Motion management within two respiratory-gating windows: feasibility study of dual quasi-breath-hold technique in gated medical procedures

Taeho Kim[1,2,3], Siyong Kim[1,4], Yang-Kyun Park[5], Kaylin K Youn[1], Paul Keall[6] and Rena Lee[2]

[1] Department of Radiation Oncology, Mayo Clinic, Florida, USA

[2] Department of Radiation Oncology, Ewha Womans University, Seoul, Korea

[3] Department of Radiation Oncology, University of Virginia, Virginia, USA

[4] Department of Radiation Oncology, Virginia Commonwealth University, Virginia, USA

[5] Department of Radiation Oncology, Massachusetts General Hospital, Massachusetts, USA

[6] Radiation Physics Laboratory, Sydney Medical School, University of Sydney, Sydney, Australia

Corresponding author: renalee@ewha.ac.kr

Keywords: quasi-breath-hold biofeedback, respiratory motion management, duty-cycle

Abstract

A dual quasi-breath-hold (DQBH) technique is proposed for respiratory motion management (a hybrid technique combining breathing-guidance with breath-hold task in the middle). The aim of this study is to test a hypothesis that the DQBH biofeedback system improves both the capability of motion management and delivery efficiency. Fifteen healthy human subjects were recruited for two respiratory motion measurements (free breathing and DQBH biofeedback breathing for 15 min). In this study, the DQBH biofeedback system utilized the abdominal position obtained using an real- time position management (RPM) system (Varian Medical Systems, Palo Alto, USA) to audio-visually guide a human subject for 4 s breath-hold at EOI and 90% EOE ($EOE_{90\%}$) to improve delivery efficiency. We investigated the residual respiratory motion and the delivery efficiency (duty-cycle) of abdominal displacement within the gating window. The improvement of the abdominal motion reproducibility was evaluated in terms of cycle-to-cycle displacement variability, respiratory period and baseline drift. The DQBH biofeedback system improved the abdominal motion management capability compared to that with free breathing. With a phase based gating (mean ± std: 55 ± 5%), the averaged root mean square error (RMSE) of the abdominal displacement in the dual-gating windows decreased from 2.26 mm of free breathing to 1.16 mm of DQBH biofeedback (*p*-value = 0.007). The averaged RMSE of abdominal displacement over the entire respiratory cycles reduced from 2.23 mm of free breathing to 1.39 mm of DQBH biofeedback breathing in the dual-gating windows (*p*-value = 0.028). The averaged baseline drift dropped from 0.9 mm min^{-1} with free breathing to 0.09 mm min^{-1} with DQBH biofeedback (*p*-value = 0.048). The averaged duty-cycle with an 1 mm width of displacement bound increased from 15% of free breathing to 26% of DQBH biofeedback (*p*-value = 0.003). The study demonstrated that the DQBH biofeedback system has the potential to significantly reduce the residual respiratory motion with the improved duty cycle during the respiratory gating procedure.

1. Introduction

Breathing motion, if not properly managed, can cause geometric miss of the target and unnecessary irradiation of critical structures during radiation therapy. In addition, respiratory motion can induce errors like imaging artifacts (Yamamoto *et al* 2008, Langner and Keall, 2010, Yang *et al* 2012) that are systematic and remain the same through the whole treatment process, resulting in adverse impact on clinical outcome (Theuws *et al* 1998, Hugo *et al* 2009, Marks *et al* 2010). To reduce respiratory motion-related errors, various respiratory motion management techniques have been proposed such as motion-encompassing, respiratory gating, breath holding (BH), abdomen compressing, and real-time tumor tracking (Keall *et al* 2006a). In clinical practice, the gating and BH technique have been widely used (Berson *et al* 2004, Linthout *et al* 2009) and several respiratory motion-guidance systems using an external surrogate (Wang *et al* 1995, Kini *et al* 2003, George *et al* 2006, Lim *et al* 2007, Locklin *et al* 2007, Venkat *et al* 2008) were combined with these techniques for both imaging and beam delivery (Wang *et al* 1995, Arnold *et al* 2007). However, a breath-hold practice was often limited by patient pulmonary function while reducing the residual motion in acquisition (Keall *et al* 2006a). In contrast, the respiratory gating technique often suffered from residual motion during implementation (Berbeco *et al* 2005) and lengthened practice while requiring minimal patient cooperation.

Recently, a hybrid technique combining free-breathing-based gating and multiple short breath-holds called quasi-breath-hold (QBH) biofeedback has been proposed by Park *et al* (2011). In their study, it was demonstrated that QBH biofeedback could reduce phase-shift, residual motion, complexity, and discomfort. However, QBH biofeedback previously introduced was based on a single-phase gating window and provided the limited duty-cycle improvement compared with a conventional gating maneuver.

The current study is to propose a dual QBH respiratory motion management technique that has two respiratory gating windows, each at different phase. Intuitively, it is expected that increasing the total breath-hold time would improve duty-cycle. However, how well human subjects can comply with such a dual breath-hold strategy should be evaluated. The specific aim of this study is to test a hypothesis that the DQBH biofeedback system has potential to improve both the accuracy and efficiency. The assessment of the DQBH biofeedback system has been performed with 15 healthy human subjects in terms of the root mean square error (RMSE) of the abdominal displacement and delivery efficiency within the gating windows. In addition, the abdominal motion reproducibility using the DQBH biofeedback system in the aspects of cycle-to-cycle variability in displacement, respiratory period and baseline drift has been investigated.

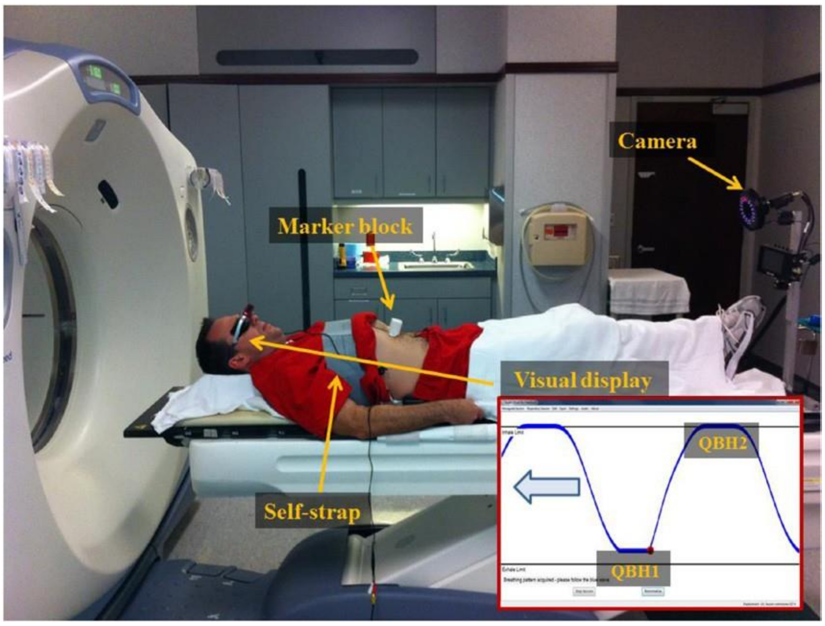

Figure 1. The QBH biofeedback system consisting of the RPM system and audiovisual devices. The goggles of the DQBH biofeedback system show a guiding wave (blue curve) and a marker position (red ball) in real-time. In the visual guidance, 4 s breath-hold at the 90% EOE and 4 s breath-hold at the end of inhalation in respiratory cycle are shown (gray shaded areas with QBH1 and QBH2).

2. Method and materials

2.1 *DQBH biofeedback*

The QBH biofeedback system was proposed to provide voluntary multiple breath-hold guidance in gated medical imaging and gated treatment practices (Park *et al* 2011). QBH biofeedback is a respiratory biofeedback technique which utilizes a hybrid approach combining breathing guidance with breath-hold task in the middle. In the previous study, the QBH biofeedback system employed QBH at only one phase, preferably at the end-of-exhalation (EOE) and we rename it as single QBH (SQBH). In the current study, the DQBH biofeedback system has been proposed where two breath-holds are employed within each respiratory cycle, one at the end-of-inhalation (EOI) and the other at the 90% EOE ($EOE_{90\%}$).

The DQBH biofeedback system utilizes real-time respiratory motion signals obtained using the RPM system (Varian Medical Systems, Palo Alto, USA) consisting of an infrared camera and a marker block placed on the abdomen of the subject as shown in figure 1. The RPM system is also combined with audiovisual devices (i.e. electronic goggles and two room speakers) for biofeedback purpose. In addition, the DQBH biofeedback system is operated using in-house developed software, interfaced to the RPM system, that can provide a subject- specific DQBH guidance curve. A similar software without DQBH capability has been previously demonstrated to be effective (Kim *et al* 2012). In an actual process, a patient-specific visual guiding wave is formulated from the patient's own deep-breathing samples.

2.2 *Maneuver assessment*

Before the main feasibility study, a maneuver assessment study was performed. Based on the findings from the previous pilot study (Kim *et al* 2013), three different DQBH maneuvers (2–2, 4–4 and 6–6 s QBH combinations at EOI–EOE) have been tested with four volunteer human subjects. The subject-specific guiding wave (basic wave) obtained under deep-breathing condition was manipulated by adding dual breath-hold moments at EOI and 90% EOE ($EOE_{90\%}$). Note that 90% EOE instead of 100% EOE was chosen to keep certain amount of biofeedback capability of the subject. In the simulation, each subject underwent the respiratory motion measurements with three different maneuvers (5 min measurement for each maneuver) and then the results were analyzed to determine the optimal maneuver with which the main study would be carried out. According to the evaluation, 4 s breath-hold at 90% EOE and 4 s breath-hold at EOI in each respiratory cycle was implemented in the DQBH biofeedback system in the full study described in the next section.

2.3 *Duty-cycle and residual motion assessment*

The improvement in the abdominal motion reproducibility within the dual-gating windows using the DQBH biofeedback system has been assessed with 15 healthy human subjects [mean age: 37, age-range: 19–51, mean body mass index (BMI): 24, and BMI-range: 18–38]. The healthy human subjects underwent two respiratory motion measurements: one for 15 min measurement under free breathing (FB) and the other for 15 min measurement under DQBH biofeedback breathing.

Respiratory signals obtained from the RPM system were analyzed to evaluate duty-cycle according to three different gating window widths (1, 2, and 3 mm). In addition, the RMSE of abdominal displacement was investigated in the both dual-gating windows and entire respira- tory cycles. The RMSE of period was also computed from each waveform. To determine base- line drift, the slope of the linear fit on the collected entire data was investigated. Quantitative statistical comparison of RMSE in displacement and period, baseline drift and duty-cycle from the different breathing conditions was performed using the paired Student's *t*-test and evaluated in a spreadsheet program (Excel 2010, Microsoft, Redmond, USA).

3. Results

Four simulation studies with three different DQBH maneuvers have been completed with four healthy human subjects prior to the full studies with 15 healthy human subjects. Based on the results of the simulation studies, 15 healthy human subjects underwent 30 respiratory motion measurements, 15 under FB and 15 under 4–4 s DQBH biofeedback.

3.1 *Maneuver assessment*

Figure 2 shows the result of maneuver assessment study in which three different DQBH maneuvers were tested with four volunteers. In figure 2, both duty-cycle (for four sets of data with the scale on the left vertical-axis) and displacement RMSE (for two sets with the scale on the right vertical-axis), averaged over all of four volunteers, are plotted according to DQBH maneuver (i.e. EOI–$EOE_{90\%}$ combination of 2–2, 4–4, and 6–6 s). Duty-cycle (black lines) was evaluated under the condition of four different displacement bounds from the guiding wave (i.e. 1, 2, and 3 mm displacement, and no displacement limit from the guide). No displacement limit means that the beam is always on during the quasi-breadth-hold period no matter how much the abdominal position is displaced (denoted as 'phase based gating'). Two conditions were considered for displacement RMSE evaluation, during the entire cycles (blue line) and the breadth-hold phases only (red line).

As can be seen, the duty-cycle increased with QBH length at the expense of increased displacement RMSE within the beam-on phases. However, the RMSE of the abdominal dis- placement in the entire respiratory cycles did not continuously increase with QBH length and showed a minimum with the 4–4 s maneuver. This implies that the 4–4 s might be more comfortable and/or stable, especially when the treatment time is longer. Therefore, the 4–4 s maneuver in DQBH biofeedback has been chosen for the main study on duty-cycle and residual motion assessment for 15 volunteer subjects.

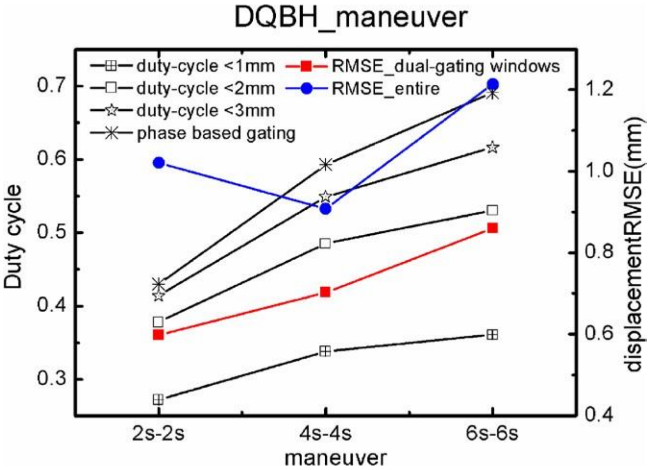

Figure 2. Averaged duty-cycles with 1, and 3 mm width of the dual-gating windows are shown as two breath-hold moments in DQBH biofeedback increase. Phase based gating is determined by the ratio of the designated moments to the full respiratory period in the phase domain. In addition, the averaged RMSE of the abdominal displacement in the entire respiratory cycles and within the dual-gating windows are presented. RMSE_ entire denotes RMSE of displacement in the entire respiratory cycles and RMSE_dual-gating windows denotes RMSE of displacement within the dual-gating windows.

3.2 *Abdominal motion reproducibility within the dual-gating windows*

In figure 3, 15 sets of abdominal motion data both under FB (columns, *a*, *c*, and *e*) and under DQBH biofeedback (columns, *b*, *d*, and *f*) are shown. Note all of cyclic data are overlapped in the phase domain, and the red curve in each plot indicates the average respiratory motion in FB cases and the guiding wave in DQBH biofeedback cases. Two flat regions can be easily observed in the plots with DQBH biofeedback as intended in the guiding wave (i.e. QBH1 and QBH2 in figure 1). The amplitude of the respiratory motion, averaged over all 15 volunteers,was larger with DQBH biofeedback because of deep-breathing (24.0 ± 8.9 mm) than that with FB (8.9 ± 5.5 mm). The period of the respiratory motion also increased from 5.8 ± 2.2 s with FB to 14.8 ± 1.7 s with DQBH biofeedback.

As can be seen in figure 3, the DQBH biofeedback system was able to produce much more reproducible abdominal motion in both period and displacement. In addition, the variation of the displacement within the gating windows (indicated with blue horizontal bars at the bottom of each plot) was reduced under DQBH biofeedback compared to FB.

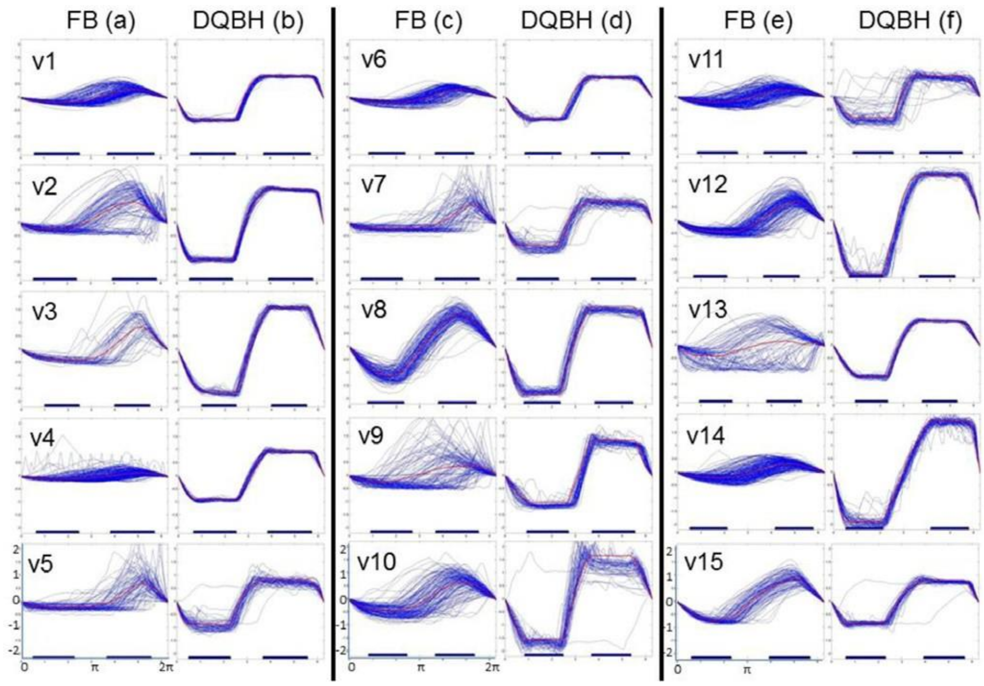

Figure 3. Abdominal motion data with FB (column: *a*, *c*, *e*) and with DQBH biofeedback (column: *b*, *d*, *f*) from 15 studies. A constant *y*-offset value (mean position of the abdominal motion data for the entire respiratory cycles) has been applied to the displacement values of each dataset to increase the clarity of the figure. The red curve in the plots with FB indicates the average respiratory motion while the red curve in the plots with DQBH biofeedback indicates the actual guiding wave during the measurements. The gating windows are indicated with blue horizontal bars at the bottom of each plot.

Table 1 summarizes the RMSE, averaged over all volunteers, for both displacement and period in the whole phase, and the baseline drift of abdominal motion. The results of paired Student *t*-test (i.e. *p*-values) comparing FB and DQBH are also given. As shown, there was a significant reduction with DQBH biofeedback in all of parameters, displacement RMSE, period RMSE, and baseline drift. In detail, the RMSE of abdominal displacement from the mean in the whole phase decreased from 2.23 mm with FB to 1.39 mm with DQBH biofeedback: 37% of displacement error reduction with DQBH biofeedback (*p*-value = 0.028). Note that displacement from the guiding wave in DQBH biofeedback, which is more relevant than the displacement from the mean, was 1.69 mm. For period displacement, 76% reduction (from 2.68 s with FB to 0.66 s with DQBH biofeedback) was observed (*p*-value = 0.018). The baseline drift obtained using a linear fit was also reduced from 0.9 mm min^{-1} with FB to 0.09 mm min^{-1} (90% reduction) with DQBH biofeedback (*p*-value = 0.048). When only the dual-gating windows were considered and no displacement bound was given (i.e. 'phase based gating'), the displacement RMSE from the mean for FB and from the guiding wave for DQBH decreased from 2.26 mm with FB to 1.16 mm with DQBH biofeedback (48% reduction, *p*-value = 0.007). Note, once again, displacement was evaluated from the mean in FB and from the guiding wave in DQBH biofeedback, and the displacement RMSE from the mean is 0.95 mm with DQBH (59% reduction, *p*-value = 0.002). As illustrated, statistical significance of the reduction of RMSE in both displacement and period, and baseline drift using DQBH biofeedback was supported by the paired Student's *t*-test (*p*-value).

Table 1. Averaged RMSE and baseline drift of abdominal motion and paired Student *t*-test *p*-values (FB denotes free breathing and DQBH denotes DQBH biofeedback).

	RMSE in displacement (mm)	RMSE in period (s)	Baseline drift (mm min^{-1})
FB	2.23	2.68	0.90
DQBH	1.39 (−37%)	0.66 (−76%)	0.09 (−90%)
p-value	0.028	0.018	0.048

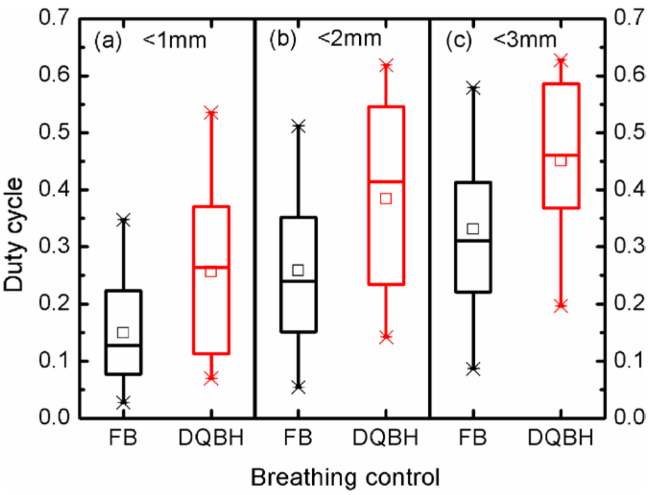

Figure 4. Box plots of the duty cycle with (*a*) 1 mm, (*b*) 2 mm and (*c*) 3 mm width of the dual-gating windows are shown. The box represents the interquartile range between 25th and 75th percentiles, and the square and the horizontal line in the box represent the mean and the median, respectively. The vertical lines outside of the box represent the range, and the cross marks close to the ends of vertical lines represent between 99th and 1st percentiles.

33 *Delivery efficiency with the duty-cycle analysis*

Figure 4 shows a comparison of duty-cycle between FB and DQBH biofeedback. As shown using box plots, the value of duty-cycle significantly improved with DQBH biofeedback. In detail, the duty-cycle with 1 mm width of the displacement bound within the dual-gating windows (figure 4(*a*)) increased from 15% of FB to 26% of DQBH biofeedback (73% relative improvement, *p*-value = 0.003). Figure 4(*b*) shows the duty-cycle with 2 mm displacement bound also increased from 26% with FB to 38% with DQBH biofeedback (46% relative improvement, *p*-value = 0.002). When the displacement bound was 3 mm, the relative improvement of the duty-cycle was 36% with *p*-value = 0.002 (33% duty-cycle with FB versus 45% with DQBH biofeedback). Note in the case there was no limit on the displacement bound (i.e. ‘phase based gating’), the duty-cycle was 55 ± 5%. In figure 5, increase in duty-cycle with DQBH biofeedback is shown under (*a*) 1 mm, (*b*) 2 mm and (*c*) 3 mm width of the dual-gating windows. Using DQBH biofeedback, 12 of 15 volunteers showed increase in the duty-cycle when the dual-gating windows was within 1 mm. For dual-gating windows having the width of within 2 and 3 mm, duty-cycle increase was observed from 13 out of 15 volunteers.

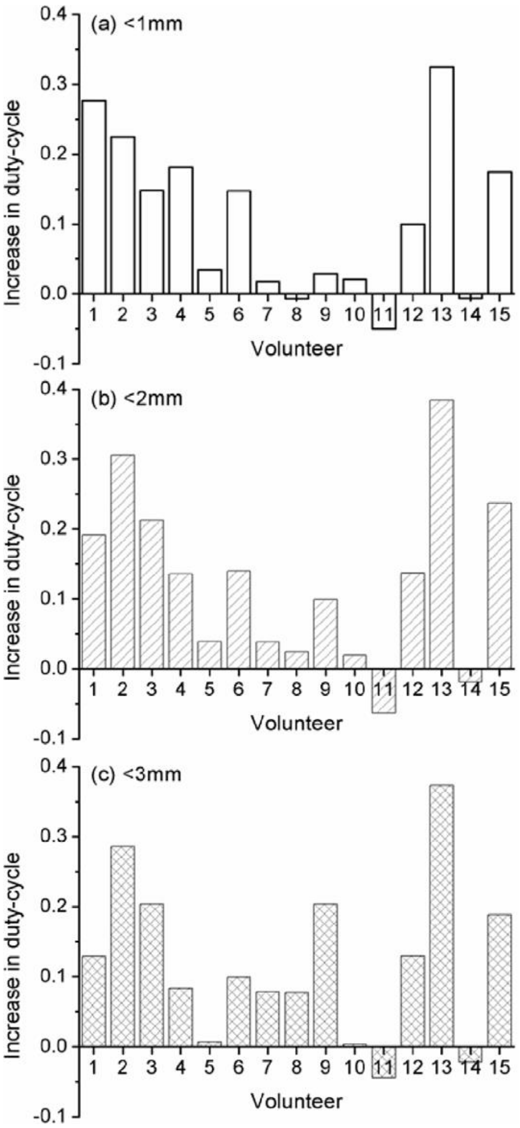

Figure 5. Increase in duty-cycle with (*a*) 1 mm, (*b*) 2 mm and (*c*) 3 mm width of the dual-gating windows are shown.

4. Discussion

In this study, the feasibility of the DQBH biofeedback system, designed to minimize the variation of both displacement and period, and baseline drift while improving the duty-cycle, was investigated. Compared to FB, the duty-cycle under DQBH biofeedback (without displacement limit) showed significant increase (about 83% from FB). It is also observed that when the same amount of duty-cycle is to be achieved for both FB and DQBH biofeedback, more accurate motion management could be achieved with DQBH biofeedback. While, for instance, 26% duty-cycle is obtained with 2 mm displacement bound under FB, the same duty-cycle can be obtained with only 1 mm displacement bound under DQBH biofeedback, demonstrating DQBH's achievement of the primary goal of accuracy improvement in respiratory motion management.

The proposed DQBH biofeedback is a hybrid technique combining breathing-guidance with breath-hold task in the middle. The breathing-guidance technique such as the audiovisual biofeedback (AV) method is widely applied in clinic because of the improvement in the reproducibility of respiration motion. Vankat *et al* (2008) reported that RMSE in displacement was reduced from 1.6 mm with FB to 0.78 mm with AV biofeedback (55% improvement). However, the conventional AV biofeedback method does not manage the residual respiratory motion effectively within the gating window. For instance, the figure 3 of the report by Vanket *et al* shows the breathing pattern with ~1.3 cm of the peak-to-through displacement and ~50% duty cycle gating window under AV biofeedback may include ~3 mm residual motion within the gating window. In contrast, our report shows that RMSE displacement within the dual- gating windows (55% duty cycle) is 1.16 mm from the guiding wave (0.95 mm from the mean wave) with DQBH biofeedback due to residual respiratory motion management by breath- hold task combined with the AV biofeedback.

Obviously, having two breath-holds within a breathing cycle may be considered not easy to do. It is, however, demonstrated that DQBH biofeedback is not significantly difficult to follow and would not degrade overall respiratory motion. The RMSE of abdominal displacement in the whole phase, for example, was reduced from 2.23 mm with FB to 1.39 mm with DQBH biofeedback (~37% improvement).

Compared to the SQBH biofeedback previously introduced by some of our group (Park *et al* 2011), the duty-cycle under DQBH biofeedback (without displacement limit) showed an about 45% relative increase from that of SQBH while keeping the similar level of residual respiratory motion management. Park *et al* reported that 7 s SQBH prompted ~61% duty-cycle. However, we realized that the threshold of comport level should be monitored because of possible oxygen deprivation at the EOE, especially when QBH is performed continuously without breaks. In contrast, DQBH biofeedback reduced this concern by using two breath- holds at the EOI and at the 90% EOE under the continuous respiratory motion management. Although not systematically evaluated, in fact, we observed that having QBH at EOI makes easier to do QBH at EOE for many volunteers.

In DQBH biofeedback, a patient-specific visual guiding wave is formulated from the patient's own deep-breathing samples. Therefore, the respiratory motion increases from ~9 mm with FB to ~24 mm with DQBH in amplitude and from ~6 s with FB to ~15 s with DQBH in period, respectively (while conventional AV biofeedback does not alter the respiratory period and the amplitude of the mean wave from FB). Increase in period with DQBH lengthens the preparation (or simulation) time for obtaining the visual guiding wave and exercise. However, once prepared, the actual execution time becomes shorter than that with FB as reported in this study. For instance, when the displacement bound was 3 mm, the duty-cycle with FB is 33% of the respiratory period in our study (i.e. the beam is on for

33% of the respiratory period). Compared to FB, DQBH biofeedback with the 3 mm displacement bound provides 45%.

As discussed in this report, the abdominal motion is increased by DQBH biofeedback because of utilizing deep-breathing pattern to reduce possible oxygen deprivation. Although the DQBH biofeedback improves the reproducibility of respiration motion, increase in the abdominal motion escalates the organ motion range. However, DQBH biofeedback aims to manage the residual respiratory motion within the gating window than the total respiratory motion range. Although the organ motion range was increased with DQBH biofeedback, the displacement speed is still similar: 9 mm per 6 s (1.5 mm s^{-1}) with FB and 24 mm per 15 s (1.6 m s^{-1}) with DQBH. In addition, RMSE within the dual-gating windows was significantly reduced from 2.26 mm with FB to 1.16 mm from the guiding wave (0.95 mm from the mean wave) with DQBH biofeedback in figure 3, which is more important in terms of accurate beam delivery.

In a recent report, the pilot project of this study, six different DQBH biofeedback maneuvers (2–2, 3–3, 4–4, 5–5, 7–5, and 9–5 s for EOE-EOI combination) based on moderate deep breathing with three human subjects have been tested (Kim *et al* 2013). Compared to the previous study, we have evaluated three different maneuvers (2–2, 4–4 and 6–6 s) based on full deep breathing with four human subjects prior to the full study. In the previous study, they found the lowest mean absolute error with 4–4 s of DQBH biofeedback although the differences from others were not significant. In this study, the RMSE of the abdominal displacement within the dual-gating windows showed a gentle increase with QBH length increase. However, 4–4s DQBH maneuver showed the least RMSE when entire phase was considered. In addition, most of the volunteers experienced minor drowsiness during the simulation with the 6–6 s maneuver in DQBH biofeedback, especially at the end of simulation, implying possible oxygen deprivation due to continuous long QBHs. Therefore, we implemented 4–4 s breath-hold maneuver in DQBH biofeedback for the full respiratory motion measurements.

In the current study, one of breath-hold positions was chosen at 90% deep-exhalation. The exhalation position is easily achievable with high reproducibility over the respiratory cycles (Keall *et al* 2006a), resulting in a high success rate of the gating in medical imaging and radiotherapy. Instead of EOE, however, 90% EOE was selected to keep certain amount of air so that subjects could have more control capability and feel less discomfort with breadth-hold. However, if the initial baseline drift occurs during the procedure (which is mainly downward), the baseline drift can be detected by tracing the patient's breath-hold position at EOI (the deep-inhalation position) while the breath-hold position at 90% EOE may hinder detection of the baseline drift. In this report, we observed the insignificant baseline drift (0.09 mm min^{-1}) with DQBH biofeedback and the breathing position at the inhalation remained in the procedure, indicating the initial baseline drift insignificant. However, regular AV biofeedback without the breath-hold period can help to detect the baseline drift in the procedure, especially during breaks between a field and next. The other breath-hold position was set at deep- inhalation because the deep-inhalation position is very beneficial in tumor motion control and sparing healthy tissues (Keall *et al* 2006a, Hayden *et al* 2012). The deep-inhalation fully expands lungs, resulting in more separation of critical organs from the tumor. However, keeping inhalation position consistent is not easily achievable with poor position reproducibility so breath-hold guidance at deep-inhalation position is necessary during the procedure. Note that although the patient manages its breathing at the dual-gating windows under DQBH biofeedback guide, in principle, there are some trade-off in dual-gating positions which are position instability at EOI and insufficient organ separation at

EOE.

In a pilot study by Geneser *et al* (2011), it has been demonstrated that dual-gating technique can reduce intensity-modulated radiation therapy (IMRT) delivery time while maintaining treatment plan quality. Combining DQBH biofeedback with the proposed IMRT planning technique by Geneser *et al* can be beneficial in improving treatment efficiency (duty cycle) and radiation conformality (tumor control and critical organ protection).

To apply the findings from this study to patients with compromised lung function, a couple of potential issues need to be considered. First, the 4–4 s maneuver of DQBH biofeedback used in this study might not be optimal for actual patients. Therefore, a patient-specific maneuver depending on lung function needs to be determined prior to the procedure. Second, more intensive training sessions prior to treatment would be critical for successful implementation of the DQBH, especially for patients having poor compliance performance. Third, for clinical use of the DQBH biofeedback with imaging systems, the increased respiratory period by DQBH biofeedback may make a normal 4-dimensional computed tomography (4DCT) imaging not easy under the current 4DCT imaging systems due to a long period, and the resulting increased imaging dose to the patient. However, we believe when the DQBH is well established, there is no need for 4DCT but gated CT at two phases is enough. In case, continuous two-phase scan is not feasible, users can do scan in serial manner (i.e. finish one phase and then do the other phase). Therefore, both scanning time and imaging dose can be reduced significantly compared to conventional 4DCT which is often mandatory for FB based gating technique. Fourth, the local target uncertainty might increase with DQBH biofeedback relative to SQBH biofeedback or deep inspiration breath hold (DIBH) due to dual-gating. However, increase in duty-cycle would decrease overall treatment time and might decrease global time related uncertainty such as patient external motion and baseline drift. Therefore, further investigations on such issues would be beneficial before clinical use. Fifth, for clinical use of the DQBH, a radiation delivery system with a dual gating capability (Geneser *et al* 2011) or a tracking capability (Keall *et al* 2006b) is needed and a planning system capable of handling dual phases is required as well. Although it is not expected for most clinics be able to implement the proposed strategy easily, by virtue of recent advancement on tumor tracking technology combined with imaging modalities [e.g. on-board x-ray tube(s) with fluoroscopy capability and electro-magnetic transponder based marker detection system(s)], we believe the DQBH delivery is doable.

In this study, we demonstrated that the DQBH biofeedback system improves a duty-cycle while reducing the variation in displacement, phase and baseline drift in respiratory cycles. With improving abdominal position reproducibility, the proposed system can be significantly beneficial to gated thoracic medical imaging and gated radiotherapy. This system can also be applicable to other regions affected by respiratory motion, such as the breast, pancreas, liver, kidney and esophagus.

5. Conclusion

The study demonstrated that the DQBH biofeedback system improved the abdominal motion reproducibility with improved duty-cycle within the dual-gating windows. This system combined with both a delivery system capable of tracking and a planning system dealing with dual phase optimization can provide clinically applicable motion management for gated radiotherapy.

Acknowledgments

This study was supported by the Industrial Strategic Technology Development Program (10035527) funded by the Ministry of Knowledge Economy (MKE, Korea).

References

Arnold J F T, Mörchel P, Glaser E, Pracht E D and Jakob P M 2007 Lung MRI using an MR-compatible active breathing control (MR-ABC) *Magn. Reson. Med.* **58** 1092–8

Berbeco R I, Nishioka S, Shirato H, Chen G T and Jiang S B 2005 Residual motion of lung tumours in gated radiotherapy with external respiratory surrogates *Phys. Med. Biol.* **50** 3655

Berson A M, Emery R, Rodriguez L, Richards G M, Ng T, Sanghavi S and Barsa J 2004 Clinical experience using respiratory gated radiation therapy: comparison of free-breathing and breath-hold techniques *Int. J. Radiat. Oncol. Biol. Phys.* **60** 419–26

Geneser S, Kielar K, Kim T and Xing L 2011 Reducing gated IMRT delivery times: dual-gating

Med. Phys. **38** 3686

George R, Chung T D, Vedam S S, Ramakrishnan V, Mohan R, Weiss E and Keall P J 2006 Audio- visual biofeedback for respiratory-gated radiotherapy: impact of audio instruction and audio-visual biofeedback on respiratory-gated radiotherapy *Int. J. Radiat. Oncol. Biol. Phys.* **65** 924–33

Hayden A J, Rains M and Tiver K 2012 Deep inspiration breath hold technique reduces heart dose from radiotherapy for left-sided breast cancer *J. Med. Imaging Radiat. Oncol.* **56** 464–72

Hugo G D, Campbell J, Zhang T and Di Yan D S 2009 Cumulative lung dose for several motion management strategies as a function of pre-treatment patient parameters *Int. J. Radiat. Oncol. Biol. Phys.* **74** 593–601

Keall P *et al* 2006a The management of respiratory motion in radiation oncology report of AAPM Task Group 76 *Med. Phys.* **33** 3874–900

Keall P J, Cattell H, Pokhrel D, Dieterich S, Wong K H, Murphy M J, Vedam S S, Wijesooriya K and Mohan R 2006b Geometric accuracy of a real-time target tracking system with dynamic multileaf collimator tracking system *Int. J. Radiat. Oncol. Biol. Phys.* **65** 1579–84

Kim S, Park Y-K, Lee J, Choi K and Ye S-J 2013 Double-ends quasi-breath-hold (DE-QBH) technique for respiratory motion management *Med. Phys.* **40** 286–7

Kim T, Pollock S, Lee D, O'Brien R and Keall P 2012 Audiovisual biofeedback improves diaphragm motion reproducibility in MRI *Med. Phys.* **39** 6921

Kini V R, Vedam S S, Keall P J, Patil S, Chen C and Mohan R 2003 Patient training in respiratory-gated radiotherapy *Med. Dosim.* **28** 7–11

Langner U W and Keall P J 2010 Quantification of artifact reduction with real-time cine 4D computed tomography acquisition methods *Int. J. Radiat. Oncol. Biol. Phys.* **76** 1242–50

Lim S *et al* 2007 Guiding curve based on the normal breathing as monitored by thermocouple for regular breathing *Med. Phys.* **34** 4514–8

Linthout N, Bral S, Van de Vondel I, Verellen D, Tournel K, Gevaert T, Duchateau M, Reynders T and Storme G 2009 Treatment delivery time optimization of respiratory gated radiation therapy by application of audio-visual feedback *Radiother. Oncol.* **91** 330–5

Locklin J K, Yanof J, Luk A, Varro Z, Patriciu A and Wood B J 2007 Respiratory biofeedback during CT-guided procedures *J. Vasc. Interv. Radiol.* **18** 749–55

Marks L B, Bentzen S M, Deasy J O, Kong F M S, Bradley J D, Vogelius I S, El Naqa I, Hubbs J L, Lebesque J V and Timmerman R D 2010 Radiation dose-volume effects in the lung *Int. J. Radiat. Oncol. Biol. Phys.* **76** S70–6

Park Y K, Kim S, Kim H, Kim I I H, Lee K and Ye S J 2011 Quasi-breath-hold technique using personalized audio-visual biofeedback for respiratory motion management in radiotherapy *Med. Phys.* **38** 3114

Theuws J, Kwa S L S, Wagenaar A C, Seppenwoolde Y, Boersma L J, Damen E M F, Muller S H, Baas P and Lebesque J V 1998 Prediction of overall pulmonary function loss in relation to the 3D dose distribution for patients with breast cancer and malignant lymphoma *Radiother. Oncol.* **49** 233–43

Venkat R B, Sawant A, Suh Y, George R and Keall P J 2008 Development and preliminary evaluation of a prototype audiovisual biofeedback device incorporating a patient-specific guiding waveform *Phys. Med. Biol.* **53** N197–208

Wang Y, Christy P S, Korosec F R, Alley M T, Grist T M, Polzin J A and Mistretta C A 1995 Coronary MRI with a respiratory feedback monitor: the 2D imaging case *Magn. Reson. Med.* **33** 116–21

Yamamoto T, Langner U, Loo B W Jr, Shen J and Keall P J 2008 Retrospective analysis of artifacts in 4D CT images of 50 abdominal and thoracic radiotherapy patients *Int. J. Radiat. Oncol. Biol. Phys.* **72** 1250–8

Yang J, Yamamoto T, Cho B, Seo Y and Keall P J 2012 The impact of audio-visual biofeedback on 4DPET images: results of a phantom study *Med. Phys.* **39** 1046–57