RAD_IQ: A free software for characterization of digital X-ray imaging devices based on the novel IEC 62220-1-1:2015 International Standard

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Abstract. Characterization of digital X-ray imaging devices is very important because it can be used to measure and compare the performance of detectors used in Diagnostic Radiology. This characterization is usually made through the calculation of Modulation Transfer Function (MTF), Noise Power Spectrum (NPS) and Detective Quantum Efficiency (DQE). These parameters, especially the DQE, are very important because they quantify the effect of spatial resolution, contrast and noise on Radiographic image quality (IQ). The IEC 62220-1-1:2015 International Standard provides comprehensive guidelines how to capture and analyze X-ray images to characterize digital X-ray detectors. A novel, fast and free MATLAB-based software was developed, named RAD_IQ, to calculate the Signal Transfer Property (STP), perform Noise Component Analysis (NCA), and calculate the parameters MTF, NPS & DQE of X-ray detectors based on the novel IEC 62220-1-1:2015 International Standard for General Radiography and IEC 62220-1-1:2007 for Digital Mammography. Our results were validated against well-established software products used for quantitative image analysis of digital X-ray detectors. The calculated parameters were within 5% difference compared to available software products. The conclusion of our study was that RAD_IQ can be easily used from Medical Physicists, Biomedical Engineers and researchers without any programming experience to characterize the performance of digital X-ray detectors used in Diagnostic Radiology.

1. Introduction
The purpose of medical X-ray imaging (also known as Diagnostic Radiology) is to provide sufficient information about specific aspects of human body structure or function. Hence, clinical Radiographic image quality (IQ) should be sufficient to provide the required information for a given task. IQ depends on several parameters across the X-ray imaging chain, including X-ray geometry and technique, irradiated object, X-ray detector, image processing, and reporting monitor. The most important factors that affect IQ are spatial resolution, contrast and noise [1]. Since the excess use of X-rays can cause harm to the human body it is vital to get sufficient IQ with the minimum patient dose...
(this is also known as the ALARP principle [2]). Several aspects of the Radiographic imaging chain can be optimized to achieve this. One of these is the performance of used X-ray detectors.

Digital X-ray detectors have been used clinically in Diagnostic Radiology for more than 30 years [3], including several imaging modalities such as General Radiography, Digital Mammography, Digital Breast Tomosynthesis, Computed Tomography, Fluoroscopy, Angiography / Angioplasty, Dental Imaging etc. They consist of either Computed Radiography (CR; also known as storage phosphors) or Digital Radiography (DR; also known as flat panel detectors) X-ray detectors. Over the years several developments in digital X-ray detector technologies have been taking place to optimize their performance in clinical practice [4]. Medical Physicists, Biomedical Engineers and researchers across the globe are evaluating and comparing the performance of various digital X-ray detectors used in Diagnostic Radiology.

This paper presents a free and easy to use MATLAB-based Graphical User Interface (GUI), named RAD_IQ, for quantitative image analysis of CR and DR detectors used in General Radiography and Digital Mammography. In particular, it can be used to calculate the Signal Transfer Property (STP; also known as Response Function), perform Noise Component Analysis (NCA), and calculate the parameters presampling Modulation Transfer Function (pMTF), Normalized Noise Power Spectrum (NNPS) and Detector Quantum Efficiency (DQE) [5]. The analysis algorithms are based on the latest version of the IEC standard for General Radiography (IEC 62220-1:2015 International Standard [6]) and IEC 62220-1-1:2007 [7] for Digital Mammography. The users also have the option to use processing conditions described in the European Guidelines for Quality Assurance in breast cancer screening and diagnosis [8]. It should be noted that our group has previous experience in characterizing digital X-ray detectors based on the latest IEC 6220-1:2015 standard [9-10].

2. Materials and methods

Image quality can be described in spatial or spatial frequency domain [1]. The parameters STP and NCA are calculated in spatial domain, while the parameters MTF, NPS and DQE in the spatial frequency domain. The following sections briefly describe the above parameters and how RAD_IQ can be used to calculate them.

2.1. Signal Transfer Property (STP) and Noise Component Analysis (NCA)

The STP (also known as response function) shows how the signal is transferred from input (i.e. input Air Kerma at Detector’s surface – also known as Detector Air Kerma; DAK) to output (i.e. output mean Pixel Value (PV) – also known as Digital Number (DN)) in the spatial domain. Most digital X-ray detectors have a linear or logarithmic signal response from input to output. In rare occasions they may have a power signal response. The STP defines the sensitivity of X-ray detectors to input X-rays; however, very high sensitivity corresponds to saturation at low DAK levels. Finally, STP can be used to linearize (i.e. use the inverse response function to convert output PV to input DAK levels) the X-ray images used for the calculation of MTF, NPS and DQE. The linearization process is very important, especially for X-ray detectors with non-linear response, because the performance characterization of an imaging X-ray detector is based on the linear-systems theory which considers that the imaging system is stationary, linear and shift invariant [11].

In Radiography the noise in spatial domain is described by the standard deviation (or variance, i.e. standard deviation square) over an ROI in the output X-ray image. The three main noise sources in digital X-ray imaging are electronic noise (also known as read noise), quantum noise (also known as shot noise) and fixed pattern noise (FPN; also known as structure noise) [5]. The electronic noise is independent of signal level, quantum noise increases with the square root of the signal (due to the Poisson distribution of input X-rays in temporal and spatial domains) and structure noise increases as a function of signal. The structure noise is removed through the gain correction of X-ray images. Usually the electronic noise has an effect at low signal levels, while remnant structure noise at high signal levels. The NCA analyses the three main noise components and shows their effect to the total noise as a function of signal level. NCA is applied by the following formula:
\[ SD^2 = k_e^2 + k_q^2 \cdot p + k_s^2 \cdot p^2 \] (1)

where SD is the standard deviation that describes the total noise, \(k_e, k_q\) and \(k_s\) are the coefficients of electronic noise, quantum noise and structure noise respectively, and \(p\) is the signal level, i.e. either the output PV or the linearized input signal.

2.2. Modulation Transfer Function (MTF) and Noise Power Spectrum (NPS)

The Modulation Transfer Function (MTF) describes the contrast reduction of different spatial frequencies that compose the Radiographic image and it is used to quantify the spatial resolution of an X-ray imaging system. It shows how well an input signal is transferred to the output at each spatial frequency. By definition MTF is one at zero spatial frequency and decreases as a function of spatial frequency.

Two methods are developed to measure the MTF of an X-ray detector: the slit method to calculate the line spread function (LSF) and the edge method to calculate the edge spread function (ESF) which is the integral of the LSF. Digital X-ray detectors may suffer from aliasing at higher spatial frequencies, due to their digital nature. Hence, in order to measure the image blurring without potential aliasing the presampling MTF (pMTF) can be calculated from oversampling ESF [12]. In this case an opaque and polished edge test object (e.g. 1 mm Tungsten (W) foil) needs to be placed at a shallow angle \(\alpha\) (1.5°-3°) with respect to the X-ray detector’s pixel rows and columns.

The Noise Power Spectrum (NPS) describes the spectral decomposition of the noise variance in an image as a function of spatial frequency. In other words, NPS provides an estimate of the spatial frequency dependence of the point-to-point fluctuation (i.e. noise) in the output X-ray image. The two-dimensional (2D) NPS can be extracted from the Fourier Transform of flat-field (i.e. uniform) X-ray images for a given X-ray beam quality (i.e. target/filter combination for a given tube voltage) and DAK level. The total integral of the 2D NPS is equal to the output variance. One-dimensional (1D) horizontal and vertical NPS profiles can be calculated and used for X-ray detectors characterization (i.e. 1D NPS can be combined with the pMTF to calculate the DQE – see following sections).

2.3. Detective Quantum Efficiency (DQE)

The Detective Quantum Efficiency (DQE) expresses the ability of an X-ray detector to transfer the Signal-to-Noise Ratio (SNR) from its input to output. It shows the fraction of input X-ray quanta effectively used to create an output image at each spatial frequency. The DQE combines spatial resolution, noise and contrast and it is calculated from the combination of pMTF, 1D NPS and SNR using the following formula:

\[ DQE(f) = \frac{SNR^2_{\text{out}}}{SNR^2_{\text{in}}} \cdot \frac{pMTF^2(f)}{\Phi \cdot NPS(f)} = \frac{pMTF^2(f)}{\Phi K_a NPS(f)} \] (2)

where \(SNR^2_{\text{input}}\) corresponds to the number \(\Phi\) of input quanta (X-rays per unit area (mm\(^2\))), \(K_a\) is the DAK and \(Signal\) (also known as large area signal) corresponds to the average output pixel value (or input DAK level if linearization has been applied). It should be noted that usually the term \(SNR^2_{\text{input}}\) is used in the literature [6-8] to describe the X-ray Fluence per Air Kerma ratio \(\Phi/K_a\) (in X-rays per mm\(^2\) per µGy), which depends on the used X-ray beam quality.

The DQE depends on the absorption of X-rays from the X-ray detector and varies with X-ray beam quality, tube voltage, DAK and spatial frequency. The DQE is between 0 and 1 and decreases as a function of spatial frequency because the noise has an increased effect at higher spatial frequencies. For linear and quantum-limited (i.e. quantum noise is the dominant source of noise, usually more than 80\% of the total noise) X-ray detectors the DQE is independent of DAK because the product \(K_a \cdot NPS\) is constant. However, electronic noise, remnant FPN, EMI (electromagnetic interference) or inherent non-linearity of DR detectors may increase or decrease the DQE values as a function of DAK.
The IEC standards [6-7] suggest an alternative way to linearize the X-ray images used for the MTF, NPS and DQE calculation, using the inverse of the Conversion Function (i.e. output mean PV as a function of input $Φ$).

2.4. RAD IQ

*Rad_IQ* is a MATLAB-based Graphical User Interface (GUI) to calculate STP, NCA, pMTF, NNPS and DQE based on the relevant IEC standards [6-7]. It can be used to analyse edge and flat-field X-ray images of CR and DR detectors in TIFF or DICOM format. The STP and NCA parameters can be calculated from flat-field images at various DAK levels. The pMTF can be calculated from a tilted edge X-ray image (at high DAK level) and the NNPS from a flat-field X-ray image at an average clinical DAK level (depending on the diagnostic imaging modality). Several parameters need to be set before the processing (see Figure 1): *Modality* (Radiography or Mammography), *Pixel Pitch* (in mm), *Laterality* (Left or Right – only for analysis of Mammographic X-ray beam qualities based on the European Guidelines for QA in Digital Mammography [8]; also known as EUREF), processing ROI (IEC or EUREF), *Linearization* method (STP or IEC), *SNR^2 Input* value (depending on the used X-ray beam quality [6-8]) and *Freq. bin* (in line pairs per mm (lp/mm) – 0.5 lp/mm suggested by the IEC standards [6-7] or 0.25 lp/mm suggested by EUREF [8]). When DICOM images are analysed the user has the option to automatically extract the values of the first three parameters (*Modality*, *Pixel Pitch* and *Laterality*) for the DICOM Header of the X-ray images.

![Figure 1. Parameters that need to be set for analysis using RAD_IQ](image)

The software (executable MATLAB-based GUI) is freely available [13] to be used from Medical Physicists, Biomedical Engineers and Researchers without any programming experience. They just need a small number (e.g. 4-7) of flat-field X-ray images at various DAK levels for STP and NCA analysis, an edge X-ray image for pMTF and DQE analysis, and a flat-field image at a reference DAK level for NNPS and DQE analysis.
3. Results and discussion

3.1. STP and NCA results
Figure 2 shows the STP and NCA results for a DR detector used in Diagnostic Radiology. It can be seen that the detector’s response is perfectly linear (the coefficient of determination $R^2$ is 1) and quantum noise is more than 80% (i.e. the detector demonstrates a quantum-limited behaviour) in the DAK range 1-20 µGy.

![Figure 2. STP and NCA results for a Radiographic DR detector](image)

3.2. pMTF and NNPS results
Figure 3 shows the horizontal and vertical pMTF and 1D NNPS curves of the aforementioned DR detector at a given DAK (2.5 µGy for NPS). The 2D NNPS is also shown and can be used to detect the presence of any potential artefacts (from horizontal and/or vertical FPN, the presence of anti-scatter grid, EMI noise etc). RAD_IQ also shows the horizontal and vertical pMTF50 and pMTF10 (i.e. spatial frequencies in lp/mm that correspond to MTF equal to 50% and 10% levels, respectively), and angle of the edge (ideally in the range 1.5-3 degrees according to the IEC standards [6-7], however angles up to 5 degrees are also acceptable [8]). RAD_IQ also calculates the horizontal and vertical NNPS(0.5) and NNPS(2), i.e. the NNPS values at 0.5 and 2 lp/mm, respectively. These values can be used from Medical Physicists during routine Quality Assurance (QA) to evaluate the performance of digital X-ray detectors over time.

![Figure 3. pMTF and NNPS results for the aforementioned DR detector](image)
3.3. DQE results
As aforementioned, the DQE is calculated from the combination of pMTF, NNPS, DAK and Fluence per Air Kerma ratio. Figure 4 shows the respective horizontal and vertical DQE results (for the aforementioned DR detector) as a function of spatial frequency up to the Nyquist Frequency as suggested by the IEC standards [6-7]. The software also calculates the horizontal and vertical DQE(0.5) and DQE(2), i.e. DQE values at 0.5 and 2 lp/mm, respectively.

![Figure 4. Respective DQE results](image)

3.4. Software validation

*OBJ_IQ_Reduced* [14] has been considered for more than 10 years the gold standard software for quantitative image analysis of digital X-ray detectors. *RAD_IQ* was validated against this software in terms of pMTF and 1D NNPS for given edge and flat-field X-ray images. Regarding pMTF, the average absolute value of the relative difference was 2.5%.

![Figure 5. pMTF validation against OBJ_IQ_Reduced](image)
The respective average absolute value of the relative difference for the 1D NNPS was 3.8%.

![Figure 6. 1D NNPS validation against OBJ_IQ_Reduced](image)

These results demonstrate that RAD_IQ compares well against the well-established OBJ_IQ_Reduced software and can be used as an alternative tool for quantitative image analysis.

All RAD_IQ results and figures can be saved to a specific Excel file that has been developed to store the data.

4. Conclusions
This study suggests RAD_IQ, a novel and free MATLAB-based software for X-ray performance evaluation (in terms of STP, NCA, pMTF, NNPS and DQE) of CR and DR detectors used in General Radiography and Digital Mammography. The processing algorithms are based on the respective IEC standards [6-7]. The users also have the option to select Mammographic processing conditions suggested by EUREF [8]. It has been demonstrated that RAD_IQ compares well against the well-established OBJ_IQ_Reduced and can be considered a valid alternative software for quantitative X-ray image analysis. Finally, it can be used by Medical Physicists, Biomedical Engineers and researchers without any programming experience.

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5. References
[1] Konstantinidis A 2014 Physical Parameters of Image Quality Comprehensive Biomedical Physics vol 2, ed Brahme A. (Amsterdam: Elsevier) pp 49-63
[2] ICRP Publication 103 2007 The 2007 Recommendations of the International Commission on Radiological Protection, ed Valentin J (International Commission on Radiation Protection)
[3] Lança L and Silva A. 2009 Digital radiography detectors-A technical overview: Part 2 Rad. 15 pp. 134–38
[4] Konstantinidis A C, Szafraniec M B, Rigon L, Tromba G, Dreossi D, Sodini N, Liaparinos P F, Naday S, Gunn S, McArthur A, Speller R D and Olivo A 2013 X-ray Performance Evaluation of the Dexela CMOS APS X-ray Detector Using Monochromatic Synchrotron Radiation in the Mammographic Energy Range IEEE Trans. on Nucl. Sc. 60 3969-3980
[5] Konstantinidis A 2011 Evaluation of digital X-ray detectors for medical imaging applications (London: University College London)
[6] IEC 62220-1-1 2015 Medical electrical equipment - Characteristics of digital x-ray imaging devices - Part 1-1: Determination of the detective quantum efficiency - Detectors used in radiographic imaging (Geneva: International Electrotechnical Commission)
[7] IEC 62220-1-2 2007 Medical electrical equipment - Characteristics of digital x-ray imaging devices - Part 1-2: Determination of the detective quantum efficiency - Detectors used in mammography (Geneva: International Electrotechnical Commission)
[8] EUROPEAN COMMISSION 2013 European guidelines for quality assurance in breast cancer screening and diagnosis Fourth Edition Supplements
[9] Michail C, Valais I, Martini N, Koukou V, Kalyvas N, Bakas A, Kandarakis I and Fountos G 2016 Determination of the Detectable Quantum Efficiency (DQE) of CMOS/CsI Imaging Detectors following the novel IEC 62220-1-1:2015 International Standard Rad. Meas. 94 8-17
[10] Linardatos D, Koukou V, Martini N, Konstantinidis A, Bakas A, Fountos G, Valais I and Michail C 2021 On the Response of a Micro Non-destructive Testing X-ray Detector Materials 14 888
[11] Cunningham I A 2000 Applied linear-systems theory Handbook of medical imaging. Volume 1: Physics and Psychophysics vol 1, ed J Beutel, H L Kundel and R L Van Metter (Bellingham, Washington: SPIE Press) pp 36–57
[12] Buhr E Gunther-Kohfahl S and Neitzel U 2003 Accuracy of a simple method for deriving the presampled modulation transfer function of a digital radiographic system from an edge image Med. Phys. 30 pp 2323–31
[13] RAD IQ 2021 Software for quantitative image analysis of digital X-ray detectors available online: http://aktivag.uniwa.gr/
[14] Marshall N W 2009 Calculation of quantitative image quality parameters – notes describing the use of OBJ_IQ_reduced NHSBSP equipment report 0902