X-ray imaging using amorphous selenium: Determination of Swank factor by pulse height spectroscopy

I. M. Blevis, a) D. C. Hunt, and J. A. Rowlands
Sunnybrook Health Science Centre, Imaging Research, The University of Toronto, 2075 Bayview Avenue, Toronto, Ontario M4N 3M5, Canada

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The use of photoconductors, especially amorphous selenium (a-Se), in x-ray imaging is currently of interest. A critical performance parameter of an imaging detector is the Swank factor for degradation of the signal to noise ratio, or DQE(0), due to variations in the detector response. The Swank factor is evaluated from measured pulse height spectra generated by the absorption of monoenergetic x-ray photons. The spectra show an additional width over previous theoretical expectations, but the Swank factor is still close to the high values previously predicted theoretically. © 1998 American Association of Physicists in Medicine. [S0094-2405(98)00905-5]

Key words: amorphous selenium, Swank factor, digital, x-ray, imaging

I. INTRODUCTION

In digital x-ray imaging, a variety of imaging detector systems are being investigated and compared to determine their suitability for use in clinical radiology. One of the most promising approaches utilizes an active matrix flat panel as a large area readout circuit. The x-rays are converted to electric charge for readout using one of two general methods. In the indirect method an x-ray sensitive photoconductor and a bias electrode are both fabricated directly on the readout panel for conversion of the x rays to charge without intermediary steps. The direct approach has the potential to achieve simultaneously the highest resolution, sensitivity, and image quality. The photoconductor that has received and continues to receive the most attention for this purpose is amorphous selenium (a-Se).

The image quality available using the direct approach with a-Se is related to the signal strength and the sources of noise. The signal strength is closely related to the x-ray to amorphous selenium and image quality. The photoconductor that has received and continues to receive the most attention for this purpose is amorphous selenium (a-Se).

The fluctuations in the conversion gain are a potential source of noise. They have been studied theoretically for a-Se in the mammographic energy range. Four contributing processes were considered. The nonlinear field-dependent discharge and the incomplete detector coupling do not apply to the present case of a constant bias applied with contact electrodes. The stochastic variation of the gain was estimated from the Poisson statistics of the final charge and found to be small. The dominant, though still small, theoretical effect was found to be due to the escape of K-fluorescence x-ray photons. Our own experimental measurements of pulse height spectra from a-Se using monoenergetic x rays in the radiological energy range have shown an additional, relatively large, and previously unidentified source of gain fluctuations. Thus, the purpose of the present investigation is to determine the noise contribution to digital imaging from the measured gain fluctuations in a-Se.

II. THEORY

The relative increase in image noise due to an imaging system is expressed quantitatively by the detective quantum efficiency (DQE). The DQE is defined in terms of the signal to noise ratio (SNR) output by an imaging system compared to that which was input: DQE=SNR_out/SNR_in. In general, the DQE is a function of spatial frequency f with a maximum of DQE(0) at f=0. For a system with a quantum efficiency A_q, the increase in the relative statistical noise causes the ratio SNR_out/SNR_in to be decreased by the factor A_q^\frac{1}{2}, and thus DQE(0)\approx A_q. Also, if the signal transduction for a fixed input results in a spectrum of responses x, with probability distribution P(x), then there is an additional factor first identified by Swank: A_q^\frac{1}{2} A_s for the decrease in SNR_out/SNR_in, and thus DQE=A_qA_s. For a distribution with an nth moment M_n defined by

\[ M_n = \int x^n P(x) dx, \]  

the value of A_s is calculated as

\[ A_s = \frac{M_2}{M_0} \frac{M_1}{M_1}. \]  

Using the definitions of the mean and standard deviation of a distribution:

\[ \mu = \frac{M_1}{M_0}, \quad \sigma^2 = \frac{M_2}{M_0} - \left( \frac{M_1}{M_0} \right)^2, \]  

allows A_s to be calculated directly from the distribution parameters:

\[ A_s = \frac{\mu^2}{\mu^2 + \sigma^2} = \frac{1}{1 + \sigma^2_{\mu}}, \]  

\[ A_s \] is the Swank factor.

\[ A_s = \frac{\mu^2}{\mu^2 + \sigma^2_{\mu}}, \]
where \( \sigma_{rel} = \sigma / \mu \). From Eq. (4), it can be seen that \( A_s \approx 1 \) for \( \sigma_{rel} \ll 1 \). The uncertainty in \( A_s, \delta A_s \) can be estimated from the uncertainties of the fitted parameters, and is given by

\[
\delta A_s = 2(A_s \sigma_{rel})^2 \sqrt{\left( \delta \mu_{rel} \right)^2 + (\delta \sigma_{rel})^2}.
\]

(5)

### III. Measurement

The method of pulse height spectroscopy, described in detail elsewhere,\(^8,10\) was used to measure the response to x-rays in a sample of \( a\)-\( Se \). Briefly, photons in the diagnostic x-ray energy range \( 40 < \epsilon < 140 \) keV from isotopic and fluorescent sources were incident on an \( a\)-\( Se \) layer. An electric field in the range \( 4 < E < 30 \) V/\( \mu m \) was applied through metal electrodes in contact with the layer. The absorbed photons produced charge pulses that were measured on the electrodes. The charge pulses were shaped in a multichannel analyzer and then sorted according to size in a multichannel analyzer to obtain the response distribution. Figure 1 shows the design of the apparatus. Because of the low carrier mobility in \( a\)-\( Se \), a larger shaping time constant than usual for charge pulse spectroscopy and lower counting rates were employed.

The \( a\)-\( Se \) sample was obtained from a Xerox 125 mammography plate with a measured thickness of 150 \( \mu m \). It consists of a structurally stabilized, trap compensated alloy of \( a\)-\( Se \) with a protective polymer coating.\(^11\)

Figure 2 shows a typical source-dependent spectrum of pulse amplitudes consisting of a single peak located above the low-amplitude noise. The axis has been calibrated in terms of electronic charge referred to as the preamplifier input. A fitted Gaussian curve with fitted mean \( \mu_\epsilon \) and width \( \sigma_\epsilon \) has also been added. The location of the K-escape peak is also indicated, but the spectral width obscures its detection. Figure 2 also shows a pulser spectrum indicating the measured level of electronic noise is much less than the spectral width. Therefore, it is concluded that the width is mainly due to processes in the \( a\)-\( Se \).

Excessive carrier trapping or unusually low transit time in the sample was not expected, but was ruled out as an explanation of the spectral width by a number of checks. The signal magnitude was seen to be invariant with increases in shaping time, indicating that the shaping time was adequate to collect all the charge. It was also invariant when the lowest \( \epsilon \) source was positioned either on the top or the bottom of the apparatus in Fig. 1, indicating that trapping of slower carriers was not occurring. Independent time of flight measurements on such samples have also indicated adequate carrier mobilities and lifetimes. Since the measured widths are found not to be the results of carrier trapping, they are assumed to be intrinsic and therefore true for thicker layers of \( a\)-\( Se \) as well, up to the onset of trapping effects.

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<th>( E ) (V/( \mu m ))</th>
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<th>( \sigma_\epsilon )</th>
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Figure 1. Layout of the spectrometer showing a \( \text{\(^{241}\)Am} \) source of \( \epsilon = 60 \) keV photons, in a \( \text{Pb} \) collimator. The \( a\)-\( Se \) layer on the Al substrate with an In top electrode is in the Al shielding box. The signal is conducted out of the box to the amplifier chain, Amp, and then to the multichannel analyzer, MCA, for spectral analysis.

Figure 2. A typical calibrated pulse height spectrum. The smooth line indicates a Gaussian fitted curve with position \( \mu_\epsilon \) and width \( \sigma_\epsilon \). The expected location of the K-escape peak is indicated. The pulser spectrum indicates the concurrent level of electronic noise.
For the purpose of calculating $A_s$, the fitted spectral widths were corrected for the noise measured at each value of $E$ by subtraction in the quadrature of the Gaussian measured pulser width. Table I gives the corrected values of $\mu_g$ and $\sigma_g$ as a function of $E$ and $\varepsilon$ along with their errors estimated from the shape of the $\chi^2$ function for the Gaussian fits. The corrected Gaussian parameters were then used in Eqs. (4) and (5) for $A_s$ and $\delta A_s$. The results for $A_s$ plotted against $E$ covering the range of $\varepsilon$ are shown in Fig. 3. They vary within the narrow range 0.96 $< A_s < 1.0$ in the available experimental parameter range. The calculated error bars are shown except where they are smaller than the marker symbols.

To compare with theory the empirical values of $A_s$ are replotted against $\varepsilon$ for $E = 10, 20,$ and $30 \text{ V/\mu m}$ in Fig. 4. The theoretical curve for a 100 $\mu$m $a$-Se layer with low $\varepsilon$ and $E = 10 \text{ V/\mu m}$ is also shown. In the region of overlap the experimental values are seen to lie slightly lower than the theoretical prediction due to the increased measured spectral width, but the agreement is still good. Thus, except for mammographic energies that lie close to the K-absorption edge of $a$-Se, $A_s$ is found to be very close to the maximum value of unity for x-ray transduction. Close to the mammographic energies the theory indicates that the values of $A_s$ are still high.

To compare $a$-Se with an indirect phosphor-based method of digital radiography the theoretical values for an CsI phosphor screen x-ray image intensifier of high mass loading, 0.2 g/cm$^2$ (thickness 443 $\mu$m)$^8$ are also included in Fig. 4. The lower values observed for the CsI in the mid-diagnostic range are due to K-fluorescence escape. The K fluorescence of $a$-Se occurs at the lower end of the diagnostic range. In general, although higher atomic number entails higher x-ray absorption, it also means increased K-fluorescence energies and signal degradation due to escape. Even with the additionally measured signal width in $a$-Se, the values of $A_s$ are higher than those of the CsI screens over most of the diagnostic range.

The implications for the DQE(0) of digital radiography with $a$-Se are that the losses in absorption due to the thickness of practical layers are compensated by the higher values of $A_s$. This makes the DQE(0) of the $a$-Se method and that of methods using CsI screens very close. Figure 5 shows the product $DQE(0) = A_q A_s$ as a function of $\varepsilon$ for a 500 $\mu$m layer and a 1000 $\mu$m layer of $a$-Se for the CsI screen. In the $a$-Se case, the theoretical values of $A_s$ were used for $\varepsilon \approx 40 \text{ keV}$ and the experimental values for $E = 20 \text{ V/\mu m}$ were used for $\varepsilon \approx 40 \text{ keV}$. The values of $A_q$ for the photoelectric effect were taken from standard tables. These particular values of the $a$-Se thickness were chosen to reflect present design values. The results are valid as long as charge trapping in the layers can be ruled out, as it has been for the test samples in this investigation. Figure 5 shows that the DQE(0) for the $a$-Se layers considered even exceeds that of the CsI screen for $\varepsilon$ close to the K-edge energies of Cs and I. These energies are particularly important to many radiological procedures in the human subject.

IV. CONCLUSIONS

The measurement of the pulse height distribution allows the calculation of $A_s$ from the mean and standard deviation of the experimental data. Pulse height spectra from monoenergetic x-ray sources, plotted as a function of $E$.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig3.png}
\caption{A$_s$ calculated from the corrected fitted parameters of the pulse height spectra for monoenergetic x-ray sources, plotted as a function of $E$.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig4.png}
\caption{A$_s$ as a function of $\varepsilon$ from the present measurements and the previous theoretical calculation, and for a thick CsI phosphor screen.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig5.png}
\caption{DQE(0) calculated from tabular $A_q$ data and from the $A_s$ data of Fig. 4.}
\end{figure}
ergetic x rays stopping in an $\alpha$-Se layer were recorded and used to calculate $A_s$. Although the spectral widths have an unanticipated additional width, $A_s$ was found to be very close to previous theoretical estimate at mammographic energies and to be close to the theoretical maximum of unity over the rest of the diagnostic range. The DQE(0) values for (flat panel) digital radiographic systems utilizing $\alpha$-Se is then determined by the practical layer thickness and the readout properties; the gain fluctuation noise component due to the $\alpha$-Se is negligible.

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*Correspondence should be addressed to Dr. I. M. Blevis. Electronic mail: ira@src.sunnybrook.utoronto.ca


