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MTF evaluation of a phosphor-coated CCD for x-ray imaging

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Abstract. A novel digital x-ray detector has been assembled. The imaging system is based on a phosphor-coated charge-coupled device (CCD) obtained by direct deposition of a gadolinium oxysulphide scintillator onto the detector surface. The modulation transfer function has been measured along the two directions of the digital coordinates with the narrow slit technique. A resolution limit of about 20 line pairs per mm has been obtained for both directions. The high spatial resolution currently demanded in mammography can be achieved with this imaging system.

1. Introduction

Charge-coupled devices (CCDs) have been successfully used in several scientific imaging applications. During the last several years, their high performance has also become attractive in the field of radiologic imaging. Small-field mammography systems for stereotactic localization are now available for routine clinical use. All current approaches to digital acquisition make use of a CCD image sensor coupled to gadolinium oxysulphide (GadOx) via a fibre-optics taper or lens (Piccaro and Toker 1993, Roehrig *et al* 1994). These systems provide a high-contrast limiting resolution not higher than 10 line pairs per mm (lp mm^{-1}). One of the major issues in the requirements for a digital mammography system is spatial resolution. For this reason an improvement in resolution capabilities of such an x-ray detector is desirable. A direct deposition of scintillator onto the CCD surface could give enhanced performance (Allen 1994). To this aim a high-resolution CCD x-ray detector based on printed-screen technology is under test in our laboratory. The CCD manufacturing technology employed at EEV (EEV Ltd, Chelmsford, UK) provides good x-ray hardness, enabling the device to be used in mammography without a fibre-optic stud.

The possible clinical use of such a detector depends on its assessment in terms of dose and image-quality characteristics. In this preliminary investigation we have evaluated the MTF of the prototype imaging device. The resolution performance is compared with that of a conventional screen/film mammography system.

2. Materials and methods

A block diagram of the entire imaging chain is shown in figure 1. The key element of the system is the phosphor-coated CCD manufactured to our specifications by EEV. Figure 2 schematically shows the various layers of the detector.

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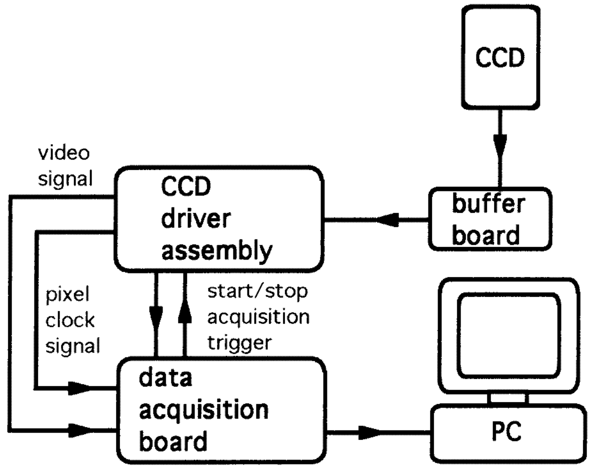

Figure 1. Block diagram of the digital imaging chain.

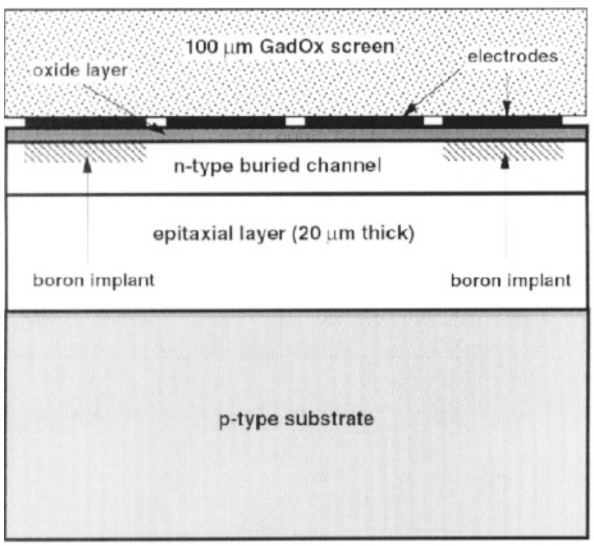

Figure 2. A schematic diagram of the various layers of the phosphor-coated CCD (not to scale). The boron implant refers to an inverted mode device for dark current reduction.

2.1. The CCD

The coated CCD is a grade 5 05-20 inverted mode or multi-pinned phase (MPP) device. The detector has a pixel pitch of 22.5 μm and 770 $\times$ 1152 pixels with a useful surface of 17.3 $\times$ 25.9 mm^2. Nominal CCD performance parameters are listed in table 1.

2.2. Fluorescent screen

A Gd_2O_2S:Eu screen 100 μm thick has been chosen as the scintillator coating. The technology provided by EEV allows one to print the phosphor powder mixed into an ink directly onto the CCD surface. The coating density of the GadOx screen is 50 mg cm^{-2} and the calculated value of light photons per absorbed x-ray of about 22.4 photons/keV (Prior 1996). An x-ray attenuation of about 92% has been calculated with this screen at the molybdenum Kα energy.

Table 1. CCD performance (nominal values).

Peak signal (electrons/pixel)	400 000
Dark signal (electrons/pixel/s) at 293 K	400
Charge transfer efficiency (%)	0.9995
Sensitivity (μV/e$^-$)	2
Readout noise (electrons/pixel) at 140 K	12

The scintillation spectrum of the screen is shown together with the spectra of other scintillators in figure 3. The GadOx:Eu screen presents a peak emission at a wavelength of 630 nm which well matches the spectral response of the CCD reported in figure 4.

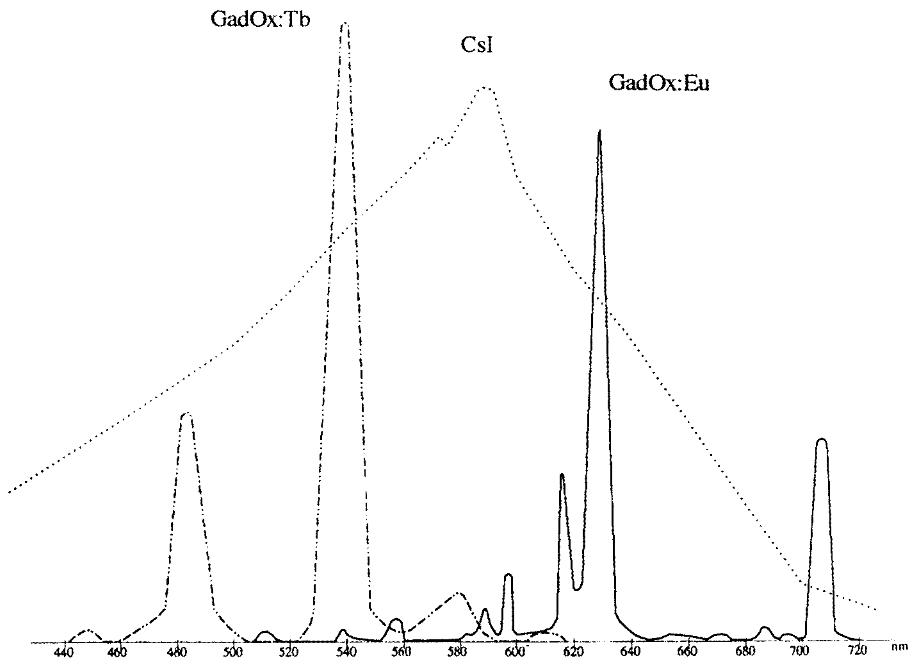

Figure 3. Scintillation spectra of three screens used for coating the CCD (Prior 1996).

2.3. The driver board

All CCD operations are driven by means of an electronics unit also supplied by EEV (CCD driver assembly model CDB01). Its main features are:

(i) slow-scan operation for very low readout noise (rates from 50 kHz to 1 MHz);
(ii) switch adjustment of readout modes (frame transfer/full frame modes, pixel and line binning);

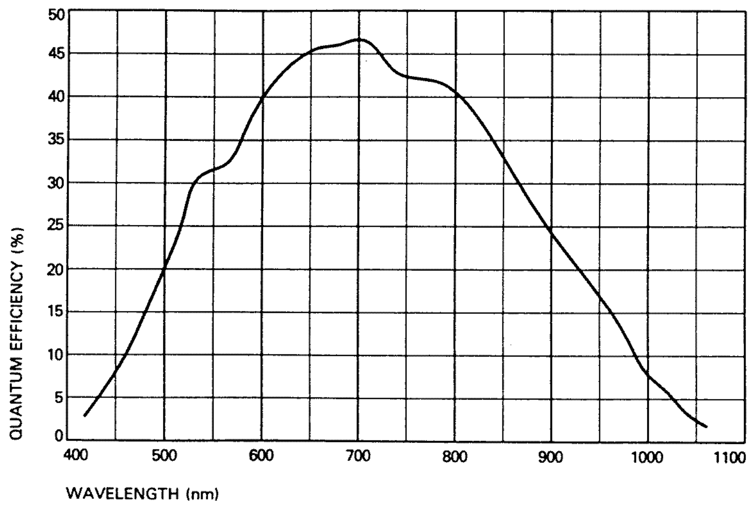

Figure 4. Optical response curve of the CCD (reprinted, with permission, from EEV datasheets).

(iii) gain selection;
(iv) multi-pinned phase mode operation for dark current reduction.

The driver assembly provides an analogue video output as well as pixel clock, line and frame blanking output signals and a 'request for integrate' input to control the CCD integration time.

2.4. Analogue-to-digital converter (ADC)

A commercially available data acquisition board integrated with a personal computer has been used to serially digitize the analogue image area. It is a DT2839 card by Data Translation Inc. that provides 12-bit resolution. The sampling of the ADC used is 500 kHz and is supplied by the pixel clock signal of the CCD driver board so as to ensure a good sampling of the video output. Data are transferred in burst mode via dual channel DMA (gap-free) and saved to disk.

The ADC also provides the trigger for starting the integration of the CCD whilst the trigger for starting the analogue-to-digital conversion is supplied by the frame blanking of the CCD driver board.

2.5. Linearity

The detector response to the x-ray exposure was measured for two kVp values. The CCD was exposed to a beam provided by a Mo-anode Mo-filtered x-ray tube for various settings of the anode current (2 s exposure): for each setting the mean grey level in a central area of the digital image was calculated.

2.6. Spatial resolution

The spatial resolution of the system has been evaluated in terms of a modulation transfer function for both directions of the digital coordinates. The evaluation of each MTF was made by means of the line spread function (LSF) measurement. LSFs were obtained by using the narrow-slit technique. A slit, 10 μm wide and 10 mm long (slit camera model 07-264 RMI), was placed in contact with the screen and imaged by exposure to x-rays at a distance of 66 cm from the focal spot with the tube operating at 28 kVp.

Since a digital imaging system is not shift invariant, the evaluation of the presampling MTF was carried out by the method developed by Fujita *et al* (1985). The overall MTF is the average of two Fourier transforms obtained from extreme alignments (centre and shifted) of the slit relative to the sampling coordinate.

The centre and shifted MTFs of the system were computed by discrete Fourier transform of the sampled LSFs as follows:

$$\mathrm{MTF}(v) = \frac{\left|\sum_{k=-\infty}^{+\infty} \mathrm{LSF}(k\Delta x)\mathrm{e}^{-\mathrm{j}2\pi vk\Delta x}\right|}{\sum_{k=-\infty}^{+\infty} \mathrm{LSF}(k\Delta x)} \tag{1}$$

where Δx is the sampling distance.

Before computing the Fourier transform, the tails of the digitized unprocessed LSFs were extrapolated exponentially to reduce the truncation error (Doi *et al* 1972). Thus, the MTF results from the sum of two contributions:

$$\mathrm{MTF} = \frac{|F\{\mathrm{LSF}(x)\} + F\{a\exp(-x/b)\}|}{\sum_{k=-d}^{+d} \mathrm{LSF}(k\Delta x) + 2\int_{d}^{+\infty} a\exp(-x/b)} \tag{2}$$

where the two constants a and b are determined by assuming that the exponential curve goes through two points of the truncated LSF and d is the truncation distance.

3. Results and discussion

The linear response of the phosphor-coated CCD as a function of x-ray exposure is shown in figure 5. The linear fits of the experimental data show a correlation factor of about 0.999 for both curves.

The resulting MTF curves are presented in figure 6. The resolution properties for both directions are very similar, with a limit frequency (determined from the 4% MTF) of 18 lp mm^{-1} and 20 lp mm^{-1} along the horizontal and vertical direction respectively. The resolution properties of the detector are limited by the light diffusion property of the phosphor layer since the intrinsic modulation transfer function of the 'ideal' CCD sensor is given by the sinc$(a\nu)$ function where a is the pixel size.

The MTF of a screen/film combination (T2/XUD manufactured by 3M) is reported in figure 6 for comparison: the resolution properties of the two imaging systems are very similar. However, it is well known that in mammographic screen/film systems the limit of detectability is due to not only quantum mottle but also lack of contrast because of film granularity. This means that their low-contrast performance is severely impaired beyond spatial frequencies higher than a few cycles per millimetre. A high-resolution quantum-limited x-ray detector could help overcome this restriction.

The high-resolution capabilities of the phosphor-coated CCD are confirmed by the radiograph of a high-contrast test object (besom test model 39 by PTW, Freiburg, Germany) which is presented in figure 7. The distance between two consecutive ticks in the reference scale is 2 lp mm^{-1}. As can be seen, a resolution limit of about 20 lp mm^{-1} is apparent. This value agrees with the results obtained from the experimental measurement of the MTFs.

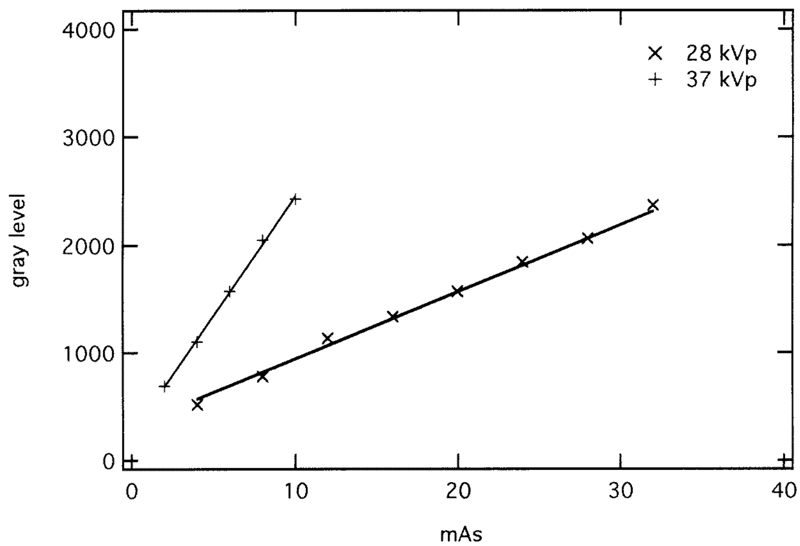

Figure 5. Detector response in terms of grey levels plotted as a function of x-ray exposure for two different kVp settings.

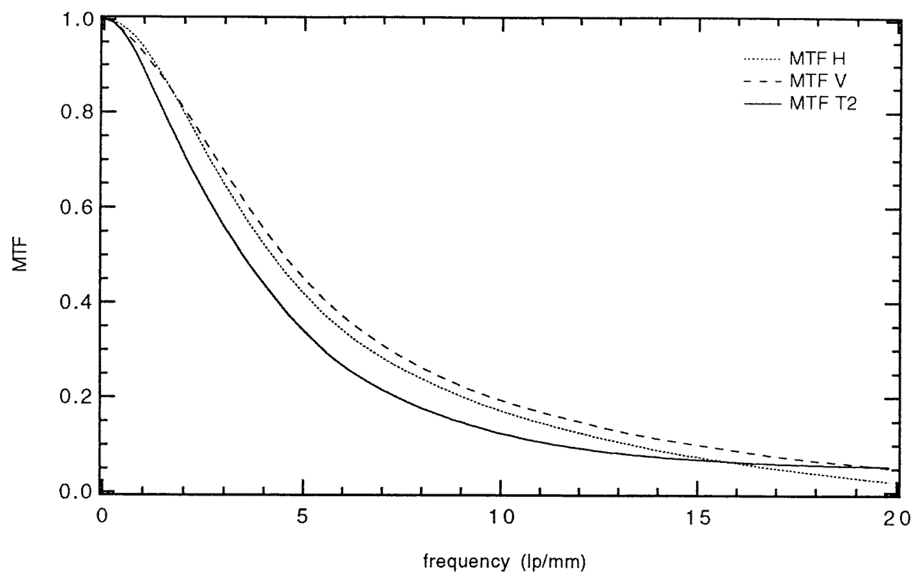

Figure 6. MTF curves obtained along the horizontal direction (dotted line) and the vertical direction (dashed line) of the digital coordinates. The MTF of a conventional screen/film combination made by 3M is reported in comparison (data from Doi *et al* 1986).

The image of the test object was acquired under the same geometrical conditions and kVp setting as those used for the LSF measurement. An exposure of 2.74 μC kg^{-1} (10.6 mR) was delivered at the entrance of the besom test surface. The exposure value, measured with a mammographic ionization chamber and associated electrometer (Radcal Corporation

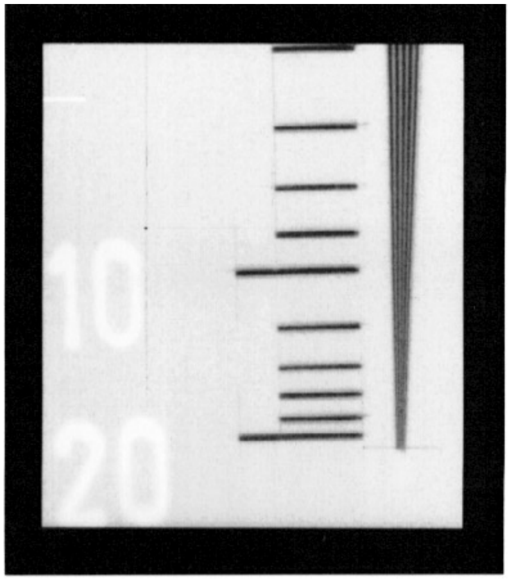

Figure 7. A digital x-ray image of a high-contrast test pattern for determining the visual resolution of the phosphor-coated CCD. The numbers in the reference scale are expressed in lp mm^{-1}. The distance between two consecutive ticks in the reference scale is 2 lp mm^{-1}.

model 10x5-6M chamber with model 1515 radiation monitor and model 1550 converter, with calibration traceable to the NIST), is comparable to the exposure required to achieve a net density of 1.0 for a mammographic screen/film combination (Barnes and Chakraborty 1982).

4. Conclusions

We have demonstrated that a digital x-ray system based on the direct phosphor coating of a CCD can provide a spatial resolution which is as high as that of a conventional screen/film combination for mammography. The full limiting resolution refers to objects with a nearly 100% contrast that do not exist in the breast. This means that the detectability of low-contrast details is limited not only by lack of spatial resolution but also by an insufficient signal-to-noise ratio (SNR). Thus, the performance of a digital mammography system are also related to other imaging characteristics, e.g. dynamic range, detective quantum efficiency, dose delivered to the patient in order to achieve a desired SNR, and ability to accommodate the current field size (18×24 cm^2). Work is in progress to address these issues.

Acknowledgments

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