Development of Instant Measuring Model for Oxygen Permeability and Water Content of Hydrogel Contact Lens

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Abstract: The diffusion coefficient D, gas solubility k of material and the thickness of lens t were used to evaluate the oxygen permeability Dk/t of contact lenses (CLs). However, the nominal value Dk/t is usually not consistent with the actual oxygen permeability of wearing CL. As the oxygen travel through the hydrogel, it need to be carried by water molecules in the lens material; thus, the higher the water content (WC) of the material, the higher the Dk/t value. In order to obtain the WC and Dk/t of wearing CL, we create a testing platform to simulate the wearing status of CL. When the light traveled through the lens, we found that the attenuation in green light is smoother than other wavelengths. Moreover, the WC is higher, its dewatering rate at room temperature is lower, and the light attenuation is relatively smaller. Comparing with the other CL of similar WC, the Dk/t of CL is higher if it has higher dehydration. In the study, we evaluated the WC and Dk/t of hydrogel CL based on the light attenuation in eight minutes. The attenuation degree of light after traveling through the CL can be used to estimate the Dk/t of hydrogel CL.

1 INTRODUCTION

The contact lens (CL) can be divided into soft CL and hard CL based on their material hardness, wherein the main material of soft CLs are hydrated polymer and hydroxyethyl methacrylate (HEMA), and the traditional hard CL material are polymethyl methacrylate (PMMA). However, the PMMA was replaced by the hydrophobic gas permeable material in recent year. Because the soft CL is relatively soft, it is easily attached to cornea; therefore, the patient will feel more comfortable while wearing. However, the eyes is prone to irritation or dryness if extended-wear CL, because the eye covered by the CL is not easy to contact with air. In addition, the high water content of CL is readily to cause the microbial and bacterial attachment, and a substantial increase of infection rate in eyes, or even result in the proliferation of capillaries around the eyes. On the contrary, the hard CL will cause a foreign body sensation (FBS) in his eyes when the patient begins to wear it, but has a better correction effect for patients with high myopia or astigmatism due to the smaller coverage area of eye. Moreover, the hard CL which has a lower water content is less susceptible to microbial and bacterial attachment, so the infection rates of eyes dropped significantly.

In accordance with (ISO-11539, 1999) standards for the classification of soft CL, The CL material can be classified by a six-part code. The category classification is based on material composition, oxygen permeability, etc., wherein the composition can be distinguished depending on the compound of silicon (Si) and fluorine (F) and the water content and ionic monomers are also included. Hard CL can be made from hexafocon, enflufocon or polymethyl methacrylate (PMMA). Soft CL materials are mostly 2-hydroxy-ethyl methacrylate (HEMA), methacrylic acid (MAA), methyl methacrylate (MMA), vinyl pyrrolidone (VP), etc. (Tranoudis and Efron, 2004), or can be stamper manufactured in different proportions of these materials.

An important indicator to evaluate the quality of CL is so-called oxygen permeability. In general, the oxygen permeability of CL is denoted by Dk, where D is the diffusion coefficient which represents the ability of the gas diffusion through the CL material; that is, the moving speed of the gas molecules in CL. k is the solubility coefficient which indicates the degree of dissolved oxygen in CL, and Dk is the

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product of the diffusion coefficient and solubility coefficient. The units of Dk value are 10-11 (cm3 O2 cm)/ (cm3 sec mmHg) or "barrier". The higher is the value of Dk, the better is the oxygen permeability of CL. In addition, the Oxygen transmissibility (Dk/t) of the local region of CL is expressed as oxygen permeability (Dk) of the material of CL is divided by the thickness (t) of CL.

There are two commonly methods to measure the Dk or Dk/t of CL, the polarographic and coulometric technologies (Fatt and Chaston, 1982, Refojo, et al., 1977, Refojo and Leong, 1979, Brennan, et al., 1986, Compañ, et al., 1996, Paterson and Doran, 1986 and González-Méijome, et al., 2008). The polarographic technique has often been used to determinate the Dk coefficient of hydrogel CL, which placed directly on the Clark-type electrode, based on the oxygen flux through the CL. Practically, this technique has its limitations during measuring Dk, such as the so-called boundary-layer effect and edge effect in the polarographic method. The boundary-layer effect leads to the underestimation the Dk/t of sample due to the difference of oxygen partial pressure on the two side of sample. In addition, the edge effect means that the lateral diffusion of oxygen occurs if the test area is not the same on both sides of sample and results in the Dk value of sample under test is slightly higher than the real value. Despite these shortcomings in the measurement of polarographic method, but it can use some experimental procedure to amend its measured value to close the actual value. For example, the measuring values could be corrected by measuring the samples of different thickness for the boundary-layer effect (Compañ, 2002), or be multiplied by a proper correction factor for the edge effect. In the coulometric method, a nitrogen carrier gas flows around the lens and transports the permeated oxygen to the oxygen detector which produces an electrical current, wherein the magnitude of oxygen through the film is proportional to the amount of oxygen. The oxygen gas transmits from upper chamber through CL film into lower chamber during the permeability process. However, the sample has a dehydration effect during test when it exposed to air; therefore, the coulometric method is not applied to the Dk measurement of hydrogel CL because the water content can cause changes in oxygen permeability. The above mentioned two methods are both well defined in the ISO standards (ISO 9913-1, 1996 and ISO 9913-2, 2000), which also referred to the restrictions on the use of two methods. The polarographic method can only measure the CLs of less than 100 Barrier, and the coulometric method cannot be applied to the hydrogel CLs. However, the polarographic (Fatt) and coulometric method in ISO can be adopted to determinate the oxygen permeation through all types of contact lenses, except the high Dk silicone based CLs. Therefore, these standards 9913-1&2 have now been withdrawn and replaced by (ISO 18369-3, 2006). The ISO 18369-3 specifies the methods of testing the physicochemical properties of CLs, which are extraction, rigid lens flexure and breakage, oxygen permeability, refractive index and water content. Therein, the soft CLs can also be made of non-hydrogel materials, such as the silicone elastomers. Based on the high performance liquid chromatography (HPLC-EC), (Oberndorf and Wilhelm, 2003) uses the reductive electrochemical detection to determine oxygen at nanomolar levels, the method had not only lens dehydration, but can minimize the edge and boundary layer effects, the Dk values of rigid and soft CL can be determined in the same manner with good reproducibility. The above mentioned measuring methods for oxygen permeability of CLs are based on the electrochemical or vacuum infiltration model, so the measuring results are often not consistent due to the different measuring method or instruments.

Therefore, this study presents a non-contact method that can reduce the measurement error came from the environment or instrument layout, and to evaluate the WC and Dk/t of CL in different manner from the absorption spectrum of CL. Therein, the full wavelength of light was provided from the halogen lamp, and the variation of light spectrum was measured from the spectrometer that facing to the light source. In addition, five types of CL with different WC and Dk/t were employed to observe the variation of intensity of transmission light in 8 minute after wearing to the experimental setup.

2 FUNDEMENTAL THEORY AND EXPERIMENT SYSTEM

2.1 Relationship between Water Content and Oxygen Permeability of Contact Lens

In general, the Dk/t of CLs is positive correlation to the WC of CLs, (Hadassah and Sehgal, 2006) presented a measurement that allowing the oxygen to pass through the lens material and investigate the oxygen permeability and transmissibility of contact lenses of different thickness and curvature. Therein, the expelled oxygen gas was collected by the dissolution in ethanol and measured by the titration of solvent, and this method could be employed in both dry and wet conditions of lenses. The results showed that the Dk value was directly proportional to the WC of lens and inversely proportional to the thickness of lens, shown as Fig. 1. Therefore, the WC of CLs while wearing could be used to evaluate the oxygen permeability of CLs.

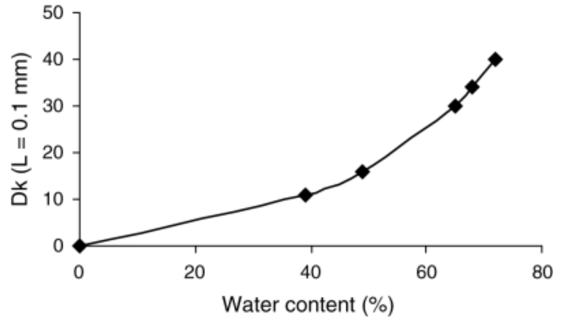

Figure 1: Dk values of lens related to the water content. (Hadassah and Sehgal, 2006).

2.2 The Spectrum of Oxygen and Water Absorption

The substances have different light absorption, reflectively and transmission while irradiated by the light. (Hale and Querry, 1973) developed that the relatively lower and stable absorption of light at wavelength of 400-600 nm, shown as Fig. 2. In addition, the oxygen also has lower absorbance and O_2 evolution rate at wavelength of 500 – 650 nm, shown as Fig. 3. Therefore, the intensity at wavelength of 500 – 600 nm was analyzed to investigate the variation of WC and Dk value while wearing different CLs.

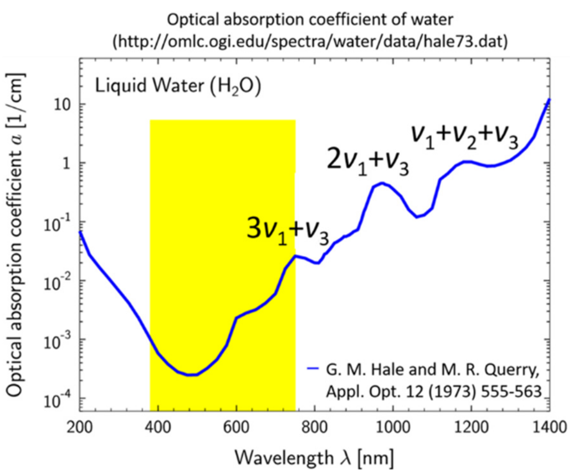

Figure 2: Absorption spectra of water. (Prahl, 2009).

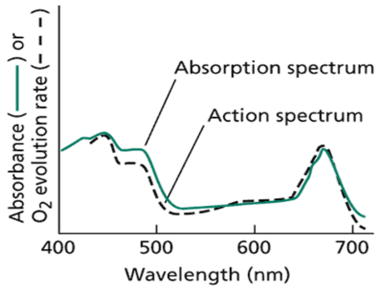

Figure 3: Absorption and action spectrum of oxygen. (Taiz and Zieger, 2015).

2.3 Development of Mathematical Model

The attenuation (κ) of light intensity was determined by intensity variation between without CLs (I_{Ini}) and wearing CLs (I_{CL}), and which was expressed as (1).

$$\kappa\,(\%) = \frac{I_{Ini} - I_{CL}}{I_{Ini}} \tag{1}$$

The κ increase with the increase of WC due to the CLs with high WC need more water to maintain its properties. Therefore, the WC of wearing CLs could be calculated when κ_{ave} of each CLs in a period was obtained, and the relationship could be expressed as (2).

$$\mathrm{WC}\,(\%) = \alpha_1 + \beta_1 \times \kappa_{ave} + \gamma_1 \times \kappa_{ave}^2 \tag{2}$$

where α_1, β_1, and γ_1 was the coefficient. In addition, the variation (V_κ) between the maximum and minimum κ in a period also could be evaluated by WC, and written as (3),

$$V_\kappa\,(\%) = \alpha_2 + \beta_2 \times \mathrm{WC} + \gamma_2 \times \mathrm{WC}^2 + \delta_2 \times \mathrm{WC}^3 \tag{3}$$

where α_2, β_2, γ_2 and δ_2 was the coefficient. Moreover, the oxygen permeability (Dk/t) of wearing CLs could be evaluated simultaneously from the variation attenuation of each CLs by Eqn. (4),

$$Dk/t = \alpha_3 + \beta_3 \times V_\kappa + \gamma_3 \times V_\kappa^2 \tag{4}$$

where α_3, β_3, and γ_3 was the coefficient.

2.4 Layout of Measuring System

In order to measure the actually Dk value while wearing CL, the optical measuring module was build in this study, and several different CLs were put on the measuring module to investigate the variation of light intensity in a period of time. Thus, the measuring results and the properties such as WC and Dk/t while wearing CLs were discussed.

2.4.1 Setup of Experiment

In the experiment, the light source was the halogen lamp with power of 150 watts, and the wavelength of light ranged UV to NIR spectrum, especially 380 to 900 nm. A holder was fabricated by 3D printer to place the CLs, and the SD1220-025-UVN spectrometer was placed at back of CLs and faced to the light source to detect the transmission intensity of the light beam. Therein, a 0.5D attenuator lens was used and placed between the CLs and light source to decay the light intensity that detected by spectrometer, shown as Fig. 4.

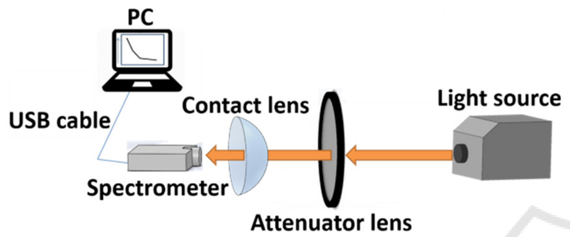

Figure 4: Layout of the instant measuring setup for wearing contact lens.

2.4.2 Process of Experiment

The experimental process was divided into four main parts, shown as Fig. 5.

(1) Turned on the light source and fixed the light intensity output from the light source by controlling the current. In addition, connect the spectrometer to the computer, and initialized the spectrometer.
(2) Measure the transmission intensity directly from the light source and 0.5D attenuator lens, and determine the value as the reference; especially without CLs on the holder.
(3) Put the tested CLs on the holder, and start to count the time that exposed on the air.
(4) Measure the transmission intensity that through the CLs, and save the date every 1 minute to observe the variation of light intensity.

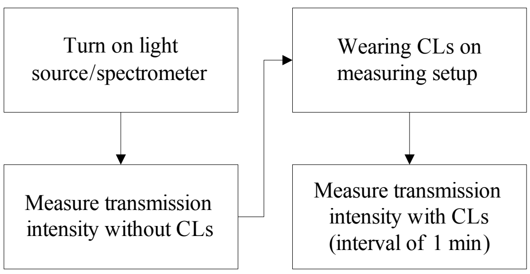

Figure 5: Experimental process for measuring the Dk/t of wearing CLs.

2.4.3 Preparation of Samples

In this study, five different types of CL from four brands including NOIST, HYDRON, TICON and BAUSCH+LOMB, and each of them has different WC and Dk/t values, which were summarized in Table 1. Therein, the samples of No. 1, 2, and 5 were used to investigate the relationship of WC and decay rate of spectrum, and the samples of No. 1, 3, and 4 with similar WC value were used to investigate the relationship of the Dk/t and difference between maximum and minimum of spectrum value in the period of 8 minutes.

Table 1: Summarized of tested samples.

No.	Brand/Model	WC (%)	Dk/t
1	MOIST/ACUVUE 1-day	58	33.3
2	HYDRON/Eye Secret 1-Day	38	26*
3	HYDRON/ UV Blocking 1-Day	55	30*
4	TICON/Hyaluronic Acid 1-Day	58	29
5	BAUSCH+LOMB/Bio true 1-Day	78	42

*: The maximum value in the interval.

3 EXPERIMENT RESULTS AND DISCUSSIONS

The purpose of our research was to develop an alternative to the conventional electrochemical or vacuum infiltration method for measuring Dk/t values of CL. To achieve our objective, we proposed an optical technology, which offers the benefit of non-contact skills and avoids measurement error with different instrument that can lead the way to higher reproducibility of measuring results. Four steps had been taken in the experiment, so that we can evaluate the WC and Dk/t by using the absorption spectrum of CL.

3.1 Spectrum Intensity after Wearing Contact Lenses

The first step of our research, three CLs with different WC were measured using the non-contact optical method as described in the formerly mentioned section. The No. 1 CL had a WC of 38%, the No. 2 CL had a WC of 58% and the No.3 CL had a WC of 78%. Take the 38% WC of CL for example, the light intensity of un-wearing CL and wearing CL can be shown in Fig. 6. The difference between the two curves can also illustrated in Fig. 6. Because the original data can't offer enough information, the attenuation of light was used to analyse in this study.

3.2 Light Attenuation after Wearing Contact Lenses

The light attenuation of CL No. 2 can be shown in Fig. 7. During the experiment, we found that the curve of light absorption rate in UV light provide a highly unstable status. This phenomenon may be caused by the measuring precision of spectrometer in 300-400 wavelength range and the basic ability of anti-ultraviolet of CL. The IR wave range in 890 to 900 nm had been chosen as standard originally, because the study by Prahl (Prahl, n.d.) indicates that there is a high absorption rate of water in IR light. The relationship between light attenuation and water content can be built up by this wave band of light.

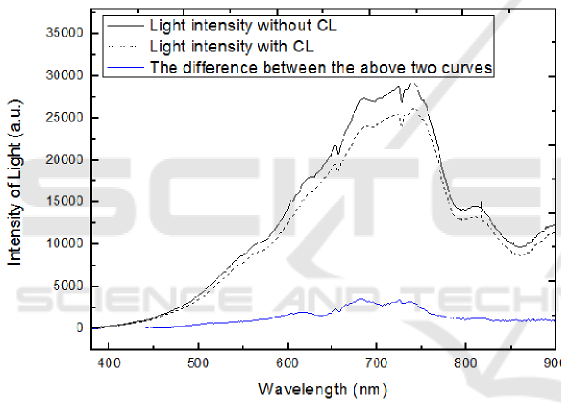

Figure 6: The light intensity with and without wearing contact lens.

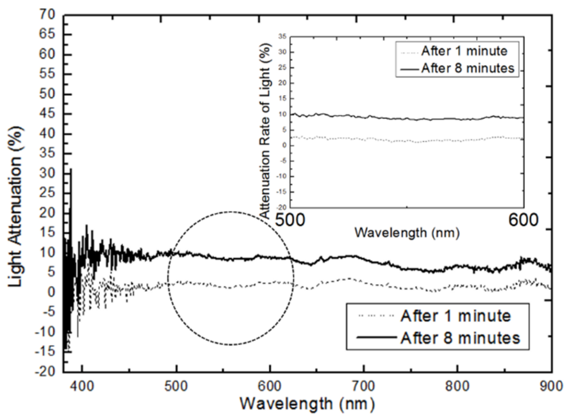

Figure 7: The light attenuation after wearing contact lens one minute and eight minutes. (the upper right corner is the enlarged view of 500-600 nm).

Unfortunately, Fig. 6 shows that there is a trend to descent in IR wavelength, so that we can't use the results as basic. On the other hand, in fig. 7, we also found that the attenuation of light in green wavelength (500-600 nm) was smoother than others. This results are entirely consistent with Hale's results (Hale and Querry, 1973). So that we chose the light ranged from 500-600 nm as the reference, the partial enlarged view is illustrated in Fig. 7.

3.3 Calculation of Water Content

When the contact lens is wearing on the human eyes, it needs to keep humid from tears by blinking eyes; otherwise, the contact lens will dry off in a period of time. In second step of our research, we found that contact lens was tendency to dry out after 8 minutes in our simulation model; then it provided error information caused by the surface cracks. Therefore, we averaged spectral attenuation from 1 to 8 minutes, the formula of attenuation was determined in Eqn. (1). Our results in Fig. 8 indicate that with increasing water content of contact lens, there is an increase in light attenuation. The average attenuation of CL with 78% WC was about 17.1% in 8 minutes; the average attenuation of CL with 58% WC was about 8.3%, and the average attenuation of CL with 38% WC was about 5.2%. From this results, we concluded that the higher water content, the more water in contact lens. Water is like a blocked layer which can resists the light to get through the CL. Therefore, we can use light attenuation to estimate the WC of an unknown contact lens by Eqn. (2) which is derived from Fig.1. The correlation coefficient α_1, β_1, and γ_1 can be calculated using Eqn. (2). Where α_1= -12.5025, β_1= 11.64322 and γ_1= -0.37138.

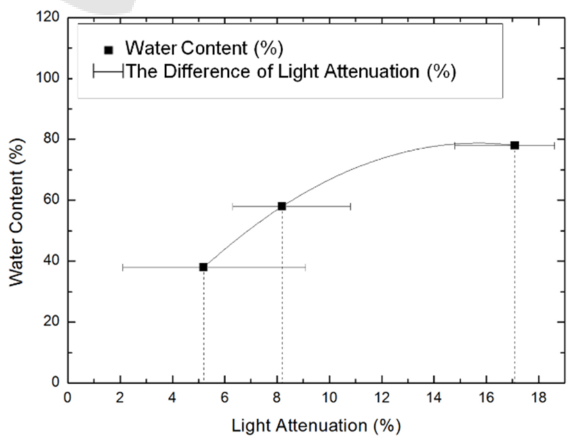

Figure 8: The fitting curve of the average attenuation and water content.

3.4 Calculation of Variation of Light Attenuation

According to the knowledge in previous section, the higher the WC of CL, the higher the Dk/t. However, this linear relationship needs to be under ideal conditions. When contact lens is worn on human eyes, it will dry out along with the wearing time. Although we blink several times to keep our eyes moist, it will still discomfort when the CL becomes dry and the WC isn't maintaining the maximum value. From the above reasons, we concluded that simple WC values would not allow us to obtain the Dk/t values. In third step of our research, we thus shift our attention to the difference between maximum and minimum attenuation of light in 8 minutes, the variation of light attenuation can also be demonstrated in Fig. 8. In Fig. 9, the images show that the brand with 38% WC has the highest difference value between max and min attenuation rate. For each of the CLs, we found that the WC increased with decreasing difference attenuation. The difference was about 7 at 38% WC of CL; the difference was about 4.5 at 58% of WC; The difference was 3.8 at 78% of WC. The results concept is intuitively and clear that the more water in the CLs, the slower the moisture out of the CLs. The equation of the difference of max and min attenuation is express as Eqn. (3). Therefore, we can apply the average of the attenuation in Eqn. (2), use the obtain attenuation to calculate the water content. Then, substituting WC in Eqn. (3) with Eqn. (2) yields the relationship between WC and the difference of maximum and minimum light attenuation. The value of the difference attenuation was defined as a correction factor in this research, which we can use this factor to calculate Dk/t value in next section. The correlation coefficient α_2, β_2, γ_2 and δ_2 can be calculated using Eqn. (3). Where α_2= 23.1557, β_2= -0.70445 and γ_2= 0.00887 and δ_2=-3.75×10^{-5}.

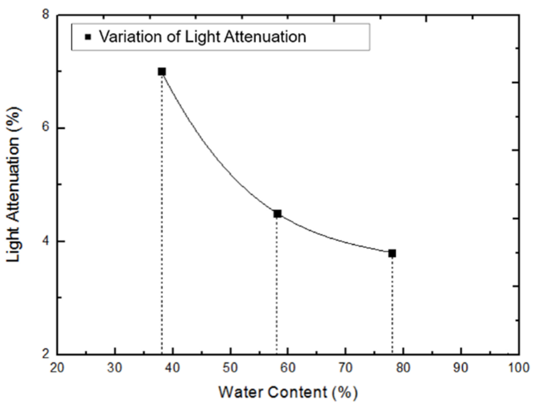

Figure 9: The fitting curve between the variation of light attenuation and water content.

3.5 Calculation of Oxygen Permeability of Contact Lens

On the basic of the abstract discussed, when the oxygen attempts to go through the material of hydrogel, it needs to follow with water molecules in the contact lenses; therefore, the higher the WC, the higher the Dk/t. However, this research took two kinds of popular CLs with both 58% WC to make a comparison. It was found that, although the two kinds of CLs shared the same WC, the Dk/t value of them were totally different. So that, this research took a correction factor that was derived by Eqn. (3) in section 3.3 to solve the problem. During the experiment, three brands of CLs with similar WC were used to comparison in the fourth step of this study. Sample No. 1, 3 and 4 in Table. 1 were used to make comparison. Since the water content of the three samples are not identical, the sample No. 3 with 55% WC needs to be fixed. When Dk/t of CL is under 40, there is a linear relationship between water content and oxygen permeability that has been well described by Hadassah (Hadassah and Sehgal, 2006). Due to the relationship, Dk/t of sample No.3 can be corrected to 31.6, the revised values is illustrated in Table 2. Then, the correction factor of section 3.3 were used as the standard to establish the curve with Dk/t value.

Fig. 10 shows that the larger variation of light attenuation, the larger the Dk/t value. The value of light attenuation represents its hydrophobic ability. When the hydrophobic ability is better, the oxygen permeability is also higher. Use the results from section 3.4, we can easily compute the Dk/t value by the Eqn. (4).

In summary, from the above experiment results, the model to collocate WC and Dk/t value has been constructed. Eqn. (2) - (4) were used to calculated WC and Dk/t by using light attenuation. The correlation coefficient α_3, β_3, and γ_3 can be calculated using Eqn. (4). Where α_3= 3.9875, β_3= 7.97879 and γ_3= -0.53788. Since the new contact lens is soaking in the water and is not at wearing status, the results

Table 2: Similar to the water content of tested samples.

No.	Brand/Model	WC (%)	Dk/t
1	MOIST/ACUVUE 1-day	58	33.3
3	HYDRON/ UV Blocking 1-Day	55	30
3*	HYDRON/ UV Blocking 1-Day (adjusted)	58*	31.6*
4	TICON/Hyaluronic Acid 1-Day	58	29

*: The value has been corrected.

obtained from the equation are slightly different from the data on contact lens box. The accuracy of WC and Dk/t values that calculated by this research are up to 95% to the value that contact lenses are practically worn on human eyes, as long as the contact lens WC is ranged from 38% to 78% and make from hydrogel.

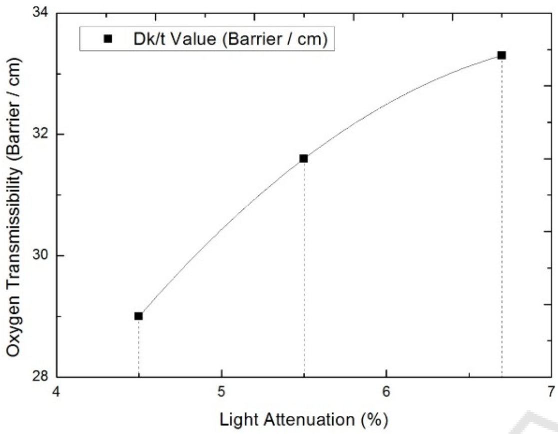

Figure 10: The fitting curve of light attenuation and oxygen transmissibility.

4 CONCLUSIONS

The CLs has gradually become more popular among patients due to the benefits of beauty and comfort. However, the human cornea does not have blood vessels and it obtains oxygen directly through the air, so it causes corneal angiogenesis when the cornea was in a hypoxic state for a long period of time, and even would lead to aging and permanent damage of the cornea if seriously hypoxia. Therefore, the CLs manufacturers continue to develop the gas permeable hydrogel CLs for patents without corneal irritation effects after a periods of wearing. Nowadays, the presented measuring methods for the Dk/t and WC of CLs are almost based on the electrochemical reaction or permeabilization within two chamber methods, and the measuring results cannot state any instant datum for user; therefore, this study presents an optical method that can evaluate instantly the WC and Dk/t of CL depended on the absorption spectrum of CL.

In the instant method, when the light travelled through the lens, we measure the light attenuation of 500- 600nm wavelength within eight minutes to comparison of five kinds of well-known product in market. The hydrogel CL is placed in a specific holder, and the both sides will be dehydrated at the same time, so that the light attenuation through CL in eight minutes is gradually stability. In the experiment, we found that the WC is an important factor of light attenuation; the average light attenuation is higher, the WC of CL is higher and the variation of light attenuation is also the larger in eight minutes. In addition, the variation of light attenuation is larger, the oxygen permeability is also greater while compared with the CL of similar WC. Furthermore, computed from the light attenuation and its variation through CL, we can build a real-time measurement model for CL's performance. In future, we can add thickness t as a correction factor to calculate the real Dk/t of contact lens with different dioptres and the instant WC and Dk/t of CL can be estimated from the light reflection when the eyes wearing the CL.

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