IMAGES ON PERSONAL COMPUTERS

Displaying Radiologic Images on Personal Computers

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This is the second article of our series for radiologists and imaging scientists on displaying, manipulating, and analyzing radiologic images on personal computers (PCs). The first article discussed the digital image data file, standard PC graphic file formats, and various methods for importing radiologic images into the PC. This article discusses the hardware, software, and user interface issues related to displaying gray scale images on PCs. In particular, this segment focuses on the process of converting the digital image into gray shades on a color monitor. A method for displaying and interactively setting the window width and window level parameters of 16-bit radiologic images on PCs with standard red green blue graphic hardware is illustrated in a sample application.
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KEY WORDS: personal computer; Red Green Blue (RGB) color model; window width; window level; brightness; contrast.

THIS IS THE SECOND article of our series for radiologists and allied imaging scientists on displaying, manipulating, and analyzing radiologic images on personal computers (PCs). The emphasis of the series is on what can be accomplished with equipment that is likely to appear on an office desktop. The first article[1] discussed the digital image data file, standard PC graphic file formats, and various methods for importing radiologic images into the PC. In this second article we discuss the hardware, software and user interface issues related to displaying gray scale images on PCs. In particular, this segment focuses on the process of converting the digital image into gray shades on a color monitor. A method for displaying 16-bit radiologic images on PCs with standard Red Green Blue (RGB) graphic hardware is described. At the end of the article, a sample application, Dr Razz, is introduced that shows many of the principles described in this series.

We have chosen to use the acronym PC to refer to a computer system that is likely to appear on a radiologist's or secretary's desktop; and we have chosen the term IBM-PC to refer to a computer system either compatible with or manufactured by IBM (International Business Machines Corp, New York, NY), typically using either the DOS, OS/2 or Windows operating environments. First we will begin with defining the important terms brightness, contrast, window width, and window level.

BRIGHTNESS AND CONTRAST

Almost everyone is familiar with the concept of brightness and contrast because brightness and contrast controls are present on standard television sets, as well as on computer displays and other cathode ray tube devices. These controls adjust the viewing characteristics of the image on the screen by changing the voltages on the cathode ray tube itself. The brightness control adjusts the overall intensity of the image, whereas the contrast control adjusts the relationships between the gray shades of the image. These controls are commonly used to adjust the display so that it is operating across its useful brightness range.

WINDOW WIDTH AND WINDOW LEVEL

The developers of the display system for the first computed tomography (CT) scanners recognized that new terminology might be useful in clarifying the new concepts that they were introducing to electronic image displays. CT scans were the first widely accepted form of images that had an inherent gray scale range that greatly exceeded 256 gray shades. Therefore, there was a requirement to reduce this image data to 256 gray shades for display.

They chose the concept of a "window" that could be moved through the contrast range of the image under user control. The width of this window represented the range of CT numbers (now called Hounsfield Units) that were selected for display (Fig 1). The concept conveyed the sense that the CT numbers within the range were passed through the "window" onto the viewing screen. Their term "window level" was used to represent the center of this range. When the level of the window was increased, the window was moved up into brighter portions of the data range, and resulted in optimal viewing

Fig 1. The window width and window level concept. The vertical scale shows the range of the CT numbers, and the approximate tissue equivalent densities. The window width (W) is the range of CT numbers that are converted into gray scale values. Values above this range are set to white, and values below this range are set to black. The window level (L) is the midpoint of the window level, expressed in CT image values. The same process is used to view MRI images.
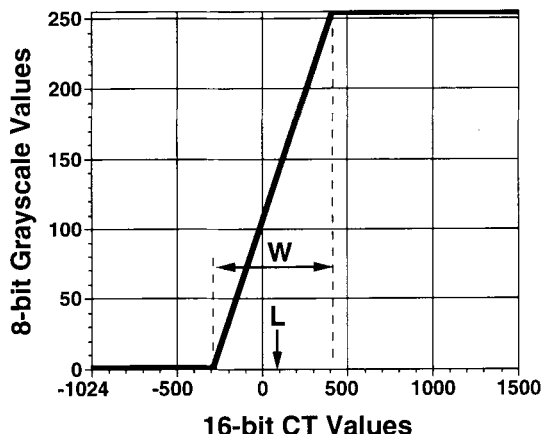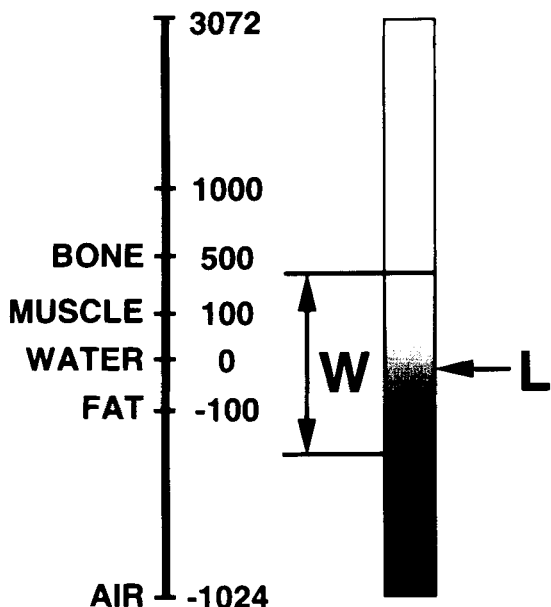

Fig 2. Window width and window level. The graph shows how the window width (W) and window level (L) parameters define the conversion of 16-bit image values into 8-bit gray scale values.

of brighter portions of the image. Combined, the window width and window level parameters define a process that converts the 16-bit CT numbers into 8-bit (256) gray scale values (Fig 2) (See the first article of the series[1] for a discussion of 8- and 16-bit digital images). A variety of terms are in common use to denote these parameters, including window width and window level, window and level, and window width and window center (or just center). The parameters are usually denoted as signed integers that are directly related to the image values. Magnetic resonance images (MRI) images must also be "windowed and leveled" before viewing. However, the window width and window level parameters of MRI images will be different than CT images because the dynamic range of MRI images is markedly different than the dynamic range of CT images.[1]

This terminology and numeric representation is straightforward to engineers, but can be confusing to others involved in medical imaging. To add to the confusion, when a user makes the window width smaller, the image contrast increases, so that window width may be thought of as the reciprocal of contrast. Similarly, when one makes the window level higher, the image gets darker, so that window level is the reverse of brightness. However, as more medical image displays are being located in clinical patient care areas, a wider range of individuals are using these displays. Typically, these individuals are confused by the window width and level

controls because they do not have an intuitive understanding of the underlying concepts.

WINDOW WIDTH AND WINDOW LEVEL CONTROLS

The controls used for setting the window width and level parameters may be of any one of a wide variety of different physical types. The early CT scanners had a stepped rotary knob that was used to select one of a relatively small number of window widths, approximately 10. Another continuously adjustable rotary knob was typically used to adjust the window level. As the cost of display hardware decreased, it became very easy to allow the computer to handle any arbitrary window width or level. Subsequently, the use of two continuously adjustable rotary knobs to select the window width and window level became more common.

Various manufacturers have explored devices other than rotary knobs to control these parameters. One common approach is to use a single trackball with window width on the horizontal axis, and window level on the vertical axis. Unfortunately, this is not a universal convention, and some workstations are designed with a reversed relationship. Using the single trackball can be confusing because two different types of hand motions are involved, and many users cannot change one value without inadvertently changing the other. Therefore, there has been a trend towards separating these two controls, either using two trackballs or two rotary knobs. In addition, some CT scanners offer push buttons that select predefined window width and window level parameters for certain tissue classes like lung, bone, or the abdomen. The push buttons usually do not replace the continually adjustable controls.

In the case of smaller viewing workstations, such as those based on Macintosh (Apple Computer, Cupertino, CA) or IBM-PC compatible computers, the mouse is the device that is most commonly available. Using the same convention as a single trackball, horizontal movements of the mouse adjust the window width, and vertical motions adjust the window level. In some environments, a trackball may be used interchangeably with the mouse. On PCs the arrow keys on the keyboard are also commonly used to adjust the window width and level parameters. Exam-

ples of window/level interface designs in various image display programs are shown in Fig 3.

The initial window width and level controls were implemented in special hardware that was a part of the display controller. In many of the more modern systems, the actual control is implemented in software, independent of the physical control device. This gives the software designers the ability to adjust the rate at which window width or level changes as the user moves the mouse or other controlling device. This method allows acceleration or nonlinear methods to be implemented that would not be feasible to perform with hardware-based controls.

Most individuals view the image while interactively adjusting the window width and level at a display console. However, many users find it helpful to be able to note the current settings in a numerical display. Therefore, many workstations display window width and window level in a manner analogous to that on a CT or MRI scanner. Unfortunately, the reciprocal nature of these values make them somewhat confusing for clinicians outside the radiology department.

Other user interface designs have attempted to clarify and simplify the window width and level controls. The Vision Ten (Torrance, CA) workstation uses a small square, with the current settings represented by a dot within the square. The horizontal location of the dot is determined by the window width and the vertical position of the dot is determined by the window level. This provides easy graphical feedback, but is not otherwise particularly intuitive or meaningful. Another method is to display a graph of the transfer function within a small square on the screen, analogous to Fig 2. An example of this type of control is shown in Fig 3C. The steepness of the ramp is determined by the window width and the position of the ramp is determined by the window level. This method is still potentially confusing to the inexperienced user because the shape of this ramp is not easily associated with the visibility of structures in the image. Further, using the mouse and cursor to move the ends of the ramp within the box is not obviously related to adjusting the brightness and contrast of the image.
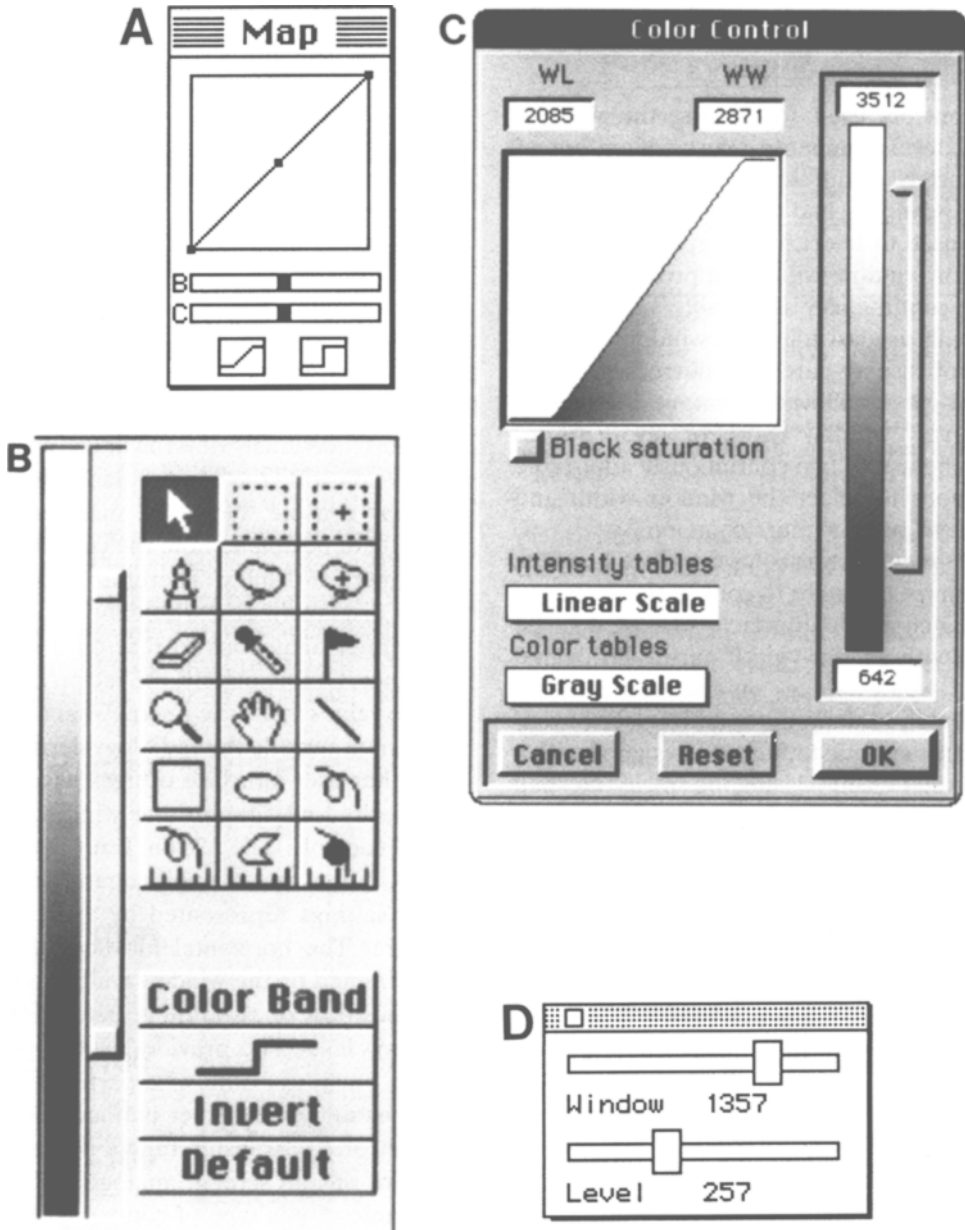
Fig 3. Examples of window/level or brightness/contrast controls in image display programs. A, Image 1.47; the brightness (*B*) and contrast (*C*) controls adjust the image by changing the color palette (palette animation). B, DIP Station 1.05; the window/level parameters are adjusted by moving the slider bar to the right of the vertical gray scale stripe. The region between the two boxes graphically shows which portion of the 16-bit image is converted into gray shades. The values above the upper box are converted to white, and the values below the lower box are converted to black. Note the similarity of the control to Fig 1. C, OSIRIS 1.0; similar to Fig 3B, the window/level parameters are adjusted by moving the slider bar to the right of the vertical gray scale stripe. The minimum and maximum 16-bit image values are shown at the top and bottom of the gray scale stripe. The window width and window level parameters are listed in the boxes labeled WW and WL. D, Dr Razz; the window width and window level controls are implemented as separate slider bars.

GRAPHIC HARDWARE

To display a color or gray scale image on a PC requires a complex interaction of the application software, the graphic hardware, and the display monitor (Fig 4). The application software loads the digital image from the disk or other storage device to system random access memory (RAM). Frequently, the image format on disk must be converted into a different format suitable for display. All or part of the image must then be transferred into the video RAM in the graphics hardware. The graphics hardware may reside on a separate graphics controller card, or may reside on the main computer circuit board shared by the central processing unit (CPU) and other computer system components. The graphics hardware then translates the digital image in the video RAM into analog video signals that are displayed as colors or gray shades on the monitor.

The relationship between the digital image in the video RAM and the colors displayed on the monitor varies according to the type of graphics hardware.

Most color graphic controller hardware and display monitors use the RGB color model. In the RGB model, each color is represented as the combination of varying shades of red, green, and blue. These three separate colors are combined by the eye to form a single unit of color. Each of the colors and its associated electronics and control mechanisms is commonly known as a channel. To display gray shades on RGB systems, the intensity of each of the channels must be equal. There are many other color models available, each with different strengths and weaknesses, but we will discuss only the RGB color model in this review because it is the model most commonly used in personal computers.
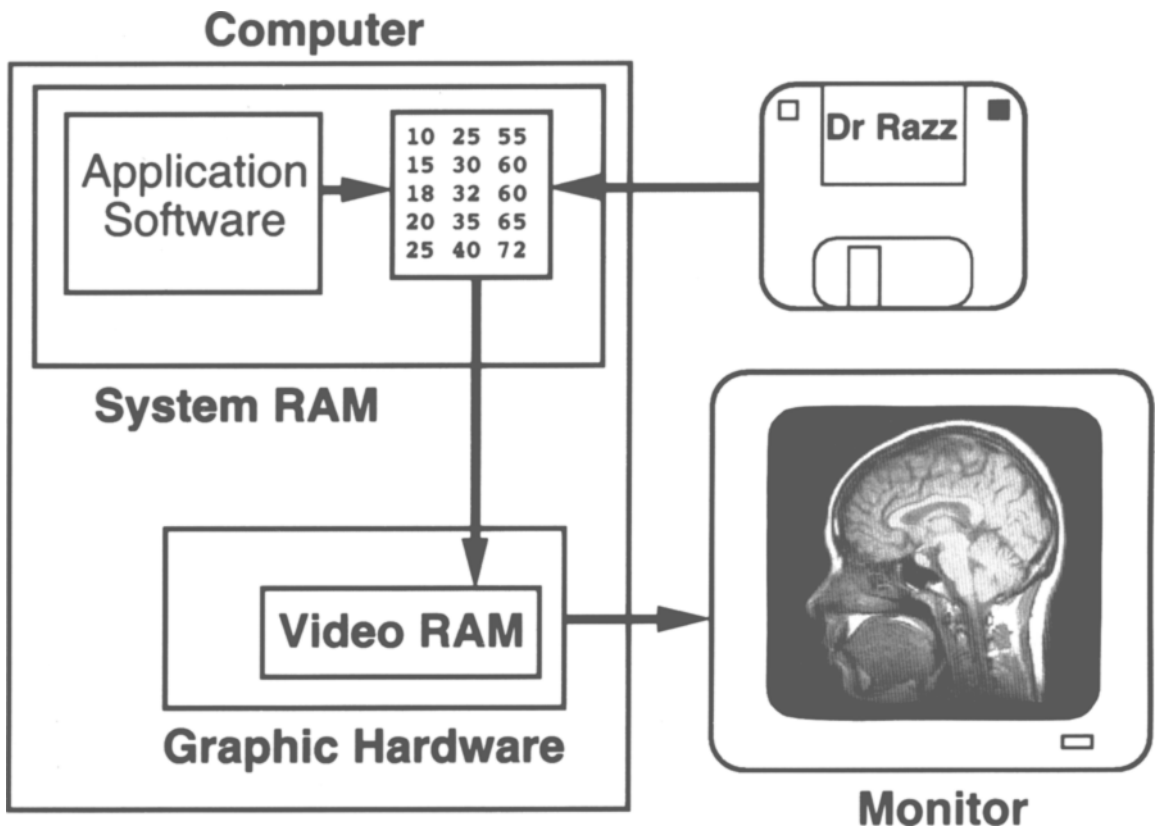

Fig 4. System operation for loading an image from disk and displaying it on a monitor. Abbreviations: RAM; random access memory.

Many color capable PCs are equipped with 8-bit graphic hardware, ie, at most 256 different colors or gray shades can be shown on the monitor at one time ($2^8 = 256$). In these computers, the determination of which color or gray shade is displayed on the monitor is determined by a hardware lookup table (LUT) (Fig 5) and a software data structure known as a color palette (Table 1). The hardware LUT converts the 8-bit image data value in the video RAM into three RGB values, one for each channel. On Macintosh computers, this arrangement is termed the indexed color model.[2] Then the RGB values from the hardware LUT are converted into three separate analog video signals by digital to analog converters. The RGB video signals are sent to the display monitor where they are converted into a displayed image (Fig 6). The color palette (Table 1), on the other hand, determines which RGB values are present in

the hardware LUT. Although only 256 colors can be displayed at one time, the use of different color palettes allows (in theory) for more than 16 million potential colors to be displayed.

Changing the appearance of an 8-bit grayscale image on computers with standard 8-bit graphic hardware is typically accomplished by changing the RGB entries of the color palette, and then using the palette to update the RGB entries of the hardware LUT. On the Macintosh and other PCs, this process is termed palette animation. The palette entries can be changed very quickly because at most 256 RGB values must be altered, and each RGB value is composed of three 16-bit integers (1 each for the red, green, and blue channels) (Table 1). After the color palette and hardware LUT have been altered, the displayed image reflects the changed palette at the next monitor update, which occurs roughly 60 times per second. Palette anima-
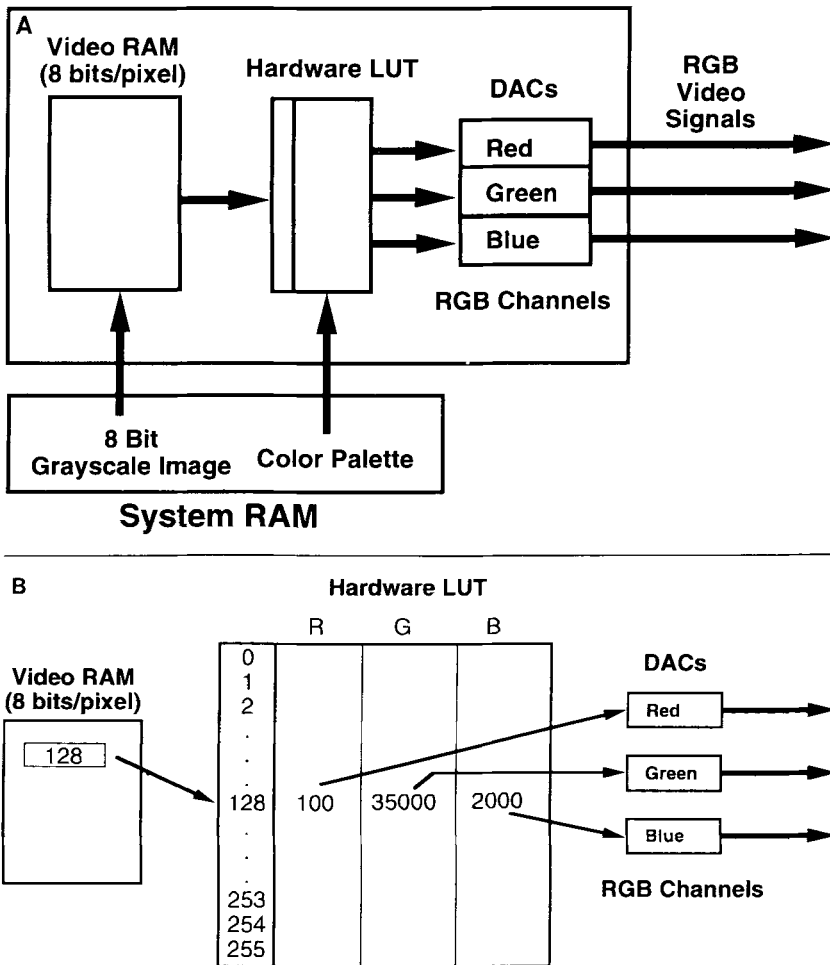

Fig 5. Eight-bit RGB graphic systems. A, Overview showing relationship of system RAM, video RAM, hardware LUT, color palette, DACs and the RGB video signal. B, Expanded diagram showing in greater detail how the hardware LUT converts the 8-bit pixel value into three separate RGB values, which are then converted by the DACs into the RGB video signals. The RGB values in the hardware LUT are derived from the software color palette (Table 1). For a gray scale image the values of the RGB channels would be the same for each index position. Abbreviations: RAM: random access memory. LUT: lookup table. RGB: red-green-blue. DACs: digital to analog converters.

Table 1. The Software Color Palette

Index	Red	Green	Blue
0	0	0	0
1	257	257	257
2	514	514	514
3	771	771	771
4	1028	1028	1028
5	1285	1285	1285
↓	↓	↓	↓
254	65278	65278	65278
255	65535	65535	65535

NOTE: Each index position in the palette is linked with three 16-bit RGB values. These values are eventually transferred into the hardware LUT (Fig 5), so that each 8-bit pixel value can be converted into three RGB values. In specific implementations, other data elements may be associated with the palette. The index value may be inferred from the position of the RGB values in the palette. For a gray scale palette, the values of the three RGB components are the same at each index position as in this example. The RGB values (0, 0, 0) at index 0 are converted to black by the RGB monitor and the RGB values (65535, 65535, 65535) at index 255 are converted to white. The values between these extremes are converted into grayshades. The specific values in this table are derived from a linear mapping of 256 values between 0 and 65535. The value 65535 is the largest value an unsigned 16-bit integer can represent ($2^{16} - 1 = 65535$).

tion allows essentially real time adjustment of brightness and contrast of 8-bit gray scale images.

PCs with graphic hardware that can display 16-, 24- or 32-bit RGB images are now increasingly common. In these systems, the pixel image value in the video RAM represents the actual RGB color value to be displayed (Fig 7). On the Macintosh computer, this arrangement is termed the direct color model.[3] These systems can display many more than the 256 colors associated with 8-bit graphic systems. Ironically, increasing the color depth in RGB display systems does not increase the number of gray scales that can be displayed. Sixteen-bit graphic hardware can only display 32 gray shades, but each pixel occupies 16 bits in the video RAM. Twenty-four–bit RGB display systems can display 256 gray shades, but each pixel occupies 24 bits in the video RAM. Fortunately, many higher resolution RGB display systems can operate in 8-bit mode, and each pixel can represent 256 gray shades while only occupying 8 bits in the video RAM.

In contrast to the RGB graphic hardware in PCs, the graphic display systems that are associated with CT and MRI consoles and many image display workstations have graphic hardware that can display 12- to 16-bit grayscale digital images without any intermediate conversions (Fig 8) (See the first article of this series[1] for a discussion of 16-bit digital images). In these systems, the video RAM stores 12- to 16-bit gray scale pixels. The hardware LUT converts the video RAM pixels into 256 gray shades for the display console. Typically, window width and window level controls determine the 16-bit image data to 256 gray scale conversion. Because this conversion is implemented in the graphic hardware, these systems allow essentially real time adjustments of the window width and window level parameters. Graphic cards capable of displaying 16-bit gray scale images are available for PCs; however, they are expensive, often equaling or exceeding the cost of the PC.

THE DISPLAY MONITOR

Conventionally, we say that 256 different gray shades are used for the image display, regardless of whether a PC monitor, CT/MRI display console, or film printer is the output device. In practice, however, the situation is more complex. Many display devices cannot display a full
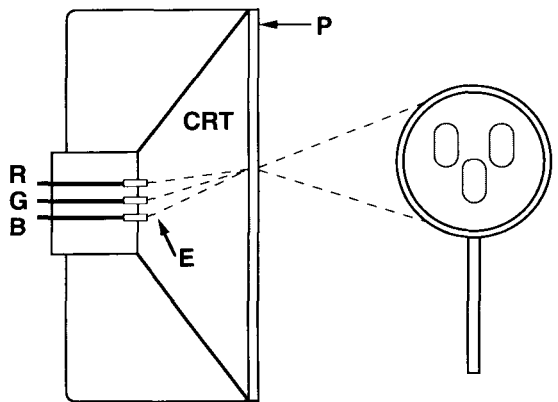

Fig 6. The RGB display monitor. Three separate video signals corresponding to the red (R), green (G), and blue (B) channels are sent to the monitor. A fourth synchronization signal is also present but is not shown. The RGB signals are converted to electron beams (E) inside the vacuum of the cathode ray tube (CRT). The electrons are accelerated to strike the phosphor coating (P) of the monitor, and light is emitted. A highly magnified view of the monitor display surface shows that each pixel is composed of three dots or bars of color, each a shade of either red, green, or blue. The eye combines these three components into a single point of color. The configuration and shape of the color components on the display phosphor varies with different monitor designs.
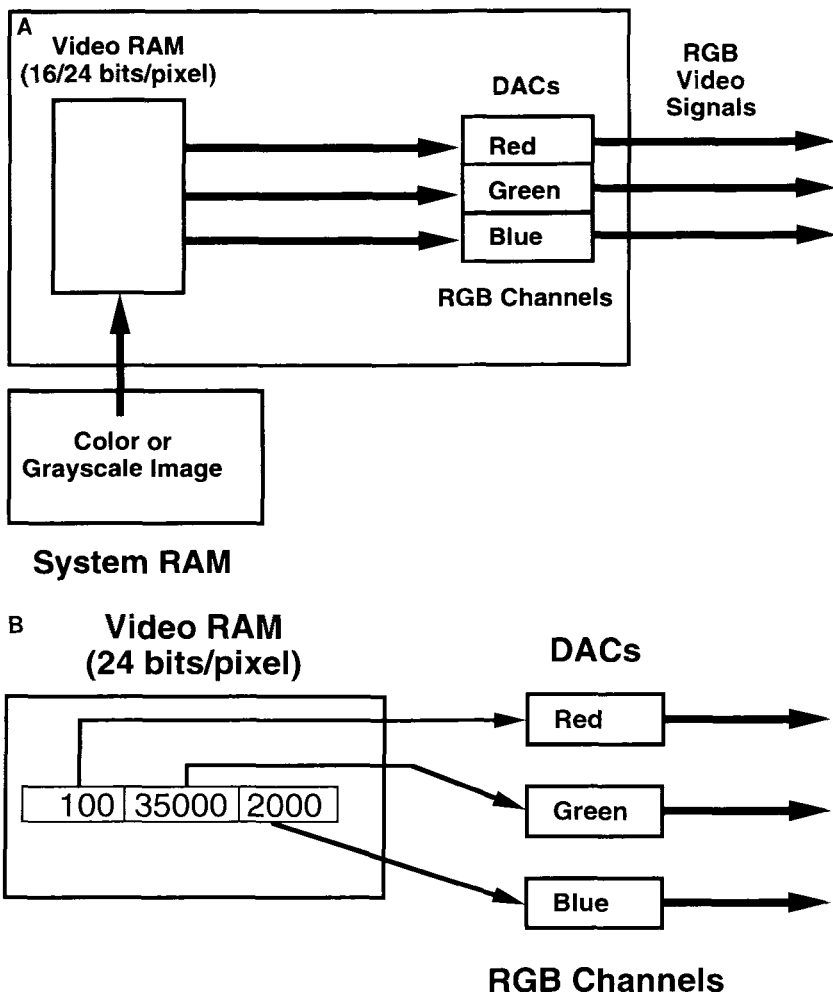
A

Video RAM
(16/24 bits/pixel)

DACs

RGB
Video
Signals

Red

Green

Blue

RGB Channels

Color or
Grayscale Image

System RAM

B   **Video RAM**
(24 bits/pixel)

DACs

| 100 | 35000 | 2000 |

Red

Green

Blue

RGB Channels

Fig 7. Sixteen/twenty-four–bit RGB graphic systems. A, Overview showing relationship of system RAM, video RAM, DACs and the RGB video signal. Each pixel occupies 16 or 24 bits in the video RAM. B, Expanded diagram showing how a 24-bit pixel in video RAM is directly converted into three separate RGB values. In a 16-bit RGB system, each pixel occupies 16 bits in the video RAM, and each RGB channel fills 5 bits of the pixel. Many 24-bit RGB graphic systems can operate in either 24-, 16-, 8-, 4-, 2- or 1-bit modes. Abbreviations: RAM: random access memory. RGB: red-green-blue. DACs: digital to analog converters.

256 gray shades, or the maximum available gray shades may not be available because the instrument is not calibrated properly. In addition, the perception of the available gray shades by the user is strongly influenced by the brightness of the displayed image, ambient light, and reflections on the monitor or film surface. Nevertheless, we shall retain the convention of stating that 256 gray shades are used for monitors and other output devices.

Inside the display monitor the three separate RGB signals from the graphic hardware are converted into electron beams that strike specific regions on the phosphor plate of the monitor (Fig 6). Each channel forms a dot or bar on the monitor that is a shade of either red, green, or blue. These three separate colors are combined by the eye to form various shades of colors. Television uses a related display system known as NTSC (National Television Standards

Committee). The RGB signals are combined at the television studio into a composite signal that is transmitted by the station. Many modern televisions have an RGB input port, and can function as the display monitor for a PC.

Radiographic images are difficult to accurately project on a display monitor. Factors affecting the image display quality of monitors include brightness (absolute luminance), dynamic range, characteristic curve, luminance uniformity, veiling glare, noise (spatial and temporal), modulation transfer, addressable matrix, spatial resolution (resolvable pixels), and geometric distortion.[4-6] Display monitors have significantly reduced brightness and spatial resolution when compared with conventional radiographic film viewed on light box. Several publications have recommended testing procedures for monitoring display monitor image quality that can be used in the clinical environment.[5,7-9]

**Video RAM
(12-16 bits/pixel)** **Hardware LUT**

DAC

**Grayscale
Video
Signal**

**16 Bit
Grayscale Image**
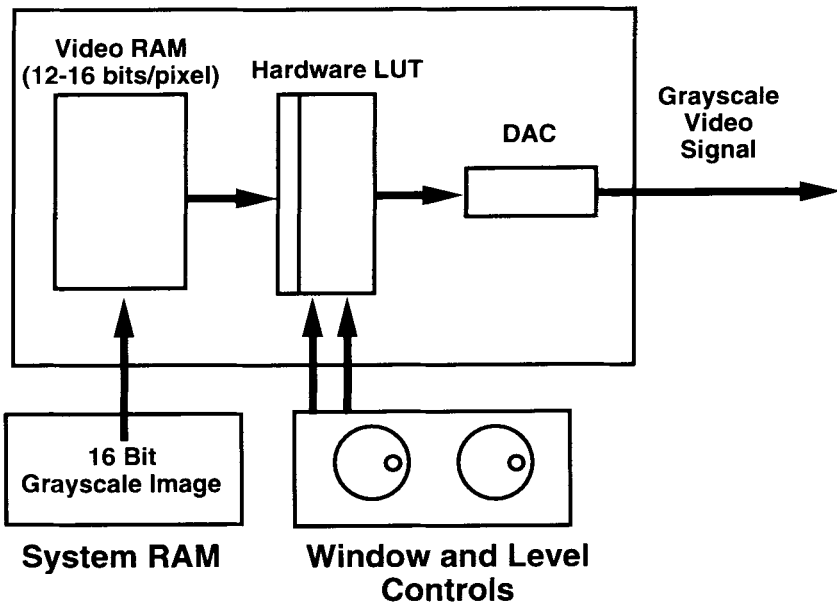
System RAM

**Window and Level
Controls**

Fig 8. Sixteen-bit gray scale graphic systems. The video RAM stores a 12- to 16-bit gray scale image. The hardware LUT converts the 12- to 16-bit pixel into a 256 gray scale value. The window width and window level controls regulate the 16-bit image value to 256 gray scale value conversion. Abbreviations: RAM: random access memory. LUT: lookup table. DACs: digital to analog converters.

At least one study has indicated that PCs can be successfully used for viewing digital radiographs.[10]

The addressable matrix and the spatial resolution (resolvable pixels) are the two monitor/graphic hardware parameters most familiar to PC users. The addressable matrix is the number of pixels in the horizontal and vertical dimension that the graphic hardware can display on the monitor. For example, a 640 by 480 pixel display system can display two MRI images (256 × 256 matrix size) side by side without reducing the image size. However, a CT image (512 × 512 matrix size) will have portions of the top and/or bottom of the image not shown on the monitor. The effective vertical addressable matrix of a monitor may be further reduced by a "menu bar" across the top of the screen, as is found in the Macintosh, Microsoft Windows, and X Window System user interfaces. Images larger than the addressable matrix of the graphic hardware can be displayed by either reducing the size of the image, or incorporating a "pan" or "roam" function that allows the user to scroll nonvisible portions of the image into the display window. The addressable matrix of several common PC graphic display systems are shown in Table 2.

On the other hand, the resolution of the monitor specifies the smallest dot or pixel that can be perceived as separate from an adjacent dot of the same size and spacing. This parame-

ter is usually expressed in terms of dot pitch, and is commonly 0.28 mm or smaller for high quality monitors. Note that the addressable matrix and monitor resolution parameters are referring to different aspects of the display system. If these parameters are significantly mismatched, image quality can be reduced. For example, if the graphic display hardware displays more pixels than the monitor itself can resolve, image blurring and fuzziness will be present.

The image display application and the imaging modality will dictate whether the quality of a given display system is sufficient. Typically, teaching, many research applications, and secondary consultation will have less stringent

Table 2. Addressable Matrix Sizes of Common PC Display Systems

Computer System	Addressable Matrix (256 colors)
Apple 14" RGB monitor, Macintosh LC III through Quadra 950 CPU models (some models may require extra video RAM)	640 × 480
Apple 16" RGB monitor, Macintosh Quadra 700 through 950 CPU monitors (some models may require extra video RAM)	842 × 640
VGA display system (IBM-PC)	640 × 480
Super-VGA display system (IBM-PC)	1024 × 768

Abbreviations: RGB, Red Green Blue; CPU, central processing unit; RAM, random access memory; VGA, video graphics array.

image display requirements than primary diagnosis from the display monitor. Moreover, we believe that CT, MRI, nuclear medicine, and ultrasound images are much easier to display with acceptable fidelity than computed or digitized radiographs.

Many users may want to upgrade their monitors and/or graphic hardware to improve the ability to display radiographic images. Purchasing a larger monitor commonly results in larger pixels on the screen. However, there is no increase in the number of pixels that may be displayed simultaneously, or in the resolution that may be perceived in images. Purchasing a better display adapter, on the other hand, allows a greater number of pixels to be displayed on the screen. However, the user may not be able to clearly see closely spaced pixels because the relatively large dot size of the monitor results in image blurring. Therefore, both new graphics hardware and a new monitor are usually purchased when upgrading the display system of a PC.

DISPLAYING 16-BIT RADIOLOGIC IMAGES ON PCS WITH STANDARD RGB GRAPHIC HARDWARE

At this point it should be evident that PCs with 8-bit or higher color resolution RGB

graphic systems cannot display 16-bit radiologic images without an intermediate process. To display and interactively adjust the window width and window level parameters of such images, the following steps are required (Fig 9):

1. The 16-bit image is transfered from the disk and stored in the system RAM. If the file format is known, then patient and examination-related information can be extracted from the header. However, even if the file format is not known, the raster image data can usually be extracted if the file is not compressed and the matrix size of the image is known.

2. Each 16-bit pixel is converted into an 8-bit value and stored in system RAM as a separate 8-bit image. An optimized method for performing this conversion using a software LUT has been described.[11] The window/level controls define the parameters for the software LUT.

3. The 8-bit image is loaded into the video RAM, and

4. The 8-bit values are translated into appropriate gray shades on a color or gray scale monitor by the graphic hardware, as described above.

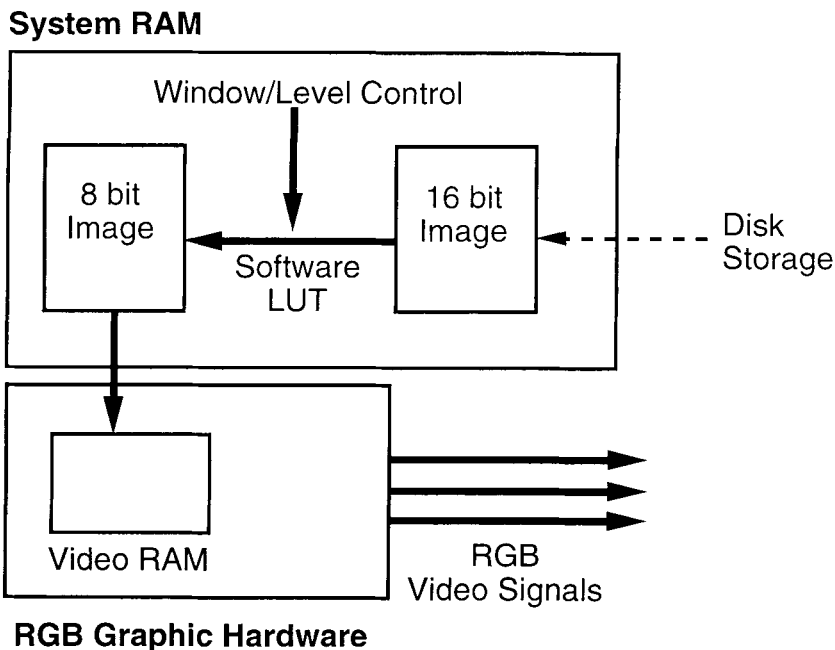5. The 16-bit image is interactively viewed with different window width and window

System RAM

Fig 9. Displaying 16-bit images on personal computers with standard RGB hardware.

level settings by changing the window/ level control, which changes the software LUT. Steps 2 through 4 are repeated each time the control is altered.

This method of displaying 16-bit images on PCs has been implemented in our image display application developed for the Macintosh, which is described in greater detail below.

PERFORMANCE ISSUES

Displaying radiologic images on PCs is a challenging task for equipment that is not specifically designed for this purpose. The performance of the system is influenced by many factors including the CPU, system memory, internal and external data bus design, hard disk drive, and graphic display hardware. There is little question that the newer PCs based on the 68040 and 80846 CPUs, and impending PCs based on reduced instruction set computer (RISC) CPU, can perform many of the image display and processing tasks traditionally performed by special purpose hardware or expensive workstations.

The CPU is a crucial factor in system performance for any task requiring image processing or analysis. The CPU is also an important component if a software LUT is used for adjusting the window width and window level parameters of 16-bit images (Fig 9). CPU performance is a factor of the specific model and the clock rate at which that model operates. In general, better performance is attained by CPUs with a higher model number, and by a faster clock rate for a given CPU model. As mentioned above, the introduction of the RISC CPUs into the PC will greatly increase system performance. In addition, the internal and external bus designs are important influences on system performance when images must be transferred from disk to system RAM, from one region of system RAM to another, and from system RAM to video RAM. Using the Macintosh computer as an example, performance of image transfer is strongly affected by the size of the internal data bus (eg, 16 versus 32 bits, 32 bits is faster) and the NuBus expansion bus performance. Because most graphic display cards on the Macintosh use the NuBus interface, the NuBus is a potential performance bottleneck for system RAM to video RAM image transfers. Some

manufacturers place additional memory on the graphic display cards where images can be stored to alleviate this problem.

The hard disk is another critical element in system performance. Hard disk performance is usually quantified by specifying the time required to find a file (seek time, measured in milliseconds) and the rate at which data can be read from the disk and transferred to the host computer (sustained data transfer rate, measured in bits per second). The latter factor is especially important for reading large image files. In addition to the hard disk itself, the hard disk–to–host computer interface is also a crucial component of system performance.

There are three different types of hard disk drives using different technologies that present unique advantages to users. Enhanced Small-Device Interface (ESDI) drives have fixed transfer rates of either 10, 15, or 24 Mbps and can accommodate different storage capacities. ESDI is managed by the CPU and works well with single-tasking environments with storage needs of up to 2 Gbytes, and can handle up to two disk drives. Integrated Drive Electronics (IDE) combines the controller and disk on the same unit. This device can handle only one drive, has a 16-bit parallel interface for data-only transfer and has a serial interface that is used to transmit sector, format, and other data. IDE costs less than EDSI because of the integrated controller and drive, and is currently the most popular system for IBM-PCs. On the other hand, the Small Computer System Interface (SCSI) interface can connect up to seven drives and other peripherals, and it provides faster data transfer rates than most of the devices mentioned above. SCSI ports are included in most Macintosh computers, and are also available for IBM-PCs. Enhancements to the original SCSI standard include fast-SCSI, which doubles clock speed, and wide SCSI, which increases bus width. Both enhancements significantly improve sustained data transfer rates.

Another common method for improving hard disk performance is to include a hard disk data cache. A data cache is special RAM located on the hard disk controller that stores the most recently accessed data from the hard disk. Any subsequent requests for that data can be retrieved much faster from the cache than from

the hard disk. Although this may not increase the speed of access of large files, such as when displaying an image, it may speed image processing and region of interest operations.

When optimizing system performance, it is important to match the capabilities of the hard disk with the hard disk interface to the computer. For example, even though different computer models may use the same SCSI standard, different models have different SCSI maximum data transfer rates. The full performance potential of a hard disk may not be completely realized if the SCSI interface is not capable of matching the sustained data transfer rate of the hard disk. Hard disk performance can be improved by adding higher performance SCSI interface cards. Performance can also be improved by using different hard disk topologies such as parallel disk arrays, but such topologies are uncommonly encountered in PCs at this time.

AVAILABLE SOFTWARE

Most of the desktop publishing packages such as Aldus PageMaker (Aldus Corp, Seattle, WA) are capable of integrating text and images. Most will accept images in multiple formats, including the tagged interchange file format (TIFF) format (See the first article of the series[1] for a discussion of the TIFF image format). Many radiologists are now using presentation software packages such as Persuasion (Aldus Corp, Seattle, WA) and PowerPoint (Microsoft Corp, Redmond, WA) to produce 35-mm slides of radiologic images. Both packages are available for both the Macintosh and IBM-PC computers. The quality of the 35-mm slides produced by these packages usually is better than the quality of 35-mm slides produced by photographing the image directly off the monitor. In addition, these packages allow the user to crop and annotate the image as desired. However, the radiographic image must first be imported into the PC.[1]

In other circumstances, using a laser printer to print the image offers acceptable output quality. Because the laser printers commonly available do not have true gray scale printing capability, the image must be reduced to a series of black dots. The appearance of gray shades is created by varying the distance between the dots, which creates darker and lighter portions of the image. This process is called digital half-toning, and is the same process used to print newspaper photographs. The relatively low cost per page of laser printer output makes this an extremely effective way to produce images for handouts and other teaching situations. Newer laser printers have expanded capability for handling images, including the Photo-Grade capability on the Apple LaserWriter Pro and other printers.

The next most sophisticated type of software is a general purpose image display package. One of the commonly available packages for PC-compatible computers is called CSHOW. This software is marketed as shareware with a registration fee of $25, and has the ability to display and print images in any one of 20 common image formats. Images larger than the available screen areas may be displayed and moved around by panning the image across the screen. The image may be made either brighter or darker with a simple function key. Some image-viewing programs in this class also include the ability to view a series of images in a cine sequence.

A more capable group of image display programs includes those designed to provide image processing and analysis. The most widely used program in this group is Image (Macintosh), which is a public domain application written by Wayne Rasband at the National Institutes of Health. Image is a full featured 8-bit image display, processing and analysis program. Sixteen-bit images can be imported, and are converted to 8 bits before display and analysis. Although not developed primarily for radiology viewing, many of its features have come from suggestions by radiologists.

Many of the commercial software packages that support image display on the Macintosh are useful and affordable. Enhance is a general-purpose package from MicroFrontier, Inc (Des Moines, IA) and MedVision is a system designed for radiology image viewing, with optional interface modules for many CT, MRI, and nuclear medicine scanners, available from Evergreen Technologies, Inc (Gaithersburg, MD). Two very powerful image analysis packages are IPLab from Signal Analytics Corporation (Vienna, VA) and Image Analyst from

Automatix (Billerica, MA). DIP Station is an advanced image processing application that can analyze 16-bit and floating-point image data sets. The application is not designed to be an image display or painting program. Advanced features include morphological image processing routines, fourier transform filtering and two-dimensional and three-dimensional reconstructions.

For the IBM-PC, a new commercial product, MedVision Viewer, supports viewing of radiology images under Microsoft Windows 3.1 and is available from Evergreen Technologies, Inc (Gaithersburg, MD). ·

OSIRIS is an noncommercial image display and analysis program developed by the University Hospital of Geneva. The program can display, analyze, and process 16-bit radiologic images. The program is modular and extensible, and has been written for several different hardware platforms including UNIX workstations (using the X-windows interface) and the Macintosh.

DR RAZZ: DEMONSTRATION 16-BIT IMAGE DISPLAY APPLICATION

We have developed an application for the Macintosh computer, "Dr Razz," which illustrates many of the principles described in this series. This application can display and interactively adjust the window width and level parameters of 16-bit radiologic images (Fig 9). The

Table 3. The Effect of CPU Model on Software LUT Performance

Computer Model	CPU	Time (s)	% Time*
Mac II	16 MHz 68020	0.51	67
Mac IIci, no cache	25 MHz 68030	0.41	65
Mac IIci, 32k cache	25 MHz 68030	0.31	63
Mac Quadra 700	25 MHz 68040	0.17	50

NOTE: Includes total time to change level control with mouse, calculate new level setting, calculate new 8-bit gray scale image from16-bit image data, and update the display. Times recorded using profiler option in Think C 5.0.

*The percent of the total time that was spent in the subroutine performing the 16-bit to 8-bit conversion.

(Adapted with permission.[11])

window width and level settings can be changed very quickly. On a Macintosh Quadra 700 computer, the window or level setting can be changed and the displayed 256 gray scale image updated approximately 5 times per second (Table 3). We consider this performance to be almost as fast as a display console or workstation that has 16-bit grayscale hardware (Fig 8). Most noncompressed CT and MRI image files can be displayed, with automatic handling of different header sizes and the Intel "little endian" byte order (See the first article in the series[1] for a discussion of the byte order in 16-bit pixels). The application will run on any color Macintosh with system software version 6.05 or greater and at least a 68020 CPU. The application is available for a nominal distribution charge. (For further information, contact Dr Gillespy at the address listed on p 151.)

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