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Exposure of Photostimulable Phosphor Plates with Red, Blue, and Green Light: Comparing Multiple Sequences Before Scanning

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Abstract

Background: This research aims to investigate the effect of changing the order of the colors by conducting 12 sequences of light exposure in red, green, or blue colors.

Methods: Human-related material was not included. An Arduino-based experimental tool was developed with a 3D-printed light-tight platform. The photostimulable phosphor (PSP) plates were irradiated using the same parameters and metallic coins as contrast material. The plates were exposed to red, green, and blue colors, with variable color order and time intervals (20 seconds, 1 second, 100 milliseconds, 10 milliseconds). The total delay before scanning and total light exposure time was fixed, 12 sequences were conducted, and each experiment was repeated twice. Resulting radiographs were imported to ImageJ software and signal-to-noise (SNR) and contrast-to-noise (CNR) values were calculated by combining the ROIs dedicated for each contrast region.

Results: SNR values were found in the range of 128.6-155.6, while CNR values were found between 63.2 and 74.7. The second experiment (R-B-G, 20 seconds) resulted in the lowest SNR (128.6) and CNR (63.2) values. In contrast, the twelfth experiment (R-B-G, 10 milliseconds) resulted in the highest SNR (155.6) and CNR (74.7) values. For 20 seconds, administration of the red color first resulted in greater signal loss than green and blue colors.

Conclusion: Results of this experiment suggest that, despite the total delay and light exposure being the same, changing color order and time interval affected the resulting signal. Testing this phenomenon with different PSP systems or investigating the logic behind it may be the subject of future studies.

Keywords: Dentistry, digital, imaging

INTRODUCTION

Photostimulable luminescence (PSL) event occurs when a proper material is exposed to an energy such as X-ray or UV light, and this energy is stored in electron-hole pairs and released as illumination upon an optical stimulus.[1] Photostimulable phosphor (PSP) imaging systems are based on irradiation of the imaging plates and then reading of the exposed plates with the scanners. As opposed to the analog films, PSP systems can be used in ambient light, however, exposure to visible light before scanning leads to fading of the energy stored in the plates and reduces the image quality.[2]

Arduino is an open-source electronics platform designed for anyone working on interactive hardware and software projects. The basic architecture consists of a microcontroller-based Arduino board connected to the peripherals such as

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sensors, lights, or motors. The system processes the information received from the sensors and generates the appropriate output based on the code.[3] In ISO/ASTM 52900:2021, "additive manufacturing" is defined as the "process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies," and "rapid prototyping" is defined as "application of additive manufacturing intended for reducing the time needed for producing prototypes."[4]

The exposure of irradiated plates to ambient light before scanning was investigated in several studies.[2,5-8] In these studies, the intensity of the light was changed in repeated experiments and the source or wavelength was fixed. Some researchers investigated the effect of the color of ambient light on PSP plates using different light sources.[9,10] In the early study, the effect of red, green, and blue colors was tested with lights produced from a single source using RGB LED units in the developed experimental device.[11]

The intensity of light, wavelength (color), and source were fixed during each of the repeated experiments in previous studies. This study aims to investigate if applying red, green, and blue light in different sequences and time intervals during each experiment influences the image quality. The null hypothesis is that there is no significant difference in image quality in different sequences because the total light output and delay time are constant.

MATERIAL AND METHODS

In this study, a previously developed experimental tool was revised to produce visible light in red, green, and blue colors to be exposed on to PSP plates before scanning, in given sequences. Human-related material was not included, and ethics committee approval, as well as informed consent obtained from the patients, was not required.

Development of Experimental Tool

The microcontroller system was based on an Arduino Mega 2560 developers board with two inputs (a TSL 2591 light sensor and a DHT11 temperature and humidity sensor) and two output (RGB LEDs) peripherals. All peripherals were connected using jumper cables without soldering. The system is powered via USB connection and no mobile battery is included. The device was updated with a new algorithm using Arduino programming language to produce lights in different sequences using Adafruit libraries of <Wire.h>, <Adafruit_Sensor.h> and "Adafruit_TSL2591.h."

The device sensor data was only used to monitor the environment inside the box and was not used to manage the actions to be taken by the system using any operator in the algorithm. A light-tight platform was designed in six parts with SolidWorks and printed using filament material with Ultimaker S3 and Creality CR10 Smart Pro 3D devices. After the pieces of the platform were produced, the electronic parts were integrated into the platform and pieces were combined to form the experimental tool (Figure 1). A more detailed description of the experimental tool can be found in the early study.[11]

Processing of the PSP Plates

The PSP plates are erased and placed in a light-tight cover. Size 2 (31 × 41 mm) plates (Dürr Dental, Germany) were irradiated using RXDC (MyRay, Italy) X-ray source (70 kV, 8 mA, 0.5 seconds). Metallic coins were used as contrast material. A total of four metal coins, each in 23.85 mm diameter and 1.95 mm thick, made of Cu-Ni-Zn alloy (75-15-10 in the inner core, 81-4-15 in the outer ring), were stacked on top of each other and secured to each other and to the hygienic cover with tape. After irradiation, half of the active surface of the plates were protected from light exposure using a half-cover, and the plates were transported to the experimental tool for light exposure. The delay between irradiation and scanning was determined as two minutes, while the

Figure 1. Arduino-based experimental tool, with the platform that holds the parts and the circuit elements embedded in it. A manually opened black door was used to transport the blue-colored imaging plate on the floor into the platform. Frontal x-ray view demonstrates the internal electronic components.

total duration was equal for each color in one minute of total exposure.

The RGB LEDs were operated with full duty cycle using a pulse width modulation (PWM) value of 255 for each color, separately, and only red, green, and blue colors were produced, without the intermediate colors. The total light output time for the three colors was the same (20 seconds) in all sequences with a total of one minute of light. A total of twelve different sequences were conducted (Table 1), in which color order and time interval varied, and each experiment was repeated twice. In the first six experiments (Round), the time interval for the transition between colors was set to 20 seconds, while in the remaining six experiments (Cycle), time intervals of 1000, 100, and 10 ms were performed between colors. In the first six sequences (20 seconds), different colors were applied sequentially once, while in the other sequences (1 second, 100 ms, 10 ms), the cycle was repeated until one minute of exposure was completed. Repeating 12 different experiments twice (12 × 2) yielded a total of 24 different images, and the repeating pairs were combined.

All procedures from irradiation to scanning of the plates were conducted in a dim ambient light condition. Plates that received one minute of light exposure within a two-minute delay after irradiation were scanned using VistaScan Mini Plus (Dürr Dental, Germany) scanner, and digital images were exported in .TIFF format.

Quantitative Image Quality Tests

Digital images were imported to the ImageJ software. A total of four contrast zones (Figure 2) were obtained in each image. Three rectangular ROIs (1.25 × 1.25) were selected in each region, and as each experiment is repeated twice, the results of six similar ROIs were combined to obtain the variables for image quality tests. Among four different regions, variables representing border values were excluded and the remaining two different regions were used to calculate the signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) with Equation I and Equation II, respectively:[12]

Eq. I

$$SNR = \frac{mean(bone)}{SD(soft\,tissue)}$$

Eq. II

$$CNR = \frac{mean(bone) - mean(soft\,tissue)}{SD(soft\,tissue)}$$

Statistical Analysis

The distribution of SNR and CNR values was evaluated with the Shapiro-Wilk test. Non-parametric tests were applied due to the small sample size (n < 30). Mann–Whitney U-test was used to compare groups, and Friedman Test was used to compare repeated samples. For method error, three samples were randomly selected one month later, SNR and CNR values were calculated, and repeatability was evaluated with intraclass correlation coefficient (ICC) and interpreted as shown in Table 2.[13] Kendall's Tau coefficient was calculated to measure the relationship between two variables. Statistically significance threshold was determined as a *P*-value < .05.

RESULTS

Repeatability was found to be moderate (ICC: 0.692, α=0.818) for SNR and poor (ICC: 0.484, α=0.652) for CNR. Shapiro-wilk test showed normality in the SNR (*P*=.141) values, while it was opposite for the CNR (*P*=.07) values. Mann–Whitney U-test (asymp. sig. 2-tailed) showed comparing "Round" and "Cycle" experiments was statistically not significant for both SNR (*P*=.336) and CNR (*P*=.522) values. Freidman Test showed comparing the repeated experiments among groups was statistically significant (*P* < .001). The Kendall's Tau correlation coefficient was found to be 0.565 (*P*=.011) for SNR and CNR values.

The mean gray values representing each region were determined by averaging the three ROIs selected in each zone. For bone, the highest mean gray value was found in Experiment 7 (247.05 ± 0.94), while the lowest value was obtained in Experiment 4 (246.3 ± 0.9). For soft-tissue, the highest value was found in Experiment 10 (130.01 ± 1.63) and the lowest in Experiment 3 (121.25 ± 1.69). The average gray values calculated in the respective regions can be found in Supplementary Table 1.

For the quantitative image quality tests, in the first six sequences (Round), SNR values were changed from 129.6 to 148.4, while CNR values were found between 63.2 and 74.6 (Figure 3). According to the SNR values, most signal

Table 1. Sequences of RGB Light Exposure According to Color Order and Time Interval

Exp*	Sequence (Round)			Int** (seconds)	Definition	Exp*	Sequence (Cycle)			Int** (ms)	Definition
1	R	G	B	20	Each color is produced for a single time in the given order	7	R	G	B	1.000	Each cycle is repeated until one minute of exposure is reached
2	R	B	G	20		8	R	B	G	1.000	
3	G	R	B	20		9	R	G	B	100	
4	G	B	R	20		10	R	B	G	100	
5	B	R	G	20		11	R	G	B	10	
6	B	G	R	20		12	R	B	G	10	

B, blue; G, green; R, red.* Exp, Experiment number.** Int, Time interval.

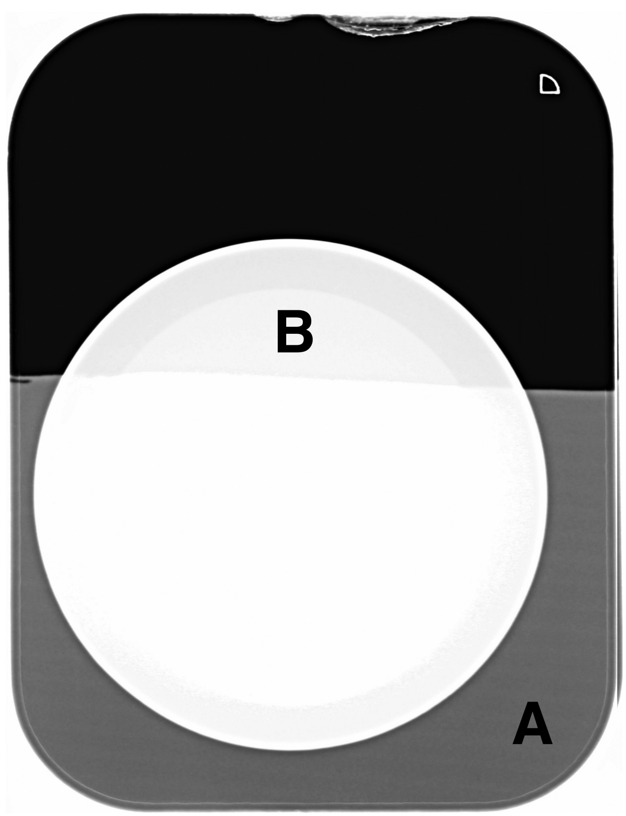

Figure 2. Contrast zones in the obtained radiographs. A Bone, B: Soft-tissue. Background in the dark half and coin zone in the light-applied side represents the margin gray values for the 8-bit image, and these areas are not included in the calculation.

Table 2. Interpretation of the Intra-Class Correlation Coefficient Values (13)

Value	Definition
< 0.5	Poor
0.5-0.75	Moderate
0.75-0.9	Good
> 0.9	Excellent

loss was observed in Experiment 2 (SNR: 128.6, CNR: 63.2) and Experiment 3 (SNR: 145.6, CNR: 74), while the least signal loss was observed in Experiment 6 (SNR: 148.4, CNR: 74.6) and Experiment 5 (SNR: 147.4, CNR:72.5). For the Cycle experiments, SNR values were changed from 140.9 to 155.6, while CNR values were found between 70.1 and 74.7 (Figure 4). According to the SNR values, there was an inverse association between time interval and impact on image quality.

DISCUSSION

Present studies on ambient light exposure to PSP plates before post-irradiation scanning were the main source of motivation for this present study, in which the ambient light was modulated acknowledgment of the Arduino platform and additive manufacturing technologies. Results obtained in this study, which compared different sequences with red, green, and blue colors, suggest that if the colors are administrated in various rows in one round, quantitative image quality parameters decreased less with blue color when compared to the red and green, if blue was applied first. In experiments with one second and up to the second order less, monotonic relationship was found between the time interval and the signal loss.

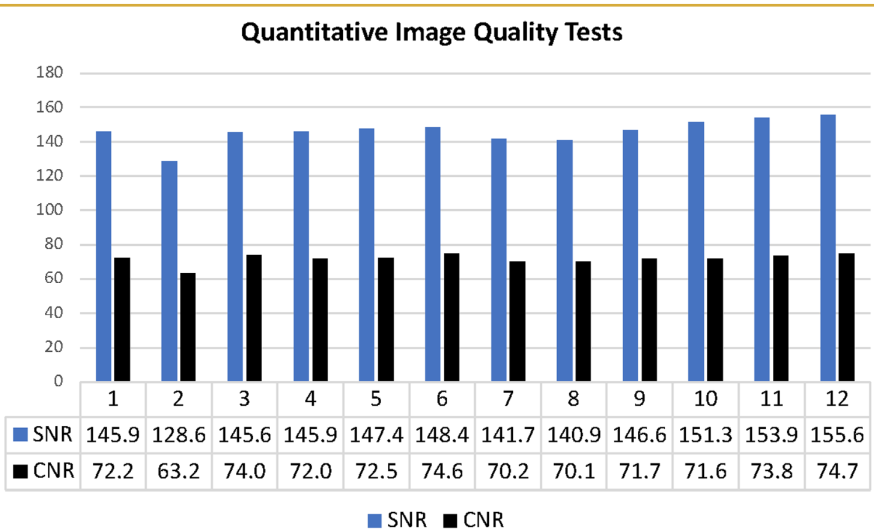

Figure 3. Signal-to-noise ratio (SNR) and Contrast-to-noise ratio (CNR) values calculated according to the results of twelve different experiments. Experiments 1 to 6 are "round" and 7 to 12 are "cycle" sequences.

The effect of ambient light after irradiation and before scanning was the subject of previous studies. A study investigated the effect of different light intensities (300, 150, or 20 lux), and found that the signal-to-noise ratio (SNR) decreased as increased duration and intensity of visible light exposure.[2] Another study investigated the duration of light exposure from 0 to 98 seconds (control: 130 seconds) using a viewing box (1700 lux) as the light source and scored the images with five radiologists. The authors reported that the erasure of plates may require a time interval as small as 5 seconds, however, incomplete erasing did not cause significant loss of diagnostic image quality.[5]

In a study, the pre-exposed plates were exposed to visible light of different spectrums: "Cool white" and "Aquarium" fluorescent tubes and incandescent filament bulb lamps. Light exposure/erasing was performed at three different light intensities: 10 000 lux (up to 30 seconds), 600 lux (up to 60 seconds), and 20 lux (up to 300 seconds). The author reported that the dose-response of the PSP plates was linearly, however, the erasing process due to light exposure was not in a linear relationship with the product of light intensity and exposure time. Multiple electron energy levels decay process and high-order kinetics of PSPs were proposed to explain this, and the differences between various light sources were reported as minor.[10] This statement may be considered to explain the rapid and irregular signal loss seen in phosphor plates, especially in the first few minutes. In another study, pre-exposed PSP plates were placed in four different environments of white light, yellow light, natural ambient light (fixed to 150 lux), and dark room, for various times and then scanned. The authors reported that yellow light can cause more signal loss in some conditions.[9] The results of the present study are not suitable for comparison with these studies, where different light sources were used for different colors of light and kept constant during the experiment.

In the previous study, the experimental tool was used created to compare the effect of red, green, and blue colors, separately. Two different calibration methods were used (PWM and LUX), to ensure that the maximum light output of each color was conducted and to equalize the illumination on the surface based on the optic sensor readings. Findings of the previous study, in which only one of the colors was produced in each experiment, suggest that the green ambient light was safer than red and blue color, with the LUX calibration, in terms of signal loss.[11] The current study differs from the earlier experiments as the total delay and light output were the same, except the prosperities of light was modulated during each experiment. In the previous study, different colors were applied separately in each repetitive experiment, whereas in this present study, all colors were applied equally in each experiment. Moreover, the delay between x-ray exposure and scanning was standardized, whereas only the row of color administration and time intervals were changed. Therefore, even though the same tool was used, however, the questions investigated in the two separate studies are completely independent of each other.

In this study, the findings of Round and Cycle experiments can be evaluated individually. In Round experiments, the initial exposure to blue light resulted in the least signal loss in the final image. The administration of the red color in the first row affected the image quality more than the green color, based on the SNR. This may be related to the red color of the laser used to scan PSP plates.[2,10] The direct proportionality between time interval and signal loss in Cycle experiments can perhaps be attributed to the effect of the time it takes until the light output power reaches maximum efficiency at very low time intervals. It should also be considered that the repeatability scores of moderate and poor might have an impact on the results.

Although the results of this study are not expected to be directly adapted to the clinic, it may contribute to the development of materials since it is an experiment on phosphor plaque artifacts that has not been done before. In addition, it was aimed to point out that the related systems, which are suggested to be used in ambient light owing to their broad dynamic range and restoration software, are adversely affected by the type and intensity of ambient lighting, and must be carefully processed until the scanning is completed.

The main limitations of the study include small sample size, use of a single brand of PSP system and the possibility of using advanced electronic circuit elements. This work could be improved in terms of repeatability and reproducibility by developing a more autonomous device that operates in complete darkness and automated segmentation tools for image quality tests to increase standardization in repetitive experiments.

CONCLUSION

The results of this study suggest that there are minor differences in image quality tests if the sequence of colors is changed while keeping the scan delay and total light time constant. Further experiments with larger sample size and different PSP brands are encouraged to further investigate such variations.

Availability of Data and Materials: The data that support the findings of this study are available on request from the corresponding author.

Ethics Committee Approval: The study contains no human-related material and ethics committee approval is not required.

Informed Consent: The study contains no human-related material and informed consent is not required.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept/Design – H.A., K.O.; Supervision – K.O.; Materials – H.A., K.O.; Data Collection and/or Processing – H.A.; Analysis and/or Interpretation – H.A., K.O.; Literature Review/Writing – H.A.; Critical Review – K.O.

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Supplementary Table 1. Gray Values Obtained by Combining Three ROIs Selected in the Respective Image Areas

Experiment		Zone	Mean	Std. Dev.	Minimum	Maximum
Round	1	Soft-tissue	124.65	1.69	116	134
	1	Bone	246.60	0.94	243	251
	2	Bone	246.47	0.85	242	251
	2	Soft-tissue	125.40	1.92	114	153
	3	Soft-tissue	121.25	1.69	111	131
	3	Bone	246.64	0.96	243	252
	4	Bone	246.30	0.90	243	250
	4	Soft-tissue	124.74	1.69	111	136
	5	Bone	246.54	1.30	242	250
	5	Soft-tissue	125.24	1.67	114	134
	6	Soft-tissue	122.61	1.66	114	132
	6	Bone	246.48	0.91	242	250
Cycle	7	Soft-tissue	124.69	1.74	113	144
	7	Bone	247.05	0.94	243	254
	8	Soft-tissue	124.01	1.75	113	144
	8	Bone	246.58	1.00	242	250
	9	Soft-tissue	126.07	1.69	115	139
	9	Bone	246.96	1.07	242	251
	10	Bone	246.66	0.88	242	252
	10	Soft-tissue	130.01	1.63	118	140
	11	Bone	246.70	0.88	243	250
	11	Soft-tissue	128.43	1.60	120	137
	12	Bone	246.69	0.93	242	253
	12	Soft-tissue	128.30	1.59	117	139