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Computed radiography: a higher dose?

Introduction

Computed radiography (CR) acquires ordinary radiographic projections in digital form. CR is based on photostimulable phosphorescence (PSP). Radiation produces a latent image that is "developed" by scanning with a light source. The scanning light source releases energy that accurately portrays the spatial distribution of radiation on the detector. The released energy is collected and converted into a digital image file. CR is distinguished from direct radiography (DR), which can be described as any imaging system that produces a digital radiographic image without a latent image and includes systems that depend on fluorescent intensification screens.

There are now three major manufacturers and a fourth minor manufacturer of CR systems. While models and manufacturers differ, the physical properties affecting dose are shared by all. Two advanced CR systems may significantly improve imaging properties; these are discussed later.

CR has three undeniable advantages over conventional screen-film radiography that arise from the digital nature of the image. A CR image can be distributed electronically to any number of physical locations for viewing and storage. The presentation of the image can be modified. The latitude of CR exceeds that of screen-film by more than two decades of exposure. Furthermore, CR media are reusable.

However, CR has inherent limitations in its ability to capture radiographic sharpness; these also arise from the digital nature of the image. The digital image is composed of picture elements (pixels). The dimensions of the pixels determine the smallest features that can be resolved. The sharpness of a conventional screen-film image is limited by the size of the grains of the intensification screen material. Even fast screens have resolutions that exceed the finest CR systems, and "detail" screens are far better. Computed tomography (CT) has taught us that limited spatial resolution can be compensated for by superior contrast resolution. However, contrast in CR is limited to 10 or 12 bits of resolution. The smaller the pixel size, the fewer X-rays contribute to the intensity in the pixel, and the worse the effect of quantum noise. The larger the pixel size, the coarser the matrix and the worse the sharpness. Enough X-rays must reach the detector to produce a diagnostic radiographic image.

Pediatric imaging demands a great deal from CR. The subject contrast is limited, the clinical features are small, and we are especially concerned about the radiation dose.

Radiographic speed of CR

Radiographic speed is formally defined as the inverse of the exposure necessary to produce a density of 1 optical density (OD). The density of a CR image is entirely arbitrary, leading some practitioners to assert that radiographic speed has no meaning for CR [1]. The term "speed class" is a familiar term in radiography. Screen-film speed classes include the old "par speed," calcium tungstate 100-speed "detail" systems, medium-speed systems, 400-speed "fast" rare-earth systems, up to 800-speed ultrafast systems. The higher the speed class, the

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less dose is required to make an acceptable exposure. If CR is to replace screen-film, we need to make some comparisons to our "old standards".

CR has an extremely wide exposure latitude, more than four decades (a factor of 10,000; Fig. 1). An ordinary radiographic projection of human anatomy is easily captured within two decades of exposure, the typical latitude of a screen-film detector. This suggests that radiographic anatomy might be captured in the lowest two decades of the CR detector instead of the middle two decades; this would lead to a tenfold dose reduction. The fallacy in this reasoning is apparent when one estimates the number of photons contributing to a pixel at 0.1 mR versus 0.01 mR (Table 1).

Much of the CR literature recognizes that quantum noise in the low exposure regions of the image limits the speed class of the system. Detective quantum efficiency (DQE) is the imaging property that describes how well the detector makes use of incoming photons in order to produce an image. Hillen et al. (1987) noted that the DQE of an early CR system was inferior to screen-film for all but low spatial frequencies which implies that more radiation would be needed to match the noise characteristic of screen-film radiography [2]. Although improvements in the technology have been made over the years, this is still true [3]. Huda et al. (1996) found that CR needed to be operated at 300-speed class in order to match observer scoring of mottle for a 600-speed class screen-film system; operating at 200-speed class reduces mottle to negligible levels, but at a cost in radiation dose [4].

Our hospital performs general purpose CR examinations at 200 speed and extremity examinations at 100 speed. This is not a tremendous change from our prior screen-film practice. We had been using a 250-speed screen-film system for general purpose examinations because our radiologists valued the better sharpness of the medium-speed system over the lower dose afforded by the 400-speed systems. Coincidentally, the densities produced by our Fuji CR system operated with a test menu in fixed exposure data recognizer (EDR) mode closely simulate the densities produced by a 200-speed screen-film system (Fig. 2).

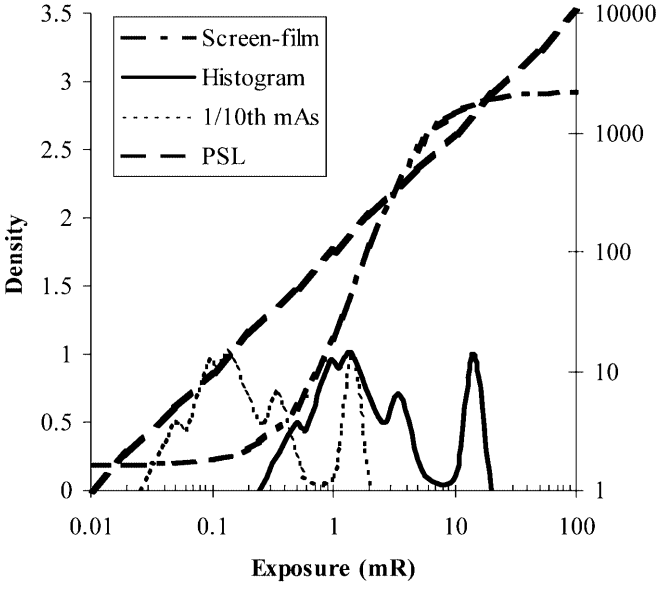

Fig. 1. Detector characteristic function. CR (photostimulated luminescence, *PSL*) has a much greater latitude than screen-film. The histogram of a properly exposed radiographic projection is easily captured by both screen-film and CR. The histogram at one-tenth exposure (1/10 mAs) is captured by CR but not by screen-film

Table 1. Approximate quantum noise for an 18×24 cm cassette (100 μm square pixels)

Exposure (mR)	Photons/pixel	Noise (%)
0.1	133	8.6
0.01	13	27.4

Other technical factors affecting dose

In order to achieve the anticipated radiographic speed, the appropriate quality of X-rays must reach the detec-

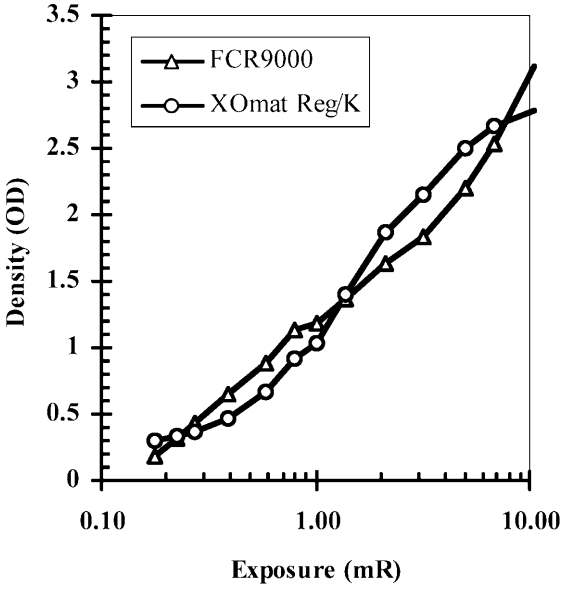

Fig. 2. Similarities in densities between CR and screen-film. Exposures shown are using a Leeds TODR[CR] test object at 75 kVp and 1.5 mm added Cu. STVA imaging plates were scanned in a Fuji FCR 9000 using fixed exposure data recognizer mode and S = 200 with the AVE 2.0 test menu selection. Kodak XOmat regular screens have a similar k-edge and make a 200-speed class system with Kodak XOmat K film

tor. The energy preferred by CR is different from that of many conventional screen-film systems (Table 2). Ignoring this factor has led to many inappropriate comparisons. The energy that reaches the detector is influenced by the kilovolt potential (kVp), filtration, patient thickness, and other factors.

Appropriate technique includes appropriate means of scatter reduction. Scatter degrades contrast and contributes to patient dose. CR may be more sensitive to scatter than conventional screen-film systems [5]. Appropriate collimation reduces both scatter and the irradiated volume of the patient. Use of scatter reduction grids with large patients improves contrast but increases patient dose. Unfortunate choices of grid line rates can result in artifacts. Moiré patterns appear in the CR image when the grid line rate is near the pixel sampling rate and when the line rate is a harmonic of the display pixel rate.

Appropriate technique also includes methods for exposure factor control. The usual method is photo-timing but methods for adjusting photo-timers must be adapted for CR [6]. Manual (non-phototimed) technique is used more frequently in pediatric radiology, but no authoritative technique guides have been established for pediatric CR. Film density is the test of under- and over-exposure in screen-film radiography; however, density in CR is automatically adjusted and is arbitrary.

Thus, what faces practitioners of CR is a detector system that can produce images of superficially similar appearance when operated at widely different radiographic speeds and doses, with no established technique guide and no simple indication of under- or over-exposure.

Table 2. k-edges of conventional screens and CR (after Curry et al, reference 15)

Brand name	Composition	k edge (keV)
Fuji CR	BaF*X*:Eu (*X* = Br and/or I)	37
Agfa CR	BaSrF*X*:Eu (*X* = Br and I)	37
Kodak CR	BaF*X*:Eu (*X* = Br or I)	37
Cronex Par Speed/Hi Plus	$CaWO_4$	70
Lanex Fine/ Medium/Regular	Gd_2O_2S:Tb	50
Quanta V	Gd_2O_2S:Tb + LaOBr:Tm	50 and 39
Quanta III	LaOBr:Tm	39
Xomatic Fine	$BaPbSO_4$	37
Xomatic Regular	$BaSrSO_4$:Eu	37
Quanta Detail	$YTaO_4$:Tm	17
Quanta Fast Detail	$YTaO_4$:Nb	17
GAF Rarex B Midspeed	Y_2O_2S:Tb	17
Curix Blue R4	BaFBr	37

Exposure factor control in CR

"Exposure factor creep" is well known in CR practice [1, 7]. Observers complain about the noise in CR images exposed at 1/4 to 1/2 of an appropriate level. Gross artifacts are not readily apparent in CR images until the exposure level is ten times what is appropriate. Radiologic technologists soon discover that images are less frequently rejected when over-exposed than when under-exposed. This leads to a general increase in the amount of radiation used in CR examination, unless quality processes are in place to enforce exposure factor control.

Exposure factor control in CR must rely on calculated indicators of exposure. Each of the three major manufacturers of CR provides a numerical value that indicates the amount of radiation that reaches the CR imaging plate. Interpretation of these values is complicated by factors such as collimation, calibration of the CR scanner, and examination-specific image processing.

Table 3 is an example of an exposure indicator guide used to conduct quality control on general-purpose CR examinations performed at 200-speed class. The guide could be modified for extremity examinations performed at 100-speed class and for higher speed classes.

Dose in pediatric radiographic examinations

The dose from ordinary radiographic examinations has captured little attention lately because the dose from an individual examination is typically hundreds of times smaller than a CT or fluoroscopic examination of the same anatomy. Even though many more ordinary radiographic examinations are performed than CT or

Table 3. QC evaluation based on exposure index [16]

Sensitivity (S number)	Agfa (lgM)	Kodak (exposure index)	Indication	Action
> 1000	< 1.45	< 1250	Underexposed	Repeat view
601–1000	1.45–1.74	1250–1549	Underexposed	QC exception required
301–600	1.75–2.04	1550–1849	Underexposed	QC approval required
150–300	2.05–2.35	1850–2150	Acceptable range	
75–149	2.36–2.65	2151–2450	Overexposed	QC approval required
50–74	2.66–2.95	2451–2750	Overexposed	QC exception required
< 50	> 2.95	> 2750	Overexposed	Repeat view

fluoroscopic examinations, practitioners tend to think in terms of risk to the individual patient rather than to the population as a whole, and the risk to an individual child from one or a few radiographic examinations is obviously small. This being the case, heroic efforts to reduce dose in ordinary radiography are considered of little practical value.

Some states (notably, Texas) mandate entrance exposure limits for ordinary radiographic projections. The Food and Drug Administration (Center for Devices and Radiological Health) has conducted the "Nationwide Evaluation of X-ray Trends" (NEXT) survey for several years for a small number of projections. There is a new effort by the American Association of Physicists in Medicine to establish "reference levels", that is benchmark exposure levels that should prompt further investigation by medical physicists. The American College of Radiology is formulating a radiographic accreditation program that includes entrance exposure and quality guidelines. All of these programs have two major shortcomings: they address only exposures for normal adult dimensions, and they do not address portable examinations (about half of all radiographic examinations).

There are several reasons for addressing radiation dose in portable examinations. Bedside examinations are performed on the sickest patients in the hospital. Bedside examinations are usually the lowest quality images in the hospital, because of the restrictive conditions and exigent circumstances under which the examinations are performed. The patients often have lengthy stays and repetitive radiographic examinations to monitor progress [8]. The mean birth weight of patients in neonatal intensive care units (NICU) has steadily decreased. The fetuses with worrisome exposure radiation in utero 20 years ago are the patients on which we are performing repeated portable examinations today.

The problem of estimating radiation dose in pediatric examinations is complicated by the wide range in patient size. Although there is no strict relationship between size and age, models and technique guides are virtually always tabulated in terms of chronological age [9, 10]. Study of these models demonstrates the dramatic effect of collimation on organ dose. For an anteroposterior (AP) view of the chest, limitation of the field to exclude the gonads causes the gonad dose to be up to 100 times lower. This effect is less pronounced in older girls and in AP views of the abdomen where excluding the gonads from the field is impractical.

Singleton [8] measured exposures of 8.7 mR to the chest, 6.6 mR to the thyroid, and 0.25 mR to the gonads in portable chest examinations of infants weighing less than 1.5 kg. He showed that 50 to 100 chest examinations might be performed over the several months before the infant is discharged. Poznanski [9] tabulated the gonadal dose (from earlier work by Aspin [10]) for a 6-month-old infant at between 0.038 and 5.9 mrem for males and 0.091 to 7.9 mrem for females for an AP chest view, most of the variation depending on field size. The dimensions of their 6-month-old infants approximate those of the BRH newborn phantom, but at 4 kg are much larger than Singleton's NICU patients [11]. These data were reported before the advent of CR, so we can safely assume they were obtained with conventional screen-film detectors, although they probably do not represent radiation-sparing rare-earth screens.

The BRH newborn phantom tells us that the organ dose in of entrance exposure for the AP chest view is 7 to 14 mrad/R to the testes, 6 to 50 mrad/R for the ovaries, and 857 mrad/R to the thyroid, depending on collimation (assuming a 3.0-mm Al half value layer, HVL). For the AP abdomen, the values are 152 to 1120 mrad/R to the testes, 580 mrad/R to the ovaries, and 5 to 25 mrad/R to the thyroid. Clearly, we should be concerned with dose to the thyroid in bedside chest examinations and to the gonads in bedside abdomen examinations.

For an individual patient who had a long residence in our ICU, we estimated the total radiation dose from ordinary radiographic CR examinations. This boy was 4.5 months old on admission and had dimensions similar to the BRH newborn phantom. Over 9 months, the patient had 200 chest examinations and 33 abdomen examinations. Only one repeated view was recorded. There were also three CT examinations consisting of 56, 43, and 27 slices, three fluoroscopic examinations including 10, 9 and 11 archived digital spot images, and a skeletal survey. Using the exposure indicator reported for each view, the dimensions of the patient, and a model for tissue HVL, we were able to estimate the entrance exposure for each examination. We found an average of 11.9 ± 4.4 mR per AP chest examination and 12.7 ± 3.1 mR per abdomen examination. The total exposure was 2.38 R from chest examinations and 421 mR from abdomen examinations. The organ dose was estimated using fractions derived for the BRH newborn phantom. The dose to the testes was 17 mrad (0.17 mGy) from chest examinations and 64 mrad (0.64 mGy) from abdomen examinations. The dose to the thyroid was 2.0 rad (20 mGy) from chest examinations and 2.1 mrad (0.02 mGy) from abdomen examinations.

Most data on the risks associated with human exposures to radiation are based on one-time whole-body exposures. Exposures such as the ones above were fractionated, allowing repair processes to occur during the interval between examinations. These doses, therefore, should be somewhat less effective than one-time exposure, and risk estimates based on one-time exposures would constitute an upper limit. If we take the risk of lifetime cancer mortality attributable to a single acute exposure per unit dose for a newborn as about 13% per Gray, we would estimate the upper limit of risk for this

patient to be about 0.26%. These examinations seemed to have raised his lifetime risk of cancer by about a quarter of one percent [12]. However, the patient was transferred to us without accompanying radiographs. If he had already been a long-term resident of an ICU elsewhere, his exposure history could easily include 100 additional bedside examinations.

Strategies for radiation management in CR

The principle of ALARA requires us to seek ways to reduce CR doses. We can divide such activities into technical issues and practice issues.

Technical issues involve both the hardware and the operator. The CR device can be operated at any radiographic speed class chosen by the radiologist. Many institutions operate at 400 speed for general purpose examinations rather than the 200 speed that we use; the higher speed class involves less radiation to the patient but results in a noisier image. Another drawback is that when less radiation is used to produce the image, less image processing can be applied to enhance the image.

One way to limit the radiation exposure in CR examinations is to institute and closely monitor exposure indicator guidelines. Had our technologists met our exposure indicator target, the entrance exposure would have been 8.1 mR for both AP chest and AP abdomen examinations, for a dose reduction of 1/3. For this method to be successful, all CR units must be calibrated in a standard manner. Another way to limit exposure is to use a technique guide optimized for CR rather than for a particular screen-film system. This implies that technologists will actually measure patient thickness and source-to-image distance (SID) and will adjust technique factors accordingly. Yet another method, appropriate for both conventional and CR systems, is the use of additional filtration. Additional Al filtration of 2 to 3 mm can significantly reduce the entrance exposure without any noticeable effects on image quality [13]. Where photo-timers are used, adjusting the photo-timers specifically for CR can standardize doses from CR examinations.

Two advanced CR systems have unique ways of increasing the DQE and reducing patient exposure. The first uses a special transparent-based imaging plate and collects stimulated luminescence signal from both sides of the plate. The second uses a special ''needle crystal'' imaging plate that dramatically decreases blurring of the luminescence signal and also allows much greater coating weights than standard imaging plates [14].

Changes in practice can have the most dramatic impact on radiation dose but are the most difficult to implement. For example, how many of the 233 radiographic examinations were really important to the care of the child described above? If only 100 were relevant to the care of the patient, the dose could have been reduced by 50%. The notion that every patient in the ICU needs a chest examination every morning negates the ALARA principle. The dialog between radiologist and referring physician that could reduce unindicated examinations seems impractical when one considers the number of examinations in a modern hospital. Unlike CT and fluoroscopic examinations, ordinary radiographic examinations are usually performed before the radiologist is aware they have been scheduled. An ''examination request'' is effectively an ''examination order''.

Conclusions

Present CR systems can produce images at any arbitrary speed class. However, operating at greater than 200-speed class increases quantum mottle. CR is more tolerant of under- and over-exposure than screen-film systems, and a lack of vigilance can result in unnecessarily high radiation doses. Vigilance involves interpretation of numerical exposure indicators whose precise meaning is subject to technical factors. Technique guides for screen-film systems are probably not optimized for CR, and this leads to higher doses than necessary. The problem of excess dose is most acute in portable examinations, where long ICU stays can result in hundreds of examinations for a single patient. Described here are radiation management activities that can maintain doses at acceptable levels.

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