Three Monochrome Displays From a Single, True Color Video Display Controller

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Some nuclear medicine computer displays, as well as many image processing workstations are "true color" machines characterized by independent memory and grey scale mapping for each of the red, green and blue color channels. Other color image display systems produce a color image from a single grey scale map composed of red, green, and blue intensity values ("pseudo color"). In the true color system the final image is obtained by overlays of three independent color images. In an effort to present complete nuclear medicine studies for diagnosis from cathode-ray tubes (CRTs) we have employed a true color display to present three times as much spatial information as the system was designed for by directing each color output from the display controller to a different monochrome black and white (b/w) monitor. Therefore our system displays a $512 \times 512 \times 24$ -bit true-color image, or three $512 \times 512 \times 8$ -bit monochrome images, or any combination of smaller size matrices. Monitor requirements, cabling, and general software considerations are detailed here. The ability to display complete nuclear medicine studies on CRTs (as currently presented on film) has been provided by adding monitors and software revisions to a commercially available nuclear medicine computer system.

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WITH THE INCREASE in the number of digital diagnostic imaging procedures in radiology and the rapid development of low cost display technologies and networking, a serious trend toward "filmless" departments can be foreseen. The increasing number of digital modalities (computed tomography [CT], ultrasonography [US], magnetic resonance imaging [MRI], digital subtraction angiography [DSA]) strongly favors the development of Picture Archival and Communication Systems (PACS)

environments. Although the concept of PACS has become quite clear in the last decade, its implementation has been rather slow for various reasons. Substantial technological problems involving storage, transmission, display, and digital interaction (input/output) remain to be solved, display in particular. With the growing number of "personal" workstations (Digital Equipment Corporation, Boston, MA, Sun Microsystems, Incorporated, Mountain View, CA, Hewlett Packard, Palo Alto, CA and Silicon Graphics, Mountain View, CA just to name a few major manufacturers) true color display of digital data is available on relatively affordable desktop machines. Realizing the potential of these color display stations to triple the amount of monochrome spatial information, the goal in this study was to optimize the display aspects of a PACS environment such that the maximum monochrome display capability is achieved. An example will be given based on the digital data volume and display needs of an all-digital nuclear medicine department. While certain departments, like diagnostic x-ray are beginning to incorporate digital techniques in their procedures, others, like CT, MRI, and ultrasound, are more suited to digital display due to the inherent digital nature of the image formation. However, the volume of data obtained in CT, MRI, and ultrasound is hindering, for the time being, the fast development of a filmless department. We will discuss the requirements of PACS displays and illustrate a possible contribution to a cost effective monochrome CRT display capability for nuclear medicine.

REQUIREMENTS OF PACS DISPLAYS

Focusing on the display environment of PACS systems, the following considerations should be addressed: (1) Displays and viewing stations must have associated large memories to display complete patient studies. (2) Displays also have to be large enough to accommodate previous studies or correlative studies obtained from different imaging modalities (US, CT, MRI, NM, DSA, etc) and may also include correlative anatomical atlas images.¹ (3) Rapid access to all

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the data is mandatory. An access time to equal or beat is the current speed at which films are retrieved on standard viewboxes or alternators and the time required to retrieve correlative studies from different radiologic modalities. (4) Some imaging modalities require cine-displays, the capability to show a sequence of frames from different time intervals. (5) Color images may be utilized to enhance features in otherwise monochrome images (nuclear medicine, Doppler ultrasound, MRI and three dimensional data presentation). Pseudo color is often used for such enhancement purposes. Pseudo color image display uses only one 8 bit image plane directed to a single color monitor. Color graphics have also become a standard feature of display stations in medical imaging for enhancement purposes. Display requirements are similar to those for pseudo color images. (6) Image manipulation involving basic digital image processing techniques: windowing, zooming, smoothing, interpolation, rotations, inversions, and mirroring of images is required.^{2,3} (7) Annotation of all digitally displayed data is mandatory. (8) Photography of images still remains a requirement for most interdepartmental needs and referring personnel, therefore any data on a video screen should be available for hardcopy recording.

REQUIREMENTS OF NUCLEAR MEDICINE PACS DISPLAYS

For this work the above PACS display requirements were applied to the typical case load of the nuclear medicine department at the University of Colorado Health Sciences Center. The department consists of four scintillation cameras, two of them with single proton emission computed tomography (SPECT) capabilities, all interfaced to two acquisition and processing computers (Picker International PCS 512 [Cleveland, OH] and DEC PDP 11/34A GAMMA 11 system [Digital Equipment Corporation, Boston, MA] with Picker VSV02 display). An average of 15 procedures per day is completed. The need for nuclear medicine PACS displays becomes even more evident if one notes that all new camera-computer systems are designed for complete digital data acquisition including total body imaging. With this in mind a "filmless"

nuclear medicine department may have the following display requirements:

(1) The ability to display complete patient studies including static and/or dynamic images. The static images may be 128×128 or 256×256 matrix images with 1 to 12 images per study. The dynamic portion of our studies produce 16 to 100 frames of 64×64 matrix images. These may either be filmed as static images, archived on video tape for later playback or stored on the system disk for cine-display. If filmed, 32 selected or summed images with 64×64 resolution are recorded. In most cases, the processing of dynamic studies and SPECT acquisitions generate an additional 2 to 4 graphs and/or $32 \times 64 \times 64$ views that also need to be displayed alongside the acquired images. In addition, a comparable number of functional images may be generated in certain cases to be displayed in cine mode. If whole body images are obtained, two images, at least 256×512 for the anterior/posterior and posterior/anterior views respectively, must be displayed. Thus nuclear medicine studies will have a variety of display requirements ranging from 64×64 dynamic acquisitions to high resolution 512×512 images. Often images from previous examinations must be displayed alongside the current study for comparison during a reading session. For example, renal transplant patients require frequent hippuran and diethylene-triaminepentacetic acid (DTPA) studies to monitor tubular necrosis, rejection, and cyclosporine toxicity.⁴ Oncology patients are screened with bone scintigrams at regular time intervals in search of secondary metastases to stage possible evolution of primary cancer.

(2) The ability to display correlative studies from different imaging modalities. Nuclear medicine must be able to accommodate large size matrices from other imaging modalities. These may include digitized chest x-rays, ultrasound, CT, and MRI. Presently the use of digital chest x-ray and ultrasound are not widespread, and a typical MRI or CT study requires the display of 40 to 60 images. MR images are mostly 256×256 while CT images are in general displayed in 512×512 mode.

(3) Rapid access to all images in a study and

to all studies of interest for a specific reading session. The retrieval and display of images from the display's mass storage is not instantaneous, however, single image access time should compete with alternator motion (several seconds) and rapid study access time must compete with alternator motion through the entire set of panels (up to 1 minute) including file room access for unanticipated studies (in the order of 10 to 15 minutes).

(4) Cine or movie mode display is very important and has to be available for a series of studies such as gated blood pools and first-pass studies, renal clearance studies, gastroesophageal reflux, and gastrointestinal bleed studies, gastric emptying, as well as tomographic acquisitions (SPECT) where stress versus rest is often presented side by side. In many instances, such studies are archived and viewed on video tape, thus cine display times need only be competitive with video tape archival, retrieval, and display times. At the University of Colorado Health Sciences Center, department studies are viewed directly on the computer display screen.

(5) Pseudo color image presentations are used frequently in nuclear medicine studies, such as phase analysis in nuclear cardiology⁵⁻⁹ or bullseye display of myocardial perfusion with Tl-201^{10,11} (functional images used for a relative quantitation of Tl-201 uptake). In addition, pseudo colors are frequently used in reconstructed SPECT data to enhance the uptake of radiopharmaceutical or photopenic areas in the organ of interest. They enhance the graphics and functional images obtained from analysis software running on present systems. True color display is not used in nuclear medicine.

(6) Basic image processing capability. This is without doubt the major advantage of digital displays and should at least include the following functions implemented with key strokes or with interactive devices (mouse, joystick, or trackball): zooming, smoothing, and contrast enhancement. Bone scans are a good example for the need of such basic image manipulations in terms of detail enhancements. Overlay of regions of interest and associated statistics is also desirable.

(7) Complete annotation of images on all monitors of a display system: each static image

has to show at least the patient's name, type of study, acquisition date and time, appropriate scales, and other identification commonly used by physicians when reading scintigrams.

(8) Photography has to be available through standard multifformat cameras or laser cameras to produce copies of the displayed images in the proper format for consultations or referring physicians.

DISPLAY OF COLOR IMAGES

From the trichromatic theory of color vision it is known that it is possible to match an arbitrary color by superimposing so-called primary colors, eg, red, green, and blue in an additive color reproduction system or yellow, magenta, and cyan in a subtractive color matching model.^{12,13} True color video displays are of the red, green, blue (RGB) type, and images have three independent components based on red, green, and blue signals that are added for the final analog display. True color images require an RGB display controller where each color gun used to represent an image can be mapped independently. Digital data is mapped through a look-up table (LUT) before being converted to an analog signal on the video screen. The LUT assigns discrete intensity values between 0 to 255 to each channel (red, green, blue), as the digital data for that channel streams through it. In most natural scenes, the red, green, and blue component of an image are all mapped by the same LUT function to determine their final intensity value in the image. A linear (ramp) LUT is usually the default choice, though is not a requirement (Fig 1). In many cases the red, green, and blue images can be stored in separate 8-bit deep planes and mapped independently through their own LUT. An alternative would be one 24-bit deep bit plane capable of holding all three primary images. The use of color monitors allows the display of any type (pseudo, false, and true) color images by "superimposing" red, green, and blue LUT values on a CRT screen with three phosphors that glow in the red, green, and blue regions of the visible spectrum. However the output of each primary component is independent of the final display device. Hence the red, green, and blue components can be used independently

Fig 1. (A) The red channel of a true color image is displayed in monochrome using the red LUT. Pixel values in each channel can assume values between 0 and 255.

Fig 1. (cont'd) (B) The 3 independent monochrome red, green, and blue images (from right to left) are shown using the linear mapping functions from above.

with monochrome (b/w) monitors. Black and white monitor screens contain only one phosphor, requiring the output of only one color channel with intensities determined by its LUT. Although color monitors can also be used to display b/w images, they are less desirable than

b/w monitors because of their variable persistence characteristics.

IMPLEMENTATION

We have integrated a group of three B/W monitors with the original color monitor on a

true color image display controller to triple the amount of displayable monochrome data (Fig 2). The group of three b/w monitors and the single RGB color monitor are switch selectable at the operators console. The display controller modified for this application is a Picker VSV02, (a DEC Q-BUS device) which has the capacity for three 8-bit deep image memories each holding 512×512 images. The system uses one video display controller for the RGB outputs allowing true color image display using all three bit maps (Fig 3). The VSV02 display controller is manufactured by Picker and is attached to a DEC PDP 11/34A UNIBUS machine through a UNIBUS/Q-BUS converter. The VSV02 display processor (Q-BUS) is also installed in the Picker PCS 512 computer (an 11/73 based Q-BUS device). The VSV02 has only one image

plane in its standard configuration. For true color display, two commercially available additional bit planes have been added. The two additional memory planes are identical hardware to the first except for their Q-BUS addresses. In one position of the monitor switch, the R, G, and B video signals (from the three image planes) are directed to the color monitor for true color display. In the other position of the RGBS video switch (BLACK BOX Model GR-SW575A), the red, green, and blue video signals of our true color display controller are fed to 3 monochrome (b/w) monitors (Fig 3). The external synchronization signal ("sync") is "daisy chained" from the system color monitor to all three b/w monitors and terminated at the end. An ELECTROHOME Model ECM 1301 was the standard 480 line color monitor used in the setup. It has loop through capability and switch selectable impedance on R, G, B, and sync signals. Three types of b/w monitors have been used at various times in this application: Conrac Model CVA 17, (Conrac, Covina, CA) Panasonic Model WV-5410 (Panasonic, Secaucus, NJ) and Sanyo Model DM 8012CX (Sanyo, New York, NY). Their main requirement is loop through capability for both video and sync signals.

Standard nuclear medicine image handling software provided by Picker utilizes pseudo color as well as b/w display for both images and graphics displayed with the GAMMA 11 analysis software. None of this software utilizes these optional additional bit planes. Hence new software had to be implemented to make use of the additional video memory. With the VSV02 video memory, immediate switching between different data sets is allowed by a simple change of address for the video memory board. The toolkit provided with the Picker system provides a single function call to change the address of the image bit plane to which video display programming is directed. Consequently software was written to load the bit planes with a change of display memory address whenever a given bit plane was full. This software can accommodate all the image formats used by the University of Colorado nuclear medicine department, ie, 64×64 , 128×128 and 256×256 as both inter and intra monitor (bit plane) matrix size mixing is allowed in this automatic load mode. Graph-

Fig 2. Prototype set-up. Three static bone scans are displayed in survey mode on three monochrome monitors showing the display capacity of the multimonitor set-up. In a clinical setting the three monitors shown should be the same type and models.

Fig 3. Schematic drawing of the true color video display controller and its RGB channels connected to the RGB and three monochrome monitors. These monitors had loop through capability to allow distribution of the external sync. Superimposed monochrome images, shown here on the color monitor, can be avoided with a switch to select either the RGB or the 3 monochrome monitors.

ics are stored in pixel format so that graphical displays are handled just like images.

Additional software was developed to allow unique annotation of each image on any of the three b/w monitors. Annotation on images is handled in the VSV02 hardware and the standard Picker PCS software by a hardware character generator with any desired color mixing. This is not usable in monochrome multimonitor displays since any one of the primary R,G,B colors will only be displayed on one monitor and mixed color will appear on more than one monitor. In addition, a unique definition of character color for each bit plane is not allowed. Therefore software was developed to add the demographic information associated with each image to the image matrix itself.

The last item considered was the photography of information from any of the three screens. One solution is to connect only the green image plane output to the b/w multifformat camera and copy the red or blue image plane to the green

before photography. This proved to be a rather slow process when implemented. A more practical solution for our application was a three-position switch to direct either the red, green, or blue video output to the multifformat camera or paper output. This is feasible in our case because the multifformat camera is dedicated to one computer only. In a shared environment the software solution may be advantageous.

RESULTS

Results are presented in the order of this study's nuclear medicine PACS requirements.

The functionality of the triple monitor monochrome display described above has been tested in a clinical environment. In this nuclear medicine implementation it is explicitly assumed that a depth of 8 bits per image pixel in digital nuclear medicine data yields sufficient grey levels for diagnostic purposes. Therefore three screens are able to display a total of three 512×512 matrices, $12\ 256 \times 256$, $48\ 128 \times 128$

or 192 64×64 digital images. Most studies will fit within these constraints eg, thyroid, liver/spleen, brain scans, renal and cardiac studies as well as SPECT, and will not require any additional or more complex programming. Most routine static and dynamic procedures of the University of Colorado's nuclear medicine department can be displayed on three screens.

The multimonitor set-up becomes valuable when used to display a full bone scan as shown in Fig 4 (most 256×256 static images or whole body 512×512 image). Whole bone scans can be reviewed in survey mode (Fig 4A) and zoomed up views can be displayed selectively (Fig 4C). Flow studies such as renal DTPA studies and cardiac acquisitions and processed data for first

Fig 4. (A) Three complete bone scans are displayed in survey mode over the three monochrome monitors. (B) Twelve views of the bone scan of the uppermost monitor in A displayed in full resolution over the three monochrome monitors.

pass and equilibrium gated studies including phase analysis and cine displays all benefit from a multimonitor display. Technically a combination of different matrix sizes can be incorporated into the video memories. The set-up at the University of Colorado is illustrated with a liver/spleen scan, a complete bone scan, and

Fig 4. (cont'd) (C) Three selected views that have been zoomed by a factor of two. Each magnified view corresponds to one of the 4 images shown on the three monitors in B.

lung perfusion scan in Fig 5. Magnified views of the individual scans can be obtained as shown in Fig 5B. Data display can be organized to accommodate complete single patient studies, multiple studies of the same patient, or different patient studies.

In the University of Colorado's present setup, simultaneous display of entire CT and MR studies for correlative studies along with nuclear medicine is not feasible. Problems posed by digital chest radiography have not been solved yet since chest x-rays might require 2048×2048 16-bit display capabilities or even 4096×4096 as recently suggested.¹⁴

Access time was comparable to the time required to fetch manually films and display them on view boxes and alternators. Direct memory access (DMA) allows rapid loading of byte mode images on all screens. Word mode dynamic studies take more time since scaling operations prior to display are involved, requiring approximately one minute.

Cine display with interactive manipulation of movie speed is solved uniquely with this display. Images were loaded from disk into the three image planes and cine display produced by switching inter and intra image addresses. Results were obtained for renal clearance studies in combination with graphics.

Since pseudo-color enhances images and is used effectively in functional imaging, a fourth RGB color monitor was used for those special cases. Pseudo-color cine and static displays have to be viewed separately without simultaneous display of the corresponding dynamic or static study. Examples are: phase analysis in gated blood pool (dynamic) and bull's eye display for relative quantitation of Tl-201 myocardial perfusion used in SPECT imaging.

Simple keystrokes allow magnification of selected screen quadrants (hardware zooming) and individual pictures if so desired. Contrast can also be adjusted and modified interactively through input by external devices such as a trackball, mouse or joystick in single image planes. In the present hardware configuration images originating from different image screens can be magnified separately with different zoom factors. Different LUTs can be applied, if

Fig 5. (A) Three different complete studies (lung perfusion, liver/spleen and bone scans) are displayed on the three monochrome monitors. (B) Selected magnified views of the individual studies. The lung perfusion and liver/spleen scans are static 128×128 16-bit images. The static bone scan images are shown in survey mode and can be individually displayed in their full 256×256 resolution.

needed, to the three different image planes to enhance independently the image details.

During display each image and/or each screen has to be annotated. Annotation was performed by writing characters into the image matrix prior to image display to allow identification on all three screens.

Photography was accomplished through a manual switch to direct any of the three channels toward output to a multifunction camera.

DISCUSSION

All nuclear medicine computers are (or can be) equipped with color monitors allowing black

and white display of studies as well as the use of pseudo-colors for enhancement purposes. Since color display is not required for most images, the addition of three b/w monitors to our configuration allowed us to display three times the spatial information by switching the output of each color plane to a monochrome monitor. Of course the switching mechanism still gives us the capability to feed the RGB output into one color monitor for color display requirements.

Our color display system utilizes an external composite sync signal but the same results would be achieved with systems carrying "sync on green" if the green signal is fed to the external sync connectors on each of the monochrome monitors. External sync (vertical and horizontal) is most frequently encountered as composite sync and may be included with the green video signal. The separate composite sync signal can be distributed to each display device with an amplifier such as a Shintron Model 336 Video Distribution Amplifier or "daisy chained" when "loop through" connectors are provided on the monitors. Switch terminators on monitors are extremely variable. Some have separate termination switches for RGB and sync and these are the most desirable.

The technology presented is available and can be implemented in the case of nuclear medicine. An alternate solution to a "filmless" nuclear medicine department could include the implementation of work or display stations networked to the dedicated nuclear medicine computer at a much higher cost however. Display of complete studies was feasible with one limitation: static bone scans acquired in 256×256 were restricted to 12 views. Sometimes we found the need to display up to 16 views for one scan. Simultaneous display of previous scans was not possible in this case.

Since all commercially available nuclear medicine computers now offer archival storage on optical disks the digital display of different data files in follow-up patients seems to be the next logical step. Other imaging modalities produce larger size digital images as well as a much larger data volume. The display of massive quantities of digital data requires larger video memories than the one we have used and programmed in the present case. Although

megabytes of memory have dropped in price, the monitor technology for 1024×1024 and even 2048×2048 displays that eg, CT and MRI digital displays require has slowed the pace for an all digital radiology department due to their cost. Correlative studies with CT and MR could be done with simultaneous data display from all three modalities. Obviously an alternative, though a costly one, 1024×1024 display capabilities requiring only two or three color display controllers would be a more ideal PACS station for general use in radiology.

Access time was slowed in the present implementation due to the individual image annotation before display. A slightly different approach however can be used: automated annotation can be performed according to the study's protocol immediately after acquisition and hence considerably speed up data presentation.

Cine-mode with variable speed was controlled with interactive joystick input. The only challenge was color cine displays, which could be analyzed in a second step and do not present a major difficulty in our approach. Sometimes we found it necessary in myocardial SPECT imaging to display static pseudo color images together with a sequence of b/w images or even b/w cine display to correlate diagnostic findings: this cannot be achieved with the present set-up and would require an additional RGB display controller for more color capabilities or simultaneous b/w and color displays.

All basic image manipulations had to be solved with additional software, which makes the execution more time consuming than the built-in capabilities of more powerful display processors. These would however imply a much higher cost for the user. In addition to cost, digital display adds control over grey scales on individual images (contrast enhancement) as well as zoom capabilities for selected region of interest or individual images. Some additional programming allows one to enhance considerably the value of digitally displayed data through processing techniques such as interpolation, smoothing, and rotation of images.

The hardware character generator could be used for color display. The b/w screens annotation was performed through direct pixel loading

of video memories: this also had the advantage of using a much larger selection of characters than those available from the hardware. Also, vertical annotation as well as different character sizes is made possible to annotate graphics.

The Picker and Gamma-11 nuclear medicine computer systems architecture allowed an efficient implementation of this display software.

Ultimately, digital display of studies represents a more efficient solution for radiologic data handling than the use of films distributed among alternators. Even cost might be reduced in combination with the proper type of archival storage. The implementation of a "total digital diagnostic environment" will allow the production of any number of original copies on film or paper. Viewed from referring clinician needs, this will allow access through local area networking, digital data base, telephone lines, or satellite communications.

CONCLUSION

We have shown that multimonitor monochrome data display controlled by a single RGB true color video controller is able to present

efficiently three times the image display data for conventional monochrome images and still retain the ability to display the complex color images required for functional image and graphics display allowing cine displays in real time in addition to static image displays. This has been achieved with the addition of monitors and software. Additional software was required and has been implemented in a nuclear medicine computer system. The University of Colorado VSV02 system, which included two additional video memory boards not contemplated in the basic commercial system, was upgraded to a true color model and hence allows display of true color images up to 512×512 pixels in size or three monochrome eight-bit images up to 512×512 pixels each. The methods applied here can be applied to the 1024×1024 true color display processors or 1024×1024 true color work stations available today. For our application each of the primary colors is used with the same linear LUT. An open architecture allowed major additions to the user software and also permits software revisions as they are needed.

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