Color in Medical Imaging

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Color is playing a more and more important role in adding information to otherwise black-and-white medical images.

The field of radiology dates back to 1896, when Röntgen first exposed film with x-rays. Those monochrome images created a field that remained largely colorless until the development of real-time color Doppler imaging in the early 1980s. Since that time, the use of color has grown rapidly with new applications of three-dimensional visualizations.

The rise of imaging techniques that combine anatomical information and functional or molecular information is driving color to the forefront. Thus, a century of monochrome imaging is giving way to an emergence of color displays of medical images.

Red and blue for blood

The direct exposure of film by x-rays dominated radiological imaging during the first half-century after Röntgen's initial exposure of the human hand.

One early use of color involved multiple exposures of an object using different x-ray energies (Figure 1).[1] These exposures, rendered as color information, were studied for the additional differential information that they might contain. However, this technique had a number of disadvantages, including the need for higher total x-ray exposure, and it therefore was not widely used.

In the early 1980s, the Tokyo-based ultrasound imaging company Aloka introduced a real-time color Doppler scanner. Blood flow velocity, previously unquantified in ultrasound (or in x-ray and CT scans without specialized contrast protocols) could be visualized at many frames per second.

In color Doppler ultrasound, the reflected ultrasound waves from rapidly moving blood flow undergo a Doppler frequency shift. (In practice, a phase shift is measured during repeated pulses.) This shift is proportional to the blood flow velocity, enabling the identification of the blood flow direction.

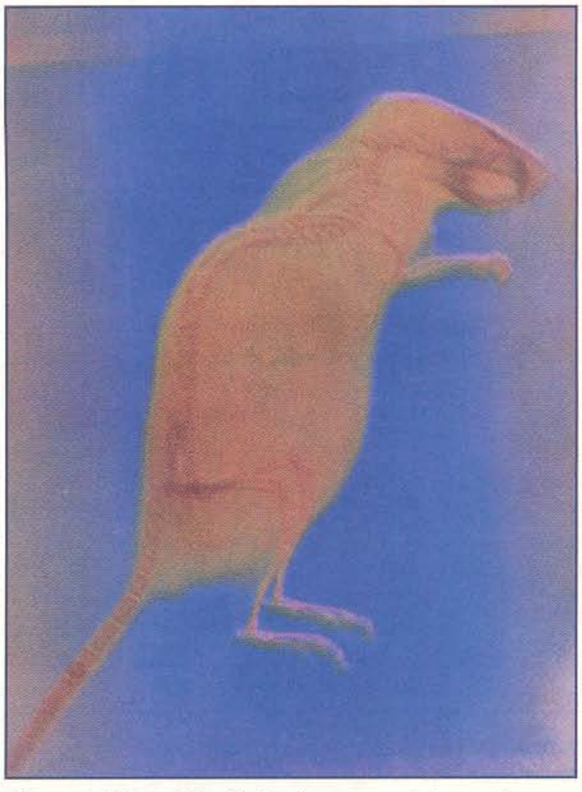

Figure 1. One of the first color x-ray pictures of a mouse displays three independent pieces of information at every spot. The three negatives were radiographs made at 40, 60 and 80 kV on anodes of iron, molybdenum and silver, respectively. Reprinted by permission of John Wiley & Sons Inc.

Conventionally, images indicated blood flow toward the ultrasound probe as shades of red, with deeper saturation indicating higher velocities; blood flow away from the ultrasound probe was blue (Figure 2). Images could show additional information, such as the turbulence of the flow, in green or by using other hue and saturation combinations.[2]

The medical community readily welcomed the ability to visualize blood flow direction and velocity, including the timing with respect to the heart contraction cycle.[3] Thus, within a few years, every high-end ultrasound scanner incorporated sophisticated color Doppler capabilities. The widespread and sudden dissemination of color in medical imaging created a new opportunity for color hard-copy devices for still frames as well as for color VCR recordings for real-time video sequences.

New information is key

In the 1990s, color overlays found use in functional MRI images of brain activity (based on changes dependent on cerebral blood oxygen level) and MR diffusion tensor images for visualizing white matter fiber tracts (Figure 3).

Conventional MRI provides anatomical information about living tissues, rather than imaging functional activities such as blood flow variation and nerve fiber connectivity. Diffusion tensor imaging is an invaluable tool for the in vivo study of cerebral white matter diseases at a microscopic level. It measures the rate of water diffusion through white matter fibers, transferring this information to color images as fiber tracking.[4] Combined with functional MRI, it may improve our understanding of neurocognitive networks and brain function.

At the same time, the new availability of computer workstations made it practical to generate 3-D visualizations of bones, blood vessels, organs and muscles by segmenting discrete objects in the stack of 2-D images and using visualization techniques to display a 3-D rendering (Figure 4). By convention, these images display bones in white, blood vessels in red, the liver in a deep maroon, and so forth, to mimic the typical colors of these structures.[5]

Initially, these color displays were limited to experimental uses because of the labor required to segment and render the visualizations. And today the main task of diagnosis continues to rely on the higher-resolution monochrome images in their original state before postprocessing for 3-D renderings.

A different use of color that remained largely experimental (or did not achieve widespread adoption) was the use of subtle shading called "B-color" in ultrasound imaging.[6] Human psychovisual experiments suggested that the addition of subtle shading to a high-contrast image could enhance the detection of low-contrast lesions, compared with using conventional monochrome displays. The idea was not to employ the garish "pseudo-color" mappings that were notorious in the early days of color display workstations, but rather some subtle and continuous color shifts. B-color is an option on some high-end scanners, but it has not realized everyday use.

The example of B-color and that of the 3-D renderings suggest that radiologists have a strong preference for traditional monochrome images unless the color images provide new physiological data, as in the case of functional MRI and color Doppler ultrasound.

Combining imaging techniques

In medical imaging, different techniques reveal different features of the human body. Combining them can provide new information for physicians. For example, a major leap forward for the detection of tumors has been achieved by combining positron emission tomography with CT scan imaging: PET/CT.[7]

PET is a noninvasive nuclear imaging technique that captures images of tissue function on a biochemical and physiological level. PET images are obtained by injecting a radiolabeled compound, usually attached to glucose, into the bloodstream. This compound circulates in the body, reaching the target tissue that is undergoing metabolic changes.

Conventional imaging methods such as x-ray, CT and MRI show physical, anatomical structures of the body. But metabolic changes in tissue usually occur before one can detect anatomic changes,

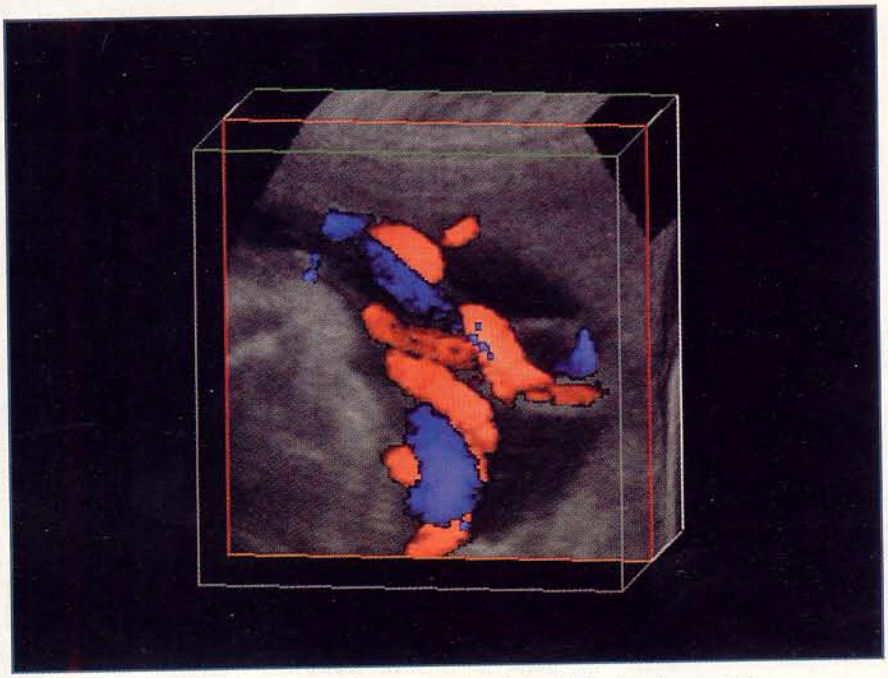

Figure 2. In a color Doppler ultrasound image, blood flowing toward the ultrasound probe is represented in red and that away from the probe in blue.

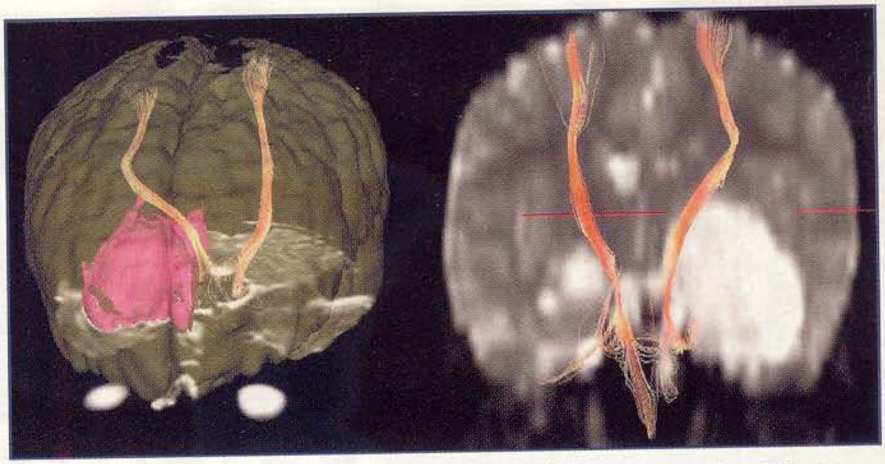

Figure 3. Magnetic resonance diffusion tensor imaging measures water diffusion through white matter fibers, in this case pointing out a tumor. On the left is a 3-D rendering of the pyramidal tracts, tumor and brain surface extracted from T2 weighted data. On the right is a coronal section of tractography. Reprinted with permission of **European Journal of Radiology.**

so PET can detect abnormalities in cases where a CT imaging study is still unremarkable.

In the PET/CT technique, images of the local uptake of the radiolabeled glucose produce exquisitely sensitive, but somewhat blurry, 3-D data sets. Co-registering these data with high-resolution, anatomical 3-D images from the CT scan can show "hot spots" of uptake resulting from tumor growth on specific structures such as the liver or the lymph nodes.

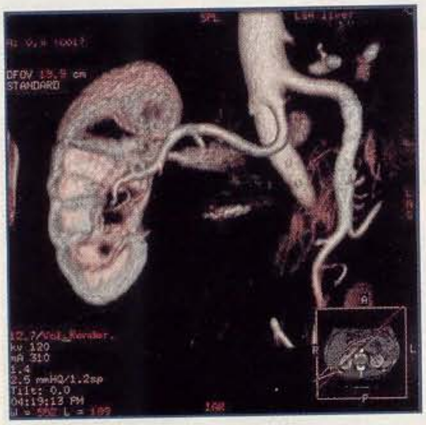

Figure 4. Rendering data from a renal exam provides a 3-D view of anatomical structures.

To visualize this multichannel information as a co-registered 3-D data set, color brings immediate advantages. Conventionally, the CT anatomical rendering appears in monochrome (or with low saturation), with the PET information superimposed using color schemes (Figure 5).

Although PET/CT scanners are expensive and limited in availability, their growth rate is dramatic. It is likely that the number of PET/CT scans will continue to grow rapidly in the US and other developed countries, and these images will require color displays and hard copies.

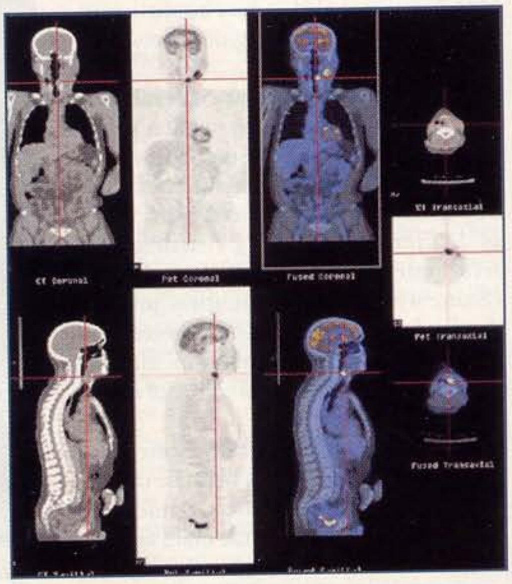

Figure 5. Positron emission tomography and CT scanning look deeply into a patient with known hypolaryngeal cancer and an indication of local metastasis. PET shows a second lesion adjacent to the tumor, which shows invasion of the soft tissue with local metastasis and central necrosis. Courtesy of the University of Zurich.

Other imaging techniques can be co-registered to provide more information to a physician for diagnosis. For example, MRI and ultrasound detect different tissue properties (Figure 6). A color image can display simultaneous information from each modality after registration.

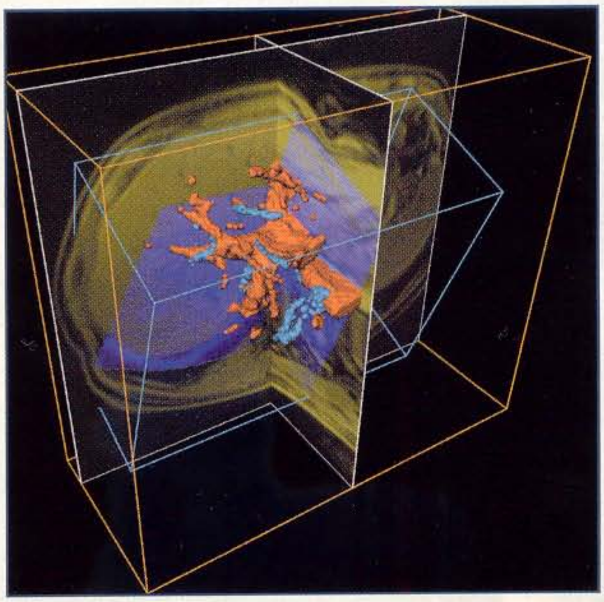

Figure 6. A 3-D liver image shows the result of vessel registration and data fusion between two image modalities: MRI (yellow) and ultrasound (blue). Courtesy of Brian Porter, University of Rochester.

New meets old

Some of the techniques mentioned earlier are moving from experimental to mainstream. Specifically, VirtualScopics of Rochester, N.Y., has achieved fully automated 3-D renderings of complex anatomy (Figure 7). This ability expands the use of color to new areas, including the change over time of anatomical structures known as "image biomarkers."

The concurrent dissemination of picture archiving and communication systems for digital radiology and of increasingly powerful workstations makes it easier to create, manipulate and communicate with 3-D color renderings. Other rapidly expanding sources of multispectral data come from the growing use of molecular imaging compounds and probes, and from multiple-pulse sequences in MRI. These techniques provide additional data to co-register with anatomical reference images. Color continues to be the dominant tool for achieving the desired synthesis.

This rapid growth of color imaging does not imply the demise of monochrome images. For the foreseeable future, hundreds of millions of mammograms, chest x-rays, and ultrasound, CT and MRI scans will continue to be read as monochrome images. However, the growing flood of co-registered functional and physiological data will continue to drive the advanced techniques into standardized color formats. ☐

Meet the authors

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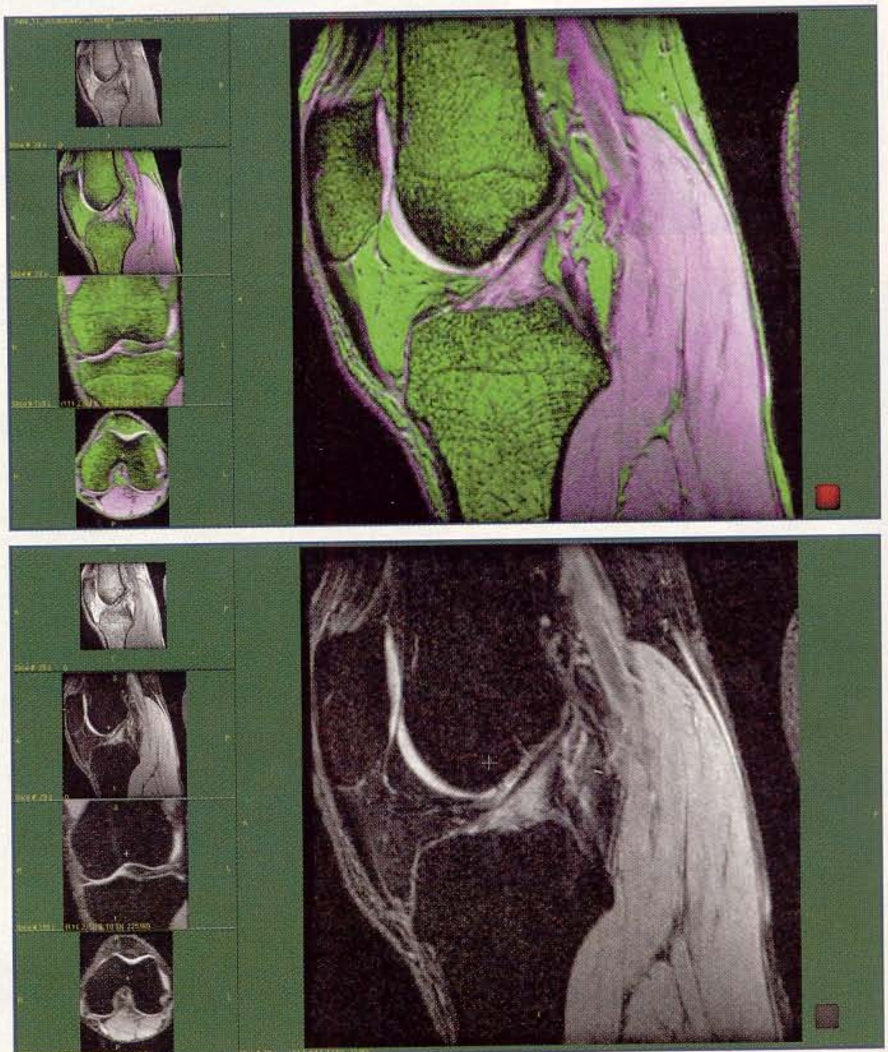

Figure 7. A composite MRI image (above) shows the detail of inner structures and the cartilage boundary more clearly than a gray-scale MRI image (below). The composite fuses a T1-weighted data sequence with a T2-weighted data sequence. The T1-weighted image is on the red channel, and the TS image is on the green and blue channels of the composite RGB image. Courtesy of VirtualScopics.