

Original Research Article

# The Effect of Motion Artifacts on Near-Infrared Spectroscopy (NIRS) Data and Proposal of a Video-NIRS System

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## Keywords

Near-infrared spectroscopy · Blood oxygen level-dependent imaging · Deoxygenated hemoglobin concentration · Motion artifacts · Video-NIRS system · Word fluency · Mini-Mental State Examination

## Abstract

**Aims:** The aims of this study were (1) to investigate the influence of physical movement on near-infrared spectroscopy (NIRS) data, (2) to establish a video-NIRS system which simultaneously records NIRS data and the subject's movement, and (3) to measure the oxygenated hemoglobin (oxy-Hb) concentration change ( $\Delta$ oxy-Hb) during a word fluency (WF) task. **Experiment 1:** In 5 healthy volunteers, we measured the oxy-Hb and deoxygenated hemoglobin (deoxy-Hb) concentrations during 11 kinds of facial, head, and extremity movements. The probes were set in the bilateral frontal regions. The deoxy-Hb concentration was increased in 85% of the measurements. **Experiment 2:** Using a pillow on the backrest of the chair, we established the video-NIRS system with data acquisition and video capture software. One hundred and seventy-six elderly people performed the WF task. The deoxy-Hb concentration was decreased in 167 subjects (95%). **Experiment 3:** Using the video-NIRS system, we measured the  $\Delta$ oxy-Hb, and compared it with the results of the WF task.  $\Delta$ oxy-Hb was significantly correlated with the number of words. **Conclusion:** Like the blood oxygen level-dependent imaging effect in functional MRI, the deoxy-Hb concentration will decrease if the data correctly reflect the change in neural activity. The video-NIRS system might be useful to collect NIRS data by recording the waveforms and the subject's appearance simultaneously.

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## Introduction

Near-infrared spectroscopy (NIRS) is a light-based technology used to monitor the tissue oxygen status. Many studies using this modality have focused on task-based approaches to examine the cerebral hemodynamic responses evoked by stimuli or during cognitive activities [1]. Given its low operational cost, ease of use, portability, and the ability for patients to be relatively more mobile during studies, NIRS lends itself well to the examination of hemodynamic changes in a clinical setting [2]. Because NIRS interrogates arterial, venous, and capillary blood within the field of view, the derived saturation represents a “tissue” oxygen saturation measured from these three compartments [3]. The blood volume in subcutaneous tissue may increase when a subject tilts his/her head, and this might cause alterations in NIRS data.

Motion artifacts manifest in NIRS data as brief signal inflections 1–2 orders of magnitude larger in amplitude than the hemodynamic signal [4]. Several methods for motion artifact detection and cancellation have been reported in the literature [4, 5]. In the context of the NIRS experimental design, the motion correction methods fall into two distinct categories: those that require some additional input beyond the standard NIRS data set, and those that do not [5]. The former category requires an input signal that is highly correlated with the NIRS motion artifacts but not with the NIRS functional response. A reference NIRS signal can be acquired simultaneously with the standard functional NIRS experiment using an additional NIRS channel. The latter category uses postprocessing techniques that typically take advantage of the distinct amplitude and frequency characteristics of motion artifacts in order to remove them. Despite the prevalence and variety of motion artifact correction techniques, there is little evidence that the application of any of these approaches to functional NIRS actually improves its accuracy. In addition, once motion artifacts have been identified, there is no well-established approach to their removal [5]. Thus, it is useful and important that NIRS data be acquired without motion artifacts whenever possible. By utilizing a video camera and software which went on public sale, we tried to establish a video-NIRS system which is affordable to many researchers and medical doctors in clinical situations.

Blood oxygen level-dependent (BOLD) contrast imaging is most commonly used in functional MRI (fMRI), and provides an indirect measure of the preceding neural activity in the brain [6, 7]. When neurons are active, oxygen consumption increases. This causes changes in local metabolic activity, which in turn modulates blood vessel diameters and produces an overcompensation of the oxygenated blood concentration. Oxygenated blood has a higher ratio of oxygenated hemoglobin (oxy-Hb) to deoxygenated hemoglobin (deoxy-Hb) than deoxygenated blood. oxy-Hb is diamagnetic and exerts little influence on the local magnetic field, whereas deoxy-Hb is paramagnetic and causes signal loss in the corresponding volume elements of the image [7]. Based on the results of BOLD MRI acquired simultaneously with NIRS data in the rat brain, Kida et al. [8] suggested that the influence of hemodynamic changes on the signal intensity of the BOLD effect could be elucidated by NIRS. Thus, the deoxy-Hb concentration in NIRS data will decrease, similar to what can be seen with the BOLD effect in fMRI, if the data correctly reflect the change in blood volume caused by the cognitive task. We may reasonably hypothesize that a decrease in deoxy-Hb concentration in NIRS data can be utilized as a marker of correct acquisition of NIRS.

The goals of this study were as follows: (1) to investigate the influence of physical movement on NIRS data, especially the significance of deoxy-Hb concentration change; (2) to establish an affordable video-NIRS system which simultaneously records NIRS data and the appearance of the subject during acquisition; and (3) to measure the oxy-Hb concentration change ( $\Delta$ oxy-Hb) during a word fluency (WF) task using the video-NIRS system, and to compare the results with the number of words from the WF task, as well as with the score on the Mini-Mental State Examination (MMSE).

## Experiment 1: Relationship between Physical Movement and Artifacts in NIRS Data

### *Subjects and Methods*

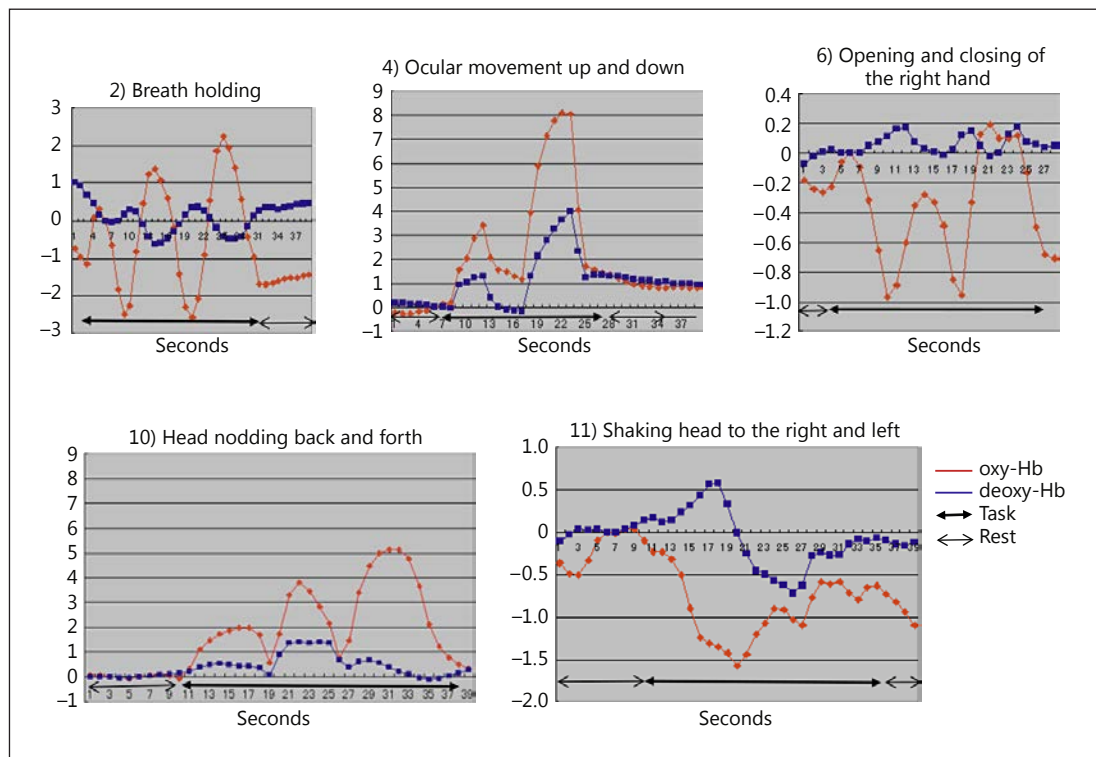
The subjects were 5 healthy young volunteers (2 male and 3 female;  $36.0 \pm 5.0$  years old). Using the NIR-200 device, the data on oxy- and deoxy-Hb were obtained from the bilateral anterior frontal regions. A 2-channel functional NIRS imaging system (NIRO-200; Hamamatsu Photonics KK, Japan) was used to noninvasively investigate the changes in oxy- and deoxy-Hb concentrations [9]. The sampling time for the recording was 0.5 s (2 Hz), and the recordings were transferred online from the NIRO-200 monitor to a personal computer. The NIRO-200 utilizes 3 kinds of near-infrared light (775, 810, and 850 nm) generated by 3 laser diodes used as light sources. Two optical fiber bundles (2.5 m length; 3 mm diameter) carried the light to the right and the left prefrontal cortex, whereas 2 optical fiber bundles of the same size (one for each lobe) collected the light emerging from the frontal areas. Using double-sided adhesive tape, the thin paper-like probes were positioned according to the landmarks of the International 10–20 System for electroencephalogram electrode placement [10]. For the left side, the detector was centered on Fp1 and the emitter was placed at a distance of 4 cm from the detector along the line connecting Fp1 and F7; for the right side, the detector was centered on Fp2 and the emitter along the line connecting Fp2 and F8 (interoptode distance 4 cm). The 2 functional NIRS measurement points (channels) were defined as the midpoint of the corresponding detector-illuminator pairs (distance set at 4 cm). The probabilistic anatomical correlation for these cranial markers is the prefrontal cortex [11, 12]. In order to prevent misalignment of the attached probes, a hair band was placed on top of the probes. The NIRS data were obtained while each subject performed the following 11 movements: (1) deep breathing (for 20 s); (2) breath holding (for 5 s, 2 times); (3) blinking (10 times); (4) ocular movements up and down (for 3 s in each direction, 2 times); (5) ocular movements to the right and left (for 3 s in each direction, 2 times); (6) grasping and opening of the right hand (3 times); (7) grasping and opening of the left hand (3 times); (8) grasping and opening of both hands (3 times); (9) head shaking to the right and left (3 times), (10) head nodding forward and backward (3 times); and (11) jiggling a knee (for 10 s).

### *Results*

Among a total of 55 measurements, deoxy-Hb was increased in 47 (85%) (deep breathing, 3; breath holding, 4; blinking, 4; ocular movements up and down, 4; ocular movements to the right and left, 5; grasping and opening of the right hand, 5; grasping and opening of the left hand, 5; grasping and opening of both hands, 4; head shaking to the right and left, 4; head nodding forward and backward, 5; jiggling a knee, 4). Typical changes in oxy-Hb and deoxy-Hb concentration are shown in Figure 1. The deoxy-Hb concentration was unchanged in 3 measurements (5%; deep breathing, 1; ocular movements up and down, 1; head shaking to the right and left, 1), and only 5 measurements (9%) showed a decrease in deoxy-Hb concentration (deep breathing, 1; ocular movements up and down, 1; blinking, 1; grasping and opening of both hands, 1; jiggling a knee, 1).

### *Discussion*

The present results confirm that physical movement can influence NIRS data – not only movements of the face and head, but also those of the upper and lower extremities. These results are congruent with those reported in the literature, which investigated the relationship between NIRS data and respiration [13], a Valsalva maneuver [14], a bow [15], upper extremity movements [16], finger movements [17], a WF task [18], a visual cognitive task [19], and clenching teeth [20]. Based on the BOLD effect of fMRI, the deoxy-Hb concentration



**Fig. 1.** Typical changes in oxygenated (oxy-) and deoxygenated hemoglobin (deoxy-Hb) concentration during physical movement.

should be decreased during the performance of cognitive tasks. This suggests that NIRS data showing decreased deoxy-Hb concentrations reflect the blood hemodynamic changes during the task. It seems reasonable to suppose that in NIRS data presentation, we should show changes in not only oxy-Hb but also deoxy-Hb concentrations. In order to correctly measure the blood hemodynamic changes induced by a cognitive task and to ascertain the absence of facial and/or physical movement, a NIRS system that prevents physical movement and records the appearance of subjects during acquisition is needed. We proposed that such a system would be achieved by recording the NIRS data and the appearance during the task performance at the same time (video-NIRS system).

## Experiment 2: Establishment of the Video-NIRS System

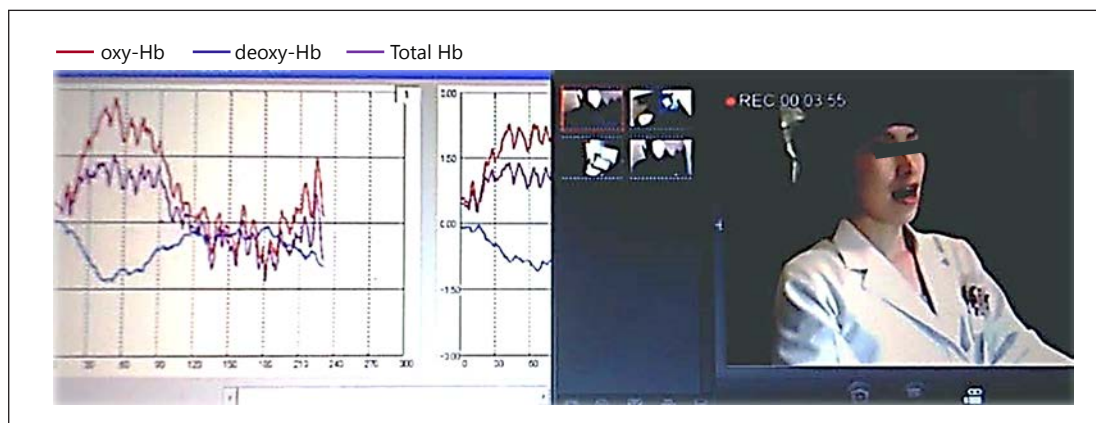
### Subjects and Methods

The subjects were 176 community-dwelling healthy elderly people who received a medical checkup of the brain at Kinan Hospital (24 male and 152 female;  $72.0 \pm 6.0$  years old). They were the same subjects who participated in another project investigating a nonpharmacological intervention in elderly people for dementia prevention (Mihama-Kiho project) [21]. In order to prevent motion artifacts during NIRS data acquisition, we put a pillow made of buffer materials on the backrest of the chair for stabilization of the head (Fig. 2), and a hair band was placed around the head.

In order to record the NIRS data and the appearance of the subjects during their task performance, we set up the video-NIRS system (Fig. 3). This system consisted of the NIRS



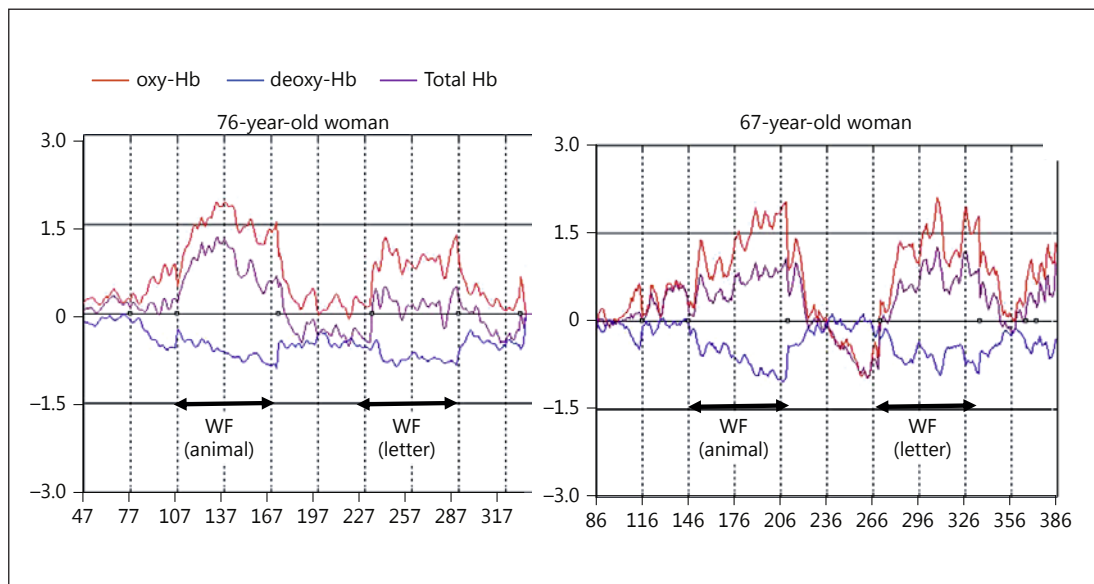
**Fig. 2.** Pillows made of buffer material (a) which were used for fixation of the head (b).



**Fig. 3.** A screen capture of the video-NIRS (near-infrared spectroscopy) system. Using the data acquisition and the video capture software, the NIRS data and the appearance of the subject were simultaneously recorded. We can see the change in oxygenated (oxy-) and deoxygenated hemoglobin (deoxy-Hb) concentration and the appearance of the subject at the same time.

device, a personal computer, and a video camera. We connected the NIRO-200 to a personal computer by a cable, and using multichannel data acquisition and analysis software (NIRS-graph; Photonics Innovations Co. Ltd., Hamamatsu, Japan), we displayed the NIRS data on the screen of the computer in real time during the subjects' task performance. In addition, using a Web camera with video capture software (snagit10; TechSmith Corporation, Japan), the





**Fig. 4.** A typical waveform during the WF task. Note that the deoxy-Hb concentration decreased during the task performance. This is congruent with the BOLD effect on fMRI. BOLD, blood oxygen level-dependent; WF, word fluency; fMRI, functional MRI; oxy-Hb, oxygenated hemoglobin; deoxy-Hb, deoxygenated hemoglobin.

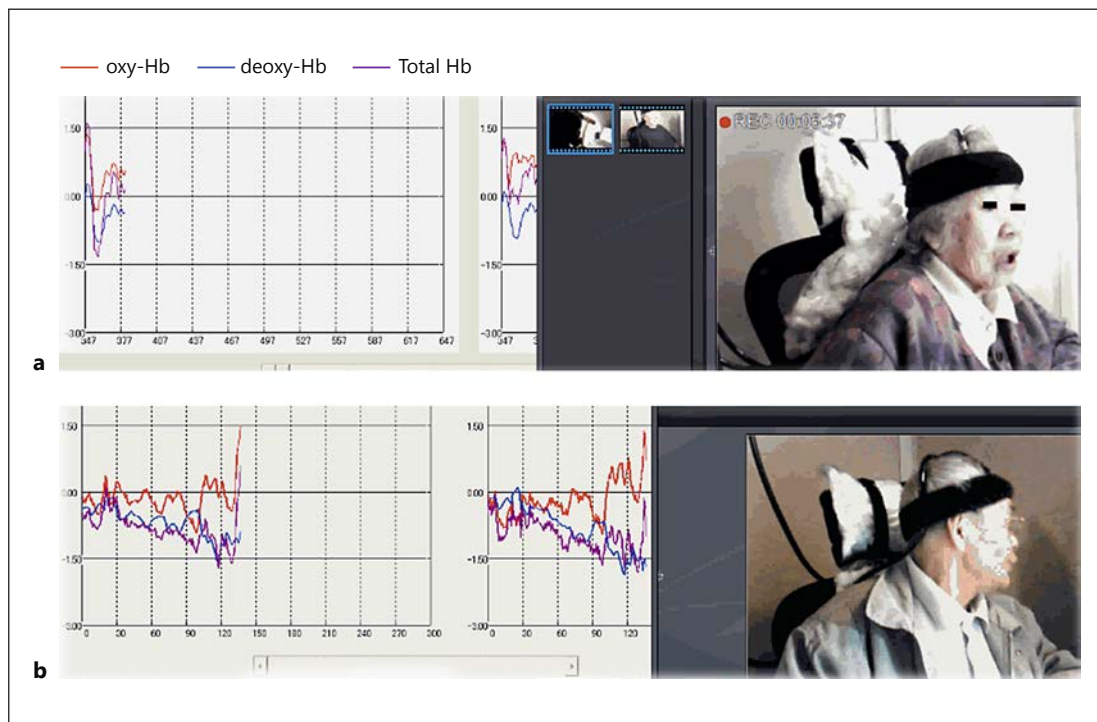
appearance of the subject was displayed on the computer screen simultaneously with the NIRS data. With fixation of the head, each subject performed the WF task for 60 s. The subject was required to say an animal's name and words whose initial pronunciation was "ka," as many as he/she could think of. We counted the number of words the subject enunciated. Using the NIRO-200, data on oxy- and deoxy-Hb were obtained from the bilateral anterior frontal regions. We observed the change in these waveforms and the absence or presence of physical movement in the subject at the same time.

#### Results

Among the 176 subjects, the deoxy-Hb concentration was decreased in 167 (95%). Typical patterns of waveforms of oxy- and deoxy-Hb concentrations are shown in Figure 4. Note that, besides an increase in oxy-Hb, the deoxy-Hb concentration decreased during the performance of the WF task. This phenomenon is congruent with the BOLD effect on fMRI. Nine subjects (5%) showed an increase or no change in deoxy-Hb concentration. In these patients, we could identify physical movement during the WF task by video recording. It is noteworthy that, even in the case of a decrease in deoxy-Hb concentration in the NIRS data, we could assess the state of the subject during the task performance, and could judge whether the data might have been contaminated by motion artifacts or not. In 2 subjects, we could identify the physical movements during the performance of the WF task even when their deoxy-Hb concentration was decreased (Fig. 5).

#### Discussion

We established a video-NIRS system using data acquisition and video capture software which is affordable to many researchers and medical doctors in clinical situations. We stabilized the head of the subject in order to reduce motion artifacts. With the video-NIRS system, we were able to record NIRS data and the appearance of the subject during his/her task performance simultaneously. The fixation of the head made it possible to prevent physical



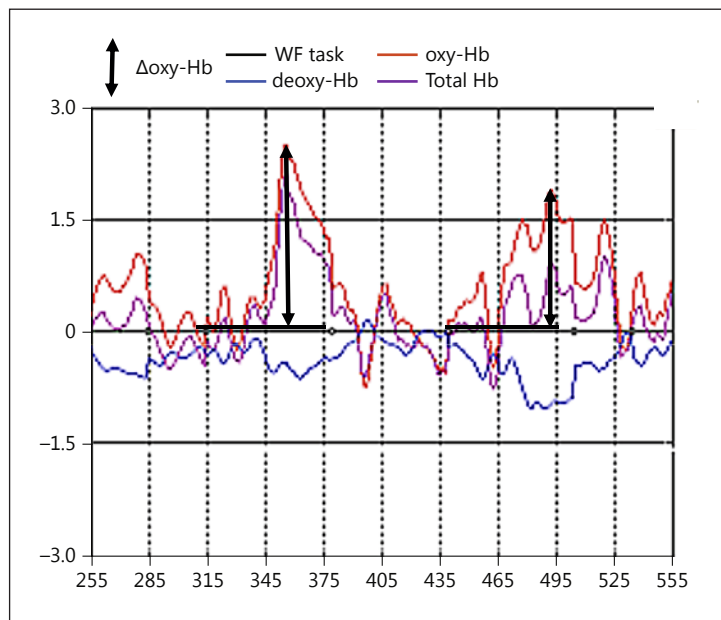
**Fig. 5.** Examples of screens of the video-NIRS (near-infrared spectroscopy) system during physical movement. **a** The subject moved her head forward. **b** The subject turned his head leftward. Note that, at first glance, the deoxy-Hb concentration was decreasing. But, from the video recording, we would know that this change might be caused by motion artifacts. oxy-Hb, oxygenated hemoglobin; deoxy-Hb, deoxygenated hemoglobin.

movements of the subject, and the deoxy-Hb concentration during most of the trials decreased, which is congruent with the BOLD effect in fMRI. Through the simultaneous recording of the NIRS data and the subject's appearance, we could assess whether the results might have been derived from the blood hemodynamic change in the brain, or from motion artifacts.

### Experiment 3: Amplitude Measurement during the WF Task Using the Video-NIRS System

#### Subjects and Methods

The subjects were 347 community-dwelling elderly people (70 male and 277 female;  $73.8 \pm 7.0$  years old; MMSE score  $26.01 \pm 4.505$ ). None had an apparent history of change in handedness. Of the total number of subjects, 165 were persons whose deoxy-Hb concentration was decreased without any motion artifacts in Experiment 2. An additional 182 subjects were seen at the memory clinic of Kinan Hospital. The inclusion criteria were as follows: (1) the subjects had completed the WF task and the MMSE; (2) the deoxy-Hb concentration measured by the video-NIRS system was decreased during the performance of the WF task; and (3) there were no motion artifacts during the WF task as assessed by the video-NIRS system. The probes were put in the bilateral frontal regions. The  $\Delta$ oxy-Hb was measured by the amplitude of the concentration at the beginning of the WF task (Fig. 6). We performed a preliminary analysis of 89 subjects to assess the difference in the amplitudes of the right and



**Fig. 6.** The  $\Delta$ oxy-Hb was measured by the amplitude based on the level at the beginning of the WF task. oxy-Hb, oxygenated hemoglobin; deoxy-Hb, deoxygenated hemoglobin;  $\Delta$ oxy-Hb, oxy-Hb concentration change; WF, word fluency.

**Table 1.** Preliminary analysis of the difference in amplitudes between the right and the left frontal lobe

	Animal WF		Letter WF	
	mean	SD	mean	SD
Right	18.4	7.1	21.9	9.1
Left	17.9	9.4	21.4	10.9
<i>p</i> value	0.77		0.81	

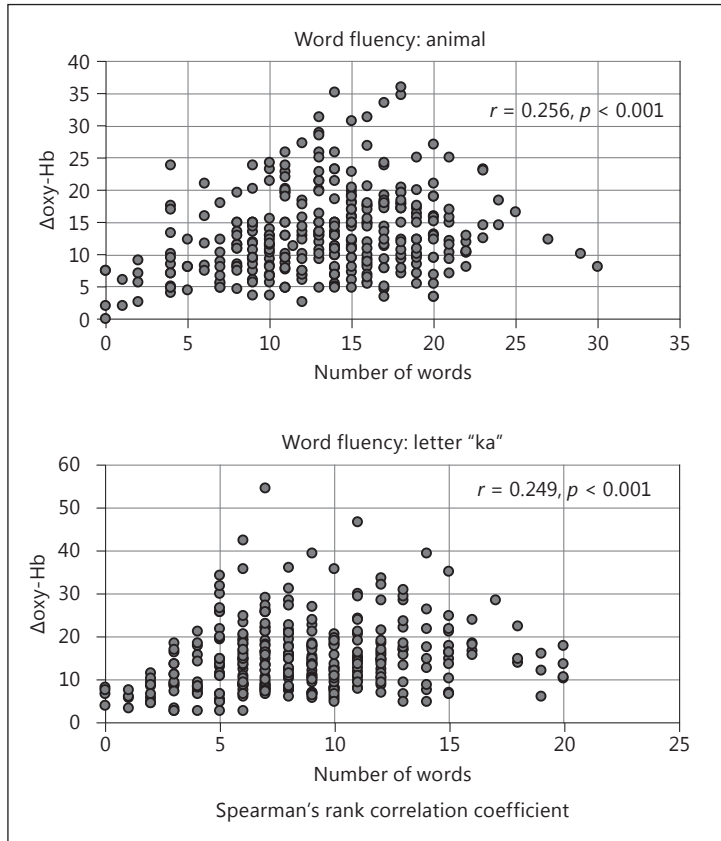
SD, standard deviation; WF, word fluency.

left hemispheres. In the letter WF task, a higher amplitude was observed in 34 and 44 subjects in the right and the left frontal lobe, respectively. In 11 subjects, the amplitudes were the same in both hemispheres. In the animal WF task, 32 and 50 subjects showed higher amplitudes in the right and the left hemisphere, respectively, and 7 subjects showed the same in both hemispheres. The differences in mean amplitudes in either task between the two hemispheres were not significant (Table 1). For the statistical analyses, the data from the right or left frontal region were used randomly. Correlation coefficients were calculated by Spearman's rank correlation coefficient, and were interpreted as indicative of small (0.0–0.2), fair (0.2–0.4), moderate (0.4–0.7), and strong (0.7–1.0) associations. Independent *t* tests were used for continuous variables. We regarded the result as significant if the *p* value was <0.05. All statistical analyses were performed using IBM SPSS Statistics version 23 software (Chicago, IL, USA).

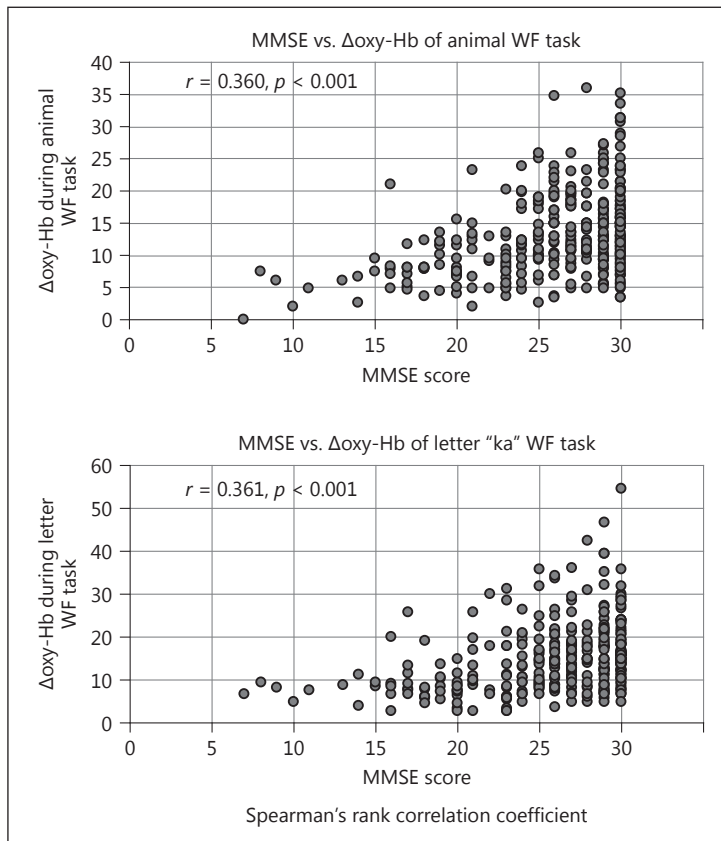
### Results

The  $\Delta$ oxy-Hb was fairly negatively correlated with age (animal WF:  $r = -0.361$ ,  $p < 0.001$ ; letter WF:  $r = -0.308$ ,  $p < 0.001$ ). The number of words was significantly correlated with the  $\Delta$ oxy-Hb during the animal and letter WF tasks (Fig. 7). The MMSE score showed a fair and significant correlation with the  $\Delta$ oxy-Hb in both WF tasks (Fig. 8). The cutoff score of the

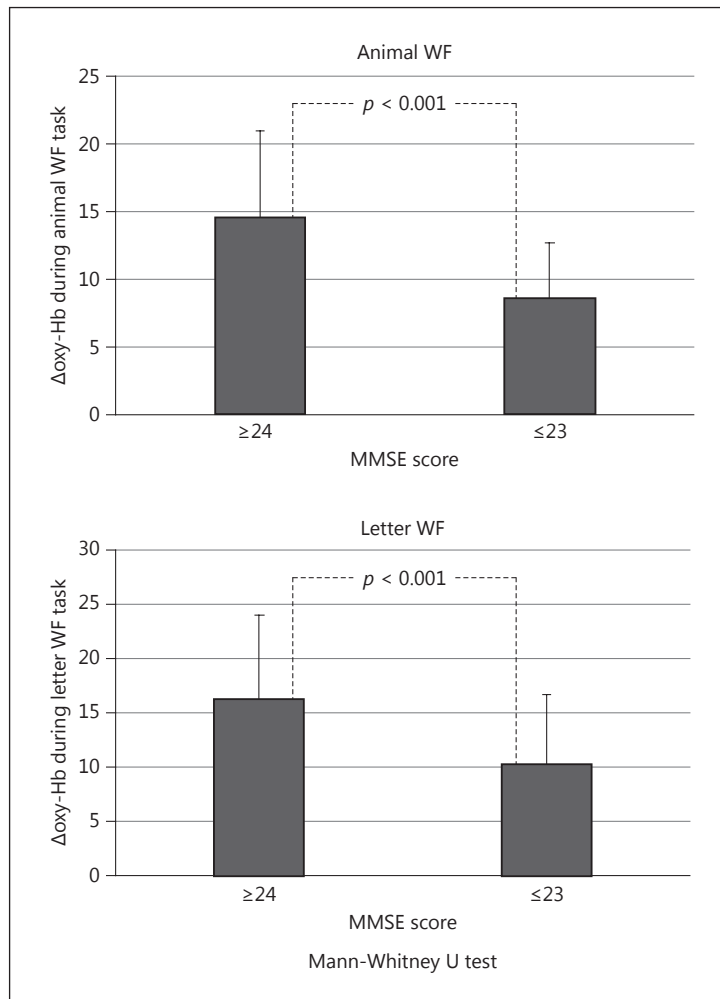




**Fig. 7.** Correlation between the oxygenated hemoglobin concentration change ( $\Delta$ oxy-Hb) and the number of words in the animal and letter word fluency tasks.



**Fig. 8.** Correlation between the oxygenated hemoglobin concentration change ( $\Delta$ oxy-Hb) during the animal and letter WF tasks and the score on the MMSE. MMSE, Mini-Mental State Examination; WF, word fluency.



**Fig. 9.** Comparison of the oxygenated hemoglobin concentration change ( $\Delta$ oxy-Hb) depending on the score on the MMSE. MMSE, Mini-Mental State Examination; WF, word fluency.

**Table 2.** Oxygenated hemoglobin concentration change during the animal and letter word fluency tasks for the groups according to MMSE score

MMSE			Animal WF				Letter WF				
	score	mean	SD	words	SD	amplitude	SD	words	SD	amplitude	SD
≥24	28.04	1.959		14.95	4.397	14.551	6.3436	9.61	3.890	16.264	7.7480
≤23	19.01	3.719		8.19	4.815	8.535	4.1213	5.39	3.566	10.317	6.4150

MMSE, Mini-Mental State Examination; SD, standard deviation; WF, word fluency.

MMSE is set at 23/24, so we compared the difference in  $\Delta$ oxy-Hb during the WF tasks between the groups above and below a score of 24 (Table 2; Fig. 9). The group with normal MMSE scores showed significantly better results with regard to the number of words than the group with scores of 23 or less (animal WF:  $p < 0.001$ ; letter WF:  $p < 0.001$ ). The  $\Delta$ oxy-Hb of the normal MMSE score group was significantly larger in both the animal and the letter WF task (animal WF:  $p < 0.001$ ; letter WF:  $p < 0.001$ ) (Fig. 9).

### Discussion

Using the video-NIRS system, we investigated the relationship between the  $\Delta$ oxy-Hb and the number of words of the WF task and the MMSE score. The WF task is known as a test that assesses frontal lobe function. As expected, the  $\Delta$ oxy-Hb was correlated with the number of words generated during the WF task, which also helped support the validity of the video-NIRS system. The  $\Delta$ oxy-Hb was also significantly correlated with the MMSE score, and the group with a lower score showed a significantly lower  $\Delta$ oxy-Hb. There is general agreement that the frontal lobe participates in executive function and attention, and is activated when a subject performs any kind of cognitive task. This indicates that the relationship between the  $\Delta$ oxy-Hb and the MMSE score is reasonable. These findings suggest that it might be possible to apply the video-NIRS system as a biomarker for the diagnosis of cognitive decline as in patients with dementia.

### General Discussion

The results of the present experiments can be summarized as follows: (1) physical movement can influence NIRS data; (2) in NIRS data acquisition, head fixation is important; (3) as with the BOLD effect of fMRI, NIRS data showing decreased deoxy-Hb concentrations might reflect blood hemodynamic changes in the brain; (4) the video-NIRS system, which simultaneously records NIRS data and the subject's appearance, is useful; and (5) the  $\Delta$ oxy-Hb measured by the video-NIRS system was congruent with our expectation based on findings that have been established in the field of neuropsychology. The video-NIRS system was easy to establish, and inexpensive. We think that the findings of the present study may open the door to more appropriate utilization of NIRS as a biomarker of cognitive function based on its utility, validity, and affordability.

We should pay attention to decreases in deoxy-Hb concentration when we analyze NIRS data during cognitive tasks. When we measure brain activity using positron emission tomography and fMRI, we need to fix the subject's head securely in order to prevent motion artifacts. Though it has been said that NIRS can be relatively mobile during data acquisition, our results revealed that physical movement, not only of the head but also of the extremities, may cause artifacts on NIRS data, and that such artifacts made the deoxy-Hb concentration increase or remain unchanged. Therefore, with NIRS, the trials in which the deoxy-Hb concentration was decreased reflected the change in brain function correctly. Alternatively, the trials where the deoxy-Hb concentration did not show any decrease might be contaminated by the physical movement, which can alter the blood volume of veins and capillaries in the muscles and skin under the probes.

The video-NIRS system is useful to assess whether NIRS data have been obtained correctly or not. We built the system without using special devices or software, so it was not expensive. With this system, we can observe the waveform and the subject's appearance simultaneously. We can judge whether the origin of the data is derived from actual brain activation or from motion artifacts. We know that similar analyses using special software and devices can be done in a laboratory setting, but we propose that the video-NIRS system has an advantage in that it is inexpensive, easy to use, and convenient especially in clinical situations. Furthermore, the appropriateness of the video-NIRS system was assessed by the relationship between the  $\Delta$ oxy-Hb and the WF task or MMSE score. The  $\Delta$ oxy-Hb agreed with an a priori assumption based on the characteristics of each cognitive test.

This study has some limitations. First, we do not know the degree to which physical movement can affect NIRS data. It is possible that, within some range, slight movements can be permitted during data acquisition. Second, with the present system, we need to visually

identify any physical movement of the subject. By using an acceleration sensor, it would be possible to display an alarm on the screen with the NIRS data and video recording. Third, there are cognitive tasks that require the subject to write or draw by hand. A counterplan for preventing motion artifacts during writing or drawing will be implemented in the next version of the system. Fourth, the video-NIRS system is no necessary and sufficient condition, but a minimum requirement. Considering the fact that there were many reports in the literature which did not show any deoxy-Hb concentration data, the present findings may facilitate correct measurement of brain activity. Lastly, we only performed a statistical analysis of groups with normal and abnormal ranges of MMSE scores. In order to utilize the video-NIRS system for the diagnosis of dementia, a comparison between subjects with normal cognitive function, mild cognitive impairment, and dementia is needed. We are planning to measure the  $\Delta$ oxy-Hb with various neuropsychological assessments using the video-NIRS system.

In conclusion, fixation of the head is important for NIRS data acquisition during cognitive tasks. It is recommended that NIRS data where the deoxy-Hb concentration is decreased should be selected, because those are congruent with the BOLD effect in fMRI. The video-NIRS system is useful to collect correct NIRS data by recording the waveforms and the subject's appearance simultaneously. The video-NIRS system may be useful as a biomarker of cognitive function. However, further studies are needed to apply the system as the biomarker for the diagnosis of dementia.

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### Statement of Ethics

All subjects gave informed consent after the purpose and procedure of the examination had been fully explained. The study was approved by the Ethics Committee of Kinan Hospital, and all experiments were conducted in accordance with the Declaration of Helsinki.

### Disclosure Statement

No conflicts of interest are reported.

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