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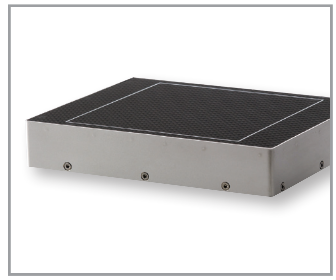
X-RAY IMAGING



"Noise Equivalent Dose" – Comparing low-dose detector quality

IMAGE SENSORS | **X-RAY DETECTORS** | SCANNERS | IMAGE PROCESSING | CUSTOM SOLUTIONS

Patient care

In today's medical community, minimally invasive procedures are rapidly becoming the standard of care. While hospitals benefit from a reduced risk of complications and patient recovery costs, patients themselves enjoy early release from hospital and reduced post-operation complications and cosmetic consequences.

During a minimally invasive procedure, surgeons rely on the use of fluoroscopic X-ray images for visual feedback to guide their instruments inside the patient's body. The X-ray detector is acting as the surgeon's eyes, delivering high-quality images in real time to coordinate precise hand and instrument movements.

Given increasingly stringent patient X-ray dose regulations, hospitals need to be sure to choose the detector that delivers the best possible image quality with the lowest possible radiation.

Real-time X-ray imaging technologies

Today's digital interventional X-ray equipment uses one of the following X-ray imaging technologies to capture the patient's anatomical features:

X-ray Image Intensifiers with CCTV cameras

The prevailing real-time X-ray imaging principle. As the name suggests, the electron image created by the x-rays in the input scintillating screen is intensified using a century-old technology of high-voltage electron acceleration in vacuum. The optical image on the much smaller output scintillator is imaged onto a small CCD-sensor. The principle is conceptually similar to an inverted CRT tube.
Although praised for their very good image quality at low-dose levels, II-CCD systems are also notorious for their bulk and size, restricting patient access, as well as their susceptibility to significant image distortion and reduced sensitivity performance at extended lifetimes.

Amorphous silicon (or Thin Film Transistor, TFT) flat detectors

Originally developed for static digital radiography (DR), this technology relies on a manufacturing technology similar to that of LCD displays. TFT technology, despite limitations on minimum pixel size, still allows for pixel dimensions the application could use. However, relatively high ohmic resistivity of control electrodes limits the maximum frame rates to low tens of frames per second, while low-dose image quality remains inferior to II-CCD systems. Still, many practitioners prefer flat detectors for their unobtrusiveness, improved patient access and absence of image distortions.

CMOS flat detectors

An emerging technology, flat X-ray detectors use high-quality mono-crystalline complementary metal oxide semiconductor (CMOS) pixel technology and deliver on the promise to combine excellent low-dose image quality with the compact flat detector form factor as demanded by today's healthcare practitioners.

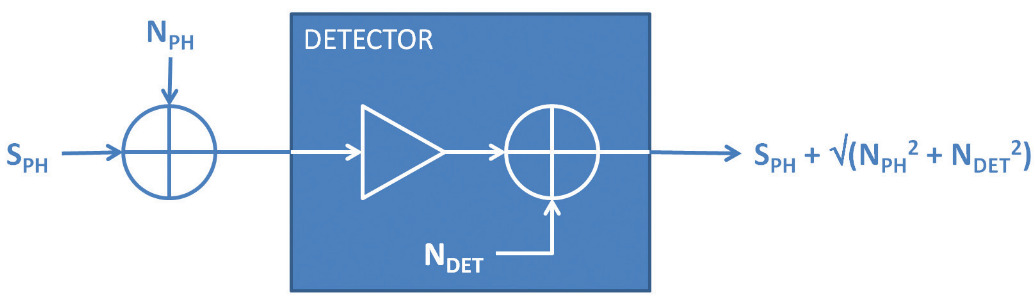
Noise Equivalent Dose (NED)

To compare the image quality of X-ray detectors, the world's standard of metric is Detective Quantum Efficiency or DQE. As a function of spatial resolution, DQE describes how well a detector is capable of maintaining the Signal-to-Noise ratio (SNR) of the X-ray image while converting the X-ray signal into a digital image. Despite its undisputed reputation, the DQE metric is quite complex and its precise measurement is challenging due to the sensitivity to small variations in the measurement conditions and the complex calculation process.

A more straightforward metric that is very effective in describing the low-dose image quality of a particular detector is Noise Equivalent Dose, or NED. Combining the detector's response sensitivity to incoming X-rays and its noise behavior, the NED parameter indicates at which X-ray dose level the X-ray photon shot noise signal equals the intrinsic detector noise floor. Lower NED values signify better image quality under low-dose conditions, enabling better diagnostics and/or reduced patient dose.

When the X-ray source is switched off, the only signal that is visible in the captured images is signal that is generated by the detector itself. We refer to this as "detector noise" or "instrumentation noise" (N_{DET}), typically consisting of read noise and dark current shot noise. At the other end of the intensity scale, when a large X-ray signal (S) is present, the influence of any detector noise is small and the SNR in the image is fully determined by the Poisson statistics[1] of the X-ray photon shot noise (N_{PH}).
As $N_{PH} = \sqrt{S}$:

$$N_{TOTAL} = \sqrt{N_{DET}^2 + N_{PH}^2} = \sqrt{N_{DET}^2 + S}$$

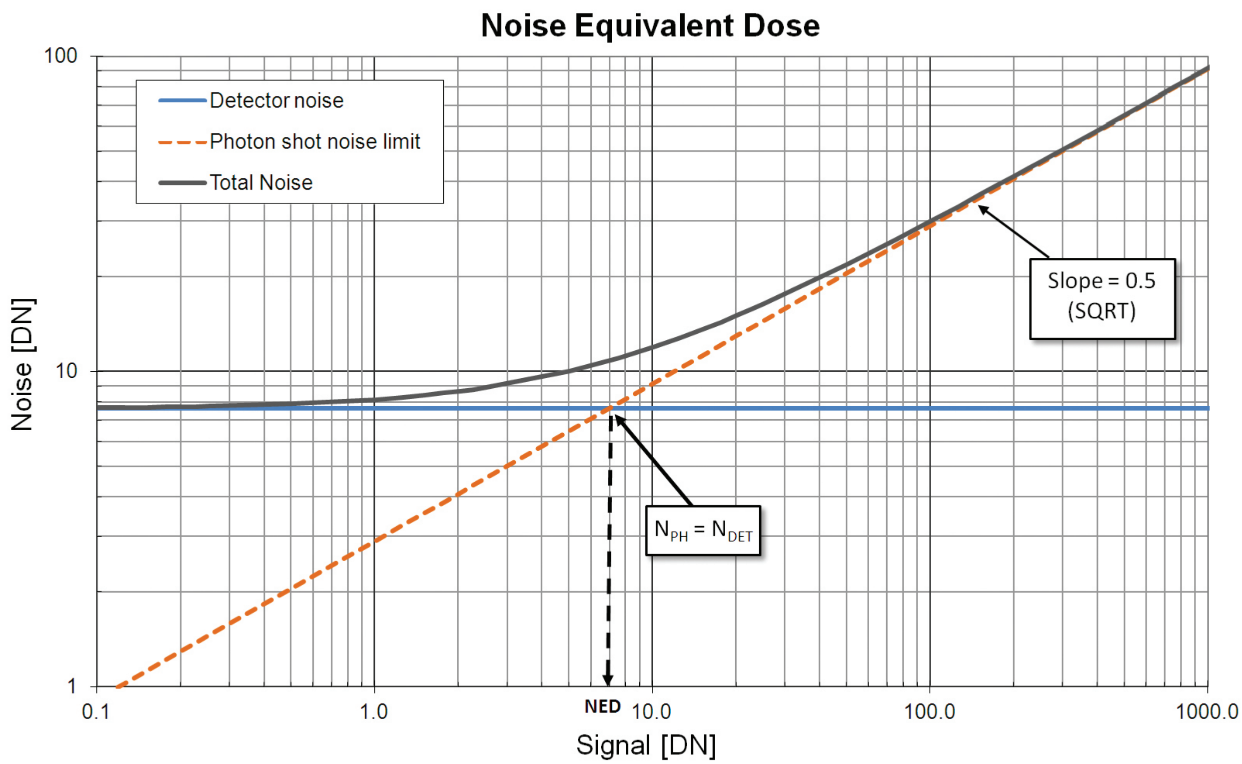


When plotting a graph of the noise versus output signal of the detector (in bits or Digital Numbers [DN]) on a log-log scale (see next page), it can be easily observed in which signal range the image quality is photon shot noise limited, or below which level (the NED cross-over point) the detector's noise characteristic becomes the limiting factor in image quality. In the imaging community, the Noise(S) graph below is commonly referred to as the Photon Transfer Curve.

At the detector's NED exposure conditions[2], the image SNR will be reduced by a factor of $\sqrt{2}$ compared to the input X-ray quantum SNR. This corresponds to the dose at which the detector's DQE(0) performance is reduced by a factor of 2.

[1] For a more in depth explanation, see e.g. http://en.wikipedia.org/wiki/Shot_noise

[2] Yadava et al.; Phys Med Biology 53(18), 5107-5121 (2008)



Understanding the NED metric

Focusing first on the right side of the graph, at high signal levels where $N_{PH} >> N_{DET}$:

$$SNR = \frac{S}{N} = \frac{S}{\sqrt{N_{PH}^2 + N_{DET}^2}} \cong \frac{S}{N_{PH}} = \frac{S}{\sqrt{S}} = \sqrt{S}$$

This part of the curve is commonly referred to as the “photon shot noise limited” detection regime, in which the detector’s noise performance is negligible and the output SNR is determined by X-ray quantum noise. The only way to improve the SNR of an image is to increase the dose to the patient, which is often not desirable. In other words, the quality of the detector is important if you are concerned about patient dose reduction.

At low dose levels, the two important drivers for good image quality are the intrinsic noise of the detector and the sensitivity of the detector to incoming X-rays. The dominant detector noise contributors are typically read noise and dark current noise, the latter becoming more important at higher temperatures and longer integration times. Detector read noise is determined by the detector pixel technology and the quality of the electronics used to drive the signals out of the pixel array and convert them to digital information.

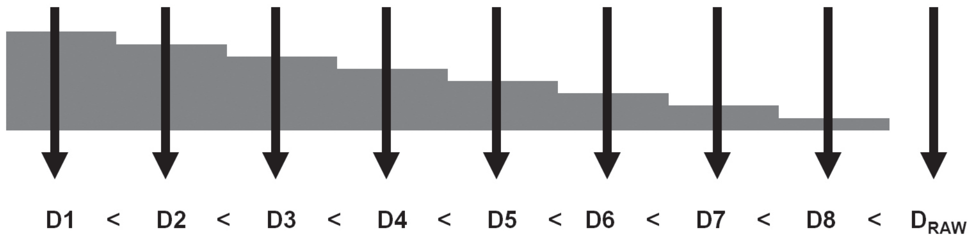
In order to obtain photon shot noise limited detection of X-rays at the lowest possible dose levels, it is important to use a detector with negligible noise compared to the generated X-ray signal and by selecting a detector that delivers a high output signal per incoming X-ray photon. This higher “conversion gain” (expressed e.g. in [DN/nGy]) will help lift the X-ray signal above the detector noise floor at lower dose levels to the patient.

Measuring NED

To determine the NED of a detector, it is sufficient to capture only a very limited number of images:

- Two dark images in the absence of X-rays
- Two X-ray images of a step-wedge phantom
- One averaged dark image in the absence of X-rays (for offset calibration)
- One averaged X-ray image without the step wedge phantom (for gain calibration)

As indicated below, a step wedge phantom is a staircase-like solid object with separate locations, each having a different X-ray attenuation factor. The average signal reading at each of the steps, and in the raw X-ray beam region outside the phantom, will give you readings of the detector output signal at a number of different dose conditions.



Using identical raw X-ray beam conditions in combination with the step wedge phantom, the response and noise characteristics of different detectors can easily be compared as the dose conditions under each of the steps will also be the same for both detectors.

In the case where no step wedge phantom is available for the test, the detector's signal response at different X-ray dose conditions can also be probed by taking individual exposures at different mAs settings, ensuring these settings are identical for each detector that is being compared.

Selecting appropriate Regions-Of-Interest (ROI's) in each step of the averaged step wedge images gives a series of signal (response) values for each detector under a series of identical dose conditions. It is advised to perform an offset-and gain-calibration on the averaged image prior to determining the ROI levels, in order to correct for any spatial non uniformities in the detector's response.

From the difference ΔI of two images (I_1 and I_2), the total image noise in the different ROI's can be calculated for both dark and step wedge images:

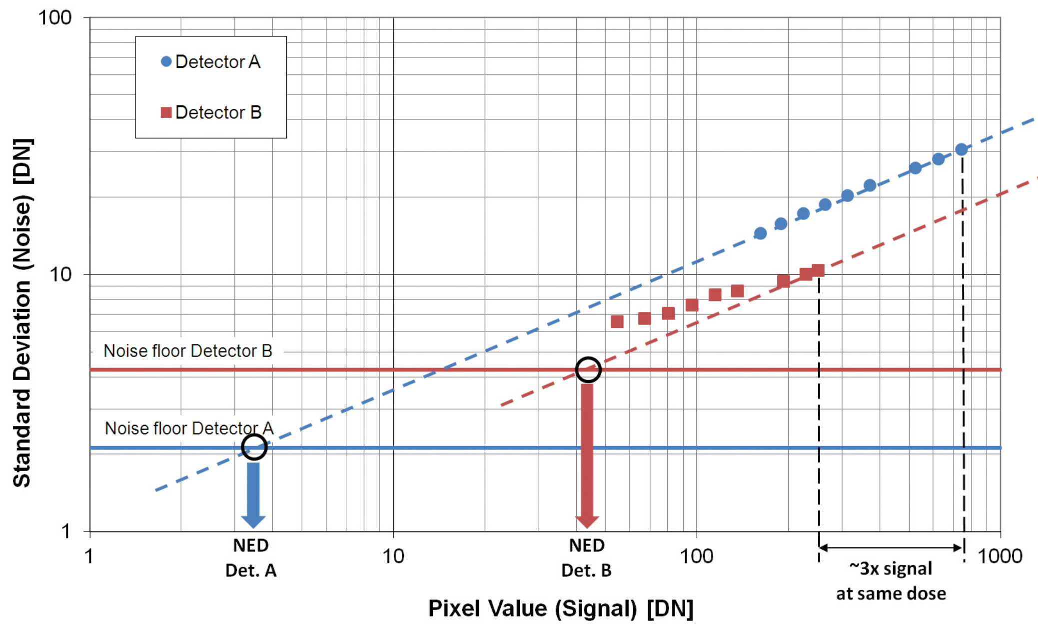
$$I_i = S_i + N_i$$

$$\Delta I = I_2 - I_1 = (S_2 - S_1) + \sqrt{N_2^2 + N_1^2} \cong N\sqrt{2}$$

Subtracting two 'identical' images also helps isolating the temporal noise contributors by cancelling out spatial-yet-constant variations in signal offset and photo response non-uniformity.

Comparing Results

The chart below shows an example of results obtained from two different X-ray detectors using the step wedge method described above. Both detectors have a 14-bit full scale output range. Each dot marker represents a particular position on the step wedge phantom, and the solid horizontal lines are the measured detector noise levels. The trend lines shown in the chart represent the photon shot noise limited response characteristics, i.e. where $N \propto \sqrt{S}$.



As demonstrated by the values on the horizontal axis, the signal levels in these tests are very low (~10nGy or 1uR per frame). Such is needed in order to find the operating range of the detectors in which the contribution of the detector noise becomes a relevant factor. Remembering that the respective measurement dots on the two curves represent measurements under identical dose conditions, it is easily observed that Detector A is approximately 3x more sensitive, i.e. delivers 3x the signal per incoming X-ray, compared to Detector B.

While Detector A still shows operation in photon shot noise limited mode, the response of Detector B clearly shows evidence of detector noise becoming increasingly dominant, or possibly of non-linearity in the detector's low signal response.

The signal level (DN value) at which the extended photon shot noise lines intersect the detector's noise floor defines the NED performance (in [DN]) of each detector. Combined with the dose sensitivity characteristic (e.g. expressed in [DN/nGy]) at the particular X-ray beam quality that is relevant to your procedure, the NED[DN] value can easily be converted to a true dose level (in [nGy] or [uR]) defining the dose limit below which the image quality is compromised by the detector's noise behavior.

The table below summarizes key detector output data for the thickest location on the step wedge phantom (the left most measurement dots), where dose to the detector is lowest:

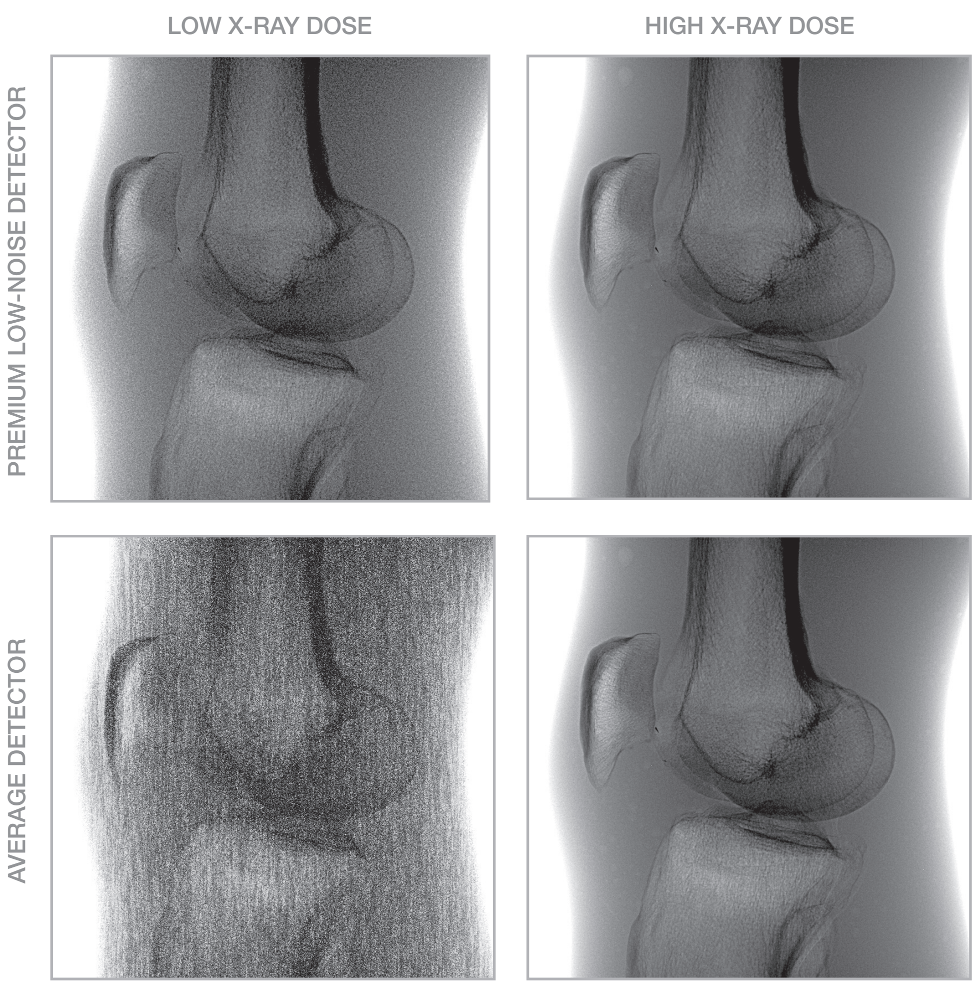
Parameter	Detector A	Detector B
Signal	162 DN	54.4 DN
Total Noise	14.5 DN	6.6 DN
Detector Noise (no X-ray)	2.11 DN	4.26 DN
Signal/Total Noise	11.2	8.3
Signal/Detector Noise	76.8	12.3

Apples-to-Apples

Finally, there are a few cautionary notes to consider when comparing NED performance between detectors:

- Be absolutely sure that the measurements were performed under identical X-ray beam quality conditions (kV/mAs, beam filtration, SID), and using the same equipment.
- Make sure that the images are captured using the same integration time across detectors. Longer integration times will increase the dose per image and therefore the average signal level.
- Always compare detector sensitivity based on equalized pixel pitch (or per pixel unit area). Larger pixels 'see' more X-rays per unit time at any given dose level, which does not necessarily imply they are more sensitive per unit area, i.e. create more output signal (bits) per incoming X-ray photon.
- When comparing detector response and noise figures, ensure that these relate to the same full scale output value. Consider which detector is more sensitive at a specific dose level: a 12-bit detector delivering an average signal level of 2500DN, or a 14-bit detector delivering an average signal of 5000DN?

Being so much more than a "poor man's DQE", the NED metric will enable you to assess and compare the raw low-dose image quality of X-ray detectors in a quick and transparent manner.



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