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Strategies for Film Replacement in Radiography
- Films and Digital Detectors in Comparison -

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Abstract

The NDT community has discussed about effective film replacement by Computed Radiography (CR) and the new Digital Detector Arrays (DDA), also known as flat panel detectors, since more than 10 years. Several standards were published by CEN, ASTM and ASME to support the application of phosphor imaging plates in lieu of X-ray film in the year 2005. One of the key concepts is the usage of signal/noise (SNR) measurements as equivalent to the optical density of film and film system class. The radiographic practice with DDAs is not yet described by any standard, but proposals are under discussion. The first qualification standard for DDAs, ASTM E 2597-07, has been published recently. The bad pixel problem has been addressed. Measurement methods were elaborated and tested at BAM for determination of parameters as basic spatial resolution, efficiency, specific material thickness range, contrast sensitivity and image lag. These procedures were used for this study.

The achieved image quality is discussed for film replacement by CR and DDAs in weld inspection. New strategies for correct DDA calibration yield an extra ordinary increase of image quality. The contrast sensitivity was enhanced up to 10 times in relation to film radiography. This could not yet be achieved by any other technology. Even restrictions in the spatial resolution, provoked by the individual picture element (pixel) size of the detector, are compensated by the increased contrast sensitivity.

Keywords: radiography, film replacement, computed radiography, imaging plates, digital detector arrays, contrast sensitivity, SNR, standards

1 Introduction

For more than 100 years industrial radiology has been based on X-ray film. Special film systems have been developed for NDT applications, which have better image quality than medical film systems but lower speed. High spatial resolution is obtained by combination of these films with lead screens instead of fluorescent screens.

Computed Radiography (CR) and **D**igital **D**etectors **A**rray (DDA) systems were developed for medical applications, which have the potential to replace the X-ray film and revolutionize the radiological technique. These detectors enable new computer based applications with new intelligent computer based evaluation methods. These technological and algorithmic developments are also applicable to new NDT procedures.

The European project consortium “FilmFree” supports the introduction of the new technologies as CR and DDA based radiography.

2 Exposure conditions and the equivalent value for the optical density and film system class

One of the basic tasks of a radiographer is the calculation of the exposure time. This depends for film radiography on:

- X-ray voltage or gamma source
- source detector distance
- material and its thickness
- detector sensitivity (e.g. film system class)
- required optical density of film.

The exposure parameter is usually calculated as the product mA·s for X-ray tubes or GBq·s (also: Ci·s) for gamma sources for a given distance between detector and source. It permits the correct exposure of a film for a given optical density and film system. Since the used radiation sources and objects are the same, if film is replaced by other detectors, the different detector properties must be considered now.

The radiographer has to determine the correct exposure conditions for the exposure assuring the required image quality. The image quality after exposure is world wide proven by the correct reading of image quality indicators (IQI). These are typically wires (EN 462-1, ISO 19232-2 and ASTM E 747), step hole indicators (EN 462-2 and ISO 19232; only 1T hole!) or plate hole indicators (e.g. ASTM E 1025). It is expected that the minimum required IQI visibility is obtained. Again, the task is to determine the correct mA·s or GBq·s (Ci·s) for exposure.

In analogy to film, an equivalence value for the optical density and the required film system (film type and development conditions, film speed) has to be determined. The equivalence value is based on selection of the correct signal-to-noise ratio (SNR) which has to be obtained. This value is equivalent to the SNR measured of an exposed and developed film at a given density. IQI requirements, source, object and geometry are the same if low unsharpness is not a problem.

The optical density D is defined for films only. Digital images of CR-systems and DDA systems cannot be described by the optical density.

The contrast-to-noise ratio CNR, which is the essential parameter for the visibility of flaws and IQIs, can be calculated from the detector response (SNR) as a function of dose as follows (small flaws only, fig. 1):

$$CNR/\Delta w = SNR \cdot \mu_{eff} \qquad (1)$$

Therefore, the image quality depends on the μ_{eff} and the detector response SNR. This applies for CR, DDAs and X-ray film. The typical term for films is instead of SNR the gradient-to-noise ratio (GNR). For NDT film systems it can be approximated:

$$GNR \approx 2.3 \cdot SNR \qquad (2)$$

Since the grey values of the pixels in the digital images (if signal is linear to dose) depend on noise and signal intensity independently on the contrast and brightness processing for image viewing, the SNR has been proposed and accepted (EN 14784-1,-2 and ASTM E 2445, E2446) as an equivalence value to the optical density and a certain film system.

3 Essential Image Quality Parameters

The basic relationships between the image quality parameters of film and any radiographic image detector are shown in fig. 1. A radiographic image is described by the following major image quality parameters:

1. **Image unsharpness** consisting of the geometric unsharpness divided by the magnification (projected unsharpness) and the detector unsharpness described by the basic spatial resolution SR_b (half value of detector unsharpness or effective pixel size).
2. **Contrast-to-noise ratio** or contrast sensitivity (smallest detectable difference of material thickness) which is the inverse CNR for linear indications. The specific CNR depends on the detector SNR and the effective material attenuation coefficient. The detector is characterized by the normalized signal-to-noise ratio SNR_{Norm} as function of exposure conditions (exposed dosage and radiation quality).

Considering practical aspects of radiographic applications an additional parameter is the **Material thickness range** (image dynamic based on the extent of material thicknesses evaluable in the same image). Since this value is fixed for films (limited by density range of 2 – 4.5 and μ_{eff}) it is usually not considered for film radiography in text books and standards. Since modern DDAs can be used even for replacement of double film technique this parameter has been added here.

Fig. 1 shows the different parameters, which determine the image quality as function of object, detector and source properties for film and digital detectors. The normalization of the measured SNR by the basic spatial resolution SR_b (see below for details) of the image detector is essential, because the measured SNR at equal dosage increases with the square root of the area of the detector pixel element (result of Poisson statistics for the X-ray photons).

The perception of fine flaws depends on the detector unsharpness, the geometrical unsharpness and the SNR or CNR respectively. If magnification technique is applied, the image unsharpness is the combined effect of geometrical unsharpness and detector unsharpness divided by the magnification.

The basic spatial resolution SR_b corresponds to the effective pixel size (square root of pixel area). SR_b can be measured at different kind and manner**.** In standard committees it was recommended to use the duplex wire method due to its simplicity (EN 462-5, ISO 19232-5 and ASTM E 2002). The measurement with the duplex wire IQI provides a total unsharpness value (u_T) in µm which is equivalent to the spatial resolution. The basic spatial resolution SR_b is calculated by:

$$SR_b = u_T / 2 \tag{3}$$

Details can be found in[1-6] and in the therein cited standards.

SR_b corresponds usually to the pixel size (pixel limited unsharpness) of direct converting systems (e.g. α-Se DDA or CdTe- DDA). It is greater than the pixel size for CR and DDA's with fluorescent converter screens. The basic spatial resolution is essential part of EN 14784 and ASTM E 2445, E2446.

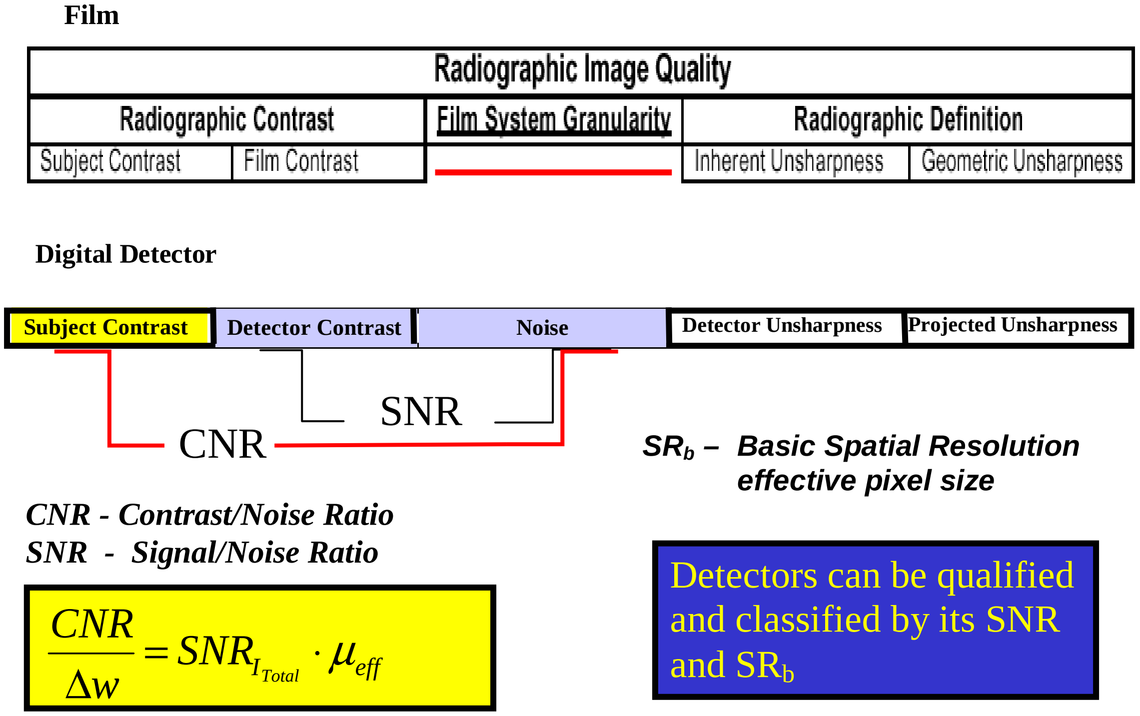


Fig. 1: Relationships between image quality parameters of film (see ASTM E 94) and radiographic image detectors [7, 8].

4 Image Quality of Computed Radiography

The image quality of CR systems is classified in accordance with the NDT film system classes. The limiting SNR_{Norm} values correspond to the limits of the similar film system class. Additionally to film classification, the basic spatial resolution of the CR system has to be provided (SR_b value in micrometer). This considers the limited spatial resolution of CR systems in comparison to films.

The major development for applications of CR in NDT film replacement was the introduction of the High Definition CR. HD-CR paves the way for film replacement in weld and fine casting inspection.

The requirements on CR systems for industrial radiography are defined in EN 14784-1 and EN 14784-2. Table 4 of 14784-2 defines the minimum spatial resolution in dependence of testing class, radiation energy and wall thickness of the object under investigation. Whereas most of the contents of EN 14784-2 is similar to EN 444 and ISO 5579 (general principles for radiographic testing with NDT film), Table 4 in EN 14784-2 is new and limits the basic spatial resolution of the used CR system.

But there exist another limiting effect in the image quality for CR systems, which is shown in fig. 2. With increasing exposure dosage the maximum achievable SNR_{Norm} value is limited. This is caused by structure noise of the used imaging plate. Scanner effects may cause additional noise as e.g. line ripple. The structure noise of the IP is a side effect of production inhomogeneities of the phosphor layer. This effect is also known from fluorescent screens. At high exposure dosage the contribution of quantum noise of the X-rays is low compared to these image structures, and as result the image quality is finally limited.

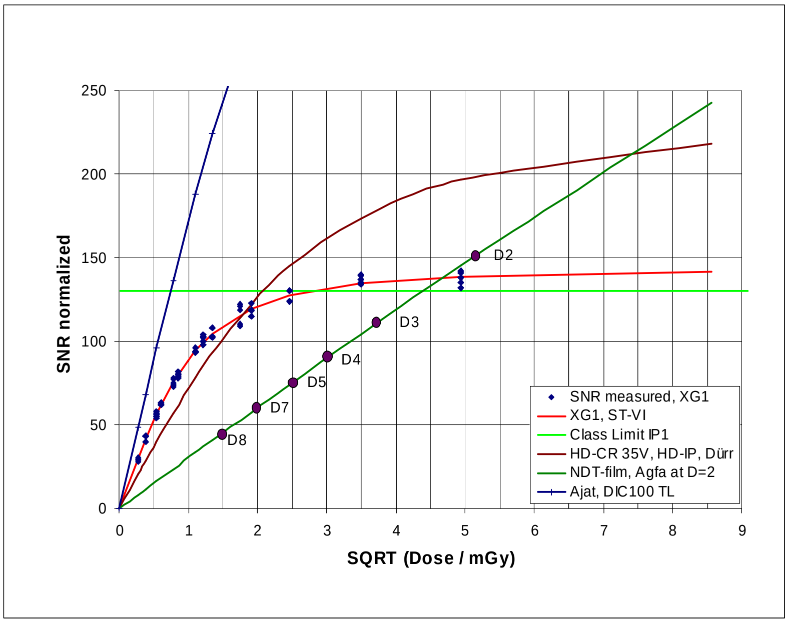


Fig. 2: Example of saturation of SNR_{Norm} by IP structure noise with the Fujifilm scanner XG-1 and ST-VI imaging plates and HD-CR 35V and HD-IP of Dürr. The maximum achievable SNR_{Norm} (saturation) value for XG-1/ST VI is 142 and 232 for HD-CR 35V/HD-IP. X-ray films from all major suppliers are at the same line as Agfa film systems. The slope of the curves is a measure for the detector efficiency. The DDA DIC 100 TL of Ajat, based on CdTe semiconductor has the highest efficiency of the compared detectors.

An example for achievable image quality at weld inspection is given in fig. 3. The exposure times are high enough, that the image noise is determined by the structure noise of these CR systems. Clearly it shows, that a standard CR system has a poorer image quality (both in SR_b and SNR_{Norm} values) compared with the best NDT film system, whereas the HD-CR system can reach a slightly higher SNR_{Norm} value compared with film, but with 8 times longer exposure time than film.

5 Comparison with Image Quality of Digital Detector Arrays (DDA)

The DDA images have been acquired using an XRD 1620 detector of the company Perkin Elmer, controlled by the software “Image.3500” of the company YXLON (see fig. 4, 5). Two different acquisition set-ups have been used:

1. the weldment directly in front of the detector (magnification ≈ 1) and
2. the weldment in between detector and X-ray tube (magnification $= 3.5$).

The last set-up requires a mini focus X-ray tube to keep the geometrical unsharpness of this set-up below 200 µm at the detector.

Small flaw indications can be visualized clearly by usage of the high pass filtering and a numerically magnified image presentation (see fig. 4, 5).

The significantly increased SNR_{Norm} of the DDA technology (measured in the base material) allows even at magnification of 1 and a basic spatial resolution of 200µm to detect crack indications, which are hidden by noise in the film image with its much better SR_b of 40µm (see fig. 5). At a magnification of 3.5 (fig. 5, right image, projected $SR_b = 70$µm) much more details can be resolved with the DDA as compared to film. This increase of image quality based on SNR_{Norm} with DDAs exceeds significantly the image quality of film radiography.

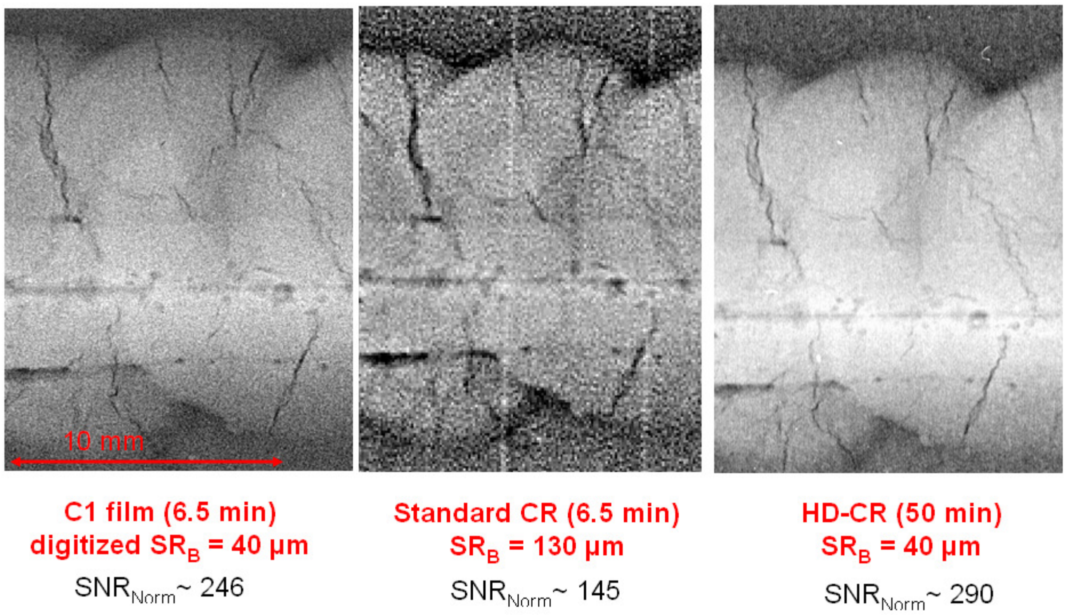


Fig .3: Comparison of a section of the BAM 5 test weld obtained with the best NDT film system class C1 (left), a standard CR system (middle) and a HD-CR system (right).

6 Enhancement of Image Quality with Usage of DDA Systems

As shown in fig. 2, the maximum achievable SNR_{Norm} of the slowest NDT films available is limited basically by the restricted working range of the viewing stations to a maximum optical density of D ≈ 4.7. This limits the maximum applicable exposure dosage too. Higher SNR_{Norm} values (higher than 250) will require higher exposure doses. But films cannot be read above D > 5. In the case of CR systems, the image quality is limited by their structure noise (see fig. 2). The maximum SNR_{Norm} measured on a HD-CR system was below 300 up to now.

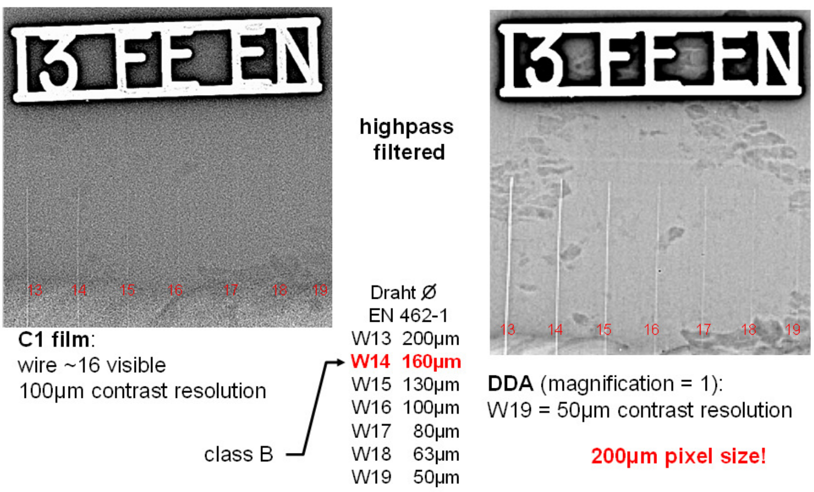


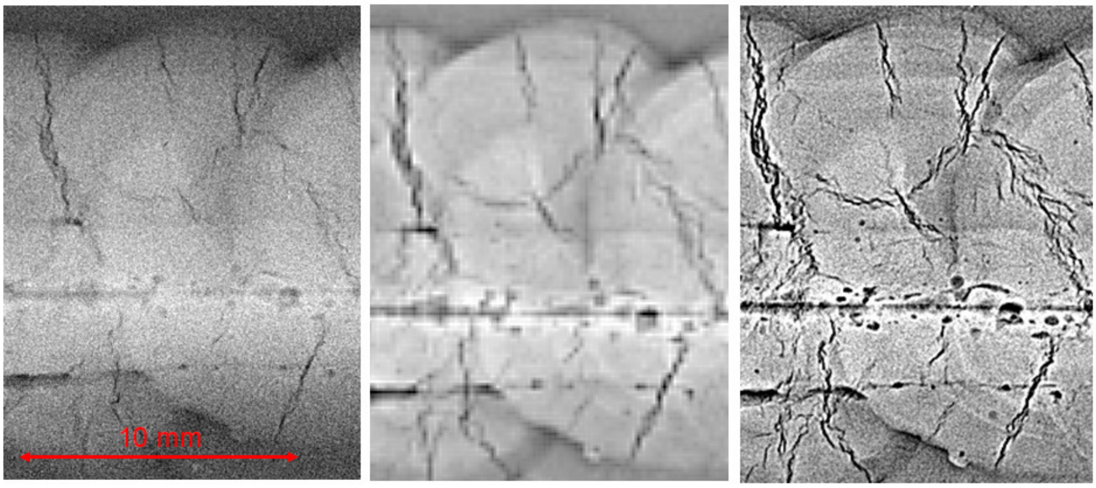
Fig. 4: Comparison of visibility of wire type IQIs according to EN 462-1 for film (left) and DDA (right) at 8mm wall thickness (images high pass filtered for better visualization). The improved SNR of the DDA allows to detect the wire W19 (50 µm diameter) at a pixel size of 200µm!

These SNR limitations with films and CR systems can be overcome with DDAs in the following way: just before saturation of the DDA an image can be read-out, the DDA is reseted and a new exposure cycle can be started. All images of such a cycle can be averaged in the computer generating an integrated image. So, the exposure time can be increased without any limit.

The SNR_{Norm} value will increase with the square root of the number of averaged read-out images and/or the dose. The exposure time of such a cycle can be extended without any technical limit. Fig. 2 shows the linear increase of SNR_{Norm} with the square root of the dosage (equivalent to the exposure time or number of integrated images).

DDAs have an essential advantage compared with film or CR:
The pixels of a DDA are arranged in a matrix and fixed during the complete exposure and read-out process. In this way small variances between each pixel (e.g. in sensitivity or offset deviations in the read-out channels) are tolerable and can be measured exactly. Because they are typically stable over time, a compensation of the deviations between the different pixels can be obtained by suitable software. This procedure is called detector calibration.

This DDA calibration is the key to an improved contrast sensitivity (high contrast sensitivity mode) and high SNR because of the reduction of the structural noise of the DDA. Compared to a "standard calibration" with single offset and gain images an adapted multi gain correction can produce a much higher SNR compensating the variations of the individual detector pixels. In this way the SNR limitations for film and CR can be overcome by a good calibrated DDA system.



C1 film (6.5 min) | DDA (1 min) magnification = 1 | DDA (6 min) magnification = 3.5

SNR_{norm}~ 246 | SNR_{norm}~ 700 | SNR_{norm}~ 780

Fig. 5: Comparison of image quality with NDT film class C1 (left column) and DDA (middle column – no magnification, pixel size 200 µm) and DDA with magnification of 3.5 (right column).

7 Conclusions[8]

New digital systems adapted to NDT requirements are suitable for NDT film replacement. The properties of NDT film systems are described in different standards. The basic parameters for digitised films and digital radiological detectors are the normalized SNR_{Norm} and the basic spatial resolution SR_B. SNR_{Norm} limits for classification can be found in several standards.

NDT film systems are limited in the achievable image quality caused by the available film systems at the market and the upper optical density (about D = 5) which can be read with film viewers. This limits finally the maximum dose for an exposure. Computed Radiography can be used for film replacement. The maximum achievable SNR_{Norm} is basically limited by the structure noise of the used imaging plates.

An essential improvement in image quality of DDA systems compared to film and CR systems was achieved with an optimal detector calibration procedure (multi-gain). DDAs allow to exceed the contrast sensitivity and SNR_{Norm} of film systems by the factor of 10 or even more. The very high SNR gives a superior contrast sensitivity (especially using magnification technique). Depending on the exposure conditions and a proper calibration, DDA systems achieve a contrast sensitivity of about 1/1000th of the wall thickness. High contrast sensitivity can compensate an insufficient SR_B.

DDAs are mostly suitable for in-house inspections, because they need stabile temperature and moisture conditions as well as careful handling. They are an excellent tool for serial part inspection, for laboratory inspections and also for Computed Tomography. Due to their high image quality, dynamic range and speed they dominate stationary applications and speed up film replacement.

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