**INTRODUCTION**

To explore how to achieve a high quality retinal image, it is important first to ask what the characteristics of that image should be. It is problematic to define image quality in terms of “showing things as they actually are.” Delving into the imaging process, one sees that “reality” is actually a relative state affected by several important variables, all of which need to be considered: not only attributes of the object being imaged, but also the light being used to image it, the imaging device, and ultimately the observer, who is conditioned by the strengths and limitations of the human visual system.

**HOW DO HUMANS SEE?**

Fundamentally, humans process the visual phenomena of the world into features resolved against background. Much of this has to do with human evolution as a species. Historically, the feature against the background may have been an attacking predator or fleeing prey. Humans can see features against background because they are different from it. That is to say, they are resolved in some manner.

There are two fundamental image attributes that determine how successfully the features of interest can be discerned against the background with which they might be confused. These are spatial and tonal resolution. Briefly, by spatial resolution is meant the number or density of the pixels (picture elements) devoted to depicting the feature of interest, and by tonal resolution is meant the difference between the appearance of the feature and the background in brightness and/or color. Spatial resolution will be explored in a future article.

Two image examples will help to illustrate the effect of varying spatial and tonal resolution on the ability to see. Figure 1a depicts a polar bear against a snowy background, and Figure 1b documents a retina with diabetic retinopathy (DR), in this case, microaneurysms (Ma), retinal hemorrhages, and intra-retinal microvascular abnormalities (IRMA), against the retinal pigment epithelial (RPE) background. These two images represent diametrically opposed interests: the polar bear does not want to be seen (especially by a seal!), while the fundus photographer intends the ophthalmologist to be able to see the retinal disease. These two instances may seem different in kind, but they are merely at opposite ends of a spectrum. The effect of varying tonal resolution through a range for both polar bear and retina is displayed in Figures 2 and 3. In Figure 2, the overall exposure is varied, affecting both brightness and contrast, while in Figure 3 only the contrast is varied. Typically, at image capture time, brightness and contrast are ganged together as in Figure 2. Figure 3 has been included to show contrast has an independent effect beyond that of brightness.

In both series it should be noted that at the left end of the scale, the features are poorly resolved against the backgrounds. As one moves to the right, the features become better defined against the background until both polar bear and DR are easily detectible. At the far right end of the scale, contrast (as well as brightness) of the

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**Figure 1:** (a) Polar bear against snowy background. (b) Retinal vessels and DR against an RPE background. Both images challenge the capabilities of the medium to depict feature against background, because in both the feature and its background have somewhat similar brightness and color.
image has been pushed far enough to see artifacts — polar bears should not have rainbow coats, and the RPE should not be so variegated but rather uniform. These examples were constructed for Figure 2 by using the Adobe® Photoshop® “Exposure” tool (on the Image/Adjust menu), and for Figure 3 by moving the “Contrast” tool (also on the Image/Adjust menu as Brightness/Contrast) separately for each of the three color channels, while holding the Brightness setting constant.

**Tonal Resolution — How Much is Enough?**

Because early color fundus cameras did not have adequate spatial resolution, many researchers were focused on improving spatial resolution as the key to obtaining better fundus images. However, as spatial resolution increased, it became apparent that tonal resolution was an equally important limiting factor in digital image quality. Obviously, having greater spatial resolution (more pixels) will not help the observer if the feature to be detected is nearly the same brightness and color as the background (i.e., has low tonal contrast). In Figure 3a, note that in the variant with the least contrast (the polar bear) is virtually indistinguishable from the snowy background, even though the spatial resolution is adequate, being unaltered from the original image.

To understand the tonal resolution requirements for good quality color fundus images, it is helpful to explore further how humans see tonal detail in images.

**More on How Humans See**

There are two major differences between humans and digital imaging systems that have important consequences for image quality.

Firstly, humans have maximum discrimination to resolve features in images that are moderately brightly illuminated. This “sweet spot” in the range of illumination occurs because of the following.

1. When images are too dark the retina detects them chiefly with the rods (scotopic vision), which cannot detect differences in color.
2. When images are somewhat brighter, the rods begin to get help from the cones (mesopic vision, which add color discrimination.
3. When the image is moderately bright, the brain is getting optimal input from the cones (photopic vision), at which point human vision has its greatest discrimination.
4. When the image is too bright (even if it is not oversaturated), the ability to discriminate features begins to decline again.

To summarize, digital images need to be brought up into the “sweet spot” of illumination for best appreciation.

Secondly, humans are more limited in the number of different tonal shades they can discriminate compared to digital imaging systems. Conventional digital systems keep track of 256 shades in each color channel. However, a human’s ability to keep track of shades is approximately an order of magnitude lower. For monochrome images, estimates of normal human discrimination in the literature range from approximately 20 shades on the lower end, to 32 shades in the middle, to 50+ shades under optimal conditions. Examine Figure 4 as a check of the ability to discriminate on a 23-step grayscale. Because spatial detail in a retinal image is captured primarily in one channel (green) the limited capability of the human with monochrome images also affects how color retinal images are perceived.
Digital Color Fundus Image Quality: the Impact of Tonal Resolution

As with spatial resolution, how much tonal resolution is needed depends upon what the observer is trying to see. Different retinal features demand different tonal resolution. Retinal features and disease abnormalities are seen against the background of the reddish-orange RPE. The “bright” features, such as the optic disc, fibrous tissue, cotton wool spots, hard exudates, and drusen, are not demanding. The difference between these often whitish features and the reddish-orange RPE background is usually detectable even in an image with poor tonal resolution. On the other hand, the “dark” features, such as normal blood vessels, Mas, IRMAs, and new vessels, are much more demanding. Because they often have the brightness and color of venous blood, which is similar in appearance to the RPE, they tend to blend into the background in an image with poor tonal resolution, especially if the image is very dark or the focus/clarity is below par.

To illustrate the impact of these limitations in human vision, examine some contrast variants of the eye with DR, restricted to a square region of interest centered on a large Ma. Figure 5 shows a series in which the Topcon Imagenet™ Adjust Exposure tool has been utilized to progressively decrease both brightness and contrast. In the variant with least contrast, using the Photoshop Information tool to measure the luminance levels inside and outside of the Ma would allow one to find the feature. However, the human eye could not actually see it directly because even in the “sweet spot” of human vision a difference of 8 luminance levels (256 shades for the digital system divided by the 32 you can see) is needed to perceive a difference. Even with a difference of 8 luminance levels between feature and background, if the image is too dark for utilization of photopic vision, or too bright for the cones to function most sensitively, the difference will still not be perceived.

Examine the series of the same DR image in Figure 6, in which the Imagenet Adjust Contrast tool has been used to adjust only contrast and not brightness. Again, measuring the luminance values within and outside of the Ma still identifies the lesion, but human vision is physically incapable of seeing it.

**Tonal Resolution Required for Retinal Features and Disease Abnormalities**

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**Analysis of Tonal Resolution**

An informal way of analyzing the tonal resolution in an image is simply to examine it critically. Fortunately, photographers have access to a very useful statistical tool, known as the luminance histogram, to determine how much of the dynamic range is actually being exercised. Typically, the luminance histogram is presented graphically as a plot, with the x-axis divided into luminance values from zero to 255, and the y-axis showing the number of pixels in the image at each luminance value. In retinal photographs, the brightness values for each color are typically clustered at different points of the dynamic range, yielding three distinct color curves.
Figure 7 shows the 3-color luminance histogram obtained from a classic film photograph: Age Related Eye Diseases Study (AREDS) Standard #12, carefully digitized for preservation. Any photographer can perform such an analysis on their photographs by exporting them from the digital camera system and importing them into Adobe Photoshop (or similar program). Simply click on the “Histogram” command on the “Windows” menu, and select the “All Channels” and “Show Channels in Color” options.

In order to eliminate “noise” from the image periphery, which is often marred by artifacts, it is helpful to select a “region of interest” (ROI) in the image, as illustrated in Figure 7. This is accomplished by selecting the elliptical Marquee tool, clicking and holding the mouse button with the cursor at the center of the image, pressing and holding the <Alt> and <Shift> keys simultaneously, then expanding the circle out from this central point by moving the mouse in any direction, stopping short of the edge artifacts, and then releasing the mouse button. Selecting the “sweet spot” of the image as the ROI “shapes up” the luminance curves and makes them easier to interpret.

Figure 8 presents a composite digital fundus image (2006 OPS Best of Show award winner) and its corresponding luminance histogram. Note that the overall configuration of the luminance curves is remarkably similar to those in Figure 7. An image with exemplary B/C/CB generates a histogram somewhat resembling a suspension bridge. The red and green peaks, located in the upper and lower halves of the dynamic range, represent the towers, and their curves represent the cables, overlapping slightly in the middle. Blue makes a minor appearance near the bottom.

Color digital fundus images have had a mixed reputation for quality. Seen from the perspective of a central reading center (UW-Madison), the best digital images match the quality of the best film images, and there is hope that as more photographers learn to use them, digital images can surpass film. Unfortunately, digital images on the lower end of the quality spectrum of tonal resolution can be very unsatisfactory, as shown in Figure 9.

**Categories of Poor Tonal Resolution**

Post-processing (enhancement) of an image can save an image that would be difficult to interpret as it came out of the photography session, and while at other times the image may have insufficient tonal resolution to be retrievable. To avoid the latter problem, the fundus photographer should shoot to obtain images that have reasonably good tonal resolution as they are taken. Following are the main types of tonal resolution problems, with examples accompanied by luminance histograms to help the reader analyze the images.
Assuming the camera’s basic settings are correctly adjusted, getting the right exposure for each eye is probably the most critical day-to-day challenge. Figure 10 is an example of an image that is taken with too little illumination to be easily interpretable. This image can still be salvaged by contrast enhancement as the “after” version shows. However, the image in Figure 9b is beyond saving. The “after” version reveals that the tonal range of the original image is so compressed that enhancing it into the range optimum for human vision produces a disastrous “posterized” artifact that would interfere with detecting subtle disease abnormalities. There is an upper limit to the amount of “stretch” that can be applied to the color curves without introducing obvious tonal discontinuities – arguably no more than four-fold or less.

Figure 11 shows an example of an image that is over-illuminated to the point of saturation in the red color channel. Not only is the detail of the feature against background in the red channel obliterated in some areas, overall the red channel overpowers the detail in the green channel so that the entire picture looks rather flat. While there is no way to recover the lost detail in the red channel, it is possible to bring out more of the pictorial information in the green channel, as the “after” version of this image shows. This was accomplished by sliding the red curve down in the dynamic range, and if necessary enhancing (both brightening and stretching) the green channel. Of course, it is better to avoid the need for such processing. If the red/green color balance of the camera is appropriate, the photographer should be able to avoid over-saturating in red while getting adequate detail in green.

With experience, the photographer can learn to see, at a glance, whether an image is over-saturated in red. The affected areas show RPE that looks washed out and uniform. Normally there should be some variegated pattern. If there is some question, examine the luminance histogram. The red channel will terminate in a cliff, perhaps as a spike, at the top end of the dynamic range, rather than terminating with a tapered right end, as is normal for a bell curve, before reaching the top of the range.

**Improper Color Balance**

The retinal scene presents something of a paradox to the digital imaging sensor. The scene appears mostly red,
but much of the critical detail is green. Because the silicon-based sensor reacts most strongly to red, this difficulty is compounded. Thus, digital cameras are vulnerable to producing images that are too strong in the red channel and too weak in the green channel.

Figure 12 illustrates an image with improper green/red balance (G/R = 0.35), accompanied by a corrected version (G/R = 0.50). Note that the second image appears to have a lot more contrast or depth than the first, making it easier to detect retinal features and disease abnormalities.

A secondary consideration in color balance is the blue/red ratio (again defined as the ratio of the blue peak location to the red peak location). In film, this ratio is typically less than 0.20, meaning that blue is de-emphasized, compared to red and green. On the other hand, many digital cameras are set up to produce a higher blue component than film. Photographers who are aware of this may even prefer the higher blue setting. It lends the image a purplish cast that some find aesthetically pleasing. However, the photographer should be aware that there is very little actual blue signal in a normal retinal image. Thus, if the blue channel is increased you are effectively enhancing a “noise” element. Figure 13 shows this bluish effect pushed toward the extreme, accompanied by a color-corrected version with blue minimized. The latter may not be as pretty as the former, but experienced graders see more detail in the image with blue under control.

**Summary**

Tonal resolution (brightness, contrast, and color balance) is a critically important factor in the quality of digital color retinal images. Photographers and their ophthalmologists need to establish criteria regarding how they want their photographs to look. Formal tools exist, e.g. the 3-color luminance histogram, which allows a photographer to analyze and manage the tonal parameters of the retinal images taken. Ultimately, the fundus photographer and ophthalmologist have responsibility for the utility of their retinal images for providing patient care and for contributing to research studies. Fortunately, photographers also have the power to make and implement informed choices about the quality of tonal resolution in their retinal images.

**Reference**