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Scientific Article

Sensitivity Response Analysis of Optical Surface Monitoring Systems Using the Fitzpatrick Scale: A Phantom Study

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Purpose: Optical surface monitoring systems (OSMSs) have gained substantial attention in modern radiation therapy, specifically in the context of surface guided radiation therapy, which offers real-time patient surface monitoring, ensuring accurate and effective radiation therapy treatments. The aim of this article is to evaluate the OSMS camera sensitivity toward different skin tones, categorized according to the Fitzpatrick scale, a universal classification of human skin tones, using a phantom.

Methods and Materials: This study used Catalyst and Sentinel OSMSs (C-RAD). The Alderson RANDO female pelvis phantom, located at the isocenter in computed tomography simulation and treatment rooms, served as an experimental subject. Eighteen skin tone−matching cotton cloths, selected on the basis of Von Luschan chromatic and Fitzpatrick scales, were wrapped around the phantom for sensitivity evaluation. Camera sensitivity was optimized by adjusting threshold/gain (100%-600%) and integration time during individual scans in both rooms. Temporal response analysis spanned 2 months, with 16 measurements for each OSMS taken in varying light conditions.

Results: The OSMSs successfully detected the surface of cloth-covered phantoms with varying mean (SD) integration times: 550 (34) to 950 (43) μs for the Sentinel system and 2300 (71) to 12,000 (400) μs for the Catalyst system. The sensitivity parameters differed for each skin tone, with lighter skin requiring shorter integration times and gain/threshold values. Darker skin tones necessitated higher parameters for optimal surface images. The reliability of the systems declined with excessive parameters, leading to noise and compromised accuracy in patient positioning.

Conclusions: Optimized sensitivity parameters tailored to individual skin tones are crucial for effective real-time patient surface monitoring in radiation therapy, as variations in skin color can affect the accuracy of measurements. The precision of skin color measurements in OSMSs relies on carefully adjusting camera sensitivity parameters. However, careful consideration is essential, as larger values are required for darker skin tones, compromising reliability. This suggests the need for exploring alternative image guidance methods for patients with darker skin tones.

Introduction

Optical surface imaging technique uses a particular range of wavelengths (generally visible light with a wavelength of 400-700 nm) to scan the surface of the object and capture the reflected light through optical scanners and charged

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couple devices to reconstruct the 3-dimensional (3D) surface of the object using photogrammetry techniques.[1] The use of the optical surface monitoring system (OSMS) technique in radiation therapy recently gained wide interest because of its advantages of real-time monitoring of the patient's surface and the capabilities of triggering the radiation therapy beam as per the signal obtained from the patient's motion during the treatment.[2-4] This technique in radiation therapy is called surface guided radiation therapy and offers several benefits, including improved patient setup and positioning, real-time monitoring, effective motion management, elimination of uncomfortable immobilization devices, noninvasive procedures, and enhanced patient safety. It plays a crucial role by ensuring precise and safe radiation delivery to target areas while minimizing exposure to surrounding healthy tissues. Because of this, there is an improved treatment outcome and reduced side effects for patients undergoing radiation therapy. Bert et al[5] found in their study that these systems can track patient motion and capture real-time surface data with good accuracy (quantity) and therefore provide valuable information for radiation therapists to make necessary adjustments during treatment sessions.

Optical light has unique characteristics of interactions (eg, absorbance, reflectance, and scattering) with the skin and underlying tissues, which affect the quality of the 3D surface reconstruction through the scanners.[6-8] Ballowitz and Avery[9] found that for every skin tone/color, optical camera sensitivity is different because of the different underlying tissues in the skin, that is, melanin, blood vessels, collagen, and chromophores, among others

Melanin, which is responsible for skin color, has a maximum absorption of 250 to 1200 nm wavelengths at varying frequencies of optical light. Blood vessels containing deoxygenated blood showed a high level of absorbance of light, having a wavelength above 320 nm compared with oxygenated blood. Similarly, collagen and chromophores of the epidermis layer of the skin affect the scattering of light and lead to fewer details and irregularities in visible areas.[6,10] Anderson and Parrish[11] also found in their study that the optical information detected by OSMS cameras can be affected by the patient's skin color; they found that the optical reflectance is lesser in darker skin tones than in lighter skin tones.

Currently, there are various commercially available OSMSs being used in radiation therapy. Some well-known systems are (1) Catalyst and Sentinel systems by C-RAD, (2) AlignRT by Vision RT, (3) Real-Time Position Management System by Varian Medical Systems, and (4) IDENTIFY by Varian Medical Systems. These systems are designed to reduce position errors and provide real-time feedback during radiation therapy by providing a surface image of the patient.[1]

Stieler et al[3] performed a detailed study based on different shapes and colors using the Catalyst single-camera system and concluded that the camera was able to detect light-colored objects more clearly than dark-colored objects. Mancosu et al[12] also found similar results using different color phantoms with EDGE linear accelerator (Varian Medical Systems) OSMS. Peng et al[13] performed a similar study but used Pantone STG-201 (Pantone Skin Tone Guide) color cards attached to a cylindrical phantom on Catalyst HD. Milewski et al[14] performed an experimental study with Catalyst HD OSMS on 3D-printed objects of various shapes (convex, concave, cylindrical, etc.) and 6 colors varying from red to black to account for the effect of skin color and contour on OSMS. They concluded that the OSMS cannot detect steeper angles and dark colors even with the highest sensitivity parameters.

In the above-mentioned studies, the impact of the different shapes and colors has been studied, but none of the studies used Von Luschan chromatic scale, which is considered the universal scale of human skin tone classification.[15] Further, the Fitzpatrick scale categorizes the 36 shades of Von Luschan chromatic scale into 6 groups, as shown in Table 1. The aim of the present study was to evaluate the camera sensitivity with different skin color tones taken from the Fitzpatrick scale using OSMS. This study investigated the sensitivity of the optical camera and scanner in terms of threshold/gain values and integration time using the Fitzpatrick scale. The present study further recommends the optimized values of camera settings for different skin tones.

Methods and Materials

The experiments involved acquiring camera sensitivity parameters for various skin colors with the use of different colored cloths (chosen with reference to Von Luschan chromatic scale) used on an Alderson RANDO female pelvis phantom (Alderson Research Laboratories) scanned with Catalyst and Sentinel systems. The measurements were taken within 2 months.

Equipment

OSMS

The OSMS is a video-based system that uses optical imaging techniques to register the reference surfaces of a

Table 1 The 36 categories of the Von Luschan scale in relation to the 6 categories of the Fitzpatrick scale

Fitzpatrick type	Von Luschan scale	Skin color
I	0-6	Very light or cream
II	7-13	Light yellow
III	14-20	Yellow
IV	21-27	Dark yellow
V	28-34	Brown
VI	35-36	Black

patient taken at the time of simulation or before the treatment delivery to a real-time 3D surface model.[16] The system consists of ceiling-mounted camera pods, a light projector, and an image sensor. The system then reconstructs the 3D surface by photogrammetry.

Simulation room (Sentinel system)

C-RAD's Sentinel system (C-Rad, Uppsala, Sweden) was used as an OSMS system in the computed tomography (CT) simulation room (Fig. 1). The surface scanning unit was mounted on the ceiling of the CT scan room with a CT scanner (Philips Brilliance Big Bore RT CT), which was used to project a laser on the patient's surface and then detect the reflected pattern from the patient's surface to produce a 3D image of the patient through triangulation technique.

Treatment room (Catalyst system)

C-RAD's Catalyst system (C-Rad, Uppsala, Sweden) was used as an OSMS system in the treatment room (Fig. 1). The surface scanning unit was mounted on the ceiling with the VERSA HD Medical Linear Accelerator (Elekta), which was used to project light patterns at multiple wavelengths on the patient's surface and then detect the reflected pattern to produce a 3D image of the patient through triangulation technique.

Phantom setting

The Alderson RANDO female pelvis phantom (Fig. 2) was used in this study for the simulation of treatment planning for patients in a CT simulator and radiation dose delivery in treatment rooms. To avoid the use of steeper and vertically angled surface detection by OSMSs, as suggested by Milewski et al,[14] the pelvic phantom was chosen for this study. The phantom was positioned on the couch at the isocenter simultaneously in the CT scan room (with the Sentinel system) and the treatment room (with the Catalyst system).

Skin tone measurement using OSMS

Out of 36 colors of Von Luschan chromatic scale for universal human skin tone, 18 different colored cotton cloth pieces were chosen (Fig. 3). The cotton cloths of skin tone numbers 4, 5, and 6 in category I of Fitzpatrick

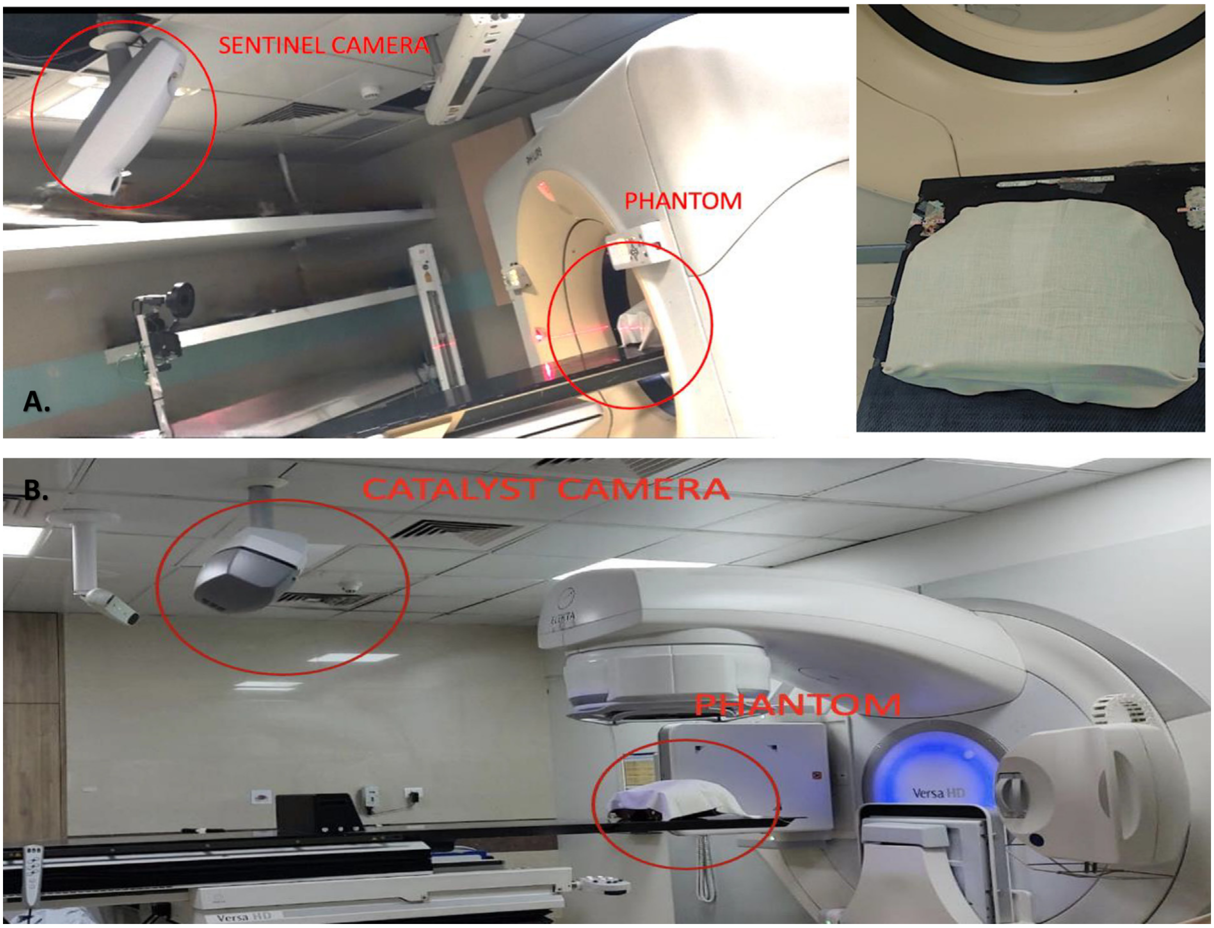

Figure 1 Schematic optical surface monitoring systems for the (A) Sentinel system and (B) Catalyst system setup with the phantom in the computed tomography simulation room and VERSA treatment room.

Figure 2 Alderson RANDO female pelvic phantom.

scale; 8, 11, and 13 in category II of Fitzpatrick scale; 14, 16, and 18 in category III of Fitzpatrick scale; 21, 23, and 26 in category IV of Fitzpatrick scale; 28, 29, 30, and 32 in category V of Fitzpatrick scale; and 35 and 36 in category VI of Fitzpatrick scale were simulated in this study. These colored cloths were selected randomly based on their availability and matching with different skin tones of Von Luschan chromatic scale. Cotton cloth was chosen in view of its excellent interaction with light in a similar way as human skin, that is, it offers a good balance between

	4	I		14	III		V	28
	5	I		16	III		V	29
	6	I		18	III		V	30
	8	II		21	IV		V	32
	11	II		23	IV		VI	35
	13	II		26	IV		VI	36

Figure 3 Eighteen different colored cotton cloth pieces used as a reference of skin tone according to Von Luschan chromatic scale.

reflection and absorption of light compared with other cloth types, namely nylon, polyester, silk, spandex, etc. Additionally, it is readily accessible and more cost-effective compared with the use of actual human skin tissues. Cotton cloth is easily adaptable to match various skin tones and conform to the body's shape. While it may not be as precise as real human skin tissue, it serves well for simulation. The selected cloth samples served as the reference for different skin tones for evaluation of the sensitivity response of OSMSs to these variations in skin colors. Each piece of colored cloth was wrapped around the phantom one by one and positioned at the machine isocenter in both the OSMSs for the subsequent data recording process.

Optimization of camera sensitivity

Initially, each cloth, when wrapped around the phantom, underwent individual scans in the CT simulation room with the Sentinel system. During these scans, the system's sensitivity to detect the surface of the cloth-covered phantom was evaluated and optimized by adjusting the 2 available camera parameters: threshold/imaging gain (100%-600%) and integration time. The process was repeated for each colored cloth with variations in these parameters. Similarly, the process was repeated using the Catalyst system in the treatment delivery room. With each system, 16 observations were obtained at each threshold/gain and integration time for each colored surface.

Temporal response of OSMS

The OSMS surface reconstruction might be influenced by variations in the lighting conditions of the CT simulation/treatment room and time. For this, the data collection was conducted across different time frames (for 2 months) under both well-lit and dark room conditions. A total of 16 repeated measurements were taken between 8:00 AM and 8:00 PM in both lighted and dark room environments, both in the CT simulation room and the treatment room. For all the colors, the variations in threshold/imaging gain and integration time were recorded, and mean and SD values were calculated for each category of the Fitzpatrick scale.

Statistical analysis

All the threshold/gain values and maximum integration times for reliable surface image detection for 16 days (observations) and 18 different skin tones captured by both OSMSs were recorded and plotted in a Microsoft Excel spreadsheet. The mean and SD of maximum integration time were calculated for each threshold/gain value. Subsequently, these 18 colors were categorized into 6 categories of the Fitzpatrick scale. The mean and SD values for these 6 categories were calculated from the data obtained from the 18 colors.

Results

Results presented in Figures 4, 5a and b demonstrate that the single-camera OSMS system successfully detected the surface of different coloured cloths covering the phantom. The systems achieved this with the lowest values of integration time ranging from 550 (34) to 950 (43) μs for the Sentinel system and 2300 (71) to 12000 (400) μs for the Catalyst system.

Camera sensitivity in the Sentinel System varied with threshold/gain and integration time. Figure 6a shows the variation of integration time for reliable skin surface detection in the Sentinel system for all skin tones (in reference to Von Luschan's chromatic scale). The mean of maximum integration time (SD) ranged from 550 (34) to 17,500 (376) μs for threshold/gain values from 200% to 600% with a step size of 100% for category I skin tone. Similarly, the integration time ranged from 600 (38) to 19,000 (585) μs for category II skin tone, 700 (43) to 20,000 (547) μs for category III skin tone, 750 (38) to 20500 (602) μs for category IV skin tone, 850 (36) to 21000 (395) μs for category V skin tone, and 950 (44) to 22500 (323) μs for category VI skin tone of Fitzpatrick scale at gain/threshold 200% to 600% with a step size of 100%.

For the Catalyst System, increasing the gain/threshold led to a decrease in integration time. Figure 6b shows that the Catalyst system performed well for all the skin tones (in reference to Von Luschan's chromatic scale) but like the Sentinel system, it also requires a different range of parameters for each skin tone. This range shows that the average maximum integration time (standard deviation) ranges from 2300(71) to 4100(79) μs for threshold/gain values from 100% to 400 % gain with a step size of 100% for the detection of category I skin tone. Similarly, the mean of maximum integration time (standard deviation) ranges from 2600 (56) to 4500 (77) μs for category II skin tone, 3000 (135) to 6000 (364) μs for category III skin tone, 4400 (107) to 7100 (58) μs for category IV skin tone, 8000 (306) to 15000 (444) μs for category V skin tone, and 12000 (400) to 20000 (486) μs for category VI of Fitzpatrick scale at gain/threshold 100% to 400 % with a step size of 100%.

Furthermore, the data analysis demonstrated a linear optimisation for the Sentinel system and a polynomial optimisation for the Catalyst system, as depicted in Figure 7. The Sentinel system followed a linear relationship ($y = 80x + 450$) for the Fitzpatrick scale with a strong correlation ($R^2 = 0.85$), whereas the Catalyst system

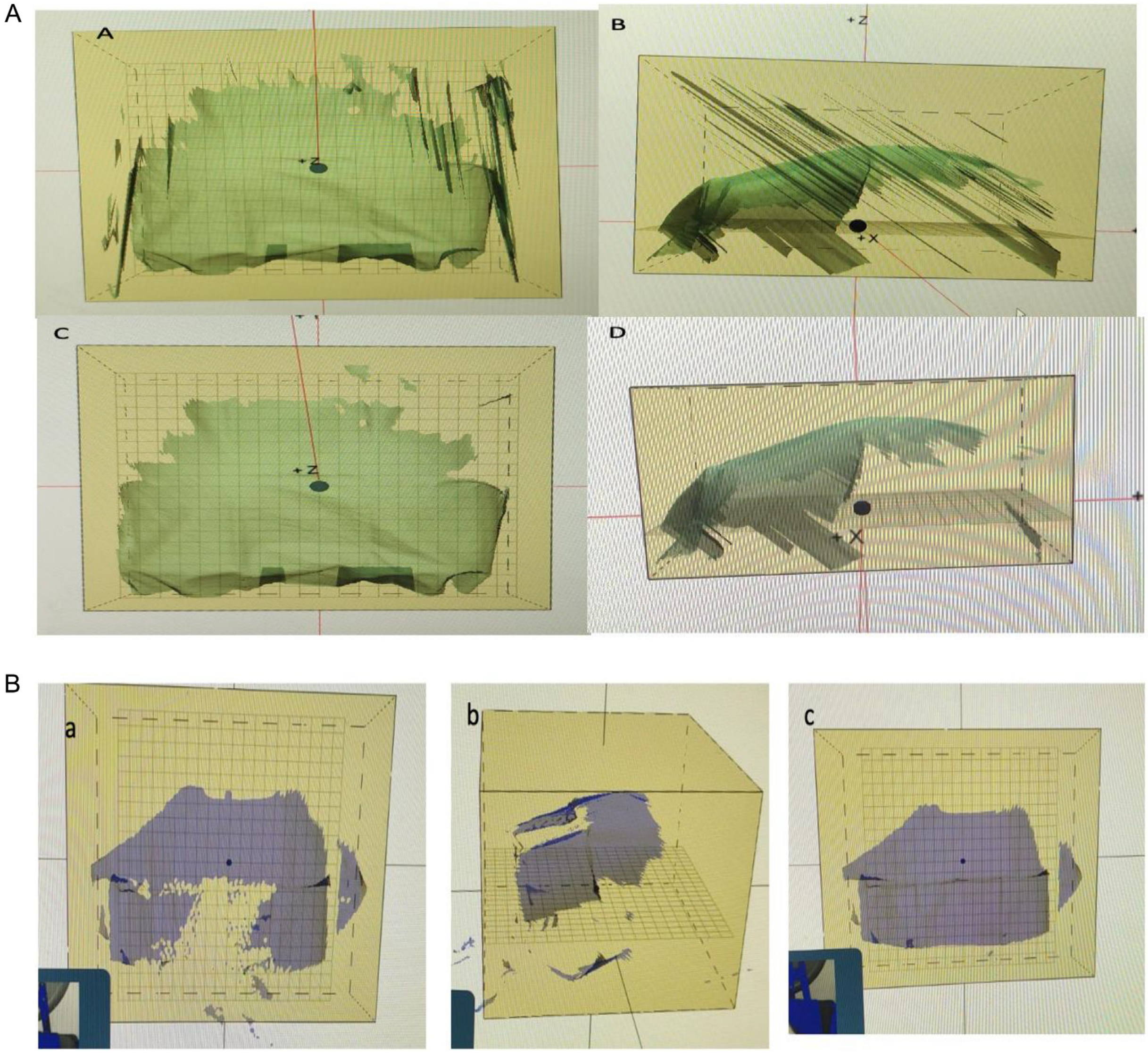

Figure 4 The scanned surface of the cloth-covered phantom at different parameters in the Sentinel system. (A and B) Noise production in the scanned surface due to high values of threshold and integration time. (C and D) Optimized surface after correcting threshold and integration time. The scanned surface of the cloth-covered phantom at different parameters in the Catalyst system. (a and b) Noise production in the scanned surface due to arbitrarily chosen values of threshold and integration time. (c) Optimized surface after correcting threshold and integration time.

exhibited a polynomial relationship ($y = 550x^2 - 2000x + 3800$) with a moderate correlation ($R^2 = 0.68$).

The repeated measurements taken for two months showed consistent threshold/gain values and integration times across different lighting conditions (well-lit and dark room environments) revealing consistent performance of the OSMS systems.

Discussion

The results suggest that both the Sentinel and Catalyst OSMS systems can detect surfaces across a range of skin tones, with adjustments in threshold/gain and integration time. Similar outcomes were observed in the studies conducted by Stieler et al.[3] Click or tap here to enter text. who focused on using a single-camera OSMS system (Catalyst) to study different shapes of pink and black surfaces which showed that the light coloured objects were detected more clearly than dark coloured objects, and by Milewski et al.[14] Click or tap here to enter text. who employed a three-camera OSMS system (Catalyst HD) for six different colours (light pink to dark grey) and shapes (convex, concave, cylindrical etc.) to conclude that OSMS cannot detect steeper angles and dark colours even with highest sensitivity parameters and by Haiyan Peng et al.[13] who used Catalyst HD system on different shades of red and yellow from Pantone STG-20 colour cards over

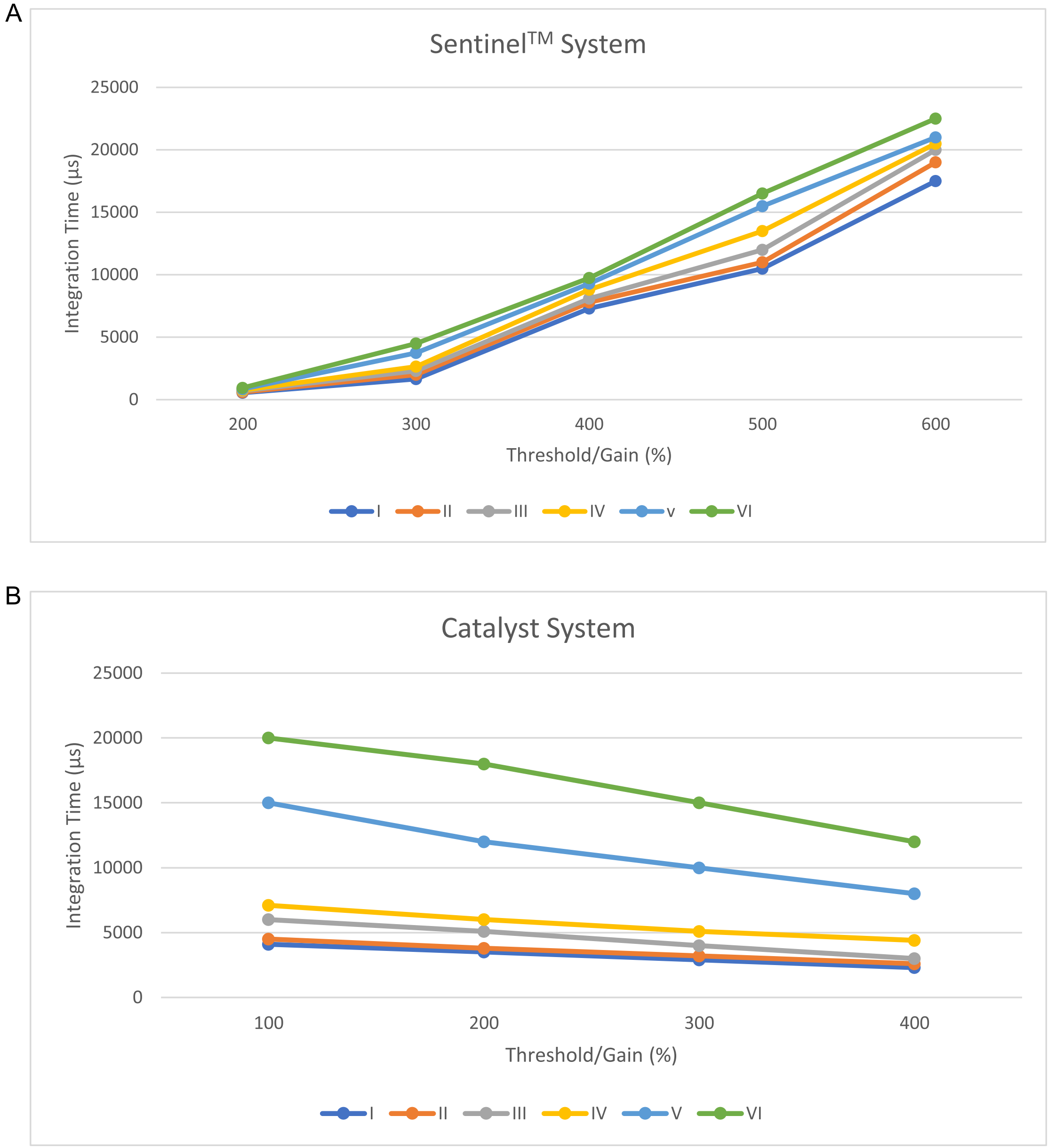

Figure 5 (A) Camera sensitivity parameter results for the colored cloth-covered phantom in the Sentinel system with the Fitzpatrick scale. (B) Camera sensitivity parameter results for the colored cloth-covered phantom in the Catalyst system with the Fitzpatrick scale.

cylindrical phantom suggesting darker skin colours require higher gain and integration time for effective imaging.

Camera sensitivity is generally determined by two parameters in commercial setup namely threshold/gain and integration time. Threshold and integration time are two key parameters that affect the camera sensitivity and, subsequently, the quality and reliability of skin colour measurements. The threshold, also known as the threshold level or imaging gain, sets the minimum amount of light or signal required for the camera to detect colour variation on the skin surface to capture the image. On the other hand, integration time, also known as exposure time, controls the duration for which the camera's sensor collects light and colour information. These parameters determine the camera's ability to accurately capture and measure subtle colour variations on the skin surface.

In the Sentinel System, as the gain/threshold is raised, the integration time also increases, thereby enhancing the camera sensitivity and producing optimal surface images. However, beyond certain parameters, the system's reliability declines due to the introduction of noise in the

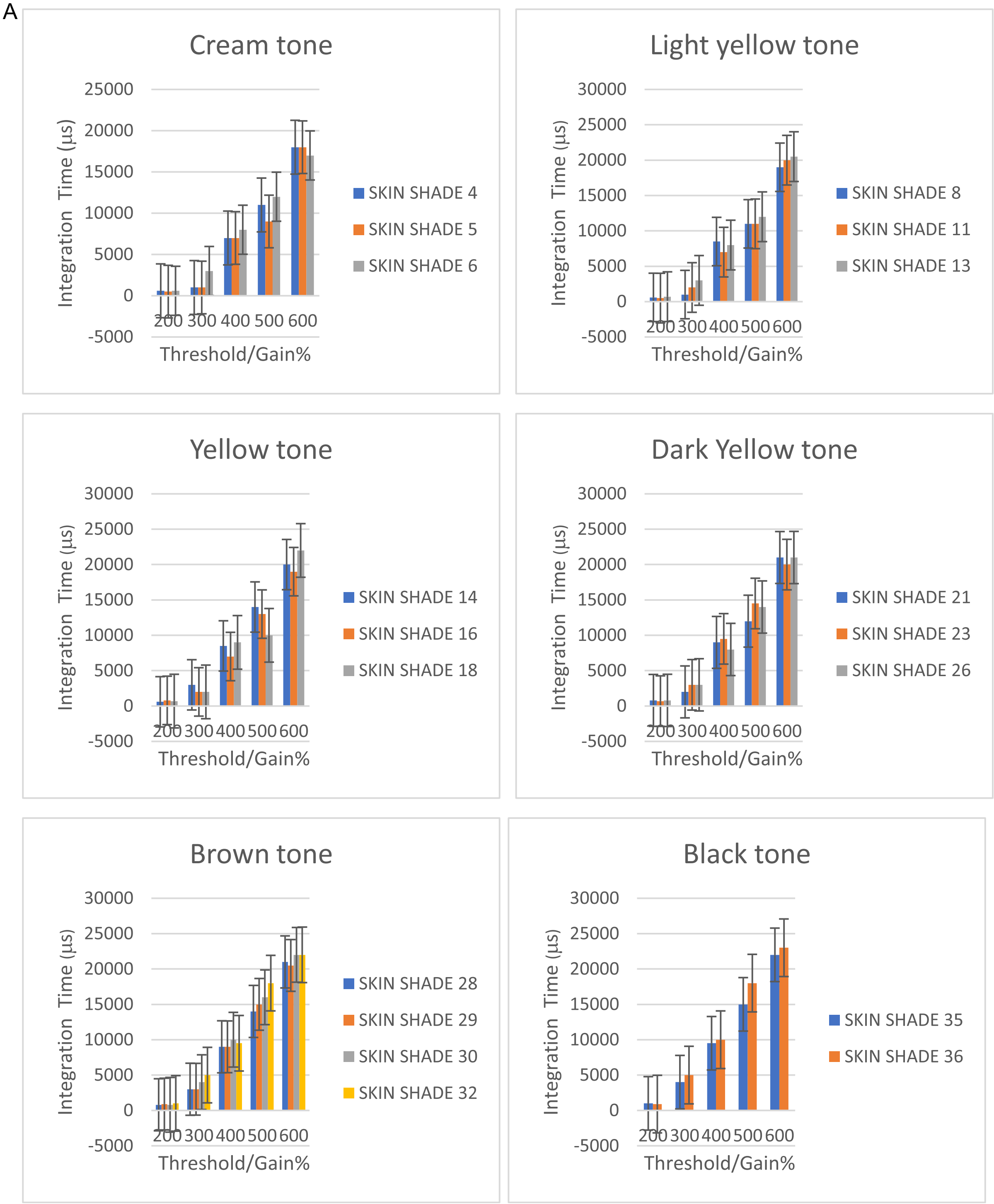

Figure 6 (A) Camera sensitivity parameters for the colored cloth-covered phantom in the Sentinel system with 18 skin tones of Von Luschan chromatic scale. (B) Camera sensitivity parameters for the colored cloth-covered phantom in the Catalyst system with 18 skin tones of Von Luschan chromatic scale.

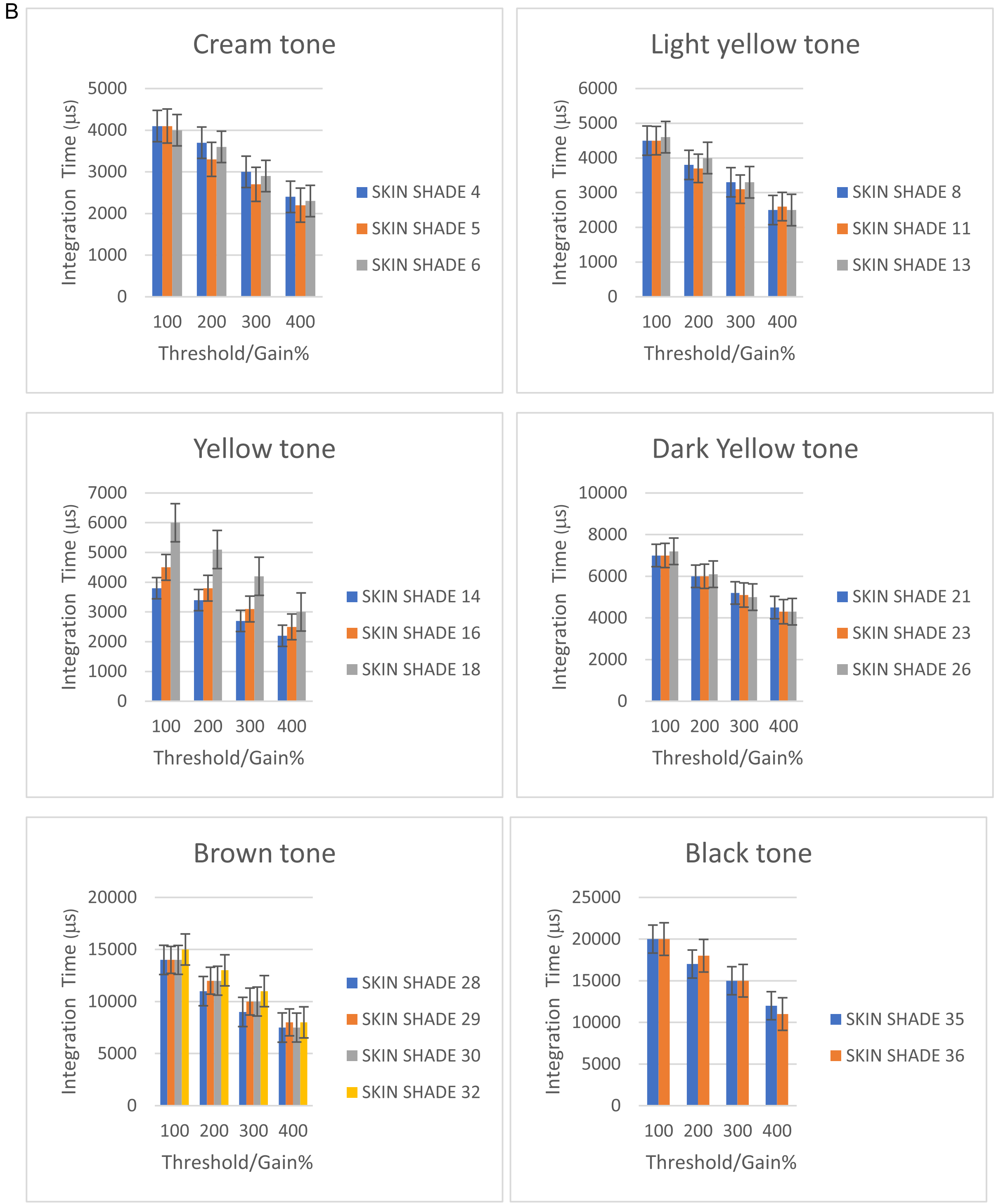

Figure 6 **Continued.**

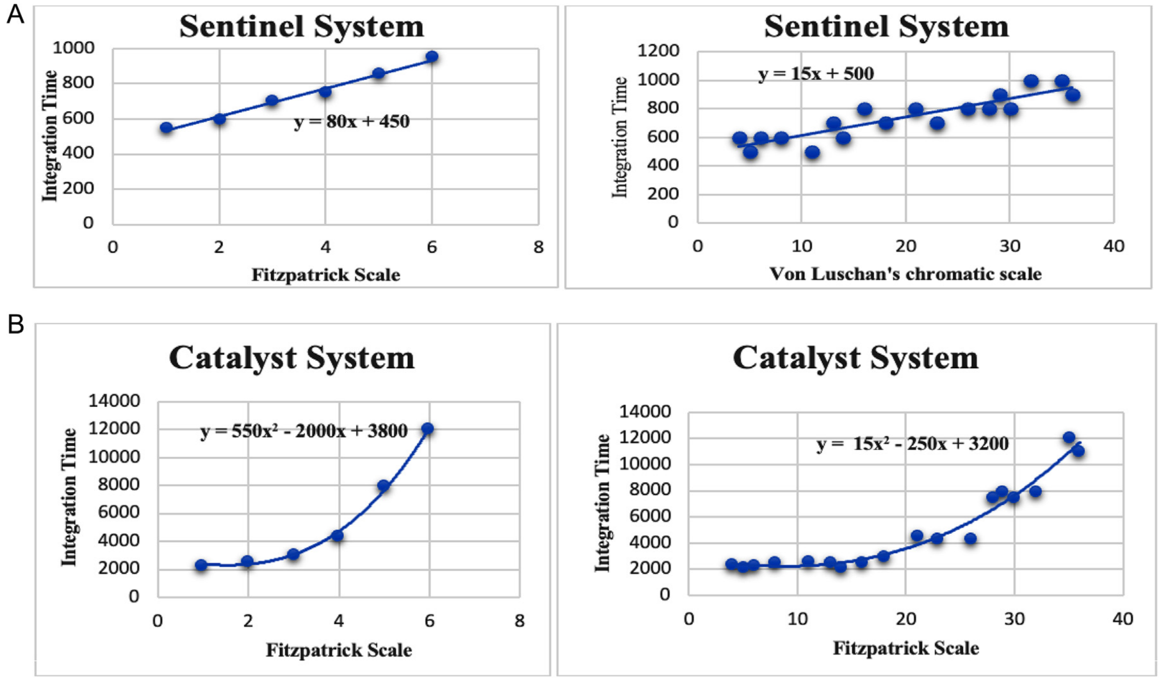

Figure 7 (A) Analysis of the Sentinel system showing a linear relationship represented by equation $y = 80x + 450$ for the Fitzpatrick scale and $y = 15x + 500$ for Von Luschan chromatic scale. This linear model accurately captures the increasing trend in integration time as the Fitzpatrick scale category rises, with an SD of 0.02. The correlation coefficient ($R = 0.92$) indicates a strong fit of the model to the data, explaining 92% of the variance in integration time based on the Fitzpatrick scale ($R^2 = 0.85$). (B) Analysis of the Catalyst system exhibits a polynomial trend represented by equation $y = 550x^2 - 2000x + 3800$ for the Fitzpatrick scale and $y = 15x^2 - 250x + 3200$ for Von Luschan chromatic scale. This polynomial model accurately captures the increasing trend in integration time as the Fitzpatrick scale category rises, with an SD of 0.12. The correlation coefficient ($R = 0.78$) indicates a good fit of the polynomial model to the data, explaining 78% of the variance in integration time based on the Fitzpatrick scale ($R^2 = 0.61$).

surface images caused by over-exposure. This over-exposure leads to insensitivity towards surface details (resulting in extra elements in the surface image). Consequently, the accuracy of the system in patient positioning is compromised.

In the Catalyst System, increasing the gain/threshold leads to a decrease in the integration time for producing the optimal surface image. However, beyond certain parameters, the system's reliability diminishes due to the production of noise in the surface images caused by over-exposure to the surface. This over-exposure renders the system less sensitive to surface details (leading to a loss of surface image) and, hence can compromise the accuracy of the system in the positioning of the patient.

Both systems showed increasing trends in integration time as the Fitzpatrick scale increases, albeit with different mathematical representations. These findings provide valuable insights into the behaviour of the camera systems with respect to varying Fitzpatrick scale categories. These results showed that when lighter skin shades were there, the OSMS systems required the shortest threshold/gain and integration time to produce a desired surface image. But with darker skin shades the parameters increase.

The Sentinel system demonstrated linear optimization in integration time with increasing Fitzpatrick scale categories, ensuring consistent and predictable sensitivity to skin tone variations. In contrast, the Catalyst system exhibited polynomial optimization, requiring a broader range of integration time settings for accurate detection, particularly for darker skin tones.

Despite variations in illumination, the systems demonstrated stability in capturing surface images over time. The consistency of the systems across various lighting conditions suggests that the OSMS systems are robust to changes in lighting conditions, ensuring reliable surface reconstruction regardless of environmental factors. This finding is crucial for clinical applications, where lighting conditions can vary. Overall, these results offer valuable insights into the optimisation of OSMS systems for various skin tones, pointing towards future improvements in system calibration and sensitivity for darker skin tones.

Conclusions

OSMS is helpful in assisting patient setup and motion management during radiation therapy treatment. The pattern of reflection of colored light and laser, depending upon the patient's surface color (skin tone), helps us optimize the OSMS with its inherent advantages compared with CT and x-ray simulation. However, this process, when used in clinical situations, has its own shortcomings, that is, camera sensitivity, variation in skin tone, skin contour, type of immobilization used, and reflective or colored markers used on the patient's surface.

In this article, the sensitivity parameters of threshold gain and lowest integration time for different skin tones were manually chosen on the basis of the aforementioned graphical representation of threshold gain and lowest integration time with respect to Fitzpatrick and Von Luschan chromatic scales derived from the different colored cloths in reference to the Fitzpatrick scale. These preliminary results showed a relationship between skin tone and imaging parameters, emphasizing the need for patients' skin tone−specific adjustments to optimize the OSMS for accurate surface reconstruction in radiation therapy treatment. In patients with darker skin tones, higher parameters are needed for optimal surface images.

The reliability of the systems declined with larger parameters when used for darker skin tones, leading to noise and compromised accuracy in patient positioning. Therefore, other conventional image guidance techniques may be preferred in such a group of patients.

Disclosures

This study was performed as a technical study by collecting phantom data in the Department of Radiotherapy and Clinical Oncology, for which no financial or any other technical help has been taken from any organization. The authors involved in the study have conducted this work themselves. There is no conflict of interest involved.

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