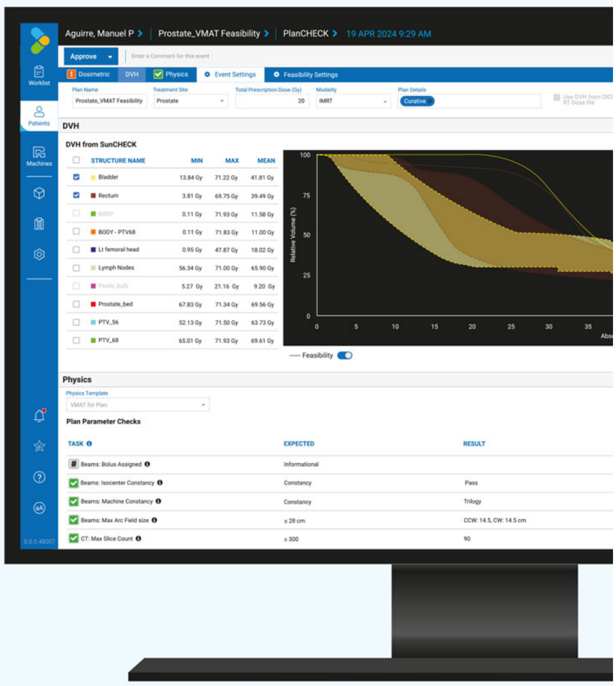
Physics in Medicine & Biology

Using surface imaging and visual coaching to improve the reproducibility and stability of deep-inspiration breath hold for left-breast-cancer radiotherapy

To cite this article: Laura I Cerviño *et al* 2009 *Phys. Med. Biol.* **54** 6853



IOP PUBLISHING PHYSICS IN MEDICINE AND BIOLOGY

Phys. Med. Biol. **54** (2009) 6853–6865 doi:10.1088/0031-9155/54/22/007

Using surface imaging and visual coaching to improve the reproducibility and stability of deep-inspiration breath hold for left-breast-cancer radiotherapy

Laura I Cerviño, Sonia Gupta, Mary A Rose, Catheryn Yashar and Steve B Jiang

Department of Radiation Oncology, University of California San Diego, 3855 Health Sciences Dr, La Jolla, CA 92037-0843, USA

E-mail: sbjiang@ucsd.edu

Received 21 May 2009, in final form 20 August 2009
Published 28 October 2009
Online at stacks.iop.org/PMB/54/6853

Abstract

Late cardiac complications may arise after left-breast radiation therapy. Deep-inspiration breath hold (DIBH) allows reduction of the irradiated heart volume at the same time as it reduces tumor bed motion and increases lung sparing. In the present study, we have evaluated the improvement in reproducibility and stability of the DIBH for left-breast-cancer treatment when visual coaching is provided with the aid of 3D video surface imaging and video goggles. Five left-breast-cancer patients and fifteen healthy volunteers were asked to perform a series of DIBHs without and with visual coaching. Reproducibility and stability of DIBH were measured for each individual with and without visual coaching. The average reproducibility and stability changed from 2.1 mm and 1.5 mm, respectively, without visual feedback to 0.5 mm and 0.7 mm with visual feedback, showing a significant statistical difference ($p < 0.001$ for reproducibility, $p < 0.01$ for stability). Significant changes (>2 mm) in reproducibility and stability were observed in 35% and 15% of the subjects, respectively. The average chest wall excursion of the DIBH with respect to the free breathing preceding the DIBH was found to be 11.3 mm. The reproducibility and stability of the DIBH improve significantly from the visual coaching provided to the patient, especially in those patients with poor reproducibility and stability.

1. Introduction

Breast cancer is diagnosed in approximately 200 000 women per year in the United States. Breast and lung cancers are the predominant causes of cancer mortality in women each year. While tumors may arise in either breast, breast cancer is slightly more common on the left than right sides (Perkins *et al* 2004). Conventional radiotherapy treatments of left-breast cancer use two tangential photon beams in order to avoid, as much as possible, irradiating the lung and the heart. Researchers have found that women treated for cancer of the left breast had higher rates of chest pain, coronary artery disease and myocardial infarction (Recht 2006, Harris *et al* 2006, Correa *et al* 2007). While it is difficult to correlate a specific risk of cardiac complication with irradiated cardiac volume, the results from these studies clearly indicate the need to reduce this volume as much as possible.

Deep-inspiration breath hold (DIBH) is a maneuver that consists of a free breathing (FB) interval followed by a breath hold at approximately 100% vital capacity during a prescribed period. The DIBH technique has two different features: (1) deep inspiration, which increases the distance from the left-breast tumor or tumor bed to the heart (Lu *et al* 2000, Sixel *et al* 2001, Remouchamps *et al* 2003) and reduces lung density, therefore increasing normal tissue sparing; and (2) breath hold, which immobilizes the tumor or tumor bed (Hanley *et al* 1999, Mageras and Yorke 2004, Stock *et al* 2006). Korreman *et al* (2005) and Pedersen *et al* (2004) have shown some of the dosimetric benefits of providing gated treatment at DIBH versus FB. These studies, which used data from 17 patients, involved treatment planning and evaluation based on regular CT scans of each patient at different breathing conditions. For left-breast-cancer patients (nine patients), the median heart volume receiving more than 50% of the prescription dose was reduced from 19.2% with FB to 1.9% with DIBH, and the median left anterior descending coronary artery volume was reduced from 88.9% to 3.6%. At the same time, the median ipsilateral relative lung volume irradiated to $>50\%$ of the prescribed target dose for both right- and left-sided cancers was reduced from 45.6% with FB to 27.7% with DIBH. They also showed that the mean anterior–posterior chest wall excursion of the DIBH with respect to the mid-FB position was 12.6 mm, while during DIBH it was 4.1 mm. DIBH also showed a potential benefit in reducing liver-irradiated volume during right-sided breast treatment.

Respiratory-gated treatments consist in delivering radiation only during certain time intervals, synchronous with the patient's respiratory cycle, when the tumor or tumor bed is in the path of the beam, while a device monitors patient breathing (Jiang 2006). During treatment of left-breast-cancer patients at DIBH, the gating window is around the DIBH level (Mageras and Yorke 2004, Remouchamps *et al* 2007). As a result of treating only during certain time intervals, gated treatment increases the total treatment time. Treatment efficiency in terms of duty cycle can be improved with the cooperation of the patient and with visual and audio respiratory coaching (Mageras *et al* 2001, Nelson *et al* 2005, George *et al* 2006, Neicu *et al* 2006, Baroni *et al* 2007). It has been shown that audio coaching alone improves periodicity of the patient breathing pattern but not amplitude or baseline drift (Kini *et al* 2003, Neicu *et al* 2006). For DIBH reproducibility, which involves only amplitude and not frequency, visual coaching is therefore more appropriate. DIBH reproducibility and/or stability have been previously studied, although with a focus on lung cancer patients and abdominal breathing, and with fiducial markers positioned on the surface of the patients or volunteers (Stock *et al* 2006, Nakamura *et al* 2007).

In order to perform respiratory gating, the breathing signal has to be monitored. There exist different methods to monitor the breath hold. The most commonly used device is a spirometer to measure air flow (Hanley *et al* 1999, Rosenzweig *et al* 2000, Mah *et al* 2000). Spirometers provide the lung volume from a baseline (for example end of exhale). An occlusion valve can be added to the spirometer, forcing the breath hold when desired and leading to forced breath hold. Voluntary breath hold can also be monitored by placing a marker block with reflectors on the patient surface, by means of an infrared camera that tracks the motion of the reflectors. Mostly used for lung gating treatments, it has also been used in breath hold treatment of upper abdomen and breast (Berson *et al* 2004, Pedersen *et al* 2004). In recent

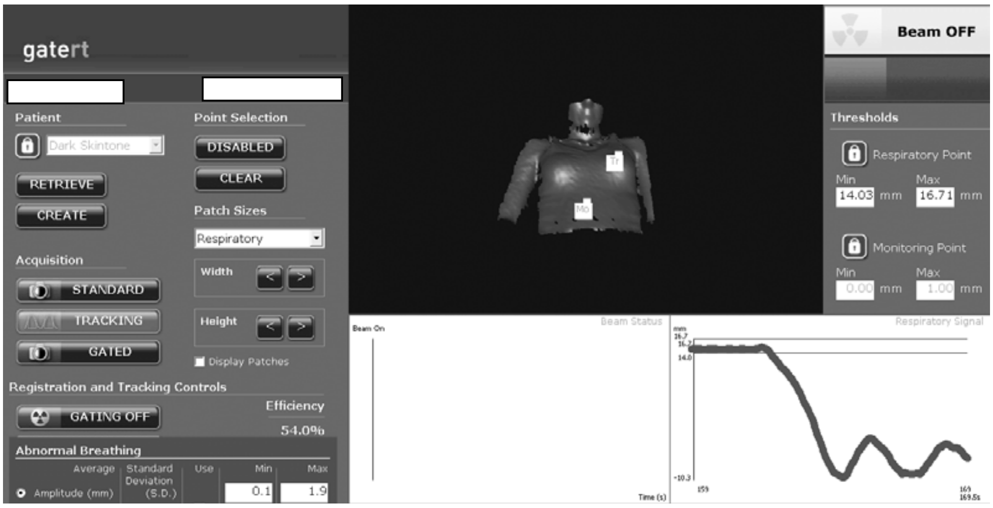


Figure 1. Reconstructed surface and breathing signal extracted from surface motion.

years, optical tracking systems have been proposed in radiotherapy (Djajaputra and Li 2005, Meeks *et al* 2005, Remouchamps *et al* 2007, Baroni *et al* 2007). The GateCT-RT system (Vision RT Ltd, London, UK) consists of one or two ceiling-mounted 3D stereo cameras focused on the patient positioned on the treatment table. The camera projects a patterned light that is used to reconstruct the 3D surface of the patient (figure 1). These systems can be used for positioning, monitoring and breathing tracking. Several investigators have evaluated the accuracy of the system in phantoms and patients, showing the ability of the system to detect fractional millimeter shifts (Bert *et al* 2005, 2006, Schöffel *et al* 2007). In left-breast-cancer treatment surface imaging provides assistance in patient setup (Gierga *et al* 2008), in addition to providing the breathing signal. Therefore, surface imaging can potentially be used to ensure reproducibility of treatment position as well as reproducibility of the DIBH.

The goal of this project is to evaluate reproducibility and stability of the DIBH in order to develop an optimal visual breathing coaching protocol to enable gating during left-breast-cancer treatments, with the aid of a 3D video surface imaging system for tracking breast motion and a set of goggles to provide visual feedback to the patient. Our results show that for some volunteers and patients, the DIBH is neither stable nor reproducible when no visual coaching is provided to the patient. However, reproducibility and stability of the DIBH are improved by using visual breathing coaching and 3D surface imaging.

2. Methods and materials

2.1. Subject recruitment

Fifteen healthy volunteers (seven females and eight males) and five female left-breast-cancer patients undergoing whole breast radiation therapy were recruited for the proposed study. The mean age of all patients and volunteers was 38 years (range 20–85).

2.2. Respiration monitoring and visual feedback

The Radiation Oncology Department at the University of California, San Diego, has acquired three Vision RT systems. One has been installed in the linear accelerator treatment room, one

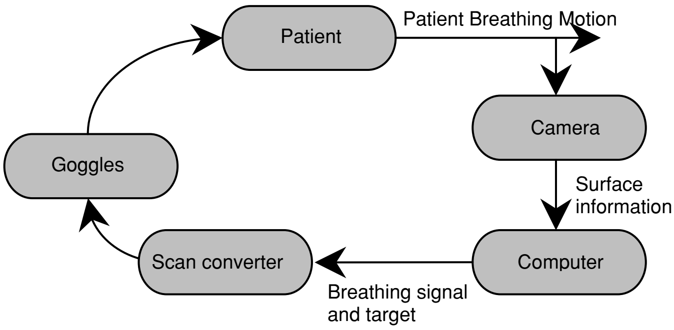


Figure 2. Schematic of the feedback system formed by the patient, camera, computer, scan converter and goggles. The camera records the patient surface images, which are sent to the computer. The computer calculates the patient breathing signal by comparing the current image with respect to the reference image, and displays this signal and the target DIBH level. The scan converter changes the resolution of the display and sends it to the goggles, which are used by the patient. The patient then modifies the breathing pattern to adapt it to the target level.

in the simulator CT room, and one is a mobile system for research purposes. The GateCT-RT software is used for tracking subject's surface motion. A set of video goggles is used together with a scan converter connected to the computer for providing visual feedback to the subject. The goggles receive the respiratory signal and the DIBH gating window for coaching from the scan converter. A schematic of the system components and flow of information between the different components is shown in figure 2. The feedback system consists of the subject, the surface imaging camera, a computer, a scan converter, and a set of video goggles. The camera records the subject's surface images in real time, which are sent to the computer. The computer extracts the subject's breathing signal from the images by comparing the real-time acquired images with the initial (reference) image. The breathing signal and the horizontal lines that identify the target DIBH window are displayed. The scan converter changes the resolution of the display and sends it to the goggles, which are used by the subject for visual feedback. The subject then modifies the breathing pattern to adapt it to the target level.

The camera in the CT simulator room was used with patients, while the mobile research camera was used for tests with volunteers.

2.3. Performance of DIBHs without and with visual feedback

Studies of reproducibility and stability of DIBH with and without visual feedback were performed on 5 left-breast-cancer patients and 15 volunteers. The Vision RT camera was first used to acquire a three-dimensional image of the person's surface. Because the final application of the present study is radiotherapy of breast cancer patients, the surface of interest to track is the breast. We selected a small tracking region of a few centimeters on the lateral surface of the breast close to the nipple that was observed to reproduce well the thoracic breathing motion. The selection of the size of this region is made based on the acquisition and registration frequency provided by the surface imaging system. We achieve a breathing signal which is sampled at 10–13 Hz, which is good to obtain a smooth signal. If the size of the region is increased, the achieved frequency slows down to a few to 1 Hz (depending on the size). Small frequencies are not appropriate to provide visual feedback to the patients, who will find it very difficult to interpret it, since any modification to the breathing pattern that they make will be reflected in the visual feedback with some substantial delay.

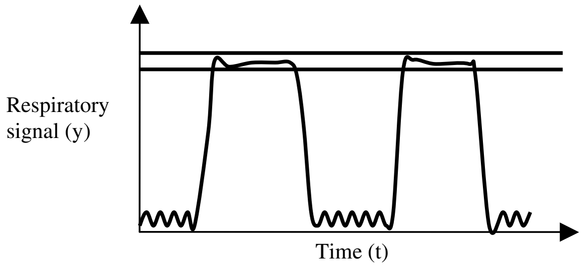


Figure 3. Breathing coaching technique. Horizontal lines indicate the DIBH target window. Subjects were asked to maintain the DIBH level between the two horizontal lines.

Patients and volunteers were asked to perform free breathing for about 1 min followed by a deep-inspiration breath hold of about 20 s (they were told when to start and to stop the DIBH). This operation was repeated four times without visual feedback and four times with visual feedback. For consistency in the breathing mechanism between different DIBHs and between different individuals, patients and volunteers were asked to perform chest breathing during the performance of the DIBH rather than abdominal breathing. Visual coaching was provided with the aid of the goggles, which were connected to the system computer and displayed the respiratory signal of the point tracked by GateCT-RT. Immediately following the non-coached set of DIBHs, the goggles were turned on so that the subject was able to see his/her own breathing signal and a DIBH target window, as indicated in figure 3. This target window was identified for each patient and volunteer as their approximate average DIBH level during the non-coached DIBHs with a small margin (of about 1–1.5 mm). During the coached DIBH, they were asked to maintain the respiratory signal within the target window. All the patients and volunteers had several training DIBHs with visual feedback for practice and comprehension of the process. The anterior–posterior chest wall excursion during the performance of the DIBHs, measured by the amplitude of the DIBH with respect to the free-breathing baseline, was calculated with and without visual coaching.

2.4. Reproducibility and stability study

Reproducibility and stability with and without visual coaching have been studied and compared. Stock *et al* (2006) investigated DIBH reproducibility and stability in lung cancer patients. In their study, the length of the DIBHs was 10 s, and the reproducibility and stability was measured in percentages of the DIBH amplitude. However, due to the fact that breast cancer patients generally do not have breathing impedance, the 20 s length was used in our study. Longer duration DIBHs allow treatments with less breath holds and therefore lead to shorter treatment times. Reproducibility and stability here will be expressed in mm, which corresponds to the units used for patient setup.

For each of the coached or non-coached series of DIBHs, reproducibility is defined as the maximum difference between different DIBH levels:

$$R = \max_{i=[1,n]} \{d_i\} - \min_{i=[1,n]} \{d_i\}, \tag{1}$$

where R is the reproducibility, d_i is the average level of each DIBH in the series, as shown in figure 4 and n is the number of DIBHs in the series. The reproducibility is given in units of length (mm). The more varied the DIBH levels, the larger this value is. Therefore, a large R value represents poor reproducibility, whereas a small R value indicates good reproducibility.

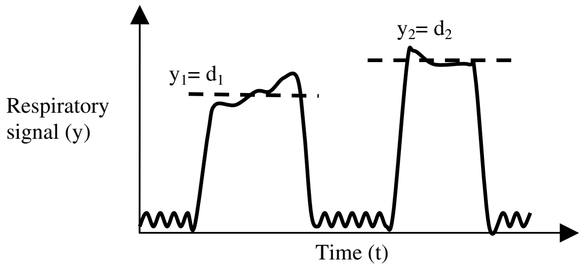


Figure 4. Graphical representation of reproducibility parameters.

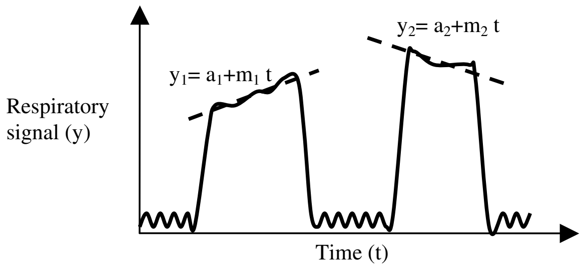


Figure 5. Graphical representation of stability parameters.

Reproducibility has been defined in the previous literature (Nakamura *et al* 2007, Yoshitake *et al* 2008, Stock *et al* 2006). However, during this study, it has been observed that the reproducibility as it has been defined here is more representative of the real surface position difference during the performance of different DIBHs.

Stability is defined as the maximum, among all the DIBHs in each series, of the amplitude change between the initial and end time points of a DIBH when it is fit by a line with least squares:

$$S = \max_{i=[1,n]} \{|m_i|\Delta t\}, \tag{2}$$

where m_i is the slope of the linear fit to each DIBH (mm s^{-1}), as indicated in figure 5, and the quantity Δt is the DIBH duration, which, in our case, is 20 s. In other words, the stability represents the maximum position change during a DIBH when it is represented by a line. Like reproducibility, it has units of length (mm). This definition of stability is closer to the definition of the maximum error at the 95% confidence level e_{95}. Because there are only four DIBHs, the maximum error has been taken instead of e_{95}. A different definition of stability has previously been used in the published literature (Stock *et al* 2006), which is defined as the average of the standard deviations of all the DIBHs. The present definition has been chosen because it is more representative of the surface motion during the performance of a single DIBH than an average value.

2.5. Statistical analysis

Paired *t*-tests were used to estimate significant statistical differences between coached and non-coached performance, for both reproducibility and stability of the DIBH. Also, the correlation between reproducibility and chest wall excursion was studied. Percentages of individuals with

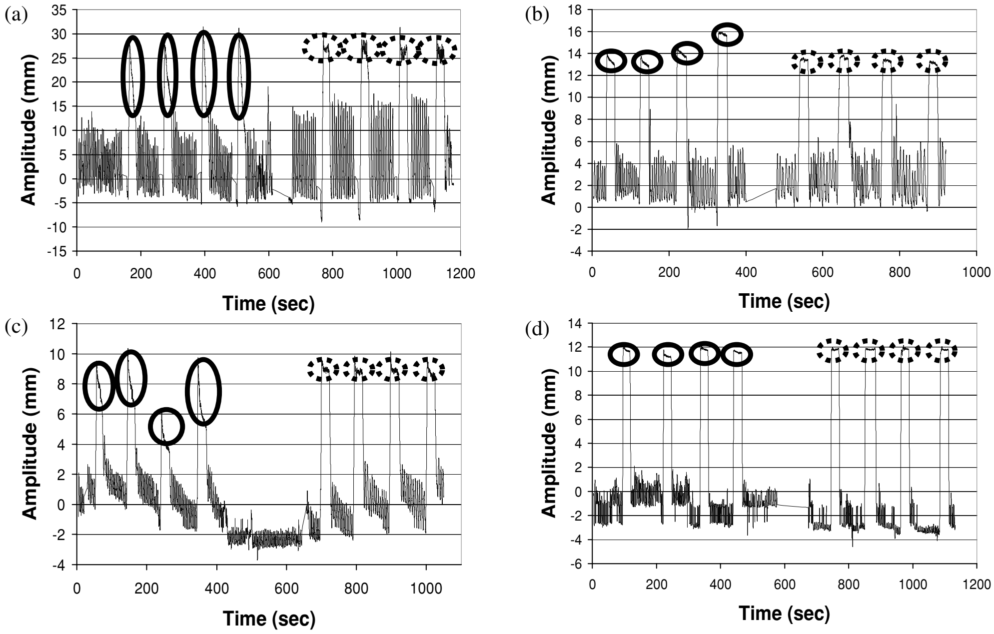


Figure 6. DIBH without and with visual feedback in four different subjects. Without visual feedback (marked in solid-line circles): subjects with poor stability (a), poor reproducibility (b), poor reproducibility and stability (c), and good reproducibility and stability (d). All achieve a good reproducibility and good stability with visual coaching (marked with dotted-line circles).

a clinically significant change (>2 mm) in reproducibility and stability between uncoached DIBH series and coached DIBH series were calculated.

3. Results

Figure 6 shows the respiratory signal (anterior–posterior motion of the tracking region, in millimeters) of four subjects versus time (in seconds). DIBHs are marked with solid-line circles in the absence of visual feedback and with dotted-line circles when visual feedback is supplied. It can be observed that there is a large variation in reproducibility and stability of the DIBH without visual feedback between individuals: volunteers whose DIBH is either not stable (a) or not reproducible (b), or both (c). The breathing signal can be both stable and reproducible even without visual coaching (d). All these four volunteers show good reproducibility and stability of the DIBH with visual feedback.

Reproducibility was calculated as indicated in equation (1) for all the individuals with and without visual feedback. The results of reproducibility are shown in figure 7. Reproducibility without visual feedback is shown in solid line and with visual feedback in dashed line. Data points 1–15 correspond to volunteers and 16–20 to patients. It can be observed that the amplitude of reproducibility is, except for one subject, smaller with visual feedback indicating an improvement with respect to the non-coached DIBH. The individual who did not improve reproducibility (subject 1) had already a good reproducibility (0.5 mm) without visual feedback. Only 25% of the individuals showed sub-millimeter reproducibility without visual feedback, as compared to a 95% of individuals with visual feedback. Taking the average

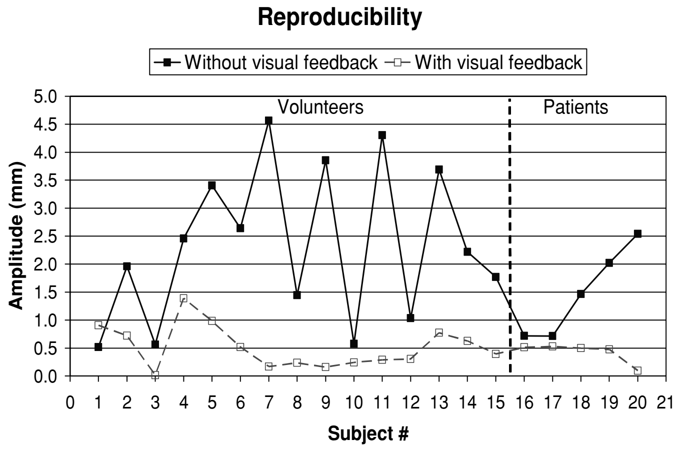


Figure 7. Reproducibility curve of all the patients and volunteers without visual feedback (solid line) and with visual feedback (dashed line). Reproducibility amplitude is lower with visual feedback for all except for one individual, indicating an improvement with respect to the non-coached DIBH.

Table 1. Reproducibility average by groups of reproducibility improvement.

Reproducibility improvement	Number of subjects (volunteers/patients)	Reproducibility without visual feedback (mm)	Reproducibility with visual feedback (mm)
No improvement	1 (5%) (1/0)	0.5	0.9
<2 mm	12 (60%) (8/4)	1.4	0.5
>2 mm	7 (35%) (6/1)	3.6	0.4

of all the volunteers and patients, the reproducibility without visual coaching was found to be 2.1 mm (range 0.5–4.6 mm). The average reproducibility with visual coaching was 0.5 mm (range 0.1–1.4 mm). A significant statistical difference between reproducibility with and without visual feedback was detected ($p < 0.001$). The breakdown of reproducibility into volunteers and patients is 2.3 mm (range 0.5–4.6 mm) for volunteers and 1.5 mm (0.7–2.5 mm) for patients without visual feedback and 0.5 mm (0.1–1.4 mm) and 0.4 mm (0.1–0.5 mm), respectively, with visual feedback.

Overall, 95% of the subjects improved reproducibility with visual coaching. Individuals were classified into three groups depending on the improvement: (1) subjects with no improvement; (2) subjects with improvement smaller than 2 mm; (3) subjects with improvement greater than 2 mm. The results of this classification are shown in table 1. 35% of all the subjects have an improvement of more than 2 mm, which can be considered clinically significant (an improvement of 2 mm would lead in general to reproducibility amplitudes smaller than 2–3 mm, which is similar to chest wall excursion during free breathing). The subjects in this group improved reproducibility from an average of 3.6 mm (range 2.5–4.6 mm) without visual feedback to 0.4 mm (range 0.1–1.0 mm) with visual feedback.

Figure 8 shows the stability values for all the patients and volunteers without visual feedback (solid line) and with visual feedback (dashed line). Stability has been calculated as indicated in equation (2). In most cases the stability amplitude was smaller with visual feedback than without visual feedback, indicating an improvement in the coached with respect

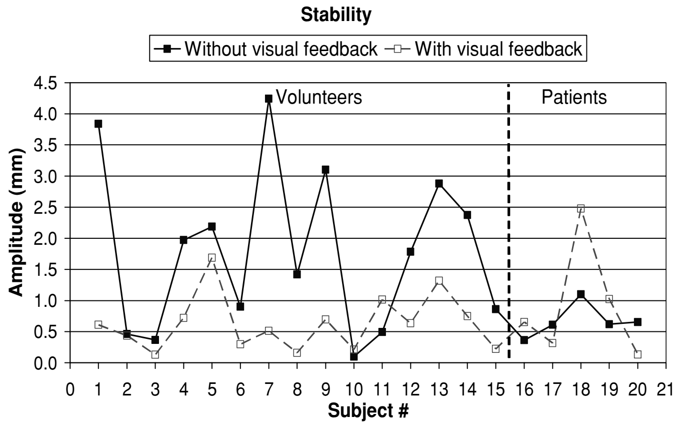


Figure 8. Stability curve of all the patients and volunteers without visual feedback (solid line) and with visual feedback (dashed line). In most of the cases stability amplitude is lower with visual feedback, indicating an improvement with respect to the non-coached DIBH.

Table 2. Stability averages by groups of stability improvement.

Stability improvement	Number of subjects (volunteers/patients)	Stability without visual feedback (mm)	Stability with visual feedback (mm)
No improvement	4 (20%) (2/2)	0.4	0.7
<2 mm	13 (65%) (10/3)	1.4	0.7
>2 mm	3 (15%) (3/0)	3.7	0.6

to non-coached DIBH. All but one of the individuals who did not improve stability with visual feedback had already sub-millimeter stability without visual feedback. 50% of the individuals showed sub-millimeter stability without visual feedback, as compared to a 75% of individuals with visual feedback. The average stability over all patients and volunteers was found to be 1.5 mm (range 0.1–4.2 mm) without visual coaching, and 0.7 mm (range 0.1–2.5 mm) with visual coaching. A significant statistical difference in stability with and without visual feedback was detected ($p < 0.01$). The breakdown of stability into volunteers and patients is 1.7 mm (0.1–4.2 mm) for volunteers and 0.7 mm (0.4–1.1 mm) for patients without visual feedback and 0.6 mm (0.1–1.7 mm) and 0.9 mm (0.1–2.5 mm), respectively, with visual feedback.

Like with reproducibility, individuals have been classified into three groups depending on the magnitude of the stability improvement: (1) no improvement; (2) improvement inferior to 2 mm, and (3) improvement larger than 2 mm. The results of this classification are shown in table 2. While 80% of the subjects improve stability, 15% have an improvement of more than 2 mm, which can be considered clinically significant. The subjects in this group improved stability from an average of 3.7 mm (range 3.1–4.2 mm) without visual feedback to 0.6 mm (range 0.5–0.7 mm) with visual feedback.

Finally, the excursion of the chest wall for each DIBH was measured as the DIBH amplitude with respect to the FB baseline immediately before the breath hold. It was observed that this excursion presents a large variability among all the different individuals. The average ±1 standard deviation of all individuals was found to be 11.3±5.3 mm. Figure 9 shows the chest wall excursion and the reproducibility previously computed without visual

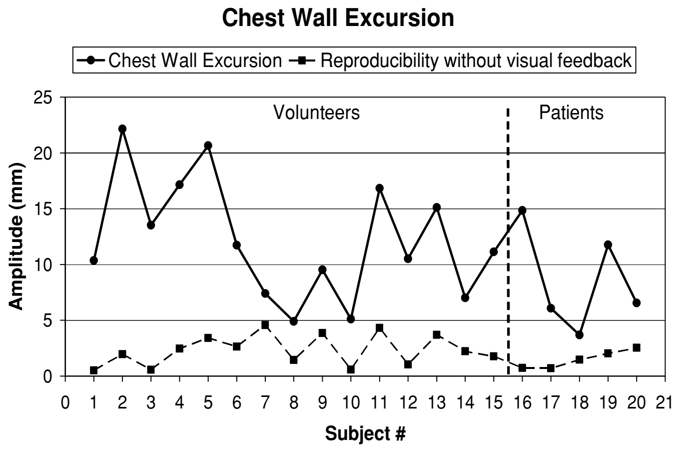


Figure 9. Average chest wall excursion and DIBH reproducibility without visual feedback for every patient and volunteer.

feedback for every patient and volunteer. A study on the correlation of both signals has been performed, showing a correlation factor of 0.28, with no statistical significance ($p = 0.24$). On average, reproducibility without visual feedback represents a 22.0% of the chest wall excursion (range 4.2–61.7%), and reproducibility with visual feedback represents a 4.8% of the chest wall excursion (range 0.1–13.5%). A significant statistical difference was detected between the ratios of reproducibility and chest wall excursion without and with visual coaching ($p < 0.001$).

4. Discussion and conclusions

The present study shows the benefit of providing visual coaching to left-breast-cancer patients for performance of DIBHs in a reproducible and stable manner. Visual feedback was provided by means of video goggles. In most of the cases, individuals were able to improve both reproducibility and stability of the DIBH. The clinical introduction of DIBH will lead to left-breast irradiation treatments with more healthy tissue sparing, especially cardiac and lung tissue. At the same time, better reproducibility and stability will improve target coverage and will allow for a reduction of radiation margins, which also contributes to the sparing of healthy tissues.

The imaging technique used in this study consisted in surface imaging. Volunteers and patients were asked to perform thoracic breathing, and a small tracking region was selected on the breast of the volunteer/patient. This selection is important because reproducibility is crucial not only for ensuring heart sparing, but also for accurate breast treatment. For this reason, a portion of the breast is imaged and tracked. This tracking region can be used for both breathing monitoring and initial patient setup, to ensure reproducibility of both DIBH and patient treatment position. The selection of a larger region of interest that includes the whole or a large area of the breast would currently limit the image acquisition frequency, but will be considered in the future.

A baseline drift of the free breathing respiratory signal after the performance of each DIBH with respect to the baseline before the performance of the DIBH has been observed, a fact that had already been noted by other investigators (Stock *et al* 2006). This baseline drift is in general reduced in amplitude after the 60 s period of free breathing following the DIBH. In addition, the 60 s rest seems appropriate for avoiding fatigue of the individual.

During the realization of this study, we observed that compliance with visual coaching was generally good for all patients and volunteers. Only one patient found difficulties in interpreting the visual feedback provided with the goggles. This difficulty could limit the clinical application of the coached DIBH to patients who can interpret the feedback. Aside from this one case, there was no significant inconvenience or discomfort to the patients in using the goggles.

It was observed that all the volunteers and patients were able to hold their breath at deep inspiration during the requested 20 s. This length is appropriate to get a reasonable treatment duty cycle for tangential breast irradiation, requiring only one or two breath holds for each tangential beam. It is expected that this will be the case for most breast cancer patients, who, in general, do not have breathing impedance. However, this might not be the case for all the patients, and shorter breath holds might be required. If that is the case, more DIBHs might be required, decreasing the duty cycle.

In some subjects, we observed an overshoot in the respiratory signal at the beginning of the DIBH. This overshoot might come naturally when performing a DIBH. However, it might be difficult to modify the DIBH level when it occurs during the coached treatment. We found that most individuals found it easier to perform the coached DIBHs by slowly breathing in until the desired respiratory target level is achieved. Achieving the target level and maintaining it was in general easy. However, modifying this level was harder.

The average chest wall excursion has been found to be 11.3 mm, a value close to the 12.6 mm found by Korreman *et al* (2005) and Pedersen *et al*. (2004) and larger than the 5.8 mm found by Stock *et al* (2006), who might not have required their patients to perform thoracic breathing and who studied lung cancer patients. The standard deviation of the average chest wall excursion is 5.4 mm, which indicates the large variability of the DIBH signal amplitude among individuals. The target DIBH level cannot therefore be generalized to all patients and instead needs to be specified individually. The patient-specific target DIBH level can be determined as an average level of a series of DIBHs (for example 3 or 4, as it has been done in the current study).

The average reproducibility changed from 2.1 mm without visual feedback to 0.5 mm with visual feedback. Although the average reproducibility without visual feedback seems small, it constitutes a 19% of the average DIBH chest wall excursion. 35% of the subjects showed a clinically significant improvement (>2 mm) in the reproducibility when visual coaching was provided, while the remaining 65% had small or no improvement. 95% of the subjects achieved sub-millimeter reproducibility when visual feedback was provided, whereas only 25% achieved sub-millimeter reproducibility without feedback. It is important to ensure treatment reproducibility for every individual, which has shown to be improved by the visual feedback procedure described in this paper.

Average stability was better (smaller) than reproducibility. The bigger breast position change occurred from one DIBH level to another one, which is measured by the reproducibility. Stability measures the change within individual DIBHs. Its average value was 1.5 mm without visual feedback and 0.7 mm with visual feedback. Visual feedback resulted in stability improvement in 80% of the subjects, although clinically significant (>2 mm) in only 15% of the individuals. This smaller clinically significant improvement is in part due to the fact that stability was already smaller than 2 mm in 70% of the subjects. Like reproducibility, stability is patient dependent and important to monitor, and we have observed that visual feedback is beneficial.

Acknowledgments

The authors would like to thank VisionRT Ltd for their financial support, Jana Cooke, MD, for the discussions on breathing and coaching, and Xiaoli Tang, Neelam Tyagi, John Lewis, Alexander Mackenzie, Nan Hu, Will Whartenby, Khalid Jarrah, Florgin Dela Luna, Shaelyn Ochoa, and Alvin Kin Chao for their help with the experiments.

References

Baroni G, Riboldi M, Spadea M F, Tagaste B, Garibaldi C, Orecchia R and Pedotti A 2007 Integration of enhanced optical tracking techniques and imaging in IGRT *J. Radiat. Res.* **48** A61–74

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

Bert C, Metheany K G, Doppke K and Chen G T 2005 A phantom evaluation of a stereo-vision surface imaging system for radiotherapy patient setup *Med. Phys.* **32** 2753–62

Bert C, Metheany K G, Doppke K P, Taghian A G, Powell S N and Chen G T 2006 Clinical experience with a 3D surface patient setup system for alignment of partial-breast irradiation patients *Int. J. Radiat. Oncol. Biol. Phys.* **64** 1265–74

Correa C R, Litt H I, Hwang W-T, Ferrari V A, Solin L J and Harris E E 2007 Coronary artery findings after left-sided compared with right-sided radiation treatment for early-stage breast cancer *J. Clin. Oncol.* **25** 3031–7

Djajaputra D and Li S 2005 Real-time 3D surface-image-guided beam setup in radiotherapy of breast cancer *Med. Phys.* **32** 65–75

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

Gierga D P, Riboldi M, Turcotte J C, Sharp G C, Jiang S B, Taghian A G and Chen G T Y 2008 Comparison of target registration errors for multiple image-guided techniques in accelerated partial breast irradiation *Int. J. Radiat. Oncol. Biol. Phys.* **70** 1239–46

Hanley J *et al* 1999 Deep inspiration breath-hold technique for lung tumors: the potential value of target immobilization and reduced lung density in dose escalation *Int. J. Radiat. Oncol. Biol. Phys.* **45** 603–11

Harris E E R, Correa C, Hwang W-T, Liao J, Litt H I, Ferrari V A and Solin L J 2006 Late cardiac mortality and morbidity in early-stage breast cancer patients after breast-conservation treatment *J. Clin. Oncol.* **24** 4100–6

Jiang S B 2006 Technical aspects of image-guided respiration-gated radiation therapy *Med. Dosim.* **31** 141–51

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

Korreman S S, Pedersen A N, Nøttrup T J, Specht L and Nyström H 2005 Breathing adapted radiotherapy for breast cancer: Comparison of free breathing gating with the breath-hold technique *Radiother. Oncol.* **76** 311–8

Lu H M, Cash E, Chen M H, Chin L, Manning W J, Harris J and Bornstein B 2000 Reduction of cardiac volume in left-breast treatment fields by respiratory maneuvers: a CT study *Int. J. Radiat. Oncol. Biol. Phys.* **47** 895–904

Mageras G S and Yorke E 2004 Deep inspiration breath hold and respiratory gating strategies for reducing organ motion in radiation treatment *Semin. Radiat. Oncol.* **14** 65–75

Mageras G S, Yorke E, Rosenzweig K, Braban L, Keatley E, Ford E, Leibel S A and Ling C C 2001 Fluoroscopic evaluation of diaphragmatic motion reduction with a respiratory gated radiotherapy system *J. Appl. Clin. Med. Phys.* **2** 191–200

Mah D, Hanley J, Rosenzweig K E, Yorke E, Braban L, Ling C C, Leibel S A and Mageras G 2000 Technical aspects of the deep inspiration breath-hold technique in the treatment of thoracic cancer *Int. J. Radiat. Oncol. Biol. Phys.* **48** 1175–85

Meeks S L, Tome W A, Willoughby T R, Kupelian P A, Wagner T H, Buatti J M and Bova F J 2005 Optically guided patient positioning techniques *Semin. Radiat. Oncol.* **15** 192–201

Nakamura K, Shioyama Y, Nomoto S, Ohga S, Toba T, Yoshitake T, Anai S, Terashima H and Honda H 2007 Reproducibility of the abdominal and chest wall position by voluntary breath-hold technique using a laser-based monitoring and visual feedback system *Int. J. Radiat. Oncol. Biol. Phys.* **68** 267–72

Neicu T, Berbeco R, Wolfgang J and Jiang S B 2006 Synchronized moving aperture radiation therapy (SMART): improvement of breathing pattern reproducibility using respiratory coaching *Phys. Med. Biol.* **51** 617–36

Nelson C, Starkschall G, Balter P, Fitzpatrick M J, Antolak J A, Tolani N and Prado K 2005 Respiration-correlated treatment delivery using feedback-guided breath hold: a technical study *Med. Phys.* **32** 175–81

Pedersen A N, Korreman S, Nystrom H and Specht L 2004 Breathing adapted radiotherapy of breast cancer: reduction of cardiac and pulmonary doses using voluntary inspiration breath-hold *Radiother. Oncol.* **72** 53–60

Perkins C I, Hotes J, Kohler B A and Howe H L 2004 Association between breast cancer laterality and tumor location, United States, 1994–1998 *Cancer Causes Control* **15** 637–45

Recht A 2006 Which breast cancer patients should really worry about radiation-induced heart disease—and how much? *J. Clin. Oncol.* **24** 4059–61

Remouchamps V M, Huyskens D P, Mertens I, Destine M, Van Esch A, Salamon E and De Neve W 2007 The use of magnetic sensors to monitor moderate deep inspiration breath hold during breast irradiation with dynamic MLC compensators *Radiother. Oncol.* **82** 341–8

Remouchamps V M, Letts N, Vicini F A, Sharpe M B, Kestin L L, Chen P Y, Martinez A A and Wong J W 2003 Initial clinical experience with moderate deep-inspiration breath hold using an active breathing control device in the treatment of patients with left-sided breast cancer using external beam radiation therapy *Int. J. Radiat. Oncol. Biol. Phys.* **56** 704–15

Rosenzweig K E *et al* 2000 The deep inspiration breath-hold technique in the treatment of inoperable non-small-cell lung cancer *Int. J. Radiat. Oncol. Biol. Phys.* **48** 81–7

Schöffel P J, Harms W, Sroka-Perez G, Schlegel W and Karger C P 2007 Accuracy of a commercial optical 3D surface imaging system for realignment of patients for radiotherapy of the thorax *Phys. Med. Biol.* **52** 3949–63

Sixel K E, Aznar M C and Ung Y C 2001 Deep inspiration breath hold to reduce irradiated heart volume in breast cancer patients *Int. J. Radiat. Oncol. Biol. Phys.* **49** 199–204

Stock M, Kontrisova K, Dieckmann K, Bogner J, Poetter R and Georg D 2006 Development and application of a real-time monitoring and feedback system for deep inspiration breath hold based on external marker tracking *Med. Phys.* **33** 2868–77

Yoshitake T *et al* 2008 Breath-hold monitoring and visual feedback for radiotherapy using a charge-coupled device camera and a head-mounted display: system development and feasibility *Radiat. Med.* **26** 50–5