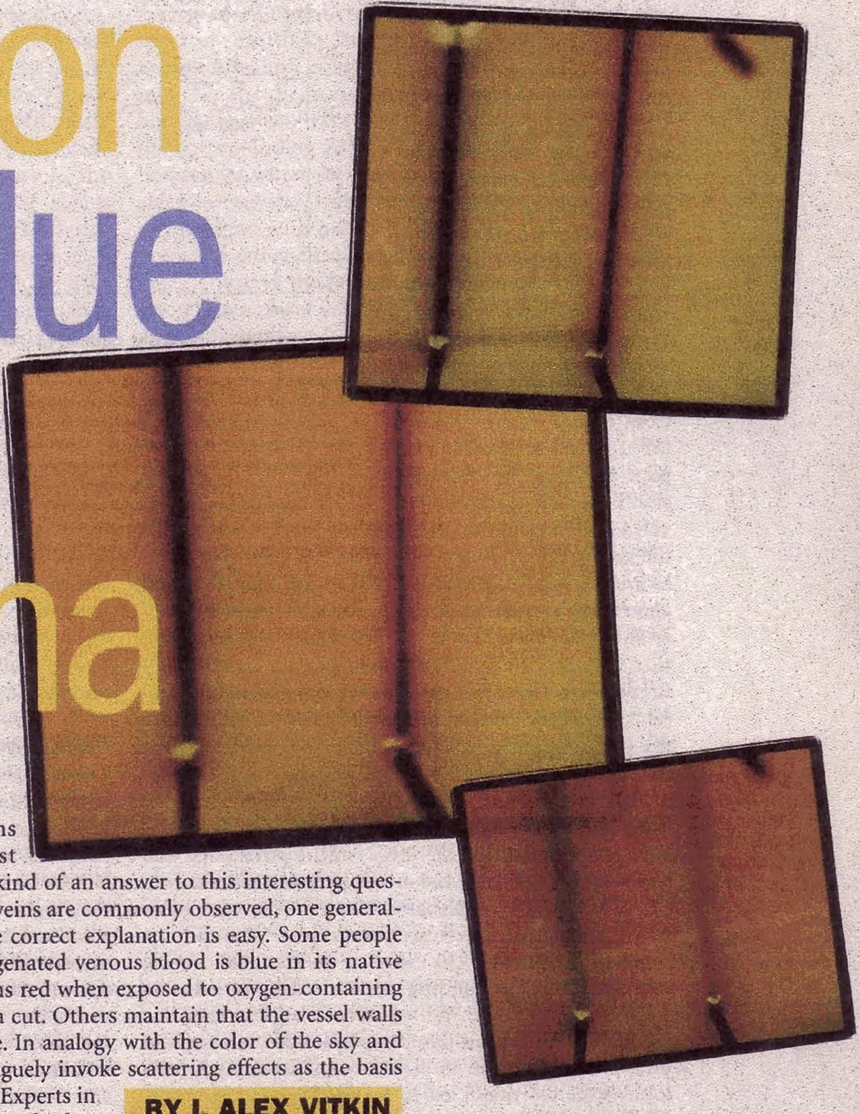
Shedding Some Light on the Blue Vein Enigma

Alex Vitkin takes a look at an interesting visual mystery—why veins appear blue. He finds his answer in retinex theory.



Why do human veins appear blue? Most people have some kind of an answer to this interesting question. Because blue veins are commonly observed, one generally assumes that the correct explanation is easy. Some people believe that deoxygenated venous blood is blue in its native state, and only turns red when exposed to oxygen-containing air such as during a cut. Others maintain that the vessel walls themselves are blue. In analogy with the color of the sky and of the sea, some vaguely invoke scattering effects as the basis of the explanation. Experts in tissue optics go a step further

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Figure 1. Photographs showing the color change of 1.2 mm inner diameter glass tubes as a function of depth in a scattering medium (a lipid colloid, with 0.34% blood to simulate capillary blood perfusion of skin tissue). The left "vessel" contains venous blood to represent a vein; the blood in the right "vessel" has been exposed to air to yield an oxygenated state, and thus represents an artery. Images: (top) depth below the surface = 0.5 mm (measured to top of tube); (middle) depth = 1.4 mm; and (bottom) depth = 2.1 mm.

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and propose that the spectral absorption properties of venous blood, as well as tissue scattering effects, are the key to understanding blue veins. In fact, this seems to be the conventional wisdom, although this "explanation" is not very satisfying—it mentions important contributing factors, but does not show how these lead to the observed vein color. Finally, someone may mention the physiology of color vision, namely the spectral response of the human eye, as a further refinement to the above "explanation."

To the best of our knowledge, however, no one has previously treated the blue vein issue quantitatively. Attracted by the ubiquity and the apparent simplicity of the problem, and hearing no consensus in the answers proposed at numerous water-cooler discussions (nor in the scientific literature!), my colleagues and I have recently studied this phenomenon.[1] We measured the spatial and spectral variations of diffusely reflected light from model vessels in scattering media (see Fig. 1, page 39) and from human skin containing prominent veins. We also quantified the absorption and scattering effects via extensive simulations of light transport in tissue, and found general agreement between these predictions and experimentally obtained reflected spectral intensities. However, neither the experimental nor simulated data were leading to the correct predictions of the observed skin and vessel colors. For example, as seen in Figure 2, even above the vein, there is greater amount of reflected red light than blue light!

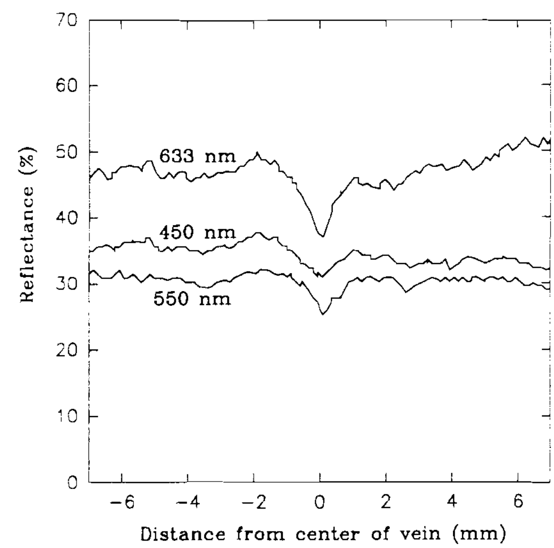

Figure 2. Spectral intensities measured above and near a prominent vein in the palm of a Caucasian volunteer. from Reference 1. The center transmission wavelength of the interference filters used during the measurement is indicated. The curves are normalized to the remitted intensity of a white reflectance standard. Both the depth and diameter of the vein were estimated with ultrasound to be 0.5 mm.

Searching for the right color model

We then searched the literature on the physiology and psychophysics of color vision and performed a standard CIE (Commission Internationale de l'Eclairage) color space calculation (see next paragraph). This did not improve matters, for the color of the tissue above the vein and of the surrounding tissue was determined to be without distinct hue. Yet we were confident that our predictions and measurements of the remitted spectral intensities, both from *in vivo* skin and scattering phantoms, were essentially correct. Clearly, something was missing in our understanding. As we eventually discovered, the missing link can be provided by the retinex theory of color vision.[2]

To a non-color scientist, a reasonable approach to determine perceived color is to measure or compute the spectrally remitted intensity from an area of interest, and to combine this result with the spectral sensitivities of the three types of photoreceptors contained in the retina of the eye. One can then apply a CIE color space calculation to determine the resultant color.[3] However, this approach does not always describe the colors we see.[4-6] For example, it does not readily explain how we can see the world in relatively unchanging colors despite the often unpredictable shifting and uneven illumination—for this surely changes the spectral intensity reflecting from different areas of the object that reaches our eyes.

In the last century, this puzzle was referred to as discounting the illumination; its modern name is color constancy. For example, it is possible to arrange the illumination of a general scene such that the spectral intensities remitted from two different objects, say a strawberry and a lemon, are *the same*, yet one looks red and the other yellow. Some color scientists were well aware that the phenomenon of color appearance is not just about computing the light scattered from the object; rather, it is a complex inferential process, of which the spectral composition of the light reaching the eye is an important component that terminates in a mental representation of the object's color that is most likely to explain the sensory input.[5, 6]

Retinex theory

The heated debates concerning the different theories of color vision were intensified by the work of Edwin Land, one of the great American inventors and entrepreneurs, and the founder of Polaroid Corp. (see *OPN*, October 1994). Beginning in the 1950s, he proposed that higher-order mental processing was involved in color vision, calling this the retinex (retina + cortex) theory.[2] Although still controversial (as are most theories in color vision!) and not unanimously accepted in the field of vision research, we found the retinex theory was able to predict the vein colors correctly.

Land's major point of departure from many other color vision theories is his claim that the spectral intensity of light reaching the eye from a given area does NOT determine the color of that area. Hence, spectral data from an area of interest is insufficient to specify its color. This is certainly in agreement with our futile attempts to explain the blue vein color. Specifically, Land stated that ". . . only our eyes can categorize the color of objects; spectrophotometers cannot."[2] He came to the conclusion that human vision was fundamentally a field phenomenon, whereby the spectral intensities emanating from the whole field of an observers view determine the perceived color of any particular area.

This is not a second-order effect along the lines of color contrast, adaptation, or after-image; according to the retinex theory, the entire visual field must be sampled to ascertain the color of a given area. This emphasis on surroundings, and de-emphasis on spectral intensity, differs markedly from artificial imaging systems and from many other color theories where the dominant factor in color determination of an object is precisely the spectral intensity reaching the eye from that object.

Instead, retinex theory claims that the human visual system determines the reflectance, or a quantity closely related to it which Land called "lightness," of every point in the visual field. If we define reflectance as the ratio between the reflected and the illuminating intensities, $R = I_{refl} / I_{illum}$, and realize that the quantity in the numerator is what actually arrives at our eyes (this is what we measured and computed in our study), it is difficult to see how our visual system can determine R without knowing the illuminating intensity, I_{illum}. This is where the importance of the surroundings comes in.

Land proposed that the ratio of the reflected intensities between adjacent areas,

$$[I_{refl} = (R \cdot I_{illum})_1] \,/\, [I_{refl} = (R \cdot I_{illum})_2],$$

will approach the ratio of the two reflectances, R_1/R_2. This assumes that the illuminations of sufficiently small adjacent areas are equal, which, in practice, they most often are. By using this equation, the confounding effects of the uneven and changing illumination are removed, the color appearance of the object is correlated with its reflectance (ratios), and the phenomenon of color constancy can be explained. Further, if the entire image is processed in terms of ratios of reflected intensities at adjacent areas, and sequential products of these ratios are computed and normalized to the maximum along many arbitrary paths leading to the point of interest,[2,7] a single number is obtained that Land termed the "designator."

This approach underscores the role of surroundings: it is not that they determine the color of a particular area *per se*, but rather that they allow our visual system to derive the spectral reflectances (Rs) based only on the input of spectral intensities (I_{refl}s), and hence assign colors to the whole scene. Repeating this process for each of the three sensitivity wavebands of the eye's photoreceptors yields a trio of designator numbers that display the color of this point of interest in a special three axis retinex color space (also called "lightness" space, see *OPN*, Oct. 1994, page 31, Fig. 3).

It is important to realize that no biological counterpart to this ratio-product process has been discovered, hence it is not clear if the retinex theory in general, and its computational model in particular, are what really happens. Perhaps future work, such as functional imaging studies of the brain, may answer these questions. In the meantime, the retinex theory has been successful in describing many aspects of color vision, including the remarkable phenomenon of color constancy.

It should be noted that there are other theories in color science that also demonstrate color appearance as more than just the physics of reflected light,[5,6] but conclusive experimental evidence to favor a particular theoretical model over other constructs is currently lacking.

Applying retinex to blue veins

Attempting to use retinex theory to describe the observed blue color of human veins, we weighted our measured and predicted reflected intensities with the spectral sensitivity functions of the retinal cones as appropriate, and computed the three retinex designators. For the measured human vein, these specified a blue color. Encouraged by this finding, we performed the corresponding retinex calculations for the simulation results, where we examined the effects of three variables—vessel size, vessel depth, and the oxygen content of the blood within it (see Fig. 1). Most of our results predicted either turquoise/blue or violet/dark red colors. To observe the former, it was necessary for a vessel greater than about 0.5 mm in diameter, to lie at a depth greater than about 0.3 mm. Thus, with insufficient size or scattering overlayer thickness, the vessel is predicted to be dark red to violet, no matter if it carries deoxygenated venous or oxygenated arterial blood. Conversely, this also yields a surprising prediction: Provided that the above minimum depth and minimum size criteria are met, even an artery can look turquoise, although with a less saturated hue than a corresponding vein. Since no blue arteries are observed in human skin, they must either be too small, lie too deep to be observed at all (typical penetration depth for visible light in Caucasian skin is $<\sim$ 2.5 mm), or have thicker walls than veins.

So now we understand why veins appear blue! It's not that they remit more blue than red wavelengths—in fact, we found the opposite to be the case—but that the decrease in red/blue ratio over the vein, compared to the rest of the skin, is such that when analyzed with retinex theory, blue to turquoise colors are indeed predicted. Hence, although light transport in tissue is a key to understanding the vein color, it is not *the* key: visual perception is also an indispensable piece of the puzzle.

It is important to emphasize that the spectral intensity data alone, without retinex analysis, gave no indication that the object would manifest blue color. In fact, CIE color space calculations of the data led to no distinct color. The retinex-predicted color is roughly independent of the oxygen content of venous blood (within a realistic range); we also noted that a small amount of blood in the surrounding scattering medium seems to enhance the observed color effects (this would be present in the skin capillary network). In other words, whatever spectral differences result from the differences in the arterial versus venous blood, *Continued on page 59*

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3-A—Ph.D. (Aug. 1997) in Electrical Engineering. Seeking R&D or academic position in optoelectronic systems and devices. Thorough knowledge in optics/photonics. Extensive research experience including integrated optics, semiconductor and ultrafast lasers, communications, WDM, fibers, optical amplifiers, semiconductor fabrication. Also holographic storage, interferometry, optical tomography, frequency conversion. Two research awards, 18 publications. Excellent communicator, teacher, team player. http://echo.phs.uiuc. edu/~kgp.

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these do not cause significant color change in the retinex model. Finally, the size and depth of the vein were important: the vein needs to be deeper than ~0.3 mm and larger that ~0.5 mm in diameter to display its characteristic bluish color. That is why a normal capillary bed does not look blue even at low oxygen saturation of the blood—the capillaries are small and often too superficial. So whether you are a "blue blooded" noble or a fair-skinned commoner, your skin looks pink, and not blue, even when you blush!

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7. E.H. Land, "Recent advances in retinex theory," Vision Res. **26**, 7–21 (1986). In this formalism, Land uses a summations of logarithms of intensity ratios along a path. The use of logs allows convenient elimination of intermediate area contributions $[\log(I_3/I_2) + \log(I_2/I_1) = \log(I_3/I_1)]$, for comparison with nearby as well as more distant surroundings, but it may also be justified on physical grounds—according to Weber's principle, small equally perceptible changes in psychophysical response correspond to proportional increments in the stimulus. See D.C. Hoaglin, "Transformations in everyday experience," Chance: New Direc. Statistics Comput. **1**, 40–45 (1988).

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