Basic Study on the Most Relaxing Respiration Period in Children to Aid the Development of a Respiration-Leading Stuffed Toy

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Abstract—**Following natural disasters, accidents, and shocking incidents, some children experience post-traumatic stress disorder (PTSD). The respiration control method, which relaxes the body and mind, may efficiently prevent PTSD. Therefore, we developed a stuffed toy that leads children's respiration using the up-and-down movement of the abdomen to help them relax. We investigated the most appropriate respiration period for children's relaxation. Data from studies on heart rate variability (HRV) biofeedback training suggest that breathing at the respiration period at which HRV is the highest is effective for improving chronic diseases. Therefore, we measured the relationship between the respiration period and physiological indices, including HRV. The participants were 10 children aged 5–12 years. HRV was the highest at a 10–12-s respiration period in all 10 children. However, the most suitable respiration period for smooth breathing and relaxation was different from that at which HRV is the highest. Therefore, the most relaxing respiration periods for children need to be determined by indices other than HRV.**

I. Introduction

Following natural disasters, accidents, and shocking incidents, especially after a major disaster such as the Great East Japan Earthquake, some victims experience post-traumatic stress disorder (PTSD). Many children as well as adults require mental care. After the Great Hanshin-Awaji Earthquake in 1995, research was conducted on how children with PTSD cope with fearful events or losses, which indicated that PTSD coping techniques should be prioritized for lower-grade elementary school girls [1]. Further, teaching mental care skills as a preventive technique, rather than as a coping mechanism, for a mental illness after a disaster is needed [1]. The respiration method relaxes the mind and body, and is an important PTSD prevention technique [2]. This method is effective and easy to learn. Breathing slowly and deeply is a good calming method during a stressful traumatic event [3].

Therefore, we developed a respiration-leading stuffed toy for children to encourage them to learn the respiration method [4]. The working of the respiration-leading stuffed toy is as follows: The session starts when the child hugs the stuffed toy and the toy begins measuring the child's pulse wave for a period. Next, the toy calculates the respiration period (RP) from the child's pulse rate (PR) variability and then moves its abdomen up and down at the same frequency as the child's resting RP to lead his/her respiration. The respiration-leading period (LP) ratio of inhalation and exhalation of 1:2 is considered the most relaxing respiration ratio [5, 6]. The movement of the abdomen slows gradually (i.e., the LP lengthens) to decelerate the child's breathing. The LP lengthens until it reaches the most relaxing RP for the child. During this session, the stuffed toy indicates the child's relaxation degree via lights, sounds, and motion. The transportability of this toy is an advantageous characteristic; children can use it at any time and location.

Before implementation, we developed a window-based program that led respiration using a bear character in its display, and conducted an evaluation in a preliminary experiment. In this experiment, the LP was kept unchanged at 4, 6, or 8 s. Children aged 5–7 years experienced difficulty in adjusting their respiration to an LP >6 s, and children aged 8–11 years experienced difficulty in adjusting their respiration completely to an LP of 8 s. As a result, we concluded that it is necessary to begin leading the child's respiration from his/her resting respiration rate. Next, we confirmed that the RP can be measured from pulse data when there is no limb motion disorder. Moreover, the PR and pulse amplitude (PLA) were the most suitable pulse indices to determine whether the child is relaxed [4].

In accordance with these results, we developed a prototype respiration-leading stuffed bear whose abdomen moves up and down. We examined how the child's respiration was led and how the child relaxed by hugging it. This device was tested on 48 healthy children aged 4–12 years (26 males and 22 females). The results showed that children aged ≤6 years, and boys tended to be poorly led compared with girls. Their respiration patterns suggested that the final LP (8 s) was too long [7].

Therefore, we intended to determine the most relaxing RP for children. Data from studies on heart rate variability (HRV) biofeedback training suggest that breathing at the RP that leads to the highest HRV is the most effective for improving chronic diseases. HRV has 2 components: the Mayer wave (approximately 10 s) and the respiration component (approximately 4 s). The amplitude of HRV becomes the highest when the RP lengthens and the respiration component resonates with the Mayer wave component. This phenomenon is called "resonance", and the respiratory frequency at which resonance occurs is called the resonance frequency (RF) [8]. It is reported that when a patient breathes at the RF, symptoms of mental and physical chronic diseases, including PTSD [2], depression [9, 10], chronic heart failure [11], hypertension

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[12], and prehypertension [13], improve. Breathing at the RF causes high-amplitude 180°out-of-phase heart rate (HR) and systolic blood pressure (SBP) oscillations [14]. The RF is reported to be 4.5–7 cpm (i.e. approximately 9–13 s in period) in adults [15], but the RF in children has not been reported. In a preliminary experiment of 6 children, the RP at which HRV became the highest was the RF range of adults [16]. The purpose of this present study was to determine whether the preliminary results can be generalized by including 4 more children, to confirm whether the RP at which HRV became the highest is the RF of the child by comparing SBP and HRV, and to determine the most relaxing respiration period in children.

II. Methods

A. Participants

Ten healthy children (4 males and 6 females) aged 5–12 years participated in the experiment (Table 1). Informed consent was obtained from the parents. This experiment was conducted with approval from the Life Science Ethics Committee of Osaka Institute of Technology.

TABLE I. PHYSICAL CHARACTERISTICS OF PARTICIPANTS

Characteristic	Participant No.									
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Age (y)	5	6	6	7	8	8	9	10	11	12
Sex	F	F	M	M	F	F	M	M	F	F
Height (cm)	106	116	114	128	130	117	131	132	144	144
Weight (kg)	16	18	20	30	30	23	26	28	33	31

Sex; F: Female, M: Male

B. Experimental protocol

Electrocardiogram (ECG), blood pressure (BP), photoplethysmogram (PPG), and respiration were obtained during the experiment. ECG was recorded using electrodes placed on the chest and abdomen of the participant. Data were amplified by a biological amplifier (Polyam4, NIHONSANTEKU Co., Ltd.). BP waveform was recorded from the middle finger or thumb of the left hand using an ambulatory BP monitor (Portapres Model-2, Finapres Medical Systems BV). PPG waveform was recorded from the tip of the index finger on the left hand using an infrared finger probe (Polypul, NIHONSANTEKU Co., Ltd.). Respiration waveform was recorded from the abdomen using a pickup device (TR-751T, NIHON KOHDEN Co., Ltd.).

First, the above-mentioned physiological indices were measured for 60 s with participants in a resting state with their eyes closed. Next, participants used a respiration-leading computer program (Fig. 1). The program included 6–7 trials. In each trial, participants were instructed to synchronize their respiration with the movement of an animated bear character on the monitor that breathed in and out at the same LP for 2 min. The LP of each trial ranged from 5 to 13 s according to the age and breathing ability of the subject. The order of LP was randomized. Five seconds after the trial started, the character began to guide the participant. The ratio of the inhalation period to the exhalation period of the character's movement was kept constant at 1:2. At the end, physiological measurements of participants in the resting state with eyes closed were repeated for 60 s. Participants assessed their degree of relaxation and the ease of following the instructions of the character using a 7-point rating questionnaire after each trial.

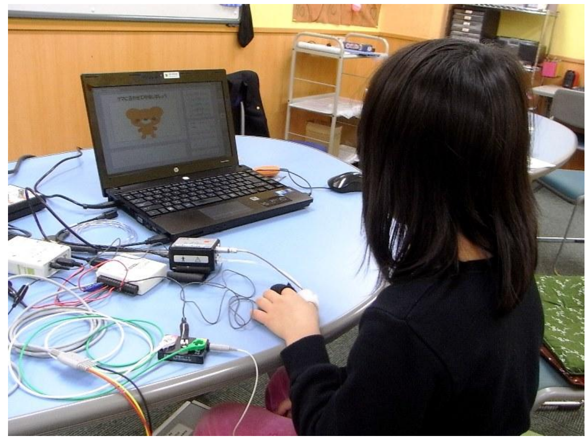

Figure 1. A scene of an experiment (a participant with sensors).

C. Analysis

All physiological index signals were analyzed using a MATLAB program. HR and amplitude of HRV were determined from the ECG (Fig. 2). SBP and amplitude of SBP variability (SBPV) were calculated from BP. PLA was analyzed from PPG. The RP of each respiration and the timing of inhalation and exhalation during the respiration-leading program were analyzed using the respiratory signal.

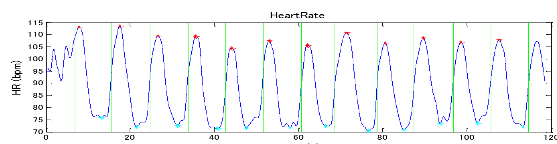

Figure 2. An example of HRV analysis

The overlap ratio was calculated using the RP and the LP. The RP inhalation period (RPI) and the LP inhalation period (LPI) of each respiration were analyzed. If there was overlap between the RPI and LPI, the overlapped time (A) and the sum time (B), which includes the overlapped portion, were determined in seconds. The overlap ratio was calculated as A/B × 100% for each respiration and was averaged over a trial. The overlap ratio equals 100% when the RPI and LPI overlap entirely, but equals 0% when the RPI and the LPI do not overlap (Figs. 3 and 4).

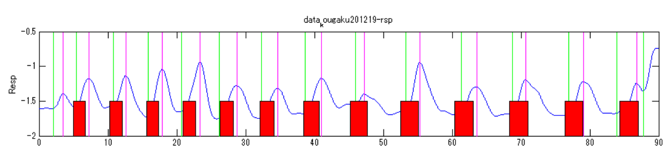

Figure 3. An example of respiration leading data

Units: seconds; Blue lines: Respiration data, Red rectangles: Periods of leading inhalation, Green lines: Start of inhalations, Purple lines: End of inhalations.

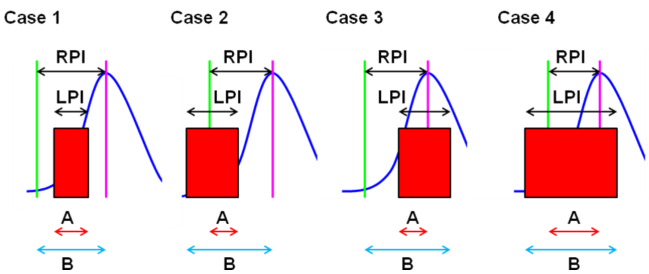

Figure 4. Illustrations for calculation of overlap ratio (A/B).

III. Results

A. Physiological indices

Table II shows the median HRV for the 10 participants during each trial. The LP was 10 s in 4 participants, during which HRV was the highest, 11 s in 5 participants, and 12 s in 1 participant. The highest HRV value of 3 participants (Nos. 5, 8, and 10) were nearly the same as the HRV value of the adjacent LP.

TABLE II. Heart rate variability of each respiration-leading period

No.	Respiration-Leading Period (LP)								
	5	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*
1	12.8	19.5	18.8	17.3	18.0	21.1			
2	39.1	37.8	37.0	36.9	36.0	42.6			
3	14.9	16.6	14.0	16.2	15.9	16.0	20.2		
4	17.9	24.2	29.0	34.8	34.1	36.2	37.9		
5	23.9	18.1	22.3	24.1	28.3	31.6	31.0		
6	23.7	24.4	27.9	29.5	29.8	29.2	33.0		
7	14.7	20.3	18.9	27.4	30.7	34.6	30.8		
8	24.6	25.5	28.2	29.9	29.5	34.5	34.9		
9		12.9	12.2	15.5	13.2	20.6	23.0	19.0	16.1
10		24.1	25.8	27.5	35.9	31.4	35.9	36.1	35.5

Units: beats per minute. Red numbers: the RP with the highest HRV; blue numbers: the RP with the second highest HRV, which is >97% of the highest value; Orange cells: the RP with the highest SBPV for a participant

Fig. 5 shows an example of successful respiration leading. The waveforms of HR, respiration, and SBP were divided at the trigger point of LP inhalation and then overlaid. The HR and SBP waveforms of the participants were not exactly 180° even in the RP with the highest HRV. BP was not measured well in children ≤7 years because their fingers were very thin. Amplitudes of HRV and SBPV became the highest (or almost the highest; No. 10) at the same RP in 4 of 6 participants aged ≥8 years.

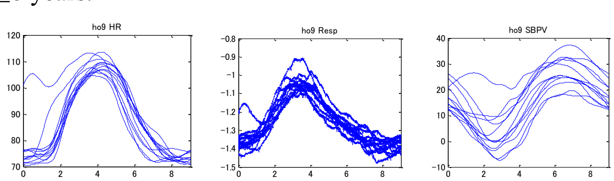

Figure 5. An example of a successful case of respiration leading

Table III shows the subjective measures of relaxation after the respiration-leading trial. A score of 7 indicated relaxation and a score of 1 meant stress after the respiration-leading trial. The RP of the lowest HR and the highest PLA, which we postulated to be an index of relaxation, were not the same as the RP at which HRV and SBPV became the highest in most participants.

TABLE III. Subjective measure of relaxation

No.	Respiration-Leading Period (LP)								
	5	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*
1	4	7	4	4	4	4			
2	6	6	6	6	6	6			
3	4	4	4	4	4	4	4		
4	7	7	4	7	4	1	4		
5	3	3	4	4	6	5	6		
6	4	4	4	4	4	6	5		
7	4	6	5	4	4	5	4		
8		4	4	4	4	3	2		
9		7	6	6	6	5	4	5	5
10		7	7	7	7	7	7	7	7

Red numbers: the RP with the highest HRV for a participant.

Green cells: The most relaxing RP, determined by HR or both HR and PLA, for a participant

Blue cells: The most relaxing RP, determined by PLA, for a participant

B. Overlap ratio

Table IV shows the overlap ratios of 9 participants. Although the respiration of participant no.8 synchronized well with the that of the respiration-leading device, the results for this participant were excluded because the inhalation and exhalation of the participant and device were opposite. The mean overlap ratio was 51.1%. Therefore, we considered values <51.1% as poorly synchronized trials; these are colored in blue.

TABLE IV. Overlap ratios for each respiration-leading period

No.	Respiration-Leading Period (LP)								
	5	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*
1	72.6	56.3	23.7	16.8	14.7	12.6			
2	59.9	67.8	44.2	40.4	32.1	43.1			
3	66.1	54.0	47.3	35.0	21.2	31.3	22.0		
4	29.2	38.2	33.7	38.1	53.0	18.0	10.2		
5	55.7	63.1	73.1	70.4	67.4	53.5	61.5		
6	46.8	51.1	53.7	60.7	50.4	37.9	43.4		
7	73.8	70.3	75.0	74.7	56.1	58.7	43.7		
9		68.1	81.3	81.6	82.0	65.0	54.1	63.1	60.0
10		52.3	49.8	59.1	66.5	61.5	70.1	60.1	75.4

Units: Percent .Blue numbers: RP lower than 51.1%.

Participants aged 5 and 6 years (Nos. 1–3) could not synchronize their respiration with an LP >7 s. Most of the participants aged 7–9 years (Nos. 4–7) showed difficulty in synchronizing their respiration with an LP ≥9–11 s. Participants aged ≥11 years (Nos. 9 and 10) synchronized their respiration well with all LPs tested. Table V shows the subjective measures of ease in following the respiration-leading device. A score of 7 indicated ease and a score of 1 meant difficulty in synchronizing respiration.

TABLE V. SUBJECTIVE MEASURE OF EASE IN FOLLOWING RESPIRATION-LEADING

No.	Respiration-Leading Period (LP)								
	5	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*
1	4.	4	4	4	4	4			
2	6	6	6	6	6	6			
3	6	4	4	4	2	5	1		
4	7	7	6	5	4	1	1		
5	7	7	7	7	7	7	7		
6	7	7	7	7	7	7	7		
7	5	4	4	2	2	4	1		
8		4	4	4	2	3	2		
9		7	4	5	6	3	3	2	2
10		3	4	4	6	5	7	4	2

Units: Points on a scale of 1-7. Red numbers: the RP with the highest HRV for a participant

IV. DISCUSSION

RF (resonance frequency) in children ranged from 5 to 6 cpm (i.e. 10–12 s long), independent of age and height. RF in adults ranged from 4.5 to 7 cpm (i.e. approximately 9–13 s long). These results indicate that the RF of children and adults are almost the same. It has been reported that RF differs between individuals, and that this difference is correlated with height [15]. In the current study, significant correlation was not found between height and RF ($r = 0.513$). The influence of tidal volume is undeniable because the amplitude of HRV is proportional to the tidal volume [17]. All participants attempted to breathe along with the respiration-leading device at long LPs (respiration-leading periods), and their tidal volumes seemed to be large at those LPs.

The phases of HRV and SBPV were not exactly 180°even at RF. This may have occurred because the respiration-leading period ratio of inhalation and exhalation was 1:2, rather than the 1:1 ratio used in previous studies. Further studies using a 1:1 ratio may confirm this. The overlap ratios indicate that children aged ≤6 years could not synchronize their respiration to an LP >7 s, whereas most children aged 7–9 years (except No. 5) showed difficulty synchronizing their respiration to an LP ≥9–11 s. Children aged ≥11 years could synchronize with all LP tested. Subjectively, children aged ≤6 years could not estimate the change in the status of either synchronization or relaxation due to respiration leading. Seven children reported low degrees of ease (≤4 points) in following the respiration-leading device at RF. Children aged ≤10 years (except No.2) did not report feeling relaxed at the RP (respiration period) at which physiological indices showed relaxation. These results concurred with those of our previous research. Physiological measurements are recommended to evaluate children's degree of relaxation and ease of following respiration leading, because children might not be able to observe themselves objectively.

The results of the current study indicate that the most suitable RP for smooth breathing and relaxing differs from the RF. Therefore, the most relaxing respiration periods for children need to be determined by indices other than HRV, such as pulse rate and overlap ratio.

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