

New Concept for Detail Sensitivity Monitoring in industrial Computed Tomography - the EURAMET Project SensMonCT

Uwe EWERT¹, Holger ROTH², Simon BURKHARD³, Josephine GUTEKUNST⁴, Virpi KORPELAINEN⁵, Anne-Françoise OBATON⁶, Ulrich NEUSCHAEFER-RUBE⁷, Thomas BLUMENSATH⁸, Marko KATIC⁹

¹KOWOTEST GmbH, Teltow, Germany, uwe@ewert-net.de;

²Waygate Technologies, Baker Hughes Digital Solutions GmbH, Wunstorf, Germany;

³METAS, Federal Institute of Metrology, Bern-Wabern, Switzerland;

⁴Microworks GmbH, Karlsruhe, Germany;

⁵National Metrology Institute VTT MIKES, Espoo, Finland;

⁶Laboratoire National de Métrologie et d'Essais (LNE), National Metrology Institute, Paris, France;

⁷PTB, Physikalisch-Technische Bundesanstalt, Braunschweig, Germany;

⁸University of Southampton, Institute of Sound and Vibration Research (ISVR), Highfield, UK;

⁹FSB, Sveuciliste U Zagrebu, Fakultet Strojarsva I Brodogradnje, Zagreb, Croatia.

Abstract

Digital X-Ray Imaging and Computed Tomography (CT) are applied in industry for flaw detection, flaw evaluation and dimensional measurement. This requires correct experimental system settings for sufficient visibility and detectability of flaws and structure elements. A new metric, the Detail Detection Sensitivity (DDS), is introduced. A related standard draft (WK84836-24) has been submitted to the ASTM E07 committee. The ASTM guide E 1441 [1] describes three essential functions for the characterisation of industrial CT (iCT) systems. These are the Contrast Discrimination Function (CDF), the Modulation Transfer Function (MTF), and the Contrast Detail Diagram (CDD). The related procedures and formulas for the determination of these functions and the DDS will be discussed, based on measurements of newly developed disk IQIs with holes of different diameters with iCT systems and by modelling. Currently, the DDS of iCT systems is evaluated by human operators which is unreliable and costly. Therefore, within the EURAMET project "SensMonCT", new disk IQIs and traceable automated measurement and monitoring methods will be developed as well as procedures to evaluate the DDS of iCT systems and its standardisation.

More info about this article: <https://www.ndt.net/?id=31446>



Keywords: Computed Tomography (CT), Image Quality Indicator (IQI), Detail Detection Sensitivity (DDS), Contrast Detail Diagram (CDD), Contrast Discrimination Function (CDF), Modulation Transfer Function (MTF), Traceable measurement, Standards.

1. Introduction

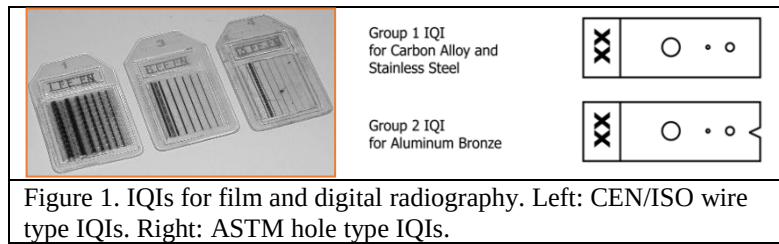
Industrial Computed Tomography (iCT) has become an essential tool for quality assurance in industrial production, particularly in Industry 4.0 applications. iCT has been developed from a scientific research technique to a quality assurance method in industrial production from sub mm scale up to medium and large investment castings and complex parts as, e.g., cars or engines. The Detail Detection Sensitivity (DDS) of these iCT systems is currently evaluated by human operators using objects with artificial or natural flaws, the so-called Reference Quality Indicators (RQI). This operator dependent evaluation is not always reliable. To increase the reliability of the evaluation, an automated numeric procedure is required to substitute the operator-based evaluation. The visibility of indications by human observers on a monitor in cross sectional 2D CT-images can be determined from the square root of the visible flaw area, the Contrast to Noise Ratio (CNR) and the spatial resolution. This was reported first for film, television tubes and eyes by [2] and the concept was modified for digital radiography by [3]. An enhanced concept for CT was published in [4, 5]. Due to the missing computing power, this was never adapted for practitioners. The latest revision of ASTM guide E 1441-19 takes up these concepts [1] and describes a more detailed procedure for the determination of the minimum contrast for the visibility of flaws based on three essential functions for the prediction of the visibility of small indications in iCT slice images by the procedure of ASTM 1695-20 [6]. A new standard draft on Detail Detection Sensitivity was submitted to ASTM E 07.01 and a traceable Image Quality Indicator (IQI) will be developed in the EURAMET Project SensMonCT [7]. The new ASTM standard practice for iCT, E 3375-24 [8], requires already to measure Contrast Detail Diagrams (CDD) for quality assurance. This paper will first address the concept of image quality and IQIs in radiography and iCT. Then, it will present a new IQI design and methodology to evaluate the image quality of iCT such as

proposed in standardisation, but also in the European project SensMonCT. Finally, the next steps of the project will be described.

2. Image Quality and Image Quality Indicators (IQI) in Radiography and iCT

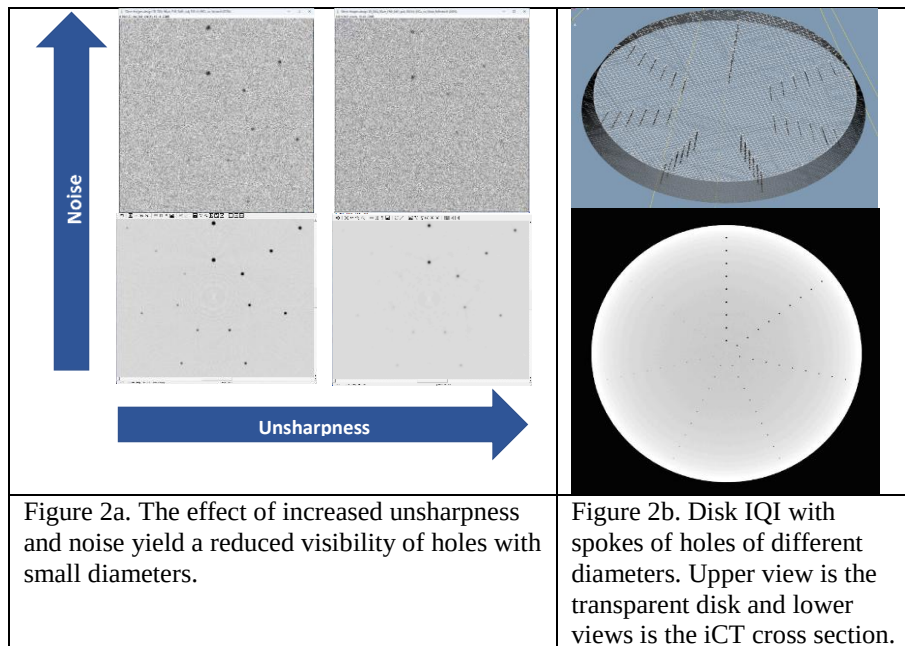
2.1 Comparison between Radiography and iCT

The image quality in radiography and CT is measured with Image Quality Indicators (IQI) or Reference Quality Indicators (RQI). This paper focusses on the IQIs. In film and digital radiography, wire or hole type IQIs are used (Fig. 1). The image quality measurement is based on the effect that the thickness of the wires or plates provokes a contrast change in the radiograph. These IQIs are not applicable for iCT, because the CT-contrast depends on the material and density differences, but not on thickness differences. ASTM E 1441 describes that the image quality of iCT slices depends on CT-contrast, noise, spatial resolution and of the indication area and shape.



iCT IQIs need to have a material contrast, e.g. attenuation difference between a specific material and air. Consequently, modified cylindrical hole type IQI can be used. The evaluation procedure for iCT is different from the 2D radiographic procedure. The numerical procedure is

based on the Contrast Discrimination Function (CDF), the Modulation Transfer Function (MTF) as described in ASTM E 1695-20, and the CDD. These functions can be calculated by CT-software tools automatically. The goal is the automated and reliable measurement of the DDS. Since this concept is mathematically complex, the standard committee ASTM E07.01 decided to develop a new standard for new test IQIs, which permits the evaluation of the DDS in iCT slices for operator based (visual) and automated monitoring of the iCT system performance in terms of image quality. This considers also the “compensation principle” that DDS can be improved by a better spatial resolution or reduced noise or both. Fig. 2a shows an example. Fig. 2b shows the schematic design of the related Al disk IQI (50 mm diameter) with seven spokes with holes of different diameter (see also Fig. 3) and an iCT cross section.



The human observer cannot distinguish in a certain range if the reduced visibility of small holes is caused due to increased noise or increased unsharpness (Fig. 2a). Consequently, increased CNR can compensate for too high unsharpness and vice versa, finally achieving the same visibility of small indications.

Rose published in 1948 [2] that human observers recognise (round) details in noisy black-and-white images according to a simple formula for hole like indications. These indications are visible for human observers, if the

hole diameter D^* (which is proportional to the square root of the projected indication area, given in pixels or voxels), multiplied by the achieved CNR, exceeds a Perception Threshold (PT):

$$PT = D^* \cdot CNR \quad (1)$$

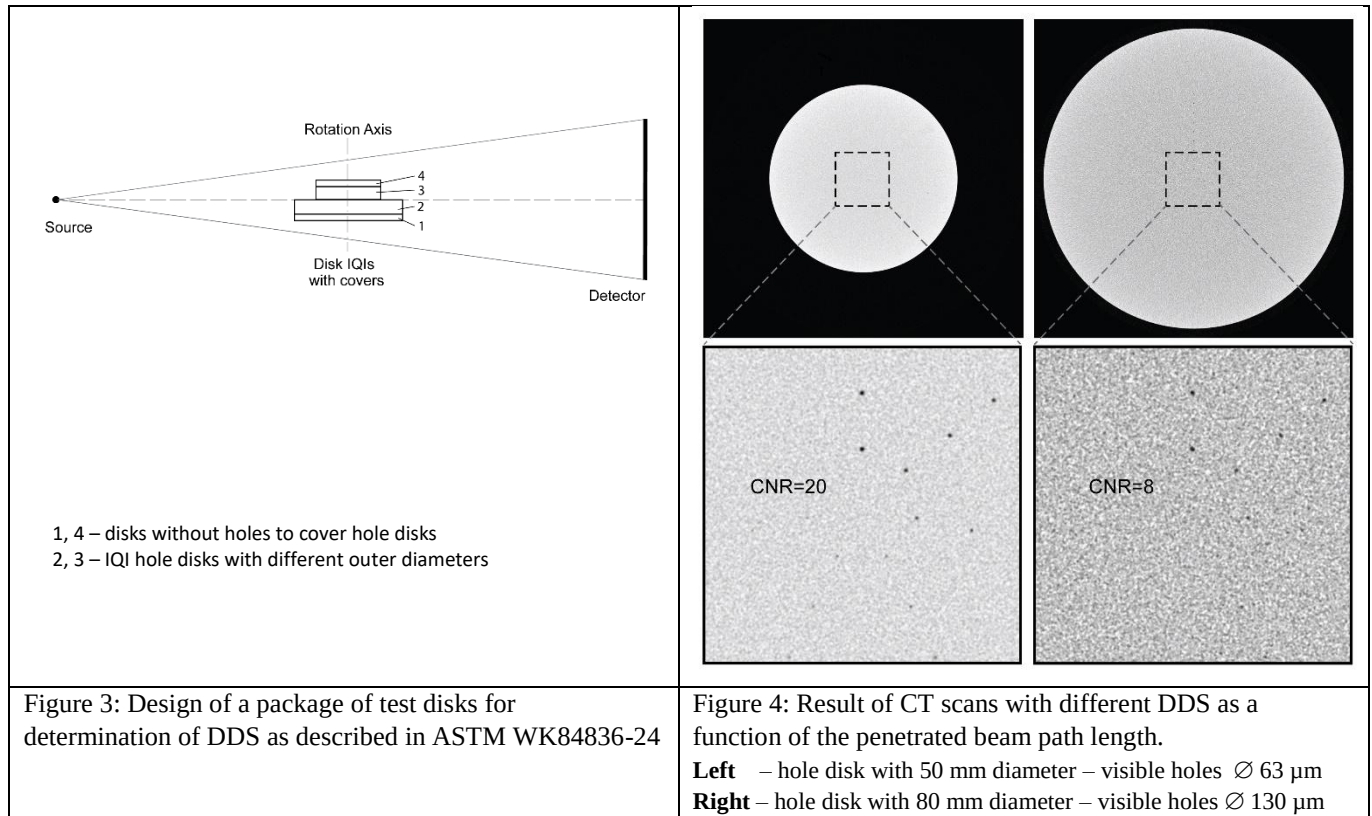
This formula works for white noise and contrast which are independent of unsharpness. The unsharpness influence on contrast and on noise is determined by a Fourier analysis to calculate the contrast sensitivity (inverse CNR) dependent of the spatial frequency. This is the basis for the application of all DDS Image Quality Indicators.

2.2 New Image Quality Indicators (IQIs) for iCT Detail Detection Sensitivity (DDS)

ASTM draft WK84836-24 describes a first design of hole disk for iCT which permits the visual evaluation of the DDS of an iCT system (see Figs. 3, 4). Related and more sophisticated DDS-IQIs for iCT will be developed and tested in the European project “SensMonCT”. Furthermore, a software for automated evaluation will be developed as well in the project. The measurement of DDS is based on a CT scan of a disk IQI. Fig. 3 describes a set of disks to determine the DDS from iCT slices by visual evaluation and numeric determination of the visibility limit (DDS_{limit}). Fig. 4 shows the result of a DDS measurement of disk slice images with different diameters and the same hole pattern. The slice image of the disk with the higher diameter shows a lower CNR and fewer holes are visible.

2.3 The Contrast Detail Diagram (CDD) Concept

ASTM guide E 1441 [1] describes the basics of iCT and explains the concept of the CDD, which can be used to predict the expected visibility (detectability) of features in noisy and unsharp images depending on



their relative object contrast and diameter D^* . This standard guide describes the basics of the CDF, the MTF, and the CDD. ASTM E 1695 [6] describes the numeric measurement procedure for CDF and MTF in detail. Considering eq. (1), the CDF is determined based on a noise analysis as a function of the spatial frequency, $\sigma_m(\mu_i)$, [1, 2], normalised to the tile size of quadratic voxel clusters with diameter D^* :

$$CDF(D^*) = 100\% \cdot \frac{\sigma_m(D^*)}{\bar{\mu}(D^*)} = 100\% \cdot \frac{1}{D^* \cdot CNR(D^*)} \quad (2)$$

with

σ_m - noise, calculated as standard deviation [1, 2]

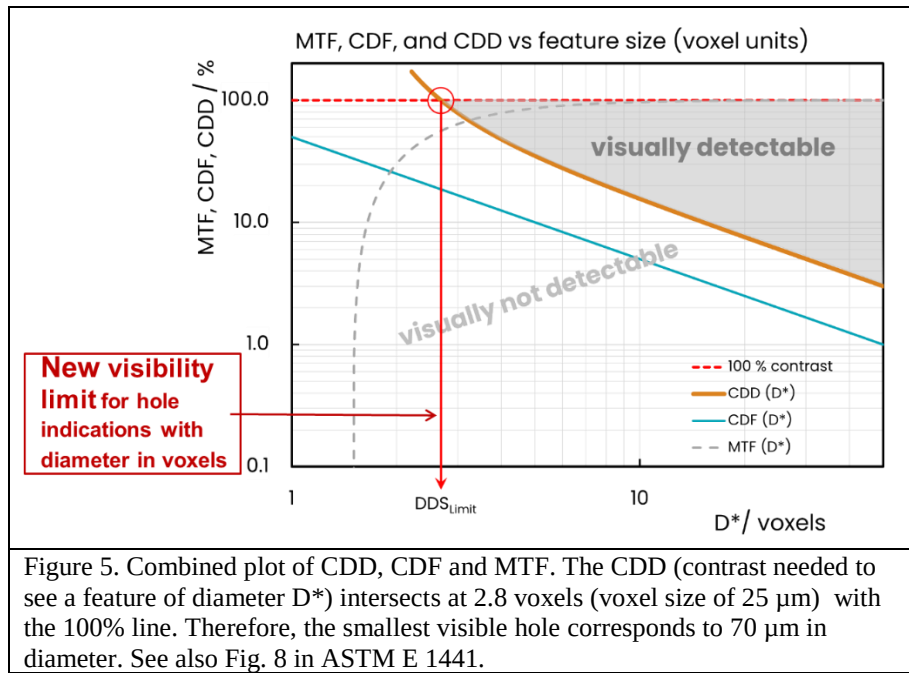
μ - linear attenuation coefficient

The CDD is calculated by:

$$CDD(D^*) = c \cdot \frac{CDF(D^*)}{MTF\left(\frac{1}{2D^*}\right)} \quad (3)$$

The factor “ c ” in eq. (3) is the physiological factor. It corrects the ratio of CDF/MTF considering the visual perception of human observers and the indication’s shape. In a Round Robin Test (2022) c was found to be $c = 3$ for hole indications (circular indications). This factor varies between 1 and 3 depending on the indication shape. Linear indications with a minimum length of 12 mm will be seen best. Additionally, the “partial volume effect” has to be considered, if the smallest lateral extension of indications in slice images is smaller than 2 voxels. The reason is the contrast reduction, if indications are partly distributed over neighboured voxels.

The CDD permits the calculation of the numeric visibility limit, DDS_{limit} . If the holes are filled with air, it corresponds to the 100% value of the measured CDD ($CDD_{100\%}$). In older presentations and publications [9, 10] the DDS_{limit} was described as the intersection point of MTF and CDD, which is not correct. From newer measurements and simulations in the project SensMonCT, it was found that the $CDD_{100\%}$ value fits best for $c = 3$ and round holes with air inside. This was also verified by theoretical considerations and simulations. A description of the measurement procedure of ASTM E 1695 for MTF and CDF can be found in [9]. Fig. 5 shows the scheme for the determination of the visibility limit from the CDD as a result of CDF and MTF measurements.



3. New Disk IQIs, New Procedure and Results of Simulations

The ASTM E 1695 procedure requires prefiltering at the tube port of two half value layers to suppress beam hardening at the edge of the disk IQI. For materials with high atomic number and/or dense materials (Inconel etc.), this is not sufficient. Thicker filters, e.g. some mm of Cu, would make the practical examination too time consuming and inefficient. So, some beam hardening (cupping) has to be accepted. Therefore, the IQI for

the procedure of ASTM E 1695 was redesigned as a “washer” like disk with a central hole. The newly designed disk IQI has a central hole of 10% of the disk diameter. The MTF is measured at the edges, inside the hole and outside the disk. The MTF, measured at the outside edge of the disk shows an overshoot as seen in Fig. 6 (blue dotted line). The contrast to air, inside the hole, is lower than outside the disk as shown on the blue line profiles displayed on Fig. 7b and Fig. 8. For a conservative calculation, the contrast of the central hole is used instead of the outer edge contrast (Fig. 7a). Fig. 7a shows a calculation results of MTF, CDF and CDD as well as DDS_{limit} values for the use of the outside and inside edges for MTF, as well as cupping correction. The result of DDS_{limit} is in between 71 and 73 μm . The CDF was calculated in the ring-like range of 6 to 15 mm radius between the central hole and the small holes, whereas ASTM E 1695 required the CDF to be calculated in a disk representing 33% of the center of the disk IQI. Fig. 7b shows

the central slice of the measured iCT volume of the disk IQI with a central hole (washer design). The calculated DDS_{limit} is marked in the Fig. 7b with $71\ \mu\text{m}$. All holes with the diameter of $80\ \mu\text{m}$ are visible. Some holes with a diameter of $63\ \mu\text{m}$ are also visible, but not all of them. Consequently, DDS_{visual} is $80\ \mu\text{m}$.

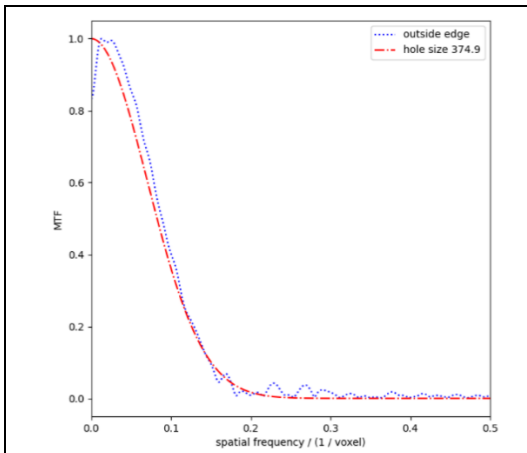


Figure 6. MTF measured at an Al-disk IQI of 50 mm diameter at the outer edge and at the inner edge of the central hole of 5 mm diameter (150 kV, 0.2 mm Cu prefilter). The MTFs were normalised to 100% for the maximum.

The “washer” like disk IQI was explored for an iCT application for an X-ray tube with a “classical” double line focal spot by simulation. Fig. 8 shows the result of the MTF, CDF, CDD analysis, as well as the focal spot shape, the profiles and the MTFs. The focal spot consists of 2 rectangular lines and the MTF becomes a sinc function with several minima. Interesting is that the MTF at the inner edge has minima close to zero, whereas the outer edge MTF has minima larger than zero. Consequently, two different DDS_{limit} values were calculated. $54\ \mu\text{m}$ for the MTF of the outer edge and $108\ \mu\text{m}$ for the MTF of the inner hole edge. The visual evaluation yielded a DDS_{visual} value of $50\ \mu\text{m}$ diameter for the just visible holes, but they are disturbed in shape by the noise. A simulation with better contrast to noise ratio (CNR) showed that all holes had a full width at half height of about $250\ \mu\text{m}$ in the profile. All holes with a diameter below $100\ \mu\text{m}$ (first minimum of MTF) were presented as rings instead of spots. The CDD from the inner hole edge MTF with a maximum, larger than 100%, at about $100\ \mu\text{m}$

did not indicate hidden indications, as expected from the theory, but modified indications were found. No hidden spots were found as derived from the CDD based on the MTF of the inner hole edge. This effect will be investigated in more detail in the future in the project SensMonCT.

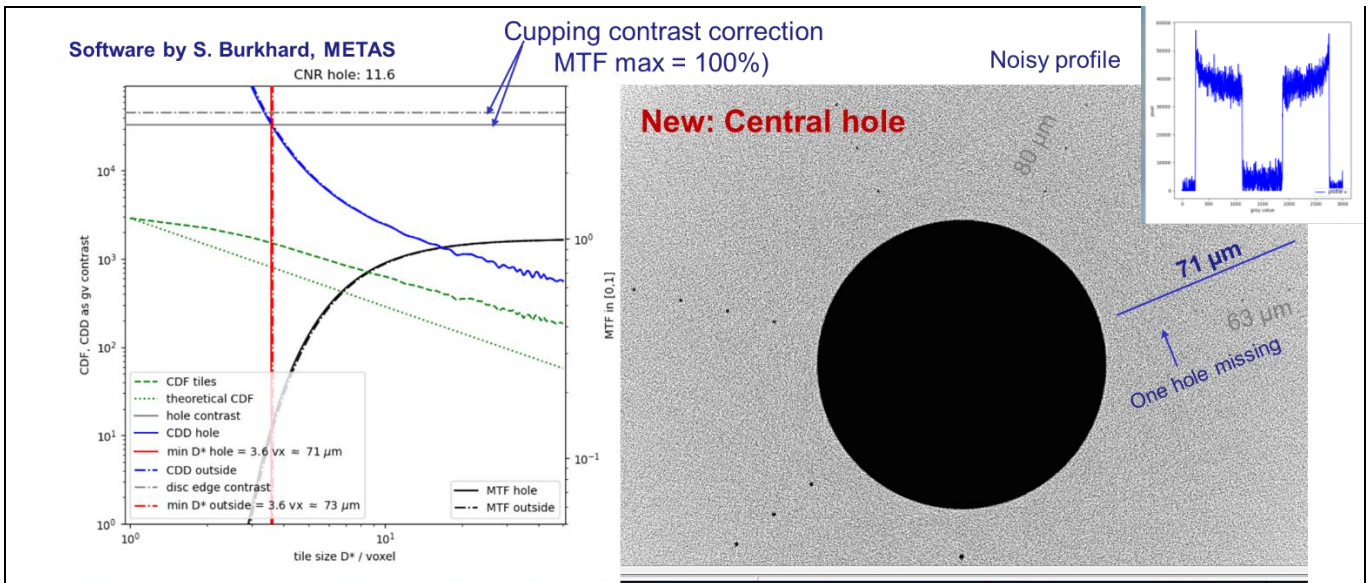


Figure 7a. Plot of MTF, CDF and CDD from a disk IQI with large central hole and small holes from $50\ \mu\text{m}$ to $200\ \mu\text{m}$, simulated with Gaussian focal spot and cupping artefact. The calculated DDS_{limit} value is $73\ \mu\text{m}$ for the circumferential MTF and $71\ \mu\text{m}$ for the inner hole MTF.

Figure 7b. Central iCT cross section of the disk IQI with central hole. All holes with $80\ \mu\text{m}$ in diameter are visible. The holes with $63\ \mu\text{m}$ diameter are not completely visible. One hole is missing. DDS_{visual} is $80\ \mu\text{m}$.

4. What's next in SensMonCT project?

In addition to the development of the disk IQI designs and of a DDS evaluation algorithm, the IQIs will be manufactured and measured by metrological tools, as e.g., optical and electron microscopy, permitting traceable measurements of the DDS of iCT systems, suitable for external audits. The accuracy of the evaluation technique and of the IQIs will be verified in a Round Robin Test. A free, publicly available, software and reference images will be provided for interested users and a related standard draft will be submitted to ISO/TC 135/SC 5 at the end of the project.

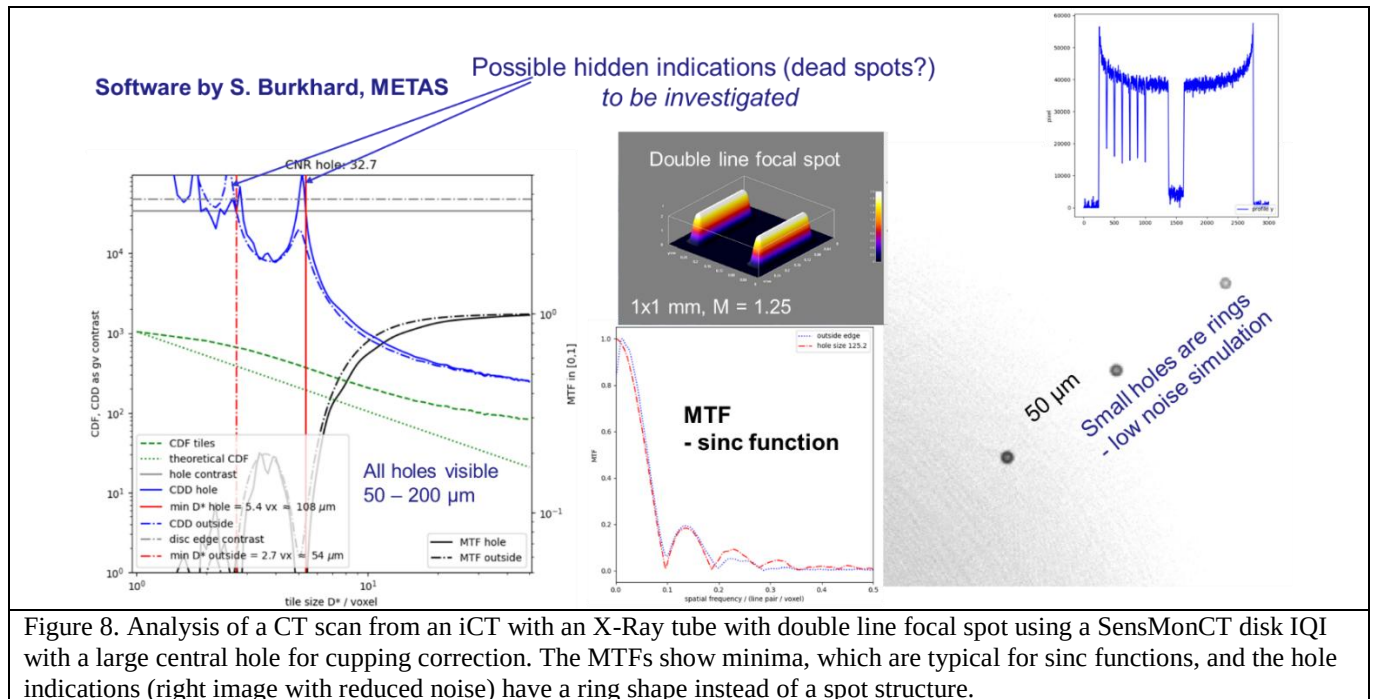


Figure 8. Analysis of a CT scan from an iCT with an X-Ray tube with double line focal spot using a SensMonCT disk IQI with a large central hole for cupping correction. The MTFs show minima, which are typical for sinc functions, and the hole indications (right image with reduced noise) have a ring shape instead of a spot structure.

5. Summary

Image Quality Indicators (IQIs) for film and digital radiography are not suitable for measurement of the Detail Detection Sensitivity (DDS) in industrial Computed Tomography (iCT) slices. ASTM E 1695 describes rod or disk IQIs to measure Modulation Transfer Function (MTF) and Contrast Discrimination Function (CDF), which permit to determine the Contrast Detection Diagram (CDD). These metrics describe the required object contrast for detection of indications depending on their diameter/size by human observers. A new standard draft, describing disk IQIs with holes of different diameters, was developed and submitted to ASTM E07.01. In the EURAMET project SensMonCT [7], a new disk design, with special hole patterns, is developed. Both disk IQIs permit to determine the visual DDS_{visual} . A related algorithm was developed, which permits to analyse the reconstructed CT slices of the disk IQIs calculating the CDD value at 100% corresponding to the numeric DDS_{limit} value. A correction of hardening effects was included. The agreement between DDS_{limit} and DDS_{visual} was proven from simulated iCT scans. The manufacturing and a related Round Robin Test will follow. The disk design permits the traceable measurement of the hole diameters and the cylindricity of the holes and disk.

6. Acknowledgements

The project (JRP 23NRM05: SensMonCTII) has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

7. References

- [1] ASTM E 1441-19: Standard Guide for Computed Tomography (CT).
- [2] A. Rose, "The sensitivity performance of the human eye on an absolute scale", *J. Opt. Soc. Am.* 38, 196-208, 1948.
- [3] Ewert, U., Zscherpel, U., Heyne, K., Jechow, M., Bavendiek, K., "Image Quality in Digital Industrial Radiology", *Materials Evaluation*, Vol. 70, No. 8, pp 955-964, 2012.
- [4] Cohen, G., and Di Bianca, F., "The Use of Contrast-Detail-Dose, Evaluation of Image Quality in a CT Scanner," *Journal of Computer Assisted Tomography*, Vol. 3, No. 2, pp. 189– 195, 1979.
- [5] Sekihara, K., Kohno, H., and Yamamoto, S., "Theoretical Prediction of X-ray CT Image Quality Using Contrast Detail Diagrams", *IEEE Transactions on Nuclear Science*, Vol. NS-29, pp. 2115–2121, 1982.

- [6] ASTM E 1695-20: Standard Test Method for Measurement of Computed Tomography (CT) System Performance.
- [7] EURAMET project SensMonCTII, <https://www.ptb.de/epm2023/sensmonct/home>.
- [8] ASTM E 3375-23: Standard Practice for Cone Beam Computed Tomographic (CT) Examination.
- [9] U. Ewert, F. Herold , H. Roth and F. Wohlgemuth, “Numeric Prediction of the Detail Visibility in industrial X-Ray Computed Tomography by Human Observers“ proceedings of 13th ECNDT2023, 3-7 July, 2023, Lisbon, proceedings in https://www.ndt.net/article/ecndt2023/papers/ECNDT2023_PAPER_412.pdf.
- [10] U. Ewert, H. Roth, F. Wohlgemuth, D. Matern, F. Herold, W. Silva, U. Zscherpel, “Numeric Prediction of the Visibility of Indications for Human Observers in digital X-Ray Imaging and Computed Tomography”, 20th WCNDT, Incheon, Korea, 27-31 May, 2024, https://www.ndt.net/article/wcndt2024/papers/A20191031-0688_E.pdf.