical practice is gated 3D thoracic MR imaging. One of the state of the art gated techniques is a real-time MR navigator that utilizes pre-RF-pulse to monitor real-time internal organ motion (usually diaphragm motion) during MR imaging.[18] However, repeated 1.5 sec long signal acquisition time after respiratory triggering and a 4 mm wide gating window can cause substantial motion artifact due to residual motion within the gated window. In addition, unpredictable variations in the cycle-to-cycle free-breathing (FB) may lead to the scan being on incorrect locations. Under the 1.5 sec of signal acquisition window in 3D thoracic MR imaging, 2 sec QBH is considered appropriate in that it secures necessary information acquirement as well keeps reasonable imaging efficiency. Regarding the relationship between the signal acquisition window and the total scan time, if signal acquisition window decreases, the residual motion can be reduced but the total scan time substantially lengthens.

In the image acquisition process, we set the imaging trigger point at 90% exhalation position with a 4 mm wide gating window in each respiratory cycle not to lose scan time efficiency too much (~6 minutes) in free breathing condition. Because the exhalation position is very reproducible over the respiratory cycles,[14] a success rate of the acquisition triggering is very high. With the acquisition trigger point near at the inhalation position, the scan time can substantially increase due to the likely low success rate of the acquisition triggering with poor position reproducibility, and the image acquisition cannot be completed without significant increase in the gating window, resulting in more residual motions and a non-practical imaging protocol in practice. In fact, several respiratory cycles did not have dark vertical lines in the navigator signals under the FB condition [Fig. 2(a)], indicating unsuccessful signal acquisition sometimes with the current gating scheme (at 90% exhalation position with a 4 mm wide gating window). However, the QBH biofeedback increased the reproducibility of the respiratory motion in the entire respiratory cycles and the stability of breath-hold position in the gating window, resulting in increase in the success rate of the acquisition triggering without substantial residual motion.

In this study, we demonstrated that the proposed system is feasible with current thoracic medical imaging in terms of motion artifact reduction without significant scan time alternation. This system can be applicable to regions can be affected by respiratory motion, such as the lung, pancreas, liver, kidney and esophagus in medical imaging and radiotherapy.

Conclusions

The study demonstrated that the QBH biofeedback improved the upper liver breath-hold motion reproducibility during the gated 3D thoracic MR imaging. This system can provide clinically applicable motion management of the internal anatomy for gated medical imaging and gated radiotherapy.

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게이트 흉부자기 공명 영상법과 함께 사용할 수 있는 의사호흡정지(QBH) 바이오 피드백

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연구의 목적은 의사호흡정지(QBH) 바이오 피드백이 의료영상획득 시간의 큰변화 없이 잔류 호흡 운동을 조절함으로써 호흡 운동에 의한 영상 오류를 줄이고, 게이트 3차 흉부 자기 공명 영상을 향상시킬 수 있다는 가설을 실험하는 것이다. 가설을 확인하기 위해 건강한 다섯 사람을 대상으로 3T 지멘스 엠알아이의 호흡 탐색기가 포함된 T2 가중 스페이스 엠알 펄스 시퀀스를 이용해 두번의 게이트 자기공명 영상 연구를 시행 하였다: 자유 호흡 상태와 의사호흡정지 바이오 피드백 호흡상태, 의사호흡정지 바이오 피드백 시스템은 알피엠(RPM) 시스템(실시간 위치 관리시스템, 베리안)을 사용하여, 복부의 외부 위치를 측정하고, 음향과 시각적으로 각각의 호흡주기의 90% 위치에서 2초 숨을 정지하도록 안내하는 방법을 사용했다. 평가방법은 의사호흡정지 바이오 피드백 시스템을 이용시 간 상부의 호흡정지모습의 재현성이 게이팅 영역 내에서 향상되는지를 지원자의 실험을 통해 평가하였다. 자유호흡상태와 의사호흡정지 바이오 피드백상태에서 3차 흉부자기공명영상내에 호흡 운동에 의한 영상 오류와 게이팅영역 내에서의 잔류 호흡 운동 조절여부도 함께 평가했다. 또한, 복부 변위의 RMSE도 (제곱근오차) 조사되었다. 의사호흡정지 바이오 피드백방법을 사용함으로 자유호흡의 경우보다 게이트 3차 흉부 엠알 영상에서 폐와 간에서 호흡운동에 의한 영상오류의 감소 결과를 획득했다(영상획득시간: ~6분). 이는 의사호흡정지 바이오 피드백사용시, 게이팅 영역에서 복부 운동 감소와 횡경막의 잔류 움직임 감소가 일치함을 의미한다. 따라서, 알피엠을 통해 얻은 복부 변위의 전체 자료에서평균 RMSE는 (제곱근오차) 자유 호흡의 2.0 mm에 비해 7 mm (67% 감소, p값=0.02)로 감소하였으며, 게이팅영역만을 고려했을때는 자유 호흡의 1.7 mm가 의사호흡정지 바이오 피드백 호흡을 사용함으로써 0.7 mm (58 % 감소, p값=0.14) 로 개선되었다. 선형 피팅을 사용하여 얻은 평균 기준 이동값은 의사호흡정지 바이오 피드백 을 사용하면 자유 호흡 5.5 mm/분보다 0.6 mm/분(89% 감소, p값=0.017)으로 감소되었다. 이 연구는 의사호흡정지 바이오 피드백을 이용해 게이트 3차 흉부 자기 공명 영상 중에 간 상부의 호흡정지 재현성이 향상되는 것을 보여 주었다. 이 시스템은 내부 해부학의 운동을 조절함으로써 게이트 의료 영상과 방사선 치료에 임상적으로 적용 할 수 있다.

중심단어: 게이팅 3차 흉부 자기공명영상, 의사호흡정지바이오피드백, 호흡운동조절