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Abbreviations:

BVAMC = Baltimore Veterans Affairs
 Medical Center
 CR = computed radiography
 DR = direct radiography
 LC = Lahey Clinic
 MSKCC = Memorial Sloan-Kettering
 Cancer Center
 PACS = picture archiving and
 communication system
 QA = quality assurance
 WMIS = Westchester Medical
 Imaging Services

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See also the other article by Reiner et al in this issue.

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Multi-institutional Analysis of Computed and Direct Radiography Part I. Technologist Productivity¹

PURPOSE: To assess whether it is feasible to measure and compare work-flow times across institutional variations, and to apply such a comparison to technologist productivity in the performance of general radiographic examinations with computed radiography (CR) and direct radiography (DR).

MATERIALS AND METHODS: The study received internal review board exemption. Participants were informed about the study and willingly participated. Observational time-motion analyses were performed at four sites at which CR and DR are used concurrently. The time taken by the technologist for patient preparation, positioning, exposure, and postacquisition processing, and for the examination as a whole, was recorded. Data collected reflect unique elements at each clinical center, and no standardized work flow was imposed. Work-flow performance times were correlated with each site profile. Preliminary statistical analyses included examination of distributions of original and combined variables. Descriptive statistics were presented as means or frequencies, depending on whether the data were continuous or categorical. Continuous variables were compared by using the Student *t* test. Timing differences between CR and DR for each clinical center were compared, and all data were analyzed by using commercially available statistical software.

RESULTS: For all four study sites, statistically significant total examination time differences were observed when comparing CR and DR ($P < .001$). The single step in the examination that was found to be the largest contributor to time difference was postacquisition processing, which accounted for 30%–100% of the total time difference between the two technologies. The most time-efficient sites were those that had in-room postacquisition processing capability and fully functional integration with the radiology information system. Investigators at two study sites compared times for two-view chest radiography only, and those at the other two study sites compared times for multiview general radiographic examinations. Only the results of two-view comparisons were reported for each site.

CONCLUSION: Overall technologist time was significantly shorter when performing tasks associated with DR than when performing comparable tasks associated with CR, a difference that appears to result largely from technology configuration, staffing, and patient management.

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Radiology has been at the leading edge of computer technology innovations in modern medicine, and, as a result, several complex and expensive technologies have been incorporated into the everyday practice of medical imaging (1). Each new technology brings changes in work flow that can affect a range of personnel, the use and configuration of departmental space, and patient management within the radiology department setting. Adopters of these new computer-based imaging technologies are increasingly calling for

quantitative data about the impact and cost-effectiveness of these technologies (2). Among the most important quantitative measures is technologist productivity, which is a crucial element in determining operational efficiency and cost in a filmless imaging department (3).

The importance of productivity has been magnified by the worsening personnel crisis in the radiologic technologist workforce. Employment projections by the U.S. Bureau of Labor Statistics suggest that an additional 75 000 radiologic technologists will be needed by 2010, largely as a result of increasing numbers of patients and current attrition in the labor force (4). National surveys have reported that the growing shortage of radiologic technologists is greatest in general radiography (ie, in both screen-film and digital radiography, excluding mammography and fluoroscopy) (5,6), which continues to account for 65%–70% of imaging department examination volumes despite increased use of imaging modalities such as magnetic resonance imaging and computed tomography (7).

Survey data indicate that the technologist staffing shortage for general radiography in U.S. hospitals currently averages approximately two full-time radiologic technologist equivalents per institution (5). One of the primary strategies proposed to address this shortage is to improve productivity through the implementation and integration of digital radiography in conjunction with the use of picture archiving and communication systems (PACS) and hospital and radiology information systems. Previous time-motion studies documented an improvement in technologist productivity after a successful transition to filmless operation (8–12). In addition to improving technologist productivity measures, the filmless transition has been reported to lessen job-related stress (9). This is widely believed to be the combined result of the elimination of film handling and processing and reductions in retake rates and lost images.

Studies that have documented an improvement in technologist productivity with the transition to filmless operation have been focused on individual institutions, a focus that limits researchers' ability to compare and to generalize from the results of these studies (8–12). Productivity measures can be affected by a number of institution-specific variables, including the patient population served, examination volume and distribution, staffing, and existing infrastructure. The technologies used may be highly variable and

affected by a number of factors, including vendor idiosyncrasies, equipment functionality and configuration, systems integration, and physical layout. In response to concerns about technology obsolescence, vendors are constantly upgrading and redesigning hardware and software. The dynamic nature of technology development limits researchers' ability to compare and contrast the relationships between competing technologies and productivity.

One area of current discussion in the medical imaging marketplace is the nature of differential gains in technologist productivity offered through the two principal digital radiographic technologies, computed radiography (CR) and direct radiography (DR) (13–15). CR refers to storage phosphor cassette-based systems (although some cassetteless CR systems are available), whereas DR refers to cassetteless technologies based on the use of image receptors such as amorphous selenium, amorphous silicon, or charge-coupled devices. In CR, the storage phosphor imaging plate replaces the conventional radiographic film cassette. The exposed imaging plate is placed into a CR plate reader, where it is scanned by a helium-neon laser. After a secondary excitation, light is emitted by electrons and captured by a photomultiplier tube that converts the data into an analog electrical signal, which is then digitized. In DR, the cassette is replaced with an electronic detector that captures the radiographic image and sends it directly to a display screen for technologist review. The end result of both technologies is a digital radiographic image, which can be processed, archived, transmitted, and displayed in an electronic format.

CR and DR do not neatly encompass uniform or circumscribed processes. These technologies are in constant flux and are used in different configurations and with varied auxiliary technologies in different institutions. In some institutions (including one in our study), for example, cassetteless CR has become a standard approach.

We hypothesized that total examination time differences between CR and DR would not be statistically significant. Thus, the purpose of this multi-institutional study was to assess whether it is feasible to measure and compare workflow times across institutional variations and to apply such a comparison to technologist productivity in the performance of general radiographic examinations with use of CR and DR.

MATERIALS AND METHODS

Overall Study Design

Because technologist productivity was the primary focus of the investigation and no patient data were collected, the external review committees at the University of Maryland Medical Center and the Baltimore Veterans Affairs Medical Center (BVAMC), Baltimore, Md, determined that the study had internal review board exemption status and that informed patient consent was not needed. Three other sites in the study also were included in this exemption. All participants in this study were aware that they were being observed for the purpose of data collection, and they participated willingly.

The study was partially supported by an industry research grant from Fuji Medical Systems USA (Stamford, Conn). However, the authors monitored all data collection and analysis and prepared the results for publication.

The study was designed and coordinated by researchers from BVAMC with the cooperation of radiologists, radiologic technologists, and technician assistants at BVAMC and three other clinical institutions in the northeastern and middle Atlantic United States. A data coordination and statistical analysis center was established at BVAMC. Data were collected over a 6-month period that varied from site to site.

Our research was focused on the operational aspects of radiology department practice, with time-motion studies performed at four participating sites: BVAMC; the Memorial Sloan-Kettering Cancer Center (MSKCC), New York, NY; the Lahey Clinic (LC), Burlington, Mass; and Westchester Medical Imaging Services (WMIS), Hawthorne, NY. Institutional and departmental profiles are summarized in Table 1, which provides information about the facility type, technologist staffing levels, annual examination volume, and number of rooms allocated for general radiography.

The CR and DR equipment and systems configuration at each institution were as follows: At the BVAMC, the CR system used was the SmartCR (Fuji), and the DR system used was the Revolution XQ/i (GE Medical Systems, Waukesha, Wis). In-room postacquisition processing was performed for cassette-based CR, and a wall-mounted Bucky grid was used for both CR and DR. At the MSKCC, the CR system used was the 9501 (Fuji), and the DR system used was the Revolution XQ/i.

TABLE 1
Institutional and Departmental Characteristics of Study Sites

Characteristic	BVAMC	LC	MSKCC	WMIS
Facility type	Governmental	Private	Private subspecialty	Outpatient
No. of beds	140	259	427	NA*
Annual volume of general radiographic examinations	40 000	140 000	59 322	15 800
Percentage performed with CR	60	90	71	35
Percentage performed with DR	40	10	29	65
No. of full-time radiologic technologist equivalents	12	227	23	6.5
No. of general radiographic rooms	4	20	7	3
No. with CR unit	3	17	6	1
No. with DR unit	1	3	1	2

* NA = not applicable.

In-room postacquisition processing was performed for cassetteless CR, and a wall-mounted Bucky grid was used for both CR and DR. At the LC, the CR system used was the 5000 Plus (Fuji), and the DR system used was the Epex (Hologic, Bedford, Mass). Out-of-room postacquisition processing was performed for both CR and DR. At WMIS, the CR system used was the SmartCR (Fuji), and the DR system used was the Epex (Hologic). Out-of-room postacquisition processing was performed for both CR and DR.

The sites were chosen on the basis of their existing radiographic examination technologies (both CR and DR in concurrent operation) and with an effort made to include a wide range of institutional variations in demographics and practices.

Variation in Radiographic Examinations

The number and type of general radiographic examinations varied with each study site because of differences in examination volumes, staffing, scheduling, and technology, resulting in an uneven distribution of CR and DR examinations among sites. Two sites (BVAMC and MSKCC) performed only two-view chest radiographic examinations during the period of study because of the system configurations used (dedicated wall-mounted CR and DR units). BVAMC used cassette-based CR, and MSKCC used cassetteless CR. At both the BVAMC and the MSKCC, cassette transport and quality assurance (QA) were performed in the radiographic examination room, with an in-room plate reader at BVAMC, and with modality workstations where the technologist performed QA at both sites. At the LC and WMIS, multiple general radiographic examinations of different types were per-

formed with a variable number of exposures because of the different technology and system configurations. At both the LC and WMIS, multifunctional cassette-based CR and DR units were employed, and cassette transport and QA were performed outside the radiographic examination room, in a centralized shared work area.

Data Collection

Standardized data collection forms were developed after direct observation of technologist work flow at the four study sites, taking into account the common steps and processes used by technologists in the performance of CR and DR examinations. Individual processes incorporated into the data collection forms included patient preparation, positioning, exposure, and postacquisition processing. Although the steps within each of these timing periods differed among institutions, they spanned similar continuous segments of the work flow. These work-flow segments were defined as follows:

Patient preparation.—This segment included patient transit, clothing change, data access and entry by the technologist, and any room setup necessary, and it lasted from the time when the technologist greeted the patient and escorted him or her to the changing room until the patient entered the room in which the radiographic examination was to be performed.

Patient positioning.—This segment began with the patient's entrance to the radiographic examination room, continued through the positioning of the patient, and ended when the technologist left the room to perform the exposure.

Exposure.—This segment comprised the actual image acquisition time.

Postacquisition processing.—This segment lasted from the end of the exposure, through processing, to completion for physician review. Postacquisition processing time was a composite of three individual steps for cassette-based CR and two steps for cassetteless CR and DR. The two common steps were image transfer and manipulation, and the single step unique to cassette-based CR was transport of the CR imaging plates to the plate reader. Image transfer time included the time required for the acquired image (after completion of the exposure) to be transferred to the modality workstation for technologist review. Image manipulation (commonly referred to as image QA) time was the time required for the technologist to review the image on the modality workstation and make any necessary adjustments to the image (annotations, window and/or level adjustments) before radiologist interpretation. Postacquisition processing was considered complete when the technologist initiated a "send to PACS" command.

These processes were timed in a consistent and reproducible fashion at each study site, under the direction of trained timekeepers using lap-split stopwatches (Seiko, Chiba, Japan) to simultaneously time both the entire examination and the individual segments.

At the end of each examination, recorded measures were entered onto a paper worksheet. Worksheets were reviewed and photocopied at each center. The original paper worksheets were compiled weekly and mailed to the statistical coordination center.

The data processing and statistical coordination center registered and accumulated worksheets specific to each clinical site. Software (Excel; Microsoft, Redmond, Wash) was used by three research assistants to generate spreadsheets for each data collection instrument. An audit of 10% of the spreadsheet data was performed to validate data entry. Statistical distributions were produced routinely to look for data anomalies (incomplete information) and possible outliers caused by extraneous delays or interruptions not related to the work-flow processes studied. Of the 1200 technician observations made during the study, approximately 30 observations were discarded as outliers by analysts who were blinded as to whether the examinations were performed with CR or with DR. These observations were discarded because they were made during an unfinished examination (an examination affected by a computer

crash, equipment failure, or patient request to halt the examination before its completion). Progress in data collection was reported monthly to the study investigators.

Statistical Analysis

The data collected at the individual sites were not commingled, because of differences in work flow, examination type, and technology among the sites. Preliminary statistical analyses included examination of distributions of original and combined variables. Descriptive statistics were presented as either means and standard errors or as frequencies, depending on whether the data were continuous or categorical. Continuous variables were compared by using a Student *t* test. Although data in regard to categorical and descriptive variables were collected, no statistical test results are reported for these data. Timing differences between CR and DR for each clinical center were compared. All data were analyzed by using software (SPSS, version 11.0.0; SPSS, Chicago, Ill). Because of the obvious differences among the four clinical sites, no attempt was made to commingle data from all four, nor was a clinic-by-clinic CR-DR paradigm ever considered for comparison. Instead, we limited our CR-DR comparisons to each site, and we compared site-specific CR-DR time differences by using the Student *t* test. The standard *P* value of .05 was divided by 4, yielding a significance level of $P < .0125$ as the threshold of statistical significance for differences in total examination time. Although other data subsets were assembled and tested as part of this study, they do not relate to the hypothesis or conclusions reported here.

RESULTS

Total Examination Time

Summary data for each participating study site are presented in Tables 2–5. For all study sites, total examination time differences between CR and DR (mean time difference range, 104.5–379.6 seconds) were found to be statistically significant ($P < .001$), with DR proving less time-consuming than CR. The most significant step in the overall timing process was postacquisition processing time (not part of our original hypothesis), which accounted for 30%–100% of the total CR-DR time differences for the four collective study sites. Postacquisition processing time differences between CR and

TABLE 2
CR and DR Times for Two-View General Radiographic Examinations at the LC

Work-Flow Segment	Mean CR Time (sec)	Mean DR Time (sec)	Mean Time Difference (sec)	<i>P</i> Value
Preparation	96.9	67.7	29.2	<.001
Positioning	175.2	132.4	42.8	.006
Exposure	17.2	15.5	1.7	.80
Postacquisition processing	200.2	98.8	101.4	<.001
Entire examination	483.5	314.5	169.0	<.001

Note.—More than 400 examinations were observed overall, but only data for two-view examinations are reported here. The numbers of two-view examinations performed with CR and DR were 67 and 68, respectively.

TABLE 3
CR and DR Times for Two-View Chest Examinations at MSKCC

Work-Flow Segment	Mean CR Time (sec)	Mean DR Time (sec)	Mean Time Difference (sec)	<i>P</i> Value
Preparation	95.3	65.5	29.8	<.001
Positioning	49.0	44.3	4.7	.01
Exposure	15.9	16.2	−0.3	.72
Postacquisition processing	121.8	7.9	113.9	<.001
Entire examination	282.0	133.2	148.8	<.001

Note.—More than 800 two-view chest examinations were observed in this study, but data from 105 examinations were omitted from the analysis because of image processing difficulties attributed to new machine installation. The numbers of included examinations performed with CR and DR were 412 and 296, respectively.

TABLE 4
CR and DR Times for Two-View General Radiographic Examinations at WMIS

Work-Flow Segment	Mean CR Time (sec)	Mean DR Time (sec)	Mean Time Difference (sec)	<i>P</i> Value
Preparation	195.8	48.4	147.4	<.001
Positioning	156.0	61.2	94.8	<.001
Exposure	35.6	12.9	22.7	<.001
Postacquisition processing	261.2	146.6	114.6	<.001
Entire examination	648.6	269.0	379.6	<.001

Note.—A total of 115 examinations were observed, but 53 examinations required more than two images and were excluded from the analysis. The numbers of two-view examinations performed with CR and DR were 24 and 38, respectively.

DR were consistent among the four study sites, despite differences in technology and work flow, with a range of 101.4–114.6 seconds.

Patient Preparation and Positioning Time

In two other work-flow segments—patient preparation and positioning—statistically significant time differences were found between CR and DR at three of the four study sites. BVAMC, the single study site that did not demonstrate significant CR-DR time differences for patient preparation and positioning, also exhibited the smallest total examination time difference between CR and DR for these two

work-flow segments combined (6.6 seconds). The combined CR-DR time differences for patient preparation and positioning at LC, MSKCC, and WMIS were 72.0, 34.5, and 242.2 seconds, respectively.

Exposure Time

No statistically significant difference in exposure time with CR versus DR was found at LC or MSKCC. Exposure time differences at WMIS and BVAMC were in sharp contrast, with DR time savings of 22.7 seconds recorded at WMIS and CR time savings of 2.6 seconds recorded at BVAMC.

TABLE 5
CR and DR Times for Two-View Chest Examinations at the BVAMC

Work-Flow Segment	Mean CR Time (sec)	Mean DR Time (sec)	Mean Time Difference (sec)	P Value
Preparation	63.3	66.0	-2.7	.77
Positioning	60.1	56.2	3.9	.49
Exposure	11.7	14.3	-2.6	.03
Postacquisition processing	124.5	18.0	106.5	<.001
Entire examination	257.7	153.2	104.5	<.001

Note.—A total of 225 examinations were observed, but changes in work flow and timing procedures required that data from 121 examinations be excluded from the analysis. The numbers of included examinations performed with CR and DR were 50 and 54, respectively.

Postacquisition Processing Time

As previously noted, postacquisition processing time was a composite of multiple individual steps, including cassette transport (CR only), image transfer, and image manipulation. Although timing was not performed for these individual steps throughout the study, representative time measurements were recorded for image display, to illustrate the impact of the technology and systems configuration on image transfer time. Image transfer times were retrospectively calculated on the basis of data from small samples at each institution. Image transfer was consistently faster for DR than for CR and averaged 3 seconds for both multifunctional and wall-mounted DR units. Corresponding average image transfer times were 20 seconds for cassetteless CR, 28 seconds for cassette-based CR with centralized (out-of-room) processing, and 46 seconds for cassette-based CR with in-room processing. The measurement of postacquisition processing time was complicated by the fact that at several institutions, individual work-flow steps were actually performed in parallel. For that reason, only the total postacquisition processing time was included in the data for each institution.

Intrasite Comparisons

LC.—Although CR and DR examinations performed at LC included various general radiographic examinations (eg, chest, abdomen, spine, and extremities), only study results with regard to two-view examinations are included in the data presented in Table 2. In our evaluation of CR-DR time differences at LC, a 2.8-minute total examination time differential was observed. Statistically significant differences were observed for both mean postacquisition processing time and total examination time between CR and DR. Postacquisition processing ac-

counted for 1.7 minutes (60%) of the total CR-DR time difference, and the remaining 40% of the total time difference was largely attributed to different preparation and processing times.

MSKCC.—Time measurements for MSKCC are presented in Table 3, which shows findings similar to those at LC, despite wide differences in technology, examination type, and work flow. A mean total CR-DR time differential of 2.5 minutes was observed at MSKCC, with 1.9 minutes (76%) attributed to postacquisition processing time differences and 0.57 minute attributed to the collective differences in preparation and positioning times. All examinations performed at MSKCC were two-view chest examinations, and the sample size at MSKCC ($n = 708$) was much larger than that at the other three study sites.

WMIS.—Despite the small sample size at WMIS ($n = 62$; Table 4), significant time differences between CR and DR were demonstrated for all individual work-flow segments documented during two-view examinations. Although technology, examination type, and systems configuration were similar at LC and WMIS, a 2.75-minute time difference in mean total CR examination time was observed between the two sites. A particularly time-consuming step in CR acquisition at WMIS was patient preparation. Mean preparation time at WMIS was 3.26 minutes, which was at least twice the patient preparation time for CR at other study sites. Similarly, CR exposure time at WMIS was twice that at other study sites. CR positioning times at LC and WMIS were more than threefold the positioning times at MSKCC and BVAMC, a difference accounted for in large part by variations in examination type, technology, and systems configuration.

BVAMC.—Time-motion data at BVAMC (Table 5) revealed that 100% of the total difference in CR and DR times could be

accounted for by postacquisition processing time. No statistically significant time savings with DR were observed for preparation, positioning, or exposure at BVAMC. The technology, systems configuration, and examination type at BVAMC were closely matched to those at MSKCC, with the one major difference being that MSKCC used cassetteless CR. When data from these two sites were correlated, nearly identical CR-DR postacquisition processing time differences (113.9 and 106.5 seconds, respectively) were observed that accounted for 76.5% and 100%, respectively, of mean total examination time differences between the two technologies. Individual DR time measurements for MSKCC and BVAMC also were found to be similar, with mean patient preparation times of 65.5 and 66.0 seconds, mean postacquisition processing times of 7.9 and 18.0 seconds, and mean total examination times of 133.2 and 153.2 seconds, respectively.

Intersite Comparison

Although CR time measurements differed substantially between individual study sites, DR time measurements were far more consistent. The least time-efficient site (ie, WMIS) recorded DR patient preparation, positioning, and exposure times that were in keeping with those at the other study sites. LC recorded the single outlier in these DR processes, with a DR positioning time of 132.4 seconds, well outside the range of 44.3–61.2 seconds for the other three sites. The DR work-flow segment that demonstrated the largest intersite variability was postacquisition processing, with a range of 7.9–146.6 seconds. This amounts to a time difference of 2.3 minutes between the shortest DR postacquisition processing time (that at MSKCC) and the longest (that at LC). An identical intersite postacquisition processing time difference of 2.3 minutes was observed for CR.

DISCUSSION

The results of this time-motion study indicate more substantial time differences between CR and DR than were previously reported. In a previous study by Andriole (16), the mean total examination times for two-view chest radiographic studies were 5.7 minutes for DR and 6.7 minutes for CR, and the difference between the two times was not statistically significant. In another study, by Mehta and Lee (13), mean total chest examination times

of 6 and 8 minutes were found for DR and CR, respectively.

The total examination time measurements for CR in our study were comparable with those previously reported in the literature, with a range of 4.3–10.8 minutes. The total DR examination time measurements in this study were substantially shorter than those previously reported, with a range of 2.2–5.2 minutes. This reduction in DR examination times is believed to be the result of advances in DR technology over the past few years, along with improvements in work flow—enhancing software programs (eg, modality work-list programs).

Although technology, systems configuration, and functionalities were different within each study site, several similarities were observed among sites when CR and DR time measurements were compared. The magnitude of total CR-DR time differences was greatest at LC and WMIS, which also had the highest total CR and DR examination times. This finding is believed to reflect differences in examination type, work flow, technology, and systems configuration. WMIS, in particular, had the most inefficient work flow (preliminary and unpublished data from our group about work flow at WMIS indicated 21 individual steps identified in the performance of a general radiographic examination with CR, compared with only 13 steps for DR). The effects of inefficient work flow were magnified by a lack of systems integration. Technologists who performed CR examinations at LC and WMIS had to leave the examination room to transport CR cassettes to the plate reader and to perform QA on a centrally located and shared modality workstation. For DR examinations at these sites, technologists could perform in-room image transfer and QA, thereby enhancing productivity and reducing total examination times.

Postacquisition processing was composed of three steps for cassette-based CR and two steps for cassetteless CR and DR because the elimination of cassettes obviated cassette transfer. CR technologists at BVAMC were aided by in-room placement of the CR plate reader, placement that greatly reduced transport time. These time savings, however, were negated by the prolonged image transfer time associated with in-room CR (46 seconds, compared with 28 seconds for centralized, out-of-room image transfer). Out-of-room plate readers are designed to accommodate multiple CR plates simultaneously, whereas in-room plate readers typically accommodate only one CR

plate at a time. Use of an out-of-room CR plate reader has the net effect of prolonging the average image transfer time per individual image from a multiple-view examination. By eliminating CR cassette transfer, the use of cassetteless CR further reduces image transfer time.

Despite the potential time savings afforded by cassetteless CR, however, CR postacquisition processing time at MSKCC was only minimally reduced compared with that at BVAMC. This is believed to be a reflection of the manner in which image QA was performed at MSKCC. Rather than use the in-room modality workstations for CR image review and manipulation, technologists instead performed QA outside the examination room, on centrally located PACS workstations. This idiosyncratic approach to work flow was observed in some instances at several of the sites and tended to adversely affect CR more than DR.

Several interesting findings were related to the process of patient preparation, which is a composite of multiple steps. In theory, all steps in a two-view radiographic examination, except the final cassette transport, should be identical for both CR and DR. At LC and WMIS, however, the distance from the patient waiting and changing areas to the CR examination rooms was farther than that to the DR examination rooms. Departmental design is a simple but potentially significant factor affecting technologist productivity. At WMIS, inefficient CR work flow was a major contributor to longer patient preparation time, with technologists entering data separately in both manual and electronic formats. At the same time, some CR technologists at WMIS were observed waiting for patients to change clothes, instead of performing preparation work such as data entry, and this idle time unnecessarily prolonged the patient preparation time.

At LC and WMIS, where multiple types of general radiographic examinations were performed by using multifunctional CR and DR units, significantly shorter positioning times were recorded for DR than for CR, with DR time savings of 42.8 and 94.8 seconds at the two sites, respectively. At the same time, exposure times at these two sites were also found to be shorter with DR than with CR, with respective time savings of 1.7 and 22.7 seconds with DR. Although the DR time savings at LC are difficult to explain, the significantly greater DR time savings in patient positioning and exposure at WMIS can be attributed to substantial differences in CR-DR work flow between

the two institutions. CR work-flow segments at WMIS were performed in series, with each segment completed before the next was initiated: A technologist would complete patient positioning, exposure, and QA for the first image and then repeat the same sequence for the second image. At many institutions, as at BVAMC, MSKCC, and LC during our study, technologists perform two tasks simultaneously. DR technologists at WMIS, however, did not complete different work-flow segments simultaneously but instead acquired the complete requisite number of images before beginning postacquisition processing, in effect prolonging both individual and total examination times.

The most efficient CR technologists were found to multitask. For example, a technologist working with a CR unit with in-room display and postprocessing capabilities could review and manipulate the first image acquired while simultaneously performing the second exposure for a two-view chest examination. This parallel work flow was most commonly employed at BVAMC, which demonstrated the shortest postacquisition CR processing time despite the use of a cassette-based CR unit.

At the two sites with wall-mounted CR and DR Bucky units used to perform two-view chest examinations only (MSKCC and BVAMC), markedly reduced CR-DR time differences were observed for patient positioning and exposure times. The CR-DR positioning time differences at the two sites were 4.7 and 3.9, respectively; and the CR-DR exposure time differences at both sites were negative values (ie, DR exposure times were greater than CR exposure times), which is the opposite of what was expected. These CR exposure time savings cannot be easily explained by technology or work flow, for which CR and DR results at the two sites were comparable. These time differences were small and had a minimal effect on the overall CR-DR total time differences between the two sites.

The one major CR technology difference between MSKCC and BVAMC was that MSKCC used cassetteless CR and BVAMC used cassette-based CR. The employment of cassetteless CR should be work-flow enhancing and result in time savings through the elimination of cassette transport and reduction in image display time. This technologic advantage was negated, however, by inefficiencies in work flow, with more individual steps identified in the performance of CR examinations at MSKCC than at BVAMC. Inefficient CR work flow at MSKCC was

further aggravated by a lack of automation and integration, not observed with DR work flow. Although DR images at MSKCC were automatically transferred to the PACS and radiology information system, CR image transfer was performed manually. CR postacquisition processing at MSKCC was delayed because the available in-room CR modality display monitors were not used by technologists for image review. Instead, technologists waited for CR images to be transferred to the PACS (which took approximately 1 minute per image) and then had to leave the examination room to review and manipulate the images on a centrally located and shared PACS terminal. DR work flow for technologists at MSKCC was more efficient because postacquisition processing was performed in the examination room, on a single integrated-modality QA workstation.

Unlike MSKCC and BVAMC, which performed two-view chest examinations exclusively, LC and WMIS performed all types of general radiographic examinations. Although this study compared work flow only in two-view examinations, the multifunctional CR and DR unit configurations used at LC and WMIS had an adverse effect on patient throughput and technologist productivity, compared with the dedicated wall-mounted chest radiographic units used at BVAMC and MSKCC. At LC, DR postacquisition processing was performed in the examination room and was immediate, but CR postacquisition processing was delayed by two critical factors: (a) out-of-room, centrally located, shared CR plate readers and QA workstations and (b) batch-mode delivery of CR cassettes by radiology department aides. Although batch-mode work flow is specifically designed to redistribute time-intensive tasks to non-technologists, it can have the detrimental effect of delaying postacquisition processing.

A number of limitations in study design, data collection, and analysis should be considered. There was substantial variation in sample size among study sites, variation that was attributed to differences in examination volume and distri-

bution, availability of timekeepers, and overall compliance at each site. Although MSKCC and BVAMC collected only two-view chest examinations for the study, LC and WMIS collected all examination types. Because examinations of all types were recorded at LC and WMIS but only two-view examinations (of all types) were included in this comparative study, the sample size of chest views from these institutions was smaller. Another methodological limitation was difficulty in timing some of the individual steps within the measured processes. For example, the timing of tasks that were performed in parallel presented difficulties, as did the timing of simple tasks that could be performed very quickly (such as image transport). For this reason, only groups of tasks (preparation, positioning, exposure, and postacquisition processing) were considered for comparison between sites. The resultant time measurements represent the complete work-flow continuum, and future studies will be needed to analyze the segments of work flow more precisely. The economic aspects associated with the acquisition and processing of images with CR versus DR have been separately analyzed, and the results of that analysis are presented in a separate article (17).

In conclusion, despite obvious institutional differences, it is possible to measure and assess the steps that make up the radiographic work flow and to compare different approaches to image acquisition, processing, and display. In this study, overall technologist time was significantly shorter for the performance of tasks associated with DR than for that of comparable tasks associated with CR, a difference that appears to be the result of a number of factors, including but not limited to department-specific work flow, departmental layout, technology implementation, staffing, and systems configuration.

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