Displays

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Overview

Radiologists spend most of their time looking at images on computer displays. In the early days of PACS, standard commercial displays lacked the brightness and resolution necessary for radiologic image display, and it was understood that poor-quality displays could result in misdiagnosis, eye-strain, and fatigue. This led to the growth of a new industry — the medical-grade imaging display. Even today, although commercial-grade displays can suffice for some use cases, medical-grade displays are usually required for routine diagnostic use. However, recognizing that this is a high-end market with a captured consumer base, the industry offers a wide range of products with a wide range of prices. But a more expensive display is not necessarily of more diagnostic or ergonomic value, and with more education about this costly equipment, the radiologist can make a better purchase decision.

Furthermore, there is a tendency to wishfully think that because these displays cost so much that they maintain themselves. Alas, this is not true. A good quality assurance program that includes calibration conformance checks is necessary to keep this equipment in proper working order and is beginning to be mandated by some states' departments of health. Otherwise, findings can be missed even when using displays that cost thousands of dollars. Most hospital information technology departments are not familiar with display calibration, and as such it becomes the radiology department's responsibility to ensure that the PACS displays are properly maintained. Fortunately, many medical display vendors recently began offering tools and services to achieve this goal.

The learning objectives for this section of the IT guide are to a) understand what characteristics distinguish one medical display from another; b) to what extent those differences matter clinically, so you know what you are paying for; and c) understand the importance of a maintenance program to keep the displays in good working order to ensure proper diagnosis.

Workstations and Video Adapters

A PACS workstation is essentially a high-end computer with above average processing power, ample memory, multidisplay video adapters, and reliable components that keep it running well for several years. In 2013, a quad core processor typically provides more than enough processing power, especially considering that most of the intensive processing is performed by the graphics processing unit (GPU) of the video adapter on these workstations. Memory usually ranges from 4 to 8 GB, but note that 32-bit operating systems, which are still widely in use today, can utilize no more than 4 GB, so buying more

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for a workstation with a 32-bit operating system is a waste unless it is anticipated that the operating system will be upgraded to a 64-bit version during the hardware's lifetime. Most 32-bit PACS applications will run on a 64-bit operating system, but this should be confirmed with the PACS vendor.

Significant advances have been made in hard drive technology in recent years; solid state drives with no moving parts are replacing traditional hard drives. Large amounts of local hard drive space are usually not needed as an increasing number of radiologists tend to rely on centralized network shared drives to store their teaching files, research data, and other personal information. Furthermore, storing personal files on shared PACS workstations is actively discouraged in many environments to maximize standardization of front-end workstations for ease of support and to prevent interference of end user content with the production system components. Centralized storage with scheduled backups allows for secure remote access and helps prevent data loss due to workstation component or hard drive failure. Heavily used workstations and those with important uptime are usually built with longer-lasting power supplies and fans and may have heat sensors and other sensors to warn of, if not prevent, impending hardware failures before they occur.

The most distinguishing hardware feature of a PACS workstation, other than the display, is the video adapter (often called the video card). This part of the computer not only provides connectivity to the displays but also may perform most of the graphics processing involved in zooming and panning images or rotating a 3-D rendering in some PACS viewers.

It is important to understand to what extent the PACS software makes use of the graphics processing power of the video adapter. Some PACS viewers are thin clients, which rely on the server to perform most of the computationally heavy processing, which is the central computer that communicates with all of the workstations. With such a system, putting extra processing power on the workstation will not yield better performance. These systems are less susceptible to performance degradation that might otherwise occur due to aging workstation hardware. Their performance is mostly dependent on the processing power of the server, which is typically easier to maintain at a high level because it is just one computer (versus the tens or hundreds of workstations). Such systems are highly dependent on reliable network speeds to transfer data quickly from the server to the workstation but tend to provide good performance to mobile devices, which, like old workstations, typically have lower graphics processing power.

Modern PACS viewing software that performs most of its graphics processing on the workstation typically does take advantage of the video adapter processing power and, as such, spending a few hundred dollars more per video adapter can be worthwhile. This is especially true for advanced visualization tasks such as surface rendering, vessel tracing, endoscopic "fly-through" views, and volume-matching techniques. It should be noted that some older PACS viewers still in use today are not designed to utilize the GPU, so buying expensive video adapters in these cases serves no purpose and will not result in performance improvement.

When selecting video adapters it is important to consider the number of displays attached to the PACS workstation. Most radiologists prefer at least two displays (although some prefer three or four) for image viewing because they're often more useful for comparisons, such as the frontal view to the lateral view of a radiograph, or the current set of images versus prior

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matching images. Most tend to use one or two additional commercial-grade displays for nonimaging workflow support applications, such as accessing the worklist, dictation system, and, increasingly, the electronic health record. The result is an array of displays, all of which need to be attached to the workstation.

The image viewing displays are typically of higher resolution than the nonimage viewing displays. High-resolution displays tend to require more expensive video adapters to support the higher pixel count, so care must be taken to match the video adapters with the intended displays. Medical display vendors always provide information on the video adapters that support their displays. The number of displays that can be connected is determined based on the number of video adapters installed in the computer — usually one or two but possibly more — and the number of physical heads per adapter — usually two. In sum, each workstation display needs its own physical video adapter head, and the adapter needs to support the full resolution of the display.

In addition, different types of video adapter interfaces are available for display connection. Until recently, the digital visual interface (DVI) has been used for most systems. The two types of DVI interfaces, single link and dual link, differ significantly in performance. Older basic adapters tended to only support single link because it was cheaper to do so, and most displays did not need dual link. However, dual-link DVI is needed for high-resolution displays. DisplayPort has been recently introduced and has performance advantages relative to DVI. DisplayPort connections support high bit-depth graphics modes, which can be used to more finely calibrate the display. For a display to be conformant with the Digital Imaging and Communications in Medicine (DICOM) standard, its light levels across the typical 256 digital driving levels of grayscale medical images need to follow the nonlinear DICOM grayscale display function. The target light levels are formulized from a display's darkest and brightest levels. The higher the number of light levels along the spectrum of black to white, the more precise the conformance.

To illustrate, consider a situation where, according to the target light level formula, the desired level for a given digital driving level is 91.1 cd/m^2. If there are fewer shades of gray available, then the only choices may be 90, 93, 96, etc. In this case, 90 cd/m^2 will be selected because it is the closest, but it will be off by 1.1. If more shades of gray are available, the choices may be 90, 91, 92, etc. In this case, 91 cd/m^2 will be selected, and the deviation from ideal will be only 0.1, thus more precisely conforming to the ideal curve. Put another way, the more colors available, the higher the chance of finding exactly the shade(s) desired.

The higher bit-depth of DisplayPort can also be used to display more colors or shades of gray at once (more than 256 shades of gray or more than 16 million colors). However, it is unclear if either the more precise calibration or ability to display more colors at once is of any real clinical benefit. DisplayPort can also support large high-resolution displays with a single cable, such as a 4-megapixel (MP) color display. This is another factor to consider when pairing a video adapter with one or more displays. Both the displays and the connecting cables must match the type of physical head on the video adapter and must be either dual-link DVI or DisplayPort to support the higher resolutions (more than 2.3 MP on a color display). It can be difficult to distinguish between dual-link and single-link cables, which have the same overall shape and look almost identical, however the single-link cables have fewer pins (Figure 1).

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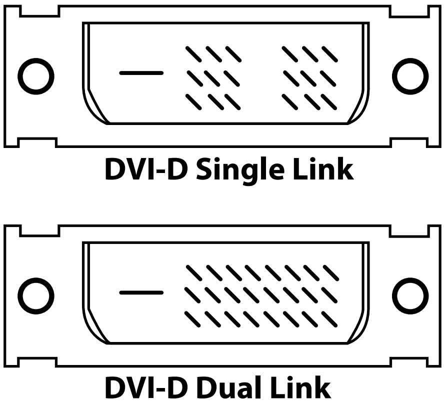

Fig 1. DVI-D single link versus dual link.

In summary, PACS workstation computers are not that different from high-performance desktop computers used in other industries except for their video adapters and displays. They can be purchased from a PACS vendor but in many cases will be purchased separately because most PACS vendors do not personally manufacture the units. A department may find it more cost-effective to procure and configure the hardware itself, using the minimum specifications provided by the PACS and display vendors. The processor, hard drive, memory, and operating system, which are standard components, are familiar to information systems departments at hospitals so it is often useful to involve them in the purchasing decision. PACS's exceptional dependence on video adapters and displays, however, is often less well understood by nonradiology IT staff. Careful planning with PACS and display vendors, with presale proposed configuration testing, can provide radiologists with maximum clinical utility at the lowest cost. Others may prefer to purchase the workstations, video adapters, and displays through the PACS vendor to gain better assurance that it all will work, but this typically comes at a higher price and with less flexibility in terms of installing other needed clinical applications on the workstation.

Luminance

Radiologic images are increasingly displayed on both medical-grade and professional graphics color liquid-crystal displays (LCD). The professional graphics displays are readily available and generally less expensive than medical-grade grayscale displays and thus very attractive for both large and small practices. Most LCD panels are backlit with cold cathode fluorescent lamps (CCFL), although newer ones use light-emitting diodes (LED) and have thinner profiles, lower power consumption, and potentially longer lifetimes. In both cases the LCD elements in front of the backlight regulate the amount of light that flows through the panel, and the backlight brightness determines the maximum display luminance, or white level. The amount of light blocked by the panel determines the minimum luminance, or black level. Both CCFLs and LEDs degrade with time and amount of use, so they need to be replaced once the luminance is no longer in compliance with established standards (a white level of at least 350 cd/m^{2}or 420 cd/m^2 for mammography) [1,21,22,23]. Medical-grade displays often have embedded sensors that monitor and adjust backlight levels, so they are more stable than professional graphics displays that require more regular

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manual recalibration. They typically have better luminance uniformity (~15%) across the viewing surface of the display than professional graphics displays (>20%) due to embedded technology that compensates for pixel luminance variation.

Why is luminance so important? Radiologic images contain up to 256 shades of gray that should be distinguishable to the average human eye. If the display is too dim, then the difference between one shade of gray and the next may be lost. The fact that a photometer can measure a difference between one shade of gray and the next above or below it does not help because photometers do not interpret radiologic images. The difference between one shade and the next has to be large enough to be perceived, and displays that are too dim do not have enough luminance to create 256 *visually perceptible* shades of gray.

The useful lifetime of a display is primarily determined by its ability to remain bright enough. Recognize that every light bulb is, as 90s singer Lisa Loeb says, "dying since the day it was born." A professional graphics display may start out with a luminance of 400 cd/m^2 or more but can decay to less than the minimum of 350 cd/m^2 within a year. Medical-grade displays counteract this problem by adding significant capacity for brightness to the backlight but running the backlight at perhaps 50% voltage on day one, and then increasing the voltage over time to maintain the light output as the backlight decays. This is part of what increases the cost of a medical-grade display: excess capacity to compensate for backlight decay and to maintain constant, high brightness output over the lifetime of the display. In general, systems should be configured to turn off the displays after a long period of nonuse to minimize this luminance degradation.

Since LED backlights appear to decay more slowly than their CCFL counterparts, LEDs are probably worth more. However, the most direct determinant of cost is the warranty and service contract with the display vendor. If a set of displays is guaranteed to run at an acceptable brightness for a minimum number of years, then the underlying technology does not directly matter. However, if a department desires to use the displays until they no longer function properly and beyond the warranty or service contract period, then LED backlit displays are probably preferable. There are two types of LED backlights: edge-lit LED backlights and direct LED backlights.

Edge-lit backlights function like CCFL backlights insofar as they have only two states: on or off. For the display to show anything the entire backlight must be on. The entire display must be backlit, even if the image has a fair amount of area meant to be black, such as the air surrounding the breast in a mammogram. Direct LED backlights are the first backlight technology to divide the display into hundreds of smaller squares, about 1 cm/side or smaller and to selectively illuminate the display area depending on the image content. In other words, why shine light behind the surrounding area of a mammogram that should be black and then try to block it? Why not just turn off the illumination altogether where it is not desired? This produces eye-popping contrast ratios, which may enhance lesion detection, although this has yet to be proven. Therefore, although direct LED backlighting may be preferable, this is an emerging technology. The FDA has approved some LED backlit displays as of press time, but all have yet to employ selective illumination.

Is brighter always better? Everything has its limits, and so too with luminance. If a display brightness is set too high (for example, over 600 cd/m^2) not only will it shorten the lifetime of the display, but depending on the type of image being displayed, it can be

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counterproductive. For example, a display presenting a chest radiograph includes a fair amount of near-white pixels representing the upper abdominal contents of the liver and spleen and may project those pixels so brightly that the eye accommodates to this higher level and is more likely to miss the subtle pulmonary nodule, which is one of the sought-after primary findings. In mammography, however, where such dense tissues are generally not in the field of view, this higher brightness is desirable to accentuate the tiny microcalcifications that indicate breast cancer. That is why mammography displays tend to run brighter than regular radiology displays.

Calibration

For a radiologist to view all she or he is supposed to in an image, it is not sufficient for the display to simply be "bright enough." There should be an even transition in the gradations from black to white. If two neighboring shades of gray are too close to each other, then the contrast between them is lost. Inversely, if the difference is too large, then the contrast is overemphasized and may cause misinterpretation. At first glance, it may seem a trivial matter to space the steps evenly, however Barten demonstrated otherwise [3,4].

The human eye adjusts to the average brightness to which it is exposed, and as brightness diverges from the point of adaptation, subtle contrast changes, such as lesions in radiographic images, are more difficult to perceive [2]. The contrast sensitivity of the human visual system can be quantified using just noticeable differences (JND) or detection thresholds, which represent perceivable changes in luminance. Most of the seminal work on modeling contrast sensitivity was done by Barten and is still used today. He determined an average human visual system response based on data (detection of sinusoidal contrast patterns on different luminance backgrounds) collected from a large subject sample and showed that the human visual system is nonlinear. In other words, the percent contrast change required for a JND at high background luminance is lower than that for a JND at low background luminance.

What does this mean? To optimize the perceptibility of diagnostic image information, we need calibration methods that account for the limitations of the human visual system. Barten's model provides a means to accomplish this by producing perceptual linearity so that contrasts are not lost across the grayscale range, from the darkest to the brightest shades. It ensures that information at low luminance levels is not hidden to preserve information at high levels and vice versa. DICOM Part 14 grayscale standard display function (GSDF) accomplishes this [5], and studies have shown that diagnostic accuracy is better with a DICOM-calibrated display than an noncalibrated display [6,7]. Although the DICOM GSDF is not perfect [8], it is the most widely used calibration method in radiology today. Moreover, several states have begun mandating periodic calibration and conformance tests of primary diagnostic displays.

The use and impact of the DICOM GSDF on medical-grade grayscale displays are rather well known, but color displays are used more widely today in radiology for diagnostic interpretation than ever before. To date, the DICOM GSDF does not have any specific recommendations for calibrating color displays in radiology, and the de facto standard is to use the GSDF for calibrating color display of grayscale images. Although older studies showed clear differences between color and monochrome displays in terms of achievable

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diagnostic accuracy (monochrome was superior to color), most recent studies show that high-quality professional graphics color displays can yield equivalent levels of diagnostic accuracy if properly calibrated and maintained [9-14].

What color is white? It seems like a simple question, but there is more than one definition. You may notice when purchasing light bulbs that some are labeled as "natural light," whereas others are "soft white" and some are "warm light," yet all of them are considered white light bulbs. These bulbs differ slightly in color tint in a way that is hard to perceive unless they are compared side by side. This characteristic is called the white point or color temperature, which ranges from a "warmer white" (slightly tinged red or yellow) to a "colder white" (slightly tinged blue). The ACR standard recommends all displays be set to the CIE daylight standard D65 white point, or a color temperature of about 6,500° F [1].

With the advent of electronic health records and the RSNA's Integrating the Healthcare Enterprise initiative, proper color display calibration is becoming increasingly important. Radiologists and other clinicians are not only viewing grayscale radiologic images with color overlays such as color Doppler ultrasounds during patient care, but they are also viewing pathology whole slide images, digital ophthalmology images, dermatology images, and a host of other visible light images [15-17]. Currently very little guidance exists on how to calibrate or characterize medical color displays. One possibility is to use color-device profiles conforming to the International Color Consortium specification for digital imaging systems color management, as it provides a standardized architecture, profile format, and data structure for color management and color data interchange between different color imaging devices. [18]

What is clear, though, is that all PACS displays must be calibrated when originally installed and must be regularly checked for conformance. Like any high-performance instrument, displays drift. No violin, no matter how expensive, stays in tune forever without intervention. Medical-grade displays have built-in photometers to measure both luminance and GSDF conformance and can use them to recalibrate as necessary. As more state governments require records be kept for this luminance and conformance data, having displays with embedded photometers is becoming increasingly desirable. The alternative is to have a support person spend time during off hours at each display to manually place an external photometer and take conformance measurements, as well as recalibrate when necessary. This can be highly time consuming and becomes less feasible when the number of displays exceeds five or ten, as it typically does in a midsize hospital or similar setting. Display resources may be geographically dispersed over the entire site portfolio of a given practice entity (which often operates in multiple locations), adding to the complexity of this task.

Medical-grade display vendors supply not only displays with embedded sensors but also provide the necessary software to connect to those sensors and periodically measure and collect data required for compliance with state policies. Many companies offer online options in which data are automatically collected and displays are then recalibrated remotely, decreasing the need for hands-on monitoring and calibration. The data can show which displays are not functioning properly and need to be either repaired or replaced, as well as life expectancy data, which can be used for budgetary purposes.

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However, that does not mean support personnel never need to examine and/or maintain the displays. No display comes with windshield wipers; someone needs to inspect them periodically for smudge marks and dust and clean them as needed. Furthermore, displays occasionally develop "bad pixels," which get stuck on a certain color and no longer change, and these can only be detected by looking at the display. Also, from time to time some PACS workstation computers develop problems that require reinstalling the operating system and software. During this reinstallation process the graphics drivers (the software that runs the displays) may not return to their proper settings. This, too, can best be noticed by looking at the display. Furthermore, the built-in photometer accuracy needs to be verified over time. To ensure this, manufacturers recommend that an external photometer certified by the National Institute of Standards and Technology be applied annually to each display to measure the accuracy of the embedded photometer and to apply corrections as needed.

The degree of rigor for a radiology department's calibration and conformance review program is a matter of preference, and some choices can be made regarding frequency and in what manner certain tasks are performed. However, developing a policy surrounding the calibration and conformance review program is a necessity. Unlike years ago, hospitals are expected to implement a policy around primary diagnostic display maintenance to ensure the safe practice of radiology.

Pixel Pitch, Resolution, and Display Size

Pixels are tiny square subunits that make up a display. The term pixel is a contraction of "picture element." The pixel pitch is the size of one side of a square pixel.

The most common characteristic used to differentiate displays, the total number of pixels, is probably the least useful. Medical displays are termed 2, 3, or 5 megapixels (MP) based on their number of pixels. However, the number of pixels in a display is more a consequence of the pixel pitch and display size rather than a meaningful parameter in its own right. The desired pixel pitch and display size are both related to the expected viewing distance.

There was some confusion during the early years of PACS when it was thought that the number of pixels of the display should depend on the number of pixels of the images being displayed. Since digital chest radiographs typically have about 5 MP, some thought that 5-MP displays should be used to render them. However, the two are not really related. A display is meant to optimize the viewing experience of the human visual system and as such should feed the eyes only as much information as they can process. The amount of pixel information that the eyes can process depends on several factors, including the quality of one's eyesight and the viewing distance. The further away the eyes are from the pixels of a display, the larger the pixels can be (resulting in fewer pixels) while still transmitting the maximum amount of information that the eyes can process.

What if the native number of pixels of the image is less than the display number of pixels? This is actually more common than not. 5-MP chest radiographs are routinely viewed on 3-MP displays. Does this mean the radiologist is missing information? Although radiologists are responsible for every pixel in the image, not every pixel must be viewed to render a diagnosis. In the days of film-based radiology, not every film was viewed close up and with a hotlight to see all of the details. Rather, images can be viewed at a resolution that fills the display. If that view demonstrates a suspicious finding, the images can be "magnified"

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by digitally zooming. Since radiographs typically have more pixels than the displays used to show them, such as a 5-MP chest radiograph on a 2-MP display, they are minified to fit the whole image on the display. Therefore, digitally zooming actually just de-minifies them, revealing the full resolution and bringing the details to an optimal physical size for visualization. An image of lower resolution than the display, such as a 0.25-MP CT image on a 2-MP display, can be portrayed at 1 image pixel per display pixel (i.e., full resolution).

The manner in which a display is used determines the typical viewing distance. For handheld devices, the viewing distance is less than an arm's length, typically about 10 inches (25 cm). Tablets are usually viewed at 15 inches (38 cm). Laptop computer displays are typically viewed at 20 inches (51 cm) since the display is attached to the keyboard. Modern desktop workstations used in diagnostic radiology have two or four displays and sometimes more. These are usually placed in an arc around the radiologist and set further back to allow keyboard and mouse interaction. The typical viewing distance for radiology workstations is 25 to 35 inches (64 to 89 cm). For extensive work at a radiology station, this range maintains the extraocular muscles in a relaxed state and is recommended to minimize eye strain. While reviewing images and consulting with others, the viewing distance can be 40 inches (102 cm) or more.

A large display window can present organs of interest in full view with good detail. As the radiologist scans detail in small regions using receptors in the retinal fovea, peripheral vision receptors draw attention to other anatomic regions of interest. However, if the display window is too large, structures of interest can go unnoticed. A display window with a diagonal size that is three-fourths of the viewing distance is most appropriate. For a 30-inch viewing distance, the appropriate diagonal size is 22.5 inches, which is about the diagonal size of a medical-grade display. This represents a +/- 22 degree visual field that includes the region of the retina with maximum peripheral field receptors. Multiple displays are then used to present studies done at different times or different views of the same study.

If the pixel pitch of a display is too large, a fine textured pattern is visible, and oblique edges have a staircase appearance. These artifacts disappear for a pixel density of about 57 pixels per degree of vision (the basis of the concept that Apple Inc. has popularized as "retina display"). The optimal pixel pitch that produces an artifact-free image with continuous tone is then a function of the viewing distance. No benefit is achieved by using a smaller pixel pitch. Making the pixel pitch too small for the viewing distance can create a shrunken appearance and needlessly increase the cost of the display. Using a display with a larger pixel pitch for the viewing distance can show some artifact, but if the pixel pitch is only slightly larger than optimal, the artifact is likely to be negligible and unlikely of any diagnostic consequence.

	Viewing Distance inches (cm)	Diagonal Size inches (cm)	Pixel Pitch µm per pixel
Small handheld	10 (25)	7.5 (19)	78
Tablet handheld	15 (38)	11 (29)	117
Laptop	20 (51)	15 (38)	156
Workstation	25–35 (64–89)	19–26 (48–67)	195–273
Consultation	40 (102)	30 (76)	312

Table 1. Typical viewing distance, appropriate size, and recommended pixel pitch for five types of displays.

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The most commonly used medical-grade displays measure 21 inches on the diagonal and come in 2-, 3-, and 5-MP varieties with pixel pitches of 270, 210, and 170 microns, respectively. According to Table 1, 5-MP display pixels are much smaller than ideal for a workstation at even the closest viewing distance, 3-MP display pixels are optimal for the closest workstation distance, and 2-MP display pixels are best suited for the upper range of workstation viewing distances. Although many radiologists are more familiar with 3-MP displays, 2-MP displays are likely of equal diagnostic value, considerably less expensive, and already in widespread clinical use for general radiology. Note that FDA requirements for mammography are different.

Conclusion

Display technologies will continue to evolve and improve our ability to faithfully and reliably render both monochrome and color medical images to maximize diagnostic accuracy and interpretation efficiency. Displays are likely to continue to increase in luminance longevity and contrast ratio, and it would not be surprising if color displays completely replace grayscale displays altogether within five years. As color rendering and management become standardized, choosing which type of display to use, under what circumstances, and to what standard it should be calibrated will hopefully become easier. Cost considerations are increasingly guiding display selection, but it is important to remember that even professional graphics displays can be used effectively for diagnostic interpretation of radiologic images if basic set up and calibration guidelines are followed [1,5,22,23]. Higher resolution displays do not necessarily translate into better diagnostic quality. No matter the type of display used, a policy for calibration and conformance checking should be established and implemented with a centralized monitoring system to ensure that displays are properly maintained for diagnostic quality.

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