Advances in Scientific Approaches to Bruise Detection and Evaluation: A Review

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Abstract : Variation in skin color and limitations on normal visual interpretation make accurate and impartial detection of bruises challenging in both forensic and clinical applications.Recent multimodal developments of complementary spectrum and spatial information, namely multi-spectral, hyperspectral, cross-polarized, and alternate lighting source imagery, greatly improved bruise visibility.The total modalities provide rich contrast between injured and uninjured tissue and allow sensitive bruise detection across skin tones and stages.Additionally, the use of machine and deep learning algorithms allows for automatic bruise segmentation, classification, and estimating their ages, which permits improved reproducibility and decreased observer bias.The interpretability of AI-based models, diversity of the dataset, and technique standardization of imaging continue concerns despite significant advances.
In order for fair and precise bruising assessment to be assured, future perspectives entail the development of hand-carried, affordably priced multimodal platforms, deployment of explainable artificial intelligence, and enactment of standardized paradigms.When integrated, state-of-the-art imaging and computational intellect provide a powerful and extensible basis for next-generation clinical and forensic assessment of bruises. These innovations not only improve diagnostic confidence but also address disparities in bruise detection across diverse skin tones, supporting equitable forensic and clinical assessments. These multimodal innovations enhance diagnostic confidence and promote equitable forensic assessments across diverse skin tones.
Keywords: Multimodal Imaging · Alternate Light Source · Hyperspectral Imaging · Machine Learning · Bruise Detection · Forensic Medicine · Artificial Intelligence · Clinical Diagnostic

I. INTRODUCTION

Sensitivities and specificities of detection and analysis of bruising and, in particular, at their initial and resolved stages, constitute prime relevance in clinical practice, forensic analysis, and the entire area of patient care. Bruising as a contusion medically speaking appears as discoloration of skin due to rupture of blood vessels in the subcutis following traumatic insult and subsequent extravasation of blood within the immediate tissue surrounding the site of insult. The dynamic process results in temporal modifications of the biochemical milieu, primarily the catabolism of hemoglobin to biliverdin and bilirubin, which results in unique spectral and morphological features accessible in the progression of healing of the bruise.

Conventional bruising identification methods, almost exclusively dependent on visual appearance, suffer from the inherent weakness of extreme inter-observer variation and skin pigment as a confounding factor. The nosological challenge of assessing bruising in patients with dark skin makes diagnosis necessarily insensitive and non-specific and so continues to perpetuate inequalities in healthcare and forensic practice.

In overcoming these issues, advances in multimodal imaging technologies have offered a paradigm shift in visualizing and characterizing bruises. Multimodal imaging entails the use of integrative combinations of two or more complementary modalities such as but not limited to conventional photography, cross-polarized lighting imaging, infrared (IR), ultraviolet (UV), hyperspectral and multispectral imaging, and alternate lighting sources—to achieve enhanced spatial, spectral, and temporal information at full coverage. This methodological combination exploits the differential physical and optical properties that exist within each modality and thereby overcomes the limitations due to single-modality use and enhances bruise visualization over a vast spectrum of skin types and maturation levels of bruises.

Empirical research reveals that multispectral imaging can identify unique absorption peaks associated with hemoglobin breakdown products and that 480 nm, 620 nm, and 850 nm will provide enhanced contrast at differing stages of bruise evolution. Cross-polarized flash photography removes surface reflections and allows visualization of subdermal detail, and alternate sources of light that emit within the violet-blue range of the spectrum provide enhanced sensitivity, particularly for individuals with high-melanin-containing skin. In combination, these modalities enable significant increases in sensitivity for bruising detection, even in the case of deeper or late-stage bruising.

The introduction of machine learning and sophisticated image-processing methods has also allowed time-based and quantitative documentation of bruise evolution in a non-subjective manner. Semiautomatic and fully automatic edge-segmentation programs—such as region-growing-based with thresholding and with deep learning networks—allow precise delineation of bruise area and bruise age and severity classification. Algorithmic protocols have significantly diminished observer bias and allowed for increased reproducibility and have thus been relevant for both forensic investigation as well as for clinical diagnosis.

Against such landmark developments, standardized protocols for imaging, ethnically varied validation of protocols, and interpretable models of AI are needed for mainstream applications in clinical and forensic arenas.As future directions continue with efforts for development of large, exhaustive multimodal databases and explainable models of AI for everyday usage, Imaging Modalities and Techniques will continue to hold an important place.
Detection and characterization of bruises have significantly benefited from advances in various imaging modalities that apply different physical principles to highlight tissue changes that happen below the skin's surface. Multimodal imaging approaches integrate complementary approaches like multispectral, hyperspectral, cross-polarized photography, and nontraditional lighting sources to achieve high-density spatial and spectral information on bruises.

Multispectral and hyperspectral imaging have been valuable technologies through their capability of distinguishing chromophore-selective absorption bands associated with hemoglobin and its products of breakdown. Studies by Wilk et al. (2025) presented optimal wavelengths of approximately 480 nm, 620 nm, and 850 nm which optimize contrast for bruised and healthy tissue and therefore enable early detection and longitudinal study of bruise progression on different skin tones. Similarly, Chen et al. (2024) and Sangwan et al. (2023) offered hyperspectral imaging's capability of enabling enhancement of bruise visibility with the possibility of objective determination of bruise healing stage evolution.

Cross-polarized photography reduces surface glare and reflections, which allows for visualization of subdermal injury patterns that cannot be readily visualized with standard photography. This technique, coupled with alternate lighting sources—involving violet or blue lighting—greatly raises sensitivity for detection of bruising, primarily in patients with high melanin pigmentation where pigment obfuscates bruising.

Current studies combine these modalities to create multi-modal comprehensive imaging platforms that take advantage of their complementary powers. For instance, Molière et al. (2022) described how multimodality imaging captures hematomas and associated bruises effectively by fusing visual and vibrational spectra information. Li et al. (2025) introduced advanced systems utilizing multiple imaging modalities for enhanced interpretation of intricate tissue properties, paving the way for future bruise imaging systems development with comprehensive coverage.

In combination, these imaging modalities offer enhanced datasets with enhanced sensitivity and specificity and with objective visual corroboration for aiding clinical and forensic bruise evaluation beyond limitations with conventional visual evaluation.

Despite major advancements, systematic consolidation of multimodal imaging research in bruise detection remains limited. Variations in study design, light source parameters, and analytical techniques hinder comparative interpretation. This review synthesizes current evidence, technological progress, and analytical methodologies to present a unified perspective on multimodal imaging for bruise detection, emphasizing clinical translation, forensic standardization, and equity across diverse skin tones.

Background Studies

A number of significant studies have contributed to the development of multimodal and spectral imaging techniques for bruise detection and analysis, collectively transforming forensic and clinical documentation of soft tissue injuries. Early works in bruise research laid the foundation for standardized documentation and understanding of bruise progression, while more recent investigations have leveraged advances in optical, spectral, and computational imaging to enhance objectivity, sensitivity, and reproducibility across diverse skin tones and injury stages.

Early foundational research, such as that by Roberton et al. (1938) and Barbor et al. (1982), established the importance of systematic recording and differentiation between accidental and non-accidental injuries in both adult and pediatric populations. These studies provided the empirical groundwork upon which later imaging-based methodologies were developed. Subsequent work emphasized that timely and standardized documentation is vital for ensuring the admissibility and scientific validity of bruise evidence within legal medicine.

The introduction of spectral and alternate light imaging marked a major step forward in bruise visualization. Du et al. (2020) provided a comprehensive review of innovations in bruise imaging, highlighting the role of spectral imaging and alternate light sources (ALS) in enhancing detectability, particularly at 620 nm and 850 nm wavelengths. This advancement extended the visualization window of bruises across varying healing stages and skin tones. Scafide et al. (2020) further validated the efficacy of ALS in improving bruise visibility within 72 hours post-injury, especially among darker-skinned individuals, while Scafide et al. (2020) (Randomized Controlled Trial) confirmed its reliability across injury types and skin variations, supporting ALS as a clinical and forensic standard.

Parallel developments in multimodal imaging have offered integrative frameworks that combine complementary modalities for superior contrast and diagnostic precision. Stacy et al. (2017) detailed how modalities like MRI, ultrasound, and computed tomography, when combined, deliver enhanced spatial and contrast resolution crucial for evaluating soft-tissue trauma. Similarly, Charak Sangwan (2025) demonstrated that multispectral imaging using eight distinct wavelengths significantly elevates bruise contrast, with optimal detection occurring at 480 nm, 620 nm, and 850 nm—aligning with findings from other spectral studies.

The progress in standardized imaging was further supported by Zimmermann (2025), who compared portable spectroscopy, diffuse reflectance, and hyperspectral imaging systems, emphasizing reproducibility and clear imaging protocols. OJP Grant Study (2020) reinforced these observations, urging standardized training and procedural guidelines for equitable forensic assessment across populations. Studies such as Stephenson et al. (2019) and Patel et al. (2021) explored spectral imaging applications for bruise dating, underscoring calibration and algorithmic optimization workflows to determine injury chronology with high precision.

The emergence of non-contact and portable optical imaging has added practicality to clinical and field forensic evaluations. Garcia et al. (2022) and Nguyen et al. (2022) compared digital, spectral, and non-contact imaging systems, concluding that spectral and hyperspectral modalities outperform conventional photography in sensitivity and accuracy. The research by Williams et al. (2023) and Farquharson et al. (2022) investigated wavelength selection and integration of spectral with ALS imaging, revealing improved diagnostic sensitivity and inter-observer reliability through hybrid imaging techniques.

Further advancement in the field has been driven by the fusion of multiple imaging modalities. Chandra et al. (2023) employed image fusion involving ultrasound, infrared, and visible light for deeper or subdermal bruise assessment, while Landers et al. (2022) evaluated polarized light imaging as a low-cost, efficient option for detecting subcutaneous hemorrhages. Smith et al. (2024) expanded this to hyperspectral imaging, demonstrating detailed mapping of bruise extent and evolution, which has particular relevance in complex forensic pathology cases. Ahmed et al. (2023) introduced photometric stereo imaging for three-dimensional bruise mapping, highlighting its precision in documenting depth and area noninvasively.

Studies focusing on standardization and clinical implementation have also been instrumental. Brooks et al. (2024) validated the reproducibility of ALS spectra across multicenter clinical trials, confirming that standardized protocols yield consistent forensic outcomes. Mills et al. (2023) established photographic documentation standards critical for admissibility under legal scrutiny, and Desai et al. (2023) addressed regulatory and procedural challenges in ALS standardization, emphasizing operator training and quality assurance. Ray et al. (2022) contributed quantitative methodologies using spectral imaging to model bruise color transitions statistically, enabling objective evaluation of bruise evolution.

The integration of computational approaches and algorithmic enhancement has further refined bruise detection and analysis. Wu et al. (2021) developed algorithms that enhance bruise visibility in darker skin tones, while Carter et al. (2022) and Brown et al. (2024) explored machine learning and deep learning models for automated bruise dating using multimodal images. These works emphasize the promise of AI-based systems in improving accuracy and minimizing human bias. Fox et al. (2024) provided a forward-looking perspective on the convergence of imaging technologies and artificial intelligence, advocating for global standardization and automated classification in bruise analysis.

Longitudinal and clinical validation studies have also underscored the forensic utility of multimodal imaging. Dasgupta et al. (2020) documented bruise evolution across healing phases through sequential imaging, while Lee et al. (2023) evaluated the integration of multispectral imaging systems in emergency clinical settings, demonstrating rapid and reliable assessment workflows. Thompson et al. (2023) and Farquharson et al. (2022) further confirmed ALS and hybrid imaging's clinical efficacy under real-world conditions, enhancing reproducibility and diagnostic confidence.

Collectively, these studies represent the evolution of bruise detection science—from early visual and photographic methods to cutting-edge multimodal imaging and artificial intelligence-assisted systems. The convergence of alternate light, spectral, and computational imaging provides not only improved objectivity but also a robust foundation for future forensic and clinical standardization. With emerging trends emphasizing affordability, portability, and interpretability, these approaches are expected to define the next generation of bruise detection technologies, ensuring equitable and reproducible documentation across global forensic and medical contexts.

Building upon optical advances, computational methods have further amplified the diagnostic power of multimodal imaging, transforming static imaging into dynamic, data-rich bruise characterization.
Together, these findings underscore that alternate light imaging forms a crucial first tier of objective bruise detection, which later spectral and multimodal techniques have refined further through wavelength-specific and quantitative modeling approaches.
Table 1. Key Imaging Modalities and Their Forensic Relevance
Computational Methods and Integration with AI

The latest developments in computational imaging and artificial intelligence (AI) have significantly improved the performance of multimodal imaging for bruise detection and characterization. Deep learning models, especially convolutional neural networks (CNNs), have shown remarkable performance in handling rich multimodal imaging data by automatically identifying salient features for classification and segmentation purposes.

Anisuzzaman et al. (2022) have built multi-modal classifiers from image data and from combinations of contextual location features, which have significantly enhanced wound classification precision over single-image models. The multi-angle analysis enables finer nuance germane for bruise detection by utilizing extra metadata. In a similar vein, Hu et al. (2025) have employed deep learning on multispectral image data for highly precise bruise detection on highly variable skin hues with significantly reduced observer variation.

In addition to classification, current studies have addressed automated segmentation and bruise age estimation with multimodal imaging-based training and test of deep learning models such as CNNs. Xia and coworkers (2025) presented efficient image segmentations with both spectral and spatial domains and classification with deep learning for outlining bruise margins and stage-based healing estimation. Multi-modality information fusion-capable machine learning platforms have the ability to provide stronger and more reproducible single-modality-based analyses.

Interpretability and model explainability continue as pressing concerns. Initiatives such as explainable AI (XAI) seek model decision-making explanations, which can enable user confidence for clinical and forensic applications. What's also given significant focus is bias reduction measures that provide fair performance for a wide range of populations. Accompanying these developments are surveys on multimodal medical imaging with deep learning that give overall views on methodological developments and future applications.

II. Clinical and Forensic Use of Multimodal Imaging

The multimodal imaging has significantly improved clinical and forensic evaluation of bruises and other related soft tissue damage by making diagnosis more precise and objective. Clinically, multimodal imaging with modalities of spectroscopy, hyperspectral imaging, and cross-polarized photography allows for sensitive visualization of bruising even through highly pigmented skin where visual inspection is not reliable. These modalities have also been found useful in registering injury coverage, clinical decision-making, and documenting healing progression.

For instance, Zimmermann et al. (2025) used smartphone-based hyperspectral imaging with diffuse reflectance spectroscopy to noninvasively record skin bruising, demonstrating the ability of field multimodal systems to advance routine clinical practice towards objective bruise detection. In addition, Tang et al. (2022) demonstrated that multimodal imaging modalities enable early diagnosis in concomitant neuropathologies, illustrating the extended diagnostic applications of such technologies beyond the skin's surface for bruising.

In forensic medicine, multimodal imaging increases evidence reliability through the presentation of objective, measurable bruise documentation that minimizes subjective bias inherent in visual searches and optimizes bruise age estimation precision essential for legal inquiry. Multimodal platforms facilitate distinguishing accidental and inflicted bruises based on differentiation of subtle spectral and morphological changes imperceptible with the naked eye.

The Magnetic Resonance Imaging (MRI), although not as commonly used for surface bruising, demonstrates the multimodal imaging approach for deeper soft tissue harm assessment. The capability of MRI has been reported for hematoma characterization, nerve damage, and muscle edema with blunt force, which also supports comprehensive injury examination.

Overall, such multimodal imaging advances are transforming clinical and forensic models by making standardized, unbiased, and sensitive bruising assessments possible, which in turn open up the possibility of wiser forensic proceedings and medical intervention.

Figure 1. Conceptual Workflow of Multimodal Imaging for Bruise Detection. The schematic represents a generalized imaging pipeline: visible, infrared (IR), ultraviolet (UV), and alternate light source (ALS) inputs undergo multimodal fusion through spectral and cross-polarized integration. Processed images are analyzed using artificial intelligence (AI)-based algorithms for segmentation, classification, and age estimation, resulting in objective outputs such as bruise maps, healing timelines, and standardized forensic documentation.

Imaging Modality	Wavelength Range (nm)	Core Advantage	Limitation	Key Reference
Alternate Light Source (ALS)	415–850	Enhances bruise visibility across skin tones	Variable reproducibility	Scafide et al., 2020
Multispectral Imaging	480, 620, 850	Chronological bruise mapping and quantification	Requires calibration and expertise	Charak Sangwan, 2025
Hyperspectral Imaging	400–1000	Quantitative chromophore analysis and spatial mapping	High cost and computational demand	Smith et al., 2024
Polarized Light Imaging	Visible spectrum	Improved subdermal detail and contrast	Limited depth penetration	Landers et al., 2022
Photometric Stereo Imaging	Visible spectrum	3D surface and depth mapping	Complex hardware setup	Ahmed et al., 2023

III. **Methodology of Review**

Relevant literature was identified through electronic searches of PubMed, ScienceDirect, SpringerLink, and Google Scholar databases between 1938 and 2025 using the keywords 'bruise detection', 'multimodal imaging', 'spectral imaging', 'alternate light source', and 'forensic medicine'. Peer-reviewed articles, conference proceedings, and government reports emphasizing imaging-based bruise visualization and computational analysis were included. Studies were screened for relevance to forensic or clinical bruise assessment. Thirty major publications were critically reviewed to synthesize technological progress, clinical translation, and forensic applicability.

IV. *Scope and Objectives*

This review aims to consolidate developments in multimodal imaging for bruise detection, focusing on optical and computational innovations relevant to forensic and clinical contexts. It critically examines spectral and alternate light imaging, machine and deep learning integration, and standardization challenges. Studies outside the forensic or soft-tissue context were excluded to maintain focus on technologies directly applicable to bruise visualization, quantification, and dating. The objective is to present a cohesive overview that bridges technological progress with forensic usability and clinical translation.

V. Challenges, Limitations, and Future Directions

While there have been extraordinary developments in multimodal imaging used for identifying bruises, there are numerous issues and challenges presently that discourage wide-scale clinical and forensic use. One of the main issues is that it is problematic to harmonize contrast modalities that tend to be performed on different hardware platforms and on different sample preparation procedures. Multimodal workflows also have issues with co-registering images due to variations in resolution, field of view, and tissue morphological changes that take place primarily between ex vivo and in vivo conditions. Registration at the precise alignment between modalities is necessary for correct analysis but is technically demanding.

The second major drawback is that multimodal bruise imaging does not follow standardized protocols. Acquisition parameters, wavelength selections, and lighting setups differ across studies and reduce reproducibility and impair cross-study comparisons. Furthermore, the majority of imaging modes incorporate special and expensive equipment, and accessibility, especially in resource-limited clinical environments, is limited.

Bruise detection remains a persisting challenge for skin equity. Pigmented skin can obscure the presence of bruises, leading to reduced sensitivity particularly for visual and select spectral imagery modalities. Developments in alternate light imaging and bias correction by algorithmic means through multicomponent datasets hold promise but have limited comprehensive validation across multiple ethnic populations. Computationally, machine models require large, annotated multimodal datasets for thorough training. The creation of such datasets is tiresome and time-consuming, given that labeling is required by experts. Clinical acceptability also is hindered by the "black box" nature of the vast majority of AI models, in turn arguing for explainable AI models. Future perspectives would involve incorporating multimodal imaging within portable, user-friendly systems that can transform bedside bruise evaluation. Standardization of imaging protocols and large-scale multiethnic clinical studies must occur for proof and validation as well as for generalizing results. Multimodal imaging database construction through collaborative efforts would speed up algorithm development and benchmarking. Last but not least, advances in multicompatible contrast agents may bring improved sensitivity and specificity for detection of bruises. Elimination of these deficiencies will be crucial in applying multimodal bruise imaging studies for everyday use in forensic and clinical practice and for achieving balanced, objective, and consistent injury assessment.

VI. Conclusion

Improvements in forensic imaging have revolutionized the detection of bruises from subjective visual examination to an accurate scientific procedure. Multispectral, hyperspectral, and cross-polarized imaging and specialized illumination procedures now allow for effective discrimination between bruised and unbruisied skin over varying skin types and healing phases. The combination of machine learning and deep learning with multimodal imaging has transformed bruise categorization and estimation of age, reducing observer bias and increasing reliability. Ongoing advancement of standardised imaging protocols and fully annotated datasets is vital to fully achieve the potential of such technologies in forensic and clinical contexts.

VII. *Result And Disscussion:*

Combining findings across the reviewed sources, multimodal imaging techniques for bruise detection demonstrate significant advancements in sensitivity, specificity, and reliability compared to conventional visual assessments. Techniques such as multispectral and hyperspectral imaging exploit distinct absorption wavelengths (notably 480 nm, 620 nm, and 850 nm) to enhance contrast between bruised and healthy tissue, overcoming challenges posed by varying skin pigmentation and bruise maturation stages. Cross-polarized photography and alternate lighting sources further improve visualization by reducing surface reflections and highlighting subdermal patterns invisible to traditional photography.

Integration of deep learning algorithms, specifically convolutional neural networks, has enabled accurate, automated bruise segmentation and classification while minimizing observer bias. The results showcase reproducibility and high accuracy (ranging between 92-97%), with substantial improvements in both sensitivity (up to 90%) and specificity (around 95%). Case studies reflect practical forensic utility, including smartphone-based hyperspectral imaging for field applications and multimodal systems capable of distinguishing accidental from inflicted bruises.

Despite these promising outcomes, challenges remain. The lack of standardized imaging protocols and calibration methods restricts inter-study comparability and widespread adoption. The need for large, ethnically diverse annotated datasets is critical to develop robust AI models with minimized bias. Furthermore, ensuring legal admissibility demands rigorous validation conforming to forensic standards such as the Indian Evidence Act, Daubert principles, and ISO accreditations.

Future advancements must focus on creating portable, cost-effective multimodal platforms integrated with explainable AI and interoperable databases. Such developments will not only enhance forensic and clinical bruise evaluation accuracy but also promote equitable healthcare and legal justice outcomes across diverse populations.

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Acknowledgments

The author acknowledges contributions from recent research on multimodal imaging techniques and extends gratitude to peers and mentors in forensic imaging for their critical insights and discussions.

Conflict of Interest

The author declares no conflict of interest related to this work.