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Optical profiles of cathode ray tube and liquid crystal display monitors: implication in cutaneous phototoxicity in photodynamic therapy

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Abstract

Recent clinical reports suggest that overexposure to light emissions generated from cathode ray tube (CRT) and liquid crystal display (LCD) color monitors after topical or systemic administration of a photosensitizer could cause noticeable skin phototoxicity. In this study, we examined the light emission profiles (optical irradiance, spectral irradiance) of CRT and LCD monitors under simulated movie and video game modes. Results suggest that peak emissions and integrated fluence generated from monitors are clinically relevant and therefore prolonged exposure to these light sources at a close distance should be avoided after the administration of a photosensitizer or phototoxic drug.

1. Introduction

Cutaneous photosensitivity is a disorder primarily caused or exacerbated by exposure to UV and visible light [1]. Photosensitivity reactions may be broadly categorized as phototoxic or photoallergic in nature [2,3]. Phototoxic disorders can be caused by exogenous photosensitizers and phototoxic drugs, which predictably lower the threshold for abnormal photocytotoxic responses in skin tissues. Several factors, such as the spectrum, intensity, and duration of the light irradiation, quantity and location of the photosensitizer on or in the skin tissues, thickness of the horny layer, degree of melanin pigmentation, and immunological status of the affected person may influence the severity of photosensitivity reactions [4].

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Photodynamic therapy (PDT) is a disease site-specific therapeutic modality. It involves systemic or local administration of a photosensitizer (e.g., hematoporphyrin or chlorophyll derivative) or prodrug [e.g., heme precursor 5-aminolevulinic acid (ALA) or its ester derivative] followed by irradiating the disease site with nonthermal visible light of appropriate wavelength(s). PDT has been approved for the treatment of several malignant and nonmalignant diseases (e.g., lung and esophageal cancer, actinic keratosis, age-related macular degeneration) [5]. Depending on the photosensitizer used, local or general cutaneous photosensitization can last days to weeks because of the accumulation of photosensitizer in the skin tissues. In general, the light absorption spectrum of PDT photosensitizers consists of multiple peaks in the Soret and *Q* bands. Patients receiving photosensitizers are always advised to stay away from direct sunlight and bright ambient light until the photosensitizer concentration in the skin tissues decreases to a safe level to avoid cutaneous phototoxicity [6].

It is generally believed that light emission from television and computer monitors is safe for patients receiving PDT treatment. However, recent clinical reports suggest that exposure to light emissions of cathode ray tube (CRT) or liquid crystal display (LCD) monitors after topical or systemic administration of a photosensitizer could cause noticeable skin phototoxicity [7,8]. These cases clearly indicate the potential risk associated with overexposure to a monitor for certain patient populations. However, the relationship between the optical profile of monitors and phototoxicity has not been reported before. In this study, we examined the light emission profile of CRT and LCD monitors under simulated movie and video game modes. Results suggested that prolonged exposure to these light sources at a close distance should be avoided after receiving a PDT photosensitizer or phototoxic drug.

2. Materials and Methods

A. Setup of CRT and LCD Color Monitors

A 16 in. CRT monitor (Dell E770s), 15 in. flat panel fluorescent backlit LCD monitor (Dell 1505FP) (hereafter “LCD”), 21.5 in. widescreen LED backlit LCD monitor (iMac mid-2011 model) (hereafter “LED”) were used as model monitors. The resolution of monitor screens was set to 800×600 pixels and a refresh frequency of 60 Hz. The brightness and contrast of the CRT monitor was adjusted to 50% of manufacturer settings with RGB intensity values fixed at 50% each. The light intensity of a plain white screen on the CRT at a fixed source-to-sensor distance of 18 in. was recorded by pointing the sensor of a power meter at the center of the screen in the absence of ambient light. The brightness of the white screen LCD and LED was adjusted to generate the identical emission intensity at the same source-to-detector distance as the CRT (i.e., $6.5 \mu\text{W}/\text{cm}^2$). The intrinsic irradiance profiles of white screen CRT, LCD, and LED under the same settings were measured under the active screen size ranging between 15 and 17.2 in. The color temperatures of monitors were measured with a 1080 HD resolution video camera-recorder (Panasonic HDX900) equipped with a HDTV lens (Canon KJ10EX10.5B IRSE). Color temperatures of CRT, LCD, and LED monitors at above settings were 8000, 6400, and 6500 K, respectively.

B. Video Streams

To maintain the same experimental conditions for measuring the optical profiles of the two monitors, a DVD movie stream was played back on all three monitors and a prerecorded video game was played back on the CRT and LCD monitors. To prepare the movie stream, a 10 min clip (hereafter “movie”) was selected from the DVD of the animation film Cars (Disney Pixar). Each measurement was started at the same point on the track Title 1 at time point 00:10:00 and played until the time point 00:20:00. To prepare the video game stream, a popular computer video game Age of Empires II: The Conquerors Expansion (Microsoft Game Studio) was played continuously by a proficient player for a total of 78.27 min. The entire game section was recorded. To maximum the optical profile changes of the game, the recorded section was fast forwarded to generate a 10 min video stream (hereafter “game”). The prerecorded movie stream was played back on the CRT, LCD, and LED monitors. The prerecorded game stream was played back on the CRT and LCD monitors. The movie and game streams were played back on the CRT and LCD monitors in full screen mode (4:3 aspect ratio). The movie stream played back on the LED monitor had an active picture size of 17.2 in. diagonal at the same aspect ratio as the other two monitors.

C. Power Meter and Spectrometer

A digital optical power and energy meter (PM130D, Thorlabs, Newton, New Jersey) equipped with a Si photodiode power sensor ($\phi = 9.5$ mm, 200–1100 nm; S130VC, Thorlabs, Newton, New Jersey) was used to measure the total light emission. A portable miniature spectrometer (USB 2000, Ocean Optics, Dunedin, Florida) was used to record the wavelength and intensity distribution of the monitor emissions. The wavelength (467.5–1143.4 nm) of the spectrometer was calibrated using a mercury-argon lamp (HG-1, Ocean Optics, Dunedin, Florida) before each use. The integration time for acquiring a spectrum was set to 45 ms to maximize the dynamic range of the measurement without saturating the spectrometer. The sensors of the power meter and spectrometer were placed at a fixed source-to-sensor distance of 18 in. from the center of the monitors to mimic the facial position. The power meter and spectrometer were connected to a computer. Data acquisition was carried out using manufacturer provided software (SpectraSuite, Ocean Optics, Dunedin, Florida) in the absence of ambient light.

D. Measurement of Optical Irradiance

The starting time point of the recording was initiated at the same movie or game image frame and the total optical irradiance of the movie or game was captured continuously for 10 min on the power meter at a fixed rate of three readings per second. The wavelength was set at 635 nm for the Si photodiode power sensor. The histograms were generated based on the distribution of optical irradiances and medians were determined by the 50% points of cumulative ratio.

E. Measurement of Wavelength Distribution

Before each measurement, the background was recorded and the device calibrated in the dark for automatic corrections. Full spectra (467.5–1143.4 nm) of the CRT and LCD monitors were then recorded for the movie and game, respectively. Data acquisition

frequency was one reading per second. The spectrometer was calibrated using a NIST calibrated tungsten-halogen light source (LS-1-CAL, Ocean Optics, Dunedin, Florida) for absolute power density measurements before each experimental section. The average power and integrated power (in $\mu\text{W}/\text{cm}^2/\text{nm}$) within the visible range, i.e., between 467.5 and 800 nm, were analyzed, respectively. The raw data acquired from the spectrometer consisted of 600 individual files and all were combined into a single file containing the respective wavelength and absolute irradiance readings using Labview 8.5 software. Data were plotted using Matlab 2010b software.

3. Results

A. Irradiance Profiles of CRT and LCD Monitors

To determine the intrinsic irradiance profile of each monitor, the monitors were set up to display a white screen that generates the same total emission intensity under the active screen size ranging between 15 and 17.2 in. The irradiance was measured by the spectrometer under the identical settings. Figure 1 shows the relative irradiance of each monitor. The CRT and LCD monitors generated several sharp peaks, whereas the LED two broader peaks. No significant emission was detected beyond 740 nm. The integrated output of the visible range from the LCD and LED was 40% and 60% higher than that of the CRT.

To determine the irradiance profiles under the movie and video mode, the optical irradiances of the CRT, LCD, and LED were measured for 10 min during the prerecorded video streams for the movie and game using an identical setup with active picture size ranging between 15 and 17.2 in. The detector was placed 18 in. from the monitor center to mimic the facial position. For the movie, the values of optical irradiance ranged between 0.25 and 3.5 $\mu\text{W}/\text{cm}^2$ for CRT and LCD [Fig. 2(a)] and between 0.2 and 9.7 $\mu\text{W}/\text{cm}^2$ for LED monitor. For the game, the values of optical irradiance generated from the CRT and LCD ranged between 0.7 and 1.5 $\mu\text{W}/\text{cm}^2$ [Fig. 2(b)].

Based on the histograms, the median irradiance for the movie on the CRT, LCD, and LED monitors was 0.91, 1.08, and 2.42 $\mu\text{W}/\text{cm}^2$, respectively [Figs. 3(a)–3(c)]. The average irradiance over a period of 10 min for the movie on the CRT, LCD, and LED monitor was 1.09, 1.20, and 3.05 $\mu\text{W}/\text{cm}^2$, respectively. The 50% points of the cumulative ratio of the game on the CRT and LCD monitors were 1.28 and 1.24 $\mu\text{W}/\text{cm}^2$, respectively [Figs. 3(d) and 3(e)]. The average irradiance over a period of 10 min for the game on the CRT monitor and the LCD monitor was 1.29 and 1.25 $\mu\text{W}/\text{cm}^2$, respectively.

B. Spectral Profiles of CRT and LCD Monitors

The spectral irradiances generated by the CRT and LCD monitors were examined in the visible range (i.e., 467.5–800 nm) for 10 min during the prerecorded video streams of the movie and game using identical setups. Figure 4 shows three-dimensional graphs of the wavelength (nm), time (s), and the spectral irradiance ($\mu\text{W}/\text{cm}^2/\text{nm}$). Clearly, there were distinct differences in the spectral profiles between the different types of monitors. For instance, during the movie, the LCD monitor showed more peaks than the CRT monitor, whereas the LED monitor generated much broader peaks than the CRT and LCD monitors.

To further estimate the spectral fluence at each wavelength, the spectral irradiances over a period of 10 min were integrated. As shown in Fig. 5, there were distinct differences in spectral fluence distributions between the CRT, LCD, and LED monitors but the spectral fluence distribution between the movie and game was similar for the same type of monitor. For the CRT's emission during the movie stream, the order of peak height was 626, 706, 617, and 595 nm. The integrated fluence under the curve (467.5–800 nm) was 1.092 mJ/cm². An identical distribution but a different integrated fluence (0.898 mJ/cm²) was seen on the CRT's emission during the game stream. For the LCD's emission during the movie stream, the order of peak height was 611, 545, 587, 620, and 630 nm, respectively. The integrated fluence was 1.410 mJ/cm². For the LCD's emission during the game stream, the order of peak height was 611, 545, 626, 706, and 587 nm. The integrated fluence was 1.401 mJ/cm², which was similar to that of the movie stream. However in contrast to the sharp peaks characteristic of the CRT and LCD monitors, the LED's emission during the movie stream generated two broader peaks at 605 and 514 nm, respectively. The integrated fluence was 1.831 mJ/cm².

4. Discussion

Although photosensitizers have high selectivity toward cancerous cells, they can also accumulate in normal skin tissues [9]. The transitional uptake and retention of photosensitizer in the skin tissues after a systemic or topical application of a photosensitizer during PDT can lower the threshold for abnormal photocytotoxic responses in the skin and therefore poses a potential risk of cutaneous photosensitization. In particular, the systemic application of hematoporphyrin-based photosensitizer can cause a prolonged cutaneous photosensitization due to its slow clearance rate.

Direct exposure of bare skin to strong light after PDT can cause severe skin phototoxicity although the superficial light irradiation has a limited tissue penetration depth. Therefore, the patient is advised to avoid direct light exposure to the skin after the administration of the photosensitizer. The length of light avoidance after PDT depends on the retention time of photosensitizer in the normal skin, which can be affected by the nature and dose of photosensitizer and its administration route, and body site [9], which can range from days to weeks after a single administration of photosensitizer [5,10]. For Photofrin, skin photosensitization can last up to several weeks. For ALA/PpIX, it might last for a few days. After that period of time, the light exposure will not cause harm. Typical patient warnings state that patients who receive the photosensitizer must take precautions to avoid exposure to direct sunlight, light at close proximity, or bright indoor light. The latter often refers to examination lamps, dental lamps, operating room lamps, floodlights, and halogen lamps.

Incidences of post-PDT skin phototoxicity are often associated with patients who fail to heed the advice of strict light avoidance. Rather than indoor light, sunlight exposure shortly after receiving an exogenous photosensitizer or prodrug presents a major risk factor for skin phototoxicity. Although rare, exposure to CRT or LCD monitor emissions after PDT can also cause cutaneous phototoxicity on bare skin [7,8]. Current patient warnings have not listed the potential risk of exposure to light emission from TV and computer monitors. It is reasonable to suggest that future guidelines and patient warnings should include the

avoidance of overexposure to common indoor light sources, such as computers, video games, and TV monitors (at a close distance) after receiving topical or systemic administration of a photosensitizer.

Color CRT monitors use a phosphor-coated screen. Phosphors are arranged in strips and emit visible light when exposed to an electron beam generated within the CRT. Three beams are used in CRT monitors to excite red, green, and blue color in combinations needed to create the various hues that form the picture. CRT monitors are gradually being replaced by LCD flat panel monitors in households and offices. The light emitting mechanism of LCD monitors is different than that of CRTs. LCD displays use two basic techniques for producing color: passive matrix or thin film transistor. Basically, LCD monitors utilize two sheets of polarizing material with a segmented liquid crystal solution between them. An electric current passes through the liquid causing the crystals to align so that the light emission of individual pixels can be controlled. LCD monitors are typically backlit by a white light fluorescent (fluorescent-backlit) or LED light (LED-backlit) source since the liquid crystals generate no light of their own.

This study examined the light emission profiles of common CRT, LCD, and LED monitors utilizing simulated movie and video game streams. The range of optical irradiance generated from the movie stream was broader than that from the game stream (see Fig. 2). The 50% points of the cumulative ratio for the game were slightly higher than that of the movie (see Fig. 3). Using a representative figure of $1 \mu\text{W}/\text{cm}^2$ as an example, it can be estimated that 10 min exposure to a monitor at a distance of 18 in. can deliver a total fluence of $0.6 \text{ mJ}/\text{cm}^2$, i.e., $60 \mu\text{J}/\text{cm}^2/\text{min}$ to the skin surface. This estimated fluence rate is considerably lower than that of sunlight or PDT light, which are typically at 10^1 – $10^2 \text{ mW}/\text{cm}^2$ range. The moderate monitor settings (e.g., the total emission intensity of $6.5 \mu\text{W}/\text{cm}^2$ at the measurement point), randomly selected video streams, and longer sensor-to-monitor distance (e.g., 18 in.) might cause an underestimate of the fluence rate. It should be noted that the actual light emission profiles depend on several factors, including the size and configuration of monitor screen, program being played back on the screen, and its duration. The light fluence received by the skin is also affected by the screen-to-face distance and their alignment. Furthermore, the light fluence inside the skin of a multilayered geometry can be significantly affected not only by light source but also by tissue optical properties [11]. The point measurement at a single fixed distance has its limitations and it may not reflect the true dynamic nature of how the patient is exposed to computer and TV monitors.

For 10 min of the movie or game the integrated fluence from the CRT's visible emission (467.5–800 nm) measured by the spectrometer at the same face position (i.e., 18 in. from the monitor) was approximately $1 \text{ mJ}/\text{cm}^2$. This value was higher than that estimated from the optical irradiance ($0.6 \text{ mJ}/\text{cm}^2$) measured by the Si photodiode. It needs to be pointed out that the Si photodiode used in this study is wavelength dependent. As the wavelength was set up at 635 nm, it might underestimate the actual total optical irradiance. Interestingly, under the same condition, the integrated fluence from the LCD or LED was 40% or 80% higher than that of the CRT. The active diagonal screen size of the CRT, LCD, and LED was 16, 15, and 17.2 in., respectively. Under the white screen mode, the relative fluence of visible emission from the LCD or LED was 40% or 60% higher than that of the CRT when the total

emission intensity was set up at the same level (see Fig. 1). Although the difference in the screen size might contribute to some variation, this finding suggests that the common assumption that LCD and LED monitors might be safer than older CRT monitors is incorrect in terms of potential risk of skin phototoxicity.

As shown in Figs. 4 and 5, there were distinct differences in terms of the spectral fluence distribution between CRT and LCD monitors but the spectral fluence distribution between movie and game streams was similar for the same type of monitor. For the CRT during movie or video streams, wavelength peaks of emission light were located at 595, 617, 626, and 706 nm, respectively. For the LCD during movie or video streams, wavelength peaks of emission light were located at 545, 587, 611, 620, and 630 nm, respectively. Interestingly, in contrast to the sharp multiple peaks of CRT and LCD monitors, LED monitor emission during the movie stream generated two broader peaks at 605 and 514 nm, respectively. The peak position and order of peak height under the movie and video mode were slightly different to that under the white screen mode. Nevertheless, these wavelengths closely overlap with the *Q*-band absorption peaks of common PDT photosensitizers (e.g., HpD, PpIX, and hypericin) [12,13].

In some cases, the back of the hands can be exposed to monitor light while working on the keyboard. A recent report indicated that mild phototoxicity could occur on the back of both hands after PDT when the hands were exposed to an LCD monitor for a few hours [8]. To estimate hand exposure, the sensor of the power meter was placed on top of a standard keyboard and perpendicular to the surface of a CRT or LCD monitor. The total optical irradiance was recorded at various positions along the entire keyboard surface [data not shown]. It was estimated that the light dose received by the back of hands was approximately 10% of the facial dose.

It has been a concern that overexposure to UV and visible radiation in the presence and absence of photosensitizer might be also detrimental to the eye and subsequently to vision [14]. In general, ocular phototoxicity after PDT is rarely reported although mild phototoxicity of the eyelid (e.g., edema) can occur after PDT without affecting the vision [8]. One possible explanation might be that the accumulation of photosensitizer in the retina tissues is much less than that in the skin tissues. Nevertheless, this assumption deserves further investigation.

In summary, our results suggest that the optical and spectral profiles of emissions from color monitors are clinically relevant. Therefore, prolonged exposure to monitor emissions at a close distance might pose as a potential risk to the face, eyes, and hands. Future guidelines on post-PDT care and patient warnings should include the avoidance of overexposure to common light sources, such as computers, video games, and TV monitors after receiving a topical and systemic administration of a photosensitizer. This should be emphasized to certain high-risk patient populations, e.g., teenagers who may play video games for extended periods of time and people who receive repeated topical application of a photosensitizer or prodrug at a short period of time or work long hours in front of a large and bright monitor screen. The same caution is also applicable to patients who take drugs known to cause photoallergic, photosensitive, and phototoxic reactions.

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Fig. 1. Irradiance profile of white screen of CRT, LCD, and LED monitor. Insert: relative fluence—normalized to CRT (100%).

Fig. 2. Time course of total optical irradiance ($\mu\text{W}/\text{cm}^2$) measured in the 200–1100 nm range and over a 10 min period. (a) Movie stream and (b) game stream on CRT and LCD monitors.

Fig. 3. Histograms of optical irradiance generated by CRT, LCD, and LED over a period of 10 min. Movie stream on (a) CRT, (b) LCD, and (c) LED monitor. Game stream on (d) CRT and (e) LCD monitor. The 50% points of the cumulative ratio and corresponding median irradiance were marked on each histogram.

Fig. 4. Spectral irradiances measured over 10 min of the movie stream on (a) CRT, (b) LCD, and (c) LED monitor, and the prerecorded video game on (d) CRT and (e) LCD monitor.

Fig. 5. Spectral fluences from integrating the spectral irradiances over the 10 min of playback time for the movie stream on (a) CRT, (b) LCD, and (c) LED monitor, and for the prerecorded video game on (d) CRT and (e) LCD monitor.