Journal of Digital Imaging

Processes Involved in Reading Imaging Studies: Workflow Analysis and Implications for Workstation Development

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Software development for imaging workstations has lagged behind hardware availability. To guide development and to analyze work flow involved in interpretation of cross-sectional imaging studies, we assessed the cognitive and physical processes. We observed the performance and interpretation of body computed tomography (CT scans and recorded the events that occurred during this process. We studied work flow using a bottleneck analysis. Twenty-four of a total of 54 cases (44%) involved comparing the images with those of prior scans. Forty-seven of 54 scans (87%) were viewed using windows other than soft tissue, or compared with precontrast scans. In 46 cases (85%), the interpretation stopped to return to a previous level for review. Measurement of lesions was performed in 24 of 54 (44%) cases, and in 15 (63%) of these cases, measurements were taken of lesions on old studies for comparison. Interpretation was interrupted in 14 of 54 cases (26%) by referring clinicians desiring consultation. The work flow analysis showed film folder retrieval by the film room to be the bottleneck for interpretation by film. For picture archiving and communication system (PACS) reading, the CT examination itself proved to be the bottleneck. We conclude that workstations for CT interpretation should facilitate movement within scans, comparison with prior examinations, and measuring lesions on these scans. Workstation design should consider means of optimizing time currently not used between interpretation sessions, minimizing interruptions and providing more automated functions currently requiring physician interaction.

KEY WORDS: PACS, workstation design, time and motion analysis, radiology, computers

THE CLINICAL USE of PACS (picture archiving and communication system) and teleradiology require the successful employment of interactive gray-scale workstations. The key ingredient in the user acceptance of gray-scale workstations is a streamlined and intuitive display protocol. Studies have been conducted on the requirements of interactive gray-scale workstations.[1-6] Technology is available for implementing interactive 2K × 2.5K × 8/12-bit gray-scale workstations. Many PACS use interactive gray-scale workstations with two monitors driven by 4K × 4K × 12-bit frame buffers and 2K × 2.5K × 8-bit video buffers. However, hardware development has preceded development of user-intuitive software. Significant improvements in the display protocol[7–20] of these workstations is yet required.

A display protocol, the sequence in which the gray-scale workstation displays present digital image data, may be modeled and evaluated with a mean value analysis using Little's law.[8] Little's law is a key result in conducting mean value analysis of any system. It results in one equation in three unknowns: the mean number of jobs in a system, the mean arrival rate, and the mean time in the system. Little's law states that the average number of jobs in a system, E, is equal to the mean arrival rate of jobs to the system, λ, times the mean time for a job to flow through the system, T. Thus, $E = \lambda T$. A display protocol is a collection of steps using selected resources and the mean time they are

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Online publication 28 January 2003
doi: 10.1007/s10278-002-6000-2
The introduction to this paper is
doi: 10.1007/s10278-002-0032-5

Table 1. Resource Utilization Table for CT Film Reading

Step	Technologist	Modality	Printer	Resident	Radiologist	Film Room Personnel	Average Time (min)	
Patient examination	1	1	0	0	0	0	25.653	T_{PE}
Print film	1	0	1	0	0	0	6.520	T_{PF}
Film to archive	0	0	0	0	0	1	9.473	T_{FA}
Hang film	0	0	0	1	0	0	1.512	T_{HF}
Pull old examinations	0	0	0	0	0	1	58.690	T_{PF}
Disruption	0	0	0	1	1	0	2.603	T_{DI}
Read film	0	0	0	1	1	0	7.108	T_{RF}
Dictate	0	0	0	1	0	0	1.693	T_{DC}
Throughput per minute	0.031	0.039	0.153	0.077	0.103	0.015		

NOTE. Bottleneck is the film room personnel (0.015 jobs/minute).

used. A complete set of the display protocol steps is a job.

It is important to examine the entire process of image acquisition and interpretation to find the key elements for protocol optimization. The first order of business in using Little's law is to define what the system is, in this case, the process of generating and reading computed tomography (CT) cases. Then, we observe the series of events in the system and measure the time required for each step. Evaluation of the results can help to identify the rate-limiting step and thereby focus attention on the bottleneck.

METHODS, RESULTS, AND ANALYSIS—WORKFLOW ANALYSIS

The workflow analysis was performed by an independent observer who monitored each step of CT examinations as they were performed. Using a digital stopwatch, the times for each step in the throughput tables were recorded for 10 separate body CT examinations. Some overlap occurred in certain steps (ie, filming of some images occurred while scanning in several cases). The data from the 10 samples were entered into Microsoft Excel (Microsoft Corp., Mountainview, CA) spreadsheet for analysis.

Measuring the bottlenecks of the throughput due to a display protocol was accomplished using a resource table. A resource table lists the steps, resource entities used, and mean time per printed with permission step of the chosen display protocol. Table 1 documents the resources and steps in conducting a CT film reading. When taken together, the eight steps in Table 1 are a complete job. The "disruption" step is due to the referring physicians or any other disruption that interferes in the task of CT film reading. The average time for each step is the result of measuring the mean time required to complete the designated step. Table 2 is the resource utilization for using PACS in reading CT examinations.

All systems experience a bottleneck, defined as that resource that limits the upper bound on the throughput rate λ. From Table 1, the smallest of the maximum mean throughput rates identifies the bottleneck resource: (a) if the technologist is completely busy, then the upper bound on the mean throughput rate $= 1/(T_{PE} + T_{PF}) = 0.031$ jobs/min; (b) if the modality is completely busy, then the upper bound on the mean throughput rate $= 1/T_{PE} = 0.039$ jobs/min; (c) if the laser primer is completely busy, then the upper bound on the mean throughput rate $= T_{PF} = 0.153$ jobs/min; (d) if the resident is completely busy, then the upper bound on the maximum mean throughput rate $= 1/(T_{HF} + T_{D} + T_{RF} + T_{DC}) = 0.077$ jobs/min; (e) if the radiologist is completely busy, then the upper bound on the mean throughput rate $= 1/(T_{Di} + T_{RF}) = 0.103$ jobs/min; and (f) if the film room personnel are completely busy, then the upper bound on the mean throughput rate $= 1/(T_{FA} + T_{PF}) = 0.015$ jobs/min. The resource with the smallest of these upper bounds on the mean throughput rates is the bottleneck, ie, retrieval of film folders by the film room personnel. Hence the smallest upper bound of the mean throughput is 0.015 jobs/min. Thus, if this display protocol is used for reading CT films, and if this system was in use for 12 hours/day (720 minutes), then 10.8 jobs (CT readings) would be completed.

Table 2. Resource Utilization Table for CT PACS Reading

Step	Technologist	Modality	PACS	Resident	Radiologist	Average Time (min)	
Patient examination	1	1	0	0	0	25.653	T_{PE}
Transfer images to PACS	1	0	1	0	0	5.842	T_{TP}
Disruption	0	0	0	1	1	2.603	T_{DI}
Retrieve and display new images from workstation	0	0	1	1	0	0.392	T_{NU}
Retrieve and display old examinations from network	0	0	1	1	0	1.838	T_{OL}
Retrieve and display old examinations from archive	0	0	1	1	0	8.755	T_{AR}
Read case	0	0	1	1	1	4.205	T_{RC}
Dictate	0	0	0	1	0	1.693	T_{DC}
Throughput per minute	0.032	0.039	0.048	0.051	0.147		

NOTE. Bottleneck is the technologist (0.032 jobs/minute).

Certainly, all interpretation does not cease while waiting for the film room to retrieve a folder, but interpretation on that case is postponed while other cases not requiring retrieval are interpreted. This search for films itself disrupts the process of interpretation.

For reading CT from PACS (Table 2), we found the bottleneck to be the technologist conducting the patient examination (T_{PE}), a process that could be streamlined by application of the principles illustrated here to the individual steps that constitute the examination. Bottleneck analysis can also proceed to the next smallest upper bound of mean throughput rate, in this case transferring the images into the PACS, a step that has received attention at our institution. With optimized software, several studies can be sent at one time, or the process could be automated to occur at the time of registering the next CT case. Image data compression will likely improve this throughput as well.

We were also interested in determining the operating boundaries for our chosen system, CT scanning and interpretation. For clarity, we demonstrate a simple case. We can simplify our resource table (Tables 1 and 2) to two groups: those functions of the technologist (T_{Tech}) with all the other steps can be grouped together as T_{System}. Thus,

$$T_{Tech} = T_{PE} + T_{PF}$$

Then we conduct a mean value analysis of the upper bound on the throughput as a function of the number of users (technologists). This takes into account the effect of multiple simultaneous users on our system. Little's law provides the mean throughput rate of jobs (λ) through the overall system due to E jobs (number of examinations) in the system:

$$\text{Throughout rate } \lambda = \frac{E}{T_{Tech} + T_{System}}$$

where: T_{Tech} is the mean time for the Technologist, T_{System} is the mean time for the rest of the system; and E is the number of jobs in the system due to how work flows through the system. Figure 1 illustrates the upper and lower bounds on the mean throughput as a function of the number of users. The upper bound on the mean throughput is given by

$$\lambda \leq \min \frac{1}{T_{Tech} + T_{System}}$$

The upper bound is the best case scenario, whereas as more technologists are added, there is increased throughput. This can continue to the breakpoint ("x"—Fig 1), where the system

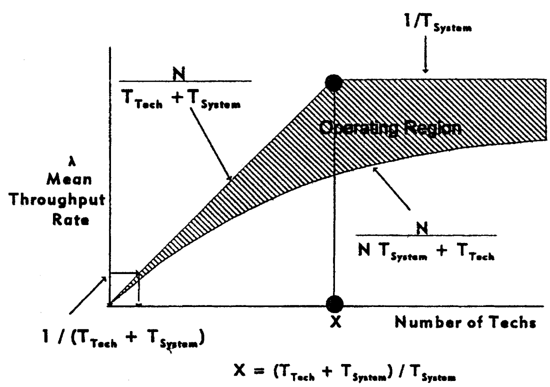

Fig 1. Operating region for CT scanning using T_{Tech} (time for technologist's activities) and T_{System} (time for the rest of the system) as an example.

saturates at $1/T_{System}$. Past this point, the system cannot continue to increase throughput rate. The lower bound on the mean throughput is given by $\lambda \geq \min\ [1/_{Tech},\ N/(T_{Tech} + NT_{System})]$. The term, $[N/(T_{Tech} + N\ T_{System})]$, is based on the fact that if technologist "N" decides to use the system, then in the worst case, all the previous technologists will first be serviced before serving technologist "N." We also evaluated the process of reading a CT scan described in the following section.

Interpretation

We also observed interpretation sessions on a total of 54 body CT scans and recorded categories of events that occurred during this process. Each occurrence of a process during a case was measured only once. Therefore, these results represent a minimum of occurrences per case. Cases were randomly selected from the workday and were a mixture of inpatients and outpatients referred for CT of the chest, abdomen, or pelvis. The PACS workstation used was constructed by EMED (E-Systems, San Antonio, TX) and consisted of two 2K monitors supported by a 486 PC and connected by fiber to a PACS system. Retrieval time to display was 1 second from workstation hard disk, 1 minute 18 seconds from the fileserver, and 8 minutes 45 seconds from the optical disk jukebox archive.

The total cases viewed during observation was 54. In 24 of these cases (44%), interpretation involved comparing the images with those of prior scans. In nine cases (17%), the CT scans were compared with other modalities, including plain films, magnetic resonance imaging (MRI), and ultrasound. Forty-seven of 54 scans (87%) were viewed using windows other than soft tissue (default window = 350, level = 40), or compared with precontrast scans. In 46 of the cases (86%), the interpretation stopped to return to a previous level for review. Measurement of lesions was performed in 24 of 54 (44%) cases, and in 15 (63%) of these cases, measurements were taken of lesion(s) on previous studies for comparison. Attenuation (measured in Hounsefield units) of a region of interest was measured in two current cases (4%). Interpretation was interrupted in 14 of 54 cases (26%) by referring clinicians desiring consultation. There were 21 instances (39%) of interruptions due to radiology-related activities such as injection of contrast, scan review, or phone calls to the reading room. Interpretation was prolonged in 76% of cases (22 of 29) by teaching of residents. Cases involving interruptions took an average of almost twice as long to interpret (mean, 15 minutes; range, 12 to 18 minutes) as those without (mean, 8 minutes; range, 4 to 12 minutes).

DISCUSSION

For PACS to be accepted as a replacement for film, workstations and display protocols must be designed with the user foremost in mind to optimize the diagnostic process. Currently, most radiologists interpret films that are usually displayed on rollerscopes or mounted on view boxes. Many of these devices permit the simultaneous display of up to 12 sheets of film, each containing 12 or more CT images. Film viewing may not be the best paradigm to follow in designing a display station. With the development of reliable, price-competitive PACS systems, many hospitals may find electronic archiving and display an acceptable and desirable alternative to film.

It will come as no surprise to many radiologists that the film room was the bottleneck for film reading of CT studies. This points to an advantage that PACS has over film-based reading: availability of comparison studies. These previous examinations are critical for many follow-up CT studies, especially on oncology patients, in whom several lesions may be followed for change in size. In situations in which both PACS and film are available, a major use of the PACS station is the retrieval of old studies when the old films are unavailable. After identification of the bottleneck, performance of the film room could be optimized, and this bottleneck would be eliminated. The next longest time required is the patient examination itself. The CT examination requires some minimum amount of time, but it too can be streamlined by applying a bottleneck analysis.

For PACS reading, the examination itself was the bottleneck, followed by retrieving old studies from the archive and transferring the current study to the PACS system. In an optimized PACS system, old studies would be prefetched during times of low system use (at night). Increased workstation storage capacity as disk drive capacity plummets in cost can cut time to access recent comparison films.

For these few studies compared, PACS reading required less time than did film reading. This finding was not in agreement with the work of Beard et al,[4] and Foley et al,[9] who found film reading faster. This may be because of the small number of cases studied, fewer interruptions, or the relative greater experience of our readers with PACS workstations.

We found that the most common task while reading was to display the current case on different window and level settings. This function should have the option of constant on-screen display when desired and should be easily available to the screen at all times when using default values appropriate to the type of case. Unlike plain radiographs, CT cases should be initially displayed in the most common window for interpretation of that type of study (such as brain windows for head CT), not by levels determined by the use of a histogram.

Critical for user satisfaction is the ability to move easily from patient study to study and within a study from image to image. Diagnosis of a cross-sectional imaging study is a process that involves integration of slices into a mental stack of three-dimensional information. This can be accomplished by moving between pages of matrixes of images in a folder or moving forward and back though individual images in a study to follow an organ or visualize an abnormality in three dimensions. This "stack viewer" could mean that high-resolution 2,000-line monitors are not necessary for CT diagnosis because 512×512 images can be displayed at full resolution on smaller, less expensive monitors. Viewing images one on one side by side would make more workstations available for the same amount of funding. Gur et al,[3] in a study of variable rates of viewing such stacked images, found it desirable to have user-selected rates available. A joystick-type of control could access these images and permit the reader to "drive" and to have the ability to stop and go back to examine more closely a perceived abnormality. Navigation back to a previous image was our second most frequent occurrence.

Another component of interpretation that occurred in almost half of the examinations was the comparison with previous examinations. This task can be made easier by a method of "linking" and "unlinking" a pair of images from the two examinations. Once the same level is linked on each study, the examination can be studied by paging through each image or group of images. The comparison study should keep up with the new case, most efficiently by slice position incrementation. If the studies get out of synch, the studies can be unlinked, and one study can be adjusted for slice position. Then, the examinations could be linked and moved forward again in synch. Chang and Zeigelbein[21] developed an algorithm for MRI viewing that automatically maintains the previous study at the correct slice for comparison. This would greatly improve many PACS display protocols.

Comparing images may be best done when only one image is on screen at one time. In this way, the radiologist is compelled to focus on the one image without distracting influences of other images. A cine mode of paging through an imaging study one slice at a time may be best for diagnosis. Seltzer et al[22] found that cine display of spiral CT data enabled readers to detect smaller nodules in chest CT than did film.

Once the two slices are displayed for comparison, the next task was often to measure lesions on both the old and new studies. Certain key images with measurements overlaid could be tagged so that when a new study is interpreted, the lesion in question was measured and the measurements are available. This annotation system can also aid in speed of diagnosis if the lesions on follow-up scans can be measured and most accurately compared using the same points. The "grease marks" should have the attribute of being easily toggled on and off. Markers such as these may make identification of lesions easier for referring clinicians.

PACS stations in physicians' offices or in clinics will enable clinicians to review patients' scans without interrupting interpretation. However, clinicians' acceptance and use of these workstations is dependent on an interface that is truly intuitive. Interpretations must be available to be viewed along with the images.

The radiologists' input to the clinician's image review will not be lost if images with electronic "grease marks" annotating abnormalities can be displayed.

Many of these display functions could be improved by automation. The next study to be read could be queued up with the prefetched comparison study loaded into memory and previous interpretation ready. These would decrease the amount of operator wait time for data to be transferred to the workstation.

Interruptions must be dealt with effectively or minimized, as this study shows that they frequently occur during interpretation. Image interpretation is the most critical part of the path for patient care and for radiologist efficiency. To optimize throughput for interpretation, readout sessions could be regularly scheduled during the day. This would permit hands-on procedures to be scheduled around the sessions. Locating interpretive radiologists in uninterruptable areas remote from the image-generating facility and clinical areas could reduce interruptions drastically.

It is important to optimize time spent in the workstation environment between readout sessions. This period could be spent electronically signing reports, reading and answering electronic mail, learning through a teaching file, or developing teaching cases. A utility could be designed as a part of the PACS system to store and display teaching cases. Certain images could be selected for the teaching file. These images would be annotated, and some clinical data could also be copied and pasted from the radiology information system to the teaching file. A utility to code the case with the ACR code would make the cases easily accessible. Another module could be created to export images to another workstation for slide making, a time- and resource-consuming activity in academic centers.

One aspect of workstation development that has largely been overlooked in the radiology literature is ergonomics. Horii et al[23] studied room lighting and design features in regard to PACS workstation placement and summarized workstation design elements.[24] They stressed workstation integration into overall room and department design. Even though most PACS installations will likely go into existing reading rooms without funding for extensive renovations, workstation siting should be done with ergonomic consideration. Seating is another important element of workstation functionality. Some have found that the upright posture places strain on the back and neck, recommending a more reclined position with the arms and feet supported.[25,26] Taking the total concept of workstation design into consideration, these PACS stations could include seating, arm, and foot support in their design.

Clinicians could be better served if images were conveniently available (a PACS terminal in the clinic or operating room), well annotated (with overlays on the study indicating the pertinent findings), and promptly interpreted (with an interpretation attached to the PACS images when read). When consultation is needed, a constantly available consult radiologist could view the same images and interact effectively with the referring clinician.

Workstation design is critical to the success of clinical PACS. If the console and display protocol software are not intuitive and easy to use, radiologists will not see this as a solution, and the success of PACS will be solely dependent on economics.

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