Review Article
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Contrast enhancement in forensic medical photography using histogram equalization

Abstract

Photographs are commonly used in forensic medical practice to document injuries observed during the medical examination. Accurate photographic capture of the injuries is crucial for being able to communicate the presence and importance of these injuries. The photographic process and the creation of electronic or printed images affect the visibility and reproducibility of the observations. Histogram equalization (HE) has become a common tool for image enhancement. Different HE algorithms are available, and the chosen algorithm will affect the appearance and color fidelity of the image produced. The limitations and benefits of HE should be known by the forensic examiner before employing HE on patient images. To understand these limitations, the examiner must also understand the science behind color spaces, image enhancement techniques, and the diagnostic or imaging goal of the photographs being taken of a patient. The use of HE for forensic medical photographs is poorly researched, and at this point, courts should be skeptical when reviewing patient photographs enhanced by HE, particularly standard HE, if the findings are not observable in the unenhanced image.

Keywords: forensic examination, forensic photography, histogram equalization, image processing, contrast enhancement

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Abbreviations: HE, histogram equalization; RGB, red green blue; CMYK, cyan magenta yellow black; CIE, International Commission on Illumination; PMS, Pantone matching system; ICC, International Color Consortium; SHE, standard histogram equalization; AHE, adaptive histogram equalization; CLAEH, contrast limited adaptive histogram equalization; MHE, multi-histogram equalization; RMSHE, recursive heam-separate histogram equalization; ERBMAHE, exposure region-based modified adaptive histogram equalization; HSV, hue saturation value; PSNR, peak signal-to-noise ratio; FSIM, feature similarity index; AI, artificial intelligence

Introduction

Images used in medicine include those from radiography, nuclear medicine, magnetic resonance, positron emission, ultrasonography, and photography, among others.[1] After acquiring an image, decisions must be made about how to process it for presentation to the clinician to optimize interpretation. Image processing can involve choices about size, resolution, color, contrast, and format. Enhancing or manipulating image contrast can help the clinician better distinguish features, thereby improving the recognition of normal and abnormal findings? Several techniques can be employed, including histogram equalization. Histogram equalization (HE) can improve the visibility of objects that are initially nearly indistinguishable.[2] It can be used to enhance medical photographs, especially to improve contrast and visibility of anatomical structures. Conventional histogram equalization effectively increases contrast in low-contrast images. However, it may also introduce artifacts, excessive enhancement, or loss of fine details, which can compromise diagnostic utility and visual naturalness.[3–6]

To address these limitations, several advanced HE techniques have been developed and validated in the published literature. Modified adaptive histogram equalization methods, such as exposure-region-based approaches and contrast-limited adaptive histogram equalization, have demonstrated improved contrast enhancement, brightness preservation, and retention of fine details in medical images, including chest X-rays and pathology slides.[7,8] These methods segment images into regions based on exposure and apply region-specific enhancements, reducing the risk of over-enhancement while preserving diagnostic features.

In addition, hybrid approaches that combine HE with wavelet-based post-processing or spatial frequency analysis have shown further improvements in visual quality and informational entropy, supporting better clinical interpretation and feature extraction.[9,10] Human visual system-based modifications also help maintain the natural appearance of photographs while enhancing local details.[11]

Histogram equalization and its advanced variants are widely used and validated for improving the quality of medical images, but careful selection of the specific algorithm is necessary to avoid potential drawbacks such as unnatural appearance or loss of diagnostic information.[11]

The application of HE to medical photography is a more recent development, an extension of histogram equalization's utility to improve visualization in medical imaging systems. This newer application for contrast enhancement remains unknown to many in the medical community. Histogram equalization may have a specific application for forensic clinicians using photo-documentation to identify and demonstrate injuries.

Medical photography to document findings

The quotation "Use a picture. It's worth a thousand words." is commonly attributed to Arthur Brisbane in 1911.[93] A common interpretation is that an image of something provides robust documentation which would be challenging to write down in words. In medicine, observed findings on patient examination are documented in words as part of the physical examination. Many electronic healthcare records also allow the inclusion of body diagrams and photographs in the patient's medical record. "The patient's record is only as good as the accuracy, depth, and detail provided."[12] In cases involving patients who are potential crime victims, a detailed description of injuries or findings can be crucial to the successful prosecution or exoneration of a suspect. Photographs can add detail to the documentation of the patient's observed findings. Photographs also have significant evidentiary value.[13] Photography is commonly used in such investigations to document findings at the scene and from the body.[14,15]

Limitations of photographs

While photographs are crucial to documenting findings, there are limitations to a photograph's ability to record what was observed accurately.[16,17] Photographs are two-dimensional images of what were three-dimensional objects. Relationships between objects in three-dimensional space can be lost or difficult to interpret, particularly in a single image.[17] Light from the environment and from a flash or other light source near the camera can cause overexposure and underexposure, resulting in highlights and shadows and inaccurate colors.[18] These highlights and shadows can obscure the appearance of a finding or can result in over interpretation thereby causing the viewer to identify false objects in the image. Dark areas, such as bruises, can appear similar to shadows, and vice versa: shadows can be misinterpreted as bruises.[19] Even professional photographers can produce images with large color deviations from the original, despite using high-end cameras and standardized lighting conditions.[20] Colorations can appear different in photographs compared to direct observations due to the effects from the camera type, white balancing, image exposure, image processing, and from images being printed using ink, toner, or projected using phosphorescent, liquid crystal, or light-emitting diode systems.[21] Photographic images will always represent what was seen, but can never be stated to reproduce what was observed completely.[20] Because photographs have limitations on accurately recording what was visually seen, various enhancement methods have been created to assist seeing elements of the image. Techniques such as brightness control, hue and saturation control, highlights and shadowing adjustments, and sharpen image tools have been created for use in image display software. These same techniques are used in medical imaging to adjust digital radiographs and magnetic resonance images either before or during the radiologist's interpretation.[22] Because medical photographic images are now digital, some of these same techniques can be used on medical photographic images to potentially improve the viewer's ability to see and recognize details and findings in the images. Because HE manipulates the colors displayed in an image, the basis of color generation in images needs to be understood.

Image color

Color management is crucial in both photography and printing to ensure that the colors in your images are reproduced accurately. However, the color space used for photography differs significantly from that used for printing. Understanding these differences is essential for photographers, graphic designers, and anyone involved in the production of visual media.

Color spaces in cameras and screens

Color space for photography generally refers to the digital standards and models used to capture and display images on screens. The most common color spaces in photography include sRGB, Adobe RGB, and ProPhoto RGB. Images on cameras and other electronic devices are represented as a combination of three colored pixels. The pixel colors are composed of red (R), green (G), and blue (B) hues, which are represented by the acronym RGB. Each color hue intensity can vary between 0, no brightness, and 255, full brightness, giving 256 hues for each color, which is 8 bits of data each. In the RGB color space, the combination of 3 colors with 256 hues each provides 16,777,216 possible colors.

sRGB

sRGB (Standard Red Green Blue) is the widely used color space for digital images. It has a relatively narrow gamut, meaning it covers a smaller range of colors than other color spaces. However, sRGB is compatible with most digital devices, including monitors, cameras, and web browsers. This makes it the preferred choice for images intended for viewing on screens or for sharing online. Due to its universal compatibility, sRGB is often the default color space for most digital cameras and consumer-grade monitors. It ensures images look consistent across devices without extensive color correction.

Adobe RGB

Adobe RGB offers a broader gamut than sRGB, allowing for more vivid, saturated colors. It is beneficial for professional photography and graphic design where accurate color representation is critical. Adobe RGB is often used for images that will be edited and printed, as it offers greater flexibility for color adjustments. The wider gamut of Adobe RGB enables more detailed color gradation. It is especially beneficial in scenarios where color depth is essential, such as high-quality photo prints and detailed graphic work.

ProPhoto RGB

ProPhoto RGB has an even broader gamut than Adobe RGB, encompassing almost all the colors visible to the human eye. It is predominantly used in high-end photography and post-production, where maximum color fidelity is required. However, not all devices can accurately display ProPhoto RGB images, so it is mainly used in controlled environments with calibrated equipment. The extensive range of colors in ProPhoto RGB is ideal for detailed image editing and professional printing, where preserving subtle nuances and shades of color is paramount. This color space is particularly favored by photographers who work in RAW formats and require the highest level of color precision.

Color spaces in prints

Printing requires a different approach to color management, as the process involves converting digital images into physical prints. The most commonly used color spaces in printing are CMYK, Pantone, and Hexachrome. Images printed on paper rely upon the reflection of light to build the image. Individual dots of color are placed onto the paper. The color, brightness, and texture of the paper affect the human perception of details in the printed image.[23] Many laser and ink jet printers use cyan (C), yellow (Y), magenta (M), and black (K), creating a CYMK colorspace.

CMYK

CMYK (Cyan, Magenta, Yellow, and Black) is the standard color model for printing. Unlike RGB, which is based on light, CMYK is based on ink pigments. This color space is subtractive, meaning it starts with white and subtracts colors to create different hues. CMYK has a narrower gamut than RGB, so specific colors can appear less vibrant in print than in their digital counterparts. Accurate color conversion from RGB to CMYK is essential to achieve the desired print quality. Understanding the limitations of CMYK is vital for designers, as specific vibrant colors in RGB may not translate well into print. Using CMYK profiles and soft proofing techniques can help mitigate these discrepancies.

Pantone

The Pantone Matching System (PMS) is a standardized color reproduction system widely used in printing. Pantone colors are created with specific ink formulations, ensuring consistency across different print and material types. This color space is ideal for brand identity and packaging, where precise color matching is crucial. Pantone offers a broader color range than CMYK, enabling more vibrant, accurate prints. Pantone colors are often used in offset printing and branding projects where maintaining color consistency across various media is essential. The system is highly regarded in the design industry for its reliability and precision.

Hexachrome

Hexachrome is an enhanced color printing system developed by Pantone. It uses six colors (cyan, magenta, yellow, black, orange, and green) to extend the gamut of printed images. Hexachrome produces more vivid, saturated colors than CMYK and is used in high-quality printing applications where color accuracy is paramount. By adding orange and green to the standard CMYK mix, Hexachrome can reproduce a broader range of colors, making it suitable for detailed and vibrant prints. This system is particularly beneficial in printing complex graphics and images where maintaining color depth and richness is critical.

Device independent color spaces

Several color spaces are not dependent upon the device's manufactured specifications for accurate color reproduction. The Munsen Colorspace and the various iterations of the CIE Colorspaces are device-independent colorspaces. These are often implemented to preserve colors when data is shared across networks and across devices.

Human color perception and color spaces

All the above-listed color spaces do not actually correspond with the recognition of colors by human visual perception by stimulation of retinal receptors in the eye. While the human eye contains red, green, and blue visual receptors, the perceived light frequencies do not map directly to the 256-bit spectrum used in the RGB color space. The light used to illuminate a transmitted image (on a screen) or a reflective image (on a print) affects color perception.[24] Color spaces have been developed that more closely match human color perception; examples include HSL (Hue, Saturation, Lightness), HSI (Hue, Saturation, Intensity), and HSV (Hue, Saturation, Value).

Practical implications of color spaces

For photographers and designers, understanding these differences is crucial for optimizing their workflow. When preparing images for print, it is essential to convert RGB images to CMYK and make necessary color adjustments to ensure the print matches the digital image as closely as possible. Using tools like ICC profiles and calibrated monitors can help achieve accurate color representation. Additionally, designers should familiarize themselves with Pantone and Hexachrome systems when working on branding and high-quality print projects to ensure color consistency and vibrancy across various media.

Forensic photographers must also understand the differences in color spaces used by devices and the ways they are interpreted by human perception. Various devices may display colors that do not match the color initially encoded in the image. Additionally, a color displayed by a backlight device (computer) may appear different from a similar color shown by a reflective device (photo paper). Human perception will determine how different these colors appear. The ability to recognize contrast between colors depends on the viewer's ability to distinguish the colors; thus, the color space and color representation can directly affect the human viewer's ability to perceive color differences.

A variety of other color spaces are used, depending upon the application and devices. Some color spaces may more accurately portray particular colors, such as human skin tones. Little discussion in the medical literature exists about the use and potential implications of these alternative colorspaces in medical photography.

Enhancement of images

The enhancement of images captured by photographic methods is common by photographers. "The aim of image enhancement is to alter some characteristic or characteristics of an image in order to improve its appearance."[25] An image of an injury or mark may also be subjected to enhancement techniques to better demonstrate the observed finding. The Scientific Working Group on Digital Evidence (SWGDE) provides guidance to forensic photographers and image processors on standards to follow when enhancing an image. Their processing guidelines state that if changes are made to an image through image processing, the following criteria should be met:[26]

I. The original image is preserved and processes are performed on a working copy.

II. Processing steps are documented, see SWGIT Section 11 Best Practices for Documenting Image Enhancement, in a manner sufficient to permit a comparably trained person to understand the steps taken, the techniques used, and to extract comparable information from the image.

III. The end result is presented as a processed of the image.

IV. The recommendations of this document are followed.

As discussed in this review, the HE methodology follows these criteria when applied by a trained examiner.

Image histograms

Each image can be represented by counting the number of pixels of each intensity for each pixel color. The hue intensity is placed on the x-axis, ranging from 0 to 255. The y-axis is the proportion of pixels in the image having each color hue intensity. This representational method creates three hue histograms: red, green, and blue. An additional histogram can be created for the brightness of the image pixels from black to white using grey scales. For black-and-white or grey scale images, this brightness histogram is the only histogram that can be created. In color images this brightness histogram can be used to interpret whether an image is under-exposed or over-exposed.[27]

Images having a predominance of a few colors or significant highlights and shadows may have color histograms that are skewed. In photographs of people, particularly when skin is the photographic focus, the expected colors in the images will be limited to those found naturally occurring on the human body, or any associated materials that are next to or on the body when the photograph is taken. Human skin colors are predominantly brown, pink, and yellow, with little blue or green. Thus, the color histograms of human skin will skew towards the middle of the red channel and towards the ends of the blue and green channels.

Contrast in images

Contrast between elements in an image is a measure of how much they differ from each other so that they can be visualized as separate elements. Depending upon the type of image, this contrast is achieved by differences in brightness and/or color. When taking photographs, other aspects can also influence contrast, such as depth of field, focus, lighting, and texture. In this discussion of contrast enhancement, only hue or brightness techniques used to adjust contrast in photographs will be considered.

Tonal contrast is the difference between elements in an image based on their brightness or darkness. This is the only method for achieving contrast in black-and-white or grey-scale images. Color contrast is the difference between elements in an image based on the colors. This effect may also be influenced by color brightness, but this brightness adjustment should be considered a separate effect in color images, which can also affect contrast.

Histogram equalization algorithms

Histogram equalization is a powerful and popular image-processing technique used to enhance image contrast.[28] By redistributing pixel intensities, it ensures the image histogram becomes more uniform, thereby improving visibility and detail. Several algorithms can be employed to achieve histogram equalization, each with its own merits and applications. This article explores the algorithms used for histogram equalization, analyzing their functionality and effectiveness. While traditional histogram equalization is widely used, several advanced and alternative techniques—such as exposure region-based modified adaptive histogram equalization, adaptive gamma correction, and local S-curve transformation—demonstrate superior performance in enhancing contrast while preserving brightness and fine details.[7,29–31]

Techniques such as entropy-based subhistogram equalization, mean- and variance-based subimage histogram equalization, and triple-clipped histogram-based enhancement further improve detail retention and reduce artifacts compared to standard histogram equalization.[9,32,33] Methods that incorporate texture analysis, fuzzy logic, and spatial mutual information have demonstrated improved visual quality, noise suppression, and preservation of diagnostic features across various medical imaging modalities.[29,31,34,35]

Recent studies consistently show that these advanced approaches outperform conventional histogram equalization across objective metrics and expert evaluations, supporting their preference for clinical image enhancement.[7,31,36]

Standard histogram equalization

Standard Histogram Equalization (SHE) is the most basic form of histogram equalization. It works by mapping the original image histogram to a uniform histogram. The process involves computing the cumulative distribution function of the pixel values and using it to transform the intensity values. This method is straightforward and widely used for its simplicity. However, it might not be effective for images with high contrast variations, as it can lead to over-enhancement and loss of details.

Adaptive histogram equalization

Adaptive Histogram Equalization (AHE) improves upon the standard method by considering local histograms in smaller regions of the image. Instead of applying a single transformation to the entire image, AHE divides the image into rectangular blocks and performs histogram equalization on each block independently. This approach enhances local contrast and details more effectively. Nevertheless, it can introduce noise and artifacts, particularly in homogeneous areas.

Contrast limited adaptive histogram equalization

Contrast Limited Adaptive Histogram Equalization (CLAHE) is an extension of AHE designed to mitigate noise amplification. It limits the contrast enhancement by clipping the histogram at a predefined value before equalization. This limitation prevents over-amplification of noise, resulting in a more balanced enhancement. CLAHE is highly effective in medical imaging, where preserving subtle details is crucial.

Histogram matching

Histogram Matching, also known as histogram specification, is a technique that transforms the histogram of an input image to match a specified histogram. This specified histogram could be derived from another image or designed based on desired characteristics. Histogram matching is helpful in applications where a specific visual appearance is required. It provides better control over the enhancement process but requires a reference histogram, making it less flexible than other methods.

Multi-histogram equalization

Multi-Histogram Equalization (MHE) divides the image into multiple regions, each with its own histogram. By equalizing the histogram in each region separately, MHE achieves a more refined enhancement. The regions can be defined based on pixel intensity ranges or spatial locations. MHE can address the limitations of standard equalization by preserving local details and avoiding over-enhancement. However, the choice of regions and their boundaries can significantly impact the result.

Bi-histogram equalization

Bi-Histogram Equalization splits the image histogram into two separate histograms based on a threshold value. The threshold is typically set to the median intensity value, dividing the histogram into low- and high-intensity regions. Each region is then equalized independently. This method is beneficial for images with bimodal histograms, where different parts of the image require distinct enhancements. Bi-Histogram Equalization maintains overall contrast while effectively addressing specific areas.

Recursive mean-separate histogram equalization

Recursive Mean-Separate Histogram Equalization (RMSHE) is a variant of bi-histogram equalization. It recursively divides the histogram into sub-histograms based on mean intensity values and equalizes each sub-histogram. This recursive approach ensures that even finer details are enhanced. RMSHE adapts to varying contrast levels within the image, making it suitable for complex images with multiple regions of interest.

Gamma correction-based histogram equalization

Gamma Correction-Based Histogram Equalization combines gamma correction with histogram equalization to achieve a more balanced enhancement. Gamma correction adjusts the image brightness before equalization, ensuring that intensity values are more evenly distributed. This method is effective for images with non-linear intensity distributions, where standard equalization might fail to provide satisfactory results.

Fuzzy logic-based histogram equalization

Fuzzy Logic-Based Histogram Equalization employs fuzzy logic principles to control the equalization process. By defining fuzzy rules and membership functions, this method adjusts intensity values based on the degree of membership in different regions. Fuzzy logic provides a more flexible approach to enhancement, enabling better preservation of details and avoiding abrupt intensity changes. This technique is advantageous for images with complex, fuzzy boundaries.

Neural network-based histogram equalization

Neural Network-Based Histogram Equalization leverages the power of artificial neural networks to learn the optimal equalization parameters. By training a neural network on a set of images, this method can automatically adjust the intensity values to achieve desired enhancements. Neural network-based equalization is highly adaptive and can handle a wide range of images with varying characteristics. Although it requires training data and computational resources, it offers superior performance in complex scenarios.

Numerous algorithms use histogram equalization for different image processing needs. From standard methods to advanced approaches such as neural networks, each algorithm offers unique advantages and addresses specific challenges. Understanding these algorithms and their applications is essential for selecting the most appropriate method to enhance image contrast effectively. By leveraging the right algorithm, professionals can achieve remarkable improvements in image quality, advancing fields such as medical imaging, remote sensing, and digital photography, including digital medical photography.

Histogram equalization in medical photography

Clinical rationale and technical consensus

The diagnostic assessment of visible injuries relies heavily on the accurate visualization of wound margins, tissue color, and subtle textural features. Color medical photographs are a critical adjunct to the clinical record, supporting diagnosis, monitoring, and, in some cases, forensic documentation. However, suboptimal image quality, such as poor contrast, uneven lighting, or device variability, can obscure diagnostically relevant features and compromise clinical interpretation. The medical imaging literature strongly supports the use of histogram equalization—specifically, adaptive methods such as contrast-limited adaptive histogram equalization (CLAHE)—to enhance contrast and feature visibility in color medical photographs, provided that color fidelity is preserved and artifacts are minimized.[7,37–39]

A key technical consensus is that applying histogram equalization directly to each RGB channel is discouraged due to the risk of color distortion and unnatural appearance, which can mislead clinical assessment.[37,39,40] Instead, the recommended approach is to convert the image to a color space that separates luminance (brightness) from chrominance (color information), such as LAB or HSV. Histogram equalization or CLAHE is then applied exclusively to the luminance channel, preserving the original hue and saturation relationships. This method has been validated across multiple studies for its ability to enhance diagnostic features while preserving tissue's natural appearance.[7,37–39,41]

Adaptive and region-based methods, including CLAHE and exposure region-based modified adaptive histogram equalization (ERBMAHE), further improve outcomes by limiting noise amplification, preventing over-enhancement, and balancing contrast across unevenly illuminated regions.[6,7,41] These methods are supported by robust quantitative and qualitative evidence, including improved image quality scores, higher diagnostic accuracy in automated classifiers, and expert visual assessment.[7,37,38,41]

One current proprietary camera system with built-in histogram equalization is the CortexFlo by Fernico. This system features an option called "Enhance Contrast" in the photograph review menu to apply histogram equalization to the image. Although the camera system's literature does not specify how HE is implemented, as seen in Figures 1 and 2, the histograms seem to be modified using a SHE protocol rather than an adaptive or region-based HE method. Consequently, these images do not retain perfect color fidelity. Instead, the dominance of mid-channel red colors decreases, while the mid-channel blue and green are enhanced. The goal of this approach is to improve the visibility of blues, yellows, and greens that may be present in a bruise by reducing the red coloration's dominance. This method is not the standard way histogram equalization is used to improve contrast while preserving color accuracy, as we discuss below, but rather to highlight the less visible colors in bruising.

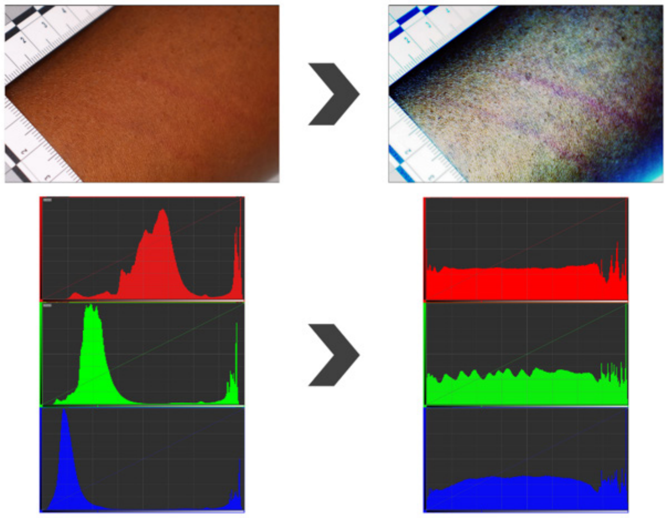

Figure 1 Belt Injury.

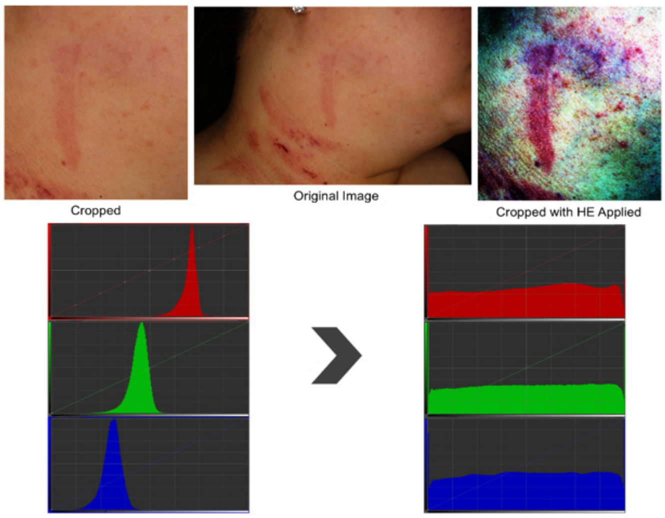

Figure 2 Neck Injury.

Stepwise process for application of histogram equalization

Image acquisition and color calibration

The foundation of effective diagnostic enhancement is the acquisition of high-quality, standardized color photographs. Images should be captured under consistent, diffuse lighting, with a neutral or royal blue background to optimize contrast, especially for skin of color.[42] The use of a color calibration guide, such as the MacBeth Color Checker Chart or a ruler with color swatches, is essential

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for correcting color and exposure variability introduced by camera sensors and environmental conditions.[43–45] The calibration guide should be included in at least one image of each injury, positioned close to the region of interest and under the same lighting conditions. This enables mathematical transformation of the image's color data to a device-independent standard (e.g., sRGB or CIE Lab*), minimizing color distortion during subsequent processing.[45]

The American College of Surgeons and other clinical guidelines recommend bracketing the image series with photographs displaying patient identification, date, time, and photographer's name, and including a standardized scale for size reference.[44,46] Images should be acquired in a lossless format (TIFF or PNG) at a minimum spatial resolution of 800 × 600 pixels (preferred: 1024 × 768 or higher) and 24-bit color depth, as recommended by the American Telemedicine Association and Primary Care Commissioning.[45]

The importance of lighting and background selection is illustrated in the figure from Grinnell et al published in JAMA Dermatology, which demonstrates how different light sources and backgrounds affect the appearance of skin of color.(Figure 3)[42] Neutral/white tones are preferred, and flash photography should be avoided to prevent shadows and color shifts.

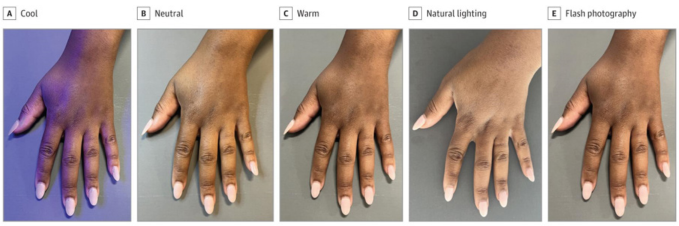

Figure 3 Clinical images with different tones.

Digital Photography Guide for Dermatologists with Special Considerations for Diverse Populations. JAMA Dermatol. May 31, 2025.

Content used under license from the JAMA Network® © American Medical Association: will need to get this image and ask for permission to publish.

Color space transformation and enhancement

Once a calibrated, high-quality image is acquired, the next step is to convert the image from its native RGB color space to a color space that separates luminance from chrominance. The two most widely used color spaces for this purpose are LAB (Lab*), also known as CIE, and HSV (Hue, Saturation, Value).[31,37–39] In LAB, the L channel represents lightness (luminance), while a and b encode color information. In HSV, the V channel represents brightness, with H and S encoding hue and saturation.

The image is converted using standard functions in medical imaging software such as Image J/Fiji, MATLAB, or Python's OpenCV/scikit-image libraries.[7,37,38] After conversion, the luminance channel (L in LAB or V in HSV) is extracted for enhancement. This channel is the target for histogram equalization, as modifying it does not affect the underlying color relationships critical for clinical interpretation.[37–39]

Contrast enhancement can be performed using CLAHE or an advanced adaptive method. CLAHE operates on small regions (tiles) of the image, limiting the amplification of noise by clipping the histogram at a predefined threshold. Recommended parameters for CLAHE include a tile size of 8 × 8 to 16 × 16 pixels and a clip limit of 2.0 to 4.0, but these should be optimized based on image characteristics and clinical requirements.[7,37,38,41] For example, Zhou et al[37] demonstrated that applying CLAHE to the luminosity channel in LAB space improved image quality scores from an average of 0.0404 to 0.4565 in a dataset of 961 poor-quality retinal images, with preserved natural appearance and enhanced diagnostic features.[37] Jin K et al[38] reported similar improvements in degraded fundus photographs, with area under the curve values for disease classifiers exceeding 0.97 after enhancement.[38]

After enhancement, the processed luminance channel is recombined with the original chrominance channels (a and b in LAB, or H and S in HSV) to reconstruct the full color image. The enhanced image is then converted back to RGB for display, storage, or further analysis.[37–39] This workflow preserves color fidelity and avoids the gamut problem, where color values fall outside the valid display range.[40,47]

For images with complex color relationships or where hue preservation is critical (e.g., wound assessment, dermatology), advanced algorithms such as hue-preserving and channel-adaptive equalization may be used. These methods maintain the ratio similarity across color channels, further reducing the risk of color degradation.[39,40,47]

When using the CortexFlo camera system by Fernico during forensic medical examinations, the color-space transformation does not appear to occur; instead, the image remains in sRGB color space in both the camera and on the display.(Figure1 and Figure 2)

Handling uneven lighting and shadows

Medical photographs often exhibit uneven lighting or shadows, which can confound global histogram equalization and lead to over-enhancement or loss of detail in poorly illuminated regions.[3,6,7] Adaptive and region-based methods are recommended to address these challenges. CLAHE inherently adapts to local contrast variations, but for images with pronounced exposure differences, region-based segmentation and enhancement are superior.

The Exposure Region-Based Modified Adaptive Histogram Equalization (ERBMAHE) method, as described by Gangwar et al,[7] segments the image into underexposed, well-exposed, and overexposed regions using algorithms such as 9IEC. Each region undergoes adaptive contrast enhancement via a weighted probability density function and power-law transformation, with parameters optimized by particle swarm optimization (PSO).[7] This approach achieved a peak signal-to-noise ratio (PSNR) of 31.10 dB, entropy of 7.48, and feature similarity index (FSIM) of 0.98 in a dataset of 600 chest X-ray images, with expert validation confirming improved visibility of critical features.[7] While developed for radiological images, the principles are directly transferable to color photographs of injuries.

Other advanced methods include entropy-based adaptive sub histogram equalization, which divides the histogram into segments based on entropy and equalizes each sub histogram independently, and context-based energy equalization with clipping limits, which uses spatial adjacency information to balance enhancement.[48] These methods are particularly effective for images with no uniform illumination, as they preserve brightness and fine details while avoiding over-amplification in any single region.

For severe lighting artifacts, structural compensation enhancement and multi-exposure fusion strategies can be employed. These involve estimating local ambient light maps, generating structural maps of illumination compensation, and fusing multiple corrected images to achieve balanced exposure and natural appearance.[49,50]

Evaluation of diagnostic quality and artifact presence

The diagnostic utility of enhanced color medical photographs must be rigorously evaluated using both quantitative and qualitative metrics. Quantitative metrics provide objective, reproducible measures of image quality, while qualitative assessment by medical experts ensures that clinically relevant features are preserved and artifacts are minimized.

Key quantitative metrics include spatial resolution (minimum 800 × 600 pixels, preferred 1024 × 768 or higher), color resolution (24 bits), signal-to-noise ratio (SNR), peak signal-to-noise ratio (PSNR), entropy, modulation transfer function (MTF), feature similarity index (FSIM), and color distance metrics (e.g., ΔE in CIE Lab*).[45,51,52] For example, Gangwar et al.,[7] reported PSNR values of 31.10 dB and FSIM of 0.98 for their optimized ERBMAHE method, indicating high-quality enhancement with preserved diagnostic features.[7] Entropy values above 7.0 are generally indicative of improved information content without excessive noise.[7,33]

Qualitative assessment involves expert visual review of the enhanced images to confirm the visibility of wound margins, tissue texture, and color changes. Experts also identify artifacts such as color distortion, over-enhancement, noise amplification, and artificial edges.[53,54] The CLEAR Derm consensus guidelines recommend detailed documentation of artifact types and their distribution, including pen markings, rulers, hair, lighting conditions, and color calibration status.[53] Consistency and standardization in acquisition and display protocols are essential for reliable interpretation.[54]

A comprehensive evaluation should integrate both quantitative and qualitative metrics, with clear documentation of acquisition conditions, processing algorithms, and display calibration. This approach ensures that enhancement improves diagnostic utility while maintaining color fidelity and minimizing confounding artifacts.[45,53,54]

Documentation, reporting, and regulatory compliance

Meticulous documentation and regulatory compliance are essential for the clinical and forensic use of enhanced injury photographs. The American College of Surgeons and the HIMSS-SIIM Enterprise Imaging Community emphasize that medical photographs are protected health information and must be managed with the same confidentiality, security, and documentation standards as other medical records.[46] Enhanced photographs must be stored in secure, HIPAA-compliant systems, with role-based access, audit trails, and metadata association.[55–57]

All steps in image acquisition and processing must be documented in the electronic medical record or equivalent system. This includes patient identification, date and time of acquisition, photographer's name, the photograph's context, and details of the processing algorithms and parameters used (e.g., software version, CLAHE tile size and clip limit, color space transformation).[46,55,58] The original, unprocessed image must be retained and archived alongside the processed version, with clear linkage between the two to allow for independent verification.[55,56,58]

In forensic contexts, additional requirements for chain of custody, authentication, and evidentiary integrity apply. Every transfer, access, or modification of the image files must be documented, and images must be stored in secure, tamper-evident systems.[46,56,58,59] Consent for photography and image processing must be obtained and documented, with specific reference to the intended use (clinical, research, publication, forensic). (Grinnell et al 2025) Patients have the right to access their photographs and to withdraw consent for secondary uses.

Quality assurance and regular staff training are recommended to ensure adherence to standardized protocols and to maintain the clinical and legal validity of enhanced photographs.[44,60,61] Institutional policies should define requirements for medical photography, including consent processes, access controls, and audit trails.[55,62]

Recent advances and clinical validation

Recent advances in histogram equalization algorithms for color medical photographs of skin and wounds have focused on hybrid and region-adaptive methods that combine histogram equalization with wavelet transforms, fuzzy logic, entropy-based segmentation, and human visual system models.[7,11,29,33,48,63] These methods address the limitations of conventional histogram equalization, such as over-enhancement, loss of fine detail, and color distortion, and have been validated in medical imaging studies for their ability to enhance contrast, preserve brightness, suppress artifacts, and maintain color fidelity.

For example, Hanlon et al demonstrated that combining wavelet-based transformations with CLAHE significantly improved the visualization of dermal features in reflectance confocal microscopy images of skin, with preserved details, reduced noise, and increased contrast.[63] Gangwar et al's[7] ERBMAHE method achieved superior PSNR, entropy, and FSIM values in chest X-ray imaging, with principles directly applicable to skin and wound photographs.[7] Fuzzy and entropy-based adaptive equalization methods have shown superior performance in preserving fine details and suppressing noise, critical for accurate assessment of wound margins and tissue viability.[33,34]

Clinical validation studies in retinal imaging and skin injury analysis provide indirect but compelling evidence that advanced histogram equalization techniques improve the visibility of diagnostically relevant features and support more accurate assessment and monitoring.[37,38,41,64] For example, Zhou et al reported that their enhancement protocol improved image quality scores from 0.0404 to 0.4565 in poor-quality retinal images, with preserved natural appearance and enhanced diagnostic features.[37] Jin et al.,[38] demonstrated that enhanced images facilitated more efficient screening for retinal diseases, with AUC values for disease classifiers exceeding 0.97.[38] Mattsson et al.,[64] validated the use of digital image analysis for quantitative monitoring of erythema in thermal injury, supporting the broader concept that digital enhancement of color photographs can improve diagnostic monitoring of pathophysiological changes.[64]

In summary, the current consensus is that adaptive and region-based histogram equalization methods—particularly those incorporating wavelet transforms, fuzzy logic, entropy-based segmentation, and human visual system models—offer significant improvements over traditional methods for color medical photographs of skin and wounds. Quantitative and qualitative validation studies support these advances and are increasingly available in medical imaging software platforms (Table 1).[7,11,29,33,48,63]

These steps, supported by robust evidence and clinical guidelines, enable the photographer to confidently apply histogram equalization to enhance diagnostic interpretation of color photographs of injuries, ensuring optimal visualization of clinically relevant features while maintaining color fidelity and compliance with clinical and forensic standards.

Image artifacts in medical photography and medical imaging

Image enhancement methods in medical photography—including post-acquisition processing, color calibration, image compression, and lighting adjustments—are widely used to improve image quality and highlight diagnostic features. However, these methods can introduce a range of artifacts, such as color distortion, compression artifacts, lighting inconsistencies, and manipulation effects. Color distortion may arise from improper calibration or lighting, while compression artifacts can degrade image quality, especially at high compression ratios. Manipulation effects, whether intentional or inadvertent, can alter the appearance of lesions or anatomical structures, and lighting inconsistencies can obscure or exaggerate clinical findings.[29,45,65,66]

Table 1 Adapted from the research synthesis, summarizes the recommended protocol steps for histogram equalization in LAB/HSV color space, including key considerations and supporting references

Step	Description	Key considerations	References
Image Acquisition	Capture high-quality color photograph	Standardized lighting, color calibration	Zhou M et al.[37]; Jin K et al.[38]; Song KS et al.[39]; Gangwar S et al.[7]
Color Space Transformation	Convert RGB to LAB or HSV	Use software tools (ImageJ, MATLAB, Python)	Zhou M et al.[37]; Jin K et al[38]; Naik and Murthy[40]; Huang Z et al.[41]
Luminance Channel Extraction	Extract L (LAB) or V (HSV) channel	Target for enhancement	Zhou M et al.[37]; Jin K et al.[38]; Naik and Murthy[40]
Apply CLAHE/HE	Enhance luminance channel	Prefer CLAHE; optimize parameters	Zhou M et al.[37]; Jin K et al.[38]; Stark JA[6]; Grinnell M et al.[42]
Recombine Channels	Merge enhanced luminance with original chrominance	Preserve color fidelity	Zhou M et al.[37]; Jin K et al.[38]; Naik and Murthy[40]
Convert to RGB	Return to RGB for display/storage	Accurate color representation	Zhou M et al.[37]; Jin K et al.[38]
Quality Assessment	Visual and quantitative evaluation	Use objective metrics, expert review	Stark JA[6]; Vander and Naeyaert[43]; Bloemen EM et al.[44]; Quigley EA et al.[45]; Cocanour CS et al.[46]
Documentation	Record all processing steps	Ensure transparency and reproducibility	Gangwar S et al.[7]; Kumar and Bhandari[31]; Nikolova and Steidl[47]; Arici T et al.[3]

Potential side effects or artifacts introduced by commonly used alternative image enhancement methods in medical photography include:

Color distortion: Automated white balance and AI-based color correction algorithms in smartphones and editing software can introduce inaccuracies, particularly in images of skin of color, leading to misrepresentation of true skin tones and potentially impacting clinical assessment.[42]

Loss of diagnostic authenticity: Use of filters, high dynamic range, portrait mode, or other enhancement features can alter the baseline appearance of lesions or skin, introducing artificial smoothness, blurring, or exaggerated contrast that may obscure subtle clinical findings.[42]

Over-enhancement and unnatural appearance: Aggressive application of adaptive gamma correction or texture-based enhancement can result in excessive contrast, edge artifacts, or loss of structural similarity, which may compromise the diagnostic value of the image.[29]

Compression artifacts: Image compression, especially at high ratios or with lossy formats, can introduce blockiness, color banding, and loss of fine detail, which may affect the interpretation of subtle findings.[45]

Distortion from lens or software: Wide-angle lenses and certain digital zoom or cropping techniques can stretch or distort anatomical features, while background removal or artificial editing can further alter the clinical context.[42]

Color distortion between media types: Image may not appear identical in color, shadowing, and highlights between digital display and printed display. These differences may be affected by the use of image processing systems such as histogram equalization. Digital displays often appear brighter than images printed on paper, an effect known as "screen-to-print disparity."[67,68] Knowledge of how images will be displayed in court proceedings may favor the use of HE in some photos to promote easier observation of findings in the evidentiary forensic medical report.

To minimize these artifacts, the medical literature emphasizes the importance of minimal post-acquisition processing, careful control of lighting and background during image capture, and preservation of original image data for clinical use.[42,45]

For medical photography, artifact reduction relies on optimal image acquisition: use diffuse, neutral/white lighting, avoid flash and mixed color temperatures, select appropriate backgrounds (e.g., royal blue for darker skin, black for lighter skin), and maintain consistent patient positioning and camera settings. Filters, high dynamic range, and post-processing edits should be avoided to preserve diagnostic authenticity. Updated device models and careful use of autofocus and zoom can further reduce distortion and color inaccuracies. (Grinnell et al 2025)

Artifacts introduced by image enhancement methods can impact the accuracy of clinical decision-making by misrepresenting skin tone, lesion morphology, and other diagnostic features, leading to inaccurate assessments. For example, color distortion may result in the misclassification of pigmented lesions, while excessive contrast enhancement or smoothing can obscure subtle morphological changes critical for diagnosis. Manipulation effects, even when unintentional, can alter the perceived size, shape, or color of lesions, potentially leading to misdiagnosis or inappropriate management.[45,65,66]

In medical photography, enhancement methods such as adaptive gamma correction, histogram equalization, and texture-based algorithms can introduce artifacts including color distortion, loss of diagnostic authenticity, and over-enhancement, which may obscure subtle clinical features or misrepresent lesion morphology.[29] These artifacts are typically related to post-processing and can directly impact visual interpretation and clinical decision-making.

However, digital radiography is prone to artifacts from equipment defects, calibration flaws, acquisition technique errors, and signal transmission failures. Processing-induced artifacts, such as those from improper gain calibration or detector saturation, can degrade image quality and obscure anatomical details, but are often identifiable and correctable with quality control protocols.[69]

CT imaging is particularly susceptible to physics-based artifacts such as beam hardening, photon starvation, and metal-induced streaks. Enhancement algorithms like metal artifact reduction (MAR) and dual-energy CT can mitigate these, but may also introduce new artifacts or fail to fully restore diagnostic information, especially in the presence of extensive metallic hardware.[70–72] Patient movement and scanner-based imperfections further contribute to artifact burden.

MRI is affected by a wide range of artifacts, including motion, magnetic susceptibility, chemical shift, and aliasing. Enhancement and artifact reduction techniques—such as optimized pulse sequences, respiratory gating, and parallel imaging—can reduce some errors but may also introduce spatial misregistration, signal loss, or simulate pathology if not properly applied.[73–78] The complexity of MRI physics means that artifact recognition and mitigation require specialized expertise.

In summary, artifact-related errors in medical photography are primarily post-processing and color-related, while radiography, CT, and MRI are more affected by acquisition, hardware, and physics-based artifacts. The clinical impact and mitigation strategies are modality-specific, and understanding these differences is essential for accurate image interpretation and clinical decision-making.[29,69,70,73]

Recognition of image manipulations and artifacts

Evidence demonstrates that even experienced clinicians have difficulty reliably detecting digital manipulation in medical photographs, with low sensitivity and poor interobserver agreement. This increases the risk of misdiagnosis, miscommunication, and potential medico legal consequences, as clinical decisions may be based on images that do not accurately represent the patient's condition.[45] Furthermore, inconsistencies in color calibration and lighting can compromise the reproducibility and reliability of clinical decisions, particularly in longitudinal follow-up or telemedicine settings, where accurate comparison of serial images is essential.[45,65]

To minimize the impact of artifacts, consensus guidelines recommend minimal post-acquisition processing, standardized lighting conditions, and the use of color calibration procedures when feasible. Retaining original, unprocessed images and acquisition metadata is emphasized to ensure transparency, reproducibility, and the ability to audit or re-evaluate images if needed.[45,53,65] In both clinical and research settings, it is essential to report all preprocessing and post processing steps, as well as any potential artifacts, to maintain scientific rigor and support accurate interpretation of image-based data.[53]

Despite these recommendations, important limitations remain, including the lack of universally accepted color calibration standards and limited data on the impact of artifacts in artificial intelligence driven (AI-driven) diagnostic systems. Further research is needed to establish robust protocols for artifact detection and mitigation, particularly as image-based artificial intelligence becomes increasingly integrated into clinical workflows.[45,53]

Diagnostic accuracy between computer monitor images and printed images

The appearance of medical photographs and medical images can differ when viewed on a computer screen compared to when printed on paper or photographic paper. This difference is due to several factors, including display device characteristics (such as luminance, contrast, resolution, and color calibration), print media quality, and viewing conditions.

Images displayed on diagnostic monitors typically offer higher dynamic range, better contrast, and more consistent color reproduction when properly calibrated, as recommended by the American Telemedicine Association and the PCC SF teledermatology guidelines.[45] Monitors allow for image manipulation (zoom, brightness, contrast adjustment), which is not possible with printed images.[79] However, the subjective image quality of printed images can approach that of monitor displays if high-quality printers and appropriate paper (e.g., direct thermal prints, glossy paper) are used, but significant differences remain depending on the print medium and printer technology.[80–83]

Studies have shown that direct thermal prints and monitor displays provide superior image quality compared to inkjet prints on regular paper, with statistically significant differences in perceived image quality and diagnostic sensitivity.[80,81] Additionally, the physical properties of monitors (such as higher luminance and spatial resolution) generally facilitate greater information transfer than most printed media, although advances in printing technology have narrowed this gap for documentation purposes.[82,84]

Diagnostic accuracy when interpreting medical images on monitors versus printed formats is generally equivalent or superior with high-quality monitors but can be inferior with lower-quality displays or paper prints, especially for subtle findings. In radiology, multiple studies have shown that soft-copy interpretation using radiology workstations yields statistically significant improvements in sensitivity, specificity, and overall accuracy for computed tomography scans compared to film-based interpretation.[85] For sonography, interpretative accuracy is similar between monitor and film display formats.[86] In digital mammography, both soft-copy and printed-film displays provide comparable diagnostic performance, with no significant differences in sensitivity, specificity, or area under the receiver operator curve.[87,88]

However, printed paper images—especially those produced with standard printers—are less sensitive for detecting small or low-contrast lesions compared to laser film or high-resolution monitors.[89] High-quality liquid crystal display monitors outperform cathode ray tube monitors and hardcopy prints in nodule detection, provided they meet physical acceptance criteria for luminance and resolution.[90] Lower-resolution or poorly calibrated monitors result in inferior diagnostic performance compared to hard copies or high-end displays.[91,92]

In dermatology, consensus guidelines from the American Telemedicine Association and the PCC SF recommend calibrated, high-resolution monitors for optimal image interpretation, noting that color management and calibration are critical for diagnostic fidelity.[45] Printed images can be acceptable for documentation, but diagnostic accuracy is best maintained with digital display systems.

Clinical outcomes are not directly compared in most studies, but the literature supports that diagnostic accuracy—and thus potential clinical outcomes—are maximized when using high-quality, calibrated digital displays rather than printed formats, especially for subtle or small lesions.[85,89–91]

In summary, the appearance and diagnostic utility of medical images are influenced by the display modality, with monitors generally providing superior and more consistent image quality compared to most printed formats, unless high-end printing techniques are used.[45,80,81,84,94–97]

Conclusion

The application of histogram equalization to color medical photographs of visible injuries for diagnostic enhancement is poorly studied. Color fidelity appears to be best achieved by converting the image to a color space that separates luminance from chrominance (LAB or HSV), applying adaptive histogram equalization (preferably CLAHE) to the luminance channel, and recombining with the original color channels. This workflow preserves color fidelity, enhances diagnostically relevant features, and minimizes artifacts. Advanced adaptive and region-based methods further optimize enhancement in images with uneven lighting or complex textures. A current single manufacturer that uses histogram equalization, identified as a contrast filter, for image enhancement in their proprietary system appears to use standard histogram equalization algorithms.[98] No published peer-reviewed literature has analyzed the interpretation, error rate, or effectiveness of the CortexFlo HE system in forensic medical examinations. Rigorous evaluation using quantitative and qualitative metrics, meticulous documentation, and strict regulatory compliance are essential for clinical and forensic validity. Current understanding suggests that examiners and courts should be circumspect about the importance of findings observed with HE contrast enhancement in medical photographs, particularly when using a standard histogram equalization algorithm. Recent advances in algorithmic methods and clinical validation studies support the need for further research on these techniques before considering histogram equalization as a routine practice in photographs of forensically important injuries, thereby ensuring that enhanced images provide accurate, reliable, and actionable information for patient care and forensic interpretation.

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Conflicts of Interest

William Hauda works as an expert witness in court proceedings including those were forensic medical photographs are presented as evidence.

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