

The potential 'blue light hazard' from LED headlamps

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ABSTRACT

Many dental personnel use light-emitting diode (LED) headlamps for hours every day. The potential retinal 'blue light hazard' from these white light headlamps is unknown.

Methods: The spectral radiant powers received from direct and indirect viewing of an electronic tablet, an LED curing light, a halogen headlamp, and 6 brands of LED headlamps were measured using integrating spheres attached to fiberoptic spectroradiometers. The spectral radiant powers were measured both directly and indirectly at a 35 cm distance, and the maximum daily exposure times (t_{MAX}) were calculated from the blue weighted irradiance values.

Results: The headlamps emitted very different radiant powers, emission spectra, and color temperatures (K). The total powers emitted at zero distance ranged from 47 mW from the halogen headlamp to 378 mW from the most powerful LED headlamp. The color temperatures from the headlamps ranged from 3098 K to 7253 K. The t_{MAX} exposure times in an 8 h day when the headlamps were viewed directly at a distance of 35 cm were: 810 s from the halogen headlamp, 53 to 220 s from the LED headlamps, and 62 s from the LED curing light. Light from the LED headlamps that was reflected back from a white reference tile 35 cm away did not exceed the maximum permissible exposure time for healthy adults. Using a blue dental dam increased the amount of reflected blue light, but t_{MAX} was still greater than 24 h.

Conclusions: White light LED headlamps emit very different spectra, and they all increase the retinal 'blue light hazard' compared to a halogen source. When the headlamps were viewed directly at a distance of 35 cm, the 'blue light hazard' from some headlamps was greater than from the LED curing light ($t_{MAX} = 62$ s). Depending on the headlamp brand, t_{MAX} could be reached after only 53s. The light from the LED headlamps that was reflected back from a white surface that was 35 cm away did not exceed the maximum permissible ocular exposure limits for healthy adults.

Clinical relevance: Reflected white light from dental headlamps does not pose a blue light hazard for healthy adults. Direct viewing may be hazardous, but the hazard can be prevented by using the appropriate blue-light blocking glasses.

1. Introduction

Although there is growing concern that chronic exposure to artificial blue light may disrupt sleep patterns [1–6], accelerate retinal aging, and cause age-related macular degeneration (ARMD) in humans [7–10],

there is still much debate as to whether artificial light can pose a 'blue light hazard' [11–15]. In 2019, the International Commission on Illumination (CIE) issued a position statement [11] on the 'blue light hazard'. This statement concluded that the current internationally accepted exposure limits are not exceeded under reasonably foreseeable

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conditions. However, the CIE did recommend that the current 'blue light hazard' safety limit for adults should be reduced by a factor of 10 for children [11]. However, in 2019, the French Agency for Food, Environmental and Occupational Health and Safety issued a report [6,8] that raised concerns about the growing exposure to artificial blue light. The report recommended that better information should be provided to the public about the risks associated with the increased exposure to blue light. In addition, it recommended limiting the use of electronic devices that emitted a high blue light content, especially for children [6,8]. In an attempt to address the concerns about the blue light that is emitted from a wide range of electronic devices such as light-emitting diodes (LEDs), flat-screen televisions, computers, smartphones, and tablets [2,4–6,8,16–22], the manufacturers of some of these devices already offer the option to decrease the amount of blue light emitted from their products [10,23,24]. Alternatively, blue light blocking screens or glasses can be used to reduce the amount of blue light received by the eye [25–28].

1.1. The 'blue light hazard'

Research using animals and cell cultures suggests that exposure to blue light may disrupt sleep patterns, damage the retina [1–4,10,11,16–18,23,29–47], and possibly accelerate ARMD [6–8]. The damaging effects of blue light are greatest at wavelengths around 440 nm, and the effects are thought to be cumulative [6,8,38,47]. Damage occurs because the blue wavelengths of light are not blocked by the cornea, aqueous humour, lens, or vitreous humour. Instead, blue light is transmitted directly through the ocular media and absorbed by pigments in the retina. The damaging effects of blue light appear to be related to the color temperature (K) of the light source. Temperatures in the region of 3000K typically seen from incandescent sources are thought to be less hazardous than 'cool white' temperatures above 4500K that are often seen from 'bright white' light LEDs [13,48,49].

1.2. Response of the retina to light

The human eye does not react well to the peak of blue light from white light LED sources because human eyes are only about 5% as responsive to blue light between 440 nm and 450 nm (Fig. 1) compared to light around 555 nm [19,50]. Since the human pupil does not react and constrict as much when exposed to blue light compared to light at 555 nm, the human eye may be damaged by high levels of blue light without us realizing we are being exposed to excessive amounts of blue light [50]. Even small changes in pupil diameter will have a large effect on the amount of light that enters the eye; for example, a 4 mm diameter

pupil (area 12.57 mm²) will allow 4 times more light to reach the retina than the 2 mm diameter pupil (area 3.14 mm²). Since the eye is more responsive to light in the 520 to 590 nm region, e.g., light from a halogen light source, this makes the ratio of the blue light to the red-green wavelengths in the white light from LED sources important, and the source should ideally contain more red-green wavelengths and less blue.

1.3. Safeguards already present that should prevent excessive exposure to blue light

Most countries follow international safety standards such as those from the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [47], the American Conference of Governmental Industrial Hygienists (ACGIH) that limit the exposure to most hazards in the workplace and at home [51], or the European Union Directive on the minimum health and safety requirements regarding the exposure of workers to risks arising from artificial optical radiation [38]. The potential 'blue light hazard' from LED lights used in nail salons [39], dental curing lights [52–55], and the effectiveness of the blue light blocking shields found on curing lights [26,27] have already been well reported. Although low-power light bulbs, computers, and tablets should not pose a hazard to healthy adults [11,20,56], concerns have been raised [6,19,22]. In one study, a computer display switch with three blue LED indicators was assessed [22]. Using a worst-case viewing distance of 10 cm, the maximum daily exposure (t_{MAX}) to one blue LED indicator on the switch was only ~ 60 min [22]. Another study published in 2021 by a team of researchers from the U.S. Department of Health and Human Services reported that some of the LED flashlights tested posed a potential risk for retinal damage because t_{MAX} could be as short as 40 s [19].

The safe exposure limits used in these standards [38,47,51] are based mainly on animal studies that have looked at acute and prolonged exposure to blue light. The natural aversion response of the human eye to bright light usually limits single exposures to less than 0.25 of a second. However, dental personnel are trained to focus their stare on brightly illuminated white teeth as they watch what they are doing when working on these teeth. Thus, they may not evoke this aversion response [12,34,57]. Also, it must be remembered that these recommended exposure limits apply to healthy adults. These limits do not consider the use of photosensitizing medications or the viewer's age, either of which can increase the risk of phototoxic or photoallergic reactions to blue light [6,19,20,34,51,58,59].

1.4. Relevance of the blue light hazard to the dental profession

It has been estimated that, on average, a person spends about 4 h a day viewing digital display devices that emit blue light [10,28,60]. Dental professionals work in a brightly lit environment and are exposed to even more artificial blue light from curing lights, headlamps, and operatory lights [55,61]. Although the potential retinal risk of the blue light from some dental curing lights has been well reported [12,53,54,62,63], many dentists are unaware of the potential 'blue light hazards' in the dental office, and many do not use adequate eye protection [55,64,65]. In addition, few are aware of the potential risk from bright white light LEDs because they perceive that the light is white, not blue. Consequently, dentists may unknowingly expose themselves, their assistants and their patients (Fig. 2a) to hundreds of times the amount of blue light received by the general public, unless the dentist takes precautions (Fig. 2b). A recent study of 12 dentists who had used dental curing lights for 10 or more years compared them to eight control subjects who did not use curing lights [9]. Although no visual defects or ocular pathologies were found in either group, it is concerning that the dentist group had increased macular thickness, a higher incidence of macular vessel tortuosity, and greater variance in their macular pigment optical density values [9].

Many dental professionals also use magnification. This increases the

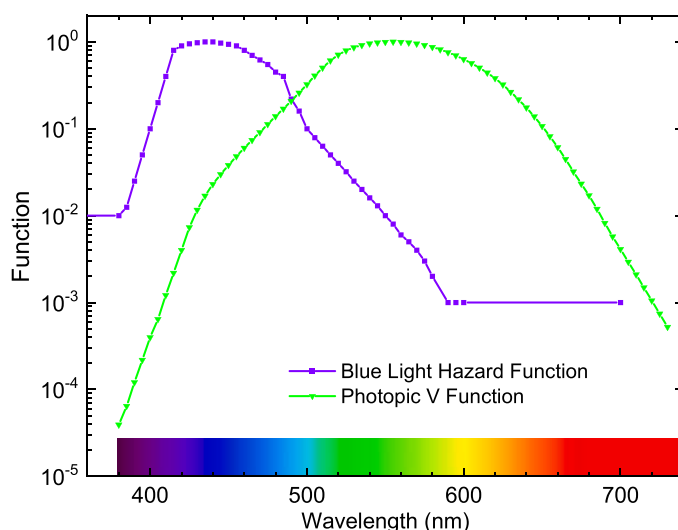


Fig. 1. Blue light hazard and photopic V-functions[47,50].

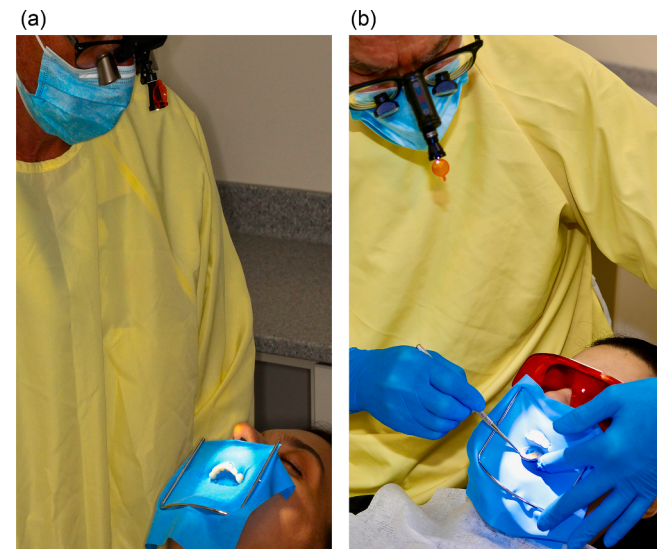


Fig. 2. a: Example of a patient who may be at risk of receiving an excessive amount of blue light because they are not wearing protective eyewear. 2b: Example of a white-light LED headlamp used to illuminate the teeth. Here, the white teeth are viewed against a blue-colored dental dam used to isolate the teeth and the patient is wearing protective eyewear.

optical radiant power entering the eye through the pupil [53]. Initially, dental headlamps used a halogen bulb as the light source to deliver the white light; however, almost all headlamps now use LEDs to produce the white light, and some of these LEDs can emit large amounts of blue light. In addition, dental dams are often used (Fig. 2). These dental dams come in various colors, and the reflected light from blue-colored dams may increase the potential for the ‘blue light hazard’ to occur compared to when a black or green color of dental dam is used.

Given the general public concerns [2,4–6,8,16–20,22] and the widespread use of bright white LED headlamps, this study examined and characterized the light from white light headlamps to determine if the daily cumulative exposure limit (t_{MAX}) to the blue light from these headlamps may be exceeded at the dental office. In addition, the effect of the color of the dental dam was examined under what the authors considered were the worst-case clinical conditions where the eye was 35 cm from the headlamp. The hypotheses were that:

- 1 The different brands of white light LED dental headlamps evaluated will deliver similar color temperatures (K), radiant powers, and emission spectra.
- 2 When using the international guidelines, the direct viewing of LED headlamps at a close working distance of 35 cm will not exceed the t_{MAX} ‘blue light hazard’ limits.
- 3 When using the international guidelines, the indirect viewing of the light from LED headlamps reflected back from a white reflective tile at a distance of 35 cm will not exceed the t_{MAX} ‘blue light hazard’ limit.
- 4 The maximum daily exposure limit (t_{MAX}) when indirectly viewing the reflected light from LED headlamps will not be affected by the color of the dental dam.

2. Materials and methods

The light output from one halogen headlamp and six LED headlamps, all used on their brightest setting, was examined with the headlamps and a detector fixed onto an optical bench (Table 1). Although a previous study looking at the blue LED indicators on a switch [22] used a distance of 10 cm, in the present study, 10 cm was deemed to be too close for dentistry, and the 35 cm distance was chosen as the closest reasonable working distance that a dentist might use. The maximum output from

Table 1
Headlamps examined, their manufacturers and identifiers used. (See Supplemental information for images of the headlamps).

Headlamp, (Identifier) and Type	Manufacturer
SurgiTel: 2.42-Watt Halogen bulb	SurgiTel, Ann Arbor, MI
Spark (A): LED	Orascopic, Madison, WI
Lumadent (B): LED	Lumadent, Reno, NV
Q-Optics (C): LED	Q-Optics, Duncanville, TX
SurgiTel-Cool (D): LED	SurgiTel, Ann Arbor, MI
SurgiTel-Neutral (E): LED	SurgiTel, Ann Arbor, MI
SurgiTel-Warm (F): LED	SurgiTel, Ann Arbor, MI

the headlamps was measured under three different conditions:

- 1 Direct, zero distance (0-mm), with the headlamp fixed at the entrance to an integrating sphere attached to a fiberoptic spectrometer.
- 2 Direct, with the headlamp 35-cm away from the entrance aperture into the integrating sphere (Fig. 3a).
- 3 Indirect, with the headlamp (Fig. 3b) fixed at a distance of 35 cm from a standard white reflective tile.
- 4 Indirect, with the headlamp and the integrating sphere (Fig. 3b) fixed at a distance of 35 cm from a dental dam stretched over the white tile, but with an opening to the white reflective tile.

2.1. Power measurements

To provide a reference light source that the general public may be exposed to at zero (0 mm) and 35 cm distances, the light from a white

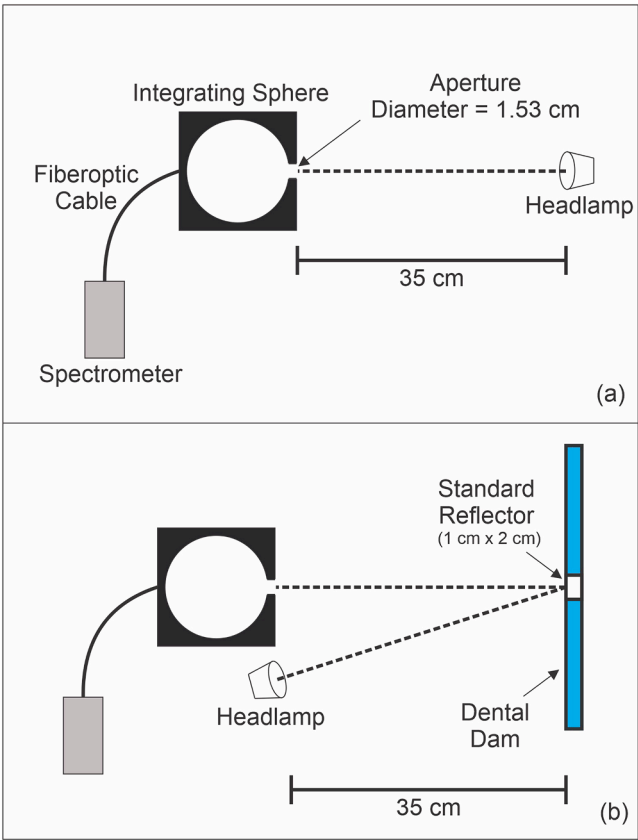


Fig. 3. Schematic showing the arrangement of direct (a) and indirect (b) measurements of the headlamps using the Ocean Insight Spectrometer and a collection area of 1.84 cm²(See Supplemental information for images of the experiment).

screen of an iPad tablet (Apple Computers, Cupertino, CA, USA) set on maximum brightness was recorded using previously described methods [66,67]. A 6-inch integrating sphere (Labsphere, North Sutton, NH, USA) connected to a pre-calibrated fiber-optic spectrometer (Flame-T, Ocean Insight, Orlando, FL, USA) measured the total power and the spectral radiant power from the headlamps at the 0-mm distance with the headlamps at the entrance to the 19-mm diameter aperture into the 6-inch integrating sphere. This 19-mm aperture into the sphere was wide enough to capture all the light from all the headlamps at the 0-mm distance. Then, direct light delivered at a distance of 35 cm from the light source was then measured using a smaller integrating sphere (FOIS-1, Ocean Insight, Orlando, USA) connected to a fiber-optic spectrometer (STS, Ocean Insight, Orlando, USA). This smaller sphere and STS spectrometer used a larger diameter fiber and larger slit size than the Flame-T spectrometer. This smaller sphere had a 15.3-mm diameter entrance aperture and was better suited to measuring low light irradiance levels than the larger sphere. To provide a reference light source that the dentist may also be exposed to, the direct light from a Bluephase PowerCure (Ivoclar Vivadent, Schaan, Lichtenstein) LED curing light on the 3-s high output setting was also measured into the sphere at a distance of 35-cm. The headlamps were measured in a random order three times, and their batteries were fully charged.

2.2. Beam profile at 35 and 55 cm distance

The irradiance distribution in a plane normal to the optical axis, commonly referred to as the beam profile, was measured from each headlamp as the light shone onto a standard white reference tile (#58-611: Edmund Optics, Barrington, NJ, USA). This tile is calibrated and standardized according to a National Institute of Standards and Technology (NIST) reference surface to provide a standard white surface with a 99% reflectance. The headlamps were fixed 35 cm and 55 cm away from this white reference tile. The images produced on the tile were measured at a distance of 35 and 55 cm using a laser beam analyzer (Model SP503U, Ophir-Spiricon, Logan, UT, USA) and previously described methods [68]. The difference between the spot size of the images produced at the 35 and 55 cm distances was used to calculate the beam divergence of each headlamp. The reflected spectral radiant power from the headlamps was also measured using the integrating sphere fixed at a distance of 35 and 55 cm away from the white reference tile. Since the headlamps delivered different powers, each two-dimensional (2D) color-coded image was scaled to its own maximum value in BeamGage software (OphirSpiricon), where red represents a high irradiance (100%), and purple represents a low irradiance.

2.3. Maximum permissible daily ocular exposure time

To determine the total luminous power and the maximum exposure time (t_{MAX}) at a distance of 35 cm before the 'blue light hazard' time limit would be exceeded in an 8 h workday from the 6 brands of LED, and the one halogen headlamp, the direct and indirect spectral radiant powers received into the integrating sphere were weighted using either the 'blue light hazard' or the photopic V function (Fig. 1). According to the ACGIH guidelines [51], for the two geometries used in this study with an angular subtense greater than 11 mrad, $t_{MAX} = 100/L_B$, where t_{MAX} is in units of seconds and L_B is the blue weighted radiance [51] in units of $W/cm^2/sr$. The Commission Internationale de l'Éclairage (CIE) photopic luminous efficiency function $y(\lambda)$ or $V(\lambda)$ is a standard function that the CIE has established. It was used to convert radiant power into luminous (i.e., visible) power to reflect the sensitivity of the human eye to different wavelengths of light [50]. The 'blue light hazard' was also calculated from the indirect light that had been reflected back from either a blue (isolate latex-free, Devmed Int. Dublin, Ireland), teal-green dental dam (Patterson, St. Paul, MN, USA), or a black latex dental dam (Sanctuary, Perak, Malaysia). These dams had a hole that was 12.6 by 23.6 mm in size so that the standard white reflective surface tile

(#58-611: Edmund Optics) could be viewed through this hole. The hole approximated a viewing area that covered 3 teeth (see Supplementary images).

3. Results

The emission spectra from the iPad, the halogen headlamp and the LED headlamps at the 0 mm distance are reported in Fig. 4. The locations of the blue (λ_B) and the green/red (λ_G) peaks are noted, together with the ratio of the blue to the green/red peaks (λ_B/λ_G). All the white light LED-based headlamps and the iPad emitted a characteristic emission spectrum peaking in the region between 430 to 460 nm, with a second broader band in the 550 to 600 nm range (Fig. 4). This emission spectrum was different from the grey-body like spectrum emitted from the halogen headlamp (Figs. 4a and b). The SurgiTel warm headlamp was the only headlamp where the blue (λ_B) peak @449 nm was lower than the second peak (λ_G).

The color temperatures from the headlamps ranged from 3098 K to 7253 K (Table 2). The maximum daily exposure limit (t_{MAX}) to direct viewing the headlamps at a distance of 35 cm ranged from 53 to 220 seconds for the LED headlamps (Table 2) and 810 seconds for the halogen headlamp. The mean total radiant power from the LED headlamps on their maximum setting measured at the 0-mm distance into the integrating sphere ranged from 108 mW for the Q-Optics to 378 mW for the Lumadent (Table 2). This was more than a threefold difference in the radiant power from these headlamps. The iPad delivered 0.41 mW, and the halogen headlamp delivered 47 mW under identical conditions. Thus, at the 0-mm distance, the iPad delivered a radiant power entering into the 19 mm diameter aperture of the larger integrating sphere that was 114 times less than the halogen light and 922 times less than headlamp B. When measured at a distance of 35 cm from the entrance to the sphere, the irradiance from the curing light was 0.83 mW/cm^2 and the irradiance from the headlamps ranged from 2.0 to 12.3 mW/cm^2 . In all cases, the spot size from the headlamps was smaller and brighter than the rather diffuse image from the curing light when viewed at the 35 cm distance (Fig. 5).

The beam profile images of the light from the headlamps (Fig. 6), when shone onto the standard white tile at a distance of 35 cm, show that all the headlamps delivered a light beam that would cover an entire arch of maxillary teeth. All three SurgiTel headlamps delivered a focused beam of light with a region of higher irradiance (represented by the red color in Fig. 6) at the center that would cover 2 or 3 teeth. In contrast, the Spark, Lumadent and Q-Optics delivered a more diffuse light. The halogen headlamp delivered the largest spot size.

The radiant powers of light emitted at a distance of 0 mm in the 400 to 480 nm range compared to the 480 to 700 nm region are illustrated in Fig. 7. In the 400 to 480 nm region, the powers from the Q-Optics, the Spark and the SurgiTel Warm headlamps were similar, but the power emitted in the 480 to 700 nm range was almost 3x greater from the SurgiTel Warm headlamp (280 mW compared to 108 mW). The direct measurements of the radiant power and photopic luminous V-weighted radiant powers from the 6 LED headlamps and the halogen headlamp at a zero distance of 0 mm are illustrated in Fig. 8. Note the prominent blue light emission peak from all the LED headlamps. The strong blue light emission peak (λ_B) from the Cool version (D) of the SurgiTel headlamp is particularly apparent in the blue light-weighted irradiance shown in Fig. 9.

Fig. 9 also shows that the SurgiTel Cool headlamp delivered the most amount of blue light and the highest blue light-weighted irradiance when viewed at a distance of 35 cm. Therefore, this headlamp was chosen to illustrate the maximum reflected spectral irradiance and the maximum blue light-weighted irradiance that was reflected back from three different colors of the dental dam that were 35 cm away. The reflected light was measured with and without rubber dams over the standard white reflective tile (#58-611: Edmund Optics). The effect of the rubber dam was measured when it had a hole (12.6 by 23.6 mm) to

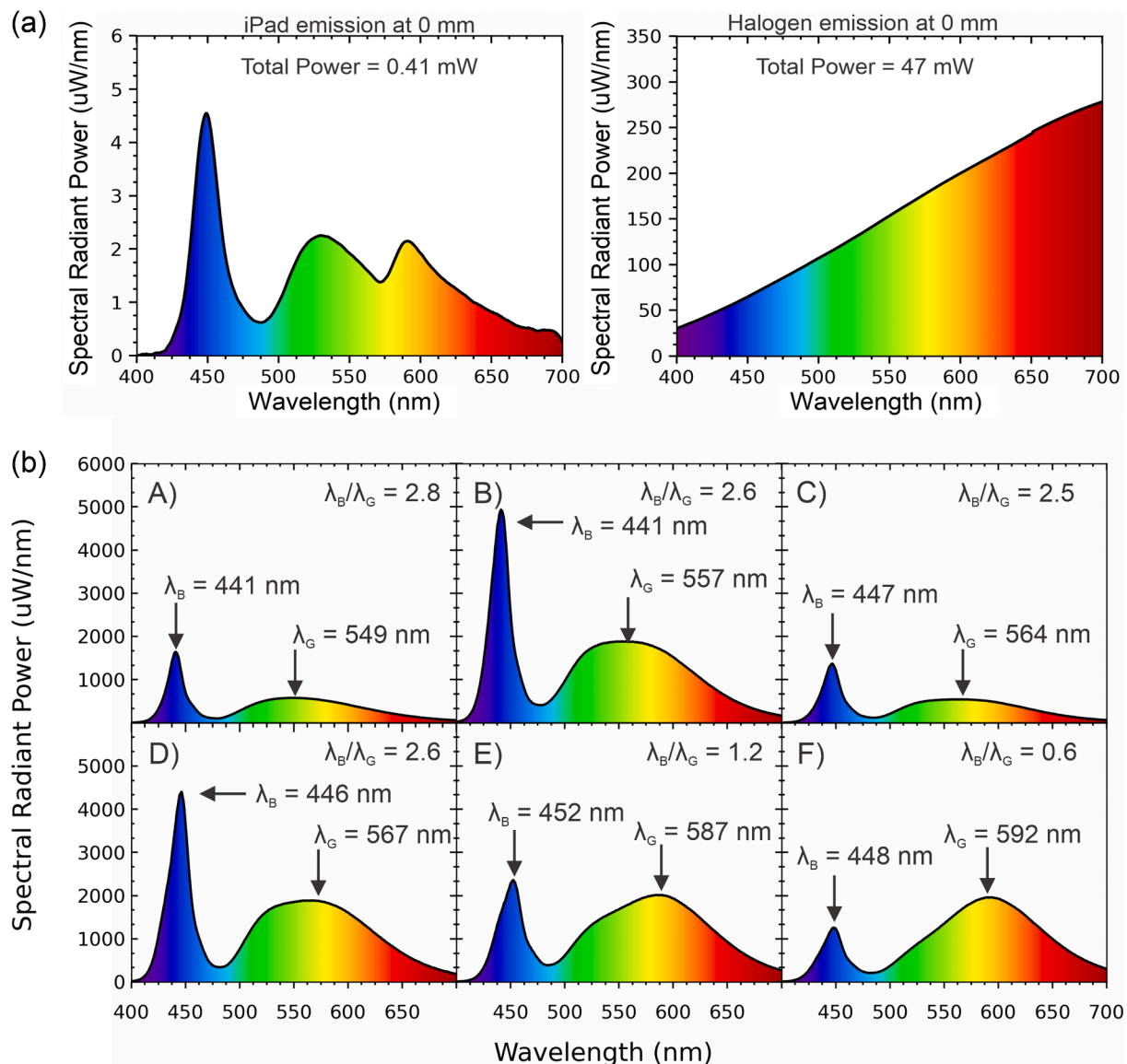


Fig. 4. Emission spectra from the: a) iPad and halogen headlamp, b) 6 LED headlamps at a distance of 0 mm. The locations of the blue (λ_B) and the green/red (λ_G) peaks are noted together with the ratio of the blue to the green/red peaks (λ_B/λ_G). Note: The very different spectral radiant powers from the iPad and the halogen lamp compared to the LED headlamps. The SurgiTel warm is the only headlamp where the blue (λ_B) peak @449 nm is lower than the second peak (λ_G).

approximate a viewing area that covered 3 teeth. Thus, in this case, the indirect light was reflected back from the reflective tile viewed through the hole and from the surrounding dental dam. The results are illustrated in Fig. 10. Note how the blue-colored dental dam increased the spectral irradiance in the blue range and the very different irradiance scales compared to the scales used ($\text{nW}/\text{cm}^2/\text{nm}$ vs. $\mu\text{W}/\text{cm}^2/\text{nm}$) for the direct measurements made at the same distance of 35 cm (Fig. 9). The mean maximum total daily exposure time for indirect viewing of the blue, teal-green and black dental dams and just the white NIST Traceable Reference Reflector (Edmund Optics) at the 35 cm distance from the 6 LED headlamps are reported in Table 3. In all cases, the maximum exposure times (t_{MAX}) were increased when the blue rubber dam was used compared to when the teal-green or black rubber dam was used. However, since the calculated times were all longer than 24 h (Table 3), the indirect light values from light reflected from either the reference tile or any of the rubber dams do not pose a 'blue light hazard'.

4. Discussion

This study did not determine the effects of the LED headlamps on the human retina or the total amount of blue light a person might receive every day from all sources. Instead, internationally accepted safety standards [38,47,51] were used to determine if the blue light-weighted irradiance from white light headlamps used in the dental office posed a 'blue light hazard'. Using these internationally accepted guidelines, the study found that the indirect light reflected back from the white reference tile at a close working distance of 35 cm posed no risk to healthy adult humans. However, if the LED headlamp was viewed directly at a distance of 35 cm, the t_{MAX} cumulative total time could be as short as 53 s in an 8 h day. The t_{MAX} for the PowerCure curing light was 62 s, the warm white LED headlamp was 205 s, and the halogen headlamp was 810 s (Table 2).

The emission spectrum from the white light halogen source is typical of grey body radiation that peaks in the infra-red region and has an effective color temperature of 3100K. This emission spectrum (Fig. 4a) is completely different from a tablet or a white light LED. Fig. 4b shows

Table 2

Mean (standard deviation) of the radiant power (mW), temperature (K), luminous power (lm), beam divergence, and the daily maximum total exposure time (s) for direct viewing at 0 mm and direct viewing at a distance of 35 cm.

Light Source and (Letter Code)	Radiant power (mW) at a Distance of 0-cm	Color Temperature (K)	Luminous power at a distance of 0-cm (lm)	Radiant power (mW) at 35-cm	Irradiance (mW/cm ²) at 35-cm	Beam divergence (degrees)	Spot Size (cm) at 35-cm	Spot Size (cm) at 55-cm	Maximum exposure time (t _{MAX} in s) for direct viewing at 35-cm
iPad	0.41 (0.01)	N/A	N/A	0.025 (0.0002)	N/A	N/A			N/A
Bluephase Powercure 3s mode	1534 (6)	N/A	N/A	1.53(0.01)	0.83(0.01)	N/A	N/A		62 (1)
Halogen	47 (0.2)	3114 (2)	12 (0.2)	3.6 (0.1)	2.0 (0.08)	14	12.4	17.2	810 (40)
Spark (A)	110 (5)	7253 (44)	34 (1.0)	4.4 (0.1)	2.4 (0.03)	11	8.5	12.3	134 (2)
Lumadent (B)	378 (4)	7065 (40)	115 (0.5)	10.6 (0.2)	5.8 (0.1)	12	10.0	14.2	53 (1)
Q-Optics (C)	108 (2)	6449 (36)	33 (0.6)	4.1 (0.2)	2.2 (0.1)	9	7.6	10.7	220 (10)
SurgiTel-Cool (D)	367 (3)	6283 (2)	115(0.6)	22.7 (0.5)	12.3 (0.3)	13	9.0	13.4	62 (1)
SurgiTel-Neutral (E)	339 (2)	4138 (0.6)	114 (0.5)	19.5 (0.2)	10.6 (0.1)	13	8.7	13.2	110 (2)
SurgiTel-Warm (F)	280 (15)	3098 (2.5)	98 (5.0)	16.6 (0.2)	9.0 (0.1)	13	8.7	13.3	205 (4)

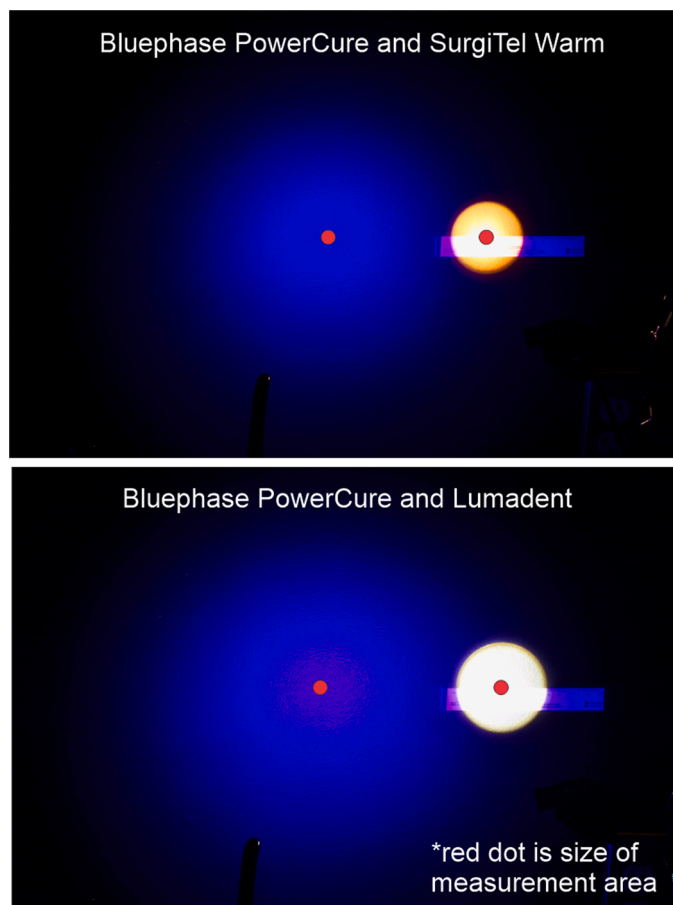


Fig. 5. Spot sizes from the Bluephase PowerCure curing light, the SurgiTel Warm (spot size = 8.7 cm diameter), and the Lumadent (spot size = 10.0 cm diameter) headlamps at a distance of 35 cm. The red (15.3 mm diameter) dot represents where the irradiance is measured. Note the ruler scale on the images, the different spot sizes, and colour of the light from the SurgiTel Warm and the Lumadent headlamps. Note also how diffuse the light appears from the curing light compared to the headlamps.

that, unlike the halogen headlamp, all the white light LED headlamps had a pronounced blue region in their emission spectrum that was centered between 440 and 450 nm. Since the brightness of objects perceived by human eyes is not proportional to the actual brightness (Fig. 1), but is instead related to the amount of light in the green-red region [50], this pronounced blue light emission band potentially poses a 'blue light hazard'. The colour temperature (K) and total power output from the headlamps on their maximum power settings measured at 0-mm distance into a 19 mm diameter aperture into the integrating sphere varied greatly (110 mW to 378 mW). Table 2 and Fig. 7 show that the Lumadent was the most powerful headlamp, delivering 7060±40 K at 378±4 mW. In contrast, the Q-Optics was one of the least powerful LED headlamps delivering only 6450±40 K at 108±2 mW at 0 mm. The halogen headlamp delivered 3114±2 K, but only 47±0.2 mW at a distance of 0 mm. Thus, the first hypothesis that all the LED dental headlamps evaluated would deliver similar color temperatures (K), radiant powers, and emission spectra was rejected.

The risk of blue-light mediated injury should be determined by weighting the irradiance at each wavelength to the potential that specific wavelength is thought to cause the ocular damage [38,47,51]. The direct measurement of the radiant powers, the V-weighted radiant powers, and the 'blue light hazard' weighted radiant powers from the 6 LED and the halogen headlamps (Figs. 7–9) illustrate the contribution of the prominent blue light emission peak to the total power and to the 'blue light hazard' from the LED headlamps. In all cases, the radiant power from the halogen lamp was less, the amount of blue light was far less, and t_{MAX} was longer (810 s). In the 480 to 700 nm region, although the total powers from the Lumadent and all three SurgiTel headlamps were similar, the powers in the 400 to 480 nm blue range were notably different (Fig. 7), the ratio of the blue peak to the green-red peaks ranged from 0.6 to 2.8 (Fig. 4b) and the t_{MAX} times were also different (Table 2). The blue light emission peak (λ_B) and the weighted blue light hazard spectrum from the Cool version (D) of the SurgiTel headlamp is particularly apparent when viewed directly at the 35 cm distance shown in Fig. 9.

When one considers that the general public is concerned about the very low amounts of blue light from electronic screens, the screen of an iPad on its brightest setting delivered only 0.41 mW when measured at the zero mm distance into the 19 mm aperture into the larger sphere and only 0.025 mW at a distance of 35 cm. In contrast, the headlamps delivered up to 921 times more power than the iPad at zero mm distance (0.41 mW vs. 378 mW) and 908 times more power than the iPad at the 35 cm distance (0.025 mW vs. 22.7 mW). While these power values cannot be directly compared because the entrance apertures into the

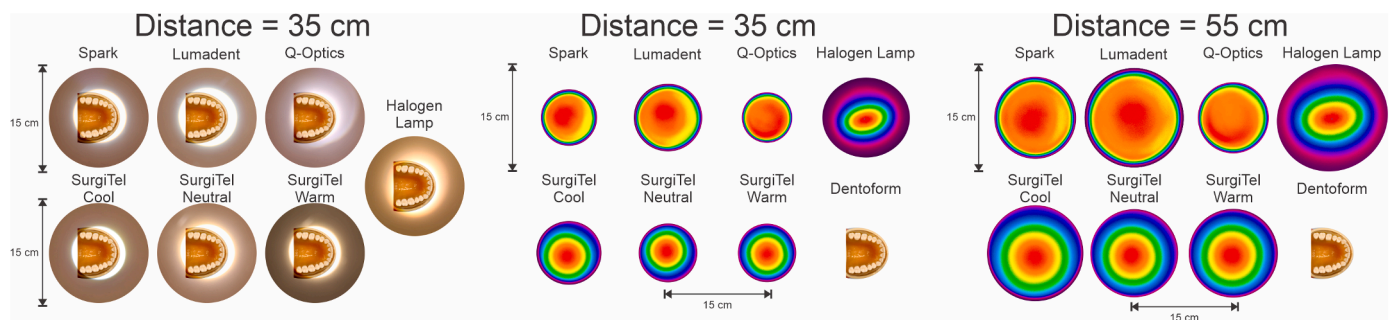


Fig. 6. Spot sizes and beam profiles from the headlamps reflected from a standard white reflector at a distance of 35 and 55 cm. Red represents high (100%), and purple represents a lower irradiance. Note the different spot sizes and beam distributions relative to the size of the maxillary arch.

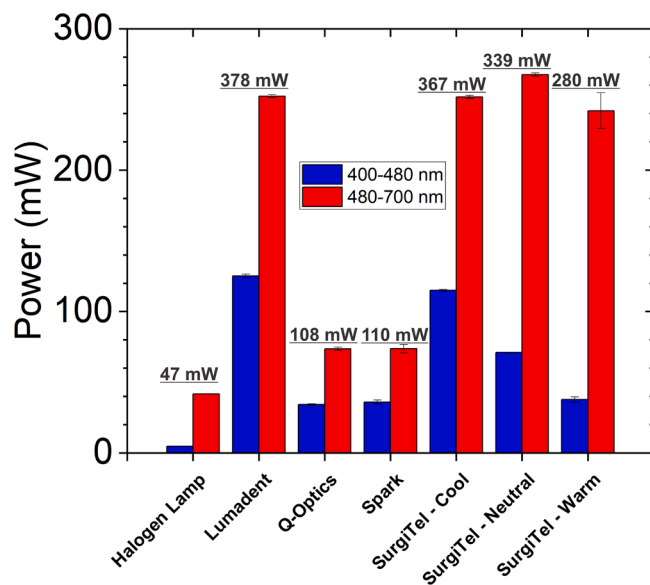


Fig. 7. Direct viewing at a distance of 0 mm. Mean total power and the power emitted in the 400 to 480 nm range and the 480 to 700 nm range from the 6 LED and 1 halogen headlamps.

spheres were different (19 mm for the larger sphere and 15.3 mm for the smaller sphere), it is reassuring that the ratio of the power values obtained using two different methods at the two distances were very similar (908x and 921x). Table 2 also shows that the maximum daily exposure limits when the headlamps were directly viewed at a distance of 35 cm ranged from 53 seconds for the Lumadent to 220 seconds for the Q-Optics headlamps, and up to 810 seconds for the halogen headlamp. If the CIE recommendation that the current 'blue light hazard' safety limit for adults should be reduced by a factor of 10 for children is followed [11], then t_{MAX} from at least one brand of LED headlamp viewed at a distance of 35 cm may be as short as 5 s for children. Of note, the cumulative t_{MAX} 53 s time limit from one LED headlamp is similar to the 40 s limit for some LED flashlights when viewed at a distance of 20 cm [19].

The differences in the radiant powers and the V-weighted radiant powers measured at a distance of 0-mm (Figs. 7 and 8) compared to the blue light-weighted irradiance at 35-cm (Fig. 9) illustrate how the emission spectra and the beam profile from the light source affect the potential 'blue light hazard' (t_{MAX}). This is particularly evident in Fig. 5 where the spot sizes of the white light from the SurgiTel Warm (8.7 cm) and the Lumadent (10.0 cm) headlamps were well defined, smaller, and brighter than from the LED curing light at the same distance. The headlamps clearly delivered a more coherent beam and, in all cases, a higher irradiance at 35 cm than the LED curing light. Table 2 reports that

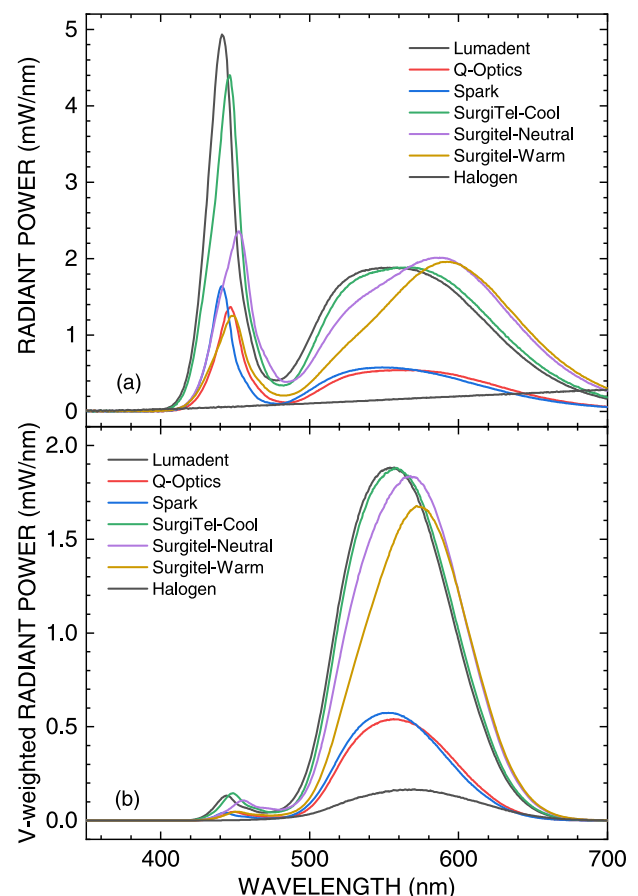


Fig. 8. Direct viewing of the headlamps at a distance of 0 mm. Total radiant power (a) and V-weighted radiant power (b) from the 6 LED headlamps measured through a 19 mm aperture into the larger integrating sphere. Note the prominent blue light emission peak from the LED headlamps.

the curing light delivered an irradiance of 0.83 ± 0.01 mW/cm², the Lumadent headlamp delivered 5.8 ± 0.1 mW/cm², the SurgiTel Cool delivered 12.3 ± 0.3 mW/cm², and the SurgiTel Warm delivered 9.0 ± 0.1 mW/cm² at a distance of 35 cm. Fig. 5 also illustrates the warmer colour of the light from the SurgiTel Warm compared to the Lumadent headlamp. This observation is supported by both the temperature results (Table 2) and the emission spectra (Fig. 4). Although the Lumadent and the SurgiTel Cool delivered the largest luminous powers of 115 lm at 0 mm, the SurgiTel Warm headlamp also emitted a high luminous power of 98 lm. This was warm white light at 3098 K and it had an estimated t_{MAX} exposure time of 205 s if viewed directly at a distance of 35 cm. The slightly higher luminous power of 115 lm from the Lumadent headlamp

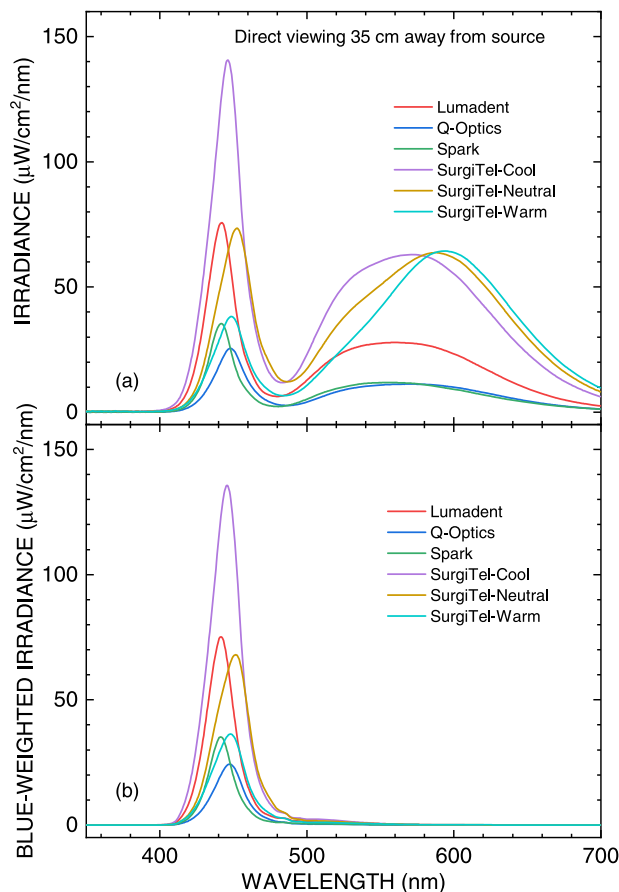


Fig. 9. Direct viewing at a distance of 35 cm of the spectral irradiance measured through a 15.3 mm aperture into the smaller integrating sphere. (a), and the blue-weighted irradiance (b) of the emission spectra from the 6 LED headlamps. Note the prominent blue light emission peak from the Cool version of the SurgiTel headlamp.

was cool-white light at 7253 K, and the maximum cumulative exposure time (t_{MAX}) from this headlamp was only 53 s when viewed directly at a distance of 35 cm. While the Q-Optics and the Spark headlamps delivered low amounts of blue light in the 400 to 480 nm region (Fig. 7), their total radiant powers and luminous powers were also relatively low. Although the SurgiTel Warm headlamp delivered a similar power in the 400 to 480 nm region, the luminous power was greater (Fig. 8), and the total radiant power from this headlamp was almost 3 times greater than from the Q-Optics or the Spark headlamps. This illustrates how beam collimation affects the irradiance beam profiles from the headlamps (Figs. 5 and 6) and the effects of the different emission spectra (Fig. 4) on t_{MAX} (Table 2). Therefore, the results may be misleading if hazard calculations are based on measurements taken at a zero mm distance. Instead, the measurements should be 'blue light hazard' weighted [38, 47,51], and made at a reasonable working distance to account for beam collimation. A distance of 35 cm was used in this study, but other distances will likely produce different results depending on how focused or collimated the light beam is from the source.

The second hypothesis that persons in the dental operator may be exposed to high levels of blue light is supported by Table 2 and was accepted. At a distances of 0 mm and 35 cm, some headlamps delivered a radiant power output that was 900+ times more than an iPad. Thus, this study shows that dental personnel may be the perfect 'canaries in the coal mine' to study the effects of chronic exposure to blue light in humans. While it is unlikely that the dental assistant would look at the light from a headlamp for several minutes, some dental appointments do last for two or more hours (7200 + seconds), and patients may very

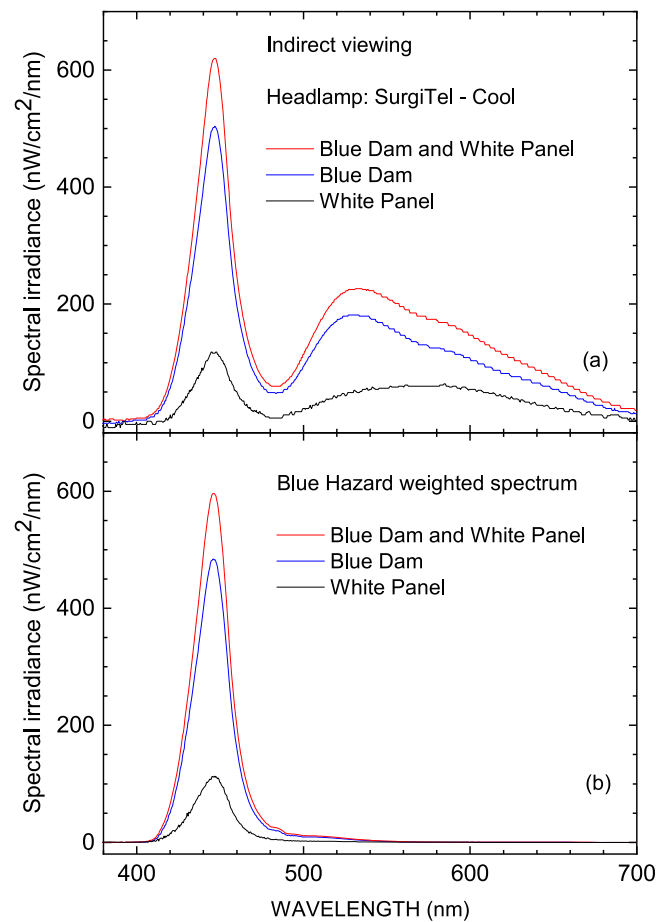


Fig. 10. Indirect viewing of the reflected blue light-weighted irradiance (nW/cm^2) measured at a distance of 35 cm into the smaller integrating sphere. The lower image shows the blue-weighted irradiance (nW/cm^2) of the emission spectra from the SurgiTel Cool headlamp (D) that was reflected from the surface of three different colors of the Dental Dam. Note the effect of the blue-colored dental dam on the spectral irradiance and the different scales from the direct viewing results seen in Figs. 8 and 9.

easily be exposed to direct light from the headlamp that is 35 cm away for 53 to 220 seconds (Fig. 2a). Thus, it is recommended that patients should wear protective eyewear (Fig. 2b) during the appointment [12, 25–27,40,54,69] that will protect their eyes from the blue light present in the curing light, LED headlamps, and from the LED operator light.

The indirect power outputs from the headlamps on their maximum power settings reflected from the white reference tile at the 35 cm distance were much less than the direct measurements at the same distance (4.1 mW to 22.7 mW), and they also varied considerably (Table 2). However, the third hypothesis that indirect viewing of the headlamps would not exceed the 'blue light hazard' in an 8 h day was accepted because, even in the worst-case scenario (Light D, SurgiTel Cool), when the light was reflected back from the white reference tile, it would take 74 h (Table 3) to exceed the maximum permissible exposure during an 8 h workday, and this is impossible. Since the results at 35 cm were not considered dangerous, only the 35 cm distance results are reported (see Supplemental data for more information). Nevertheless, Table 3 and Fig. 10 show that using a blue-colored dental dam reflected more blue light. This increased the blue light hazard and reduced the maximum permissible exposure time. Thus, the fourth hypothesis was accepted. This result is to be expected because a surface that appears blue should contain more blue light than a surface that appears green or black.

Fig. 6 illustrates that the spot sizes and beam profiles were different, but they all fully covered an entire arch of teeth. The ideal beam from

Table 3

Mean ($\pm$ standard deviation) maximum cumulative exposure time (in hours) for indirect viewing at 35 cm of the 6 LED headlamps against the blue, teal-green and black dental dams or just the white NIST Traceable Reference Tile (Edmund Optics).

Headlamp	Dam/Reference Tile Reflector	Maximum cumulative exposure time (hours)(t_{MAX})
Spark (A)	Blue	290 (10)
	Teal-green	1030 (20)
	Black	940 (20)
	Reference Tile	310 (20)
Lumadent (B)	Blue	113 (1)
	Teal-green	410 (20)
	Black	403 (2)
	Reference Tile	140 (10)
Q-Optics (C)	Blue	290 (20)
	Teal-green	910 (20)
	Black	960 (20)
	Reference Tile	410 (70)
SurgiTel-Cool (D)	Blue	96 (2)
	Teal-green	329 (5)
	Black	326 (5)
	Reference Tile	74 (5)
SurgiTel-Neutral (E)	Blue	170 (5)
	Teal-green	530 (20)
	Black	629 (5)
	Reference Tile	139 (5)
SurgiTel-Warm (F)	Blue	310 (20)
	Teal-green	1008 (2)
	Black	1200 (5)
	Reference Tile	250 (10)

LED headlights would be a uniform, achromatic beam without glare and that does not have separated colors. This study found that the color temperatures ranged from 3098 K to 7253 K for the headlamps (Table 2). The color temperature (K) appears to be related to the ‘blue light hazard’ and temperatures in the region of 3000K are thought to be less hazardous than ‘cool white’ temperatures above 4500K [13,48,49]. In addition, the best color for everyday living and viewing artwork is reported to be between 3600 K [70] and 3777 K [71]. Thus, the halogen (@3114 K) or the SurgiTel Warm LED (@3098 K) headlamps should deliver a more pleasing color to the viewer compared to the cool-white light headlamps that deliver light above 4500 K.

Keeping in mind that there are concerns that the general population may now be exposed to additional blue light from all sources [6,8,19,39], it should be recognized that the dental profession is chronically exposed to high levels of blue light that is in addition to what the general public already receives [27,52–54,72]. This increased exposure to blue light has only happened in the past 15 years with the increased use of LED lighting both in the home, in the workplace, and with the increased use of digital displays [10,28,60]. However, early evidence suggests that dentists who use curing lights may have greater changes in their retinas [9]. Also, the maximum recommended exposure times do not consider age or the presence of any photosensitivity when setting this limit. Thus, clinicians should remember that patients, especially children, and office staff with photosensitive conditions such as porphyria or those who are taking photosensitizing medications will be more susceptible to photo-toxic or photoallergic reactions to blue light [19,34,51].

Future studies should examine high output LCUs that claim they can photocure RBCs in just one 1 s [73,74]. This makes these LCUs attractive to dentists who wish to shorten treatment times, but they may pose a greater ‘blue light hazard’. Future studies should also record the cumulative amount of blue light received by dental personnel and patients from all sources in the workplace and at home to determine the total cumulative exposure that dental personnel receive in a typical 24 h and how much blue light patients receive during a dental appointment. In addition, dental personnel should be followed for a longer time to

determine whether the retinal signs already reported [9] develop into frank retinal pathologies. This information will help determine if the standard used to determine the photobiological risk for the general public might not be stringent enough for dental professionals [9,16]. Finally, until more information is known about the effects of chronic blue light exposure on the retina and sleep patterns, it is recommended that every attempt be made [6,8,40] to reduce the additional blue light received by dental personnel and patients. This includes using blue light blocking glasses or screens [25–28], and warmer white light LEDs that do not emit as much blue light [13,48,49]. In view of the CIE statement [11] and the concerns raised by French Agency for Food, Environmental and Occupational Health and Safety [8], this is especially important when treating children.

5. Conclusions

- 1 The color temperatures (K), radiant powers, and emission spectra from the headlamps tested were all very different and they did not all deliver a similar ‘blue light hazard.’
- 2 Among the six LED-based headlamps tested in this study, the Surgi-Tel Warm headlamp emitted a high luminous power of 98 lm at 3098 K. It offered the longest cumulative daily exposure time (t_{MAX}) of 205 s when viewed directly at a distance of 35 cm. The Lumadent headlamp also emitted a high luminous power of 115 lm, but this was cool-white light at 7253 K. The maximum cumulative exposure time (t_{MAX}) from this headlamp was only 53 s when viewed directly at a distance of 35 cm.
- 3 Patients should wear protective eyewear that specifically blocks out blue light.
- 4 Indirect viewing at a distance of 35 cm of the reflected light from LED headlamps did not exceed the cumulative daily exposure time (t_{MAX}) for healthy adults in an 8 h day.
- 5 Using a blue color of dental dam increased the hazard and decreased the maximum cumulative daily exposure time (t_{MAX}), but t_{MAX} was still greater than 24 h.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary images and a presentation associated with this article can be found, in the online version, at doi:10.1016/j.jdent.2022.104226.

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