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Analysis Study of Spectral and Thermal Properties of Near-Infrared Blocking Ophthalmic lenses

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Abstract

Near-infrared (NIR) blocking ophthalmic lenses are commercially available, but data supporting their properties and performance are difficult to find. This study aims to provide objective data through clinical results of NIR blocking ophthalmic lenses and to verify color reproducibility and thermal properties and performance according to the influence of NIR for practical use. Near-infrared blocking spectacle lenses (NIBSL) (polymerized, coated) and other types of spectacle lenses (clear, tinted) were manufactured and classified into 0, 2, and 3 grades (10 types) of luminous transmittance. The near-infrared environment was configured and the color reproducibility evaluation factors, such as sharpness (MTF50), chromatic aberration (CA), and color accuracy (△E), were compared in an outdoor environment (1000 lux). The thermal properties were analyzed by observing the temperature changes on the surface of the spectacle lens and pig skin in real time in environments of 36℃ and 60℃. NIBSL showed no difference in object discrimination and color recognition compared to other types of spectacle lenses. In terms of thermal characteristics, NIBSL showed a smaller increase in lens surface temperature, and the pig skin temperature was maintained lower, showing excellent insulation performance. These results suggest that NIBSL can be used in everyday life without problems in visual ability and color reproducibility, and may be useful in protecting eyes from the thermal hazards of near-infrared light. In addition, we presented a new research method that improves the accuracy and reliability of optical functional spectacle lenses in the near-infrared region (harmful to humans).

Keywords: *Color Reproducibility, Near-Infrared, Near-Infrared Blocking Ophthalmic Lens, Pig Skin Temperature, Thermal Properties.*

Introduction

Climate change and natural changes resulting from rapid environmental destruction cause various problems around us and can pose serious risks to human life. Among these, increased exposure to solar radiation due to ozone depletion and prolonged exposure to artificial light sources due to the advancement of digital environments are causing various discomforts to humans and contributing to vision problems and ophthalmic diseases. Understanding the significant impact of climate change on human health, especially eye health, is crucial.

Rising temperatures, reduced humidity, and air pollution from climate change led to increased radiation exposure, contributing to the development of dry eyes. Risks such as eye pain, swelling, redness, burns, and surface inflammation become widespread [1]. Solar radiation interacts with biological tissues through photochemical and thermal actions. Photochemical effects primarily result from ultraviolet wavelengths, while thermal effects result from infrared wavelengths. Photochemical effects occur in the violet-blue light region, and thermal effects occur in the yellow-red light region [2, 3]. On Earth, the solar radiation spectrum comprises more than 6% ultraviolet, 38–39% visible light, and approximately 54.3% infrared. near-infrared (NIR) accounts for over 40% of the solar spectrum and can penetrate not only the retina but also subcutaneous tissues [4,5]. Eye health is affected by the

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temperature and exposure duration of solar radiation; cataracts, pterygium, and macular degeneration are all adverse effects of prolonged solar radiation exposure [3]. Human tissues, bone marrow, reproductive organs, and ocular components such as the lens and retina are highly sensitive to radiation, especially to low linear energy transfer infrared radiation, which can interact with various cells and molecules [6]. When infrared radiation heats superficial tissues (skin and cornea) and transfers heat deeper into tissues through conduction, deeper tissues can become heated. The biological effects of heat depend significantly on temperature increases above physiological levels and exposure duration [7, 8].

Solar infrared radiation ranges from 780 nm to 1 mm in wavelength and is categorized into near-infrared (Infrared A, 780–1,400 nm), mid-infrared (Infrared B, 1,400–3,000 nm), and far-infrared (Infrared C, 3,000 nm–1 mm) [9]. Strong exposure in the NIR range can cause thermal damage to the retina and acute cataracts in the lens. Even weak NIR radiation can induce cataracts with prolonged exposure [3].

The human iris absorbs 53–98% of NIR radiation in the 750–900 nm spectrum, and the degree of absorption and resulting damage significantly depend on pigment concentration [10]. The lens absorbs NIR radiation above 900 nm but does not affect the vitreous and aqueous humor. Generally, 96% of wavelengths between 760 and 1,400 nm are invisible to the eye, transmitted through ocular media, and focused on the retina. In the NIR region, thermal effects dominate, and excessive exposure can cause enzyme denaturation in the retina and choroid due to critical temperature increases. Because the retina's regenerative capacity is highly limited, damage can severely impair vision [11, 12].

The normal ocular surface temperature ranges between 32.9 and 36°C, varying with ophthalmic conditions or environmental factors [13]. The average ocular surface temperature at the corneal center is 34.3±0.7°C, unaffected by corneal thickness or anterior chamber depth. The highest temperatures are measured around the nasal conjunctiva and corneal limbus, approximately 0.45–1°C higher than at the corneal center. Ocular surface temperature decreases by 0.01–0.02°C annually, with the rate of change increasing after middle age [14, 15]. Buccella et al. reported that prolonged direct sunlight exposure raises human ocular temperature, and a rise in internal ocular temperature by about 3–5°C can lead to chronic inflammation and early cataract formation [16]. Zarei et al. also found that corneal temperature increased by 5°C under maximum radiation intensity without wearing glasses, potentially leading to cataracts with prolonged exposure [17]. Maintaining ocular temperature within the normal range could mitigate ocular side effects from temperature increases.

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) provides guidelines for biological damage risks to skin and eyes. The photochemical retinal hazard due to optical radiation is wavelength-dependent, expressed as the retinal thermal hazard function R(λ) [18]. Along with photochemical damage, thermal retinal damage can occur across a wide wavelength range of 380–1,400 nm. Natural NIR radiation (NIR) has the beneficial effect of stimulating melatonin production in healthy cells, and NIR radiation is also positively utilized in research on treating eye diseases and managing vision [19, 20]. However, human eyes are most exposed to harmful rays, including NIR, in daily life and occupational settings. Understanding the dual aspects of such harmful rays and NIR radiation is crucial, as is considering protective measures against long-term exposure.

Clear spectacle lenses are widely used for vision correction, and various tinted lenses adjust the intensity and spectral distribution of light as optical filters or mitigate photosensitivity to maintain visual perception. However, considerations must be made as they can affect contrast sensitivity, color vision, and visual response time [21-23]. Standard tinted lenses selectively transmit specific wavelengths of light, advantageous for reducing chromatic aberration, but their spectral transmittance can vary depending on the lens color and concentration. Near-infrared blocking spectacle lenses (NIBSL) also exhibit unique tints based on their blocking rates. These tints affect certain portions of the visible spectrum, potentially altering image clarity and color reproduction, thus necessitating assessments of color fidelity. In South Korea, recognizing the hazards of NIR radiation, NIR-blocking lenses are manufactured and commercially available, and studies on their blocking efficiency, color reproduction, and thermal insulation effects have been conducted in academic circles [24, 25]. However, extensive research that comprehensively explains the properties of NIR-blocking spectacle lenses remains insufficient.

This study evaluates the color reproduction and analyzes the thermal properties of NIR-blocking spectacle lenses. To assess color reproduction, we established measurement conditions in accordance with the International Organization for Standardization under outdoor illuminance conditions (1,000 lux) to determine if there were differences in object identification and color perception. Additionally, we measured and compared the surface temperature of the spectacle lenses and pig skin temperatures in real-time at 36℃ and 60℃ to analyze thermal properties. All experiments were conducted using temperature and humidity-controlled environments to minimize external interference and ensure consistent experimental conditions. NIBSL must be adequate in distinguishing objects and perceiving colors to avoid visual impairments, and the thermal properties of NIR radiation, known as thermal radiation, pose significant risks to eye health. Considering the initial research stage on NIR and blocking spectacle lenses, studies on color reproduction and thermal properties will support the theoretical basis of NIR-blocking spectacle lenses and aid in interpreting clinical outcomes.

Materials and Methods

Research Subjects

Spectacle lenses are classified into grades 1 to 4 according to ISO 8980-3 standards [26]. The lenses studied here include Near-infrared blocker polymerized spectacle lenses (NIBPSL) classified under luminous transmittance grades 0 and 2, Near-infrared blocker coated spectacle lenses (NIBCSL) at grade 0, Near-infrared blocker coated + tinted spectacle lenses (NIBC+TSL) matching the luminous transmittance grades 0, 2, and 3 of the polymerized lenses, clear spectacle lenses (CSL) at grade 0, and tinted spectacle lenses (TSL) at grades 0, 2, and 3, comprising a total of 10 types (Table 1). The blocking rates of Near-infrared blocking spectacle lenses (NIBSL) were as follows: 30% for grade 0 polymerized and coated lenses, 95% for grade 2 polymerized lenses, and 30% for grade 2 and 3 coated lenses. All lenses were designed with an anti-reflection (UV420) coating, refractive index (n=1.60), and a spherical design with a vertex power of 0.00D, matching commercially available polymerized, coated, clear, and tinted spectacle lenses manufactured by company S. Since the color intensity of NIR-blocking spectacle lenses varies with blocking rates, the standard tinted lenses used for comparison were tinted to match the luminous transmittance of the NIR-blocking spectacle lenses.

Table 1. Classification of Subject Lenses

Grade(n=6)	Near-infrared blocking spectacle lenses	Grade (n=4)	Other types spectacle lenses
0, 2	Near-infrared blocker polymerized spectacle lenses (NIBPSL)	0	Clear spectacle lenses (CSL)
0	Near-infrared blocker coated spectacle lenses (NIBCSL)	0, 2, 3	Tinted spectacle lenses (TSL)
0, 2, 3	Near-infrared blocker coated + tinted spectacle lenses (NIBC+TSL)	-	-

Near infrared Blocking Grade 0: polymerized and coatings 30%, Near infrared Blocking Grade 2: polymerized 95%, Coatings 30%, Near infrared Blocking Grade 3: coatings 30%

Research Methods

Color Reproduction

Color reproduction was analyzed by measuring sharpness (MTF50), chromatic aberration (CA), and color accuracy (△E). Measurements were conducted under three different conditions: room temperature environment (18℃~25℃) without exposure to NIR radiation, 36℃ representing the highest summer temperatures recorded in Korea over the past 10 years according to the Korea Meteorological Administration, and 60℃ which is higher than the recommended cautionary temperatures indicated by spectacle lens manufacturers, after 60 minutes of NIR radiation exposure. A Temperature & Humidity Chamber (TH-PE-100, Jeiotech Co, Daejeon, South Korea) was used to control temperature and humidity. Since there were no differences in measurements between conditions with and without NIR exposure, the average of three trials was used for analysis.

A test environment conforming to ISO 12233 [27] standards was established under outdoor illumination conditions of 1,000 lux with a D65 standard light source. Target lenses were mounted onto a camera (D-7100, Nikon Co, Tokyo, Japan) to photograph the test charts. An SFRplus chart (Imatest Co, Boulder, CO, USA) was used for analyzing sharpness and chromatic aberration, and a 24-patch X-Rite Color Checker chart (Imatest Co, Boulder, CO, USA) was used for analyzing color accuracy.

Quantitative values for NIBSL of luminous transmittance grades (0, 2, 3) were compared against other types of spectacle lenses (clear, tinted) using the image analysis software Imatest 4.0 (Imatest Co, Boulder, CO, USA).

Resolution and Chromatic Aberration

Resolution is measured based on the contrast differences between the dark gray squares and the lighter gray background of the SFRplus test chart. Images of the SFRplus chart were captured, and using the Modulation Transfer Function (MTF) theory [28], resolution quality was quantitatively expressed as MTF50 (Line Width per Picture Height: lw/ph), representing the spatial frequency at which modulation is 50%. Higher resolution values indicate clearer object visibility.

Chromatic aberration refers to variations in refractive index according to wavelength, causing dispersion in the focal points and focal lengths, resulting in color fringing at object edges. Chromatic aberration (Area pixels) is quantified by pixel deviation; larger values indicate stronger aberration or greater blur, whereas smaller values indicate better aberration control.

Color Accuracy

The RGB color space was developed based on research from the 1920s. In 1931, the International Commission on Illumination (CIE) mathematically standardized human color perception by quantifying colors into X, Y, and Z color spaces. In 1976, the CIE refined previous color systems and established the Lab* color space, where L* denotes perceptual brightness, and a* and b* represent the four unique colors perceived by humans: red, green, blue, and yellow. The Lab* color space is perceptually consistent and efficient for measuring perceived color differences between two images. The color difference between two images is calculated as Delta E (△E), which quantifies differences between two colors in three-dimensional space [29]. The Color Difference value in the CIE Lab* color space is calculated using the formula below.

$\triangle L^* = L2^* - L1^*$ Lightness Difference (1)

$\triangle a^* = a2^* - a1^*$ Red – Green (2)

$\triangle b^* = b2^* - b1^*$ Yellow - Blue (3)

$\triangle E^* = (\triangle L^*2 + \triangle a^*2 + \triangle b^*2)1/2$ Color Difference (4)

In this study, color accuracy was assessed as a test to verify the color reproduction capability of digital images. The difference between the reference color coordinates and the color coordinates produced by the test camera was quantified as the Delta E (△E) values for the four primary colors (Red, Green, Blue, Yellow). Lower △E values indicate colors closer to the original hues, signifying higher color accuracy and better color reproduction.

Thermal Properties

Measurement Environment

The surface temperature of spectacle lenses and pig skin was measured and compared using NIBSL (polymerized and coated) and other types of spectacle lenses (clear and tinted) at temperatures of 36℃, representing the average highest summer temperatures in Korea over the past 10 years, and 60℃, which is above the caution temperature of 50℃ indicated by spectacle lens manufacturers. A sealed Temperature & Humidity Chamber (TH-PE-100, Jeiotech Co, Daejeon, South Korea) was used to create controlled NIR environments at 36℃ and 60℃. Spectacle lenses were exposed to NIR radiation for 60 minutes per trial (three trials, cumulatively 3 hours) under both temperature conditions. Since no differences were observed across measurements, the average values were used for analysis. During thermal property analysis, pig skin temperature changes at 36℃ and 60℃ (Table 9) were compared using previous research by the authors [30].

Temperature Measurement Method

For thermal property verification, a single-channel digital thermometer capable of measuring temperatures from 50 to 1,300℃ was placed outside the Temperature & Humidity Chamber, connected externally to a mounted sensor (K-type thermocouple) capable of measuring temperatures from -40 to 200℃. An infrared lamp (Philips Infrared-R95E, POLAND) was installed inside the chamber to enable external on-off operation, exposing the test lenses and pig skin to NIR radiation for 60 minutes per session (three sessions, cumulatively 3 hours). Each measurement session involved two lens types paired with pig skin, with their positions alternated left-to-right each session to minimize errors from directional airflow within the chamber.

Measurement of Spectacle Lens Surface Temperature and Pig Skin Temperature

Pig skin is widely recognized and used as a substitute for human skin in various studies due to its similarities in structure, moisture content, and physiology.

① A supporting stand considering the vertex distance (12 mm) was placed in an experimental Petri dish.

② The test lens was positioned on the stand, and thawed experimental pig skin was placed beneath it.

③ Temperature sensors were attached to the apex of the lens surface and the center of the pig skin, connected externally to the thermometer.

④ Temperature changes recorded by the external thermometer were captured as real-time video for 60 minutes.

⑤ Recorded video was reviewed in 5-minute intervals, and the average temperature changes over three measurements for the full 60 minutes were analyzed.

⑥ To account for variations in initial starting temperatures, differences between the initial temperature and average temperatures at 10, 30, and 60 minutes were analyzed.

Results

Color Reproduction Under Outdoor Conditions (1000 Lx)

Sharpness

The sharpness of near-infrared blocking spectacle lenses compared to other types of spectacle lenses at luminous transmittance grades 0, 2, and 3 showed no statistically significant differences (p>0.050) (Table 2).

Table 2. Comparison of the Sharpness Subject Lenses

Lens of Category	Grade	Sharpness (MTF50)		
		Mean ± SD	Z	*p*
NIBCSL	0	2638.74±58.59	-1.88	0.060
CSL	0	2692.62±41.62		
NIBC+TSL	0	2635.56±81.36	-0.14	0.889
TSL	0	2673.08±66.48		
NIBPSL	0	2693.94±59.92	-1.36	0.174
TSL	0	2673.08±66.48		
NIBC+TSL	2	2431.94±71.49	-1.01	0.312
TSL	2	2403.47±131.27		
NIBPSL	2	2466.28±36.12	-1.30	0.194
TSL	2	2403.47±131.27		
NIBC+TSL	3	2386.54±48.55	-1.36	0.174
TSL	3	2369.02±50.74		

Chromatic Aberration

In luminous transmittance grade 0, the chromatic aberration of near-infrared blocker polymerized spectacle lenses was significantly higher than that of tinted spectacle lenses (p<0.050). At grade 2, the chromatic aberration of near-infrared blocker polymerized spectacle lenses was significantly lower compared to tinted spectacle lenses (p<0.050). Chromatic aberration differences between lenses at grade 3 were not statistically significant (p>0.050) (Table 3).

Table 3. Comparison of the Chromatic Aberration of Subject Lenses

Lens of category	Grade	Chromatic aberration		
		Mean ± SD	Z	*p*
NIBCSL	0	0.19±0.12	-0.84	0.401
CSL	0	0.21±0.06		
NIBC+TSL	0	0.21±0.07	-0.96	0.337
TSL	0	0.19±0.05		
NIBPSL	0	0.25±0.03	-2.35	0.019
TSL	0	0.19±0.05		
NIBC+TSL	2	0.41±0.14	-0.14	0.889
TSL	2	0.44±0.07		
NIBPSL	2	0.30±0.04	-4.03	0.000
TSL	2	0.44±0.07		
NIBC+TSL	3	0.44±0.12	-1.01	0.312
TSL	3	0.51±0.09		

Color Accuracy

Blue Region

In the blue region, color accuracy showed no statistically significant differences among lenses at grade 0 (p>0.050). At grade 2, the △E value of near-infrared blocker polymerized spectacle lenses was significantly higher than that of tinted spectacle lenses, showing statistical significance (p<0.050). At grade 3, no statistically significant differences were found (p>0.050) (Table 4).

Table 4. Comparison of Blue Color Accuracy of Subject Lenses

Lens of category	Grade	Blue color accuracy (△E)		
		Mean ± SD	Test statistic	*p*
NIBCSL	0	25.80±2.91	Z=-0.35	0.726
CSL	0	25.12±4.17		
NIBC+TSL	0	25.52±1.78	t=0.75	0.461
TSL	0	25.03±1.44		
NIBPSL	0	28.78±5.30	Z=-1.68	0.093
TSL	0	25.03±1.44		
NIBC+TSL	2	21.12±5.98	Z=-1.10	0.271
TSL	2	24.45±2.14		
NIBPSL	2	28.58±2.55	t=4.30	0.000
TSL	2	24.45±2.14		
NIBC+TSL	3	13.96±1.09	Z=-0.29	0.772
TSL	3	15.12±2.65		

Green Region

In the green region, color accuracy showed no statistically significant differences among lenses at grade 0 (p>0.050). At grade 2, the △E value of near-infrared blocker polymerized spectacle lenses was significantly higher than that of tinted spectacle lenses (p<0.050). At grade 3, the △E value of tinted spectacle lenses was significantly higher than that of near-infrared blocker coated + tinted spectacle lenses (p<0.050) (Table 5).

Table 5. Comparison of Green Color Accuracy of Subject Lenses

Lens of category	Grade	Green color accuracy (△E)		
		Mean ± SD	Test statistic	*p*
NIBCSL	0	19.55±1.94	Z=-0.29	0.772
CSL	0	18.94±2.98		
NIBC+TSL	0	20.91±0.82	Z=-0.69	0.490
TSL	0	20.88±1.06		
NIBPSL	0	23.12±3.68	Z=-1.90	0.057
TSL	0	20.88±1.06		
NIBC+TSL	2	16.78±1.67	t=-0.87	0.394
TSL	2	17.29±1.19		
NIBPSL	2	21.91±1.44	t=8.59	0.000
TSL	2	17.29±1.19		
NIBC+TSL	3	13.47±0.97	t=-5.31	0.000
TSL	3	16.08±1.40		

Yellow Region

In the yellow region, color accuracy showed no statistically significant differences among lenses at grade 0 (p>0.050). At grade 2, the △E value of tinted spectacle lenses was significantly higher than that of near-infrared blocker polymerized spectacle

lenses (p<0.050). At grade 3, the △E value of near-infrared blocker coated + tinted spectacle lenses was significantly higher than that of tinted spectacle lenses (p<0.050) (Table 6).

Table 6. Comparison of Yellow Color Accuracy of Subject Lenses

Lens of category	Grade	Yellow color accuracy (△E)		
		Mean ± SD	Test statistic	*p*
NIBCSL	0	5.89±0.33	t=-1.13	0.271
CSL	0	6.18±0.80		
NIBC+TSL	0	5.61±0.20	t=1.51	0.145
TSL	0	5.48±0.23		
NIBPSL	0	6.97±2.07	Z=-1.59	0.112
TSL	0	5.48±0.23		
NIBC+TSL	2	15.82±2.65	t=-1.08	0.292
TSL	2	16.92±2.35		
NIBPSL	2	9.42±1.45	t=-9.41	0.000
TSL	2	16.92±2.35		
NIBC+TSL	3	17.52±0.66	Z=-2.77	0.006
TSL	3	14.44±2.52		

Red Region

In the red region, color accuracy showed no statistically significant differences among lenses at grade 0 (p>0.050). At grade 2, the △E value of tinted spectacle lenses was significantly higher than that of near-infrared blocker polymerized spectacle lenses (p<0.050). At grade 3, the △E value of near-infrared blocker coated + tinted spectacle lenses was significantly higher than that of tinted spectacle lenses (p<0.050) (Table 7).

Table 7. Comparison of Red Color Accuracy of Subject Lenses

Lens of category	Grade	Red color accuracy (△E)		
		Mean ± SD	Test statistic	*p*
NIBCSL	0	28.33±1.77	Z=-0.84	0.401
CSL	0	27.10±2.51		
NIBC+TSL	0	29.08±0.68	t=0.93	0.362
TSL	0	28.76±0.94		
NIBPSL	0	29.00±2.33	t=0.33	0.747
TSL	0	28.76±0.94		
NIBC+TSL	2	30.16±1.00	t=0.37	0.715
TSL	2	29.98±1.35		
NIBPSL	2	23.07±4.10	Z=-4.10	0.000
TSL	2	29.98±1.35		
NIBC+TSL	3	30.27±0.63	t=3.11	0.005
TSL	3	29.46±0.64		

Thermal Properties

Spectacle Lens Surface and Pig Skin Temperatures At 36℃ And 60℃

Surface Temperature of Lenses

At 36℃, the surface temperatures of luminous transmittance grade 0 spectacle lenses were statistically significant (p<0.050). Luminous transmittance grade 2 and 3 lenses did not show statistical significance (p>0.050) (Fig. 1).

At 60℃, the surface temperatures of grade 0 spectacle lenses and grade 2 near-infrared blocking spectacle lenses were statistically significant (p<0.050). However, grade 2 tinted spectacle lenses and all grade 3 spectacle lenses showed no statistical significance (p>0.050) (Fig. 2).

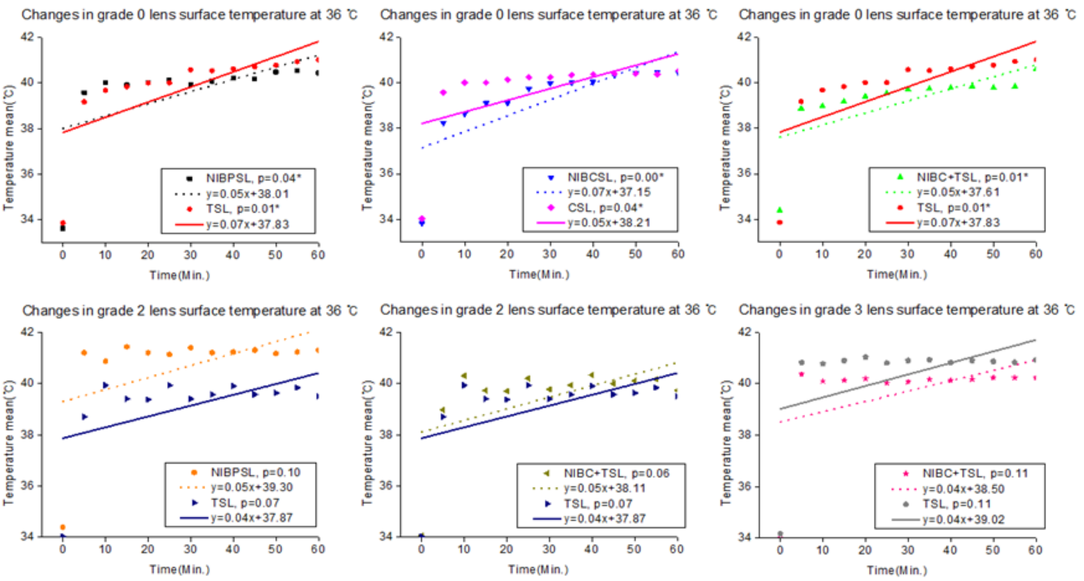

Fig. 1. Regression Analysis of Subject Lenses Surface Temperature Over Time For 60 Minutes (36℃).

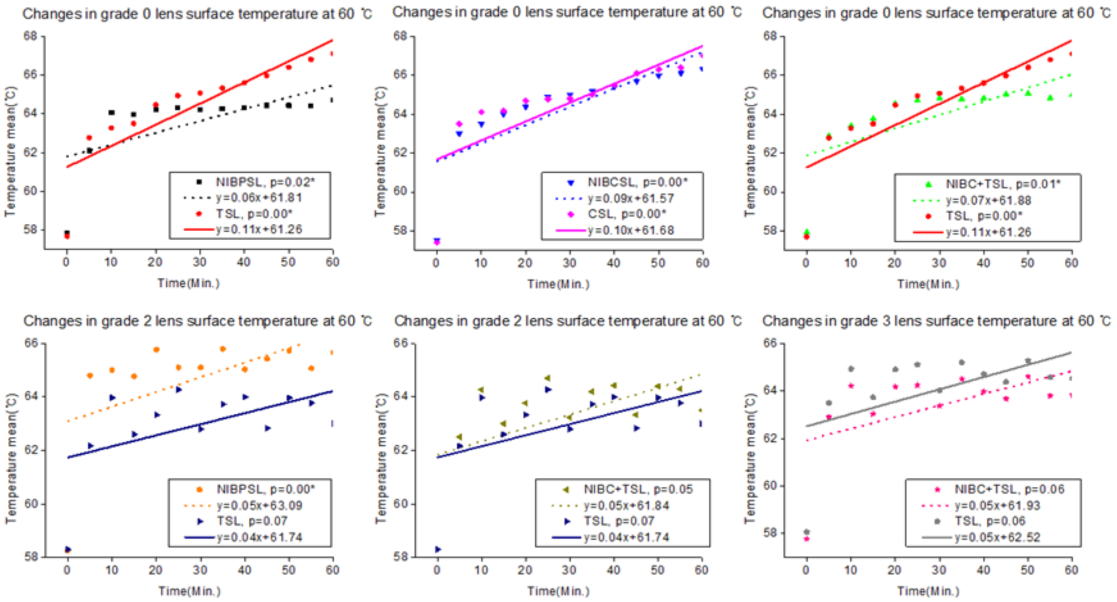

Fig. 2. Regression Analysis of Subject Lenses Surface Temperature Over Time For 60 Minutes (60℃)

Pig Skin Temperature

At 36℃ and 60℃, the pig skin temperatures for all spectacle lenses across luminous transmittance grades 0, 2, and 3 were statistically significant ($p<0.050$) (Fig. 3) (Fig. 4).

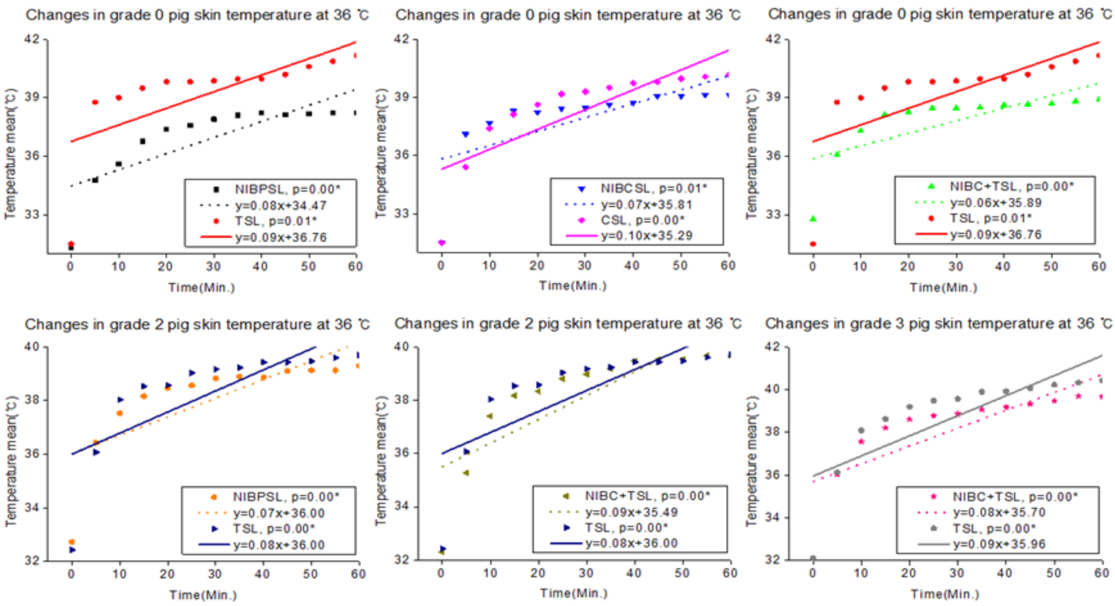

Fig. 3. Regression Analysis of Subject Lenses Pig Skin Temperature Over Time For 60 Minutes (36℃).

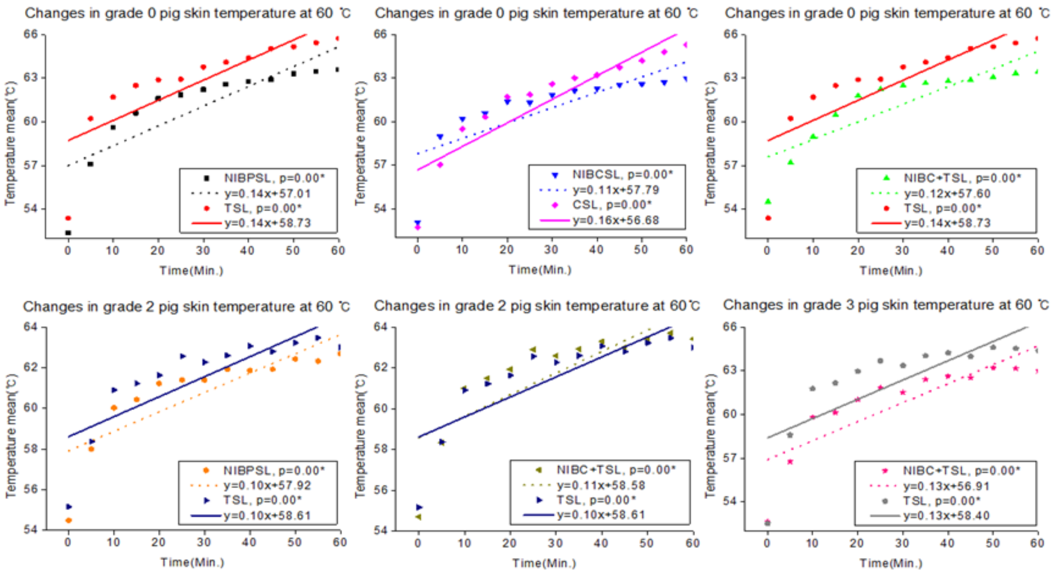

Fig. 4. Regression Analysis of Subject Lenses Pig Skin Temperature Over Time For 60 Minutes (60℃)

Temperature Gradient of Spectacle Lens Surface and Pig Skin At 36℃ And 60℃

Lens Surface Temperature Gradient

At 36℃, the surface temperature gradients of spectacle lenses at luminous transmittance grades 0 and 2 were not statistically significant ($p>0.050$). The grade 3 lenses showed statistically significant differences ($p<0.050$) (Table 8). At 60℃, the surface temperature gradients of lenses at grades 0 and 3 were not statistically significant ($p>0.050$). For grade 2 lenses, statistical significance was observed ($x2 = 6.489$, $p = 0.039$); however, post hoc analysis indicated no significant differences ($p>0.050$) (Table8).

Table 8. Gradient In Surface Temperature At 36℃ And 60℃

Temperature	Lens of category	Grade	Lens surface temperature		
			Mean ± SD (℃)	Test statistic	*p*
36℃	NIBPSL	0	6.49±0.27	x^2=5.301	0.258
	NIBCSL	0	5.84±0.93		
	NIBC+TSL	0	5.36±0.82		
	CSL	0	6.22±0.27		
	TSL	0	6.54±0.68		
	NIBPSL	2	6.79±0.28	x^2=5.956	0.051
	NIBC+TSL	2	5.87±0.32		
	TSL	2	5.58±0.28		
	NIBC+TSL	3	6.00±0.09	Z=-1.964	0.050
	TSL	3	6.70±0.09		
60℃	NIBPSL	0	6.45±0.33	x^2=3.607	0.547
	NIBCSL	0	7.40±1.40		
	NIBC+TSL	0	6.48±0.88		
	CSL	0	7.90±1.51		
	TSL	0	7.45±1.92		
	NIBPSL	2	6.99±0.36	x^2=6.489	0.039
	NIBC+TSL	2	5.87±0.54		

	TSL	2	4.96±0.63		
	NIBC+TSL	3	6.03±0.42	Z=-1.091	0.275
	TSL	3	6.44±0.45		

Pig Skin Temperature Gradient

At both 36℃ and 60℃, the temperature gradients of pig skin under spectacle lenses at luminous transmittance grades 0, 2, and 3 were not statistically significant (p>0.050) (Table 9).

Table 9. Gradient in Pig Skin Temperature At 36℃ And 60℃ A)

Temperature	Lens of category	Grade	Pig skin temperature		
			Mean ± SD (℃)	Test statistic	*p*
36℃	NIBPSL	0	5.91±1.43	χ^2=8.023	0.091
	NIBCSL	0	6.92±0.73		
	NIBC+TSL	0	5.47±0.84		
	CSL	0	7.46±1.42		
	TSL	0	8.51±1.09		
	NIBPSL	2	5.24±0.39	χ^2=3.467	0.177
	NIBC+TSL	2	6.37±1.15		
	TSL	2	6.53±0.85		
	NIBC+TSL	3	6.56±1.06	Z=-0.655	0.513
	TSL	3	7.23±1.18		
60℃	NIBPSL	0	9.41±2.00	χ^2=3.100	0.541
	NIBCSL	0	8.60±1.39		
	NIBC+TSL	0	7.11±2.34		
	CSL	0	9.74±2.90		
	TSL	0	10.33±2.02		
	NIBPSL	2	6.88±1.34	χ^2=1.067	0.587
	NIBC+TSL	2	7.64±1.24		
	TSL	2	6.89±1.07		
	NIBC+TSL	3	8.38±1.60	Z=-1.528	0.127
	TSL	3	9.94±1.33		

a) Data adapted from Sensors 25, 3556 (2025). [30]

Discussion

Near-infrared blocking spectacle lenses (NIBSL) are manufactured using either a polymerization method, which involves mixing optical lens base monomers with NIR-absorbing dyes, or a coating method that forms a thin film with NIR-blocking properties on the lens surface. Recently, the coating method has been favored over polymerization due to the high production costs, low economic feasibility, and low visible light transmittance of the latter, which reduces visibility. The coating method is particularly advantageous as it allows for the integration of additional functions such as blue light blocking.

Optical thin films are nano-scale layers where materials with high and low refractive indices are alternately deposited. These layers cause interference of light waves reflected at different interfaces. Thin-film interference technology precisely controls NIR reflectivity and allows the design of filters that selectively reflect or transmit specific wavelengths. This capability can be used to improve the efficiency of NIBSL.

NIR thermal damage varies depending on the absorption and scattering of energy within the tissue exposed to a given amount of incident energy from a light source [31]. Scattering arises from non-uniform tissue composition with varying refractive indices, and absorption depends on the type of medium the light propagates through. In the retina, melanin is the main NIR absorber, concentrated in the retinal pigment epithelium and localized in the choroid [32]. It was discovered that near-infrared rays penetrating the human body are absorbed by hemoglobin in blood vessels, myoglobin in superficial muscles, and bone cortex, and that they can be used for biologically beneficial purposes, but at the same time, they can have negative effects [33]. NIR can have both beneficial and harmful biological effects, yet the necessity for protection against NIR exposure is not well recognized. Compared to the well-studied risks of blue light and UV radiation, research on NIR remains limited and lacks systematic evaluation.

This study compared NIBSL with other types (transparent and tinted) at luminous transmittance grades 0, 2, and 3, evaluating their color reproduction properties including sharpness (MTF50), chromatic aberration (CA), and color accuracy (△E), as well as thermal properties. The study subdivided transmittance levels more finely than previous studies [24, 25], improving the accuracy of color reproduction evaluation and reliability of thermal assessments through long-duration tests in a temperature and humidity chamber.

Under outdoor conditions (1,000 lx), there was no significant difference in sharpness between NIBSL and other types, which aligns with the findings of Kim et al. [25], who found no difference between NIBSL and tinted lenses at grade 2 transmittance. Chromatic aberration was higher in grade 0 near-infrared blocker polymerized spectacle lenses (NIBPSL) than in tinted lenses, but significantly lower at grade 2. This suggests that chromatic aberration can vary based on blocking agents and manufacturing methods. NIBSL show no disadvantage in distinguishing objects or obtaining sharp images.

For color accuracy, there were no significant differences at luminous transmittance grade 0 in blue, green, red, and yellow regions. At grade 2, significant differences were observed: in the blue and green ranges (450-570 nm), tinted lenses were closer to the reference chart colors, while in yellow and red (570-780 nm), NIBPSL were closer.

Human color perception is detected by three types of photoreceptors: short-wavelength (S), medium-wavelength (M), and long-wavelength (L) cones (cones). L cones respond most strongly to light of red wavelengths (long wavelength), M cones respond most strongly to light of yellow to green (medium wavelength). S cones respond most strongly to light of blue (short wavelength). Of these, L cones, which respond to long wavelengths, are the most abundant [34, 35].

Therefore, NIBPSL with high blocking rates may reduce the burden on L-cones and enhance red color accuracy. NIBSL using different manufacturing methods showed a trend where near-infrared blocker coated + tinted spectacle lenses (NIBC+TSL) were closer to reference colors in blue and green, and polymer spectacle lenses in yellow and red. Even with the same luminous transmittance, higher NIR blocking yielded better accuracy in the long-wavelength range.

At grade 3, NIBC+TSL showed significantly better color accuracy in green, while other types performed better in yellow and red. Therefore, when manufacturing NIBC+TSL, the color accuracy in the long-wavelength range should be secured as much as that of other types of lenses.

CNIRP guidelines warn that exceeding NIR exposure limits can cause serious retinal damage. A 1°C rise in core body temperature can trigger physiological changes and lead to thermal stress over 24 hours [36, 37]. If the body's core temperature rises by more than about 1°C, various changes in health may occur, and it is recommended to limit temperature increases to 2°C to 5°C to prevent abnormal thermal stress in the human body [38, 39]. Since the eyes are connected to core body temperature, reducing temperature increases caused by NIR can help lower the risk of thermal damage to the eyes.

This study, NIBSL and other types of spectacle lenses (clear, tinted) were exposed to a near-infrared environment for 60 (repeat 3 times) minutes, and the temperature of the spectacle lenses surface and pig skin was observed in real time. Thermal properties were analyzed by comparing the overall temperature change observed in real time and the difference from the initial temperature at 10, 30, and 60 minutes.

At 36°C, NIBPSL showed slightly higher initial surface temperatures but increased gradually. NIBC+TSL had the most stable increase. At grade 0, NIBPSL and NIBC+TSL showed less surface temperature rise compared to tinted lenses. Grades 2 and 3 showed minimal differences among lenses.

At 60°C, grade 0 NIBSL showed smaller surface temperature increases than other types spectacle lenses, particularly polymer and coated + tinted lenses. Grades 2 and 3 NIBSL had less surface temperature increase compared to grade 0, especially NIBC+TSL, which maintained relatively low surface temperatures.

Pig skin temperature, used as a human skin analog, showed the highest increase under clear spectacle lenses (CSL) at 36°C. NIBC+TSL caused the smallest increase. Clear and tinted spectacle lenses (TSL), which do not block NIR, led to greater skin temperature increases. Grades 2 and 3 NIBSL also tended to maintain lower skin temperatures, confirming the thermal shielding benefits of NIBSL.

At 60°C, similar trends were observed. CSL and TSL caused faster increases in both surface and pig skin temperatures. NIBSL better controlled temperature rise and exerted less thermal influence on pig skin.

Spectacle lenses surface temperature and Pig skin temperature continued to rise over time across all transmittance grades and environments.

In terms of surface temperature change rate, at 36°C, grades 0 and 3 lenses from other types had higher increases than NIBSL. At grade 2, NIBSL showed higher surface temperatures. Among grade 0 NIBSL, polymer types had higher temperatures than coated + tinted types. NIBPSL had similar or slightly lower temperature change rates than TSL. TSL generally showed higher temperature change rates, particularly at grade 3. NIBC+TSL had relatively lower rates, demonstrating the effectiveness of combining coating and tinting.

At 60°C, other types of spectacle lenses had higher surface temperatures than NIBSL at grades 0 and 3. At grade 2, NIBSL had higher temperatures, consistent with the trend at 36°C. Among grade 0 NIBSL, both coating + tinting and polymer methods showed similar temperature change rates. Overall, NIBSL had smaller changes than other types, especially NIBC+TSL at grades 0 and 3.

For pig skin temperature change rates at 36°C, NIBSL—particularly coated + tinted—had lower values than other types of spectacle lenses across all grades. This confirmed that NIR blocking affected pig skin temperature changes. At grade 0, coated+ tinted NIBSL had lower changes than NIBPSL. NIBPSL had 5.91°C change at grade 0 and 5.24°C, at grade 2. NIBC+TSL had the lowest changes at 5.47°C (grade 0) and 6.56°C (grade 3). TSL showed higher changes across all grades, indicating higher sensitivity to NIR-induced heat. Thus, NIBSL effectively controlled NIR heat transfer.

At 60°C, grade 2 TSL showed lower skin temperatures than NIBC+TSL but higher than NIBPSL. At grades 0 and 3, NIBSL had lower skin temperatures than other types of spectacle lenses. Among grade 0 lenses, NIBC+TSL had lower temperatures than NIBPSL. Overall, NIBSL showed lower temperature changes than other types of spectacle lenses, especially NIBC+TSL at 7.11°C (grade 0). Grade 2 NIBPSL also showed relatively low temperature changes. This suggests that NIBSL effectively block NIR heat impacting the skin. In contrast, other types of spectacle lenses showed higher changes due to limited or no NIR blocking.

The temperature differences in pig skin between NIBSL and other types of spectacle lenses were 2.60°C (NIBPSL vs. TSL at 36°C, grade 0), 3.04°C (NIBC+TSL vs. TSL), and 0.54°C (NIBCSL vs. CSL). At grade 2, the differences were 1.29°C (NIBPSL vs. TSL) and 0.16°C (NIBC+TSL vs. TSL). At grade 3, it was 0.67°C (NIBC+TSL vs. TSL). At 60°C, differences were 0.92°C (NIBPSL vs. TSL at grade 0), 3.22°C (NIBC+TSL vs. TSL), 1.14°C (NIBCSL vs. CSL), and 0.01°C (NIBPSL vs. TSL at grade 2). At grade 3, NIBC+TSL showed 1.56°C lower temperature than TSL. At grade 2, TSL had a 0.75°C lower skin temperature. These results show that NIBSL offer the best insulation at grade 0 and can be effectively used in daily life.

We must recognize the risks of NIR exposure even in daily environments and artificial light sources. To prevent long-term thermal photochemical eye damage and skin aging around the eyes, NIR protection is necessary. NIBSL can be effectively used for eye protection.

Conclusion

In terms of sharpness and chromatic aberration, Near-infrared blocking spectacle lenses (NIBSL) showed no significant differences from other types of spectacle lenses (clear, tinted), indicating no notable distinction in object recognition or obtaining clear images. For color accuracy, no significant differences were observed at luminous transmittance Grade 0. At Grade 2, lenses of other types of spectacle lenses were significantly closer to primary colors in the blue and green (short-wavelength) regions, while near-infrared blocker polymerized spectacle lenses (NIBPSL) were closer to the primary colors in the yellow and red (long-wavelength) regions. A similar significant pattern was observed at Grade 3, except in the blue region. The color accuracy of NIBSL, when compared with other types of spectacle lenses, did not differ in daily environments that require high luminous transmittance. However, when luminous transmittance is lower, NIBSL should be manufactured and selected with consideration of the blocking rate and fabrication method (e.g., polymer-based).

At 36℃ and 60℃, the surface temperature of the spectacle lenses showed that spectacle lenses with lower luminous transmittance (Grade 2 and 3) retained less heat on the surface. Compared to NIBSL (0.04–0.09℃), other types of spectacle lenses exhibited higher temperature increases (0.04–

0.11℃), and NIBSL maintained relatively lower surface temperatures. For pig skin temperature, most NIBSL (0.06–0.14℃) showed consistently lower or comparable temperatures than other types of spectacle lenses (0.08–0.16℃), indicating a better heat shielding effect on the skin. In both thermal environments, lens surface temperature and pig skin temperature tended to rise over time for all Grades 0, 2, and 3 lenses.

The gradient in spectacle lenses surface temperature at both 36℃ and 60℃ generally showed a lower trend for NIBSL compared to other types of spectacle lenses. At 36℃, pig skin temperature variation was lower for NIBSL than for other types of spectacle lenses. demonstrating a better insulation effect. Among NIBSL with the same blocking rate, coated lenses had better insulation performance than polymer-based lenses. At 60℃ as well, pig skin temperature variation was generally lower for NIBSL, again indicating superior insulation. Coated NIR-blocking lenses outperformed polymer-based ones in insulation effectiveness at equivalent blocking rates.

The maximum difference in pig skin temperature between general and NIBSL was 3.04℃ (Grade 0), 1.29℃ (Grade 2), and 0.67℃ (Grade 3) at 36℃, and 3.22℃ (Grade 0), 0.01℃ (Grade 2), and 1.56℃ (Grade 3) at 60℃—with NIBSL consistently showing lower skin temperatures. Considering that a rise of more than 1℃ in the human body's internal temperature can cause physiological effects, these results are meaningful.

In conclusion, NIBSL can be used in daily life alongside other lens types and can help reduce the photochemical risks to the eyes by blocking the thermal effects of near-infrared radiation. This study provides objective data and clinical evidence for NIBSL and offers new guidelines and improved methodologies for future clinical research design.

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Data Availability

All data generated or analyzed during this study are included in this published article. Further inquiries can be directed to the corresponding authors.

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