# Fast Photoelectric Estimation of Oxygen Transmissibility of Silicone Hydrogel Contact Lens

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Keywords: Silicone-Hydrogel Contact Lens, Water Content, Oxygen Transmissibility, Photoelectric Method.

Abstract: Nominal oxygen transmissibility (Dk/t) values on commercial product packages are usually of the lens material instead of the actual values of contact lenses (CLs) derived based on their power. To evaluate the Dk/t values of CLs of different powers, we developed a rapid photoelectric method. In the experiment, a photodiode was employed to detect variations in the light intensity passing through silicone hydrogel (Si-Hy) CLs over a period. Light intensity variations can indicate the water content (WC) and power of Si-Hy CLs and help calculate the Dk/t of Si-Hy CLs of different powers. Experimental results indicated that the WC and specific power of Si-Hy CLs were determined by the initial attenuation voltage, which ranged from 0.73 to 1.15 V for the lenses tested herein, whereas the WC varied from 38% to 56%. The Dk/t of Si-Hy CLs at -3.00 D was determined from the voltage variation over 3 min after reaching the peak voltage and the Dk/t corresponding to a specific power could be evaluated from the ratio of initial attenuation voltage of a lens having a specific power to that having -3.00 D. The results of this study can serve as reference information for quality control in factories.

## 1 INTRODUCTION

Contact lenses (CL) are classified as hard and soft based on the hardness of the lens. Traditionally, polymethyl methacrylate (PMMA) and hydrogels have been used as the main materials to manufacture hard and soft CLs, respectively. However, in recent years, rigid materials with gas permeability have been developed as a substitute for PMMA for manufacturing hard CLs to improve oxygen permeability and fit on the eyes (Bergenske et al., 1987; Harmano et al., 1994). Soft CLs have typically been manufactured using water-containing and gel-like plastics, and they are more pliable than hard CLs, which makes them more comfortable to wear. However, over several hours of use of soft CLs, the cornea gradually becomes hypoxic and the eye feels dry because soft CLs do not allow air to permeate through. Therefore, the oxygen permeability (Dk) of a CL is an important parameter when selecting CL products. According to the ISO 11539 standard for the classification of CLs, the material type is described using a six-part code depending on the material composition, namely water content (WC), percentages of ionic and nonionic monomer, contents of silicone and fluorine, and oxygen permeability (ISO11539, 1999). The main materials used to manufacture soft CLs include 2-hydroxyethyl methacrylate, poly-2-hydroxyethyl methacrylate, methacrylic acid, and vinyl pyrrolidone (Tranoudis et al., 2004); in all of these materials, the higher the WC is, the higher the oxygen permeability is. In general, the typical oxygen permeability of hydrogel lenses ranges from 25 to 50 (($cm^3[O_2] \times cm)/(cm^2 \times s \times mmHg$)), but oxygen permeability is limited to 80 (($cm^3[O_2] \times cm)/(cm^2 \times sec \times mmHg$)) even if the WC of a lens is 100% (Sweeney et al., 2006), as shown in Fig. 1.

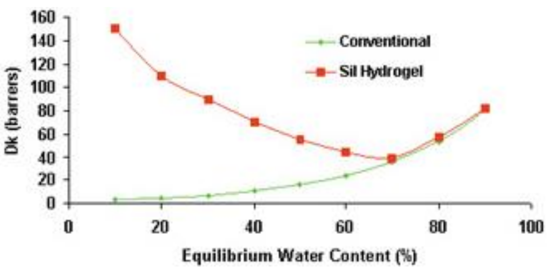


Figure 1: Relationship between oxygen permeability and WC of hydrogel and Si-Hy CLs (Jones, 2002).



Tsai, H-Y., Hsu, C-N., Lin, Y-H., Huang, K-C. and Shum, P.
Fast Photoelectric Estimation of Oxygen Transmissibility of Silicone Hydrogel Contact Lens.
DOI: 10.5220/0006619702050212
In *Proceedings of the 6th International Conference on Photonics, Optics and Laser Technology (PHOTOPTICS 2018)*, pages 205-212
ISBN: 978-989-758-286-8

The oxygen transmissibility Dk/t of a lens is defined as the ratio of the oxygen permeability Dk of a CL material and the thickness t of a local region of the CL. Moreover, the oxygen permeability Dk is determined by the diffusion coefficient D and solubility coefficient k, where D and k represent the speed of gas movement through the CL material and the degree of dissolved oxygen contained in the CL material, respectively. In addition, the unit of Dk is $10^{-11}$ $(cm^3[O_2] \times cm)/(cm^2 \times s \times mmHg)$, which equals 1 barrier (Cerle, 1972).

Harvitt et al., (1998) suggested an oxygen transmissibility value Dk/t of $125 \times 10^{-9}$ $(cm \times mL [O_2])/(s \times mL \times mm\ Hg)$ to prevent stromal anoxia, and hydrogel-based CLs cannot satisfy this requirement. Hence, silicone hydrogel (Si-Hy) was developed as a novel and revolutionary material with a Dk/t value of more than 100; this material facilitates the passage of a greater amount of oxygen through the CL to the cornea than hydrogel. With this feature, problems such as blurred vision, red eyes, and corneal swelling can be prevented over extended periods of use of soft CLs.

Coulometric (Alvord et al., 1998) and polarographic (Efron et al., 2007) methods have been employed in previous studies to measure the Dk value of a CL. ISO 9913-1 (1996) describes the polarographic method for determining Dk and Dk/t, especially for Dk values of 0–75 barrier. In the measurement process, gas flow is generated and passed through a CL, and a gold/platinum cathode and silver anode are placed centrally under the tested CL. In addition, ISO 9913-2 (2000) describes the coulometric method for determining Dk and Dk/t of rigid and nonhydrogel flexible CLs, especially for Dk values higher than 75 barrier. However, this method cannot be applied to hydrogel CLs. The polarographic method underestimates or overestimates the value of Dk at the edge of a CL owing to the difference in oxygen partial pressure; this phenomenon is called the boundary layer effect or edge effect. It can be corrected by considering the thickness of the side of the CL. To overcome the limitations of the polarographic and coulometric methods, ISO 18369-4 (2006) specifies tests of the physicochemical properties of CL materials, including extraction, rigid lens flexure and breakage, oxygen permeability, refractive index, and WC. In particular, the standard aims at simultaneous measurement of the physicochemical properties of hydrogel and nonhydrogel CLs.

Table 1: Comparison of methods for measuring oxygen permeability of CLs.

| Method | Technique | Characteristic |
|---|---|---|
| Polarographic | Generate gas flow/ Electrode detect difference of voltage | 1. For Dk value range 0-75 barrier.<br>2. For Hydrogel CL. |
| Coulometric | Generate gas flow/ Use coulometric sensor to detect pass oxygen through CL | 1. For Dk value higher than 75 barrier.<br>2. For Rigid and non-hydrogel CL. |
| Photoelectric | Irradiate light on CL/Detect variation of transmission light | 1. For Hidrogel and silicone hydrogel CL.<br>2. No limitation of Dk value.<br>3. Rapidly measuring process and without gas chamber. |

Lee et al., (2015) used the polarographic method to measure the Dk value of CLs in phosphate-buffered saline (PBS) and borate-buffered saline (BBS) solution, and the boundary effect was corrected by stacking four layers. The results showed that the Dk values of all CLs measured in BBS solution were more stable than those measured in PBS solution. Lewandowska et al., (2015) analyzed the porosity of CLs to determine the relationship between oxygen permeability and porosity. The results revealed that the highest Dk value can be obtained by using a CL mould material with the fewest pores of the largest size.

According to previous studies, methods for measuring Dk and Dk/t are based on the electrochemical or the diffusion method, and these methods require oxygen gas, a gas chamber, and several precise components, as summarized in Table 1. Moreover, the measured value is usually the ideal value instead of the actual value of the wearable.

An instant measurement model for measuring the WC and oxygen permeability of hydrogel CLs was developed by analyzing light attenuation over a specific spectrum (Hung, 2017). A spectrometer was used to detect light intensity, and the light intensity at wavelengths of 500–600 nm was analyzed over a period of 8 min. However, light intensity was measured optically, and the oxygen transmissibility of a CL considering its thickness and power was not evaluated.

Therefore, in the present study, we developed a photoelectric method for observing variations in the light transmitted through Si-Hy CLs over a specific period and for evaluating the WC and actual oxygen transmissibility value directly. In this method, optical components such as LEDs and photodiodes (PDs) are employed to replace halogen lamps and spectrometers. Moreover, we designed and fabricated a signal amplifier circuit to read the voltage transferred by the light intensity; the resulting device is portable and can serve as a substitute to conventional equipment, which are expensive.

# 2 FUNDEMENTAL THEORY AND EXPERIMENTAL SYSTEM

## 2.1 Characteristics of Silicone Hydrogel Contact Lens

Different materials used to prepare Si-Hy CLs exhibit different light reflectivity, transmission, and absorption levels when illuminated by light of different wavelengths. Hale et al. (1973) found that water exhibits relativity stable and lower light absorption at wavelengths of 400–600 nm, as illustrated in Fig. 2.

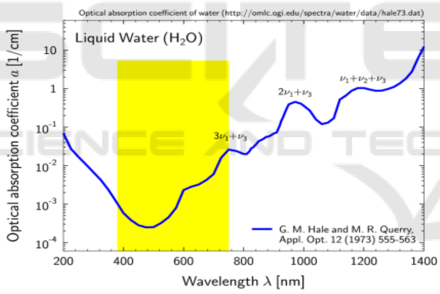


Figure 2: Absorption spectrum of water. (Hale et al., 1973).

In addition, it exhibits lower absorption and $O_2$ evolution rates for light of wavelengths 500–650 nm, as shown in Fig. 3. Therefore, we employed an LED light source with a wavelength of 520 nm to irradiate Si-Hy CLs for minimizing the measurement errors caused by water and oxygen.

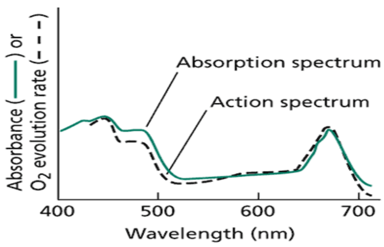


Figure 3: Action and absorption spectrum of oxygen in visible spectrum. (Taiz et al., 2015).

## 2.2 Experimental System and Measurement Process

### 2.2.1 Preparation of Silicone Hydrogel Contact Lenses

Si-Hy is a novel material used for fabricating soft CLs, and its excellent properties include higher oxygen permeability than other CL materials. In the experiment in this study, four types of Si-Hy CLs, with different WC levels, oxygen permeability levels, and eight different powers for each type of Si-Hy CL, were used to investigate the voltage variation caused by Si-Hy CLs; their nominal specifications are listed in Table 2.

Table 2: Specifications of Si-Hy CLs.

| Brand / Specification | ACUVUE OASYS | ACUVUE TruEye | Hydron Eye Secert | Cooper Vision Clariti |
|---|---|---|---|---|
| Material | Senofilcon A | Narafilcon A | Filcon I | Somofilcon A |
| Water Content (%) | 38 | 46 | 47 | 56 |
| Dk × $10^{-11}$ (cm$^3$[$O_2$] × cm)/(cm$^2$ × sec × mmHg) | 122 | 100 | 120 | 60 |
| Central Thickness @-3.00D (mm) | 0.085 | 0.085 | 0.08 | 0.07 |
| Dk/t × $10^{-9}$ (cm$^2$[$O_2$] × cm)/(cm$^2$ × sec × mmHg) | 144 | 118 | 150 | 86 |

In general, the oxygen permeability (Dk) of Si-Hy CLs decreases with increasing WC; however, Dk is affected by CL thickness as well. Therefore, the oxygen transmissibility (Dk/t) of CLs provides more accurate information about the oxygen transmission ability of CLs. Furthermore, the nominal central thickness of a CL is almost for the power of −3.00 D, but the central and edge thicknesses and their ratio change with CL power. Lira et al. (2014) used an electronic thickness gauge to measure the central and peripheral thicknesses of several CLs of different powers and re-estimated the oxygen transmissibility of each CL. Their results indicated that the CL thickness increased with increasing CL power, especially in the range of −3.00 to −6.00 D. In this study, we used a portable optical microscope to acquire cross-sectional images of Si-Hy CLs to determine their actual thickness.

#### 2.2.2 Experimental Setup

A schematic of the experimental setup is presented in Fig. 4. A green LED emitting light of wavelength 520 nm and triggered by a current of 1 mA was used as the light source, and the voltage measured using a Tekronix DPO3014 oscilloscope represented the intensity of light received by the PD; the measured value tended to decrease when the Si-Hy CL was dehydrated. In addition, a signal processing circuit was connected between the PD and the oscilloscope to transform the light signal into an electrical signal and amplify tiny variations in the signal.

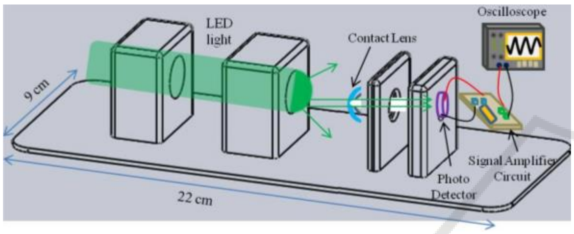


Figure 4: Schematic of experimental setup.

#### 2.2.3 Design of Signal Amplifier Circuit

Regarding the signal amplifier circuit used herein, which was designed based on reverse amplification technology, as the amount of light detected by the PD increased, the output voltage became lower. Accordingly, the light intensity would affect only the voltage signal, and the frequency would remain unaffected. Therefore, the voltage value displayed on the oscilloscope increased when the Si-Hy CL was placed on the measuring setup, which reduced the intensity of the transmitted light, and the voltage variation was 2 V, as shown in Fig. 5. Here, the frequency was unaffected by the light intensity.

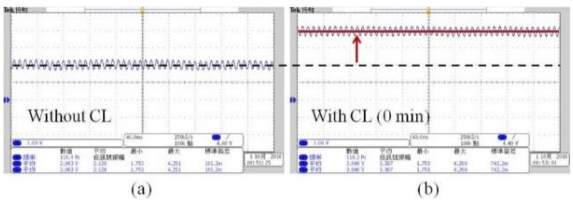


Figure 5: Voltage measured by oscilloscope with and without CLs.

#### 2.2.4 Photoelectric Method and Measurement Process

Given that the light transmission intensity is influenced by the WC of the CL, CL material, and CL thickness, the photoelectric module used herein was set up to detect intensity variations caused by different types of Si-Hy CLs and to determine their WC and power levels. Moreover, the actual oxygen transmissibility of Si-Hy CLs with different powers could be evaluated. Six main steps were involved in evaluating the actual oxygen transmissibility Dk/t of Si-Hy CLs of unknown or known power. A flowchart of this process is shown in Fig. 6, and the details of each step are described as follows.

Step (I): We used a green LED light to provide stable irradiation on Si-Hy CLs, and we applied a PD and oscilloscope to detect the intensity of light transmission and display the measured signal, respectively. In addition, we designed and deployed a signal amplifier circuit between the PD and the oscilloscope to amplify the voltage to amplify the minute variations in light intensity.

Step (II): We measured the voltage from the oscilloscope without wearing any Si-Hy CL and used this value as the reference in the following calculation process.

Step (III): After placing a Si-Hy CL on the stage of the measurement setup, we started to count time.

Step (IV): We recorded the voltage measured by the oscilloscope for Si-Hy CLs of different power and WC levels every 1 min.

Step (V): We analyzed variations in the voltage when using Si-Hy CLs relative to the reference value and then determined the WC and Dk/t values of Si-Hy CLs at −3.00 D.

Step (VI): The actual Dk/t of CL of specific power could be calculated from the ratio of initial attenuation voltage between the specific power and −3.00 D.

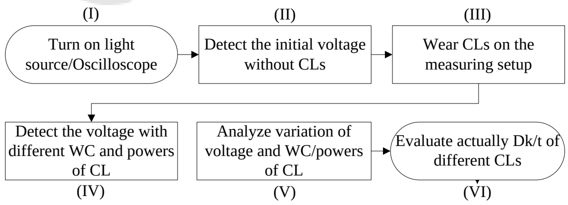


Figure 6: Flowchart for evaluating WC and actual Dk/t of Si-Hy CLs.

# 3 EXPERIMENTAL RESETULS AND DISCUSSION

## 3.1 Dehydration and Evaluation of Water Content of Contact Lenses

The material used to prepare Si-Hy CLs contains many micropores, and water fills these holes, thus blocking oxygen diffusion and reducing light transmission. Therefore, the oxygen permeability of Si-Hy CLs decreases with increasing WC, and light transmission increases when Si-Hy CLs are dehydrated. From the measured voltage values of four different types of Si-Hy CLs with a power of −3.00 D, the Si-Hy CLs with higher WC initially blocked a large amount of light to be transmitted, but they dehydrated rapidly, and the voltage signal gradually stopped changing after 3 min, as shown in Fig. 7. In addition, the dehydration ratio of Si-Hy CLs with low WC was less than that of Si-Hy CLs with high WC. On the basis of these features, users of Si-Hy CLs with lower WC would not feel strong sensations of dryness in the eye over extended periods of use; moreover, this type of Si-Hy CL has high oxygen permeability.

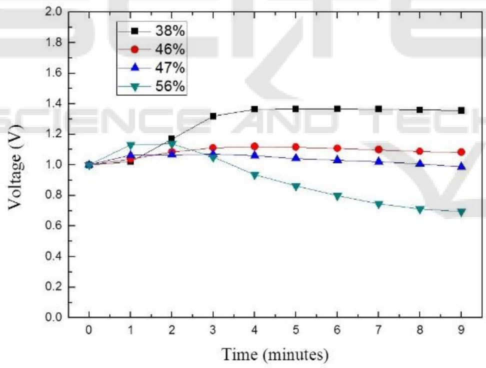


Figure 7: Attenuation voltage over 9 min in cases of Si-Hy CLs with four different WC levels.

The voltage variation between the cases of CL use and no CL use were employed to determine WC; WC was found to vary linearly with the voltage variation, as shown in Fig. 8. The initial attenuation voltage ($V_{i\kappa}$) was determined according to the voltage variation between the cases of initial CL use ($V_{0min}$) and no CL use ($V_{reference}$), as expressed by Eq. (1).

$$V_{i\kappa} = V_{0\,min} - V_{reference} \tag{1}$$

Accordingly, the relationship between the initial attenuation voltage ($V_{i\kappa}$) and WC of Si-Hy CLs at a power of −3.00 D can be given by Eq. (2). From this equation, an increase in the WC of Si-Hy CLs would result in the blockage of greater amounts of light and an increase in the attenuation voltage simultaneously. The constant in this expression was obtained using the linear equation in Fig. 8.

$$V_{i\kappa} = 0.0256 \times WC - 0.30956 \tag{2}$$

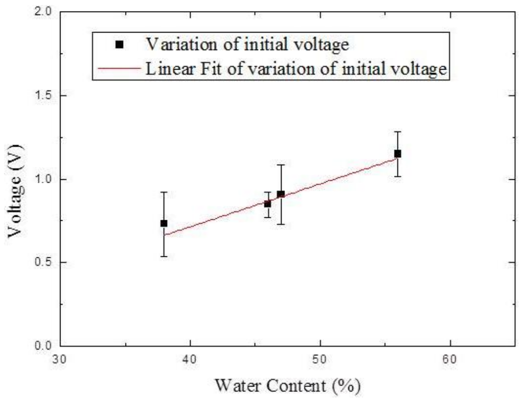


Figure 8: Initial attenuation voltage affected by WC of Si-Hy CLs.

## 3.2 Relationship between Oxygen Transmissibility and Light Transmission through Contact Lenses

When the Si-Hy CL was placed on the stage of the measurement setup, the voltage measured by the oscilloscope initially increased and peaked at a certain value. In this period, the transmission of light was affected by the WC of the Si-Hy CL. Then, the Si-Hy CL was dehydrated, the measured voltage decreased gradually, and the oxygen transmissibility of the Si-Hy CL started to affect the intensity of light transmission. Therefore, the voltage variation at 3 min after the appearance of the peak voltage could be employed to evaluate the oxygen transmissibility of Si-Hy CLs. The results showed that the oxygen transmissibility of the four different types of Si-Hy CLs (the same as those listed in Table 2) with a power of −3.00 D had a polynomial relationship with the voltage variation, as shown in Fig. 9. When the relationship between the voltage variation and oxygen transmissibility of 80–150 was established, the unknown oxygen transmissibility (Dk/t) of a Si-Hy CL with a power of −3.00D could be evaluated from the voltage variation (V) measured using the developed method and the following equation.

$$\begin{aligned} Dk/t &= 175.44 - 1101.39 \times V \\ &+ 5626.76 \times V^2 - 10996.39 \times V^3 \end{aligned} \tag{3}$$

The constant in the Eq. (3) was obtained from the fitting curve in Fig. 9. In addition, the WC decreased as the oxygen transmissibility of the Si-Hy CLs increased and the rate of CL dehydration decreased simultaneously. Owing to this phenomenon, the voltage variation of the CLs with high oxygen transmissibility was lower than that of the CLs with low oxygen transmissibility.

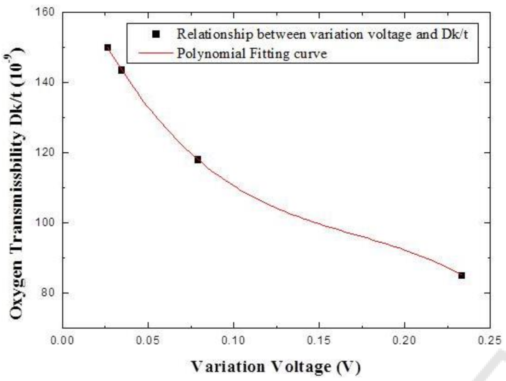


Figure 9: Relationship between oxygen transmissibility and voltage variation at 3 min after the voltage peaked.

## 3.3 Thickness and Shape of Contact Lenses

In general, the nominal thickness of a CL is defined by the central thickness and set at a power of −3.00 D. However, the thicknesses in the central and the edge regions are different, and the values change with the power of the CL. In the experimental results, we found that the central and edge thicknesses differed only slightly, and the thickness ratio of CLs with powers of −1.00 to −8.00 ranged from 2.2 to 2.6, as shown in Fig. 10. In addition, the thickness ratio ranges were similar for different types of Si-Hy CLs.

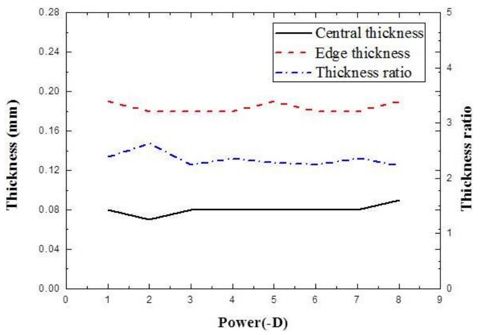


Figure 10: Central and edge thicknesses, and thickness ratio of Si-Hy CLs.

Although the central and edge thicknesses were similar for lenses of different powers, the sagittal length varied with the power of the Si-Hy CLs, as shown in Figs. 11 and 12. As illustrated in the figures, the diameter of the Si-Hy CL was fixed, and the sagittal length was determined at the position where the lens thickness was less than 0.1 mm; the length ratio ($L_r$) can be expressed by Eq. (4). The results showed that the sagittal length decreased and length ratio increased as the Si-Hy CL power increased. This is because the central and edge thicknesses are controlled to maintain wearing comfort; thus, the shapes of Si-Hy CLs are slightly adjusted to facilitate fabrication and to meet the requirements of different powers. In addition, variations in lens shape would affect the transmission intensity of light passing through Si-Hy CLs.

$$L_r = \frac{\text{Diameter}}{\text{Sagittal}} \tag{4}$$

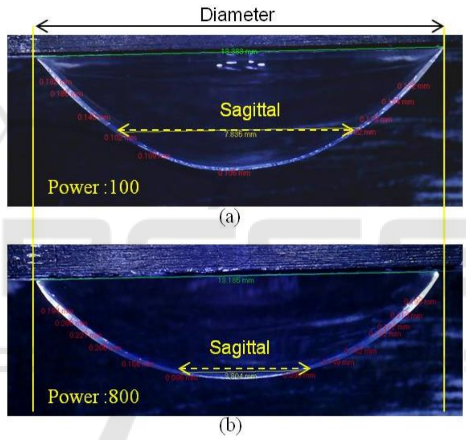


Figure 11: Schematic of diameter and sagittal length of Si-Hy CLs with powers of -1.00 and -8.00 D.

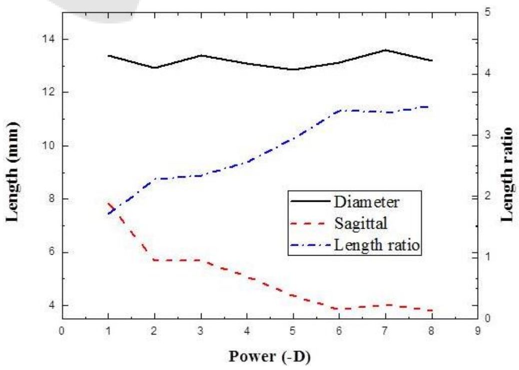


Figure 12: Diameter and sagittal length, and length ratio of Si-Hy CLs.

### 3.4 Actual Oxygen Transmissibility of Contact Lenses of Different Powers

From the preceding results, the shape of Si-Hy CLs would be affected by the lens power, and the initial attenuation voltage would be affected simultaneously. The initial attenuation voltage decreased with increasing Si-Hy CL power because the length ratio between the lens diameter and sagittal length increased, thus causing a greater amount of transmission light to be focused on the PD. Therefore, the power of Si-Hy CLs could be determined using the initial attenuation voltage. In addition, the trends could be applied to different types of Si-Hy CLs, as shown in Fig. 13.

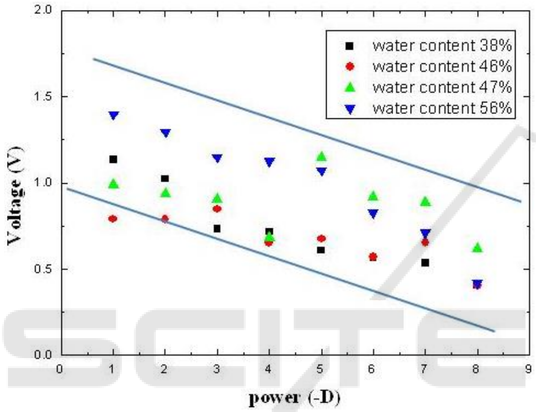


Figure 13: Effect of Si-Hy CL power on initial attenuation voltage.

Although the WC and oxygen permeability (Dk) of Si-Hy CLs of the same material are fixed, the actual oxygen transmissibility may differ slightly depending on the length ratio. An increase in the length ratio would lead to a wider region in the lens being thicker than 0.1 mm, and the actual oxygen transmissibility would decrease. Accordingly, the actual oxygen transmissibility of Si-Hy CLs at a specific power can be evaluated using Eqs. (5) and (6),

$$R' = \frac{V_{i\kappa}(@-xD)}{V_{i\kappa}(@-3.00D)} \quad (5)$$

$$Dk/t(@-xD) = Dk/t(@-3.00D \times R' \quad (6)$$

where x is the specific power of a CL, and R' is the ratio of initial attenuation voltage between the lens of a specific power and that of −3.00 D. For example, the nominal oxygen transmissibility Dk/t of Cooper Vision Clariti at −3.00 D is 86, and the initial attenuation voltages ($V_{i\kappa}$) at −6.00 and −3.00 D are 0.83 and 1.15, respectively. The ratio of initial attenuation voltages (R') of the same lens of two powers is 0.72, and the actual oxygen transmissibility of Cooper Vision Clariti at −6.00 D is 62.07.

## 4 CONCLUSIONS

In this study, we developed a rapid photoelectric measurement and evaluation method for measuring the WC of Si-Hy CLs from the initial attenuation voltage; the WC values of the lenses considered herein ranged from 38% to 56%. In addition, the power of the Si-Hy CLs influenced their initial attenuation voltage, sagittal length, and oxygen transmissibility. Thus, the initial attenuation voltage could be employed to evaluate the specific power of the Si-Hy CLs; additionally, the actual oxygen transmissibility for a given specific power of Si-Hy CLs could be evaluated from the ratio of the initial attenuation voltage of a CL having a specific power to that of a CL having a power of −3.00 D. Through this method, the WC, power, and actual oxygen transmissibility of a Si-Hy CL of unknown material and power can be evaluated rapidly instead of obtaining the nominal oxygen transmissibility at the power of −3.00 D. The advantages of the proposed method include high speed and low cost. In the future, a portable measurement instrument will be developed by designing a printed circuit board of a read circuit to replace the oscilloscope used herein in order to facilitate rapid measurement of CLs for quality examination in a factory setting.

## ACKNOWLEDGEMENTS

This work was supported in part by the Ministry of Science and Technology, TAIWAN, under Grants MOST 106–2221–E–492–017– and MOST 106–2221–E–492–011–.

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