Color in Medical Imaging

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Abstract

The field of radiology dates back to 1896 with the first direct x-ray exposure of film by Roentgen. From the next 80 years the exposure of black-and-white film by x-rays, and later, from calculated images from CAT scans, ultrasound scans, and MRI scans would dominate the hardcopy world of medical imaging. The uses of color were largely experimental and limited until the development of real-time color Doppler imaging in the early 1980s. Since that time, the uses of color have grown rapidly as 3D visualizations and multi-modality or multi-spectral images become widely utilized. The rapid growth of imaging techniques that combine anatomical information with additional functional or molecular information is driving color to the forefront, since additional information needs to be fused in the renderings. Thus, 100 years after Roentgen's experiment, a century of monochrome imaging is giving way to an emerging need for color displays of medical images.

The Monochrome Era 1900-1980

The direct exposure of film by x-rays dominated radiological imaging for at least the first half-century after Roentgen's initial exposure of the human hand (Fig. 1). Due to the increasing understanding of the need to limit exposure to x-rays, a major early focus of development was on increasing the sensitivity of film, and developing contrast agents for enhancing the vasculature and uptake of contrast by organs and lesions. Many new techniques for obtaining tomographic and 3D image data sets were developed in the second half of the 20th century; however, the great majority of CAT scans, ultrasound scans, and MRI scans up to the early 1980s were rendered and interpreted as monochrome images (Fig. 2, 3, 4). One early use of color involved multiple x-ray exposures of the same object using different x-ray energy (Fig. 5) [1]. It is an empirical fact that the absorption of x-rays within bone and soft tissues is dependent on the wavelength (energy) of the x-ray source. Thus, multiple exposures of different x-ray wavelengths, when rendered as color channel 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 did not achieve widespread use.

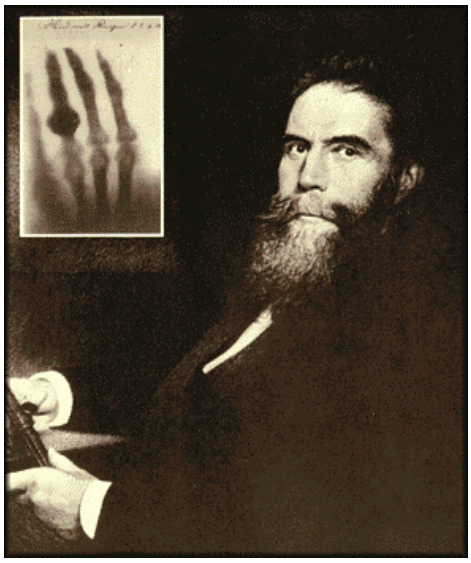

Fig. 1. Wilhelm Roentgen with X-ray radiograph of his wife's hand. (http://www.learnxrf.com)

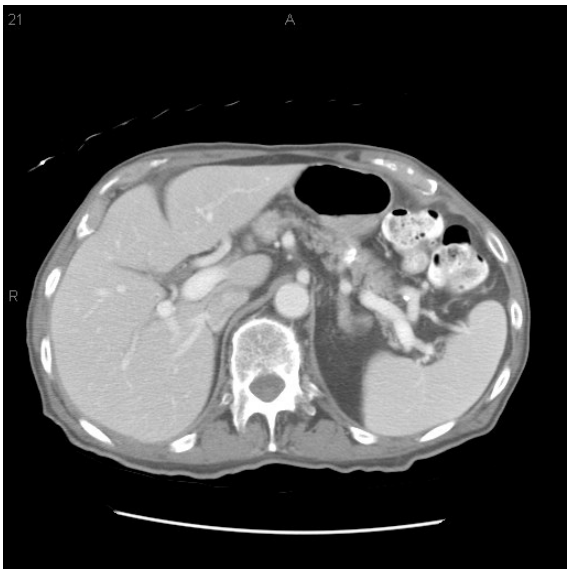

Fig. 2. CT image of the human liver. (Permission from Dr. Deborah J. Rubens)

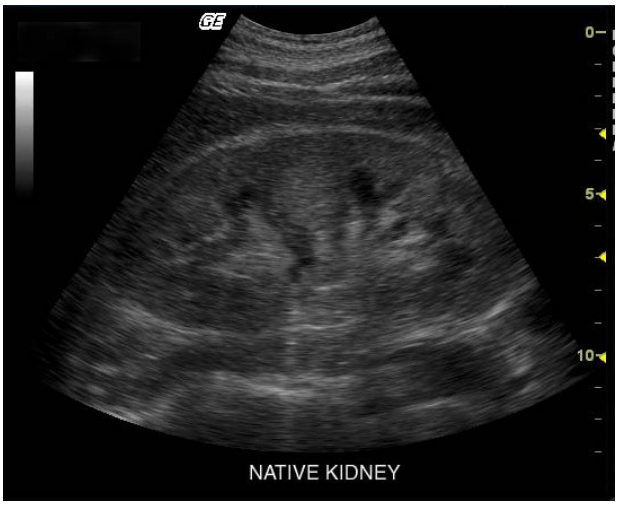

Fig. 3. Ultrasound image of the kidney. (Permission from GE Medical, copyright © GE Medical)

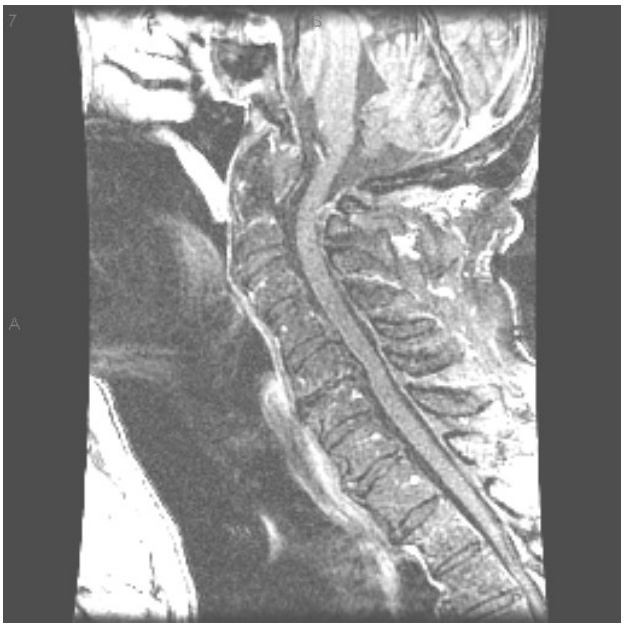

Fig. 4. MR image of the sagittal c-spine. (Permission from Dr. Deborah J. Rubens)

Fig. 5. One of the first color X-ray pictures of a mouse. The picture displays and compares three independent pieces of information at every spot. The three negatives were radiographs made at 40, 60, 80 kilovolts on anodes of iron, molybdenum and silver, respectively. (Medical Images and Displays. Mackay RS. Copyright © 1984 John Wiley & Sons, Inc. Reprinted by permission of John Wiley & Sons, Inc.)

The Era of Emerging Color 1980-2000

In the early 1980s, an ultrasound imaging company, Aloka, introduced a real-time color Doppler scanner. Blood flow velocity, previously unquantified in ultrasound (and x-ray and CAT scans without specialized contrast protocols) could suddenly be visualized at many frames per second. Blood flow towards the scanner transducer was encoded as shades of red, with deeper saturation indicating higher velocities. Blood flow away from the scanner transducer was encoded in blue. Additional information such as the turbulence of the flow, was further encoded in color, using green or other hue and saturation combinations (Fig. 6) [2]. The ability to visualize an important physiological parameter, blood flow direction and velocity, including the timing with respect to the heart contraction cycle, was readily welcomed by the medical community [3]. Within a few years time, every high-end ultrasound scanner incorporated sophisticated color Doppler capabilities (Fig. 7). A general principle that this case illustrates is that new information, beyond anatomy, needs color and naturally makes use of color to superimpose the information on the black-and-white anatomical image. This widespread and sudden dissemination of color in medical imaging created a new opportunity for color hard-copy devices of still-frames

and for color VCR recordings of the real-time color video sequences. Later, in the 1990s, the development of functional-MRI (f-MRI) images of brain activity ((Fig. 8), as well as MR diffusion tensor images for visualizing white matter fiber tracts (Fig. 9), would also produce color overlays on anatomical images.

Another emerging use of color during this period resulted from the increasing acquisition of 3D image data sets, particularly from CT and MRI scanners. The new availability of computer workstations during this period made it practicable to render 3D visualizations of bones, blood vessels, organs, and muscles by segmenting discrete objects in the stack of 2D images and then employing visualization techniques to display a 3D rendering (Fig. 10). A natural tendency is to render the bones in white, the blood vessels in red, the liver in a deep maroon, and so forth so as to mimic the typical colors of these structures [4]. However, during this era, these color renderings were limited to experimental uses, as much labor was required to segment and render the visualizations. Furthermore, the main task of diagnosis continues to rely on the higher resolution monochrome tomographic images, in their original state before post-processing for 3D renderings.

A different use of color that remained largely experimental (or did not achieve widespread use) was the use of subtle color shading called "B-color" in ultrasound imaging (Fig. 11) [5]. Human psychovisual experiments suggested that a subtle use of color shades in a high contrast image could enhance the detection of low-contrast lesions, as compared with the same task using conventional monochrome displays. It is important to note that these are not the garish "pseudocolor" mappings that were notorious in the early days of color display workstations. Rather, some subtle and continuous color shifts along with intensity were found to enhance human visual detection tasks. B-color has been available as an option of some high-end scanners and is easy to implement by the simple push of a button. However, it has not been adapted to widespread, everyday use. This example, and the example of the 3D renderings, suggest that radiologists have a strong preference for traditional monochrome images unless new and additional physiological data are available for color rendering, as in the case of f-MRI and color Doppler.

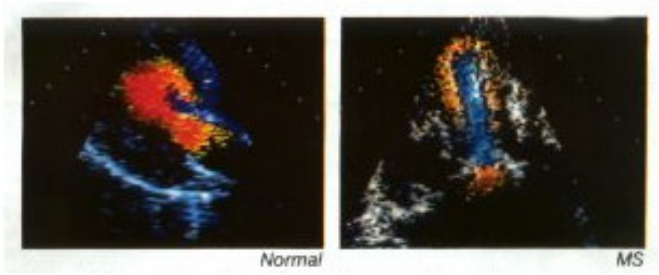

Fig. 6. Color Doppler images were captured by Aloka SSD-880CW color Doppler system. It is the world's first system to display blood flow imaging in color and real time. (Permission from Dr. Joseph S.K. Woo)

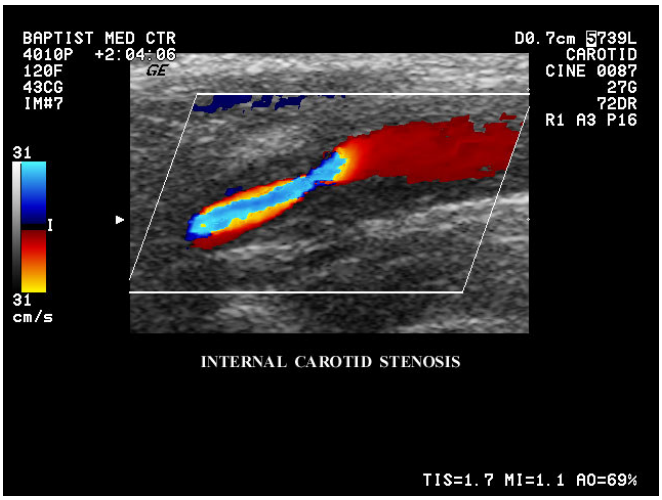

Fig. 7. Color Doppler shows a longitudinal image of a patient with internal carotid artery stenosis. The internal carotid artery shows the area of narrowing with increased (aliased) flow denoted by the blue/yellow pattern. (Permission from GE Medical, copyright © GE Medical)

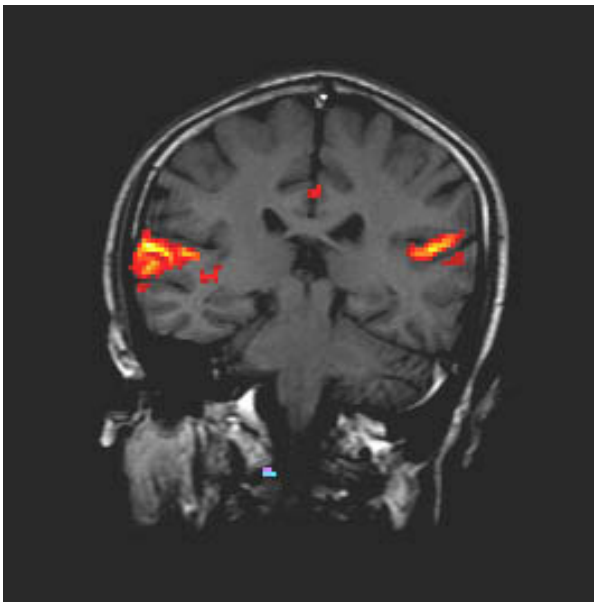

Fig. 8. fMRI technique for medical diagnostic and neuroscience applications. (Permission from Dr. Jianhui Zhong)

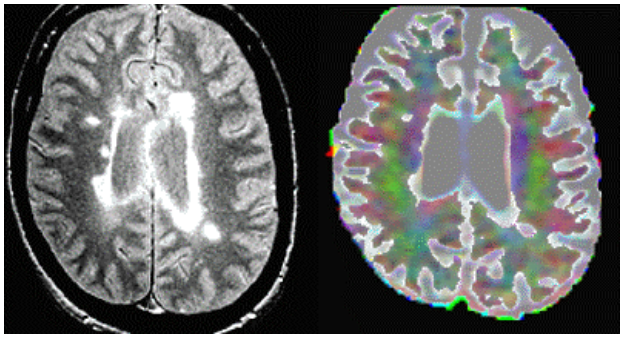

Fig. 9. Comparison of MR image and MR diffusion tensor image of the brain. (Permission from Dr. Jianhui Zhong)

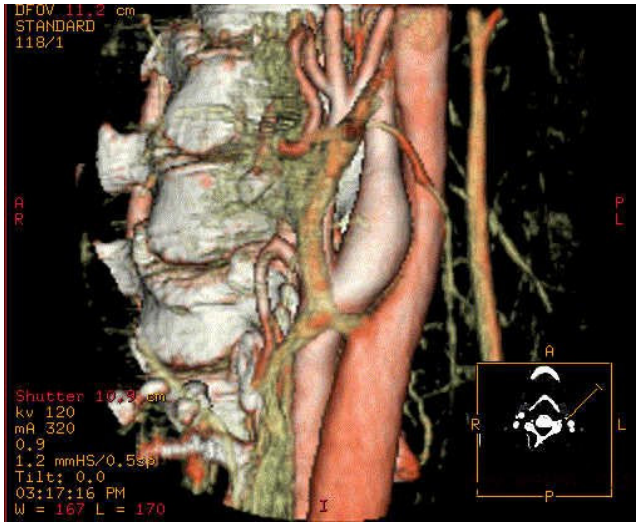

Fig. 10. Color 3D rendering. (Permission from GE Medical, copyright © GE Medical)

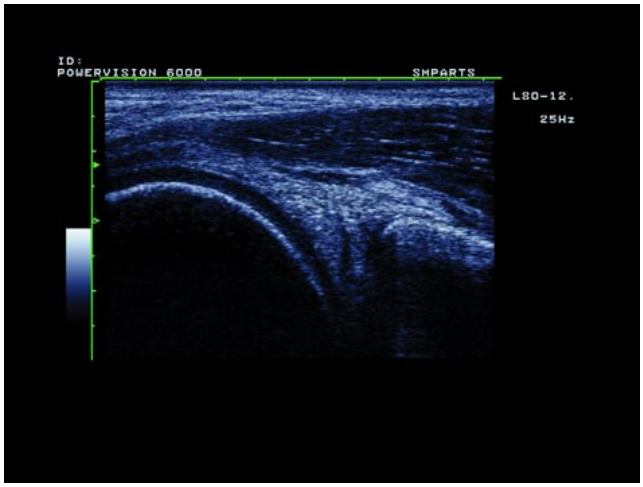

Fig. 11. The B-color palette is used to increase the contrast, which emphasizes the meniscal tear. (Clinical Image made on the PowerVision 6000 Ultrasound System and courtesy of Toshiba Medical Systems Europe. Permission from Toshiba Medical Systems Europe)

Color in Radiology in the 21st Century

A major leap forward for the detection of tumors has been achieved by the combination of Positron Emission Tomography with CAT scan imaging: PET/CT [6]. In this technique, the local uptake of a special radio-labeled glucose is imaged to produce exquisitely sensitive, but somewhat blurry 3D data sets. By scanning concurrently with CT, a high-resolution anatomical 3D stack of images can be obtained, and these can be co-registered against the PET scan. In this way, "hot spots" of uptake due to tumor growth can be located with confidence on specific structures such as the liver or the lymph nodes. To visualize this multi-channel information as a co-registered 3D data set, color brings immediate advantages. Once again, the preferred anatomical rendering in monochrome (or with low saturation) can be produced from the CT data, with the additional information from PET superimposed using color schemes (Fig. 12). Although PET/CT scanners are still limited in availability and are high cost, the rate of growth is dramatic (Fig. 13). It is likely that the number of PET/CT scans will continue to grow rapidly in the U.S. and other developed countries, and these images will require color displays and hard copies.

Some of the techniques mentioned in the earlier section are also moving from experimental to mainstream. Specifically, fully automated 3D renderings of complex anatomy have been achieved by VirtualScopics (www.VirtualScopics.com), and this is expanding the use of color to new areas, including the change over time of anatomical structures known as "image biomarkers." The concurrent dissemination of PACs systems for digital radiology and of ever-more powerful workstations makes it easier to create, manipulate, and communicate with 3D color renderings.

Other rapidly expanding sources of multi-spectral data come from the growing use of molecular imaging compounds and probes, and from multiple-pulse sequences in MRI. In these techniques, additional data are obtained, and this information must be co-registered with anatomical reference images. Color continues to be the dominant tool for achieving the desired synthesis.

It is germane to point out that this rapid growth of color images does not necessarily predict the end of monochrome images. For the foreseeable future, hundreds of millions of mammograms, chest x-rays, ultrasound scans, CAT scans, 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.

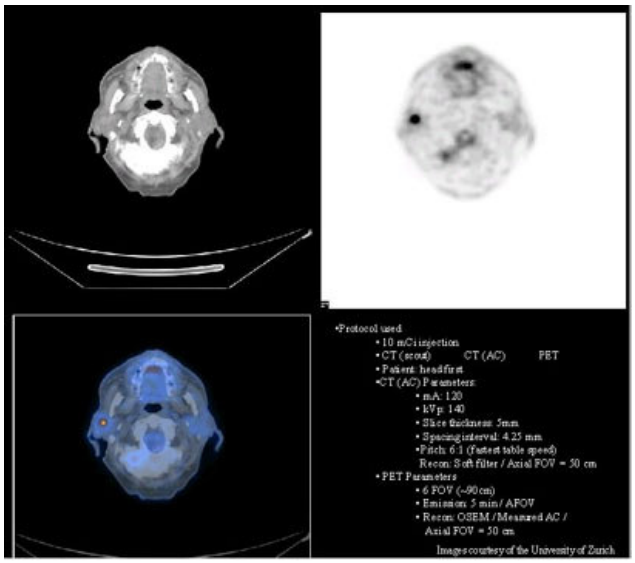

Fig. 12. PET/CT demonstrates the tumor with extension over the midline anterior with destruction of the laryngeal cartilage and invasion of the soft tissue. (Permission from GE Medical, courtesy of University of Zurich)

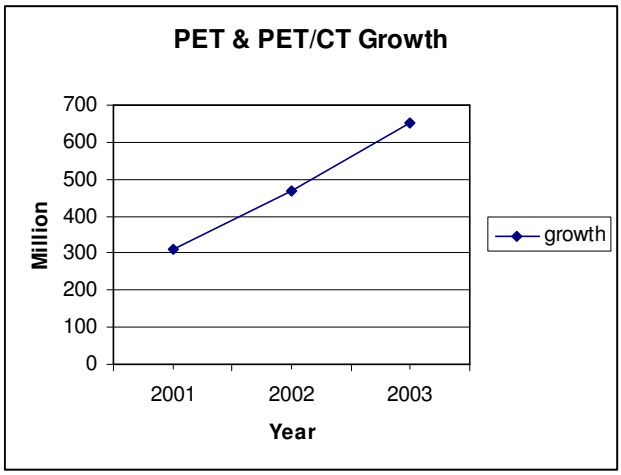

Fig. 13. The growth of PET and PET/CT scans. (Data adapted from AAPM conference notes)

Acknowledgements

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Biography

Kevin J. Parker received his BS degree in engineering science, summa cum laude, from SUNY at Buffalo in 1976. He completed graduate work in electrical engineering at MIT, receiving a PhD degree in 1981. Dr. Parker is a Professor of Electrical and Computer Engineering, Radiology, and Bioengineering at the University of Rochester since 1981. In 1998, Dr. Parker was named Dean of the School of Engineering and Applied Sciences at the University of Rochester. He is the director of the Rochester Center for Biomedical Ultrasound. Dr. Parker has received awards from the National Institute of General Medical Sciences (1979), the Lilly Teaching Endowment (1982), the IBM Supercomputing Competition (1989), the World Federation of Ultrasound in Medicine and Biology (1991), and the Joseph P. Holmes Pioneer Award from the AIUM (1999). He is a member of the IEEE, the Acoustical Society of America (ASA), and the American Institute of Ultrasound in Medicine (AIUM). He was named a fellow in both the IEEE and the AIUM for his work in medical imaging; and the ASA for his work in acoustics. In addition, he was on the Board of Governors of the AIUM for a three-year term. He is founder of Virtual Scopics, Inc., and serves on the Board of Scientific Advisors for Biophan Technologies, Inc. Dr. Parker's research interests are in medical imaging, 3-D and 4-D imaging, Doppler imaging techniques, and digital halftoning.