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ORIGINAL RESEARCH

Enhancing the Identification and Analysis of Bruises through the Application of Multispectral Imaging Techniques

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ABSTRACT

Background: The identification and imaging of sub-dermal hematomas, commonly known as bruises, are essential in instances of suspected physical abuse, as they enable the evaluation of testimonies given by both the victim and the alleged perpetrator. Modern methodologies primarily rely on visual inspection, frequently augmented by the use of alternative light sources (ALS). In an ideal scenario, alternative light sources (ALS) enhance visual contrast by exploiting variations in light absorption that arise due to the formation and clearance of chromophores within the bruise. In practical applications, however, the achievable contrast is often limited by light scattering; the short-wavelength segment of the spectrum, encompassing the majority of chromophore-specific absorption peaks, is also significantly affected by scattering from dermal tissue. As a result, this constraint limits the achievable penetration depths, thus obscuring deeper bruises. The process of bruise healing introduces additional complexity to the enhancement of contrast in Advanced Light Source (ALS) imaging. This is due to the fact that both diffusion and enzymatic activity alter the concentrations of chromophores, as well as their spatial distribution within the tissue. In order to address these substantial limitations, a multi-spectral camera, which possesses the capability to concurrently capture eight different wavelengths, is employed. This approach is coupled with observer-based scoring and a contrast-quantification algorithm to determine the most efficacious wavelength for the detection and characterization of bruises over time. **Result:** Our findings indicate that (i) the contrast of bruises exhibits a marked increase at wavelengths of 480 nm, 620 nm, and 850 nm, and (ii) the wavelength corresponding to the optimal contrast progressively transitions from 850 nm to a range between 578 nm and 480 nm as the bruise progresses through the healing process.

Keywords: Bruises, Multispectral Imaging Techniques, Chromophores, Hematomas, Advanced Light Source

INTRODUCTION

A primary objective in forensic investigations is the identification and localized determination of evidence. In the absence of trace detection, it will not be reported, thus potentially omitting crucial information. This principle is applicable in forensic medicine as well: the accurate documentation and characterization of injuries is contingent upon their detection. The process of detection assumes heightened significance in instances where the individual sustaining injuries is unable to contribute to the documentation process through verbal testimony, as in cases involving young children, individuals who are unconscious, or those who are deceased.[1,2] As a result, the detection and characterization (for example, in terms of age, size, or shape) of occult injuries are essential for the accurate triaging of living patients and for reconstructing the cause and manner of death in deceased individuals.[3–6] Occult injuries are prevalent in instances of blunt force trauma, wherein the damage predominantly manifests internally, often presenting as subcutaneous hemorrhage (i. e. , rupture of blood vessels followed by blood extravasation, typically resulting in an interstitial blood pool).[7] Such injuries, referred to as hematomas, contusions, or bruises, might not be visibly apparent to the unaided eye in the absence of

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lesions or lacerations on the tissue surface.[8] Nonetheless, contusions may manifest over time due to molecular diffusion causing the dissemination of the blood pool into more superficial tissue strata. In addition to affecting visibility, molecular processes also play a role in altering the perceived coloration of contusions. An inflammatory response triggered by the hemorrhagic event initially breaks down hemoglobin and oxyhemoglobin, which are the primary components of erythrocytes, into biliverdin. Subsequently, biliverdin undergoes reduction to form bilirubin. These reactions typically present as a reddish/purplish, greenish, and yellowish discoloration of the skin, respectively.[9] The identification of these pathophysiological alterations for the purpose of locating concealed injuries requires observable distinctions, specifically contrast, between the injured area and the adjacent undamaged tissue. A straightforward and non-invasive method that is particularly appropriate for generating or augmenting the necessary visual contrast involves the utilization of alternative light sources (ALS). The integration of these narrow-band light sources with suitable filters facilitates the visualization of the intrinsic light-absorbing or fluorescence properties of a material. By leveraging the variations in these properties, it is possible to distinguish latent and hidden traces from their surrounding materials. [10–14] Accordingly, several researchers have explored the application of Alternative Light Sources (ALS) for the non-contact detection and characterization of bruises. [15–24] Randomized controlled trials have been undertaken to assess the enhancement in bruise detection when employing ALS within the visible and long ultraviolet spectral ranges compared to white light. [24] The employment of ALS has been found to significantly improve bruise detection, especially in individuals with darker skin tones.[25] The results of this study indicate that ALS potentially contributes significantly to the improvement of forensic injury documentation. Moreover, recent comparative studies of the effectiveness of alternative light source (ALS) technology in bruise detection, in contrast with conventional white light, have demonstrated superior performance of ALS in bruise assessments. [26] Additionally, the application of deep learning techniques has been investigated in the context of bruise dating, wherein ALS within both the visible and ultraviolet spectra have been assessed for their efficacy in bruise detection. [27] Although the majority of these studies have yielded promising results, the generalization of their findings presents ongoing challenges. As a result, the absence of standardization currently impedes the application of ALS-based bruise detection and characterization within forensic practice. The primary challenges in formulating comprehensive guidelines for ALS-based bruise detection reside at the confluence of intricate light-transport phenomena and the dynamically changing characteristics of the specimen. Theoretically, the optimal contrast between a bruise and the adjacent healthy tissue is attained at wavelengths where there is a maximal disparity in their respective light-absorbing properties. In practical applications, the attainable contrast at this particular wavelength is frequently constrained by the scattering of light. This limitation arises because the wavelength region encompassing the majority of pertinent absorption peaks is subject to significant scattering by dermal tissue. Consequently, this restricts the extent to which light at those specific wavelengths can penetrate the tissue, thereby effectively concealing bruises located deep beneath the surface. To attain optimal visual contrast, these competing optical phenomena must be adequately balanced. The interaction between two simultaneous molecular processes introduces an additional layer of complexity: (i) the inflammatory response, which alters the light-absorbing molecules (chromophores), and (ii) molecular diffusion and lymphatic drainage, which modify their spatial distribution. [29,31,32] This interaction results in the optimal wavelength becoming a dynamic variable, contingent upon time. Specifically, the chemical transformations of the chromophores modify the wavelength at which their absorption properties differ maximally from the adjacent undamaged tissue, whereas alterations in the spatial distribution (i. e. , depth) of the chromophores affect the wavelength that optimizes both penetration depth and contrast. In conclusion, melanin—the compound responsible for skin pigmentation—exhibits strong absorption properties in the wavelength range of 400 nm to 500 nm, which may obscure the detection of bilirubin, characterized by an absorption peak at approximately 420 nm. Consequently, the optimal wavelength for detection is contingent upon the level of skin pigmentation. Therefore, there exists a definitive requirement for a rigorous and extensive assessment to ascertain the optimal wavelength for the detection and characterization of bruises, contingent upon the age of the bruise. In the present study, we seek to address this requirement by quantifying the wavelength-dependent contrast of bruises as a function of time. In a methodical sequence, we acquire perfectly overlapping grayscale images of the identical bodily region at eight distinct light wavelengths, doing so at a rapid pace, with a total measurement time of less than 0. 5 seconds. In pursuit of this objective, we utilize a multispectral camera (Pixelteq Spectrocam Vis) to capture reflectance images of bruises at various time intervals (specifically at bruise ages of 6 hours, 24 hours, 48 hours, 96 hours, 168 hours, 336 hours, and 504 hours) and across 8 specific wavelengths (450 nm, 480 nm, 509 nm, 542 nm, 558 nm, 578 nm, 620 nm, and 850 nm, which align with the absorption peaks of pertinent chromophores, i. e. , photoreactive biomolecules linked to the physiological processes involved in bruising). The image contrast of these bruises is quantified through two methodologies: (i) observer-

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based scoring and (ii) the computation of a contrast-to-variability metric. [33] These approaches provide thorough subjective and objective metrics for evaluating the visibility of bruises at different wavelengths, relative to the age of the bruise, thus offering a comprehensive framework for enhancing the detection and characterization of bruises within forensic applications. In conclusion, we postulate that the wavelength achieving optimal bruise visibility is likely contingent upon the bruise's temporal progression. This dependence arises due to the dynamic changes in the local concentration of optically detectable biochemical species (chromophores) associated with bruise formation and the subsequent inflammatory response.

MATERIALS AND METHOD

Study Design

The present study is analytical prospective research.

Ethical Approval

The study's protocol was composed and evaluated in alignment with the ethical guidelines articulated in the Declaration of Helsinki, as established by the World Medical Association (WMA). Furthermore, it received approval from the Institutional Ethical Committee of Government Medical College, Jalaun (Orai), U.P., India. Prior to participation, informed consent in written form was obtained from each participant. All participants retained the ability to voluntarily withdraw from the study at any point in time.

Study Population

This investigation was conducted within the Department of Forensic Medicine and Toxicology at the Government Medical College, Jalaun (Orai), U.P., India. Total 100 participants enrolled in the study were healthy volunteers aged between 25 and 60 years. Individuals presenting with blood clotting disorders, those undergoing treatment with medication that alters blood clotting, or exhibiting skin disorders or lesions on the inner forearm were included for the study. Furthermore, individuals were excluded from participation if any bruise-like markings or anomalies were observed on the inner forearm in images captured prior to the application of blunt force impact. Upon obtaining informed consent, supplementary data pertaining to age, sex, levels of physical activity (categorized as none, low, medium, high, and very high), along with medication usage, were collected through a questionnaire.

Study Procedures

Upon obtaining informed consent and the completion of the questionnaire, a RGB photograph, representing a standard digital white light image (where RGB denotes the color channels of red, green, and blue utilized to create a traditional digital photograph), was captured. Concurrently, a multispectral assessment was conducted, comprising eight single-wavelength reflectance images. These images, being black and white, illustrated the quantity of light reflected by the skin at specific wavelengths. This procedure was performed to examine the forearm for any tissue anomalies or existing bruises. Subsequently, the midpoint of the flexor aspect of the participant's non-dominant forearm was positioned beneath a tube, elevated at a height of one meter, from which a 400-gram metal weight, characterized by rounded edges, was released unpredictably onto the anterior (flexor) surface of the forearm, resulting in an impact of blunt force. The dropped weight method was employed as it represents the most standardized approach for inducing bruising. The forearm was selected as the site for bruising due to its accessibility. For the study's cohort of 100 participants, the area potentially susceptible to bruising was systematically observed over a designated period. This was achieved by capturing a standard RGB photograph alongside a multispectral measurement at eight specific time intervals: 1 hour, 6 hours, 24 hours, 48 hours, 96 hours, 168 hours, 336 hours, and 504 hours subsequent to the blunt force impact. Individual measurement series were terminated in instances where, after duration of 7 days (168 hours), no bruise was observed either in the RGB photograph or within the multispectral data at the impact location. Two methodologies were employed to evaluate the added value of multispectral imaging in comparison to RGB imaging: visual inspection of the images and the application of a contrast metric. The selection of the wavelength bands was based on spectral characteristics of the chromophores found in developing bruises, as illustrated in figure no 1. For a comprehensive elucidation of the experimental setup, please consult Reference 17. In summary, images of the inner forearm were captured utilizing a Nikon D3 camera positioned within a standardized setting and illuminated by two photographic LED lamps. A multispectral imaging system was employed to capture reflectance images across eight predetermined wavelength bands: 450 nm (15 nm bandwidth), 480 nm (25 nm bandwidth), 509 nm (10 nm bandwidth), 542 nm (10 nm bandwidth), 558 nm (5 nm bandwidth), 578 nm (10 nm bandwidth), 620 nm (20 nm bandwidth), and 850 nm (50 nm bandwidth). The images were sequentially documented by rotating the camera's high-speed filter wheel, which operates on the order of milliseconds and consists of the eight specified optical band-pass filters. This methodology diverges from prior research examining the application of ALS in multiple aspects. Initially, the provision for high-speed data acquisition is especially advantageous in mitigating the impact of subject movement on the measurement sequence while simultaneously decreasing the total duration required for measurement. This attribute is particularly beneficial when conducting examinations on bruises in pediatric subjects. Secondly, it guarantees spatial

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co-registration (near-perfect overlap) among the images at various wavelengths, thereby enhancing the precision of the analysis. Thirdly, the employment of narrow-band band-pass filters significantly augments the specificity in detecting bruise-associated chromophores, which are biochemical byproducts.

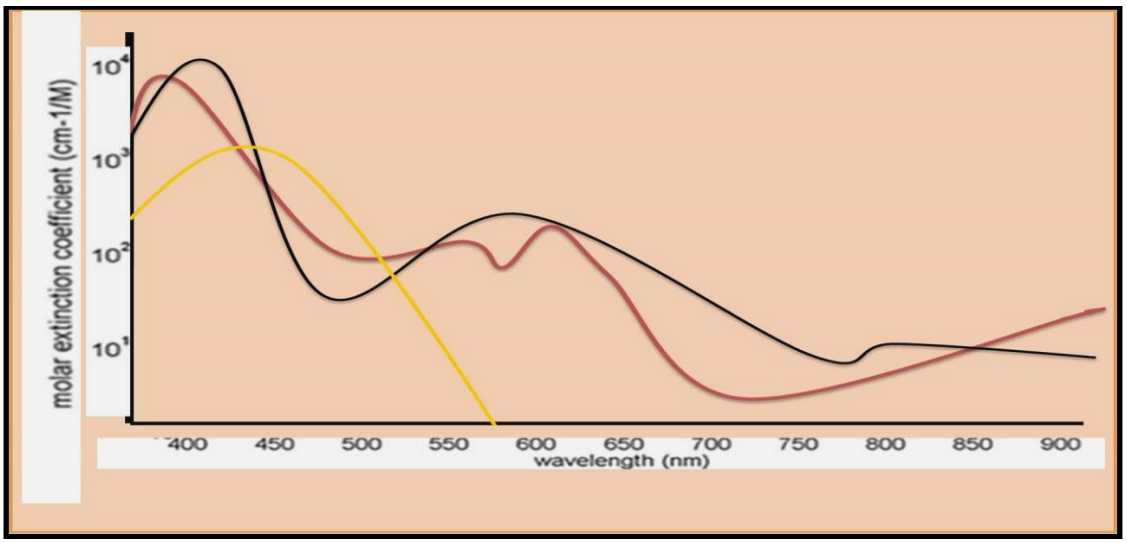

Fig 1: Wavelength bands of the multispectral camera located at the chromophore absorption peaks. (Red Line: Oxyhemoglobin, Black Line: Deoxyhemoglobin, Yellow Line: Bilirubin)

Data Analysis

Images, including the RGB photos and 8 single wavelength reflectance images from the multispectral system, were inspected and scored for bruises by two blinded researchers. A MATLAB program was used to randomly show images to researchers, who then indicated if a bruise was present. A third researcher reviewed inconsistent scoring for a majority vote.

In this study, we used the contrast-to-variability metric (CVR) of a bruise in a single-wavelength reflectance image to objectively measure the bruise's differentiability from surrounding undamaged tissue. We calculated the average and standard deviations of pixel intensities for both the bruise (b) and surrounding undamaged tissue (s) in a single-wavelength reflectance image, noted as μb, μs, σb, and σs. CVR was calculated as

$$\mathrm{CVR} = \frac{\mu b - \mu s}{\sqrt{\sigma b2 + \sigma s2}}$$

Assessing the overlap between the two pixel-intensity distributions. An elevated CVR suggests greater separation between distributions, likely enhancing bruise visibility in the single-wavelength reflectance image. The computation was done for all documented single-wavelength reflectance images to provide an objective metric for bruise visibility based on wavelength and bruise maturation. A custom script was created using MATLAB R2020a (The Mathworks Inc.). Implemented in Natick, MA, USA, to facilitate objective selection of regions of interest. These regions are the pixels showing the bruise and nearby tissue in single-wavelength images of the bruise and surrounding undamaged tissue. For each single-wavelength image, intensity thresholding using the Otsu method assigned pixels to bruise, healthy skin, and white reference categories. A random starting pixel was generated in the least intense category, indicating the bruise. A region-growing algorithm segments the bruise by analyzing neighboring pixels of a randomly chosen seed point. Pixels joined the region if their intensity differences from the mean didn't exceed a set threshold. This threshold came from the standard deviation of intensity values in the lowest class, as per Otsu's method. This procedure was repeated 100 times with randomly varied seed locations. Pixels segmented in over 90 of 100 iterations were selected for analysis. The analysis calculated the bruise's size, mean, and standard deviation of pixel intensities for the bruise and nearby tissue. Subsequently, these calculate the CVR.

Statistical Methods

For visual assessment, a one-sided sign test ($p = 0.05$), using a binomial distribution with a probability $p = 0.5$ was used to compare the number of bruises visible at each wavelength (450, 480, 509, 542, 558, 578, 620, 850 nm) from the multispectral imaging system. Contrast values in the images were examined using one-way repeated measures ANOVAs with Greenhouse-Geisser corrections for sphericity at each temporal point.

RESULTS

Visual Scoring: A comprehensive dataset was constructed, incorporating both RGB and single wavelength reflectance images from a sample of 100 individuals (46 male, 54 female), with a mean age of 36. 8 years (standard deviation ±9. 4). This dataset encompasses 468 unique temporal instances, equating to an average of 5. 8 time points per participant. Owing to logistical and scheduling constraints, it was

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not feasible to measure all subjects at each designated time point. Six participants were excluded due to the presence of markings resembling bruises or other anomalies on the inner forearm, as observed in the images captured prior to the blunt force impact. The formation of a bruise consequent to blunt force trauma was detectable using at least one of the imaging modalities in a cohort of 56 participants (comprising 26 male and 30 female subjects) whose mean age was 39. 2 years (with a standard deviation of ±10. 8 years). Illustrative instances of bruises detected at various wavelengths are presented in Figure 2 illustrates the corresponding contrast scores (refer to the subsequent section) for each wavelength at each time-point pertaining to this specific volunteer.

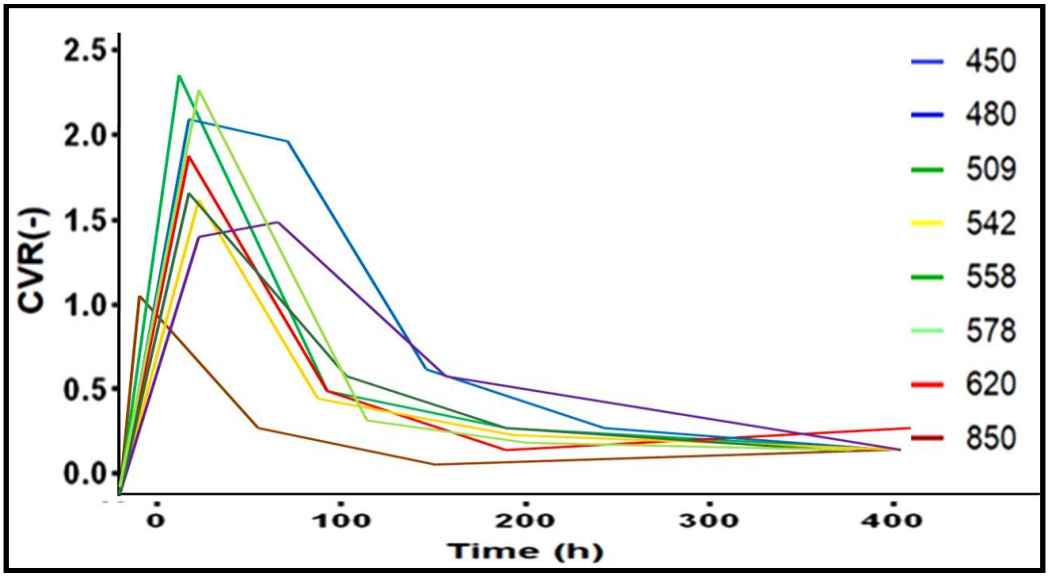

Fig 2: Contrast, expressed in CVR over time for the various wavelengths. In the first phase, the 850 nm light gives the best contrast. After further diffusion of Hemoglobin, 558 has most contrast, followed by 450 nm when Bilirubin is formed

Figure illustrates the quantity of bruises identified in images captured at various wavelengths, contingent upon the age of the bruise. Figure 3 unambiguously illustrates that the majority, consisting of 41 out of the 56 identified bruises, were discernible within a 6-hour duration following the blunt force impact. In the initial stages of development, the detection of bruises using the multispectral system at wavelengths of 620 nm (yielding 18 detections) and 850 nm (yielding 29 detections) surpasses the number identified through RGB imaging, which accounted for 14 detections. In a total of eleven instances, spanning all examined time points, bruises were exclusively observed in the RGB images and were not detected in the multispectral data. Conversely, in 92 instances, also encompassing all time points, bruises were perceptible solely in one or more single-wavelength reflectance images, while remaining undetectable in the RGB images.

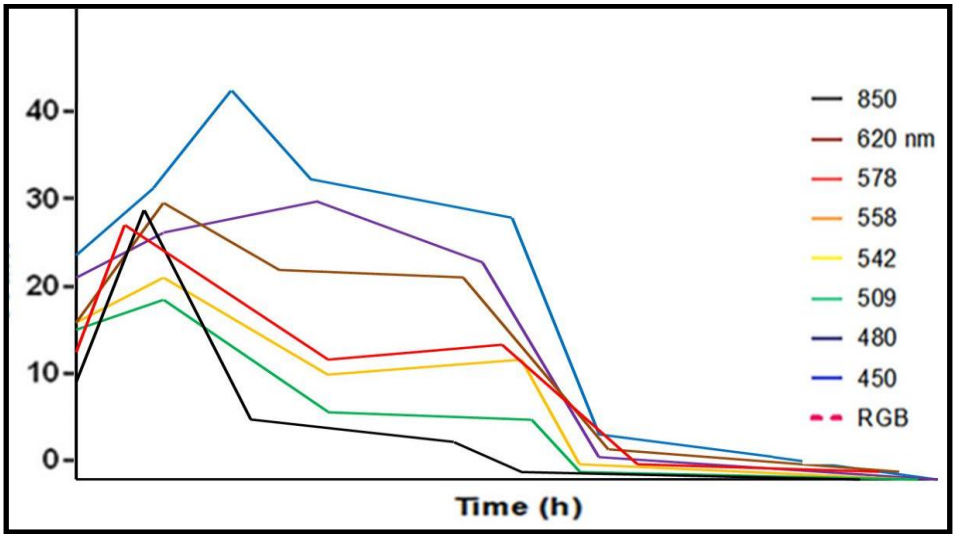

Fig 3: The number of 'detected' bruises at different wavelengths as a function of time

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Figure 4 presents a comparison between the quantity of bruises identified in the RGB images, with a maximum of 33 at 48 hours, and the quantity of bruises identified when RGB images are combined with reflectance images at wavelengths of 480 nm, 620 nm, and 850 nm. These particular wavelengths were ascertained to significantly enhance the detection of bruises. This analysis demonstrates that the probability of identifying a bruise at any stage of its healing process is notably enhanced when reflectance images at three specified wavelengths are incorporated into the evaluation, as evidenced by a statistically significant outcome of a one-sided sign test (p-value).

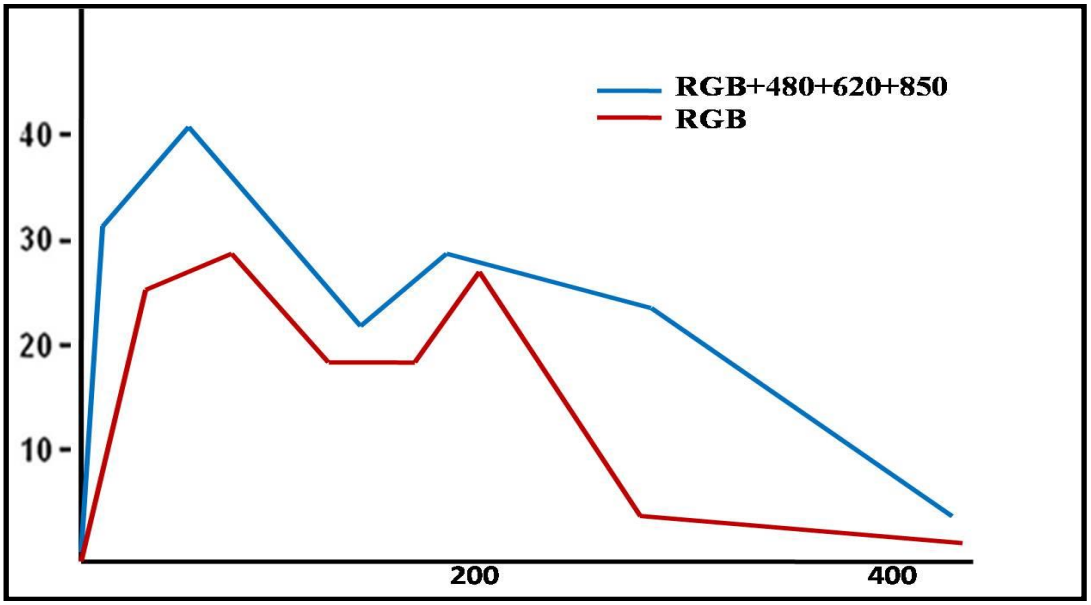

Fig 4: Comparing imaging modalities in terms of number of detected bruises as a function of time

Analysis Results – Contrast Ratios

During the initial hour, no statistically significant difference was observed in cerebrovascular reactivity for any of the wavelengths. At the 6-hour mark, the mean CVR at 850 nm was determined to be significantly higher than those observed at all other wavelengths ($F = 11.604$, $p = < 0.001$, $\eta 2 = 0.304$). At the 24-hour mark, cerebrovascular responses (CVRs) measured at wavelengths of 450 nm, 480 nm, and 509 nm were observed to be significantly diminished compared to other wavelengths ($F = 4.486$, $p = 0.018$, $\eta 2 = 0.183$). After 48 hours, the wavelengths of 578 and 620 nm exhibit a significantly higher coefficient of variation ratio (CVR) in comparison to other wavelengths. Conversely, the wavelengths of 509 and 850 nm display a significantly lower CVR than the other wavelengths under consideration. After a period of 72 hours, wavelengths measured at 450 nm and 480 nm exhibit a notably higher conversion rate (CVR) compared to other wavelengths, as indicated by the statistical analysis ($F = 6.362$, $p = < 0.001$, $\eta 2 = 0.484$). This trend persists until hours 96 and 168, as demonstrated in Figure. In Figure 5, all CVR values have diminished to comparably low levels by the 240th and 336th hours. At these specific temporal intervals, no statistically significant variation in cerebrovascular reactivity (CVR) was detected.

DISCUSSION

In this investigation, we demonstrated the enhanced efficacy of spectral imaging in detecting bruises at multiple stages throughout the healing process. Through the precise targeting of the transforming chromophore population inherent in a healing bruise, we achieved a substantial extension in the duration during which the bruises remained detectable. Furthermore, this study demonstrated that the wavelength corresponding to optimal contrast transitions progressively from 850 nm to a range between 578 nm and 480 nm throughout the process of bruise healing. This phenomenon, consequently, is consistent with both (i) the inflammatory response and (ii) the dissemination of chromophores to the superficial layers of the skin. The inflammatory response is characterized by an elevation in interstitial fluid levels, absorbent at a wavelength of 850 nm, and the transformation of hemoglobin, which absorbs at 578 nm, into bilirubin, which absorbs at 480 nm. Concurrently, the diffusion of chromophores to the superficial layers of the skin necessitates reduced penetration depths, implying the utilization of shorter wavelengths. Moreover, the representation of older contusions, especially when juxtaposed with more recent ones, may facilitate the identification of potential incidents of physical maltreatment. In conclusion, these findings align with previous research that examined the spectral detection of bruise-specific chromophores as a means to monitor and investigate the healing process in order to assess the age of a bruise.[34–36] In a prior study, researchers examined the visualization of faded, diffuse, or older bruises by employing an infrared camera alongside

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sunlight as an infrared light source.[37] Although that particular study did not identify any additional benefit from employing infrared imaging, our findings clearly indicate that infrared images, captured at wavelengths of 620 nm and 850 nm, significantly improve the detection of early-stage bruises, which typically are situated in deeper skin layers. This enhancement can be attributed directly to the increased penetration depth and the lack of more superficially positioned absorbing chromophores. In contrast to other findings, and consistent with the aforementioned previous study, our investigation revealed no significant enhancement in the detection of older bruises at these wavelengths. Alternative studies have demonstrated promising outcomes concerning the identification of bruises utilizing Alternative Light Source (ALS) within the ultraviolet (UV) spectrum.[38] Recent studies, however, have not successfully replicated these findings.[23,25] Moreover, the majority of these investigations concentrated on improving the visibility of bruises in comparison with RGB imaging or direct visual observation. In this study, we concentrated on the identification of contusions that are not discernible in RGB images or to the unaided human eye. The incorporation of multispectral imaging (MSI) into medical forensic examinations offers both potential benefits and challenges. Multispectral imaging (MSI) presents the potential to improve injury documentation and assessment by detecting subtle physiological changes that are not discernible in conventional RGB images, even when observed under ambient lighting conditions. This benefit has the potential to enhance patient comfort, especially for those who have undergone interpersonal violence, as it allows examinations to be conducted without necessitating darkened environments. It is noteworthy that Mass Spectrometry Imaging (MSI) systems are now readily accessible in the commercial market and have experienced a reduction in cost over recent years, thereby enhancing their availability to professionals in the medical and forensic fields. Furthermore, technological advancements have substantially enhanced the user-friendliness of MSI devices, thereby diminishing the degree of technical expertise necessary for their operation and interpretation. Although MSI appears promising as a diagnostic tool, further research is essential to validate its effectiveness, replicate results across varied populations, and develop standardized protocols. Moreover, the implementation of Multispectral Imaging (MSI) may require a significant shift in methodology, moving from traditional real-time macroscopic injury assessment to a dependence on high-resolution photographic evidence. This transition prompts inquiries regarding the integration of such technology into existing workflows and the establishment of professional consensus within the forensic community. It is imperative to address these considerations in order to establish MSI as a viable and impactful instrument within clinical practice.

Limitations of Study

The occurrence of bruising resulting from blunt force trauma is contingent upon both the anatomical location and the nature of the impact. Consequently, we standardized the procedure for inducing bruises by subjecting all participants to an identical impact at the same anatomical location. However, whereas certain participants did not exhibit any discernible bruising, others developed bruises that persisted for a duration exceeding three weeks. This finding unequivocally illustrates those notions, such as the visibility of an extended bruise as indicative of the extent or level of experienced violence, or the size of the bruise as representative of the antecedent force, warrant critical examination. Furthermore, it is crucial to acknowledge that the absence of a bruise does not necessarily indicate the absence of an impact or inflicted pain. As a result, during the documentation of injuries e.g., during a physical examination, it is imperative to document any verbal accounts from the victim regarding the severity and location of the experienced pain, in conjunction with the collection of physical evidence, as bruising may not manifest. Furthermore, it should be acknowledged that the lack of visible bruising documented in our study does not necessarily indicate the physical nonexistence of a bruise. The objective of our study was to assess whether the implementation of a spectral imaging system could effectively decrease the incidence of 'false negatives' observed in traditional RGB imaging or unaided visual inspection. Moreover, the cohort examined in this study comprised individuals with Fitzpatrick skin types I through III. Consequently, the present findings are predominantly applicable to individuals with lighter skin tones. The efficacy of spectral imaging in improving the detection and characterization of bruises in individuals with darker skin tones remains to be ascertained. It is observed that although Alternate Light Sources (ALS) might have produced comparable outcomes in our study configuration, the utilization of a spectral imaging system is more appropriately aligned with applications in forensic practice, given that measurements can be conducted under standard lighting conditions. Utilization of the ALS, excluding the employment of infrared sources, requires the elimination of ambient light. In conclusion, the present study involved inducing bruises on the forearm due to its ease of accessibility as a site for examination. Furthermore, a singular impact force was employed to reduce potential sources of variability. These measures facilitated the standardization of the sample set and, correspondingly, constrained the types and locations of the bruises under investigation. Nonetheless, the findings of our study—pertaining to a minor impact force applied to a physiological area composed of muscle and adipose tissue—are encouraging. It is anticipated that, in principle, these results may be

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applicable to circumstances involving higher impact forces and/or similarly structured anatomical regions.

CONCLUSION

In this study, it has been demonstrated that spectral imaging at wavelengths of 620 nm and 850 nm enhances the temporal detectability of bruises. Furthermore, these longer wavelengths have demonstrated significant efficacy in enhancing the detection of more recent and typically deeper bruises. Shorter wavelengths, exemplified by 480 nm, have demonstrated notable enhancements in the overall detection of bruises, especially in the later stages of the healing process. Our findings suggest that the optimal wavelength for detecting bruises varies according to the age and healing phase of the bruise. Specifically, the effective wavelength transitions from 850 nm to a range of 578 nm to 420 nm, and subsequently reverts to 850 nm as the bruise progresses through its healing process. The inherent dynamic complexity precludes the provision of a universal recommendation for the optimal wavelength at any particular temporal point. Nonetheless, the trends identified within our study strongly indicate that practitioners ought to integrate spectral imaging at wavelengths of 420 nm, 480 nm, 578 nm, 620 nm, and 850 nm into standard forensic examination protocols. This multi-wavelength methodology will augment the detection and localization of bruises, thereby optimizing forensic physical examinations. It is imperative that future research endeavors persist in the refinement of these spectral imaging techniques, while simultaneously investigating their applicability across a diverse array of populations and injury typologies, to further substantiate and enhance their utility within the field of forensic science.

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