Essential Parameters for the Visibility of IQIs and Small Indications in Digital Radiography

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Abstract

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 conversion formulas for wire to hole type IQI visibility were discussed and investigated again. Basically the current standard requirements of the standards ISO 19232-3, French RCCM code, ASTM E 747 and ASME BPVC Section V Article 2, Table T-276 are compared. Significant differences, especially at high energy radiography, were found in the different standards. The fixed pattern noise of some digital detectors result in different noise spectra, which influences the visibility of different IQIs and the conversion formulas for wire IQIs to hole type IQIs. Studies based on measurement of basic spatial resolution, and contrast to noise ratio were performed together with modulation transfer function measurements considering the noise spectra in dependence on the spatial frequency. Wire IQIs, plate hole IQIs, step hole IQIs and EPS IQIs based on ASTM E 746 were numerically modelled and measured to verify the influence of the different parameters. The study has been performed with film, imaging plates and digital detector arrays to analyze differences. Formulas for the conversion of perception thresholds for wire IQIs and hole type IQIs are derived. In consequence the standards for characterization and classification of computed radiography (ASTM E 2446, ISO 16371) and radiography with DDAs (ASTM E 2597) need to be revised.

Key words: Image quality, Radiography, Radioscopy, Radiology, Imaging Plates, Computed Radiography, Digital Detector Arrays, MTF, CNR, basic spatial resolution.

Sicherheit in Technik und Chemie

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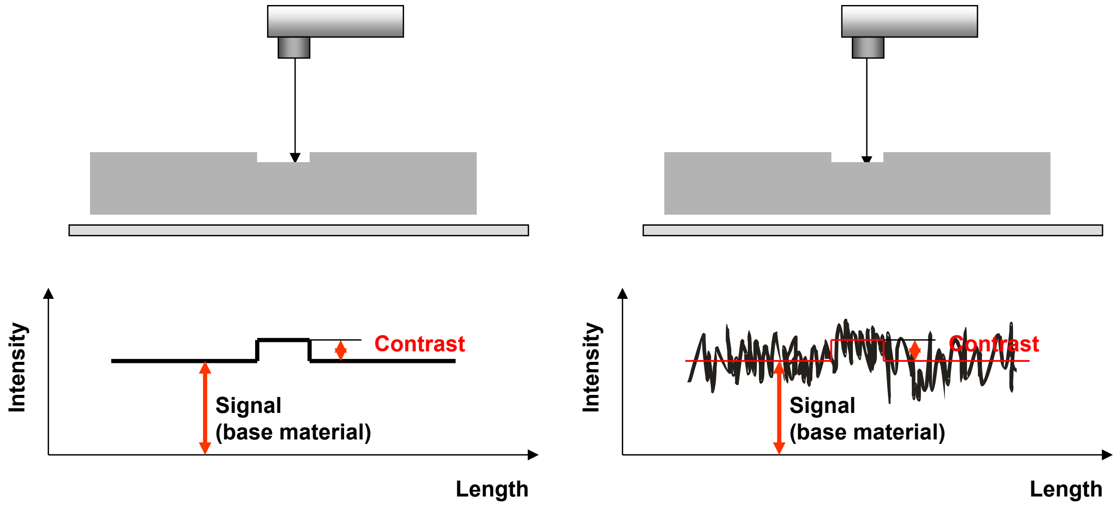
Outline

- Image quality in Radiography
- Observer model based on rose concept
- **Essential system parameters for hole visibility**
  - Basic spatial resolution (SR_b^{image}),
  - SNR and SNR_N,
  - Relative specific contrast and effective attenuation coefficient.
- Characterization standards for CR-systems and DDA systems.
- Equivalent penetrameter sensitivity (EPS) and probability of detection (POD)
- Wire visibility vs. hole visibility (ISO 19232-3, ISO 17636-2 vs. ASME BPVC Sect. V article 2 , E 747-10)
- Extended observer model based on presampled Modulation Transfer Functions and Normalized Noise Power spectra

Influence of Image Noise on Detail Visibility



Notch visible!

Contrast / Noise is high
Signal / Noise is high

Notch not visible!

Contrast / Noise is low
Signal / Noise is low

Noise Sources in Radiographic Images

Typical noise sources in digital radiography:

1. **EXPOSURE CONDITIONS:** Photon noise, depending on exposure dose (e.g. mA·s or GBq·min). *This is the main factor!* SNR increases with higher exposure dose.
2. *Limitation for the maximum achievable SNR:*
   1. **DETECTOR:** Structural noise of DDAs and Imaging Plates also called fixed pattern noise (due to variations in pixel to pixel response and inhomogeneities in the phosphor layer).
   2. **OBJECT:**
      1. Crystalline structure of material (e.g. nickel based steel, mottling)
      2. Surface roughness of test object

Calculating the Vision of Human Observer

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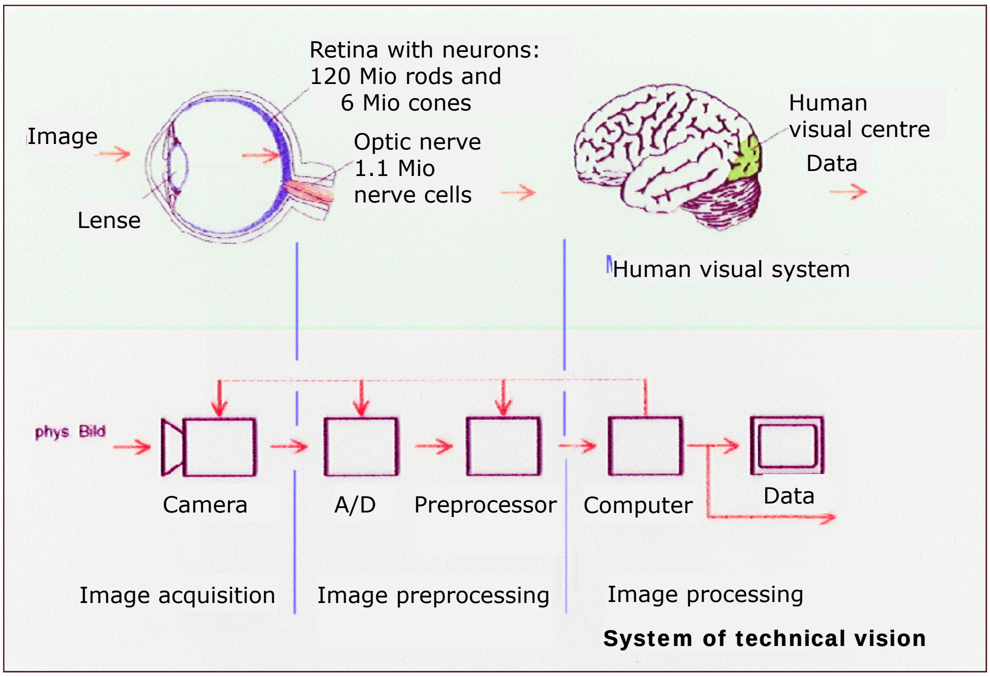

Human Observer Model: Perception Threshold PT

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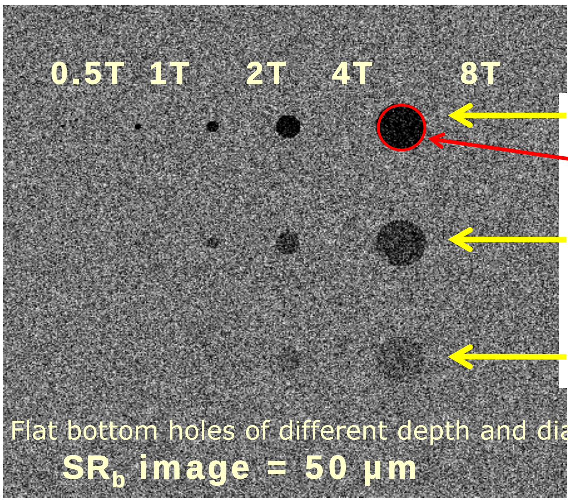
Detector = 50 µm pixel size or magnification technique



Noise = 1000
Signal = 30000

CNR = 2.5

$A_{lateral}$

CNR = 1.25

CNR = 0.625

2T = 0.5 mm / 0.02”
Calculated CNR_{min} = 1

- Large area flaws are better visible than small ones at same Contrast-to-Noise Ratio
- Each row has indications with same CNR = C_{depth}/σ
- Each column has holes with same diameter

$$PT_{const} = \frac{\sqrt{A_{lateral}} \cdot C_{depth}}{SR_b \cdot \sigma}$$

Rose approach, 1946

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

Essential Parameters for Calculation of Just Visible IQI for 1T Hole Diameter

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The essential parameters are: μ_{eff}, SNR and SR_b?

Observer Formula

$$d_{visible} = PT' \cdot \sqrt{\frac{SR_b^{image}}{\mu_{eff} \cdot SNR}}$$

Depends on **Hardware: effective pixel size**
Magnification
Focal spot size, source size

SNR - Signal to noise ratio
μ_{eff} – specific contrast, effective attenuation coefficient
SR_b – effective pixel size in the image, basic spatial resolution of image

Material,
keV, Source type
Scattered radiation
Screens and filters

Exposure time
Tube current, Activity
Detector efficiency
Source-to-Detector Distance

PT' ≈ 2,8 for 1T-holes ; slightly dependent on viewing conditions and operator

New CR Characterization Scheme

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New characterization by performance levels of ASTM E 2446-15

CR System Performance Levels	Required Minimum SNR_N (Normalized to SR_b=88.6 µm)	Permitted Maximum $iSR_b^{detector}$ Value [µm]	Permitted Maximum EPS by E746 [%][A]
CR Special	200	50	1.00
CR Level I	100	100	1.41
CR Level II	70	160	1.66
CR Level III	50	200	1.92

CR level II example:
EPS = 1.4 %
with
μ_{eff} = 0.05 mm^{-1}, SNR_N = 100,
PT = 200, $t_{testplate}$ = 19 mm

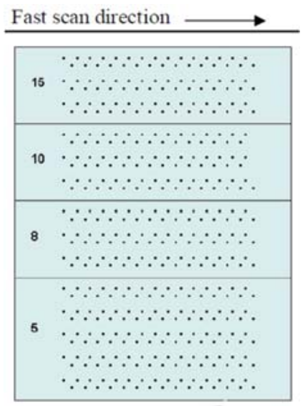
$$EPS = \frac{200\%}{19mm}\sqrt{\frac{0.0886}{0.05 \cdot 100}}$$

$$EPS = \frac{PT'}{t_{testplate}}\sqrt{\frac{SR_b^{image}}{\mu_{eff} \cdot SNR}}$$

EPS Characterization of CR-Systems - ASTM EPS Procedure E 747 -

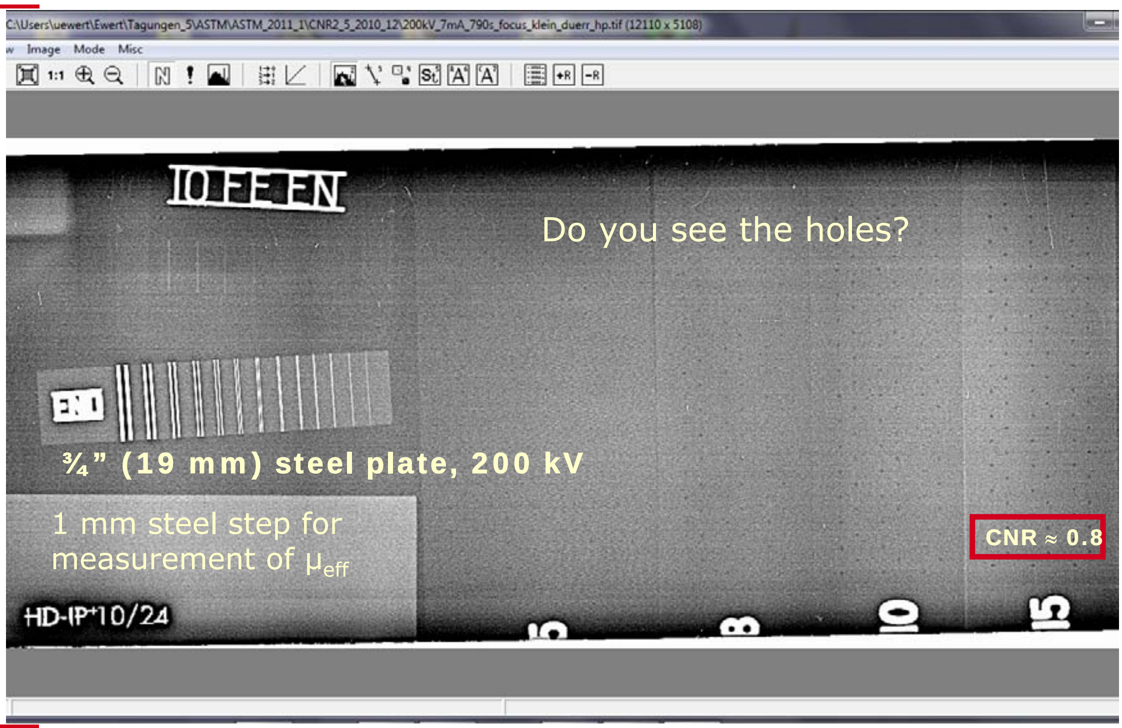
EPS – Procedure is accepted for CR qualification in *ASTM E 2445/6 and "Practice for the Use of Computed Radiography for Aerospace Casting Inspections" (USA: MAI – group, Guidelines for the Use of DDA and CR for Aerospace Casting Inspections)*

- **The EPS (equivalent penetrameter sensitivity) measurement is based on ASTM E 746**
- A smooth ¾ inch (19 mm) steel plate with a set of hole plates is radiographed at 200 kV in ≥ 1 m distance
- The exposure is performed with different mAs settings for determination of the working range.

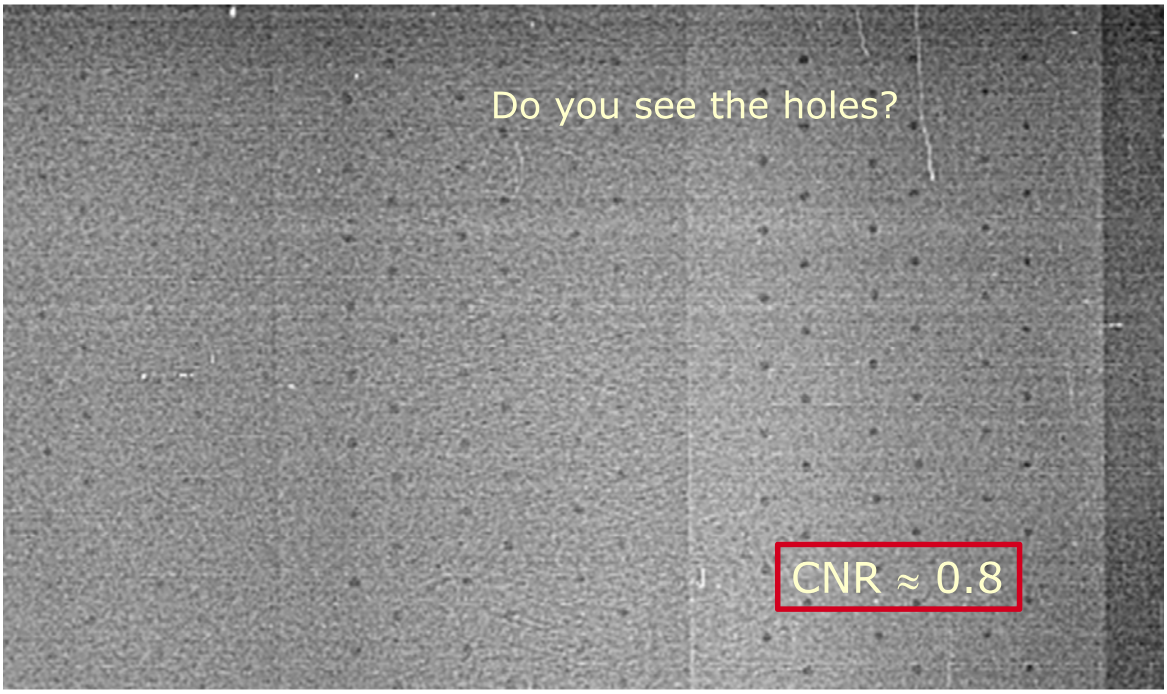


ASTM E 746

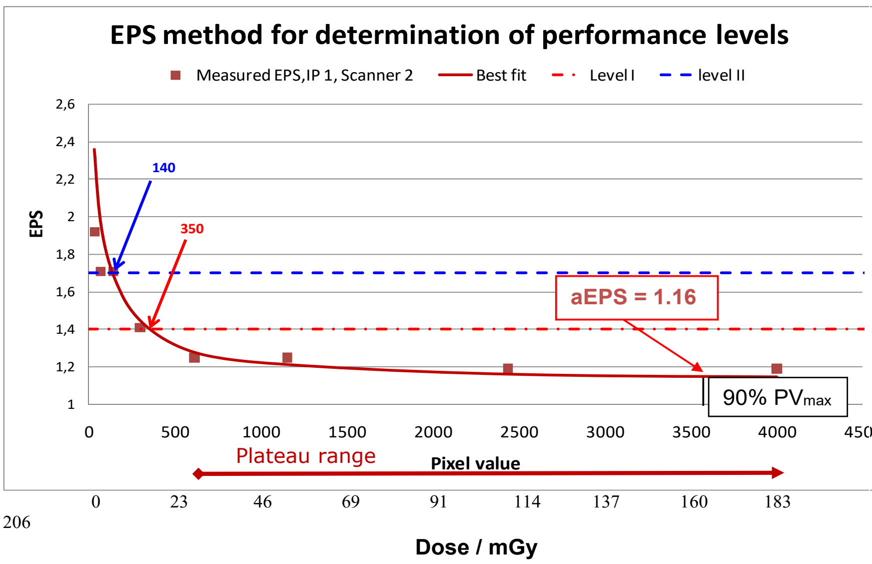
Example: EPS Test with HD CR Scanner, HD IP and Acquired with 20 µm Pixel Size

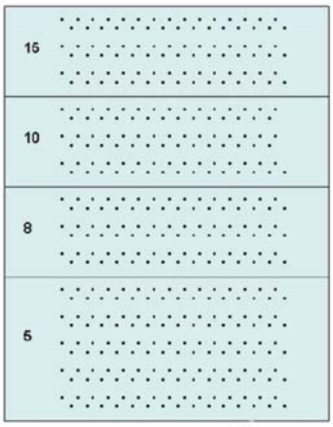


Visibility of EPS holes (E 746)



Working Range for CR (ASTM E 2445 / 6, MAI)





EPS= equivalent penetrameter sensitivity (see ASTM E 746, E 747, E 1025)

POD by EPS

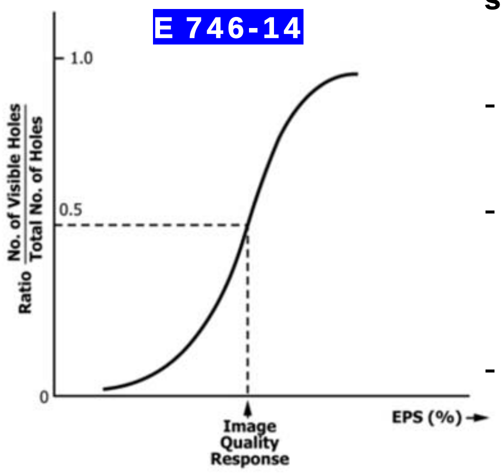
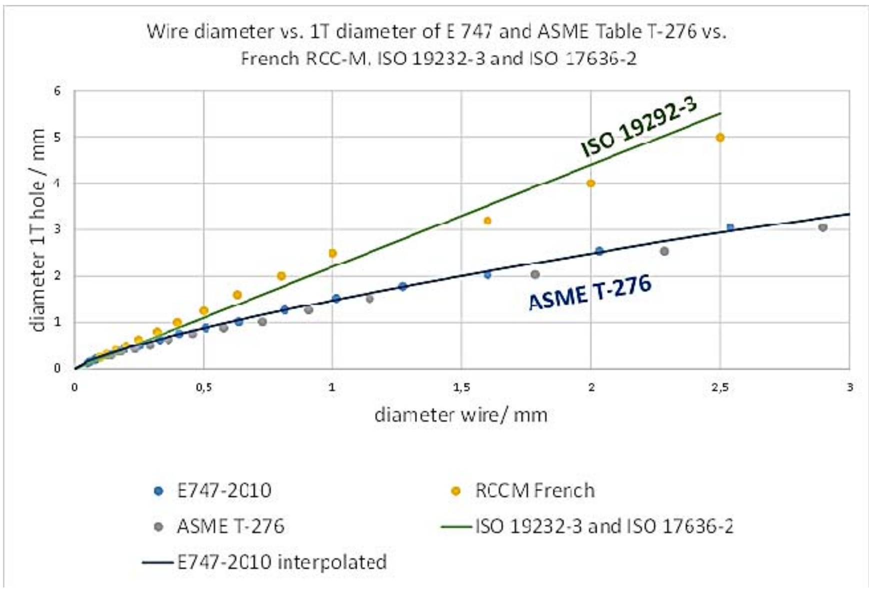


FIG. 4 Graph Method for Determining RIQI

EPS method and POD (â vs. a) method have similarities

- Visibility of holes depends on hole diameter, contrast and noise.
- Procedure: Counting of visible holes out of 30 within different rows and calculation of its percentage.
- Graph on visible hole percentage (**â**) as function of shim-EPS-values (**a**) provides a $POD_{50\%}$ value.

Wire vs. Hole Visibility



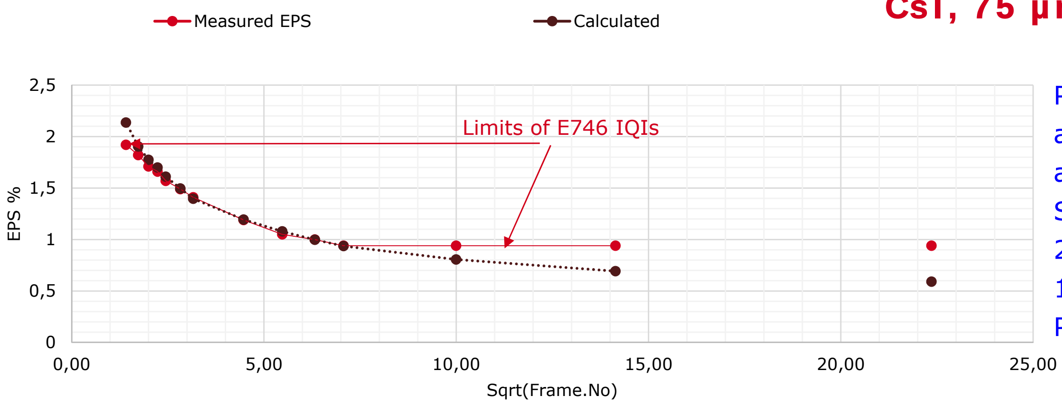
- Different international standards use different conversion equations for conversion of wire visibility to plate hole or step hole visibility.
- Both were validated, but one is obviously wrong.
- BAM evaluated the ISO conversion formula with good results.
- Therefore: *Only hole visibility is considered in the following discussion.*

Test Results for Different Digital Systems

- The concept of Rose is basically related to “white noise”, but practical results dependent on the presampled MTF and noise spectra.
- The change of PT’ in dependence on MTF and noise spectra was investigated.
- Additionally, the measured EPS is also sensitive to scattered radiation.

Example: Calculated and measured EPS [%]

Dexela 1512NDT, CsI, 75 µm



PV ~ 6600
$aSNR_N$ = 700
aEPS = 0.6%
SR_b = 0.08 mm
225 kV
19 mm steel
PT’ = 230

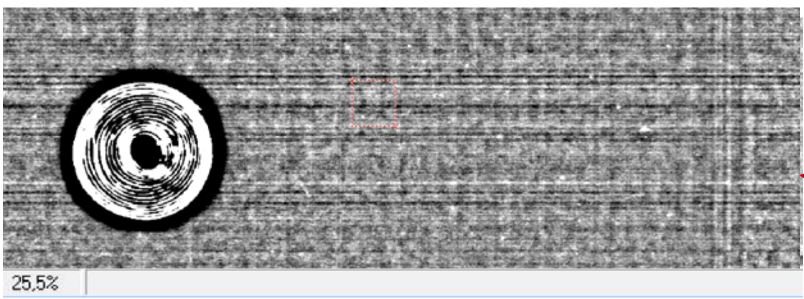
Test Results for Different Digital Systems: 1x DDA, 2x CR

PT’ should be 200!

Sensitive against scatter if μ_{eff} < 0.05 mm^{-1}

System	$SR_b^{detector}$ average mm	PT’	Contrast μ_{eff} mm^{-1}	aSNR	$aSNR_N$	aEPS %
DDA Dexela CsI	0.081	230	0.05	650	720	[1]0.59
IP standard	0.098	280	0.038	270	265	1.41
IP high resolution	0.077	280	0.036	130	145	1.85
					[1]calculated	

- Cannot be explained by Rose concept
- noise spectra required

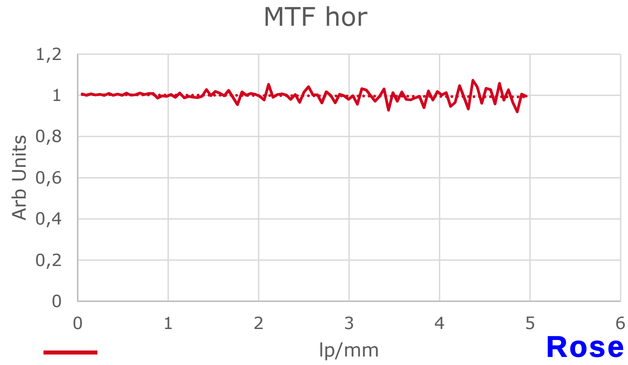


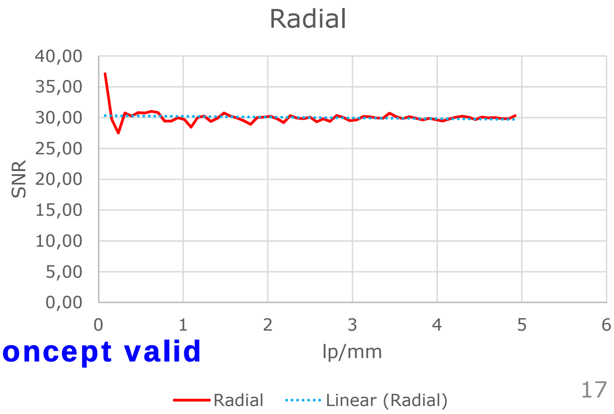
The image quality of imaging plates is limited by its **structural noise** at exposure with high dose

MTF and SNR as Function of Spatial Frequency

- **Contrast response** is measured by a *presampled Modulation Transfer Function* (**MTF**).
- **Noise response** is measured by a *normalized noise power spectrum* (**NNPS**).
- The public domain tool "**DQE panel v7**" under ImageJ was used.
- Images with "white noise" and frequency limited noise were simulated with Matlab (no scatter, no shading) to validate the procedure of "DQE panel v7".
- Two CR systems and 1 DDA system were evaluated to investigate the different PT' values obtained in experiments.

Images with pixel limited unsharpness (e.g. film) and white noise as function of spatial frequency

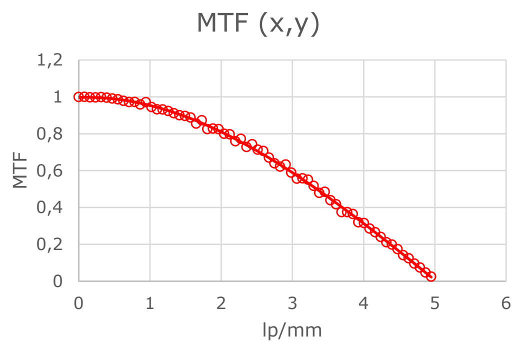


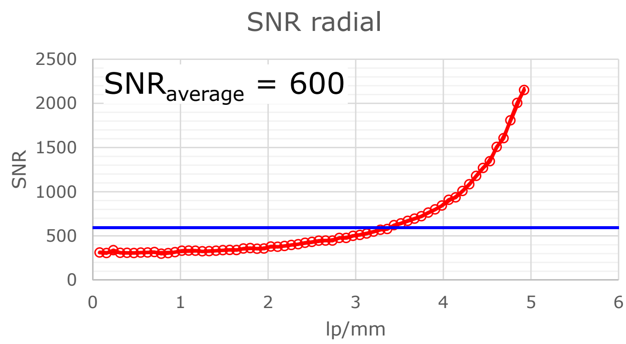


Rose concept valid

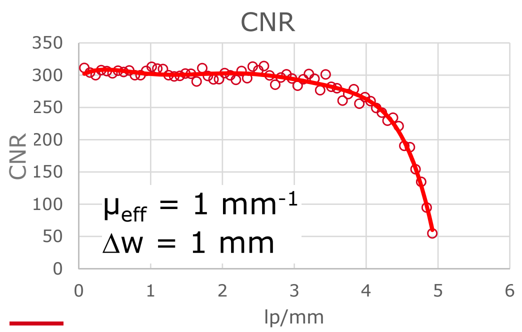
MTF and SNR as Function of Spatial Frequency

Frequency limited image, filtered with 2x2 moving average filter (e.g. digitized film)





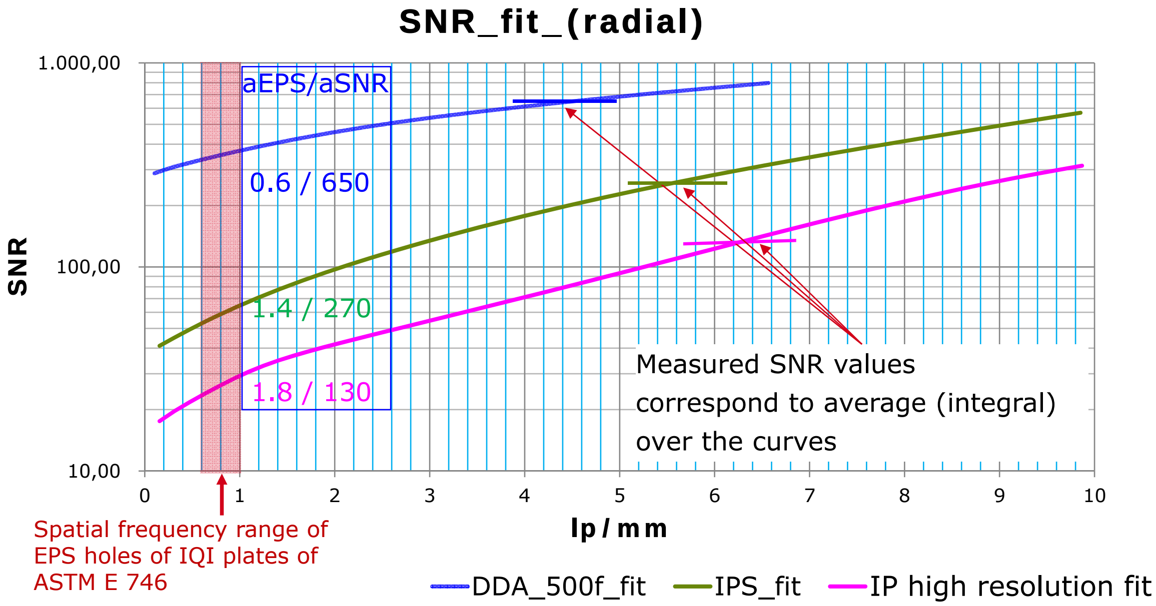
- The image with white noise has an SNR = 300
- After filtering the SNR is measured with SNR = 600
- The following formulas are used:



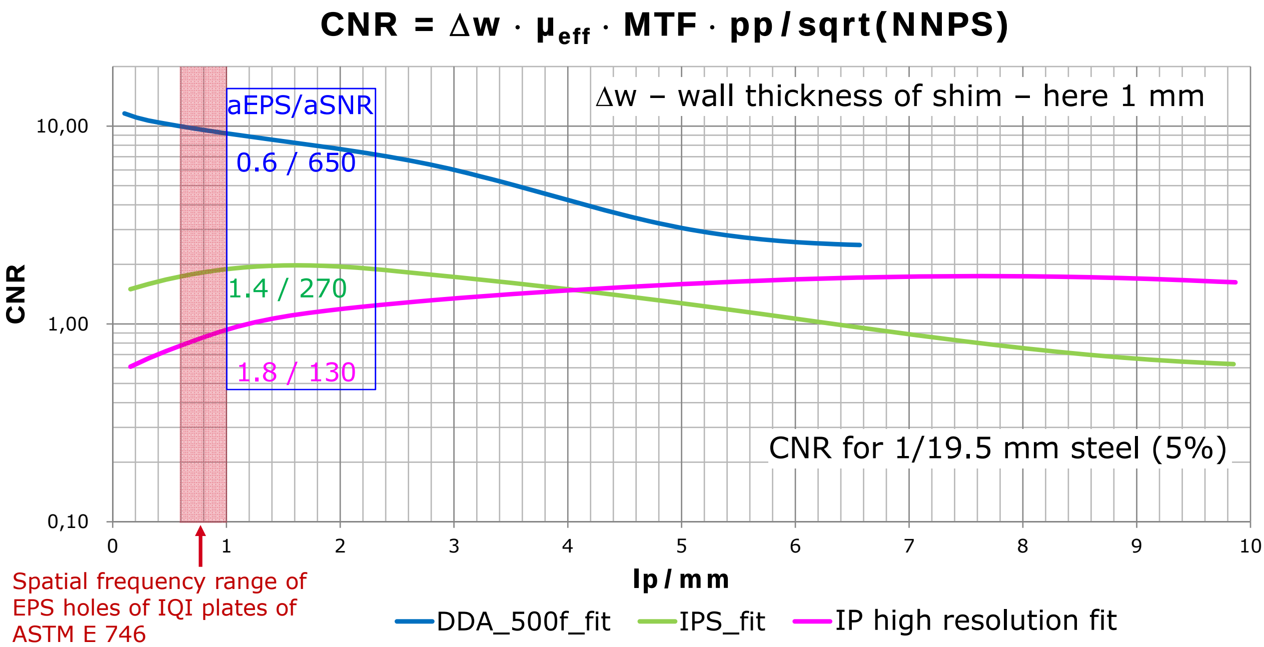
$$SNR(fs) = \frac{pp}{\sqrt{NNPS}} \qquad CNR(fs) = \Delta w \cdot \mu_{eff}(fs=0) \cdot \frac{MTF(fs)}{SNR(fs)}$$

pp – pixel pitch
fs – spatial frequency

Application Results
DDA- and 2x CR-Systems



Application Results
DDA- and 2x CR-Systems



Visibility of Holes in a Noisy Image

- The visibility calculation is based on an extended Rose concept.
- The **visibility approximation** is valid for hole images with diameters < 12 mm and at least 2x2 pixels in the hole of noisy images.
- A visibility function "V" is calculated by

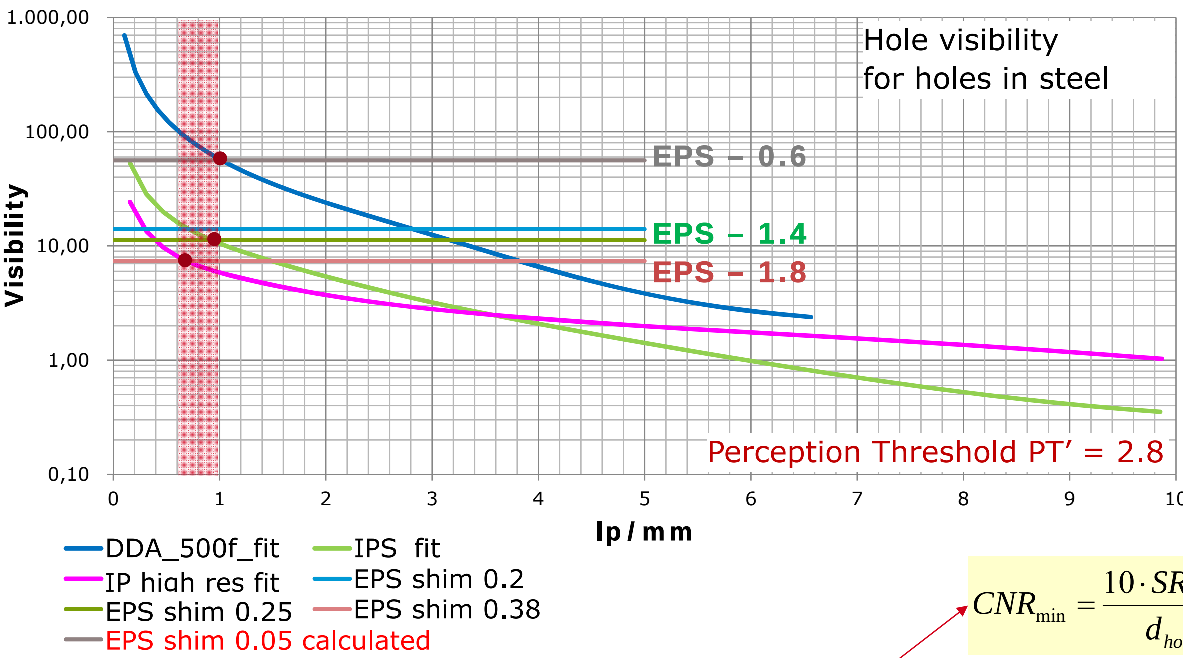
$$V(fs) = (d_{hole}/SR_b^{image}) \cdot CNR(fs, \Delta w)/(2 \cdot fs) \cdot$$

- The hole is visible if $V > PT'(EPS\_shim\_thickness\ \Delta w)$.
- The ***CNR(fs)*** is calculated here for a shim plate of 1 mm thickness with holes of different thickness (0.5 – 0.81 mm) on a 19 mm absorber plate as described in ASTM E746.
- Different PT' values are calculated based on the thickness of the EPS shims in mm (ASTM E 746).

Application Results

DDA- and 2x CR-Systems

Visibility = $\Delta w \cdot d_{hole} \cdot \mu_{eff} \cdot MTF \cdot pp\,/\,(\mathrm{sqrt}(NNPS) \cdot 2 \cdot fs \cdot SR_b)$



$$CNR_{min} = \frac{10 \cdot SR_b^{image}}{d_{hole}}$$

Ewert, Zscherpel, Heyne, Jechow, Bavendiek
Materials Evaluation, 70, No.8, pp. 955-964, 2012

Summary

- The **visibility of image quality indicators** (IQI) depends mainly on contrast, unsharpness and noise in digital images.
- **Rose** introduced 1946 that the visibility of hole indications in camera images depends on the **hole diameter (d_{hole}) and contrast to noise ratio** (CNR).
  - The indications are visible for human observers, if **$d_{hole} \cdot$ CNR > PT**, with **PT** as perception threshold.
- Additionally to the parameters SNR_N and $iSR_b^{detector}$, the **equivalent penetrameter sensitivity** (**EPS**) was introduced as classifier for determination of the performance level of CR systems in ASTM E 2446-16.
- Recent investigation have shown that the **PT value changes** in dependence on the digital system parameters.
- 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.

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Questions

End

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