EFFECTIVENESS FOR A SLEEPINESS TEST OF PUPIL SIZE ESTIMATION DURING BLINK

Minoru Nakayama
CRADLE (The Center for Research and Development of Educational Technolgy)
Tokyo Institute of Technology, O-okayama 2–12–1, Meguro-ku, Tokyo, 152–8552, Japan

Keiko Yamamoto, Fumio Kobayashi
Deapartment of Health and Psychosocial Medicine, Aichi Medical University
Karimata Yazako 21, Nagakute-cho, Aichi, 480–1195, Japan

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Abstract: Pupillary response has been used for an index of sleepiness, but the validity of the index is not clear. In this paper, the influence of blinks on the Pupillary Unrest Index (PUI) and the Power Spectrum Density (PSD) for the frequency range $0.01 < f < 0.8Hz$, as indices of pupil's instability during a sleepiness test, was examined. To estimate pupil size during blink, a procedure for collecting the clinical data was developed using Support Vector Regression (SVR). The values of PUI increased with experimental time, and the values and deviations of PUI for experimental observation were larger than the ones with SVR estimation. The blink time also increased with experimental time, and there were significant correlation relationships between the value of PUI and blink time. The mean PSD also correlated significantly with blink time. The relationship between pupillary indices and a subjective sleepiness index was not significant, as it was not in other previous works. These results provide evidence that pupillary indices were significantly affected by blink, and they did not reflect sleepiness correctly.

1 INTRODUCTION

Temporal observation of the human eye pupil is called as pupillography, and these observations can be used as an index for various human activities (Kuhlmann and Böttcher, 1999; Beatty, 1982). In particular, pupillography has been used for assessment of sleepiness and exhaustion using the eye sleepiness test, which consists of measuring the magnitude of pupillary change as a Pupil Unrest Index (PUI) and making readings of the frequency power spectrum. It is often applied to clinical observations or used in industrial engineering situations (Lüdtke et al., 1998; Wilhelm et al., 1998; Wilhelm et al., 1999). These indices have been applied to the evaluation of emotional change (Norrish and Dwyer, 2005); this analysis procedure is recognized as a significant measure.

Although these indices have also been applied to diagnostic procedures, a series of research studies of multiple sclerosis patients suggests that for healthy people there is no significant correlational relationship between PUI and subjective sleepiness indices such as the Stanford Sleepiness Score (Egg et al., 2002; Frauscher et al., 2005). This means that the evaluation procedure should be examined carefully.

A possible problem with observing the pupil is the influence of blink (Nakayama and Shimizu, 2001), because most methods of measuring pupil size are based upon processing the image of the eye. Blink can affect measurements due to the eye being obscured by the eye lid during blink. Blinks are usually discussed as an artifact in temporal observations such as mean pupil sizes or for results of frequency analysis (Nakayama and Shimizu, 2001; Nakayama and Shimizu, 2002). To resolve these problems, some methods of estimating pupil size during blink were developed (Nakayama and Shimizu, 2001; Nakayama, 2005), and the performance was examined (Nakayama, 2006).

However, the effectiveness of the estimation procedure for a diagnostic procedure (such as an eye sleepiness test) and the significance of pupil indices which include blinks have not been discussed sufficiently. In this paper, we address the influence of blink and the validity of pupillary indices by examining the effectiveness of estimating pupil size during

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Table 1: Analysis condition.

Condition	Original method	This paper
Sampling		
Sampling rate	25Hz	60Hz
Pre-processing	moving average	moving average
		SVR
Average window size	0.4sec.	0.4sec.
PUI		
Segment length	2048(82sec.)	4096(68.3sec.)
Unit for segment	16(0.64sec.)	32(0.53sec.)
N of units	128	128
Sampling rate	1.560Hz	1.875Hz
FFT		
Data length	2048(82sec.)	4096(68.3sec.)
Frequency range	0.0<f<0.8Hz	0.01<f<0.8Hz, 4Hz

Original method:(Lüdtke et al., 1998; Wilhelm et al., 1999)

blink using the support vector regression (SVR) technique.

The purposes of this paper are as follows:

1. To develop an estimation procedure using SVR for clinical pupillary observation.
2. To examine the influence of blink on the pupillary indices.
3. To examine the relationship between pupil indices and subjective sleepiness scores, and the influence of blinks on them.

2 MEASURING PUPIL SIZE

2.1 Sleepiness Test

The most popular method to assess sleepiness is a procedure which has been proposed by Wilhelm et al. (Lüdtke et al., 1998; Wilhelm et al., 1999). The measuring procedure in this paper was based on the following method.

The measuring equipment was designed to be worn on the eyes as goggles (Hamamatsu photonics:C7364). The subjects were asked to wear this equipment and to gaze at a small red LED light (infrared wave length: 890 nm) through the goggles, with a CCD camera shooting an image of the pupil. The subjects were instructed to sit and to remain awake in a semi-dark room in a building during the experiment, and were also asked to close their eyes for one minute to promote sleepiness before starting the experiment. The experiment lasted 12 minutes. The pupil diameter size was measured at 60 Hz.

This experiment was conducted between 9 a.m. and 4 p.m. in the late summer. 35 healthy males joined the experiment, their average age was 37.9 years and the standard deviation was 4.1. They were volunteer subjects and signed an agreement on the experimental procedure before it commenced.

Some parameters of the analyzing procedure which were proposed by Wilhelm et al. (Lüdtke et al., 1998) depended on the measuring equipment. One example is the sampling rate of pupil size. The differences are summarized in Table 1.

2.2 Pre-processing

Pre-processing of pupil size during blink provides a possible pupil size from the temporal sizes. To examine the effectiveness of pre-processing, the following two pre-processings were created using moving average method (MOV) and support vector regression (SVR) (Smola and Scholkopf, 1998; Nakayama, 2005). SVR and the kernel method are often used for signal reconstruction or smoothening (Bishop, 1995; Smola and Scholkopf, 1998).

2.2.1 Experimental Observation (Exp.)

This data set consisted of experimental observations without any pre-processing. During the periods of blink, the pupil diameter shows that the size was measured as 0.

2.2.2 Moving Average (MOV)

Moving average method was applied to exclude a large deviation caused by blink and noise. Wilhelm et al. conducted this method for every data series of 0.4 *sec.* (Lüdtke et al., 1998; Wilhelm et al., 1999). This means that the sampling rate is reduced to 2.5 *Hz*.

2.2.3 Estimation with Svr

This processing provided estimation diameters during blink using support vector regression (SVR) with Gaussian kernel (Smola and Scholkopf, 1998). The estimation function was derived from the training data. This training data, as a prototype of pupil response, consisted of measured pupil diameters during the blink and estimated pupil sizes. To produce the training data, a set of data containing 5000 data points collected at the beginning of observations was prepared. To obtain an optimized model, the dimension n of input vector, and a precision $\varepsilon(eps)$ and $\sigma(std)$ of Gaussian kernel needed to be calculated. A practical calculation was conducted using the *SVMTorch* package (Collobert and Bengio, 2001), and parameters were optimized. As a result, the following parameters were provided: input dimension = 45; $\sigma = 40$;

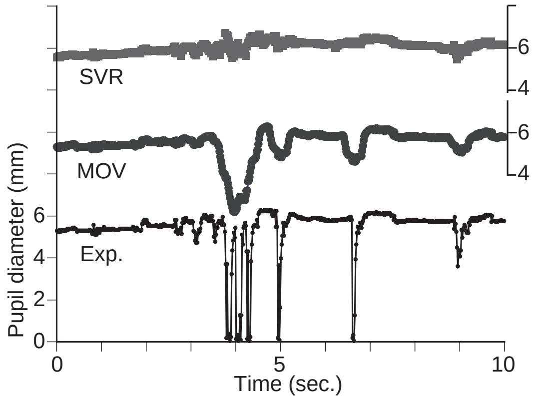

Figure 1: Example of pre-processing for pupillary change during blink.

$\varepsilon = 0.5$. Estimation accuracy was examined in the previous estimation experiments (Nakayama, 2006).

3 RESULTS

3.1 Results of Pre-processing

To examine the pupil size pre-processing performance, an example of experimental pupil size and processed data for 10 seconds is illustrated in Figure 1, listed from bottom to top as Exp., MOV and SVR. The horizontal axis shows time, the vertical axis shows pupil size with drops indicating blinks. Preprocessing with MOV shows that temporal changes are influenced by blink and all points are smoothened, although there is no null point during blink periods. On the other hand, SVR indicates the same pupil size without large blink drops and gives possible sizes of pupil diameters during blinks. As a result, an appropriate estimation procedure for clinical pupillography can be developed from this.

3.2 Results of Pupillary Unrest Index (PUI)

PUI as an index of instability of pupillography was calculated following a procedure which was modified from the original method using the parameters listed in Table 1. According to the definition of PUI as cumulative changes in pupil diameter (Lüdtke et al., 1998), firstly the data were reduced by calculating the average for periods of 32 (0.53 *sec.*) consecutive values, secondly the absolute values of the differences from one 32-value average to the next one were summarized for each 68.3 *sec*. data segment, namely 127 differences for one segment. Calculating the average

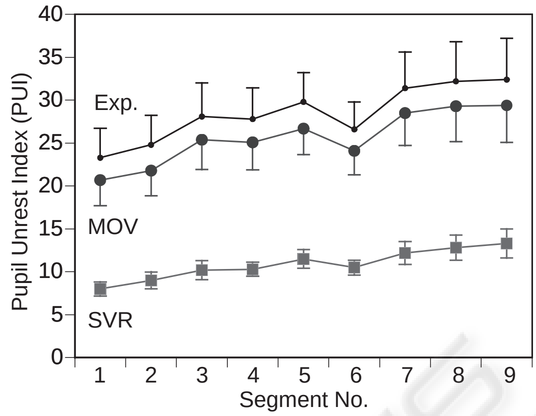

Figure 2: Result of PUIs across segments and preprocessing procedures.

prior to cumulation serves as a simple low pass filtering and excludes high frequency noise.

Average PUIs with standard error bars across the pre-processing procedure results were summarized in Figure 2. PUIs for Exp. and MOV conditions are significantly higher than the ones for SVR. According to the estimation procedure, PUI increases when pupillary temporal change includes blink drop. Therefore, PUIs for Exp. and MOV were relatively high.

Also, sleepiness may increase gradually with experimental time, so this suggests that the gradual increase may depend on sleepiness. According to the pre-processed PUI results and a previous work (Nakayama, 2006), the biggest factor in PUI change must be blink frequency, however.

3.3 Blink Time

Blink may influence a sleepiness index according to the results of PUI. Blink time is defined as the sum of blink drop duration of measured pupil diameters. Average blink times for each segment (68.3 *sec.*) were summarized as bar graphs with standard error bars in Figure 3. The figure shows that the blink time increases monotonically with the sequence number of the segment excepting segment 5. According to blink research, the estimated blink time may be around 1 minute per segment in the standard condition (Tada et al., 1991). It was suggested that the blink time after segment 5 was longer than the one for the standard condition.

These results also indicated that blink influenced PUIs. To examine the relationship between PUI and blink time, correlation coefficients were calculated across all segments and preprocessing procedures. The coefficients were summarized in Table 2. Most coefficients were significant ($p < 0.05$). During seg-

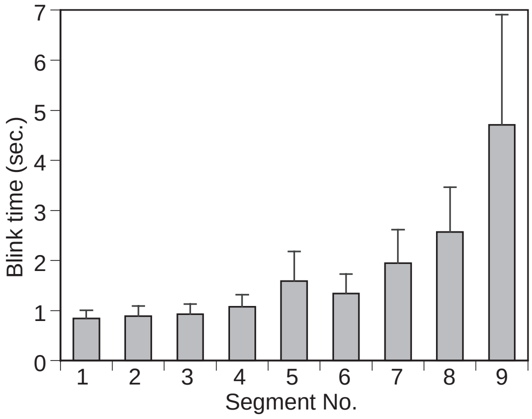

Figure 3: Average blink time for segments.

Table 2: Correlation coefficient between PUI and blink time.

Seg. No.	Exp.	MOV	SVR
1	0.95	0.95	0.42
2	0.91	0.92	0.71
3	0.93	0.92	(0.23)
4	0.90	0.92	0.41
5	0.42	0.45	0.41
6	0.64	0.65	0.34
7	0.55	0.58	0.63
8	0.69	0.70	0.58
9	(0.16)	(0.18)	0.35

N=35, ( ) not significant

ment numbers 1 to 4, there were large correlation coefficients for pupil diameters with blink times for Exp. and MOV rather than for correlation coefficients for SVR. Coefficients across all pre-processing stayed at same levels after segment number 5, when the blink times were longer than the ones in the standard condition.

These results showed that blink significantly affected PUI changes in the standard condition, and the effectiveness of pre-processing for pupils was examined while the blink times stayed at the standard level. The relationship was also affected by the incidence of additional blinking. Furthermore, these results suggested the blink time affected PUIs despite the conducting of estimations of pupil size during blink.

3.4 Frequency Analysis

Frequency power value of pupillary change, which is given by frequency analysis over 68.3 *sec*., can be used as another index of sleepiness (Lüdtke et al., 1998; Wilhelm et al., 1999). According to the procedure, the power spectrum of pupil diameter change was summarized. Figure 4 shows the results of Power

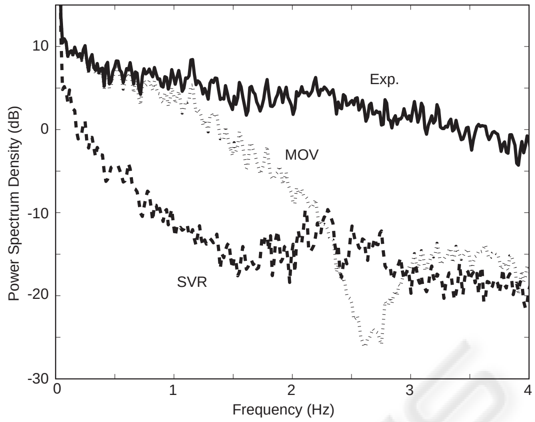

Figure 4: PSD of pupillography across pre-processing.

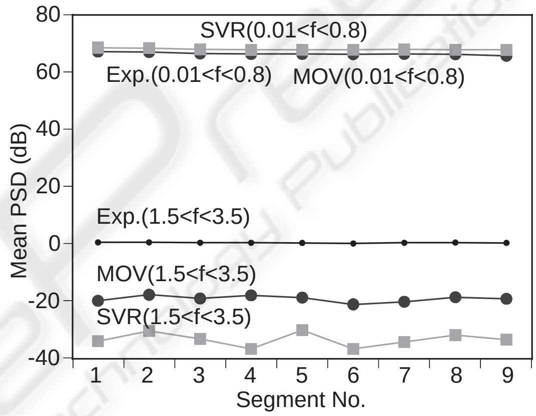

Figure 5: Averaged PSD of each segment for two frequency ranges.

Spectrum Density (PSD) for the first segment of one subject. PSD was estimated with *pwelch* function and Parzen window function of MATLAB (MathWorks Inc.). The vertical axis shows PSD in decibels (dB) and the horizontal axis shows frequency (Hz) from 0.01 to 4.0 Hz. DC component as frequency power was excepted in following analysis. The pupillary change has a low pass filter as low as 4 Hz because it is biological signal, and also pupilograms contain $0.05 \sim 0.3$ Hz components which are well known as pupillary noise (Tsukahara, 1976).

During sleepiness tests, the average power value for the frequency range ($0.01 < f < 0.8Hz$) is often evaluated as the index (Lüdtke et al., 1998; Wilhelm et al., 1999). The average PSD for frequency range ($0.01 < f < 0.8Hz$) for each segment was compared between pre-processing procedures. The results were summarized in Figure 5. According to the results of frequency analysis for the task evoked pupillography, PSDs of frequency range ($1.5 < f < 3.5Hz$) changed significantly in response to the task difficulty. Therefore, average PSDs for frequency range

Table 3: Correlation coefficients between PSDs and blink for two frequency ranges.

Seg.	$0.01 < f < 0.8Hz$			$1.5 < f < 3.5Hz$		
No.	Exp.	MOV	SVR	Exp.	MOV	SVR
1	-.36	-.36	(-.29)	0.81	0.86	0.44
2	-.38	-.38	(-.25)	0.86	0.87	0.65
3	-.35	-.36	(-.30)	0.65	0.77	(0.20)
4	-.53	-.53	-.51	0.57	0.63	(0.21)
5	-.42	-.42	-.37	(0.11)	(0.15)	(-.03)
6	-.47	-.46	-.47	(0.28)	0.37	(0.10)
7	-.52	-.52	-.46	(0.13)	(0.20)	(0.19)
8	-.55	-.55	-.53	(0.31)	0.45	(0.20)
9	-.62	-.62	(-.30)	(-.10)	(-.07)	(-.07)

N=35, ( ) not significant

($1.5 < f < 3.5Hz$) were also summarized in the same format in Figure 5. The figure shows that PSDs for ($0.01 < f < 0.8Hz$) are at the same level across segments and pre-processing procedures. The PSDs for ($1.5 < f < 3.5Hz$) have some differences amongst pre-processing, but they stay at the same levels during each experimental time point. This suggests that PSDs are not affected by a change in blink time, such as during a change in the level of sleepiness.

3.5 Blink Influence On Psd

To examine the influence of blink, correlation coefficients between blink time and average PSDs for two frequency ranges ($0.01 < f < 0.8Hz$ and $1.5 < f < 3.5Hz$) across pre-processing procedures were calculated. The results were summarized in Table 3.

All coefficients for the frequency range ($0.01 < f < 0.8Hz$) were negative values and significant except for some coefficients for SVR. There was no significant relationship between SVR and blink time during the first three segments, and some absolute values of coefficients for SVR were relatively smaller than the ones for Exp. and MOV. Most PSDs for frequency range ($0.01 < f < 0.8Hz$) correlated with blink time, however. This suggests that PSDs depend on blink time, and that the relationship is affected by the preprocessing procedure. Also, PSDs of Exp. and MOV for frequency range ($1.5 < f < 3.5Hz$) correlated with blink time during segments 1-4. There were no significant relationships between them after Segment No. 5, while blink time was longer than in the standard condition, however. These correlation relationships seem to be caused by blinks.

3.6 Relationship with a Subjective Score

Subjective sleepiness was measured for each subject using the Stanford Sleepiness Score (SSS) (Hoddes et al., 1973). 33 out of 35 subjects responded to

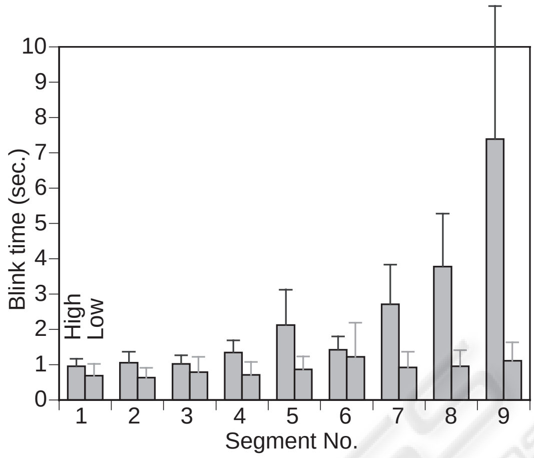

Figure 6: Averaged blink time across two sleepiness groups.

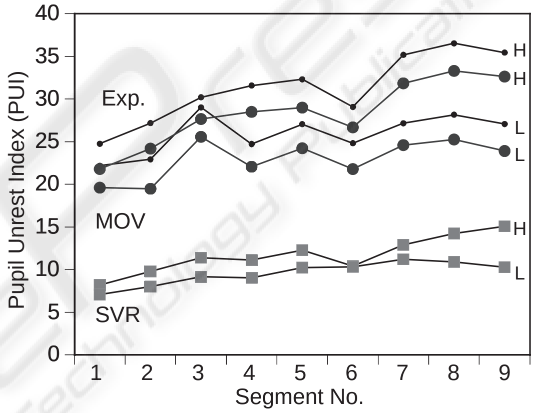

Figure 7: PUI changes with pre-processing procedures and two sleepiness groups.

this questionnaire. The scores were distributed from 2 to 4 on a 7 point scale. The correlation relationships of SSS with both PUIs and PSDs were examined. The absolute value of the correlation coefficients (r) were less than 0.15 and they were not significant ($p > 0.10$), because all subjects were healthy and scores were distributed in a narrow range. Therefore, indices of pupillography do not correlate with the subjective scores as well as in previous works (Egg et al., 2002; Frauscher et al., 2005).

4 DISCUSSION

The two observations and suggested causes which have been reported in this paper are examined here; there is an influence of blink on pupillary indices (Nakayama, 2005; Nakayama, 2006), and there is nocorrelation between pupillary indices and subjective sleepiness (Egg et al., 2002; Frauscher et al., 2005). There was some distribution of subjective sleepiness

Table 4: Correlation coefficients between PSD and blink time across pre-processing procedures and two sleepiness groups.

Seg.	$0.01 < f < 0.8Hz$						$1.5 < f < 3.5Hz$					
	High sleepiness			Low sleepiness			High sleepiness			Low sleepiness		
No.	Exp.	MOV	SVR	Exp.	MOV	SVR	Exp.	MOV	SVR	Exp.	MOV	SVR
1	(-.25)	(-.25)	(-.15)	-.60	-.60	-.58	0.82	0.78	0.57	0.88	0.97	(0.18)
2	(-.33)	(-.33)	(-.15)	(-.53)	(-.53)	(-.52)	0.88	0.88	0.74	0.87	0.96	(0.19)
3	(-.35)	(-.35)	(-.29)	(-.37)	(-.37)	(-.31)	0.76	0.78	(0.04)	0.57	0.77	(0.38)
4	-.56	-.57	-.56	(-.51)	(-.51)	(-.44)	0.52	0.55	(0.15)	0.68	0.84	(0.27)
5	-.46	-.46	(-.41)	(-.51)	(-.51)	(-.47)	(0.04)	(0.07)	(-.12)	(0.54)	0.71	(0.13)
6	-.59	-.59	-.61	(-.50)	(-.50)	(-.47)	0.42	(0.47)	(0.01)	(0.20)	(0.31)	(0.18)
7	-.55	-.55	-.51	(-.55)	(-.55)	(-.48)	(0.09)	(0.14)	(0.31)	(0.35)	(0.48)	(0.20)
8	-.60	-.60	-.62	-.65	-.65	-.60	(0.34)	0.48	0.55	0.60	0.71	(0.19)
9	-.68	-.68	(-.37)	(-.32)	(-.32)	(-.31)	(-.17)	(-.14)	(-.15)	(0.45)	0.69	(0.11)

N=35, ( ) not significant

in this experiment, such as between 2 and 5 on the 7 point scale, therefore the effect of the difference in the subjective sleepiness on the indices was analyzed. Firstly, 33 responded subjects were divided into two groups; the low sleepiness group consisted of 13 subjects who answered 2 on the 7 point scale of sleepiness, and the high sleepiness group consisted of 20 subjects who answered 3 to 5 on the 7 point scale of sleepiness, with an average rate of 3.4.

Blink time for each segment was summarized across two groups in Figure 6 using the same format as in Figure 3. In Figure 6, bars show average blink times with error bars as standard errors. In comparing the two groups, the temporal change in segment sequences were quite different. Blink times for the high sleepiness group increased monotonically, and the standard errors also increased with the average. Blink times for the high sleepiness group in the 8th segment became 7 times the length of the time of the 1st segment. On the other hand, the average blink times for the low sleepiness group did not change during the experiment. There were no significant differences in blink time between the two groups because of the large deviation in blink time, however. If blink time reflects sleepiness, the differences in blink time between the two groups may significantly affect the variation in the subjective sleepiness score.

PUIs for two groups were summarized in Figure 7 using the same format as in Figure 2. Differences of PUIs for Exp. and MOV between the two groups increased with experimental time. Also, the differences in PUI for SVR between the two groups was small and almost constant during the experiment. There was no significant difference in PUI between the two groups and three pre-processing procedures because of the large deviation in PUI, particularly for the high sleepiness group. Although there was no significant difference between the two groups, it was noted that blink affected PUI values on pupil diameter observations when blinks were not processed appropriately.

To examine the relationship between PSDs and subjective sleepiness, correlation coefficients between averaged PSDs and blink times for the two groups were summarized in Table 4 using the same format as in Table 3. Comparing correlation coefficients between the two groups of subjective sleepiness ratings, the significance of coefficients for the frequency range $0.01 < f < 0.8$Hz changed across the two groups. Coefficients in the frequency rage $1.5 < f < 3.5Hz$ were relatively stable with the subjective sleepiness ratings. According to the results, coefficients between PSD and blink time depend on both the pre-processing procedure for blink and the subjective sleepiness rating. For coefficients in the frequency range $1.5 < f < 3.5Hz$, the effect of the subjective sleepiness rating was relatively smaller than the effect in the frequency range $0.01 < f < 0.8Hz$.

The results of analyzing pupil indices during the sleepiness test coincide with the clinical claims (Egg et al., 2002; Frauscher et al., 2005); PUI does not correlate with subjective sleepiness such as SSS. Although it was suggested that the frequency power of $0.01 < f < 0.8Hz$ reflected the subjective sleepiness (Lüdtke et al., 1998; Wilhelm et al., 1998; Wilhelm et al., 1999), the relationship was not confirmed in this experiment. Additionally, even the influence of blink when the blink drops during a temporal change of pupil size were removed was examined. Considering the empirical evidence from these clinical observations, a sleepiness evaluation procedure should be developed. A discussion of this will be the subject of our further study.

5 CONCLUSIONS

In this paper, we used pupillography to examine the influence of blink and validity of pupillary indices by analyzing a clinical sleepiness test.

The following results were achieved:

1. A pupil size during blink estimation procedure using the Support Vector Regression technique for clinical pupillary observation was developed and an appropriate level of performance was obtained.
2. The influence of blink in pupillary indices such as Pupil Unrest Index (PUI) and Power Spectrum Density (PSD) of pupillography was examined. In particular, it was shown that blink time increased monotonically with experimental time, therefore the influence of blink changed as the experiment progressed.
3. The relationship between pupil indices and subjective sleepiness scores such as the Stanford Sleepiness Score (SSS) was analyzed. There was no significant relationship, but there were some differences in pupil indices between high and low SSS groups.

Development of a sleepiness test evaluation procedure which considers blink and other factors will be the subject of our further study.

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