ORIGINAL ARTICLE

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Maximizing Quality in Ophthalmic Digital Imaging

INTRODUCTION

The digital revolution in ophthalmic imaging started with the introduction of the PAR Microsystems IS-2000 digital imaging solution for color fundus photography and fluorescein angiography in 1983. Since then, several commercial digital imaging systems have been designed for ophthalmic imaging, and the market has witnessed steady improvement in digital technology over the last two decades. Recent survey data from 2004 indicate that over 70% of ophthalmic imagers are utilizing digital technology for both fluorescein angiography and color fundus photography.[1] That percentage would surely be higher if surveyed today.

Despite a history of over twenty years of experience with digital technology, there is a common perception that, even with current tools, ophthalmic digital images, especially color fundus photographs, are often disappointing and inconsistent in quality. This raises several questions for us as professional imagers: Why are images disappointing? Are the available digital tools inadequate for our specific purposes? Are we using digital technology incorrectly? Are we stuck in a film mindset? Examining these fundamental questions will allow us to find answers to the most important question at hand: what can we do to maximize digital image quality with the tools currently available to us? The following is a practical approach for maximizing quality in digital fundus imaging.

IDENTIFYING QUALITY ISSUES

Several factors play a role in the quality of our images. Sensor characteristics, spatial resolution, file compression, color management, exposure, saturation, contrast, and a lack of universal standards all play a role in the quality and consistency of our diagnostic images. Some of these factors are beyond the direct control of the end user, and are the subject of different articles in this publication. In this discussion we will concentrate on factors that imagers can control in the clinical setting to maximize image quality.

Frequently mentioned quality issues include problems such as a "noisy" or pixilated appearance, a lack of sharpness, loss of detail due to blown out highlights (blooming), and poor color reproduction that is sometimes described as "cartoon color" in fundus photographs (Figure 1). The problems that cause these conditions can be divided into two types: operational problems at the camera such as improper focus or exposure, and those that result from image processing such as oversaturation, over-sharpening and file compression artifacts. Some of these factors are simple to control through system adjustment while others, especially exposure, can be quite challenging to optimize. Even subtle adjustments can make significant changes in image quality.

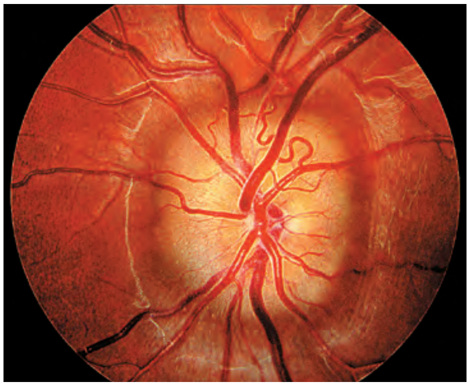


Figure 1: "Over-processed" digital fundus photograph demonstrating unnatural color reproduction and noise from oversaturation and over-sharpening.

One of the great advantages of digital imaging is the instant feedback it provides the imager, but in a busy clinical practice there may be a tendency to dismiss the need for constant assessment and adjustment to achieve quality diagnostic results. All of the suggested quality improvement strategies in this discussion rely on critical evaluation of the image on the capture monitor to identify the underlying problem and the effects of corrective measures. This emphasizes the need for a high-quality viewing system. Monitors that are properly adjusted to the viewing environment, calibrated with the use of a test image, or profiled using a color management system provide the most reliable view for judging image quality at capture. Color management is a strategy to maintain color accuracy throughout the entire digital imaging chain.[2] Color management establishes a communication framework that utilizes device color (ICC) profiles to resolve differences between imaging devices with a different color gamut. Although an important consideration in ophthalmic digital imaging, color management is beyond the scope of this paper.

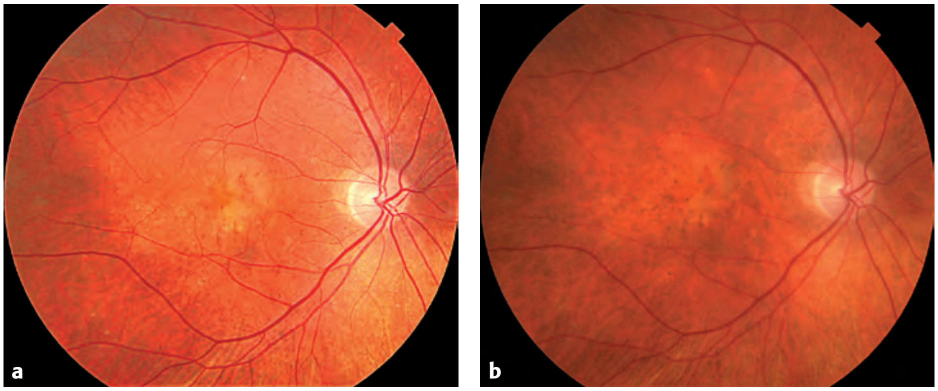


Figure 2: Slight differences in exposure can make a significant change in color reproduction quality. (a) Overexposure results in a "posterized" appearance. (b) A half-step reduction in flash output dramatically improves the color rendition and detail illustrating the need for tight exposure control in digital fundus imaging.

EXPOSURE

Controlling exposure is one of the more challenging quality issues in ophthalmic digital imaging and the importance of it is often overlooked. Most color sensors available today do an excellent job in capturing a full spectrum of color for general pictorial use, but often have a difficult time accurately rendering subtle color differences in the red, orange, yellow range. These are the most common colors encountered in fundus photography; and color transparency films do a reasonable job in rendering them accurately. Current digital sensors also respond to light in a more linear fashion than either film or the human eye, and do not offer the exposure latitude of film.[3] Even the slightest amount of underexposure, or especially overexposure, can be detrimental to digital image quality. Because of these factors, exposure must be carefully evaluated and adjusted. Overexposure affects not only brightness in color digital images, but also color rendition and detail. Overexposure can limit the range of colors recorded, creating a "posterized" look as if the images were rendered at a reduced bit-depth (Figure 2). Exposure problems aren't limited to just color imaging, however. Blooming of highlights is a problem often encountered when trying to record the wide dynamic range of fluorescence that occurs during the transit phase of angiography.

Moving to a digital environment requires a change in exposure strategy. When using film, most exposure adjustments are made by varying the flash output of the fundus camera. With a little trial-and-error, the correct exposure for a particular film can be reliably predicted for most patients at standard settings. Slight adjustments are necessary for conditions such as small pupils, unusually light, or unusually dark fundi, but otherwise exposures remain relatively constant. With digital imaging, we can no longer use this "one-size-fits-all" approach to exposure. The best settings for exposure need to be adapted to each subject or situation. Photography becomes a more dynamic process of assessing each image and often making several exposure adjustments during a single capture session. Once the correct exposure is identified for a particular field of view, successive images must still be carefully monitored because moving to different peripheral fields may require additional exposure adjustment. Even the simple practice of shifting between two halves of a sequential stereo pair can induce an exposure difference that may require a slight exposure adjustment between frames.

Although more challenging, digital exposure can be accurately controlled through a combination of flash, gain, and gamma settings. During system installation and setup, exposure tests should be conducted to arrive at ballpark gain and gamma settings for each type of imaging. Hopefully these baseline settings will land in the middle of the range of adjustability to allow adequate room for situational adjustment when necessary. Most systems allow the user to save and recall different combinations of exposure settings with preset buttons in the capture software. Many imagers use the preset buttons to recall exposure settings for normal, light, or dark fundi.

GAMMA

In traditional photographic sensitometry, gamma refers to the straight-line portion of the D-log E curve of a film and developer combination, and it relates directly to contrast. The Gamma control for digital cameras alters the normal linear relationship between subject brightness and digital output. It adjusts mid-tones and affects both contrast and saturation. The default system parameters of some fundus imaging systems employ gamma settings that unnecessarily increase color saturation and contrast (Figure 3). Images may initially look impressive at these settings, but they are often inaccurate due to an exaggerated color rendition. Exposure is more difficult to control at these gamma settings because the already limited exposure latitude is further reduced. Use trial-and-error to arrive at gamma settings that work well for each type of retinal imaging. In color fundus photography, use gamma to help control color saturation. In monochromatic photography and angiography, choose settings that create enough contrast to visualize retinal pathology without blowing out highlights. Gamma can be used to increase the low contrast inherent in fundus autofluorescence imaging. Once optimal gamma settings are determined for these different imaging types, only slight adjustment will occasionally be required during capture sessions.

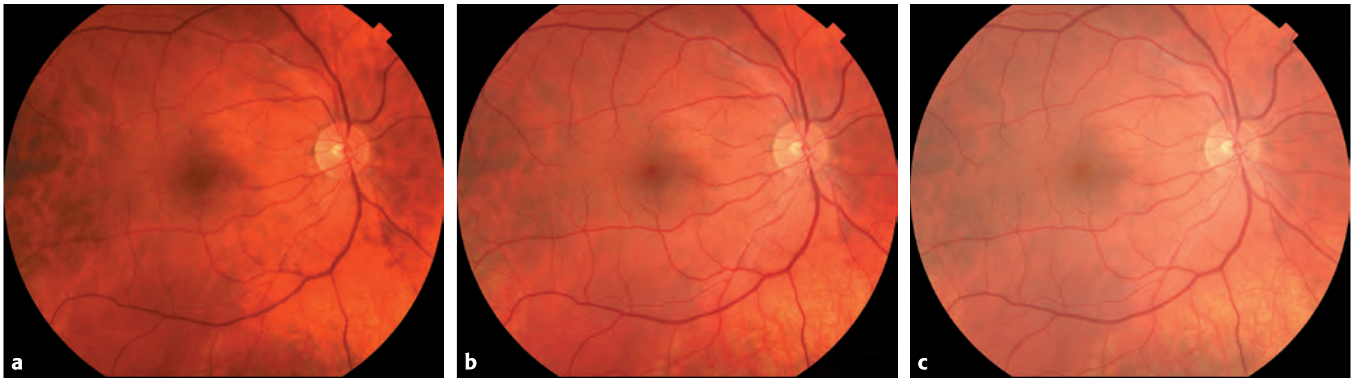


Figure 3: The Gamma control adjusts the linear relationship between subject brightness and image brightness, affecting contrast and color saturation. (a) Oversaturation from high gamma setting. (b) Normal gamma. (c) Desaturated appearance from low gamma setting.

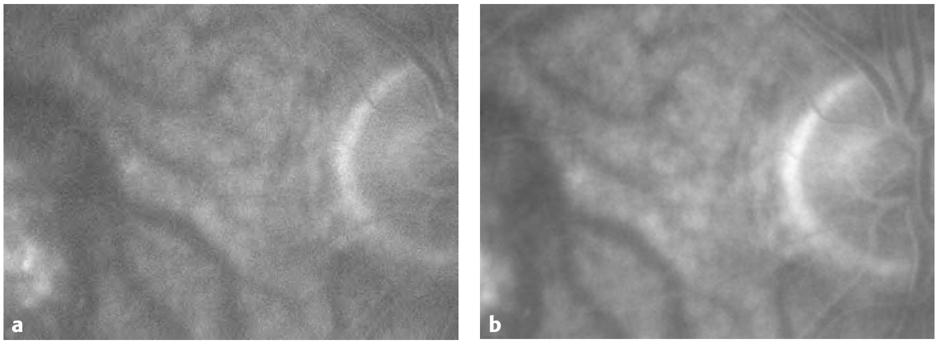


Figure 4: High gain settings may be needed to compensate for the Bayer color filter when using a color sensor for monochromatic imaging. (a) Late phase photo from a color sensor demonstrates noise from high gain settings. (b) A photograph of the same subject using a monochrome sensor with lower gain settings shows a reduction in noise and increased detail on the optic nerve.

GAIN

Gain is a very useful exposure control that is user-adjustable on most digital capture systems. Gain is digital signal amplification and it relates directly to the light sensitivity of the sensor, making it somewhat analogous to the ISO rating of film. Unfortunately, increased gain settings result in low signal-to-noise ratios that reduce image quality. In normal exposure situations, choose a gain setting low enough to minimize image noise, but not so low that high flash output is required to obtain adequate exposure. Subtle gain adjustments can be used to fine-tune the exposure when consecutive flash settings don't provide optimal exposure. One of the capture software presets buttons can be used to store this type of gain adjustment for easy recall.

Noise is often noticeable in grayscale angiographic images taken with high-resolution color sensors, especially in late phase photos (Figure 4). High gain settings are often needed when using color sensors in grayscale mode to compensate for the lower sensitivity of the sensor due to light loss from the Bayer color filter array. To reduce noise in very low-light situations such as fundus autofluorescence, set the fundus camera for maximum light transmission and flash output, and use the lowest possible gain setting.[3]

The ability to adjust gain "on-the-fly" can save an angiogram in situations where exposure would otherwise be compromised: through very small pupils, or when less than the normal or expected dose of dye is used. Even with optimized gain and gamma settings, exposure during angiography often needs to be adjusted during the early phase of a fluorescein angiogram. The initial flash setting often needs to be reduced to avoid blooming of highlights as the dye begins to reach peak brightness in the arteriovenous phase. Once peak fluorescence passes, and the dye continues to recirculate, exposure will need to be increased. Limiting overexposure is especially important because blooming effects more than image detail and aesthetics; it can mimic hyperfluorescence that could be mistakenly interpreted as fluorescein leakage (Figure 5).

The need for tight exposure control in digital retinal imaging cannot be overemphasized. It requires a careful balancing of gain, gamma and flash settings, combined with critical evaluation of image quality during capture (Figure 6). Once system settings (gain and gamma) are adjusted so the majority of exposures fall within the middle of the available flash range, exposure can usually be controlled with flash adjustment alone.

FOCUS

Another challenge in ophthalmic digital imaging is in focusing the fundus camera, especially cameras equipped with high-resolution sensors. Optically speaking, there shouldn't be a focus shift at the imaging plane between film and digital sensors. There is a common perception however, that focus adjustment seems more sensitive as if there is less depth-of-field when using high-resolution digital backs. As long as the physical size of the digital sensor is close to that of 35mm film, the perceived reduction in depth-of-field cannot be attributed to a difference in the acceptable circle of confusion at the imaging plane. Circle of confusion is a phrase that describes the point at which an unfocused spot becomes noticeable in a photograph.

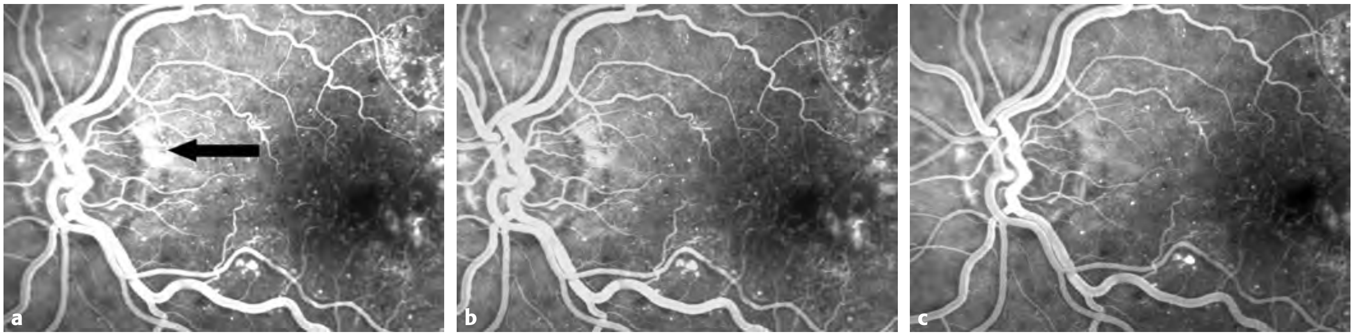


Figure 5: Overexposure or "Blooming" of highlights during a fluorescein angiogram. (a) Blooming on the temporal edge of the optic nerve is suggestive of fluorescein leakage in this patient with diabetic retinopathy. (b), (c) Slight reduction in flash output in consecutive frames eliminates blooming.

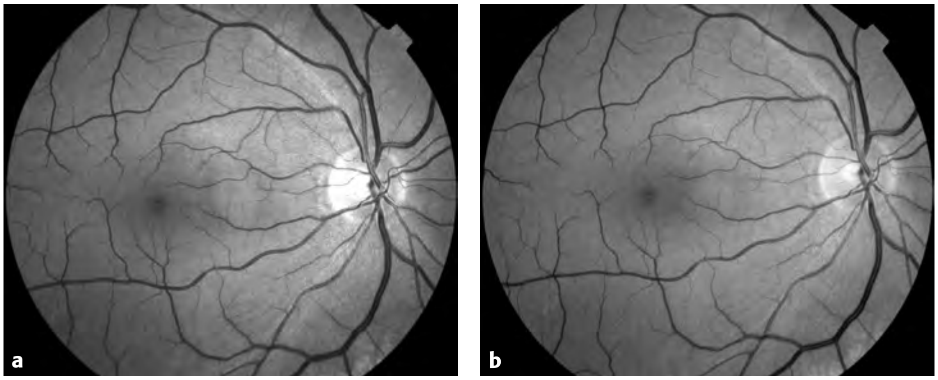


Figure 6: Digital exposure requires a careful balancing of gain, gamma, and flash output. (a) Monochromatic green photo demonstrating good overall contrast and exposure, but loss of detail in the optic nerve. A slight gamma adjustment improves detail while maintaining a similar overall contrast.

The point at which blur first becomes visible is dependent on both viewing distance and the degree of enlargement.

Other suggested causes include blurring from the anti-aliasing filter used in most sensors, or possibly the difference between the way photons strike pixel wells on a sensor versus photosensitive film emulsions. Perhaps the most likely cause of the digital focus "problem" is due to the change in viewing methods between film and digital imaging. Post-capture viewing of 35mm slides on a light box with a 5x magnifying loupe days or weeks after the subject has gone is dramatically different than immediate viewing of images displayed 12 inches high or larger on a computer monitor. We now get immediate high-magnification feedback during the capture session, and probably judge sharpness far more critically than we did with film.

Whatever the underlying reason, focus is clearly more challenging in digital fundus photography. To take advantage of the high spatial resolution of current digital sensors, focus must be carefully monitored and adjusted. The fundamental focusing techniques used in film photography remain the same, but we must adhere to them more strictly in digital imaging. Correctly adjusting the eyepiece reticle for proper focus is of paramount importance. A popular and commonly taught technique involves adjusting the crosshairs at least three successive times, noting the diopter setting each time, and using the average of these numbers.[5-7] This technique can be very problematic and should usually be avoided. In order to properly focus the fundus camera on a consistent basis, the photographer should relax their accommodation at distance to avoid accommodative shift during photography. The aforementioned average-setting technique actually promotes unnecessary accommodation and inaccurate settings. Each time the photographer looks at the numbers marked on the eyepiece, they accommodate to near, then immediately try to relax at distance before looking through the viewfinder again. Repeating these steps multiple times induces accommodative "gymnastics" and subsequent fatigue that can lead to improper settings when accommodation inevitably drifts during a photographic session. For this technique to work properly, someone other than the photographer should note and record the settings, so the photographer can keep accommodation relaxed at distance the entire time. The best strategy is to ignore the eyepiece numbers altogether, but pay constant attention to the crosshairs and image of the retina. As long as the crosshairs and the aerial image of the fundus both appear sharp at capture, the focus will be correct in a system that is properly calibrated for parfocality. Adherence to this fundamental technique is essential as even slight flaws in technique become magnified in digital imaging.

Viewing lamp brightness can also affect our ability to focus. The brighter the view, the easier it is to focus accurately. Unfortunately, viewing levels that promote good focus can be uncomfortable for the patient, adversely affecting their ability to cooperate. Briefly turning the lamp up to adjust focus, and then dropping it back down to a more tolerable level, is a simple technique that can help both photographer and patient. Alternately, a green filter can be used as a focusing aid. Because the spectral sensitivity of the human eye peaks in the yellow-green portion of the spectrum, a green filter improves the overall contrast and visibility of the fundus at brightness levels that remain comfortable for the patient. After focusing with green light, the filter is removed from the light path just before exposure. If the fundus camera is equipped with an astigmatic correction device, it can be used to improve focus in patients with significant astigmatism or when photographing peripheral fields. Using these basic techniques and carefully monitoring focus will allow us to get maximum resolution from our sensors without the need for excessive digital sharpening.

COLOR REPRODUCTION

Color reproduction is influenced by many factors. The spectral transmission characteristics of the camera optics and color temperature of the light source have a profound effect on color reproduction in both film and digital environments. In addition to these universal factors, digital imaging introduces other variables that affect color. The range of colors a digital system is capable of reproducing is limited in comparison to the human visual system. Because of the limitations, hardware and software manufacturers must make compromises in how their products deal with color information.

Ideally, all color sensors would be accurate in color reproduction right out of the box, but they are imperfect (as was film). The spectral sensitivity of the sensor itself and how the capture software processes color information will both affect the final rendering of the image.[8] The raw data captured by digital sensors must be processed before it can be displayed on a monitor or saved in an image file format. There are many different ways that digital information can be processed, and color rendition is often optimized for a specific purpose. To date, no color sensors have been specifically designed for retinal imaging. Also there are no industry-wide standards for fundus imaging; and color reproduction may be inconsistent between different systems, sensors, and software packages. Even identical systems from the same manufacturer often exhibit vastly different results, but most systems offer some degree of color balance adjustment.

Adjusting or managing color balance is a new task for many ophthalmic imagers. With film, color balance decisions were limited to choosing what type of daylight balanced color film to use. From there, color balance was monitored and controlled by the film-processing lab. In digital imaging, many of the choices we make have a direct effect on color reproduction and color balance. The first decision an imager should make is how you would like the images to look. Do you want to strive for the most accurate reproduction? Do you want your images to look like they did with a specific film, or just like the view seen through an ophthalmoscope or the camera eyepiece? Color balance could also be adjusted to enhance the visibility of specific pathology.

The simplest answer to these questions would be to try for the most accurate rendition; but defining true accuracy in color fundus imaging is an elusive proposition. The retina is always viewed with some form of artificial illumination. The spectral output of the tungsten viewing lamp in a fundus camera or ophthalmoscope is quite red, which influences the viewer's perception of "normal" or "accurate". In reality, the view we are used to seeing is heavily weighted toward a yellow-red or "warm" bias. Film-based fundus images also tend to have a warm bias that varies by film brand. Contrary to what imagers might think, film is not truly "accurate" in color.[9] Most films are balanced to produce pleasing flesh tones at the expense of true color accuracy.[10] Film's bias toward flesh tones also exaggerates the warm appearance of retinal pigmentation and blood vessels, again skewing our perception of accuracy in retinal imaging.

There are strategies for adjusting color balance to match the spectral characteristics of the illumination source to achieve color accuracy. Some systems provide a White Balance utility to match the color balance to the spectral output of the flash. This should result in images that are relatively accurate with that particular sensor and light source. Alternatively, a photographic gray card or calibration target can be used with manual adjustment to accomplish a neutral balance. Balancing to neutral results in fundus images that arguably are the most accurate in color reproduction, but they appear quite a bit "cooler" than what most observers are used to seeing (Figure 7). If this type of accurate rendition is not universally accepted as standard, then we may need to arrive at some consensus that appears "perceptually accurate" or pleasing to most trained observers.

It may be tempting to alter the color balance to enhance certain retinal pathologies, but doing so may compromise the appearance of other retinal features. For example, a balance that favors enhancement of microaneurysms or subtle drusen might adversely affect detail in the optic nerve. In most clinical settings, the better approach is to maintain an accurate, or perceptually accurate, balance at capture. Post-hoc color adjustment can then be done to enhance the target pathology without sacrificing the original rendition of the fundus. This type of post capture color enhancement is usually reserved for research or screening environments.

ADJUSTING COLOR BALANCE

Calibrate your monitor and establish a consistent viewing environment before making color balance adjustments. The color temperature of the monitor and the amount of ambient room light will affect the color appearance onscreen. The ratio of viewing lamp intensity to flash output can also affect color balance. Set the viewing lamp to your normal setting when performing any color balance adjustments. As previously mentioned, many color reproduction problems in digital fundus imaging are related to exposure and saturation. Exposure and gamma settings should be adjusted before attempting color balance adjustment. Carefully controlling exposure helps tremendously with color balance. Large differences in flash output can

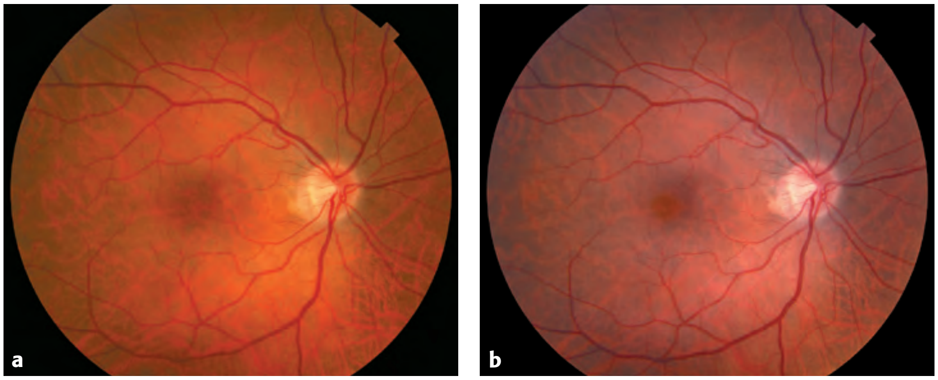


Figure 7: Color balance. (a) Perceptually accurate balance that resembles the appearance as seen through the fundus camera. (b) Neutral balance appears slightly blue or "cooler".

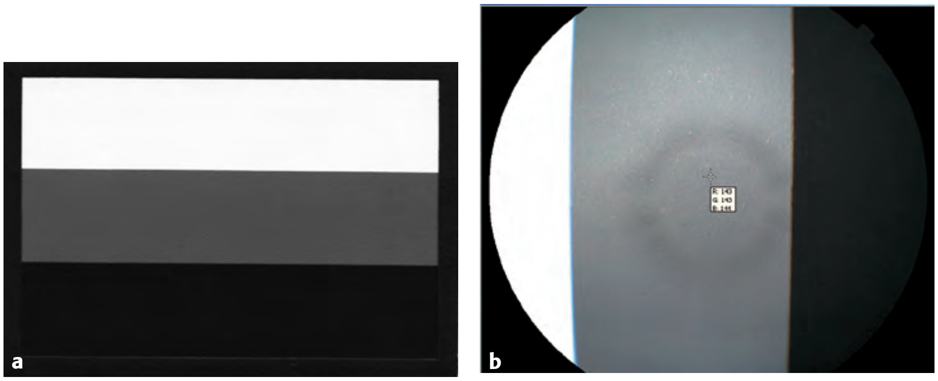
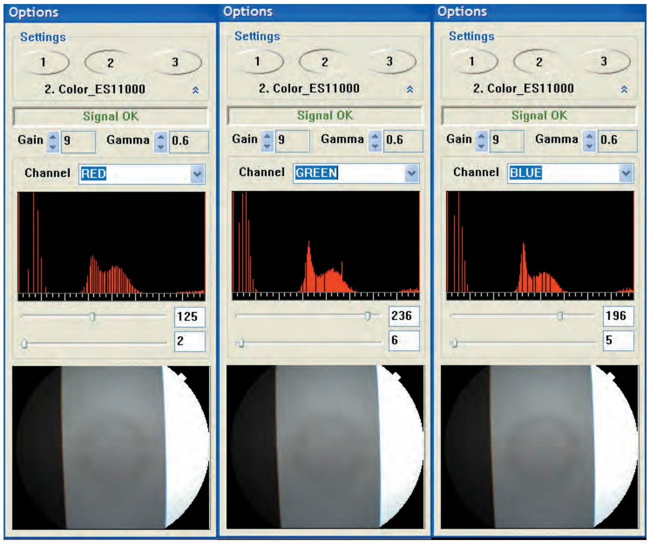


Figure 8: (a) Small (2.25" x 3.25") spectrally neutral three step gray card for adjusting color balance. (b) Measuring RGB values in the gray patch to confirm a neutral balance.



Gain 9 Gamma 0.6 Channel RED 125 2

Gain 9 Gamma 0.6 Channel GREEN 236 6

Gain 9 Gamma 0.6 Channel BLUE 196 5

Figure 9: Luminance histograms of gray card exposures can be used to establish a neutral color balance. Each color channel histogram should exhibit a similar shape and range.

change the spectral characteristics of the flash illumination.

Color balance is accomplished by altering the brightness relationships between the red, green, and blue (RGB) color channels. If adjustment is done with numerical values, one of the channels should always be set at null or zero. Amplification or gain is induced when all three channels have input values above zero, making the adjustment process unnecessarily complex. If all three channels have an amount, set the channel with the smallest number to zero and reduce the remaining channels by the same amount to maintain the RGB ratio.

A gray card or color calibration target can be used to set a neutral balance (Figure 8). The process is objective and pretty simple to perform. Simply place a photographic gray card in front of the fundus camera, focus on the card, set the viewing lamp to the normal setting, and take some test images. Import the images into Photoshop or another program that will allow measurement of RGB values. Applying an "Average" or similar blur filter before measurement will make the process easier. Make adjustments on the capture station until the ratio of RGB values is within just a few points of one another. It would be helpful if imaging vendors included an RGB measurement tool within the capture software to allow easy adjustment without having to export the images. If your capture software has a luminance histogram tool, you can use that to quickly arrive at a neutral balance before confirming the RGB values in Photoshop. A luminance histogram is a graphic representation of the distribution of brightness values in an image. Look at the shape of the curves from a neutral test target and move the histogram sliders until each color channel has a similar range and shape (Figure 9).

A calibration target like the ColorChecker Mini Three Step Gray Scale can be more reliable than a single value gray card. It has black, gray, and white values that allow you to check the balance of shadows, mid-tones, and highlights, and potentially correct for "cross-curves". Cross-curves occur when highlights lean one direction from neutral and the shadows lean the opposite direction. There isn't much that can be done about cross-curves if your system color control uses only single input values for each color channel. Histogram tools allow you to alter both the highlights and shadows to compensate for cross-curves. Once you've arrived at a neutral balance, shoot several fundus images to see if the neutral balance is acceptable in your clinical environment. Young patients, pseudophakic eyes, or more darkly pigmented fundi often look too blue when a neutral balance is used. These images are relatively accurate, but different in how these patients look through the viewfinder or how they were rendered with film.

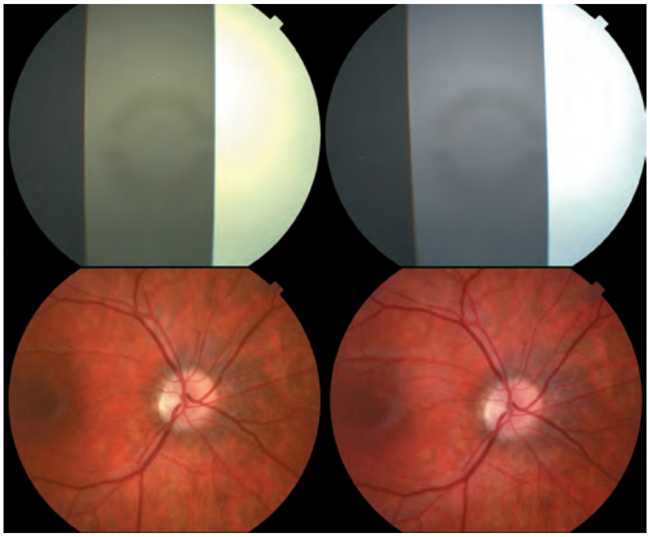


Figure 10: Difference in appearance between perceptually accurate and neutral balanced gray card and corresponding fundus images. Viewers have been conditioned to accept a warm bias as accurate, after decades of viewing the fundus with incandescent light sources and the use warm-biased color films.

Many users prefer a slightly "warm", "natural" or perceptually accurate balance (Figure 10). A warm balance can minimize the effect of lens color that varies with age and cataract formation. Currently, there are no universal standards or methods to establish such a balance. In the absence of standards, balancing to a perceptually accurate rendition becomes a subjective process of trial-and-error. It takes time and can't be accomplished on a single subject fundus. Color is influenced by inconsistent filtration from the ocular media and the wide range of fundus pigmentation in our patient population. Repeat the process of trial-and-error on several patient types to see if you can subjectively arrive at a "sweet spot" that works for most patient types. Some users develop different color balance settings to accommodate groups of patients: very lightly pigmented, children, pseudophakic, darkly pigmented, etc. Histogram tools are useful only as a general guide for this subjective process because of differences in fundus coloration from patient to patient. Balancing each patient individually so their histogram curves "match" would effectively homogenize the rendering of all patients, making them look the same rather than documenting their natural differences. When adjusting color balance through trial-and-error, it is useful to keep accurate notes of the settings, so you can return to a good setting if you stray too far in one direction.

Once you arrive at an acceptable balance at the capture station, view some images outside your immediate system to see how they might appear on review station monitors. In the absence of color management solutions, your images might appear quite different on other monitors. The monitors on many capture systems are usually higher in quality and brighter than the consumer grade monitors typically used for image review elsewhere. You might need to lower the brightness and contrast settings on your capture station monitor to produce images that can be adequately reviewed on the majority of monitors in your facility. Balancing multiple capture stations within the same facility is an additional color balance challenge. Histograms of images from the same subject can be used to adjust color balance for consistency between different capture stations with different monitors.

DIGITAL ARTIFACTS

Along with focus and exposure, the way we handle image files can have an effect on quality. Image noise from high gain settings can be exacerbated by the amount of sharpening applied to images. Sharpen filters work by identifying pixel transitions, defining edges, and then increasing the contrast between adjacent pixels. All digital images have some level of image sharpening applied to them, either in the digital camera, the capture software, or both. If all of your images appear too grainy or noisy, consult with your vendor to see if the default system settings can be adjusted to reduce the baseline amount of sharpening. Post-capture digital sharpening is a very powerful image-processing tool, but it can also be destructive to image quality. Over-sharpening is a common problem that can easily be avoided by judicious use of this tool (Figure 11). Sharpening is not a substitute for proper focus of the fundus camera and should be applied only when necessary.

File compression artifacts can also add to the appearance of noise. The JPEG format is a commonly used universal file format that relies on a "lossy" compression scheme to reduce file size. This format is popular because the compressed files take up less storage space than other formats and are efficient for transmitting across networks or distributing by email. The amount of compression can be selected by the user to find a balance between compression and quality. Although the JPEG format is quite

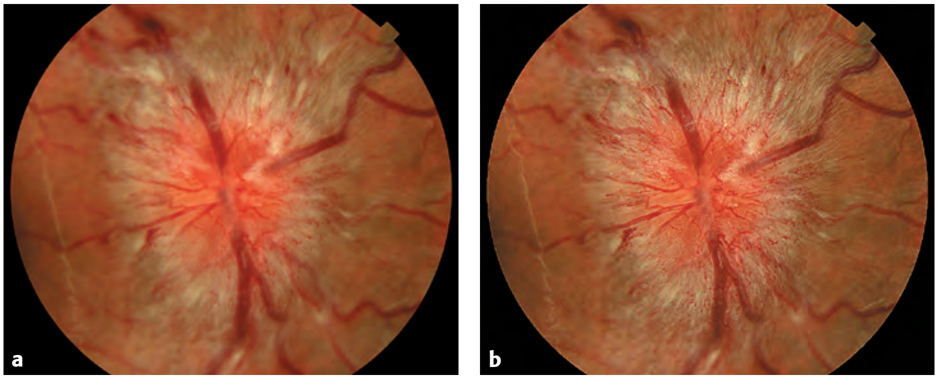


Figure 11: (a) Fundus image with minimal digital Sharpening. (b) Over-use of the Sharpen filter creates image noise.

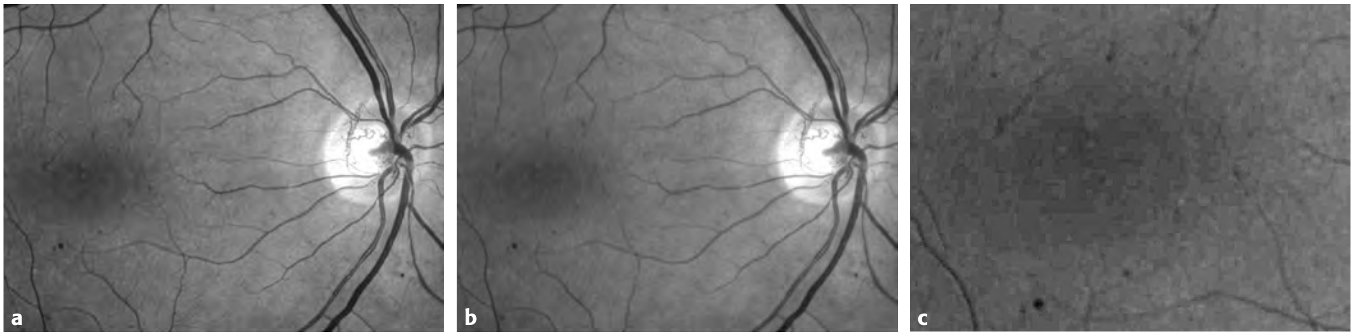


Figure 12: JPEG compression artifacts. (a) Uncompressed TIFF file. (b) JPEG compression holds up well in areas of detail such as the fine vessels on the optic nerve, but appears pixilated in the fovea where there is less detail. (c) Cropped area illustrating JPEG compression artifacts.

useful for general pictorial photography, it is inappropriate for storage of medical images. At high zoom levels, a loss of sharpness is apparent along with visible compression artifacts in JPEG files. Artifacts may appear as pixilated or crosshatched blocks that obscure detail, or "fringing" defects seen along edges (Figure 12). Each successive time a JPEG image is saved, image-quality degenerates further. To avoid this problem, limit the number of times JPEG files are altered and saved. It is best to reserve the use of this format for a final save in circumstances where compact file sizes are essential. Other image file formats like PNG or TIFF are more appropriate for preserving the integrity of medical images.

The Portable Network Graphics (PNG) format is a high-quality image file format that uses "lossless" LZW compression. It produces a good compromise between file size and image quality. It is an excellent choice for lossless compression of medical images. The Tagged Image File Format (TIFF) is a universal high-quality image file format used for publication and archiving. The TIFF format also offers optional LZW lossless compression, but this compression is seldom applied and the files can be quite large. The best strategy to reduce compression artifacts is to use a lossless file format with a computer system/network with the necessary system resources to handle larger file sizes.

SUMMARY

In order to maximize the quality of our digital images, we need to break away from a film mindset, learn to think digitally, and understand the limitations of current digital technology. Education and strong standards are needed to improve utilization of digital imaging tools. Photographers must learn to read the image on the capture monitor, identify any problems, and know what adjustments to make to improve quality. Exposure must be controlled much more carefully in a digital environment. Image-processing should be controlled to avoid the common problems of oversaturation and over-sharpening.

There is an opportunity for our profession to establish acceptable color reproduction standards for fundus imaging. We either need to accept a truly accurate color reproduction model, or arrive at a consensus on a perceptually accurate balance. Once we have consensus on a definition of acceptable fundus color reproduction, universal calibration tools can be developed to establish standards across the profession. A universal color calibration target or model eye could be adopted by all fundus imaging system manufacturers for distribution with their systems. Test exposures could then be compared against a reference image file to confirm calibration to the standard target. RGB measurement tools could be built into fundus imaging systems to facilitate color balance adjustment. Implementation of color management calibration tools would also help to improve the situation.

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