ORIGINAL ARTICLES

Ocular Surface Area as an Informative Index of Visual Ergonomics

Midori SOTOYAMA[*a], Maria Beatriz G. VILLANUEVA[b], Hiroshi JONAI[a] and Susumu SAITO[a]

a) National Institute of Industrial Health, 21-1, Nagao 6-chome, Tama-ku, Kawasaki 214 Japan
b) Nagoya University, School of Medicine, 65 Tsurumai-cho, Showa-ku, Nagoya 466 Japan

(Received February 2, 1995 and in revised form June 19, 1995)

Abstract: A large ocular surface area (OSA) is thought to be one of the causes of eye irritation and eye fatigue. Because ocular surface is very sensitive to various irritants such as dust, heat, dryness, air flow, etc., a large OSA increases the possibility of eye surface exposure to such irritants. Thus, OSA is one of the most important indices of visual ergonomics. This paper aims at making OSA an exact and practical index by first describing an accurate method of measuring it, and then clarifying the relationship between OSA, the width of the palpebral fissure, and vertical gaze direction, all of which are thought to be strongly correlated with each other. We derived the following equations:

1) $y = 0.039x_1 + 3.36, \quad r = 0.99,$
2) $y = 3.05x_2 - 0.39, \quad r = 0.97,$
3) $x_1 = 72.7x_2 - 91.4, \quad r = 0.97,$

where x_1 = **vertical gaze direction (degrees),**
x_2 = **width of the palpebral fissure (cm),**
y = **OSA (cm^2).**

Finally, this paper also introduces the practical applications of OSA measurement, and notes the differences between OSA when VDT work (word processing using a keyboard and drawing a picture using a mouse) is performed and when traditional office work without a VDT (reading, drawing, and writing) is performed.

Key words: Ocular surface area — Eye fatigue — Eye irritation — Vertical gaze direction — Eyelid — Palpebral fissure — Visual display terminal (VDT)

* To whom all correspondence may be addressed.

Introduction

In 1983, ocular surface area (OSA) was measured by Rolando *et al.* for the first time to determine the rate of tear evaporation[1]. The measurement method proposed by Rolando *et al.*, however, may give an OSA value that is actually smaller than its real value.

The eyeball surface can be divided into two convex areas, that is, the sclera and the cornea. Real OSA is the total of these two areas. Because Rolando believed that most of the OSA was made up of corneal surface, he used the corneal curvature as the radius of curvature of the whole convex surface. In other words, he ignored the sclera, which in effect gave him an OSA value that is smaller than the real value.

Because we believe OSA to be an informative index of visual ergonomics, an accurate OSA measurement method is necessary to enable accurate risk assessment. This paper, therefore, first attempts to accurately establish the principles which must be applied to estimate OSA.

Second, to permit OSA to be estimated more conveniently, this paper attempts to define the relationship between OSA, the width of the palpebral fissure, and vertical gaze direction. The human eyeball and upper eyelid move together in what is known as a physiological synergic action[2,3], and OSA and the width of the palpebral fissure are directly affected by the vertical gaze direction. Although this is well known, the quantitative relationships of each pair have not previously been clarified.

Finally, we applied OSA analysis to demonstrate differences between OSAs while performing VDT work and while performing traditional office work without a VDT as an example of OSA measurement.

Measuring Three-Dimensional OSA

The development of our method to estimate 3-dimensional (3-D) OSA can be outlined as follows: 1) measuring 2-dimensional (2-D) OSA using video images of the eye, and 2) converting the 2-D OSA to 3-D OSA.

1. Measuring 2-D OSA

OSA is defined as the area bounded by the margins of the upper and lower eyelid as shown "A" in Figure 1.

In order to determine OSA, we used a video image of the frontal eye transcribed on a 14-inch TV monitor. The accuracy of this video system was confirmed by matching real scale length and transcribed length on the TV monitor. The margin of error for this video system was at most ±1% in the horizontal direction and ±2% in the vertical direction. The linearity of this system was satisfactory for our measurements.

The surface image of the eyeball on the 14-inch TV monitor was carefully traced on a transparent sheet and is shown as traced area "A'" in Figure 1. In order to estimate the traced area, we counted the number of 0.5 cm squares (0.25 cm^2) in this area. Incomplete squares on the traced line were counted as half squares. The margin of error in this square-counting process was confirmed to be at most $\pm 1.5\%$. We were able to determine OSA using the above procedures; however, the resulting OSA image was 2-D. To obtain an accurate OSA value that would permit 3-D analysis, we devised the 2-D to 3-D conversion method described below.

2. Converting 2-D OSA to 3-D OSA

The eyeball was assumed to be a perfect sphere. The OSA is considered to be the portion of the spherical surface enclosed by the upper and lower eyelid as shown in "A" in Figure 1. Frontal view of this OSA is shown in area "B" in Figure 1, which consists of two half ellipses "B1" and "B2" as shown in Figure 1. In order to obtain the 3-D OSA, we first calculated the coefficient from the ratio of the area of ellipse to the portion of the spherical surface. Then we traced area " A'", obtained by the square-counting method as 2-D OSA, and multiplied it by the coefficient value.

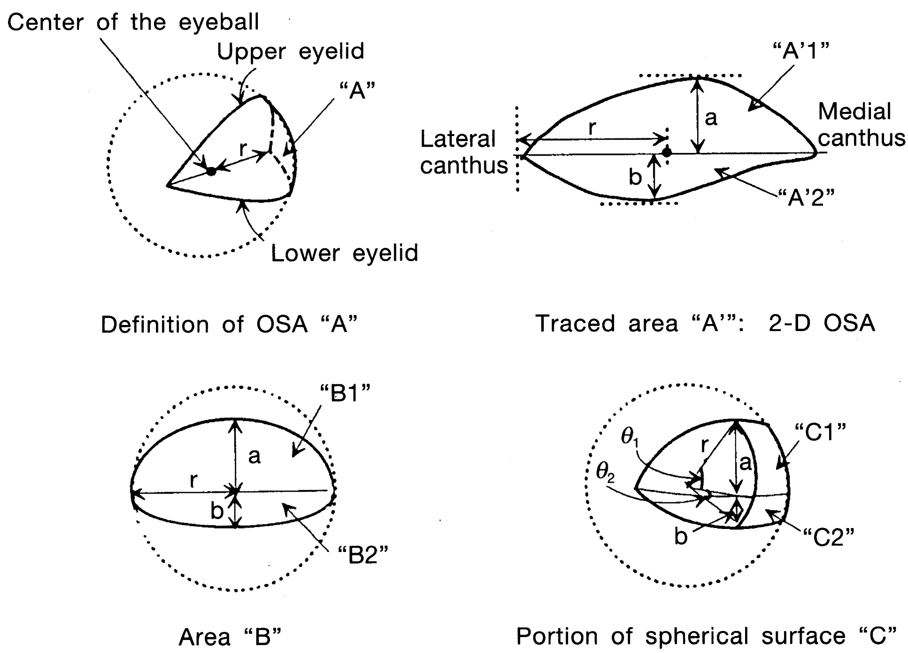

Fig. 1. Schematic diagram of the ocular surface area (OSA). A: definition of OSA, A': traced area (A'1: upper portion of 2-D OSA, A'2: lower portion of 2-D OSA), B: area used as a 2-D model, C: portion of the spherical surface used as a 3-D model.

Since not all the areas of upper and lower part of traced area "A'" are symmetric, we divided "A'" into two parts, "A'1" and "A'2", using the line between the lateral canthus and medial canthus as shown in Figure 1.

We chose area "B", which is divided into areas "B1" and "B2" as shown in Figure 1, as the 2-D model to estimate the coefficient value, and portions of spherical surface "C", which is divided into areas "C1" and "C2" as shown in Figure 1, as the 3-D model. The major axis of area "B" and the radius of the eyeball spherical surface "C" are considered to be the same length, r, which is half the length of the palpebral fissure of traced area "A'". In the present study, we assumed the length of the palpebral fissure to be the eyeball diameter. The measured length of palpebral fissure in this experiment was from 24 mm to 26 mm, which is similar to the eyeball diameter which is known to be 24 mm.

We calculated the coefficient from the ratio of the "B1" area to the spherical surface "C1". In order to obtain the 3-D ocular surface area, traced area "A'", which was obtained by the square-counting method, was multiplied by the coefficient value. Angle θ_1 of "C1" in Figure 1 was calculated from a part of the width of the palpebral fissure "a" and eyeball radius "r". Angle θ_2 was calculated in the same way.

The ratio of the area of half ellipse "B1" to the spherical surface "C1" was calculated as follows:

$$B1 = (1/2)\pi ar$$
$$a = r\sin\theta_1$$
$$\therefore\ B1 = (1/2)\pi r^2 \sin\theta_1$$
$$C1 = 4\pi r^2 (\theta_1/360) = (1/90)\pi r^2\, \theta_1$$

Then

$$B1{:}C1 = \sin\theta_1{:}\theta_1/45$$

and coefficient value C1/B1 is $\theta_1/(45\sin\theta_1)$

Using the same method,

$$B2{:}C2 = \sin\theta_2{:}\theta_2/45$$

and coefficient value C2/B2 is $\theta_2/(45\sin\theta_2)$

The 3-D OSA was calculated three-dimensionally as follows:

$$\text{3-D OSA ("A")} = A'1 \times C1/B1 + A'2 \times C2/B2$$
$$= A'1 \times \{\theta_1/(45\sin\theta_1)\} + A'2 \times \{\theta_2/(45\sin\theta_2)\}$$

If we assume that angle θ_1 is 40 degrees, which corresponds to the typical angle of a VDT operator, the ratio of the 2-D OSA to the 3-D OSA is 1:1.4. This indicates that the 2-D measurement of OSA is 30% smaller than that of 3-D OSA, and this shows the need for 3-D conversion to obtain an accurate OSA value.

Relationship between OSA, Vertical gaze direction and Width of the palpebral fissure

The three-dimensional (3-D) OSA measurement method was devised as described above. In order to estimate OSA more conveniently and practically, we investigated the relationship between OSA and the vertical gaze direction and the width of the palpebral fissure, which are thought to be closely correlated with OSA.

1. Methods

Six subjects, 21 to 34 years old, were asked to gaze at a visual target while keeping their foreheads and chins fixed on the supporters. Their frontal eye images were recorded on a VTR by a small TV camera fixed in front of the eye.

We defined Reid's line as 0 degrees in the vertical direction. Reid's line extends from the outer canthus to the center of the ear canal[4]. It lies about 10–15 degrees above the Frankfurt plane. The position of the target was varied vertically from 60 degrees below to 20 degrees above Reid's line.

To measure changing OSA by following vertical eye movements, video images of the eye were analyzed in the manner described in the section that discusses the method for measuring three-dimensional OSA.

2. Results

2.1 Relationship between the vertical gaze direction and OSA

Figure 2 shows the relationship between the vertical gaze direction and OSA. This figure shows mean values for the six subjects. Individual differences in OSA in this relationship were less than 10%. As shown in the graph, OSA increases in proportion to upward gaze direction with a high correlation coefficient. The regression equation from -50 degrees to 10 degrees was as follows:

$y = 0.039x_1 + 3.36,\ r = 0.99$ .... (1)

where x_1 = vertical gaze direction away from Reid's line (degrees)

y = OSA (cm^2)

2.2 Relationship between the width of the palpebral fissure and OSA

Figure 3 shows a close correlation between the width of the palpebral fissure and OSA. These data were gathered from the six subjects as they gazed in various vertical directions. The regression equations can be expressed as follows:

$y = 3.05x_2 - 0.39,\ r = 0.97$ .... (2)

where x_2 = width of the palpebral fissure (cm)

y = OSA (cm^2)

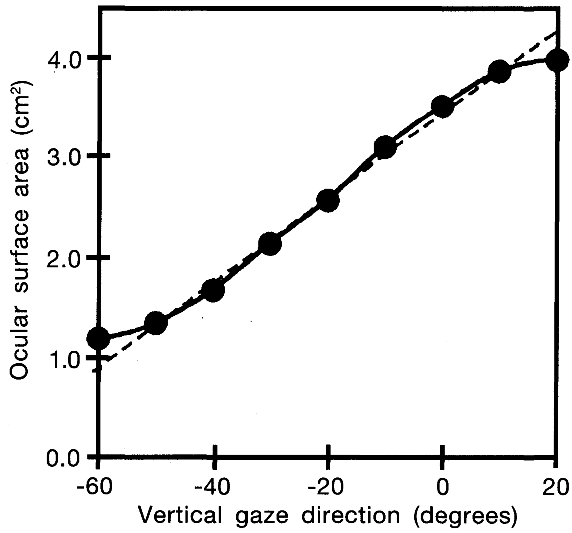

Fig. 2. Relationship between the vertical gaze direction and OSA.

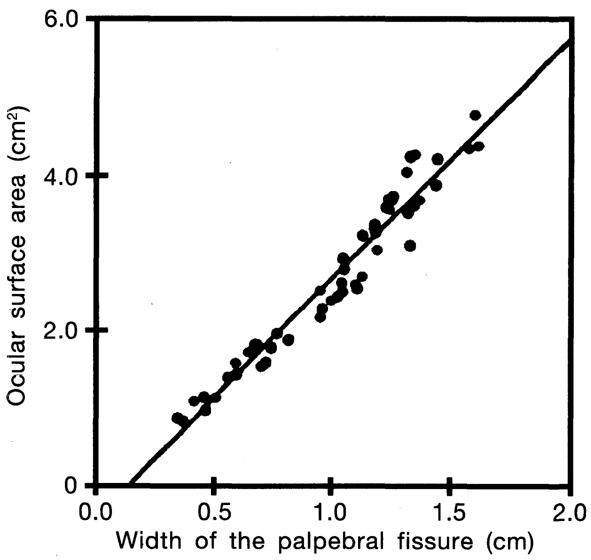

Fig. 3. Relationship between OSA and the width of the palpebral fissure (a + b in Figure 1).

2.3 Relationship between the width of the palpebral fissure and the vertical gaze direction

We found strong correlations between the vertical gaze direction and OSA, and between the width of the palpebral fissure and OSA. Thus, vertical gaze direction should be described in terms of the width of the palpebral fissure as follows:

$x_1 = 72.7x_2 - 91.4$, $r = 0.97$ .... (3)

where x_1 = vertical gaze direction away from Reid's line (degrees)

x_2 = width of the palpebral fissure (cm)

3. Discussion

We developed an accurate method for measuring OSA and found three correlations among OSA, the vertical gaze direction, and the width of the palpebral fissure.

Equation (1) shows that OSA was very accurately estimated by the vertical gaze direction. A sample estimation is provided.

Based on our previous survey of eye movements during various visual tasks, the mean vertical gaze direction of VDT operators was found to be significantly higher than that of workers who did not use VDTs[5]. The average gaze direction during work with and without a VDT was about 0 degrees and -40 degrees, respectively, from Reid's line. Using equation (1), OSA for such work was calculated to be 3.4 and 1.8 cm^2, respectively. OSA during VDT work is estimated to be 1.9 times greater than during traditional office work. This large OSA must induce the various eye problems of which many VDT operators complain.

We found a linear regression with a high correlation coefficient between the width of the palpebral fissure and OSA in the form of equation (2). This means that we can easily determine OSA accurately by measuring the width of the palpebral fissure without counting squares or performing a conversion process from 2-D to 3-D.

The same relation has already been reported by Rolando *et al.* as follows[1]:

$y = 2.8x - 0.44$, $r = 0.991$ .... (4)

where x = width of palpebral fissure (cm)

y = OSA (cm^2)

Using the same value for the width of palpebral fissure, Rolando's OSA is smaller than ours. As referred to in the introductory section of this paper, Rolando used the corneal curvature, 8 mm, as the radius of curvature of the whole convex surface. As a result, he ignored the area of the sclera. On the other hand, we used half the length of the palpebral fissure as the convex radius, which is almost the same length as the eyeball radius, 12 mm, to estimate OSA. Our OSA value is believed to be smaller than the actual OSA value, because we treated OSA as single convex; nevertheless, it must be nearer to the actual OSA value than Rolando's value.

Using equation (3), which expresses the relation between the width of the palpebral fissure and the vertical gaze direction, we can easily and accurately estimate the vertical gaze direction, which is a very important factor in ergonomic research, by measuring the width of the palpebral fissure from eye images such as photographs and video images.

Vertical gaze direction has recently become one of the most interesting topics in the field of visual ergonomics. The height of gaze direction has been found to be one of the most important factors leading to complaints of eye fatigue or visual discomfort[4,6,7]. Electro-oculography and the corneal reflex technique are currently widely used to measure the gaze direction. Regrettably, these techniques sometimes interfere with the natural behavior of the subject because equipment must be attached to the subject's head. Thus, there has long been a need to develop a new measurement method that does not necessitate touching the subject. Using equation (3), we can estimate vertical eye movement by measuring the width of the palpebral fissure of eye images. By obtaining an eye image from the side, there is no need to attach any special equipment to the subject's head. In other words, this method enables the vertical gaze direction to be estimated with minimal stress to the subject because it does not require the attachment of any instruments to the subject's head or eye, which means that the subject can move freely. This method can be applied to practical field surveys of the vertical gaze direction and eye movement.

Application: Measurement of OSA during Visual tasks including VDT operation

The increased use of visual display terminals (VDTs) in many workplaces has been accompanied by a proportionate rise in the number of workers complaining of eye fatigue or eye strain. In this section, we compared OSA while working with and without a VDT as an example of one application of OSA measurement.

1. Methods

In this experiment, we compared OSA while doing two types of visual tasks and described the features of each task. One of these tasks was VDT work, word processing using a keyboard and drawing a picture using a mouse, and the other was traditional office work without a VDT such as reading a book, drawing a picture and writing.

Data were gathered from the same subject. While the subject performed such visual tasks for ten minutes, frontal images of the eye were recorded on a VTR using a small TV camera fixed to the subject's head. We estimated OSA by measuring the width of the palpebral fissure and using equation (2). Data were collected every second for two minutes.

2. Results

Figure 4 shows the averages and standard deviations of OSA for each task. The following data were collected from the same subject. The OSA was 2.1 ± 0.9 cm^2 while word processing, 2.6 ± 0.2 cm^2 while drawing a picture using a mouse, 1.9 ± 0.3 cm^2 while reading a book, 2.1 ± 0.3 cm^2 while drawing a picture, and 2.0 ± 0.3 cm^2 while writing. The OSAs during VDT work appeared to be greater than during traditional office work. Further analyses were carried out to clarify the differences between tasks with and without a VDT. One was an analysis of changes in OSA with time, while the other was an analysis of the frequency distribution of OSAs.

Figure 5 shows a comparative study of OSA size while performing several tasks. Section (a) in Figure 5 shows changes in OSA during word processing. OSA when the subject was viewing a CRT display was 3.2 cm^2, and was 1.5 cm^2 when looking at a keyboard and a manuscript. During this word processing task, large changes in OSA were frequent. Section (b) in Figure 5 shows OSA when the subject was using a mouse to draw a picture on a CRT display. The average

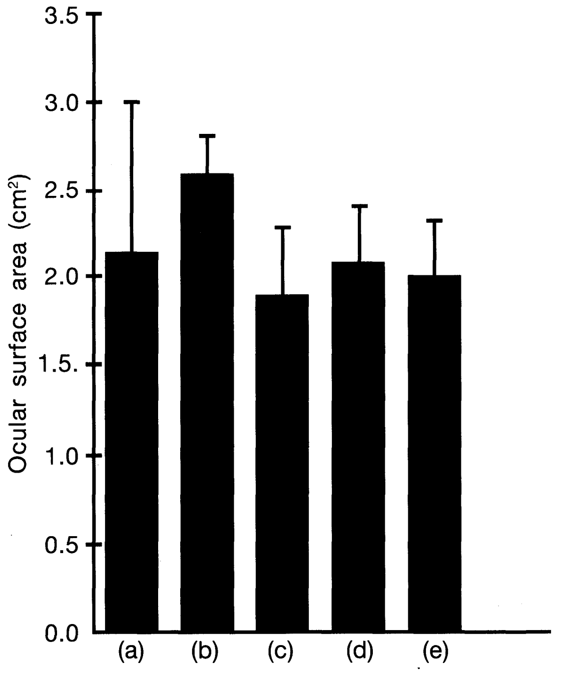

Fig. 4. Ocular surface area while performing five visual tasks. (a) Word processing with a VDT, (b) Drawing a picture with a VDT, (c) Reading a book, (d) Drawing a picture, (e) Writing.

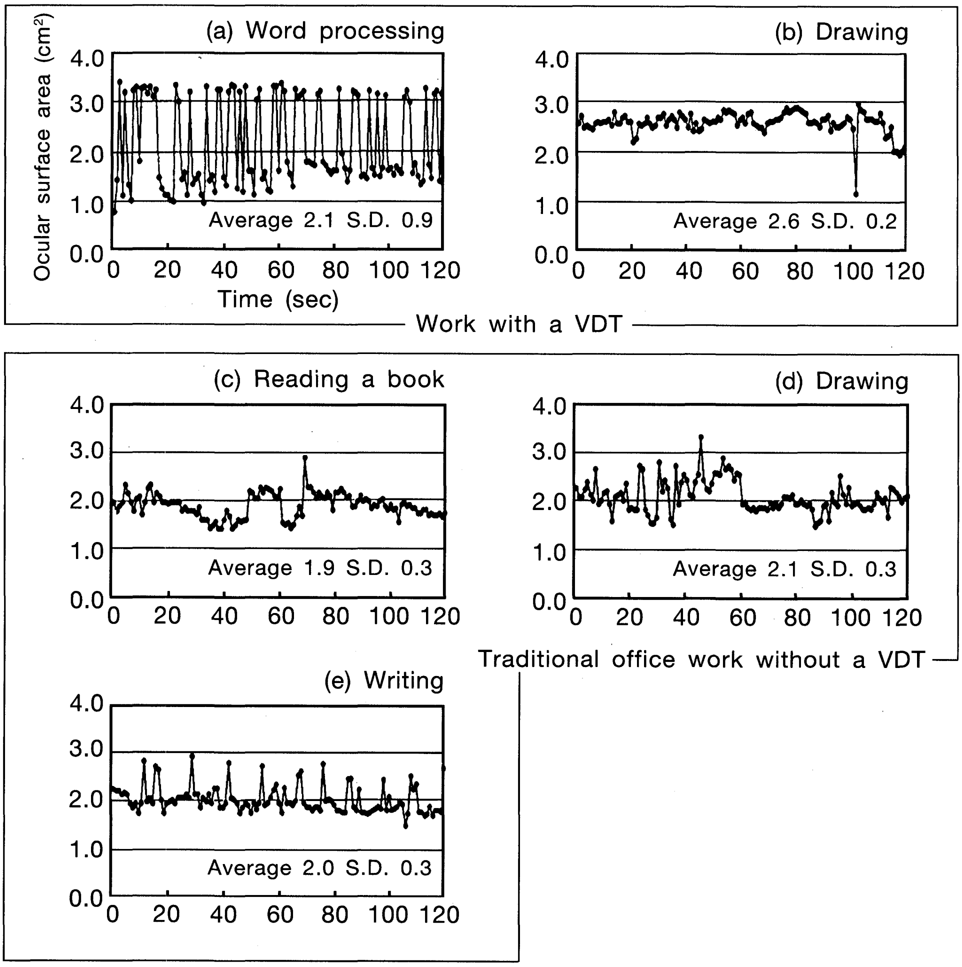

Fig. 5. Changes in OSA with time during work with and without a VDT.

was 2.6 cm^2, the largest value obtained for any of the tasks. Section (c) in Figure 5 shows OSA when the subject was reading a book. The average OSA during this task was 1.9 cm^2 with little change. Section (d) in Figure 5 shows OSA when the subject was drawing a picture. The average OSA in this case was 2.1 cm^2. Section (e) in Figure 5 shows OSA when the subject was writing. The average OSA was 2.0 cm^2. Whenever the subject glanced at a book, regular pulse-like increases occurred as shown in this figure.

Figure 6 shows the frequency distribution of OSAs for each task. The two peaks as visible in section (a) in Figure 6 were found during word processing. When the subject was drawing a picture on a CRT display, the peak of OSA distribution was located at the high end, ranging from 2.5 cm^2 to 3.0 cm^2. The

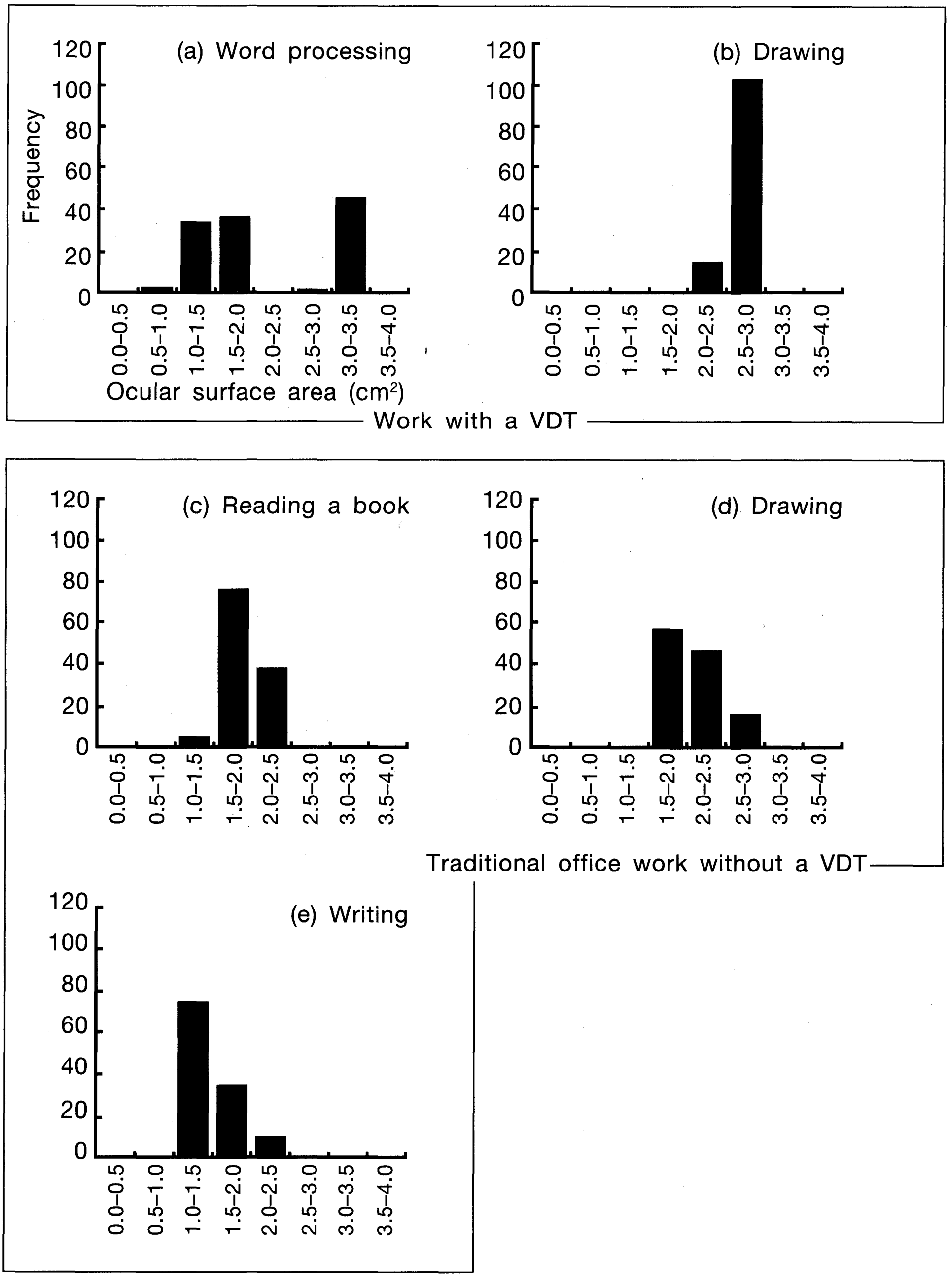

Fig. 6. Frequency distribution of OSA during work with and without a VDT.

frequency distribution of OSAs when the subject was working with a VDT was extremely different from the distribution when the subject was engaged in traditional office work without a VDT. Traditional office work without a VDT yielded only one peak in the 1.5 to 2.0 cm^2 range, and the distribution patterns for all three tasks were very similar.

3. Discussion

The results of OSA analysis with time course and the frequency distribution clarified the features of VDT work. During word processing, large changes in OSA were frequent, and when drawing with a mouse, OSA remained large throughout the task. The increase in OSA during VDT work has already been reported by Tsubota *et al.*[8], OSA was 2.2 cm^2 under relaxed conditions, 1.2 cm^2 while reading a book, and 2.3 cm^2 while viewing a text on a CRT display. They used the equation presented by Rolando for their OSA estimation; therefore, their values are smaller than ours.

The larger OSA during VDT work is considered to be one of the causes of eye fatigue because the larger OSA must increase the amount of tear evaporation from the eye surface and decrease the tear volume. Yaginuma *et al.* reported a decrease in tear volume during and immediately after completing VDT work[9]. This phenomenon very likely exposes the eye to various irritants and induces eye dryness and eye irritation during VDT work. We also confirmed that gazing upwards was more uncomfortable than gazing downwards[10].

The frequency distributions of OSAs during VDT tasks were very different from those of traditional office work as described above, and these differences are mainly caused by the position of the visual matter. The subject can easily move a book or paper to the most comfortable or preferred position during traditional office work without a VDT. However, during VDT work, one is constrained by the position of the display and keyboard at the VDT workstation. The location of the objects being viewed during work strongly affects OSA, and a large OSA is one of the causes of eye irritation during VDT work.

These facts suggest that lowering the position of the display would lower the direction of a VDT worker's gaze and thereby reduce his/her OSA. For this reason, to provide a comfortable VDT workstation, we propose that the display be directly set on the desk. According to the results of our previous studies, dark vergence shifts nearer[11] and exophoria decreases[5] when individual is gazing downwards. These phenomena suggest that downward gazing is more comfortable from the standpoint of the physiological functions of the visual system.

Conclusions

In this study, we developed an accurate system for measuring OSA, and we derived three equations. Using one equation, we compared OSAs while performing several visual tasks. Based on the results of this comparison, we recommend that setting the display directly on the desk to provide a more comfortable VDT workstation.

We have also shown that OSA provides useful information for evaluating visual work and work environments in the area of visual ergonomics.

References

1) Rolando M, Refojo MF. Tear evaporimeter for measuring water evaporation rate from the tear film under controlled conditions in human. Exp Eye Res 1983; 36: 25–33.
2) Saito S. Association of eyelids with the control system of eye movements. Fukushima J Med Sci 1975; 21: 113–24.
3) Saito S, Tada H, Tsukahara S. Eyelid-and-eyeball synkinesis in human visual system. Fukushima J Med Sci 1978; 25: 101–7.
4) Heuer H, Büwer M, Römer T, Kröger H, Knapp H. Preferred vertical gaze direction and observation distance. Ergonomics 1991; 34: 379–92.
5) Saito S, Sotoyama M, Suzuki T, Saito Sh, Taptagaporn S. Vertical gaze direction and eye movement analysis for a comfortable VDT workstation design. Work with Display Units '92, Elsevier Sci. Publ., 1993; 110–4.
6) Hill SG, Kroemer KHE. Preferred declination of the line of sight. Human Factors 1986; 28: 127–34.
7) Bergqvist Ulf OV, Knave BG. Eye discomfort and work with visual display terminals. Scand J Work Environ Health 1994; 20: 27–33.
8) Tsubota K, Nakamori K. Dry eyes and video display terminals. New Engl J Med 1993; 328: 584.
9) Yaginuma Y, Yamada H, Nagai H. Study of the relationship between lacrimation and blink in VDT work. Ergonomics 1990; 33: 799–809.
10) Abe S, Sotoyama M, Taptagaporn S, Saito Sh, Villanueva MB, Saito S. Relationship between vertical gaze direction and tear volume. Fourth International Scientific Conference Book of Short Papers, Work with Display Unit'94 1994; 1: B6-7.
11) Taptagaporn S, Saito S. Visual comfort in VDT operation: Physiological resting states of the eye. Ind Health 1993; 31: 13–28.