# Design of Useful and Inexpensive Radiology Workstations

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## 1. INTRODUCTION

In order to fully achieve the advantages associated with a radiology Picture Archiving and Communications Systems (PACS), it is crucial to have a digital display medium. A significant amount of effort has been spent developing electronic versions of the film/lightbox combination. While we have seen large numbers of workstation designs produced and described, very few are actually in service in the clinic at this time. The few situations where electronic workstations are reported in use today are mostly in ICU locations where CR is involved, the images to be seen are few, and very high resolution is not required.

Why have we not seen a proliferation of electronic workstations? Three major reasons are (1) connectivity, (2) ease of use, and (3) cost. Without connectivity to provide easy and convenient access to remote image and patient data, the workstation by itself is useless. Connectivity is an issue for PACS design, however, and will not be addressed in this paper. The ease of use and cost of a workstation for reading patient studies is a part of the design and implementation of a good workstation console, and are the focus of this paper.

First, I suggest some guidelines for designing Radiology PACS consoles and examine how existing workstations follow these guidelines. Then I will describe a classification dividing the image display problem into two categories, and cover how the design guidelines apply to each of the categories. At the same time I will detail our experience implementing two such designs on several hardware architectures. Finally, I will discuss results from our studies comparing readings done using these implementations versus readings on film and lightboxes or alternators.

## 2. Background

While there are many good rules and guidelines for designing PACS console applications, I have focussed on four guidelines that I consider to be the most crucial and the most often disregarded. These guidelines are well documented in Computer Human Interaction (CHI) literature; however, many existing workstations designs seem to have ignored them.

### 2.1 Build the tool for the task

Prior to designing any tool, the task should be well understood. The tool should be built for that task. Only a few applications, for instance the AVC for chest films [1], and FilmPlane for chest CT [2], have studied a problem and then designed a tool for that situation. Additionally, it is a good idea to incorporate prior information about the patient study to choose the specific tool or version of a tool to be used for displaying the images [3].

Most existing workstation applications are not focused on a task. By far the most common theme is to choose either a tiled or overlapping arrangement of images and then associate with the images a grab bag of operators on the images. While one of the advantages of digital workstations is the ability to apply many different operations to an image, this does not imply that the designer should include any and all operations in their application.

2.2 Simple, easily understood mental model

For the user to be comfortable and efficient using the tool, it must be natural for them to use. This will only occur if they have a simple mental model of what the tool is and what it does. It is desirable to make use of analogies to tools that users are already familiar with, for instance, a desktop metaphor.

Most applications choose a two dimensional surface as their metaphor, allowing images to be placed on the surface following either a tiled or overlapping structure. While on the surface many of metaphors seem tidy, they often have problems. One example is when using a desktop metaphor of overlapping papers where each paper represents one image from a study. In our experience, this results in a confusing scene after the user moves several images around, resulting in a lack of sense of the patient study or where to find specific images. As another example, we found that the users had a much better sense of the study if we constrained them to a fixed format tiled presentation. However, in doing this we found it more difficult to present a consistent mental model when allowing operations like zooming and window and level (W/L) on individual images.

In some cases we have found it desirable to remove features (e.g. zooming) which, if removed, allowed the mental model to remain consistent.

2.3 Very simple user interface

Just like a hammer and nail, the interface should be invisible. If the user has a mental pause between actions while trying to determine how to do something, the interface is not transparent. This means it is hampering the user from accomplishing his task. This will frustrate him as well as slow him down. Again, from CHI experience it is generally recommended to determine the task, then design a tool for that task, then prototype a tool for the task, and then iterate through many prototypes with real users before settling on a final version.

Many existing interfaces are designed as a display area with a collection of associated image operations hidden in pulldown menus or on a dedicated menu area. There are many examples of applications where the unrelated image operations seem randomly stuffed into pulldown menubars. No consideration is given to what the task steps will be and how the user can most efficiently accomplish them. For instance in an earlier version of our first display console for CT [4] there were three screens (one overall view of all the images minified to fit on one screen, and two full resolution working views). The interaction for choosing new images to appear on the working screens was to click either the *forward* button or the *backward* button on the mouse, or to point to the desired image on the overall view. We later discovered from observation and eye tracking experiments that the radiologists most common operation was to move linearly through the study and to look at up to 6-8 images at a time [5]. Since we could hold 4 images on each of the two working screens, we found that the radiologists preferred mode of interaction was to look at 8 images and then to scroll to the next 8 images. Unluckily, our interaction required them to do two separate scroll operations, one for each screen to accomplish this. This required clicking on one screen, then moving the mouse cursor to the second screen and clicking there.

It is often useful to model the task in order to design an efficient implementation. Some common modeling techniques we have used with success are the keystroke model [6] and the GOMS model [7]. For example in chest CT readings we found that by far the most common operation was to scan linearly through the images. This resulted in all of our recent workstation designs for chest CT (FilmPlane, Filmstrip) having the scroll operation be the easiest and quickest operation for the user to perform (either a mouse click or a dedicated oversized function key). Additionally, the operation was enhanced so that scrolls could affect multiple screens if the user was using these screens to provide a larger contiguous view into the study.

2.4 Interactions must be instantaneous

Probably the most common complaint observed with our earlier attempts was that it took too long. Radiologists are highly skilled and find waiting on a slow computer very irritating. Additionally, because they are highly skilled they are highly paid and with the current medical reimbursement situation most radiologists are in a sense paid by the piece. Thus time wasted waiting on the computer to act is a strong disadvantage to an electronic system's acceptance, both by the radiologist and the business manager.

Where thorough studies have examined speed and accuracy issues comparing film lightboxes with electronic workstations, the results have shown that electronic workstations are slower than lightboxes. Foley found that for body CT readings the four radiologists in the study were 33% slower on average when reading from two 1024x1024 image workstations [8]. He found that the major component of the increased analysis time was for screen changes (which required either 7.2 seconds when displaying 512x512 images, or 26 seconds for 256x256 images) [8]. Similarly, Beard found chest CT readings with FilmPlane to be slower than on film when readings were done on one 1000x1000 screen [9]. Additionally, he found that the difference in times between workstation and lightbox readings correlated with the amount of time the workstation spent doing scroll operations during a reading. Thus, if scroll operations occurred instantaneously we could expect the workstation to have a reading time comparable to that of the lightbox. This makes sense, as we know that the equivalent of a scroll operation on a lightbox is a glance, which takes a small fraction of a second.

As a result, I now use the rule of thumb that if an operation is not *instantaneous* it is not acceptable, regardless. This means that if I cannot find a way to implement scroll operations, zoom operations, W/L, image processing operations, etc. at the push of the button, they do not get included.

### 3. Design and Implementation

Of the four guidelines from the last section, building the tool for the task is the most important. While building the perfect tool might mean carrying this to the limit and building a tool for every clinical task, it is likely that there is enough overlap that a single tool can be used for several types of clinical situations. Our experience with chest CT and more recently with MR, standard chest Xrays and mammography has led me to generalize two types of display methods that fit most clinical situations. I will give some background reasoning for the classification split and then describe current designs that meet these guidelines and that can be implemented on hardware costing less than $10,000.

*Enough Screen Space?*

The most limiting factor in designing electronic versions of lightboxes is the lack of screen space. A light box, or alternator in a common 4 over 2 configuration can hold 8 films, each which potentially represents 4000 by 4000 pixels or more. This means the light box has the equivalent resolution of 16000 by 8000, while today's highest resolution monitor is 2048 by 2560. (I will not go into luminance or contrast differences in this paper). This means the lightbox can display 25.6 times more material than we can show on a single monitor. We can certainly use multiple monitors if we are willing to live with border problems between monitors, but even with 8 monitors as some commercial manufacturers have prototyped, we still have less than a third of the resolution of the lightbox.

This means that one of the most crucial aspects of a display workstation is how it handles the issue of being able to display only a portion of a study at one time. This has also led me to segregate display programs into two groups.

*sufficient screen space*: Display applications that can display the *required* amount of information on the available screen space at one time.

*insufficient screen space*: Display applications that cannot display a necessary required amount of information at once.

This is more complex than just looking at image size. It requires knowing the task and what is required to accomplish the task. For instance, in single study chest CT we found that 6-8 images may be required to be visible at one time. Less than this number caused the radiologists to have to mentally remember adjacent images. In one study we constrained radiologists to use a single 1000x1000 resolution screen when using FilmPlane. This means they could only look at four 512x512 full resolution CT images at one time. When compared with their performance reading similar images in another study where FilmPlane was configured with 2 1000x1000 screens (thus allowing 8 images to be viewed at once) we found that they took more time to complete readings with the single screen and that they resorted to mental aids like writing down findings instead of remembering them, thus indicating more short term memory overload [9].

Thus, for single study chest CTs we have chosen the threshold to be the ability to display 8 512x512 images at once. If the display system can display 8 or more CTs at full resolution at once it is considered screen space sufficient, else it would be considered screen space insufficient. I make this distinction because I believe that different display paradigms should be used for screen space sufficient as opposed to screen space insufficient situations.

## 3.1 Screen space sufficient methods

For situations with sufficient screen space we use what we have termed a "Filmstrip" orientation. The mental model is a film projector with a filmstrip running through it. The images projected are what is seen on the screen. The filmstrip itself is comprised of all the images of the study, tiled to fit on the filmstrip. The user would scroll the film up or down to see images in either direction. Modalities like CT, MR, nuclear medicine, and lower resolution Xray images would be candidates for this category. We have designed a version of this for chest CT readings. Below, I list some of the design decisions and their motivation.

*No separate Navigation view*

Adding a navigation view would change or at least complicate our mental model of a filmstrip projector. Assuming that scroll operations were instantaneous, it was felt that radiologists know where they are in the study, and could easily move to a desired location, and that a navigation view would not serve an important enough purpose to warrant complicating the mental model.

*Provide only W/L presets and scroll operations*

A primary goal was to demonstrate that workstation readings could be as fast as lightbox ones. In order to compare similar things we intentionally limited the available operations to match only those provided with a lightbox: the ability to look at images at preselected W/L settings and to look over all the images. Until we have established that we can perform readings at a speeds similar to those on a lightbox, we are not including any other operations that might cause the reading times to increase; for instance, allowing the radiologist to play with an interactive W/L operator.

*The two operations (W/L and scroll) must be instantaneous and easy*

Having limited ourselves to only W/L and scroll operations we found that we needed to provide only five logical actions: choosing one of three W/L presets (lung, soft tissue, liver) and one of two scroll motions (forward or backward). After some debate and prototyping we eliminated using the mouse and choose to use the keyboard. We use three oversized function keys (F4, F5, F6) on the Sun 3 keyboard to select the three W/L settings. These keys were labeled. The spacebar, being the easiest key to hit was chosen for forward (down) movements and any other key on the keyboard mapped to a backward (up) movement. The keys are easily struck by a single hand which facilitates holding the dictaphone in the other hand. We have found that radiologists when using the mouse, often hold it in their dominant hand and then release the mouse to pick up the dictaphone with the same hand, which causes delays when switching back and forth between the mouse and the dictaphone. This is compounded when the interaction requires the use of both hands (e.g. keyboard and mouse in addition to a dictaphone).

*Implementation*
We have implemented this system on two different hardware configurations. The first is a Megascan single screen 2048x2560 display system. The second is a Sun workstation with two 1000x1000 monitors. The same software is used for both systems, with different low level image display routines depending on the capability of the hardware. It runs under the X Window System, and is written in the C programming language.

The low level interface is slightly different for the Megascan, as this system provides some extensions to X which are utilized to enable us to accomplish the realtime scrolling and W/L operations. On the Megascan we tile the images into the Megascan frame buffer and from there we can copy in realtime (1/9 of a second to update the 2048x2560 screen) a new screen of images to the video buffer. We are also able to perform any arbitrary W/L operation on the image data as it is moved from the 12 bit frame buffer to the 8 bit video buffer. Thus, we can perform any scroll and W/L operation in 1/9th of a second. We have found that with this throughput speed, the radiologist typing on the keyboard never gets ahead of the screen updates, so there is never any lag perceptible to the radiologist.

The implementation for the Sun workstation runs using only standard X. Thus it runs on any Unix workstation supporting X. Because most of the workstations in the class we are considering (those costing less than $10,000) have 8 bit video buffers and no separate frame buffer, we had to choose a different approach for displaying the images. In order to get the speed necessary under X, the obvious choice was to preload images in memory for each of the three W/L presets. Thus three versions of the entire study windowed for lung, soft tissue and liver were computed and preloaded into pixmaps on the X server. This enables us to use the XCopyArea() function on the server to copy from a pixmap to the display screen resulting in updates rates of less than 1/10th of a second on the Sun workstations.

<u>3.2 Screen space insufficient methods</u>
In a sense, these are the situations that we cannot handle well at this time because of insufficient screen space. The user is unable to view all the information they desire at a single time. Most implementations that handle this situation attempt to provide some sort of navigation or more overall view to help you maintain a sense of what is in the patient study as well as what portion you are currently viewing.

For this situation I have chosen a mental model similar to the microscope. The images are arrayed on a two dimensional surface. The user is able to do two operations: roam around on the surface, and choose the level of magnification with which they view the surface. This enables them to zoom out and see the entire surface, or to zoom in and see the minute details of a specific region of the surface. Additionally, they can make small adjustments to their location by roaming, or make bigger adjustments by zooming out and then zooming in to the new location. This system is named PlainView.

In this case our design is based on reading mammograms. Our example protocol is to have 4 images (CC and MO of right and left breasts). Each image was digitized at approximately 4000x5000 pixels, but then cropped to just show the breast resulting in 4 images approximately 2000x2500 pixels in size.

*No separate Navigation View*

By choosing the mental mode appropriately, navigation is accomplished by zooming. An overall picture is obtained by simply zooming out to see the entire surface, so no separate navigation view is required.

*Limit to roam and zoom operations*

In order to compare against the lightbox we have again limited the available operations to only those required to view the mammograms, zooming the display and roaming the display. No W/L capability is provided as the mammograms are acquired and read at a single setting.

*Interactions simple and instantaneous*

In this case there are three actions: roam (in any direction), and zoom in and zoom out. While one could limit the roaming to discrete choices of directions (e.g. up, down, right, left) our experience has been than a continuous choice is more natural and most preferred by the users. Thus, to support roaming, a device such as a mouse, trackball, or joystick is required. Our inclination is that the trackball might be the most effective device for this task, but given that a mouse is a standard accessory on inexpensive workstations and well supported under X, we choose to use the mouse for the roaming interaction. Additionally, since most mice on workstations have three buttons using one for roaming and the other two for zoom in and zoom out, allows us to execute our three operations all with a click of a mouse button. Roaming is done by depressing the left mouse button and dragging the mouse, resulting in the image panning in the direction the mouse moves. This is similar to grabbing the microscope slide and moving it under the magnifying lens. Clicking the middle mouse button zooms in and clicking the right mouse button zooms out. All the operations, panning, zooming in and zooming out are accomplished in realtime. It is especially important that the panning be accomplished in 1/10th of a second or faster to maintain smooth roaming. If the update rate is too slow, the lag results in jerkiness or tearing of the image which is disconcerting to the user as well as increasing their interaction time.

*Implementation*

PlainView has been implemented on several different configurations including a Stellar graphics supercomputer, a Megascan display system, and a Sun workstation. The same software is used for all systems, with different low level image display routines depending on the capability of the hardware. It runs under the X Window System, and is written in the C programming language.

The Stellar GS1000 computer supports copying of image data from main memory to the video buffer over a high speed (512 bit wide) bus in 1/60th of a second. This allows us to accomplish the roaming by storing the image in main memory and copying the new image location to the video buffer each time the user makes a roaming motion. The Stellar also supports several low level image processing operations in the graphics engine pipeline, allowing them to occur in realtime. We were able to modify one of these routines to provide real time continuous interpolated zooming.

The Megascan display system supports rapid updates of the screen as described previously. The update rate of 1/9th a second is marginal though, with the users occasionally noticing the lag in roaming. The Megascan also supports realtime zoom in and zoom out by pixel replication. Since we store the original image at full resolution, we are mainly interested in allowing the user to zoom out (sample the image down to smaller sizes). Thus, while pixel replication is not a good choice for resampling images in general, it suffices for providing an overall view where accurate final detail is less critical.

On the Sun workstations we again stored all the possible display combinations in pixmaps on the server side of X so that we could quickly copy the image data into the video buffer. The trick here is to provide precomputed interpolated images because we cannot interpolate the images to a new size in real time. Based on previous experience, I choose to provide zoom increments in factors of two. Thus we precomputed the original image at full resolution at 4000x5000 by 8 bits, then proceeded to compute bilinear sampled down versions of the images at 2000x2500, 1000x1250, and finally stopping at 512x625 where we could view the entire image on the screen at once.
Storing the images requires approximately 27 Mbytes of main memory. Memory is relatively inexpensive compared to other parts of the workstation, such as the monitor, and the price of memory is rapidly decreasing, making tradeoffs that require lots of memory seems reasonable.
On the Sun we were able to achieve update rates of less than 1/10th of a second allowing us to smoothly roam as well as to zoom in and out in realtime. Note that the zoom in this case only varied between 4 discrete choices: full resolution, 1/2th resolution, 1/4th resolution, and 1/8th resolution.

## 4. Experience

### 4.1 FilmStrip

We have recently completed an experiment to evaluate the speed and accuracy of FilmStrip running on the MegaScan for chest CT readings. The Megascan was configured to show a 12 on 1 display format, yielding an image size on the Megascan very close to the normal size of chest CT film images.

The study was carried out in a similar fashion to our earlier experiment comparing FilmPlane to a film lightbox [9], with accuracy being measured by comparing the dictated interpretation report to the previous clinical report. The films were displayed on an alternator in the chest CT clinical reading area. As with the earlier FilmPlane study we found the accuracy of the workstation to be the same as the alternator viewed films. This time, however, we found that the reading times for FilmStrip on the Megascan were equivalent to those for the alternator [7,10].

We learned some additional information from observing the radiologists using FilmStrip.

*Radiologist liked it.* They all felt comfortable reading chest CTs with FilmStrip and indicated they would use such a device in the clinic.

*Field of View.* Most of the radiologists also indicated they liked having the single screen area (one screen) to look at; i.e. they preferred having the images moved to their field of view (like an alternator) rather than having to move their head to see remote images on a lightbox or multiple monitors.

*Scrolling*. Several of the radiologists were initially confused by the scrolling. Hitting a key to scroll caused the images to scroll two rows on the screen. While this is optimal in the sense of maintaining context by keeping adjacent rows in front and back of the middle two rows of images, it is disconcerting because people tend to read to the bottom a page and then expect to start at the top of a page (book analogy, English languages) or to see a new line at the bottom of the screen (computer text scrolling analogy). In order to keep at least one row of context, the other options would be to scroll 1 or 3 rows instead. The radiologists, however, did not express a strong preference for any particular choice of 1,2, or 3 rows to scroll when asked.

*Window and Level.* Because our images were taken indirectly from old clinical studies we did not have the actual W/L settings for each study. As a result, we arbitrarily choose "mean" W/L settings for lung, soft tissue and liver and applied these to all the cases. In some of the cases the radiologists felt that the W/L settings were not specific enough (especially the liver). For a clinical system it would be important to retrieve and apply the original W/L settings for each individual case.

*Study Extent.* One area where the navigation view was missed was in knowing the extent of the study. Our radiologist's initial dictation includes a description of the extent of the study. Because they could not see the entire study at once, they would scroll all the way through the study once just to see the extent, then back up and begin linearly scrolling through the study. To compensate for this we have enabled two additional function keys, HOME and END, that allow the user to jump directly to the beginning or the end of the study, respectively.

We are now testing a two screen version of FilmStrip on the Sun workstation to see if we get comparable results.

PlainView

At this time we are completing analysis of the mammography task and have not carried out a formal experiment using PlainView. We have initially prototyped PlainView on the Megascan and the Sun and have presented sets of four mammograms (CC and MO of the right and left breasts) to one of our mammographers. Her initial impression was that the PlainView mechanism is useable; however, from our observation of her, PlainView appears to be slower than film/lightbox and more cumbersome to use, especially on the Sun where we can only display 1000x1000 pixels at a time.

## 5. Discussion

The major point is that one can construct a medical image display application using standard off the shelf software and hardware that will provide both the accuracy and speed of a film/alternator. The software for both PlainView and Filmstrip is relatively simple, in our case requiring only a weeks time of someone familiar with X to code the applications. The hardware is standard off the shelf Sun sparcstations, supplemented with additional memory. The cost of the complete single screen Sun workstation with 32 Mbytes of memory was $8,737 and the cost of the complete two screen Sun workstation was $11,557.

## 6. Future work

We plan to extend the CT chest study to gather timings on 1 and 2 screen Sun versions of FilmStrip. We then plan to began studying MRI and selected types of Xrays with lower resolution requirements for use with FilmStrip. For PlainView we will complete the mammography study and then begin work on other Xray images that require higher resolution than provided by current monitors.

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