



Visibility of Image Quality Indicators (IQI) by Human Observers in Digital Radiography in Dependence on Measured MTFs and Noise Power Spectra

Uwe Ewert¹, Uwe Zscherpel¹, Justus Vogel¹, Fangzhou Zhang², N.X. Long³, T.P. Nguyen³

¹ Bundesanstalt für Materialforschung und –prüfung (BAM), Berlin, Germany, uwe.ewert@bam.de

² Dresden International University, Germany

³ VINATOM, Hanoi, Vietnam

Abstract

Digital radiographic images were analysed to predict the visibility of image quality indicators (IQI), based on normalized noise power spectra (NNPP) and modulation transfer function (MTF) measurements. The fixed pattern noise of some digital detectors result in different noise spectra, which influence the visibility of different IQIs, depending on the hole diameter. Studies, based on measurement of basic spatial resolution and contrast to noise ratio were performed together with presampled MTF measurements and the NNPS in dependence on the spatial frequency. Plate hole IQIs, step hole IQIs, and equivalent penetrameter sensitivity (EPS) IQIs based on ASTM E 746 were measured to verify the influence of the different parameters. Modelling of digital images was used to verify the applied numeric tools. A study has been performed for imaging plates and digital detector arrays to analyse differences. Formulas for the prediction of the visibility functions for hole type IQIs are derived. In consequence the standards for characterization and classification of computed radiography (ASTM E 2446) and radiography with DDAs (ASTM E 2597) need to be revised.

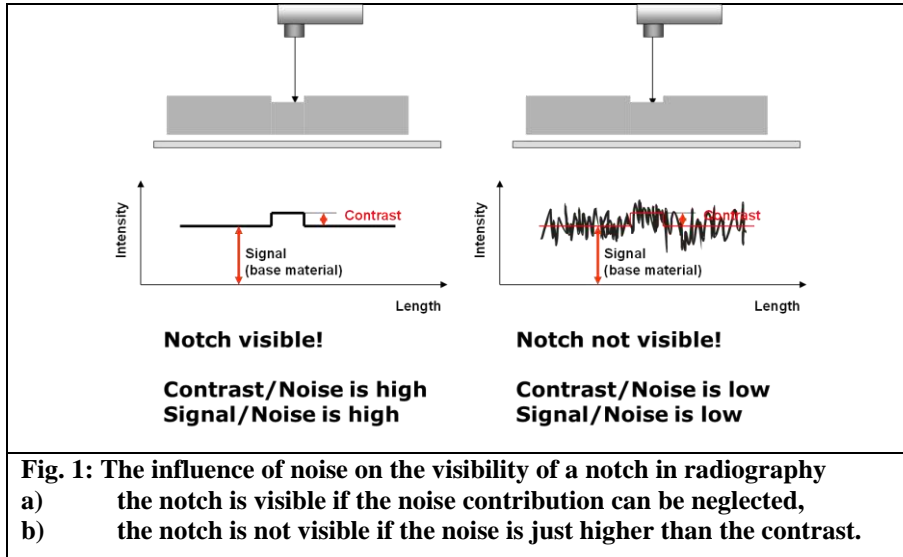
1. Introduction

The visibility of flaws and image quality indicators (IQI) by human operators has been discussed for film radiography (RT-F) over decades. Wire type image quality indicators (IQIs) have been used in Germany for evaluation of the radiographic image quality since 1935 (DIN 1915:1935) and later in most European countries. In the USA and France traditionally hole type IQIs (ASTM E 1025 since 1984 or E 1742 since 1992 or its predecessor MIL STD-543 since 1962) are used. With introduction of digital radiography and the globalization of the NDT market the formulas for prediction of the visibility of wire and hole type IQIs for human observers were discussed and investigated again. Current standard requirements on visibility requirements of image quality indicators (IQI) are given in ISO 19232-3, ISO 17636-1 and -2, French RCCM code, ASTM E 747 and ASME BPVC Section V Article 2, Table T-276. Furthermore, the concept of detective quantum efficiency [1, 2], based on NNPS and MTF, was used in radiography to determine efficiency and sensitivity of digital detectors. This concept will be applied in a modified way to predict the visibility of IQIs by human observers.



2. Current status of the prediction of IQI visibility

The quality of images, taken with digital detector arrays (DDA) or imaging plates (IP) by computed radiography (CR), is mainly limited by the ratio of contrast to noise (CNR). Missed indications may be hidden in the image noise as shown in Figure 1.



A minimum CNR (CNR_{min}) is required in ASTM E 2698 [3] for verification of the visibility of holes in hole type IQIs. The concept is based on a certain ratio of basic spatial resolution (SR_b^{image}) to hole diameter to consider the differences of hole diameter dependent visibility by human observers. The basic concept was introduced 1948 by Rose [4-6] for evaluation of TV cameras. The human eye can be considered as a camera with 10° field of view, 300 mm viewing distance and 25 mm focal length. Rose showed, that the human operator percepts larger indications at lower CNR and smaller ones at higher CNR values. The detail perception for such photon number limited camera of human observers is constant and can be described by:

$$PT_{const} = \frac{\sqrt{A_{lateral}} \cdot C_{depth}}{SR_b^{image} \cdot \sigma} \quad (1)$$

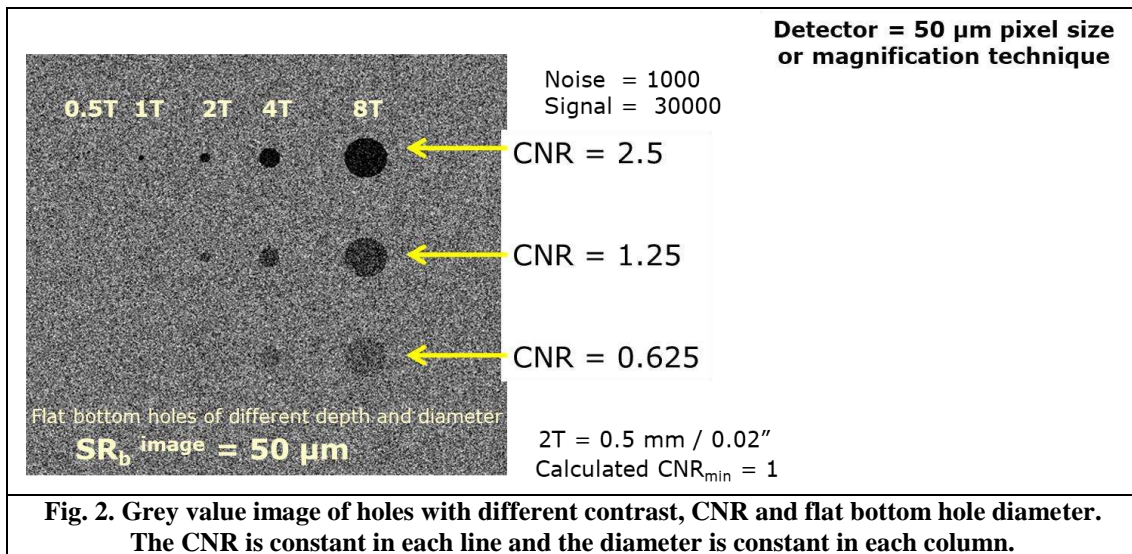
where:

- PT - detail perception threshold for human observer
- $A_{lateral}$ - area of just visible indication
- C_{depth} - mean contrast of just visible indication
- σ - noise of image
- SR_b^{image} - basic spatial image resolution (effective pixel size)

Figure 2 provides an example of the flaw area dependent visibility of holes of different diameters [7]. Holes with a diameter d_{hole} are clearly visible if the following CNR_{min} is achieved:

$$CNR_{min} = \frac{10 \cdot SR_b^{image}}{d_{hole}} \quad (2)$$

That means a CNR_{min} of 2.5 [3] is required for the hole visibility, if the ratio of $SR_b^{image}/hole\ diameter$ is 4, meaning that about 3×3 effective image pixels need to be in the hole. This requirement can be found in the MAI guideline, clause 7.2.1 [8].



Tests of the visibility of holes in relation to eq. 2 showed that the precision of the PT value scatters by about 20%. This may depend on the observation conditions but it may also depend on the influence of the structural noise of detectors. The equation (2) applies typically for IQIs with hole diameters < 10 mm.

3. Extended model for the visibility of IQIs by human observers on the basis of spatial frequency analysis

Recently an analysis of the visibility of hole type IQIs with groups of holes was carried out with EPS plates (EPS - equivalent penetrameter sensitivity) based on ASTM E 746 [9]. An anomaly was found in the evaluation of a special high resolution IP (blue colour). The EPS value of the just visible hole group was about 40 % worse than predicted. A spectral noise analysis was used to find the reason.

An analysis of measured digital images was performed to obtain SNR, CNR and noise functions in dependence on the spatial frequency f_s . A high resolution and a standard IP and a calibrated DDA were investigated. A public ImageJ software tool was used for the image analysis to determine the presampled modulation transfer function (MTF) and the normalized noise power spectrum (NNPS). The ImageJ tool "DQE panel v7" [10], which is based on IEC62220-1 [11], was tested for simulated data and applied for the analysis. More details on the measurement procedure can be found in [12]. Figure 3 shows the digital images which were evaluated with the DQE panel V7 and Figure 4 shows the images of the EPS hole plates and a duplex wire IQI.

The SNR and CNR for small thickness changes, Δw , is calculated from the measured data by

$$\text{SNR}(fs) = \frac{pp}{\sqrt{NNPS}} \quad (3)$$

$$\text{CNR}(fs) = \Delta w \cdot \mu_{\text{eff}}(fs = 0) \cdot \text{MTF}(fs) \cdot \text{SNR}(fs) \quad (4)$$

where

- pp – pixel pitch
- fs – spatial frequency
- μ_{eff} – effective attenuation coefficient, measured as relative contrast of a 1 mm step on the 19 mm plate.

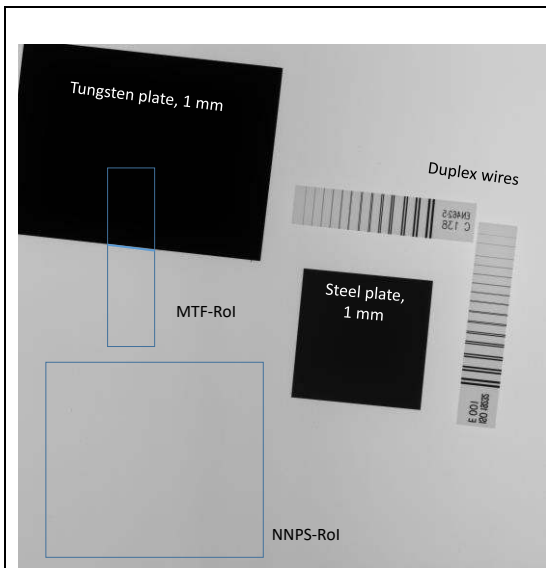


Fig. 3. Example of an exposure with a steel and a tungsten plate for contrast measurement (μ_{eff}), presampled MTF and NNPS measurements in manually selected regions of interest (RoI).

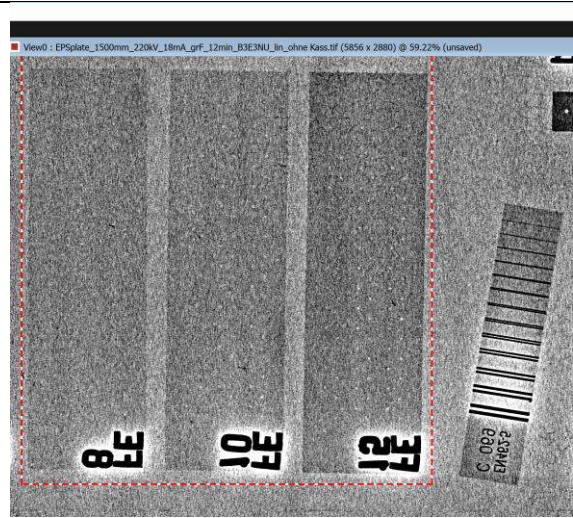


Fig. 4. Example exposure of 3 EPS plates and a duplex wire IQI on a 19 mm steel plate for visual evaluation of EPS in accordance to ASTM E 746 and determination of $\text{SR}_b^{\text{detector}}$ in accordance to ASTM E 2002. The image is high pass filtered for better illustration.

A visibility function $V(fs)$ is obtained considering the Rose concept, that human observer's sensitivity depends on the product of CNR and relative hole diameter ($d_{\text{hole}}/(\text{SR}_b^{\text{image}})$) for hole indications. The final equation for small hole indications ($d_{\text{hole}} < 10 \text{ mm}$) was derived as follows:

$$V(fs) = \frac{d_{\text{hole}}}{\text{SR}_b^{\text{image}}} \cdot \frac{\text{CNR}(fs, \Delta w)}{2 fs} \quad (5)$$

4. Results

Figure 5 shows that the high resolution IP (IPU) has a lower CNR in the range of the lower spatial frequencies, which are used for the EPS IQI test, marked in magenta. The standard IP (IPS) shows better CNR for the EPS holes in the range of 0,6 to 1 lp/mm than

the high resolution IP. The high resolution IP provides higher CNR for very small indications above 4,1 lp/mm.

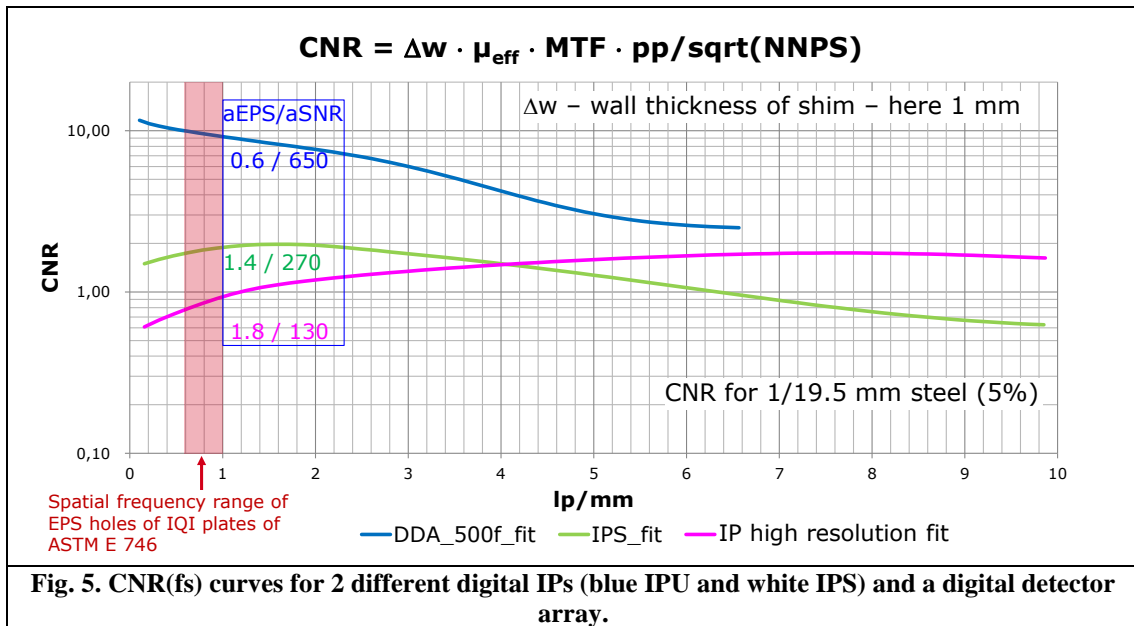
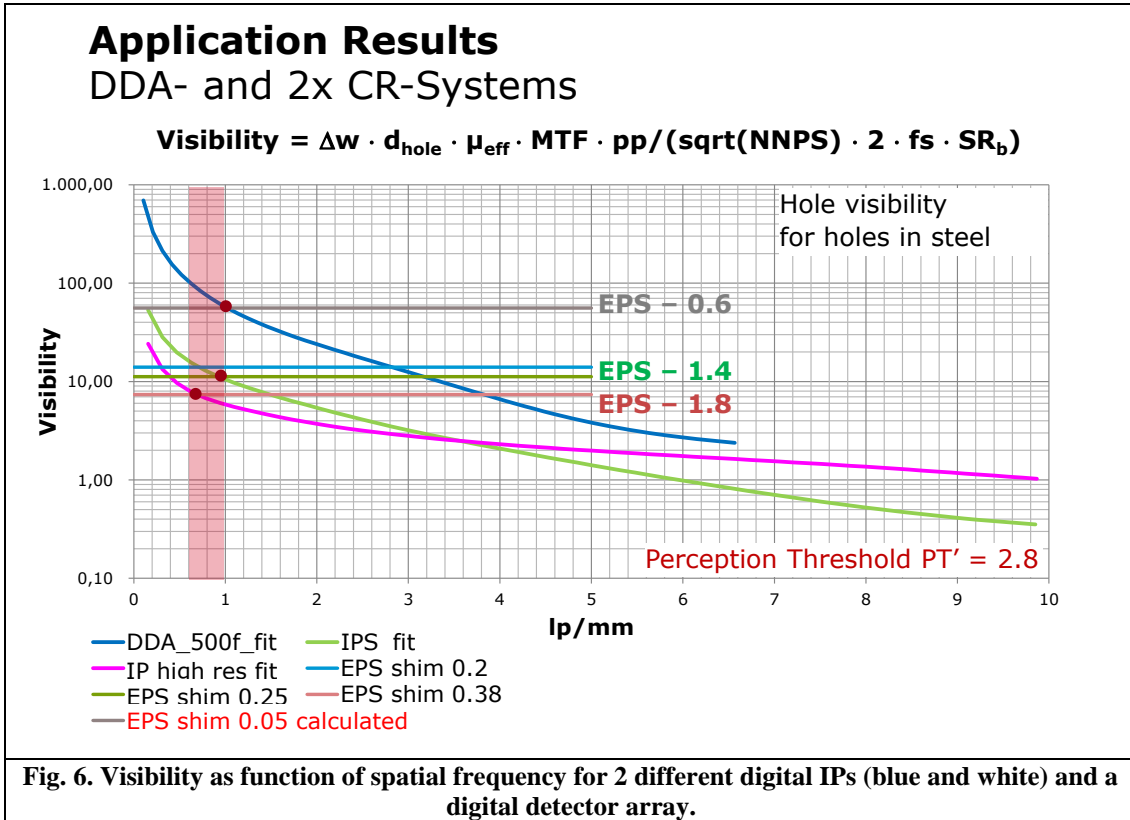


Figure 6 shows the visibility functions in dependence on the spatial frequency. The standard IP (IPS) provides even better visibility for indications up to 3,5 lp/mm. The visibility of the holes is limited by the structural noise at high exposure times. Therefore, both IPs were exposed at 220kV and higher mAmin to obtain grey values > 50% of the detector saturation value. This is based on the measurement procedure of "achievable EPS" (aEPS) as described in ASTM E 2446 [13].



The achievable EPS and CNR of the DDA depend basically on the calibration procedure (see also ASTM E 2597, [14]). Typically the calibration of the pixel response and the bad pixel interpolation provides better aEPS values for DDAs than measured for IPs.

The visibility curves as shown in Figure 6 agree with the determined aEPS values by human observers for the hole type IQIs by ASTM E 476. The values, determined by human operators are marked by dots in the graph. Five human operators evaluated the EPS radiographs, two of them with RT level 3 and special RT-digital level II certification, one NDT master student and two guest scientists after internal training with image viewing at monitors. The values were averaged and had a precision of $\pm 5\%$ (± 1 array number in reference to ASTM E 746-14, Fig. 3).

5. Conclusions

The visibility of image quality indicators (IQI) depends mainly on contrast, unsharpness and noise in digital images. Rose introduced 1948 that the visibility of hole indications in camera images depends mainly on the hole diameter (d_{hole}) and the contrast to noise ratio (CNR). The indications are visible for human observers, if $d_{\text{hole}} \cdot \text{CNR} > \text{PT}$, with PT as perception threshold for human eyes. Additionally to the parameters SNR_N and $i\text{SR}_b^{\text{detector}}$, the achievable equivalent penetrameter sensitivity (aEPS) was introduced as classifier for determination of the performance levels of CR systems in ASTM E 2446-16 [13]. Recent investigations have shown that the PT value changes in dependence on the noise spectrum for some IPs. The Rose model was extended by measurement of the presampled modulation transfer functions (MTF) and normalized noise power spectra

(NNPS). SNR, CNR and visibility curves were derived as function of spatial frequency. The results for the used (blue) high resolution IP show that the measured visibility and CNR at lower frequencies below about 4 lp/mm in comparison to a standard (white) IP is significantly lower. The visibility curves reflect the determined aEPS values by human observers.

Acknowledgements

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