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Audiovisual biofeedback improves image quality and reduces scan time for respiratory-gated 3D MRI

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Abstract. The purpose of this study was to test the hypothesis that audiovisual (AV) biofeedback can improve image quality and reduce scan time for respiratory-gated 3D thoracic MRI. For five healthy human subjects respiratory motion guidance in MR scans was provided using an AV biofeedback system, utilizing real-time respiratory motion signals. To investigate the improvement of respiratory-gated 3D MR images between free breathing (FB) and AV biofeedback (AV), each subject underwent two imaging sessions. Respiratory-related motion artifacts and imaging time were qualitatively evaluated in addition to the reproducibility of external (abdominal) motion. In the results, 3D MR images in AV biofeedback showed more anatomic information such as a clear distinction of diaphragm, lung lobes and sharper organ boundaries. The scan time was reduced from 401±215 s in FB to 334±94 s in AV (*p-value* 0.36). The root mean square variation of the displacement and period of the abdominal motion was reduced from 0.4±0.22 cm and 2.8±2.5 s in FB to 0.1±0.15 cm and 0.9±1.3 s in AV (*p-value* of displacement <0.01 and *p-value* of period 0.12). This study demonstrated that audiovisual biofeedback improves image quality and reduces scan time for respiratory-gated 3D MRI. These results suggest that AV biofeedback has the potential to be a useful motion management tool in medical imaging and radiation therapy procedures.

1. Introduction

Respiratory-related motion blurring and ghost artifacts[1] can be reduced using respiratory-gating techniques with RF navigator[2], respiratory bellows belt[3], or real-time position management system (RPM).[4] However, variations in cycle-to-cycle breathing can cause inadequate respiratory-gating in image acquisition, resulting in image artifacts and increased scan time.[5]

Audiovisual (AV) biofeedback was proposed to monitor real-time respiratory motion using a marker on the abdomen with feedback to the human subject for respiratory motion management.[6-9] A number of respiratory cycles are acquired at the beginning of AV biofeedback to prepare a guiding waveform for each subject and the guiding waveform is displayed. The regular respiration can be reproduced in that the subject matches the red ball corresponding to the present respiratory position of the subject to the guiding waveform. AV biofeedback has been previously demonstrated to improve breathing regularity in 2D MRI[8] but not in 3D MRI. The aim of this study is thus to investigate whether AV biofeedback improves image quality and reduces scan time for respiratory-gated 3D MRI.

2. Methods

2.1 AV biofeedback system setup in MRI

An AV biofeedback system has been employed to provide respiratory guidance during MR scans. Figure 1 shows the experimental setup of the AV biofeedback system for MRI. The respiratory motion signals were obtained using the real-time position management (RPM) system (Varian, Palo Alto, USA) consisting of an infrared camera and a marker block on the abdomen.

To guide real-time patient breathing in a 3T system (Skyra, Siemens Healthcare Erlangen, Germany), the visual display of the guiding waveform and red ball was displayed on a screen during MR imaging. An 18-channel body matrix coil for thoracic imaging and a head mounted mirror for the patient's view of the visual display were used.

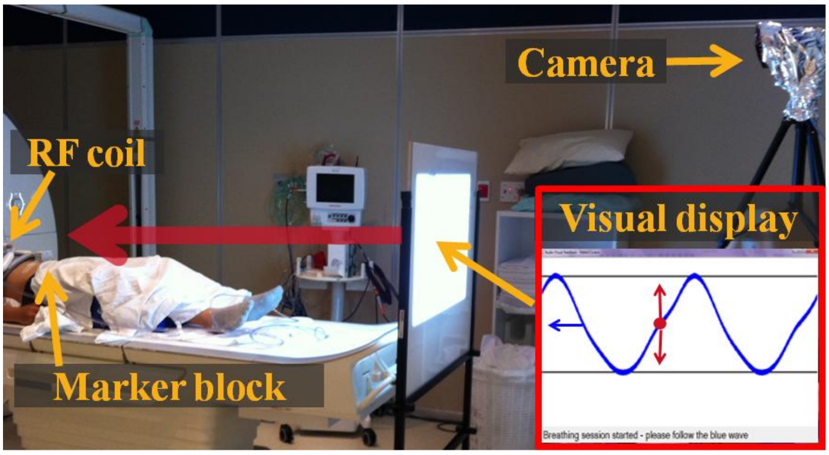

Figure 1. AV biofeedback system for respiratory-gated 3D MR imaging in a 3T Skyra Siemens MRI.

2.1 Respiratory-gated 3D MRI

The improvement in respiratory-gated 3D MR images using the AV biofeedback system combined with thoracic MRI was investigated with five healthy male subjects (aged 33 ± 6). For thoracic imaging, T2-weighted 3D SPACE (Sampling Perfection with Application optimized Contrast using different angle Evolutions) MR pulse sequence with an RF navigator placed on liver dome was employed. Typical parameters were TR/TE = 2200/89 ms, flip angle = 170^0, FOV = 380 × 380 mm^2, voxel size = 1.19 × 1.19 × 4 mm^3 and image matrix = 320 × 320 × 52.

In this study, each subject underwent two sessions to assess the image quality and gating efficiency with (AV: AV biofeedback) and without (FB: Free breathing). In order to reduce the effect of AV training on the FB results, a 15-20 minute AV training session was performed after the FB session and before the AV session. Respiratory-gated 3D MR images were acquired at three gating target positions with designated acceptance windows in the MR pulse sequence. The gating target positions at 10% (near maximum exhalation), 50% (middle) and 90% (near maximum inhalation) were set with a ±2 mm or ±4 mm acceptance window range.

The improvement of respiratory-gated 3D MR images using the AV biofeedback has been evaluated in terms of respiratory-related artifacts. The gating efficiency and the 3D MR data acquisition time have been compared. The abdominal motion was evaluated using the root mean square error (RMSE) in displacement and period obtained from the RPM system.

3. Results and Discussion

3.1 Image quality and gating efficiency improvement

Using the AV biofeedback system, respiratory-related blurring artifacts have been noticeably improved and scan time was considerably reduced as shown in Figure. 2.

3D MR images with FB (subject 1 and subject 2) were significantly blurred due to the variation of the baseline shift and amplitude in respiration. In contrast, there was noticeable reduction of blurring artifacts due to the more regular respiratory motion in the same subjects with AV (subject 1 and subject 2). 3D MR images in AV included more anatomic information such as a clear distinction of diaphragm and lung lobes. In addition, the edge and intersection of organs on 3D images were sharpened.

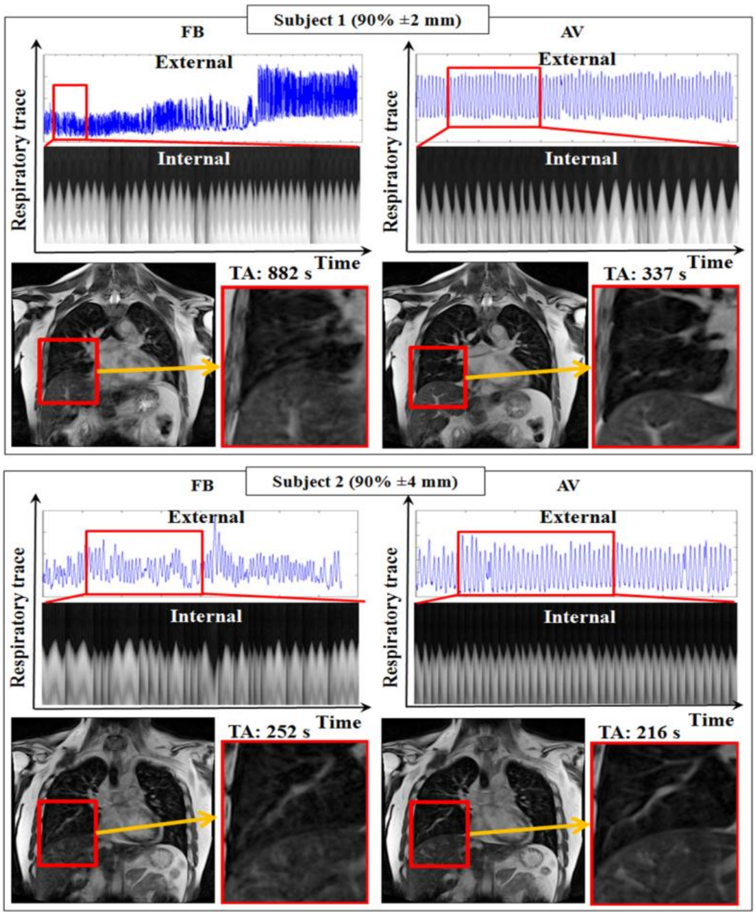

Figure 2. An example of improved image quality and total acquisition time (TA) when AV biofeedback was employed during gated 3D MR imaging for subject 1 (top) and subject 2 (bottom). Free-breathing results (left) and AV results (right) are shown. The external respiratory signal, internal diaphragm signal and images are shown. Gating was triggered at 90% of the breathing cycle (near maximum inhalation) with ±2 mm (subject 1) and ±4 mm (subject 2) gating thresholds. The regular external (abdomen) respiration correlated with the regular internal (diaphragm) respiration, leading to better image quality and shorter scan time.

In addition, regular respiratory motion using AV biofeedback reduced the incidence of unsuccessful gating, leading to a reduction of MR scan time. The scan time reduced up to 545 s and 36 s during respiratory-gated 3D MRI at 90% acceptance window in subject 1 and 2, respectively. A ±2 mm range required relatively longer MR scan time, compared to ±4 mm range, to acquire the same number of images due to the small range of acceptance window. In other volunteer cases, the considerable gating efficiency in AV compared to FB was found at 10% and 90% acceptance windows but it was quite similar at 50% acceptance window between the two breathing conditions.

The impact of AV biofeedback for gating target positions corresponding to the three acceptance positions is shown in Figure 3. A red dashed line at the top of the diaphragm for the 10% gated scan shows only small differences in the diaphragm positions for FB, however there is clearer evidence of inspiration for the MR scan where the inferior motion of the diaphragm with inspiration is apparent.

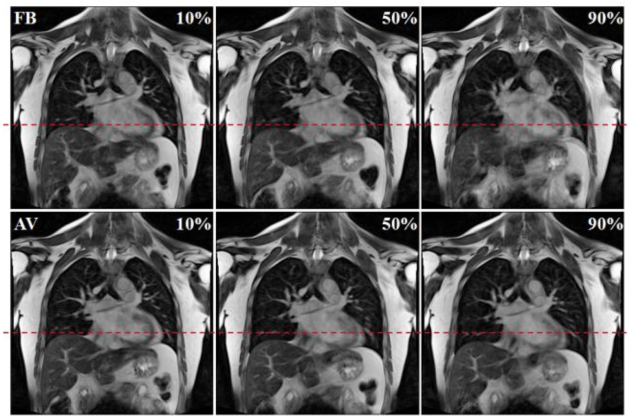

Figure 3. Improvement of gating target positions corresponding to the three acceptance windows in AV compared to FB (subject 1).

3.2 Scan time and breathing variation

Scan time was reduced (or similar) at all gating target positions due to the improvement of breathing regularity: the reduction of root mean square error (RMSE) in displacement and period in Table 1.

Table 1. Scan time and breathing variation of respiratory-gated 3D MRI.

Session	Average scan time (s)	RMSE in Average variation in displacement (cm)	RMSE in Average variation in Period (s)
FB	401±215	0.4±0.22	2.8±2.5
AV	334±94	0.1±0.15	0.9±1.3
% reduction with AV	17%	75%	68%
p-values	0.36	<0.01	0.12

An average reduction in scan time was from 401 s in FB to 334 s in AV, coming from the reduction of breathing variation in displacement (-75%) and period (-68%).

This study demonstrated the improvement of respiratory-gated 3D MR images with AV biofeedback due to improved respiratory motion reproducibility, leading to regular internal organ displacement. In addition, scan time was simultaneously reduced. The images in this study spanned the thorax and abdomen, indicating that AV biofeedback can be broadly applicable to imaging sites affected by respiration, provided that both a respiratory signal and a patient display system are available.

A limitation of the current study was that healthy human subject volunteers, and not patients, were used. Therefore, without further testing, the application of this study can only be extended to patients with similar age and lung function characteristics to the volunteers, for example some lymphoma, breast, pancreas and kidney cancer patients. In order to investigate the potential benefits of AV biofeedback for a quite different population, lung cancer patients, a clinical study has been initiated.

A potential problem for real-time audiovisual biofeedback is the time delay between the patient breathing and the projected signal. Fortunately, using the 30 Hz RPM signal the time delay between the patient breathing and the projected signal is undetectable to the user. However, with a different respiratory monitor with either a lower frame rate and/or using more processing time the projected real-time respiratory signal could be delayed or discontinuous. For such systems it is likely that further processing algorithms, such as signal prediction or smoothing algorithms would be needed.

4. Conclusion

This study demonstrated, for the first time, that audiovisual biofeedback improves image quality and reduces scan time for respiratory-gated 3D MRI. These results suggest that AV biofeedback has the potential to be a useful motion management tool in medical imaging and radiation therapy procedures.

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