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Chest Imaging Within the Radiology Department by Means of Photostimulable Phosphor Computed Radiography: A Review

Hartwig Blume and R. Gilbert Jost

Photostimulable phosphor computed radiography has been clinically used outside of Japan for more than 8 years. Results of at least 35 quantitative or semiquantitative studies have been published so far in which the clinical utility of computed radiography (CR) is compared with that of conventional screen/film radiography (FR) for the study of the adult chest within the radiology department. The results can be summarized as follows: CR is superior to FR in the mediastinum, retrocardiac region, and subdiaphragmatic recesses, as well as in the evaluation of coronary artery calcifications. CR is reported to be generally superior or equivalent in the detection and evaluation of pulmonary nodules and larger pulmonary opacities. Equivocal results have been reported for pathologies requiring the inspection of fine details, such as interstitial infiltrates or pneumothorax. The studies indicate that image processing algorithms dedicated to the delineation of specific anatomies or pathologies improve clinical performance.

KEY WORDS: computed radiography, photostimulable phosphor, thoracic radiography.

THE SUCCESSFUL CLINICAL USE of photostimulable phosphor computed radiography in the study of the thorax has been reported for portable adult chest radiographs[1-3] and in the evaluation of the pediatric chest.[4-8] A more demanding application, however, is the use of this technology within the radiology department for the examination of the adult chest. The standard chest radiograph is the most commonly performed radiology study, and its wide range of contrast and spatial resolution requirements present a significant technical challenge.

A number of quantitative or semiquantitative comparisons of computed radiography (CR) and screen/film radiography (FR) in the examination of the adult chest have been reported, but in general, each study has been focused on different anatomical structures and/or disease processes. It therefore seems appropriate to review the results published to date in order to evaluate whether CR is a suitable alternative for FR for the evaluation of the adult chest. This review will allow us to recognize the strengths and weaknesses of CR compared with those of FR, and to identify areas where additional scientific work is needed.

THE CR AND FR IMAGE ACQUISITION SYSTEMS

The low-frequency detective quantum efficiency (DQE) of Fuji's CR systems (Fuji Photo Film Co, Ltd, Tokyo, Japan) is superior to typical screen/film systems with speeds of 400 or higher.[9-12] The overall physical image quality produced by current and earlier CR systems, characterized by the modulation transfer function (MTF) and mid to high-frequency DQE as a function of exposure and x-ray spectrum, however, is inferior to the quality of screen/film systems with speeds of 400 or lower. Nevertheless, as several resolution studies with digitized screen/film radiographs indicate, the more limited MTF of CR may perhaps not affect diagnostic performance significantly.[13-17] When mild high-frequency enhancement is applied, some lack of modulation transfer of high-frequency details seems to be sufficiently compensated.[18-20] However, the greater amount of noise in CR

From Philips Medical Systems North America Comp, Shelton, CT, and Mallinckrodt Institute of Radiology, Washington University School of Medicine, St Louis, MO.

Address reprint requests to Hartwig Blume, PhD, Philips Medical Systems North America Comp, 710 Bridgeport Ave, Shelton, CT 06484.

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images should, one would expect, reduce observer performance.

The studies to be reviewed below were predominantly performed with Fuji CR systems of the second generation, CR 201, 501, and 901, and imaging plates ST II. The physical performance of these systems is practically the same. None of the reviewed studies is reported to have used a second-generation plate reader system combined with the third-generation imaging plates to improve the DQE. A few studies were conducted with the Konica system (Konica Corp, Tokyo, Japan), the Agfa system (Agfa Corp, Ridgefield Park, NJ), and an experimental Kodak CR system (Eastman Kodak Co, Rochester, NY). Although little has been published about the physical performance of these systems, their properties are assumed to be similar, but not identical, to those of the Fuji systems.

Wherever the conventional screen/film combination was identified, it was a system with speed 400 or lower. Typically, the lower the speed of conventional screen/film systems, the better the resolution and the lower the noise power. Differences exist between conventional systems of the same speed from different manufacturers because of technology and screen phosphor differences, but these differences are minor.

REVIEW OF STUDIES

Published quantitative or semiquantitative comparisons of FR versus CR for examinations of the thorax in the radiology department are reviewed. The review begins with studies in which the rendition of a broad spectrum of anatomical or pathological features is compared. Subsequently, results of studies dedicated to a particular disease process or anatomical region are presented. The results are summarized in a table ordered by disease process.

All reviewed studies are given equal weights without criticism even though relatively wide qualitative differences exist between them.

General Assessments

Positive or neutral results. In a semiquantitative study by Fuhrman et al[21-23] with an experimental Kodak CR system, eight experienced radiologists compared overall quality, resolution, and lung representation of conventional (Kodak Lanex Medium or Lanex Regular with Ortho L) and computed chest radiographs (taken with the same techniques immediately following the FR acquisition). The conventional films were independently judged to have good-to-excellent quality. The CR images were digitized to 3,584 × 4,000 pixels, ie, twice the resolution of Fuji's CR system. The CR images were presented in full-size and 2:1 minified. Both CR presentations received consistently higher scores than the conventional radiographs. In 74 of 88 cases, the radiologists indicated their confidence level in making diagnoses would be at least as high with the CR images as with the conventional films.

A receiver-operating characteristic (ROC) analysis by Greene and Schaefer et al of lung, pleural, and mediastinal abnormalities (157 patients, 6 readers, 5,652 observations) demonstrated better pooled performance and superior individual performance for five of the six readers when comparing isoexposures (140 kilovolts (peak) of FR (Kodak Lanex Medium/OC) and CR (Toshiba TCR 201).[24,25] In overall detection, indicated by the average area under the ROC curve, FR and CR were equivalent. Computed radiography was superior for mediastinal lesions and pulmonary opacities greater than 2 cm in diameter. The authors concluded that currently available commercial CR systems can replace film radiographs in the detection of a wide variety of chest lesions.

A broad ROC thorax study of Kehler et al[26] with five radiologists was carried out to assess the sensitivity and specificity for correctly diagnosing 135 patients having either a normal thorax or one or more abnormalities including tumors, pneumothorax, fibrosis, atelectasis, bone disease, mediastinal abnormality, cardiomegaly, tuberculosis, or pneumonia. The study was based on two differently processed CR images (Philips PCR 901) versus standard isoexposure [140 kV(p)] film/screen radiographs (Dupont Quanta Fast Detail/CEA Wicor-X RPL). The authors concluded that, for most abnormalities, CR at least equals FR in diagnostic performance. Computed radiography was superior or equal to standard film in both sensitivity and specificity for the majority of diagnoses. In fibrosis, medias-

tinal processes and pneumonia, the sensitivity of CR was lower, although without a statistically significant difference.

In a semiquantitative study by Krug et al,[27] two radiologists compared sets of PA and lateral radiographs acquired with both FR (Siemens Titan U2 screens, 100-speed system) and CR (Philips PCR SP). The study involved 151 patients with a broad range of thoracic abnormalities (faint cardiopulmonary masses, infiltrates, sarcoidosis, intrapulmonary primary and metastatic tumors, interstitial disease, tuberculosis, and lymphoma). The CR images were acquired with 50% of the FR exposure [125 kV(p)]. Subjective scores for rendition of mediastinal structures, the tracheal-bifurcation, and the retrocardiac space in the lateral radiographs were significantly higher for CR. Intrapulmonary nodules and Kerley-B-lines could be better delineated with CR than with FR. "Stripe-shaped" interstitial alterations (such as atelectasis) were judged to be equally well perceived, whereas the diagnosis of "net-shaped" interstitial alterations was considered less certain in CR than in FR.

Neufang et al[28] and Friedmann et al[29] reported an ROC analysis of the performance of four radiologists in diagnosing 211 sets of biplane thorax radiographs that were acquired [125 kV(p)] with both FR (Siemens Titan U2 screens, 100-speed system) and CR (Philips PCR SP, 50% exposure of FR). Computed radiography was found to be adequate for routine biplane thoracic radiography and for follow-up studies of heart size, pulmonary congestion, pulmonary nodules, pulmonary infiltrates, atelectasis, pleural effusion, and mediastinal and hilar lymph node enlargements. With 50% of the FR exposure, CR was found to be significantly superior in evaluating pulmonary nodules in the retrocardiac, mediastinal and diaphragmatic area.[29] Computed radiography proved to be especially valuable for evaluating the status of the retrocardiac region on the PA view. High-frequency–enhanced CR images were judged to be unsuited for assessing pulmonary nodules.

In a study by Prokop et al[30] related to that reported by Schaefer et al,[20] the effects of four different variations of the standard unsharp mask filter algorithm (kernel length of 1.44, 5, 25 and 70 mm) applied to computed radiographs were compared with iso-exposure conventional radiographs. Three subtle lesions (nodules, fine lines, and micro-nodular opacities) were superimposed on chest radiographs of 10 healthy volunteers. The ROC studies with eight observers including 10,800 observations indicated that large kernels worked best for nodule detection. In fine line detection, FR was only superior to CR with the ultralarge kernel; all other CR image versions were equivalent to FR images. For detecting micronodular opacities, the film/screen radiographs were superior to all CR image versions, although the images processed with the ultralarge and large kernel were better than those processed with the medium kernel size.

Negative results. MacMahon et al[31] simultaneously acquired [125 kV(p)] conventional and computed chest radiographs (Toshiba TCR 3030A) by placing a CR imaging plate (Fuji ST III) behind the sandwich of two conventional intensifying screens plus film (Kodak Lanex Medium/OC) in the same cassette. Limited subjective observer performance ratings indicated that confidence levels with CR for normal cases and cases with nodules and masses were almost identical with those of conventional radiographs. The heavily filtered CR images yielded lower diagnostic confidence levels for the most part. For the cases in which pneumothorax was present, the average confidence levels for the combined (weakly and strongly enhanced) CR images and the strongly enhanced image alone were superior to those of FR images, although statistical significance was not achieved. For infiltrates, the combined CR images were found to be slightly inferior. It should be noted that the outcome of the observer tests cannot be easily generalized because the CR plate received a lower primary exposure of a hardened spectrum compared with the conventional system. The contrast reduction, however, may be partially compensated by the absorption of patient scatter by screens and film.

The broad studies of Neufang et al[28] and Friedmann et al,[29] which were reviewed in part above, yielded negative results regarding structural processes. The confidence with CR in demonstrating or ruling out subtle pulmonary

alterations, in particular, discrete Kerley-B-lines or early stages of interstitial infiltrates, was significantly lower than with FR, independent of the chosen unsharp mask filter parameters. At the FR-equivalent exposure level, only pronounced reticular and nodular structural alterations of the lung could be reliably detected with CR. Accordingly, the authors observed that CR appears to be unsuited for monitoring pneumoconioses. They believed that patients with sarcoidosis or superinfection secondary to immunodeficiency should be examined with FR. Therefore the authors concluded that CR is presently not in a position to replace traditional FR of the chest completely.

In an ROC analysis, Löhr et al[32] compared the image quality of simulated pulmonary nodules and linear and reticular structures in an anthropomorphic thorax phantom using FR (200- or 400-speed screen/film combinations) and CR (Siemens Digiscan 901, exposed like a 400-speed screen/film system). The CR images were processed with the standard unsharp mask algorithm as well as with unsharp mask filters with rectangular, triangular and gaussian kernel shapes. In general, CR image quality in the lung fields was found to be comparable with that of the 400-speed FR only by reprocessing with finely tuned filter parameters. The observer performance with CR was better than with FR in the evaluation of the mediastinum.

Pulmonary Nodules

Positive or neutral results. Seven radiologists from two clinical institutions participated in two FROC analyses conducted by Lehmann et al.[33] The studies were concerned with the detection of peripherally and centrally placed pulmonary nodules in a chest phantom. Computed radiography (Philips PCR SP) yielded higher average areas under the ROC curve for mediastinal nodules than FR (Kodak X-OMAT S/OMATIC Regular, 117 kV_p, exposure conditions similar to CR) and equal performance for peripheral nodules.

Newell et al[34] evaluated the detection of simulated solitary pulmonary nodules of various sizes and contrast placed on a standard chest phantom in an ROC study with four radiologists and 48 sets of CR (Fuji) and equally exposed FR images ($CaWO_4$ blue emitting screens/NEW RX, 124 kV_p). The authors did not find any significant difference in the performance of the two imaging systems.

A standard ROC study and an ROC study with localization were conducted by Morioka et al[35] and 15 participating radiologists. The study concerned the detectability of pulmonary nodules in 36 sets of radiographs acquired with both CR and FR. Overall diagnostic accuracy of CR and FR were comparable; the quality of the gray scale–reversed images was slightly inferior. Diagnostic accuracy of easy cases was significantly better for the unprocessed CR image alone, the unsharp-masked image alone, and the image pair than for the screen/film radiographs. FR and unprocessed CR images were found to be superior in accuracy for difficult cases.

The capability to detect pulmonary nodules was also compared in a study of Neufang et al with four radiologists for FR (Siemens Titan U2 screens) and CR (Philips PCR SP).[36] Lateral and PA image sets from 17 patients were acquired with FR and, immediately following, with CR. The CR images were acquired at 50% of the FR exposure [125 kV(p)] and were presented in a low-frequency– as well as a high-frequency–enhanced version. Low-frequency–enhanced CR images equaled FR images in the detection of nodules and tended to be superior to FR images in demonstrating and excluding nodules in the retrocardiac and subdiaphragmatic area. High-frequency–enhanced images were judged to be inferior to both FR and low-frequency–enhanced CR.

Schaefer et al[37] performed an ROC analysis with 7,500 observations by five radiologists comparing the detectability of simulated nodules and fine pulmonary lines in isodose radiographs of 10 healthy volunteers acquired by FR and CR (Fuji FCR 901). The CR images were printed in four "commercially available" sizes, 38 × 32 cm, 29 × 23 cm, 22 × 18 cm, and 19 × 15 cm. In the detection of nodules, there were no significant differences. Receiver-operating characteristic areas for detecting pulmonary lines decreased with smaller image size, but only the smallest image format was significantly inferior to the conventional FR standard.

Schwermer et al with six radiologists conducted a comparative analysis based on a confi-

dence scale for detecting pulmonary nodules in 39 sets of PA and lateral images [125 kV(p), 1 mm Al, 0.1 mm Cu] acquired both by FR (Agfa Saphir/Cuprix RP1) and, with 28% less exposure, by CR (Philips PCR 501).[38] Preceding the comparison, the CR image processing parameters were optimized (with images not belonging to the study set) for best rendition of pulmonary nodules. With these parameters, the confidence ratings for the CR images were significantly higher than those for FR images. The superiority of the CR images was particularly apparent in the lung areas obscured by the cardiac or diaphragmatic shadows.

The ROC analysis of Yoshioka[39] demonstrated that CR showed better detectability of simulated lung nodules than did a screen/film system under the same exposure conditions.

Negative results. The ROC analysis by Morioka et al[40,41] with the participation of 10 radiologists, established that there is no statistically significant difference in the detection of either a solitary, noncalcified nodule, or a pneumothorax when comparing 24 sets of iso-exposed radiographs [110 kV(p)] obtained with CR (Philips PCR SP) and FR. However, the area under the ROC curves for detection of both abnormalities was greater for FR than for CR.

In a study by Aberle et al,[42,43] observer performance for detecting simulated nodules projected over an anthropomorphic chest phantom was better with conventional film than with the CR (Konica) soft copies. It is well known, however, that high-resolution monitors typically degrade the quality of the digital input image. Unless the degradation and viewing conditions are very well defined, the results of studies like this one cannot be generalized to other situations.

Lung Line Contours, Interstitial Structures

Positive or neutral results. The ROC study performed by Dölken et al[18] with 10 observers and iso-exposure FR [Agfa Fine/RP1, 125 kV(p)] and CR (Siemens Digiscan) radiographs of 60 patients (29 with interstitial lung disease, 31 without pathological interstitial alterations) showed no statistically significant difference between the two compared technologies. All CR images were processed with the standard unsharp mask algorithm to yield images with high-frequency and with medium-frequency enhancement. A correlation analysis of the profusion of the pathological opacities according to the ILO/UC classification showed a significant positive correlation ($P < 0.001$) for the CR and FR images with a correlation coefficient of $r_s = 0.853$.

An ROC analysis by Oestmann et al[19] of 2,160 observations on sets of CR (Toshiba TCR 201) and FR (Kodak Lanex medium/Ortho C) films from two patients [141 kV(p)] by six readers found that high-frequency enhanced digital images performed better than unenhanced digital images and that the edge-enhanced digital images performed on a par with conventional radiographs for the detection of fine linear structures.

In an ROC investigation, Schaefer et al[20] assessed the ability of six radiologists to resolve the fine linear structures of interstitial disease in isodose FR (Kodak Lanex medium/OC) and CR (Toshiba TCR 201) radiographs of 65 patients [141 kV(p)]. In separate reading sessions, the CR images were presented in six different variations of the standard Fuji unsharp mask algorithm. The moderately and more strongly high-frequency–enhanced CR images were equivalent in performance to FR images.

An ROC study by Sartoni Galloni[44] suggests that the diagnostic accuracy of CR and FR are substantially the same in detecting interstitial pulmonary pathology. The study was conducted by four radiologists comparing isodose [140 kV(p)] conventional radiographs (Kodak T-mat G film) and computed radiographs (Philips PCR Graphics, Fuji ST II imaging plates) of 80 patients with acquired immunodeficiency syndrome (AIDS). The presence of interstitial pathology was established by high-resolution CT or Ga 67 scintigraphy. No statistically significant difference was observed between CR and FR.

Negative results. An ROC study was conducted by Buckley et al[45] with 60 patients and six readers concerning the detection of fine linear contours and altered aerations due to bullous lung disease on FR (Kodak Lanex Medium/OC, 140 kV_p) and CR (Toshiba TCR 201, isoexposure) in five different reprocessing states. The disease had been proved by CT to exist in 35 of the 60 patients. The default

algorithm and the three edge-enhancing algorithms of high and medium frequencies performed less well than did plain films, but the differences fell short of statistical significance. Gray-scale reversal performed significantly less well than conventional films.

Detection of interstitial disease and pneumothorax was compared for conventional film and CR soft copies on a 2048-line monitor by Batra and Aberle et al.[46] Observer performance for both abnormalities was better with conventional film, but only for the case of interstitial disease was the difference significant. As in the previous study by Batra et al[42] reviewed above, it is noted that the results also of this study cannot be easily generalized because of the unknown properties of the CRT display.

Pneumothorax

Positive or neutral results. Results obtained by Elam et al[47] indicate equal performance for the detection of pneumothorax with CR (Toshiba TCR) and FR based on an ROC study with 45 (22 normal) sets of radiographs and four observers. The mean areas under the ROC curves were insignificantly smaller for CR. Two readers performed better with CR, the other 2 performed better with FR. (This report represents an update of the more negative results of the same group of researchers[49] reviewed below.)

Kehler et al[48] evaluated the efficacy of CR (Philips PCR) in diagnosing pneumothorax. An ROC study with 78 patients (40 normal) and four radiologists determined no significant difference between FR [Dupont Quanta Fast Detail/CEA Wicor-X RPL, 140 kV(p)] and CR (same exposure as with FR). As in a related study,[26] the investigators found that performance equivalent to that of FR was achieved with both the conventional appearing and the more edge-enhanced CR image.

MacMahon et al[31] reported positive results with respect to the detection of pneumothorax using CR (see *General Assessments—Negative Results* above).

Negative results. Fajardo et al[49] compared sensitivity, specificity, and ROC curve area for the detection of pneumothorax in 50 matched pairs of conventional [Dupont Quanta III/WDR-SR334, 105 kV(p)] and computed radiographs (Toshiba TCR 201, same exposure conditions as FR). Eight observers participated in the study of images from 25 patients. Four of the readers detected pneumothoraces statistically better in conventional radiographs. The other four readers had similar sensitivity and specificity with both techniques. Although the authors offered several hypotheses in their discussion about the partially negative outcome, they warned: "because of the morbidity associated with delayed treatment for missed pneumothoraces, these data suggest that computed radiography may not be adequate for depicting pneumothoraces in clinical practice."

Morioka et al[40,41] reported better detection of pneumothorax with FR rather than CR, although the difference was not statistically significant (see description of study under *Pulmonary Nodules—Negative Results* above).

Mediastinum

Positive or neutral results. In Bonetti's study[50] of CR (Toshiba TCR 201) and conventional radiography with 500 patients, the delineation of paramediastinal lines (anterior and posterior junction lines, right superior, and inferior paraesophageal lines, aortopulmonary window, right paratracheal line, left paraspinal line, and the wall of the bronchus intermedius) was evaluated. It was concluded that CR leads to earlier diagnosis of mediastinal and pulmonary masses than does conventional radiology.

FR (Kodak Lanex Medium/OC) and isodose CR images (Toshiba TCR 201) processed by six different sets of FCR image processing parameters of 60 patients [141 kV(p)] were compared in an ROC evaluation by Schaefer et al[51] with six radiologists concerning a broad spectrum of mediastinal lesions and pulmonary abnormalities such as nodules less than 2 cm in diameter, larger soft tissue opacities, and interstitial disease and atelectasis. Processing with high-frequency edge-enhancement and optimization of density/contrast for the mediastinum significantly improved performance of CR over FR in the detection of mediastinal lesions, while a different set of processing parameters yielded performance equivalent to FR for the detection of pulmonary abnormalities. The algorithm with the best performance for the evaluation of the

mediastinum had performance inferior to that of FR in detecting pulmonary disease processes.

Coronary Artery Calcification

Positive or neutral results. Sensitivity and specificity of CR (Fuji FCR 101) and FR (Fuji G-3/RXO-G or HR-S) in the detection of coronary artery calcification were compared by Sakuma et al for sets of PA and lateral radiographs of 77 patients [130 kV(p)].[52] For left and right coronary arteries, the sensitivity of CR was considerably higher than with FR. The specificities were similar for both methods. Fine anatomical details of calcified foci were also seen more clearly with CR.

DISCUSSION

Technical Issues

The thorax radiographs of the studies reviewed here were acquired over a relatively wide range of kV(p) and therefore with varying x-ray spectra. There is, principally, for any given anatomical detail within the projection image of a patient of given attenuation a best x-ray spectrum, ie, kV(p) and pre-filtration, that, with the given screen/film combination and scatter situation, yields the best possible signal-to-noise ratio. None of the studies reported here attempted to operate under such "optimum" conditions. Accidental operation closer to optimization, however, could easily have occurred for one or the other image acquisition system and affected the outcome of a specific study.

Most of the reviewed studies were performed with equally exposed FR and CR radiographs. In seven evaluations,[27-29,31,32,36,38]—perhaps tempted by the large dynamic range of the CR system and its autoranging feature—the researchers exposed the CR detector with up to 50% less radiation. Thereby, the CR system is placed at a disadvantage compared with the screen/film systems.

In most studies, CR and FR images were acquired subsequently during the same day, with the same projection, and on the same thorax imaging stand. Positioning and projection differences should therefore be minimal, but of course, differences can occur.

Most of the reviewed studies were conducted by comparing CR and FR films hung separately in front of a lightbox and, in turn, almost all used the standard half-size CR format. All CR images were digitally processed by using an unsharp mask edge-enhancement algorithm and specific display functions. The reviewed comparisons were performed with different states of image processing. In some cases, the standard processing parameters for chest radiography as delivered with the CR system were used. In others, specialized parameters were selected after a more or less rigorous optimization procedure. The latter subject in itself requires a complicated clinical observer study.

Considering these physical differences, it is evident that one cannot easily generalize the results of any specific clinical comparison of CR and FR. Unfortunately, in addition, comparisons of CR and FR are greatly complicated by subjective effects of the participating observers, aspects of clinical practice, and psychophysical factors.

Observer Issues

Many of the comparative studies were performed relatively soon after installing a CR system in the respective institution. Although it was often stated in these reports that physicians had become very quickly accustomed to the smaller size and the digitally processed nature of the images, learning effects will most certainly have affected the results. There is no established number of radiographs that a physician must read after introduction of the CR modality until the observer performance reaches an equilibrium. Potentially, practicing thorax radiography simultaneously with CR films and conventional films may affect operator performance. Computed radiographic and FR images do not only require different viewing conditions, but a different mind set.

Radiologists have reported that it takes several weeks or months to adapt properly to the edge-enhanced CR views. Initially, the enhancement algorithm tends to exaggerate findings such as interstitial lung disease, and incorrect conclusions may be reached if radiologists are not thoroughly experienced with CR.

Very likely, there are no radiologists who have been trained exclusively with CR images. We could imagine that radiologists only accustomed to half-size edge-enhanced radiographs

might perform differently than those radiologists with conventional training.

As is well known, one school of radiologists acquires thorax radiographs at high kV_p, the other at low kV(p). Supposedly, both schools exhibit equal observer performance given the same clinical cases on conventional radiographs. Do these two schools require different display functions for the presentation of CR images? Hardly any publication mentions that the CR image display functions were adapted to user preferences or for better performance.

Another important aspect in comparing efficacy is the gold standard. In several of the reviewed studies, the truth was established by prior CT examinations. Especially for nodule and fine linear structure detection, researchers often used external devices that simulated the pathologies. Sometimes, an independent expert panel established "truth" for the observer performance study. Without the determination of absolute truth, performance studies must be conducted with as many observers as possible in order to minimize the effect of interobserver detection errors. Therefore, the reliability of the conclusions varies among the reviewed studies.

Many reports do not mention that care was taken to select a typical mix of patients and to select cases with an appropriate spectrum of difficulty. Studies with a large number of patients will, in general, be more representative of the mixture of routinely encountered diagnostic difficulties.

Obviously then, even if the results of a specific study would demonstrate that observers achieved the same overall performance in reading thorax radiographs acquired with CR and FR, it could not be generalized immediately. On the other hand, if a preponderance of publications shows that clinical performance with CR is comparable to that with FR for a given diagnostic question, one may begin to gain confidence in the clinical use of CR.

Study Issues

Unfortunately, relatively few quantitative or semiquantitative evaluations of the clinical use of CR have been conducted. Of the more than 450 technical and clinical publications on CR of which we are aware, only 35 describe quantitative or semiquantitative clinical assessments of CR for examinations of the thorax in the radiology department. Merely one or two investigations attempt to compare CR and FR quantitatively for the majority of anatomical and pathological details encountered in thoracic radiology. For a large number of pathologies or disease states, such as fibrosis, thoracic tumors, pneumonia, sarcoidosis, tuberculosis, and bone disease, only one quantitative or semiquantitative analysis exists so far. Performance of CR versus FR has been compared in three or more publications for each of the following conditions: pulmonary nodules, large pulmonary opacities, pneumothorax, fine line and interstitial structures and abnormalities, atelectasis, and selected abnormalities in the diaphragm and mediastinal areas. For these anatomical objects or pathological conditions, one can begin to draw conclusions concerning the clinical use of CR, but certainly much work remains to be done.

Last but not least, it is emphasized that all studies have been performed in controlled, artificial environments and their results, therefore, are not necessarily applicable to the routine practice. We are unaware of any prospective, truly clinical study. It is hoped that this review will prompt evaluations under realistic clinical conditions.

CONCLUSION

Overall, CR yielded diagnostic results equivalent to those of FR, although shortcomings in selected anatomical and pathological areas led several research teams to state that (second-generation) CR cannot fully replace FR. However, for no thoracic diagnostic task was CR found to be vastly inferior compared with FR. In fact, when the body of available evidence is examined, CR performs surprisingly well for many of the problems associated with chest radiology.

Apparently, CR can yield diagnostic performance for the detection of selected diseases comparable to that of FR when specific pathology-dependent processing algorithms are used. To achieve equivalent performance over a wide

Table 1. Summary of the Clinical Quantitative and Semiquantitative Analyses

Anatomy/Disease	Reference																												Summary
	18	19	20	21 22 23	24 25	26	27	28 29	30	31	32	33	34	35	36	37	38	39	40 41 *	42 43	44	45	46 *	47	48	49	50	51	52	
General				+																										(+)
Lung/abnormalities, general					−/0							+																		+/0
Fibrosis						0/−																								(0/−)
Micronodular opacities									−																					(−)
Pulmonary nodules							+	+/0	0	0/−	0/−	+/0	0	+/0	0	0	+	+	0/−	−								0		+/0
Larger pulmonary opacities					+					0/−																	+	0		+/0
Tumors						+/0																								(+/0)
Pulmonary congestion								0																						(0)
Pneumonia						0/−																								(0/−)
Sarcoidosis								−																						(−)
Tuberculosis						+/0																								(+/0)
Infiltrates								0		−																				0/−
Atelectasis						+/0		0																				0		+/0
Pleura/abnormalities					+/0			0																						+/0
Pneumothorax						+/0				+/0									0/−				0/−	0	0	0/−				0/−
Pulmonary lines																0														(0)
Fine linear structures		0							0		0/−											0/−								0/−
Interstitial/abnormalities	0		0				−	−													0/−		−				0		0/−
Stripe-shaped interstitial alterations							0																							(0)
Kerley-B-lines							+	−																						0
Lymphoma								0																						(0)
Mediastinum/abnormalities					+/0	0/−	+	0			0	+															+	+		+/0
Mediastinal lesions					+			+																				+		+
Tracheal bifurcation							+																							(+)
Paramediastinal, paratracheal lines																											+			(+)
Retrocardiac space							+	+							+		+													+
Heart size						+/0		0																						+/0
Coronary arteries																													+	(+)
Diaphragmatic area								+							+		+													+
Bone disease						+/0																								(+/0)

NOTE. A +, 0, or − sign indicates that CR was found to be statistically superior, equivalent, or inferior, respectively. A +/0 means that CR images were judged to be superior, but that the difference was statistically insignificant, that a substantial portion of the CR images had better quality than the FR images, but not all of them, or that some observers found CR better than FR without making the difference statistically significant. A 0/− refers to the corresponding situation with a trend toward inferiority for CR. A * sign next to the reference number indicates that the images for this study were displayed on a high-resolution CRT monitor rather than as films on a lightbox. Summary scores in parentheses are based on a single analysis.

range of pathologies, more than two predefined CR processing states seem to be necessary.

In Table 1, a summary of the reviewed literature is presented. Not surprisingly, CR was found to be superior or equivalent to FR in rendering relatively faint medium-to-large details where edge enhancement and gray-scale-contrast adjustments can be effective. This is evident by the results obtained for pulmonary nodules, larger pulmonary opacities, as well as mediastinal structures and lesions. Correspondingly, due to its lower MTF and inferior high-frequency DQE, CR was found equivalent or, in some studies, inferior in rendering weak high-frequency details. Consequently, fine linear structures, interstitial abnormalities, fibrosis, and pulmonary infiltrates were sometimes less certain to be diagnosed with CR. Incidentally, these are the types of abnormality that require the most experience on the part of the observer with respect to the evolution of enhanced images.

We may conclude the following:

1. There are areas where CR is clearly superior to FR—in the mediastinum and the evaluation of coronary artery calcifications. Of these two conditions, the former is by far the more important. Underpenetrated regions of the chest radiograph, including the mediastinum, retrocardiac region, and diaphragmatic recesses, are notoriously difficult to evaluate, and CR appears to be superior in the evaluation of pathologies in these areas.
2. Computed radiography is reported to be generally superior or equivalent to FR in the detection and evaluation of pulmonary nodules, and larger pulmonary opacities. Nodules appear to be most visible in images processed with large unsharp mask kernels, rather than the algorithm typically used to provide edge enhancement for the chest.[30]
3. Equivocal results have been reported for pathologies requiring the inspection of fine details, such as interstitial infiltrates or pneumothorax. Fine lung lines are among the structures most altered by the unsharp mask enhancement algorithm, and therefore observer training and choice of image processing parameters have important bearing on the results of observer studies.
4. The great preponderance of the literature dealing with CR and chest radiology is subjective in nature. Only a small portion of the published studies are quantitative or semiquantitative in their design. More well designed, quantitative studies are required if we are to understand truly the appropriate roles for CR and FR in chest radiology.
5. Virtually all the studies reported to date have been carried out with an earlier generation of phosphor plates. The newer generations of plates offer a better DQE. It will be important, therefore, to re-evaluate our conclusions with the newer detectors. This will be of particular interest for areas where performance has been equivocal, eg, for pneumothorax and interstitial lung disease.
6. Most studies have been performed with the "standard" unsharp mask image processing algorithm and "standard" display functions provided by the CR system supplier. It should be profitable to assess different display functions and alternative spatial filter algorithms for CR, such as hierarchical filtering[53] and, of course, task-specific processing parameters, for the problem areas with equivocal performance.

REFERENCES

1. Schaefer CM, Greene R, Oestmann JW, et al: Improved control of image optical density with low-dose digital and conventional radiography in bedside imaging. Radiology 173:713-716, 1989

2. Verschakelen JA, Dhaenens F, Marchal G, et al: Photostimulable phosphor computed radiography: Experience with portable chest films. European Congress of Radiology, Vienna, Sept. 15-20, 1991. Scientific Programme and Abstracts. Berlin, Heidelberg, Springer-Verlag, 1991, p S-99

3. Witte G, Bause HW, Maas R, et al: Die laterale Thoraxaufnahme auf der Intensivstation als digitale Lumineszenzradiographie (DLR). Fortschr Röntgenstr 152: 417-420, 1990

4. Cohen MD, Long B, Cory DA, et al: Digital imaging of the newborn chest. Clin Radiol 40:365-368, 1989

5. Dietrich RB, Boechat MJ, Huang HK: Experience with phosphor imaging plates—clinical experience in pediatric radiology. SPIE 1091:242-244, 1989

6. Kogutt MS, Jones JP, Perkins DD: Low-dose digital

computed radiography in pediatric chest imaging. AJR 151:775-779, 1988

7. Lee KR, Chang CHJ, Murphy MD, et al: Computed radiographic imaging for pediatric examinations. Appl Radiol 19/6:27-34, 1990

8. Tarver RD, Cohen M, Broderick NJ, et al: Pediatric digital chest imaging. J Thorac Imaging 5:31-35, 1990

9. Hillen W, Schiebel U, Zaengel T: Imaging performance of a digital storage phosphor system. Med Phys 14:744-751, 1987

10. Sanada S, Doi K, Xu X-W, et al: Comparison of imaging properties of computed radiographic system and screen-film systems. Med Phys 18:414-420, 1991

11. Arakawa S, Saotome S, Ishida M, et al: Quantitative spectral analysis of the noise components in the computed radiography system. Proc World Congress on Medical Physics and Biomedical Engineering, July 7-12, 1991, Kyoto, Japan; Med Biolog Eng Comp 29:117, 1991 (suppl)

12. Kato H: Photostimulable phosphor radiography—Design considerations. Proc AAPM 1991 Summer School: Specifications, Acceptance Testing and Quality Control of Diagnostic X-ray Imaging Equipment. Santa Cruz, CA, July 15-19, 1991, p 860-898

13. MacMahon H, Vyborny CJ, Metz CE, et al: Digital radiography of subtle pulmonary abnormalities: An ROC study of the effect of pixel size on the observer performance. Radiology 158:21-26, 1986

14. Goodman LR, Foley W, Wilson CR, et al: Pneumothorax and other lung diseases: Effect of altered resolution and edge enhancement on diagnosis with digitized radiographs. Radiology 167:83-88, 1988

15. Lams PM, Cocklin ML: Spatial resolution requirements for digital chest radiographs: An ROC study of observer performance in selected cases. Radiology 158:11-19, 1986

16. Seeley GW, Fisher HD, Stempski MO, et al: Total digital radiology department: Spatial resolution requirements. AJR 148:421-426, 1987

17. Goodman LR, Foley W, Wilson CR, et al: Digital and conventional chest images: Observer performance with film digital radiography system. Radiology 158:27-33, 1986

18. Dölken W, Horwitz AE, Krahe T, et al: Digital and conventional chest radiographs: A comparative study on the diagnosis of interstitial lung disease in Lemke HU, Rhodes ML, Jaffe CC, et al, (eds): Proc 1991 Computer Assisted Radiology. Berlin, Heidelberg, Springer-Verlag, 1991, pp 96-100

19. Oestmann JW, Greene R, Rubens JR, et al: High frequency edge enhancement in the detection of fine pulmonary lines. Parity between storage phosphor digital images and conventional chest radiography. Invest Radiol 24:643-646, 1989

20. Schaefer C, Greene R, Llewellyn HJ, et al: Interstitial lung disease: Impact of postprocessing in digital storage phosphor imaging. Radiology 178:733-738, 1991

21. Fuhrman CR, Feist J, Cooperstein LA, et al: High-resolution storage phosphor chest imaging. Proc Chest Imaging Conference-87 (CIC-87) Madison, WI, 1987, pp 216-222

22. Fuhrman CR, Gur D, Good B, et al: Storage phosphor radiographs vs conventional films: Interpreters' perception of diagnostic quality. AJR 150:1011-1014, 1988

23. Fuhrman CR, Deutsch M, Gur D, et al: Digital radiography using storage phosphors, in Chiesa A (ed): Proc 5th Intern Symp Planning Radiol Depart. Brescia, Italy, 1988, pp 306-309

24. Greene R, Schaefer C, Oestmann J: Digital versus conventional radiographs in the detection of CT-proven chest disease. Abstracts of the ICR 89, Paris, July 1-8, 1989, p 743

25. Schaefer CM, Greene R, Oestmann JW, et al: Digital storage phosphor imaging versus conventional film radiography in CT-documented chest disease. Radiology 174:207-210, 1990

26. Kehler M, Albrechtsson U, Andersson B, et al: Assessment of digital chest radiography using stimulable phosphor. Acta Radiol 30:581-586, 1989

27. Krug B, Neufang KFR, Friedmann G: Vergleich der digitalen Lumineszenzradiographie mit der konventionellen Thoraxdiagnostik. 3. Frankfurter Gespräch über Digitale Radiographie, Oct. 5-8, 1988, Bad Nauheim, pp 342-347

28. Neufang KF, Krug B, Lorenz R, et al: Kann die digitale Lumineszenzradiographie (DLR) in der Thoraxdiagnostik die konventionelle Röntgenaufnahmetechnik ersetzen? Fortschr Röntgenstr 152:501-509, 1990

29. Friedmann G, Neufang KFR, Krug B: Digitale Lumineszenz-Radiographie (DLR) in der Thoraxdiagnostik, in Busch HP, Georgi M (eds): Digitale Thoraxaufnahmen: Fortschritt der radiologischen Diagnostik? 2. Expertengespräch im Klinikum Mannheim, Apr. 26, 1991. Konstanz, Schnetztor-Verlag GmBH, 1991, pp 35-38

30. Prokop M, Schaefer CM, Oestmann JW, et al: Postprocessing of digital chest radiographs: Which is the best compromise? European Congress of Radiology, Vienna, Sept. 15-20, 1991. Scientific Programme and Abstracts. Berlin, Heidelberg, Springer-Verlag, 1991, p S-99

31. MacMahon H, Sanada S, Doi K, et al: Direct comparison of conventional and computed radiography with dual-image recording technique. RadioGraphics 11:259-268, 1991

32. Löhr E, John-Mikolajewski V, Müller RD, et al: Digitale Lumineszenz-Radiographie in der Thoraxdiagnostik, in Busch HP, Georgi M (eds): Digitale Thoraxaufnahmen: Fortschritt der radiologischen Diagnostik? 2. Expertengespräch im Klinikum Mannheim, Apr. 26, 1991. Konstanz, Schnetztor-Verlag GmBH, 1991, pp 53-54

33. Lehmann KJ, Busch HP, Freund MC, et al: Radiography of the chest—A comparative study of analog and digital techniques, in Lemke HU, Rhodes ML, Jaffe CC, et al, (eds): Proc 1991 Computer Assisted Radiology. Berlin, Heidelberg, Springer-Verlag, 1991, pp 115-121

34. Newell JD, Seeley G, Hagaman RM, et al: Computed radiographic evaluation of simulated pulmonary nodules—Preliminary results. Invest Radiol 23:267-270, 1988

35. Moribe N, Higashida Y, Yoshioka S, et al: Effect of image processing on the detectability of pulmonary nodules: Receiver operating characteristic study for computed radiography. Radiology 177(P):207, 1990

36. Neufang KF, Krug B, Steinbrich W, et al: Detection of pulmonary nodules—A comparative study of low-dose digital luminescent radiography (DLR) and conventional

chest film, in Lemke HU, Rhodes ML, Jaffe CC, et al, (eds): Proc CAR 1989 Computer Assisted Radiology. Berlin, Heidelberg, Springer-Verlag, 1989, pp 139-144

37. Schaefer CM, Prokop M, Oestmann JW, et al: Impact of hard copy size on diagnostic performance in digital chest radiography. Radiology 177(P):250, 1990

38. Schwermer B, Witte G, Spielmann RP, et al: Vergleich digitale Lumineszenzradiographie und konventionelle Film-Folien-Technik bei pulmonalen Rundherden-eine klinische Untersuchung. Fortschr Röntgenstr 153: 161-166, 1990

39. Yoshioka S, Higashida Y, Morita K, et al: Observer performance study of image processing and incident exposure for detection of simulated nodules in computed chest radiography. Abstracts of the ICR 89, Paris, July 1-8, 1989, p 86

40. Morioka C, Brown K, Balter S, et al: Receiver operating characteristic analysis of chest radiographs with computed radiography and conventional analog films. Radiology 169(P):349, 1988

41. Morioka C, Brown K, Hayrapetian AS, et al: ROC analysis of chest radiographs using computed radiography and conventional analog films. SPIE 1091:168-171, 1989

42. Aberle DR, Batra P, Hayrapetian AS, et al: Implementation of a dedicated digital projectional radiographic system in thoracic imaging. Radiology 169(P):354, 1988

43. Aberle DR, Hansell D, Huang HK: Current status of digital projectional radiography of the chest. J Thorac Imaging 5:10-20, 1990

44. Sartoni Galloni S, Burzi M, Burci P, et al: Comparison between conventional radiography and storage phosphors digital radiography in interstitial pulmonary diseases. European Congress of Radiology, Vienna, Sept 15-20, 1991. Scientific Programme and Abstracts. Berlin, Heidelberg, Springer-Verlag, 1991, p S-190

45. Buckley KM, Schaefer CM, Greene R, et al: Detection of bullous lung disease: Conventional radiography vs digital storage phosphor radiography. AJR 156:467-470, 1991

46. Batra P, Aberle DR, Brown K, et al: Computed radiography: A study of observer performance with a high-resolution dedicated chest unit. 89th Ann Mtg Am Roent Ray Soc, New Orleans, 1989

47. Elam EA, Hillman BJ, Fajardo LL: Reader performance in detection of pneumothorax on conventional chest films versus computed radiographs. Radiology 177(P):249, 1990

48. Kehler M, Albrechtsson U, Andresdottir A, et al: Accuracy of digital radiography using stimulable phosphor for diagnosis of pneumothorax. Acta Radiol 31:47-52, 1990

49. Fajardo LL, Hillman BJ, Pond GD, et al: Detection of pneumothorax: Comparison of digital and conventional chest imaging. AJR 152:475-480, 1989

50. Bonetti MG: Computed radiography (CR) of the thorax: A new technique for mediastinum examination. Abstracts of the ICR 89, Paris, July 1-8, 1989, p 86

51. Schaefer C, Greene R, Hall D, et al: Mediastinal abnormalities: Detection with storage phosphor digital radiography. Radiology 178:169-173, 1991

52. Sakuma H, Takeda K, Hirano T, et al: Plain chest radiograph with computed radiography: Improved sensitivity for the detection of coronary artery calcification. AJR 151:27-30, 1988

53. Ranganath S: Image enhancement and restoration using multiresolution representations. SPIE 1092:436-447, 1989