Scientific Research Publishing

Journal of Modern Physics, 2018, 9, 2286-2294
http://www.scirp.org/journal/jmp
ISSN Online: 2153-120X
ISSN Print: 2153-1196

Audio-Visual Biofeedback for Respiratory Motion Management: Comparison of the Reproducibility of Breath-Holding between Visual and Audio Guidance

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How to cite this paper: Sano, N., Saito, M., Onishi, H., Kuriyama, K., Komiyama, T., Marino, K., Aoki, S. and Araya, M. (2018) Audio-Visual Biofeedback for Respiratory Motion Management: Comparison of the Reproducibility of Breath-Holding between Visual and Audio Guidance. *Journal of Modern Physics*, **9**, 2286-2294.
https://doi.org/10.4236/jmp.2018.913144

Received: October 8, 2018
Accepted: October 30, 2018
Published: November 2, 2018

Abstract

Purpose: To compare the reproducibility of breath-holding and comfort between two biofeedback guidance methods (audio and visual) in a respiratory monitoring system. **Method and Materials:** An audio-feedback respiratory monitoring device, which was modified from a visual-feedback self-respiration monitoring system (Abches, APEX Medical Inc., Tokyo, Japan) previously developed by the authors' group, was constructed. Twenty patients (13 men, 7 women; mean age, 68.5 years; range, 54 - 85 years) with tumors in the thorax or abdominal region were enrolled in the present study. Computed tomography images were acquired from all patients three times using the two (*i.e.*, audio and visual) respiration monitoring devices. To evaluate the reproducibility of breath-holding, the distance between an anatomical landmark and the tumor position was measured. Furthermore, patients were asked which guidance method they preferred (visual or audio) for comfortable breath-holding. **Results:** The two guidance methods improved the reproducibility of breath-holding compared with free-breathing, and no significant overall differences between two methods were observed (the mean displacements of the landmark-tumor distance were 2.60 ± 1.38 mm and 2.35 ± 1.63 mm, for visual and audio guidance, respectively). In five patients, the magnitude of position displacement in the series of three computed tomography images under audio guidance was twice as large as the other under visual guidance. Audio guidance was preferred to visual guidance by 65% (13 of 20) of the patients. However, the reproducibility of breath-holding did not always correspond with patient preference. **Conclusion:** There were some individual differences in the reproducibility of the visual and audio guidance methods.

More appropriate, individualized guidance methods for each patient would improve the reproducibility of breath-holding in respiratory motion management.

Keywords

Respiratory Motion Management

1. Introduction

Management of each respiration cycle effectively minimizes the internal target volume and improves the therapeutic effectiveness of radiation therapy on abdominal or thoracic organs influenced by respiratory movement. There are various approaches to patient respiratory control, such as breath-holding [1] [2], respiratory gating [3] [4], and beam tracking [5]. The breath-holding technique is the most obvious and the simplest of these approaches, which reduce uncertainties related to patient respiratory movement and increase the reproducibility of treatment.

In a previous study, our group developed a simple respiratory indicator for respiratory motion management, consisting of a two-point motion measurement at the chest and abdominal walls (Abches, APEX Medical Inc., Tokyo, Japan) [6]. Abches enables patients to self-control their respiratory level with its visual feedback during a computed tomography (CT) scan for simulation and treatment. The accuracy and effectiveness of the Abches system have been validated by several authors [7] [8]. However, there were some patients who could not perform reproducible breath-holding while under visual guidance. Respiratory motion management should not only be clinically efficient, but also practical and easy for patients. Therefore, we modified the Abches system to add an audio-guidance function. Accordingly, the purpose of the present study was to compare the reproducibility of breath-holding and comfort between breath-holdings under visual and audio guidance.

2. Methods and Materials

2.1. Study Design and Patient Characteristics

Twenty patients with tumors in the thorax or abdominal region were enrolled in the present study. The study protocol was approved by the department review board, and all patients provided written informed consent prior to participating in the study. The participants underwent multiple computed tomography (CT) simulations using two methods of self-respiratory control (visual or audio guidance), and they were asked which guidance method they preferred (visual or audio) for comfortable breath-holding. Patient characteristics are summarized in **Table 1**.

2.2. Details of the Audio-Feedback Device

The Abches system is a self-respiratory control device based on visual confirmation.

The system comprises the main body, a charge-coupled device (CCD) camera, an indicator panel, and two fulcrums that are placed on the breast or abdomen of the patient. A pointer with an indicator panel moves along with the fulcrums during respiration. A mirror is attached to the patient's head, thereby enabling them to see their own respiratory motion. Additional details regarding the device are described in a previous report [6].

During ongoing development, an audio-feedback version of the Abches system was modified from the original visual-feedback version (**Figure 1**). In the

Table 1. Patient characteristics (n = 20).

Characteristic	
Age, years, range (mean)	54 - 85 (68.5)
Sex, male/female	13/7
Treatment site	
Lung	10 (8 upper; 2 lower)
Liver	3
Pancreas	3
Thorax	2
Kidney	1
Cancer stage	
I	5
II	4
III	7
IV	4
Karnofsy Performance status, range %	80 - 100

Data presented as n unless otherwise indicated.

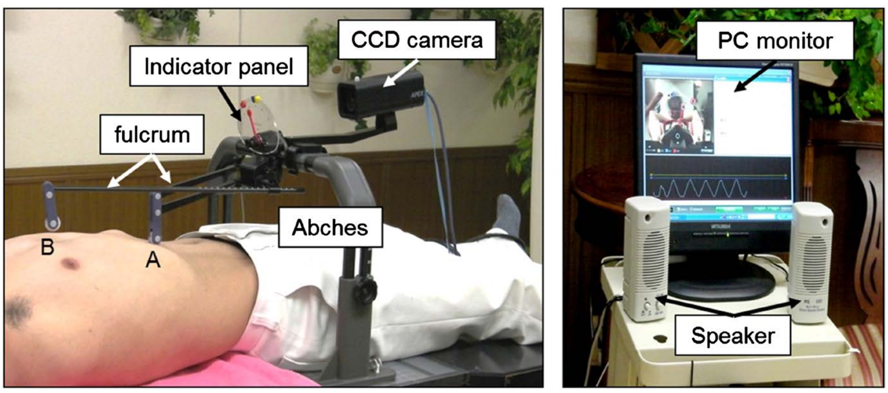

Figure 1. The audio-feedback version of the Abches system (APEX Medical Inc, Tokyo, Japan). Respiratory signals (*i.e.*, movement) from the abdomen and chest of the patient are acquired by the two fulcrums. The indicator panel is captured by a charge-coupled device digital camera attached to the Abches system; the image is displayed on a computer monitor. Monitors are installed in the treatment room and the operator room. The acquired image is used to generate the respiratory waveform. A coaching sound emitted from the speakers informs the patient of the timing of breath-holding.

feedback procedure, the indicator panel is captured by a CCD camera attached to the Abches system, and the image is displayed on a computer monitor. The acquired image is then used for image processing (template matching), and the respiratory waveform is generated from the coordinates of the template matching image. The total sampling time, from image capture to waveform generation, is approximately 90 - 120 ms. Subsequently, a coaching sound is emitted from the speakers, which informs the patient of the timing of breath-holding. As the coaching sound, beep sound was used to make the patient easily understand their own breathing phase. Three levels of the sound are generated (S_L: sound in a region lower than breath-holding region; S_B: sound in breath-holding region; and S_H: sound in a higher region than breath-holding region) (**Figure 2**). It is noteworthy that the audio-feedback version of the Abches system has no mirrors reflecting patient respiration—this enabled an isolated comparison with the conventional (*i.e.*, original) Abches system.

2.3. Respiratory Training and CT Scan Procedure

Before undergoing the CT scan with breath-holding, patient respiratory training was performed. The patient first viewed an instructional video for breath-holding using the Abches system, which was followed by a discussion with an oncologist, who described the system to the patient in more detail. The training was then performed under fluoroscopic guidance, with audio-guidance first, then with visual guidance. Respiratory waveforms from the Abches system and the fluoroscopic image were evaluated to confirm improvements in reproducibility compared with free breathing. If a breath-hold time of 10 s was achieved three consecutive times, the oncologist completed patient training. It was noteworthy that the training protocol was our routine to guarantee the tumor position reproducibility, while some patients needs more practice times.

CT scanning (HiSpeed Dxi, GE Medical Systems, Milwaukee, WIS, USA) was performed using a 2 mm slice thickness and the following settings: 120 kV, 200

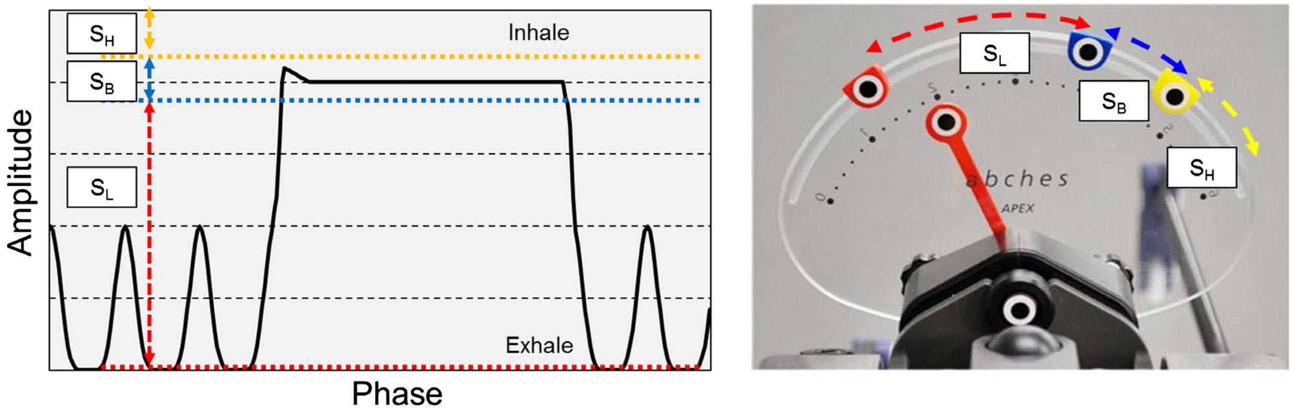

Figure 2. Sample respiratory waveform (left) and the corresponding movement of the indicator panel of the Abches system (APEX Medical Inc, Tokyo, Japan) (right). The respiratory waveform is divided into three regions based on amplitude, and cough sounds are emitted in each region (S_L: sound in region lower than breath-holding region, S_B: sound in breath-holding region, and S_H: sound in region higher than breath-holding region).

mA, 1 s per helical scan, pitch of 1.5, and 38 cm field of view of the entire thorax or abdomen (512 × 512 pixels). Average scan-time was approximately 10 - 15 s per scan, there was only one breath-hold for each patient during CT acquisition.

2.4. Comparison of Audio and Visual Guidance

The reproducibility of breath-holding was evaluated based on the distance from the anatomical landmark to the tumor, for audio and visual guidance, respectively. Figure 3 depicts the typical images. The displacements (mm) were evaluated for the coordinates of X, Y, and Z, respectively. The magnitude of the three-dimensional vector for each direction was evaluated in the same manner.

Following the CT scan, patients were asked which guidance method they preferred (*i.e.*, visual or audio) for comfortable breath-holding. The correlation between the reproducibility of breath-holding and patient preference was evaluated for audio and visual guidance. All statistical analyses were performed using JMP version 11 (SAS institute, Cary, NC, USA).

3. Results

Figure 4 shows the reproducibility results of breath-holding for all patients. There was no significant difference ($p = 0.318$) in the reproducibility between the two guidance methods (Figure 4(b)), although variations in patient preference for the two guidance methods were observed. Next, the divided scatter diagram for the two guidance methods (Figure 4(c)) was evaluated. Each region was divided by slopes of magnitude 2 and 1/2. Although there was no significant overall difference between two methods for the 20 patients, significant differences ($p < 0.063$) in the reproducibility between two methods were observed in region (i) and (iii), respectively. In five patients, the magnitude of position displacement in the series of three CT images under audio guidance was twice as large as the position displacement under visual guidance.

We also evaluated patient preferences for one of the two guidance methods.

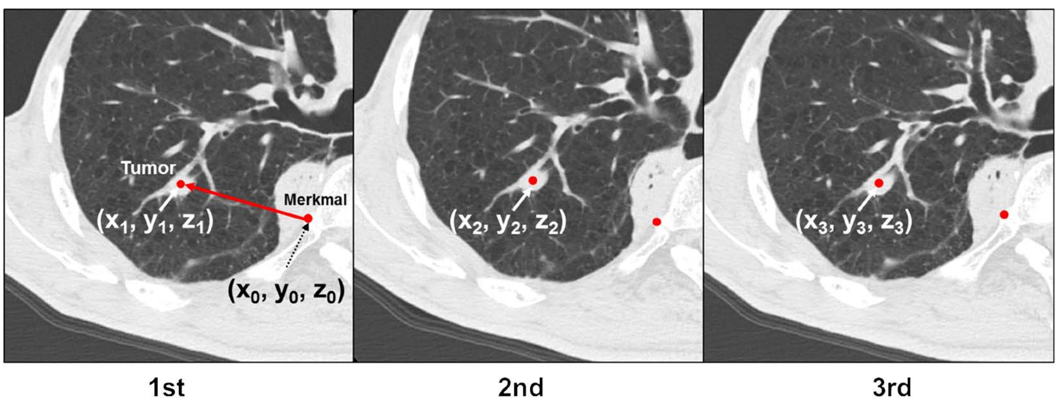

Figure 3. A series of three computed tomography images, ordered 1st, 2nd, and 3rd, demonstrate the same tumor section scanned under breath-holding. To evaluate the reproducibility of breath-holding, the distance between the coordinates of the anatomical landmark (X_0, Y_0, Z_0) and the tumor (X_{1-3}, Y_{1-3}, Z_{1-3}) were measured for each image, respectively.

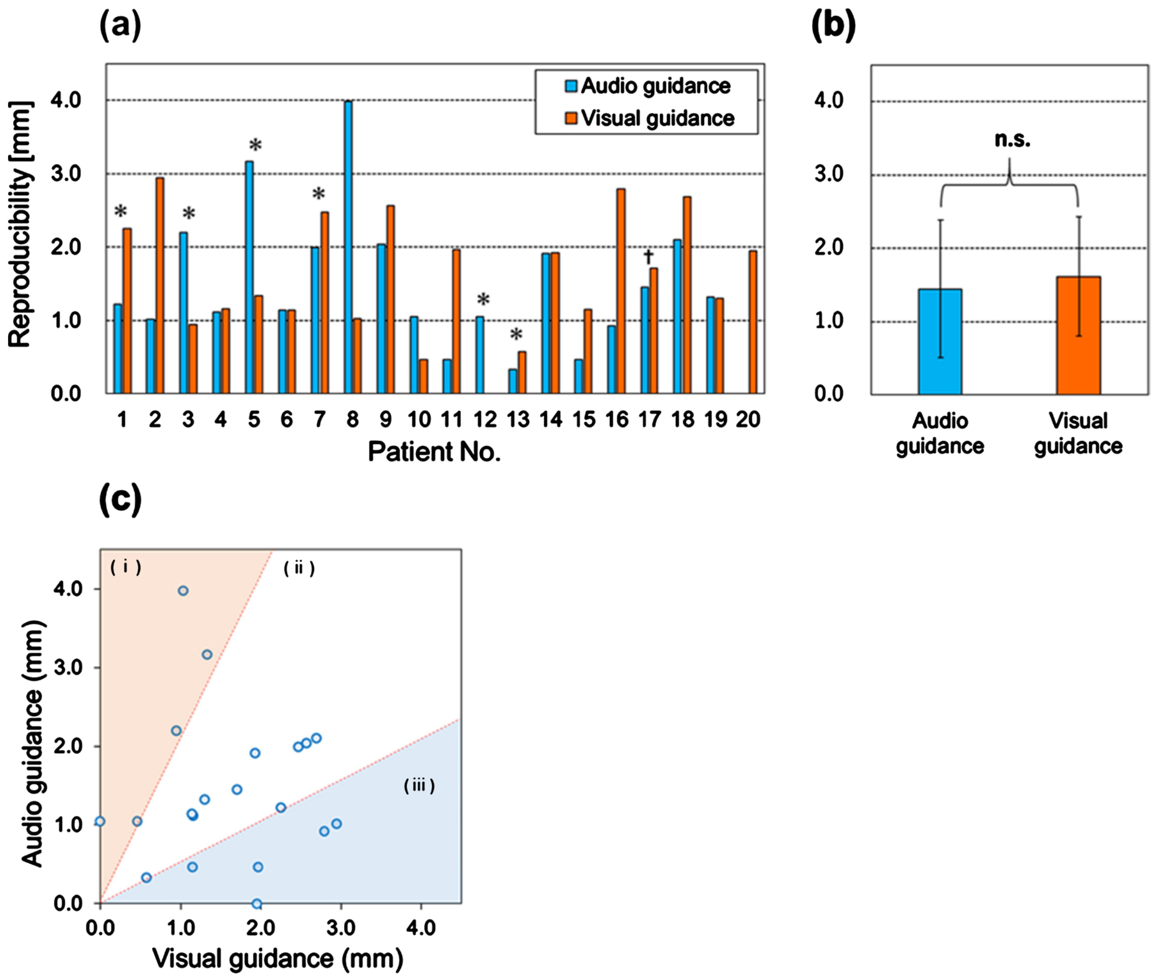

Figure 4. The reproducibility of the tumor position using two methods. (a) Result from each patient (no symbol: audio guidance is better; *: visual guidance is better; †: either audio or visual guidance is acceptable). (b) Mean overall reproducibility (all patients); no significant difference was observed (audio guidance: 2.35 ± 1.63 mm; visual guidance: 2.60 ± 1.38 mm). (c) The divided scatter diagram for the two guidance methods. Each region was divided by the slope of magnitude 2 and 1/2. In the analysis investigating the difference between the two methods, the p-values were 0.318, 0.063, and 0.031, for all data, region (i), and region (iii), respectively. All statistical analyses were performed using the Wilcoxon test.

Audio guidance appeared to be more preferred than visual guidance (response rates were 65% [13 of 20], 30% (6 of 20), and 0.5% [1 of 20], for auditory guidance, visual guidance, and either, respectively). However, not all patient answers corresponded with the reproducibility of breath-holding, as indicated by the asterisk (*) and dagger (†) symbols in Figure 4(a).

The reproducibility of breath-holding for each dimension (vertical, longitudinal, and lateral) was also evaluated (Table 2). In the overall analysis between the two guidance methods, there were no significant differences. In addition, the selection of guidance method was divided into two categories: one based on patient preference; the other based on image analysis after the CT scan. The results (for all dimensions) showed a significant trend toward poorer reproducibility based on patient preference.

Table 2. Comparison of two the guidance methods for reproducibility in breath-holding for each dimension.

	Standard deviation of tumor displacement position (mm)					
	Vertical		Longitudinal		Lateral	
	Mean ± SD	p*	Mean ± SD	p*	Mean ± SD	p*
Comparison of biofeedback						
Visual	0.72 ± 0.46	0.40	0.91 ± 0.89	0.64	0.68 ± 0.69	0.44
Audio	0.53 ± 0.39		1.06 ± 0.78		0.59 ± 0.68	
Comparison according to selection method						
Patient preference	0.75 ± 0.41	0.08	1.10 ± 0.93	0.14	0.65 ± 0.68	0.17
Imaging	0.49 ± 0.38		0.61 ± 0.69		0.45 ± 0.29	

The mean displacement and standard deviation are shown. *Calculated using Wilcoxon test.

4. Discussion

The audio-visual biofeedback system presented here would be useful for any patient, regardless of whether they were more proficient with either audio or visual guidance. The efficacy of audio-visual biofeedback for respiratory-gated radiotherapy has investigated [9] [10]; however, there have been no studies comparing the two biofeedback guidance methods (audio and visual) with regard to reproducibility of breath-holding and comfort. George *et al.* evaluated audio-visual feedback for gated radiotherapy to quantify residual respiratory motion according to the standard deviation of the respiratory signal within the gating window [9]. Venkat *et al.* evaluated two visual feedback models with different displays and cognitive loads: a bar model and a wave model [10]. Briefly, the monitor in front of the patient is turned on to display the bar or wave model visual interface; the task for the patient is to follow the bar or to maintain the ball as closely as possible over the wave. Both models were generated by pre-respiratory data obtained before CT simulation in each patient. The authors demonstrated that the wave model approach reduced cycle-to-cycle variations in displacement by greater than 50%, and variations in period by more than 70% compared with variations under free breathing. Nakajima *et al.* compared respiratory variation using selected audio-visual feedback methods [11]. They collected data from healthy volunteers using the Abches system and respiratory guiding models (bar and wave model, explained above) as visual biofeedback systems. Respiratory variations were quantified as the root mean squared error of displacement and period of breathing cycles. Results showed that all coaching techniques improved variations compared with free-breathing; however, the accuracy between these methods was not directly compared. Accordingly, we directly evaluated the efficacies of audio and visual guidance in patients who had tumors in the thorax or abdominal region.

There was no significant difference in the reproducibility of breath-holding between audio and visual guidance, although both methods improved reproducibility compared with free-breathing. However, some individual variations for each patient were observed, as shown in **Figure 4**, and there were some patients for whom either audio or visual guidance was suitable (**Figure 4(c)**). These variations depended on mainly two factors (patient characteristics and respiratory training procedure), however, further study was needed to investigate the large difference. In other words, our results demonstrated that it may be possible for some patients to improve the reproducibility of breath-holding using the guidance method most suited to their individual characteristics.

Regarding patient preferences, audio guidance appeared to be more preferred than visual guidance. However, not all answers from the patients corresponded with reproducibility in breath-holding. In addition, from the result of **Figure 4(a)**, we found that the selection of the guidance based on patient preference may lead to poorer reproducibility than selection based on image analysis after the CT scan for some cases. This contradiction might be caused by patient individual characteristics. Intuitively, the latter method should be used to achieve the best reproducibility in breath-holding. However, the difference between the two was small (mean difference < 0.5 mm for each direction). According to the TG-76 report from the American Association of Physicists in Medicine (AAPM), it is important for the patient to familiarize him- or herself with the breathing technique, and to evaluate his or her ability to achieve reproducible respiratory signals [12]. In other words, breath-hold methods require active patient participation. Therefore, we suggest that respiratory management should be informed by patient self-decision, and an appropriate determination of guidance method should be individualized according to patient personality.

There were some limitations to the present study, the first of which was the small sample size; similar future investigations should endeavor to use larger samples for more robust statistical analysis. Second, the training should have been performed in a random manner (audio guidance was performed in advance of visual guidance). Finally, the results of this study must be compared with an investigation examining a combination of the two guidance (*i.e.*, audio and visual) methods, which will be the focus of a future study.

5. Conclusion

The reproducibility of breath-holding and the efficacy of two biofeedback guidance methods (audio and visual) in a respiratory monitoring system were compared. There were some individual differences in reproducibility of the two methods. More appropriate, individualized guidance methods for each patient would improve the reproducibility of breath-holding in respiratory motion management.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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