Development of a Digital Duplication System for Portable Chest Radiographs

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To provide high-quality duplicate chest images for the intensive care units, we have developed a digital duplication system in which film digitization is performed in conjunction with nonlinear density correction, contrast adjustment, and unsharp mask filtering. This system provides consistent image densities over a wide exposure range and enhancement of structures in the mediastinum and upper abdominal areas, improving visibility of catheters and tubes. The image quality is often superior to that of the original radiograph and is more consistent from day to day. Repeat rates for portable chest radiographs have been reduced by more than a factor of two since implementation of digitization in December 1991, and the number of repeat examinations caused by exposure errors have been substantially reduced.

IN MANY HOSPITALS, copies of portable radiographs of intensive care unit (ICU) patients are produced routinely using conventional optical duplication techniques to facilitate patient management. However, in the optical duplication process, the poor quality of images that result from exposure errors or poor contrast is not improved. To provide high-quality duplicate chest images, we have developed and implemented a digital duplication system, composed of a laser film scanner (Model KFDR-S, Konica, Tokyo, Japan), a computer (SUN 3/470, SUN Microsystems, Mountain View, CA), and a laser film printer (Model KFDR-P, Konica, Tokyo, Japan)[1,2] (Fig 1). The laser scanner converts the optical density of the original film to digital pixel values. After digitization, fully automated density correction, contrast enhancement, and unsharp mask filtering are performed. Two 8 × 10-in film copies of the processed images are printed, one for interpretation by the radiologist and one for the ICU physicians. The original radiograph is archived. In this paper, we describe our 1-year experience with this system.

MATERIALS AND METHODS

Portable chest radiography is performed in our hospital using Lanex medium screens and Ortho-C film (Eastman Kodak Co, Rochester, NY) with a 10:1 grid. After chemical processing, the technologist inserts the film into the laser scanner. A 14 × 17-in radiograph is digitized into a 2,048 × 2,450-pixel matrix, yielding a pixel size of 0.175 mm, with 1,024 gray-scale levels. For each radiograph, the technologist enters a unique three-digit exam identifier, indicates whether the image is of a chest or an abdomen, and whether the orientation is vertical or transverse. The three-digit code, which is called the "daynumber," identifies the patient to our radiology information system (RIS). The RIS transmits the patient's name, hospital identification number, and exam description, which are then printed on the lower margin of the duplicate film. Portable abdominal radiographs are obtained using TMG film (Eastman Kodak Co). Parameters for the density correction, unsharp mask filtering, and contrast correction are determined automatically by the computer. These parameters are displayed and checked by the technologist. The hard copy is printed in batches of up to 11 images for convenience. To calibrate the system for fluctuations in the chemical processing of the output hardcopy, a stepwedge pattern is printed, developed, and digitized daily.

The relationship between relative exposure and pixel value is nonlinear.[3] Therefore, a linear-correction technique, such as window and level, will not recover the proper density distribution from an improperly exposed radiograph. By using the H and D curve of the film and the

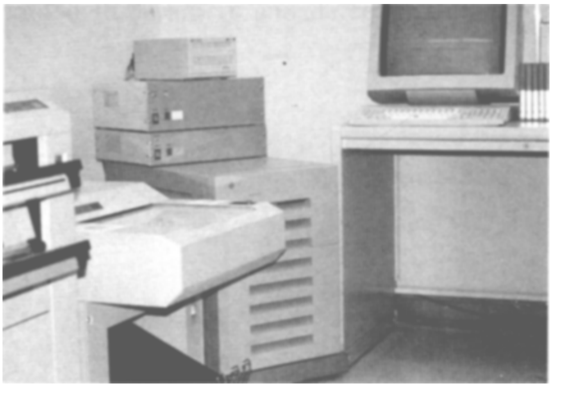

Fig 1. Digital duplication system consisting of a Konica KFDR-S laser film scanner (left center), a SUN 3/470 computer with terminal (center right and right), and a Konica KFDR-P laser film printer (left).

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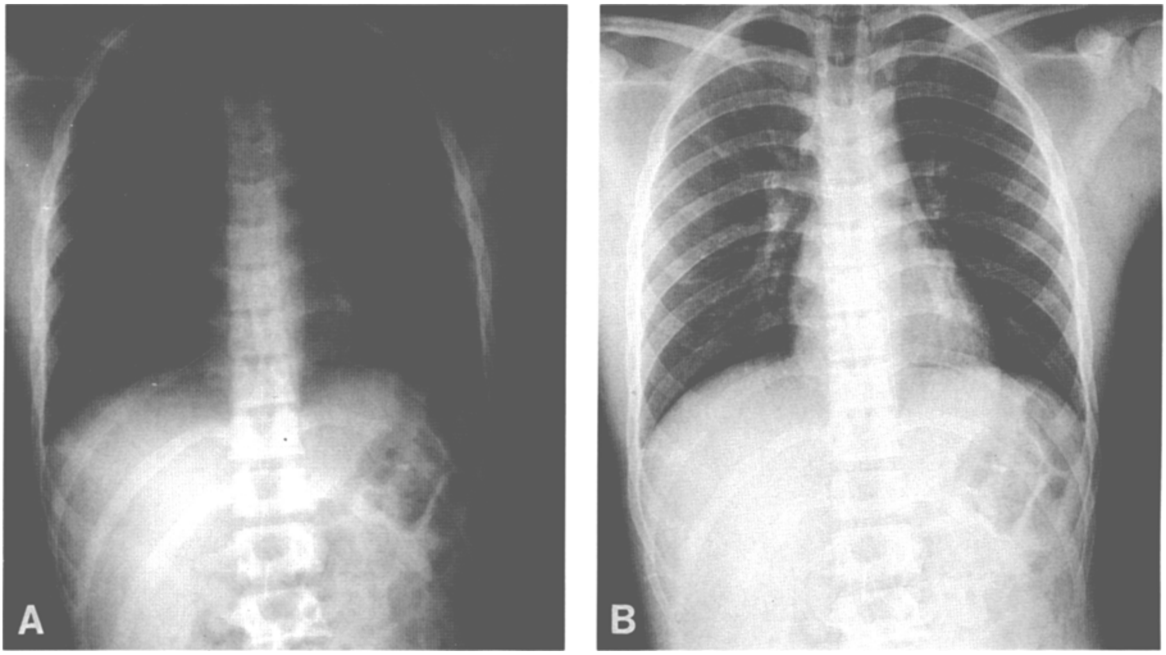


Fig 2. (A) Original portable chest radiograph with an overexposure level of 400% of the proper level. (B) Digitized processed chest radiograph that provides markedly improved diagnostic quality.

characteristic curve of the digitizer, the mapping between the original pixel values in the digitized image and the pixel values in the corrected image can be determined.[1] The H and D curve is measured using an inverse square x-ray sensitometer.[3] For the density correction, a relative exposure factor of the radiograph is estimated by analysis of the histogram of pixel values obtained from the central quarter of the radiograph.[1] Proper exposure for a chest radiograph is defined here as that which produces clearly visible peripheral lung markings and adequate mediastinal detail. We have found that a fixed 0 to 4 optical density (OD) range setting on the digitizer produces good results for the density-correction technique.

To improve the overall contrast in low-contrast images

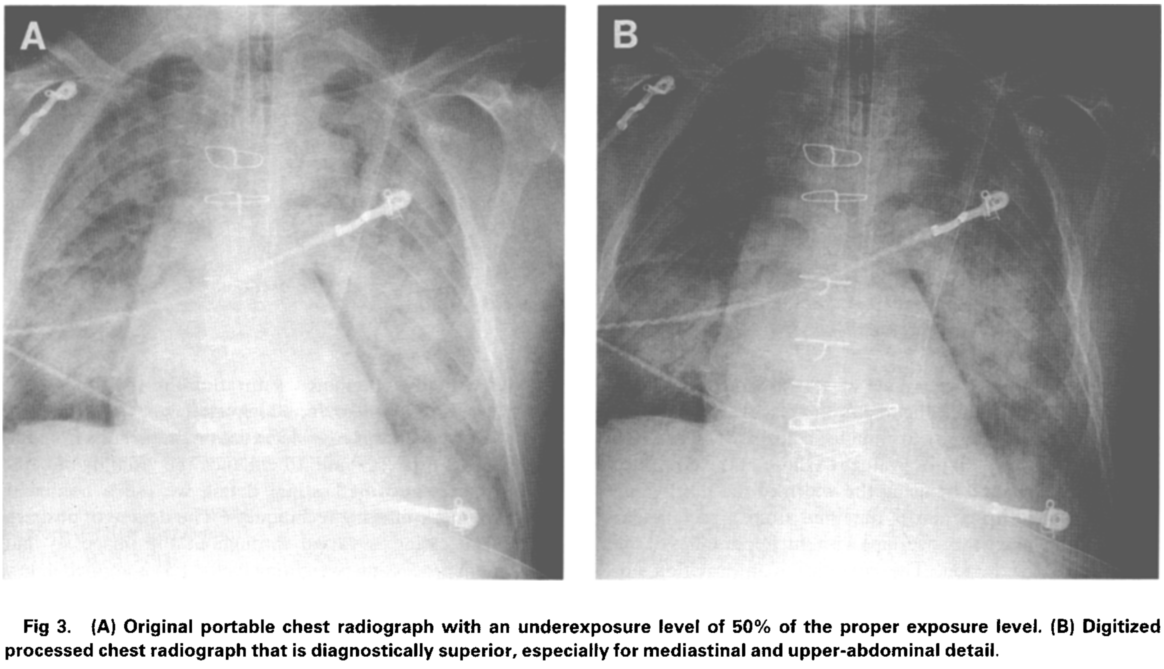
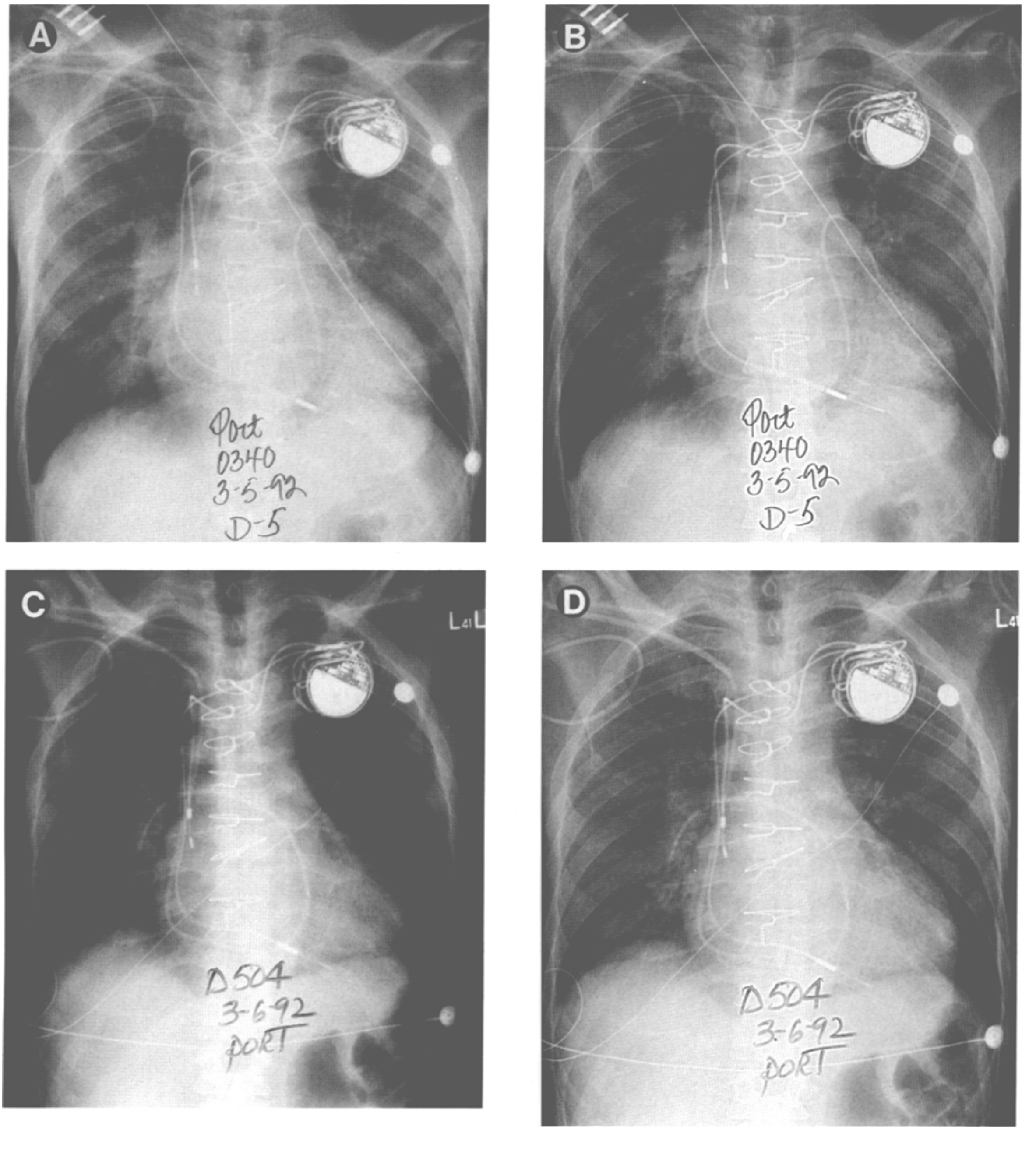


Fig 3. (A) Original portable chest radiograph with an underexposure level of 50% of the proper exposure level. (B) Digitized processed chest radiograph that is diagnostically superior, especially for mediastinal and upper-abdominal detail.



that result from large amounts of scatter caused by large patient size and grid misalignment, the pixel values in these cases are adjusted slightly to enhance contrast. The curve to be used to map the old pixel values to those of the new pixel values is determined by using the width of the pixel-value histogram. The histogram is obtained from a rectangular region in the image that overlaps with the upper lobes of the peripheral lung region. The orientation information entered by the technologist is used to position the region appropriately. Slopes of the contrast-enhancement curves are 1.1, 1.2, and 1.3, and the pivot point of each is at a gray level of 275. Use of 275 (as opposed to 512) for the pivot point, virtually eliminates saturation in the underpenetrated regions of the corrected images.

To compensate for edge degradation that results from the digitization process[3,4] and to enhance the visibility of catheters, tubes, and mediastinal detail, we use a nonlinear unsharp mask-filtering technique.[5,6] The degree of unsharp mask processing is varied throughout the image so that maximum processing (weighting factor 1.5) is applied in low OD regions such as the mediastinum, and minimum processing (weighting factor 0.6) is applied in the high OD regions such as the peripheral lung.

The effect of the image processing is clearly shown in Figs

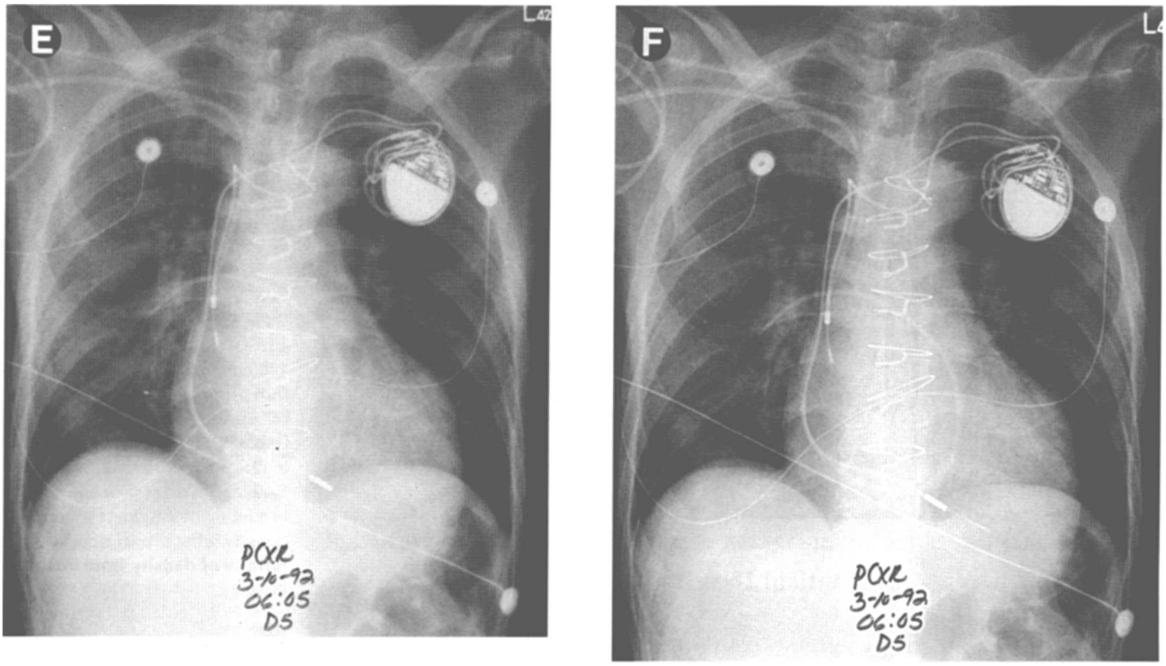


Fig 4. A series of digitally duplicated portable chest radiographs before processing (A, C, E) and the corresponding digitally processed images (B, D, F). The original radiographs (A, C, E) were determined by the density-correction program to have exposure levels of 0.8, 2.8, and 1.0 times the proper exposure, respectively.

2 and 3. Figure 2A is an original radiograph that was determined to have an exposure level four times the proper exposure level. Figure 2B is the processed image; note that relative to the overexposed image, the lung detail is visible. However, the mediastinal contrast, although comparable with normally exposed radiographs, has been reduced. Figure 3A shows an original radiograph that was determined to have received an exposure one-half times the proper level. Figure 3B is the processed image; note the overall improvement in image quality, particularly in the retrodiaphragmatic regions and in the mediastinum. These qualitative impressions are in agreement with the results of observer tests,[7] which showed that density correction improves the detectability of simulated lung nodules in the peripheral lung regions for overexposed radiographs and in the retrocardiac/retrodiaphragmatic lung regions for underexposed images.

Table 1. Rejection Rates for Portable Chest Radiographs at The University of Chicago Hospitals

	Total No. of Films	Total No. of Rejected Films	Rejection Rate (%)
Before digitizer installation*			
(10/1/90-5/1/91)	5,224	276	5.3
After digitizer installation†			
(12/21/91-11/13/92)	13,835	278	2.0

*Based on twelve weekly reports over 1.5 years.
†When digitizer was functioning.

RESULTS

Our enhanced film-digitization system is capable of producing images of sufficient quality to be used for primary interpretation by correcting for a wide range of exposure errors.[1,2] As a result, our repeat rate for portable radiographs has been reduced from 5.3% to 2.0% since implementation of the system in December 1991 (Table 1). Exposure errors accounted for 38.3% of the rejected nondigitized portable radiographs, whereas exposure errors accounted

Table 2. Distribution of Reasons for Rejection of Portable Chest Radiographs*

	Digitized Portable Film	Nondigitized Portable Film
Exposure	13.2%† (12)	38.3% (62)
Positioning	78.0% (71)	50.0% (81)
Film artifact	4.4% (4)	7.4% (12)
Fogging	1.1% (1)	1.9% (3)
Motion	2.2% (2)	1.9% (3)
Double exposure	1.1% (1)	0.6% (1)

*Measured since March 5, 1992.
†5 films, incorrect H and D curve used; 7 films, extremely underexposed.
( ) Number of radiographs.

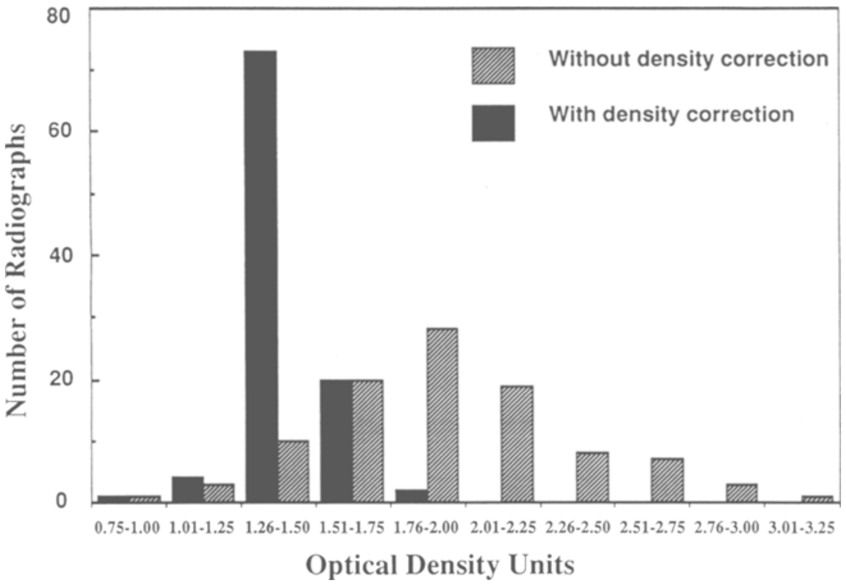


Fig 5. Histograms of the average OD in the lung regions for 100 consecutive radiographs before processing (▨) and after digital processing (■). The distribution of ODs is centered at 1.87 ± 0.42 before processing and 1.42 ± 0.14 after processing. The reduction in the range of average density reflects the improved uniformity of density from image to image.

for only 13.2% of the rejected digitized portable chest radiographs (Table 2). The rejected digitized images were caused by extreme underexposure or use of an incorrect film (TMG instead of Ortho-C). The total number of rejected digitized portable films and rejected nondigitized portable films were 92 and 162, respectively, since March 5, 1992. Because the digital system virtually obviates the need to retake radiographs for exposure errors, positioning errors are now the dominant reason for rejection.

An additional benefit provided by the system is that density variations between sequential images have been significantly reduced. The uniformity of image presentation achieved using the automated processing is shown in Fig 4 in which a series of digitized portable chest films without processing (A, C, E) and with processing (B, D, F) are shown. The processing for these images includes density correction and unsharp mask filtering. Contrast correction was not required. The original images (Fig 4, A, C, and E) were determined by the density-correction technique to have exposure levels of 0.8, 2.8, and 1.0 times the proper exposure level, respectively. Histograms of the average OD in the lung regions of 100 consecutive radiographs that were unprocessed (hatched) and processed (solid) are shown in Fig 5. The average OD in the lungs was obtained by averaging the ODs measured in four intercostal regions of the peripheral lung regions. The distribution of ODs is centered at 1.87 ± 0.42 before density correction and 1.42 ± 0.14 after correction. The reduction in the standard deviation indicates the improved uniformity of OD from image to image.

As part of our efforts to reduce density variation between images, we have modified the processing parameters of a storage phosphor computed radiography (SPCR) unit (Toshiba TCR 3030a, Toshiba, Nasu, Japan) to produce images that closely match visually the enhanced digitized film. The processing parameters for the two modalities are slightly different because of the difference in the noise and resolution properties of the two systems.[1,8] The quality of the visual match can be appreciated in Fig 6 which a series of portable chest radiographs of the same patient includes both digital film duplicates and storage phosphor computed radiographs. As with the enhanced film digitization, we print two identical SPCR images, one for radiologic interpretion and one for the ICU clinics.[6] In our department, we use the SPCR system for approximately one-half of our portable exams.

Since becoming clinically operational, the film-digitization system has been unavailable for only 6% of the time (467 hours out of the total time of 7816 hours). Most of the downtime has been caused by printer malfunctions, primarily film jams (Table 3). A more comprehensive list of the problems that we have encountered in the use of the system and their causes are listed in Table 4. Although human errors have not

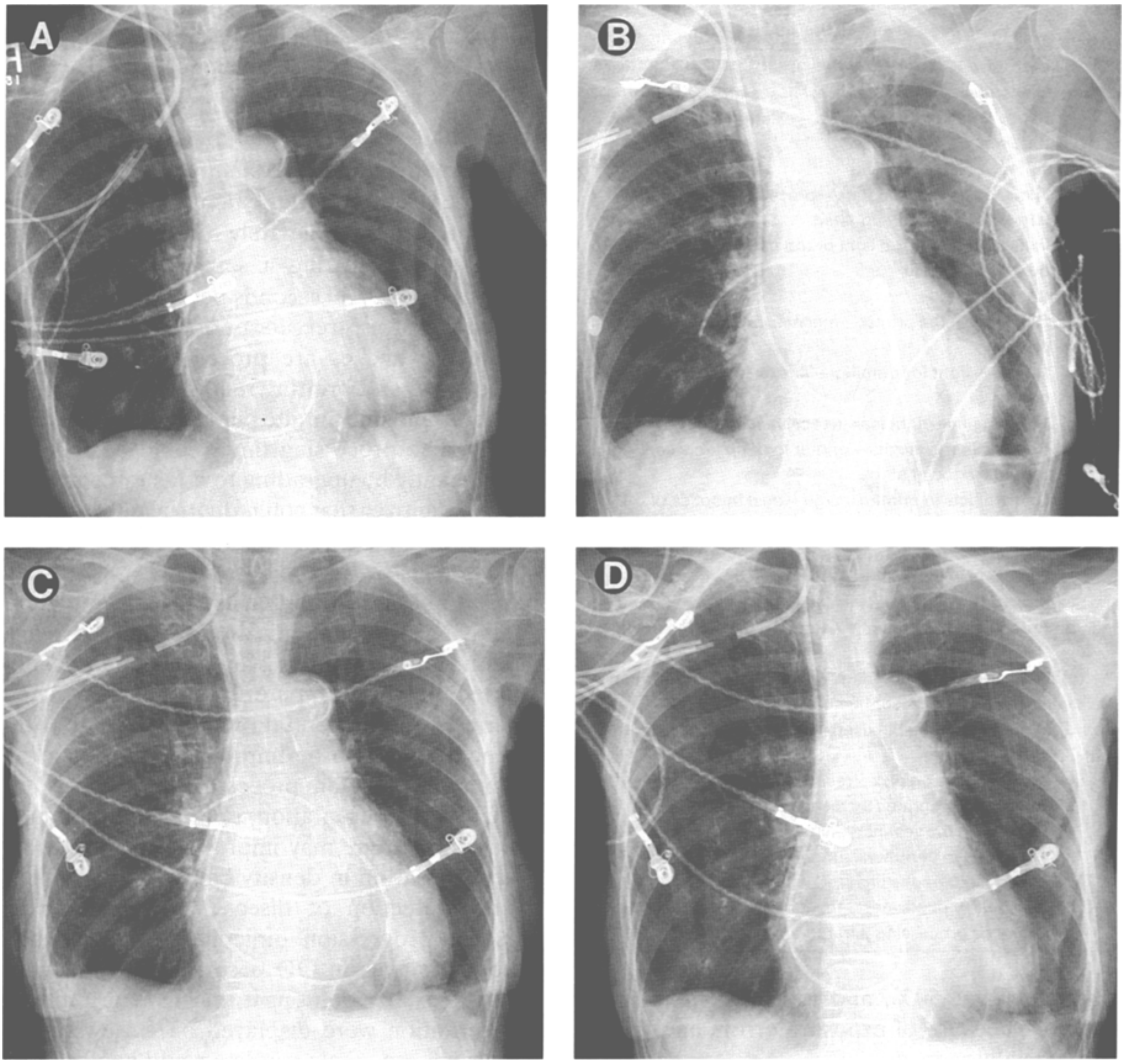


Fig 6. A series of portable chest radiographs of the same patient that includes both digital film duplicates (A and C) and storage phosphor computed radiographs (B and D). We use slightly different processing parameters for film and SPCR images to produce the closest possible visual match for day-to-day comparison.

contributed significantly to the downtime of the system, they have resulted in image quality problems or necessitated reprinting of films. We have found that as the user interface has been simplified, mistakes by the technologists have decreased.

Table 3. Reasons for Downtime of Digital Duplication System

	Number of Hrs (% total)
Printer malfunctions	336 (71.9)
Computer problems	71 (15.2)
Scanner malfunctions	25 (5.4)
No film available	17 (3.6)
Miscellaneous problems	18 (4.0)

DISCUSSION

In summary, we have developed and implemented an enhanced film-digitization system that has been operational in our department since December 21, 1991. We have found that the image quality of the digital images is often visually superior to that of the original radiograph and that it is consistent from day to day. Thus, the digital image is used by the radiologists for primary interpretation. However, the original film is still available for reference. Since implementation of film digitization, repeat rates for portable chest radiographs have been re-

Table 4. Problems Encountered in Use of Film Duplication System and Their Causes

1. Scanner errors
   a) Line artifacts in images—dust in scanner optics
   b) Ready light did not come on—electronic adjustment required
2. Computer/program errors
   a) Films too light or too dark—processor calibration curves not properly updated
   b) Films marginally too light or too dark—definition of normal too broad
3. Printer errors
   a) Film jams in the printer—mechanical problems with printer
   b) No ready light for printing—film sensor out of position
   c) Film fogging—light leak in receive magazine
   d) Bizarre binary images—printer look-up table corrupted by power surge
   e) Line artifacts in printed image—dust in optics of printer
4. Human errors
   a) Film jams in the printer—too many films in supply magazine
   b) Printed images too light—supply films loaded upside down
   c) Films too light or too dark—no calibration performed to monitor processor fluctuations
   d) Wrong look-up table used—incorrect film type indicated
   e) Lack of space on disk—research images not deleted
   f) Deletion of programs by technologist
   g) Film jam in the scanner—film input at an angle
   h) Saturation in peripheral lung—extremely overexposed radiographs digitized with 0-3 setting
   i) Poor-quality duplicates—technologists overriding the automatic processing parameters

duced by over 50%, and repeat examinations required because of exposure errors have been substantially reduced.

We have also realized a savings in film costs. A standard sheet of 14 × 17-in copy film costs approximately $2.00. One sheet of film for the laser printer costs $0.67. Thus, even with the production of two digital images, we are realizing a savings of approximately $0.66 per case, or approximately $30.00 per day with 50 portable radiographs. We estimate that the hardware components of our system, including laser film scanner, computer, laser film printer, and software, have a total retail cost of approximately $100,000. If hard copy were not required (ie, soft copy sent to the ICU), the system might cost only $40,000.

Currently, the time from insertion of the film into the scanner until the time the digital image is printed is approximately four minutes. However, after digitizing a series of radiographs (approximately 30 seconds per radiograph), the technologist is free to perform other duties while the images are processed and printed. Processing and printing require less than three minutes and one minute per radiograph, respectively. The processing times could be reduced significantly by upgrading to a faster computer. A film digitizer that could digitize automatically an entire stack of radiographs would reduce technologists' time. However, if this system were to be used to enter images into a picture archiving and communication system, the image identification number would need to be obtained by the computer in some automated manner, eg, interpretation of a bar code. Efficiency could also be improved by docking the film printer to a film processor.

Uniform presentation, such as that obtained with our system, may improve diagnostic accuracy. Variation in density between images may make detection of disease or evaluation of disease progression difficult, especially when subtle changes in OD occur, as in pulmonary infiltrates. In addition, if images with uniform presentation were displayed on a viewstation, the same gray-scale window could be used and manipulated for all images simultaneously,[9] which might improve not only diagnostic accuracy, but also the efficiency of interpretation.

We have found digital duplication to be a valuable addition to our radiology department. We believe that film digitization will be useful as an intermediate step between the conventional film-based radiology department of the present and the completely digital department of the future.

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