A New Needle-Crystalline Computed Radiography Detector

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The most successful digital radiography detectors to date have been storage phosphor plates used in computed radiography (CR). The detector is cheap, has good producibility, and is robust. Direct radiography (DR) systems are being developed based on flat-panel technology. Better image quality is claimed for some DR systems. On the other hand, DR detectors have low producibility and robustness, and a high price. A new CR detector is being developed at Agfa that combines the advantages of CR and DR. It is a storage phosphor plate made up of needle-shaped crystals. The phosphor efficiently converts absorbed x-ray quanta into photostimulable centers for efficient read out. It has a large dynamic range and its emission is efficiently detected with both photomultiplier tube (PMT) and charge coupled device (CCD). It is shown that CR systems based on the new detector offer image quality that matches that of the best DR systems.

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APPROXIMATELY 15 years ago, computed radiography (CR) was introduced. CR is a digital radiography system based on storage phosphors. A storage phosphor plate is exposed in a light-tight cassette and then read out in a flying spot scanner. The emitted light is detected with a photomultiplier tube (PMT), whose output signal is digitized to form the image. CR technology is well established. The detector is cheap, has good reproducibility, and is robust.

Direct radiography (DR) systems are being developed that directly convert x-ray signals into electrical signals. DR may lead to higher image quality than CR. Better image quality is claimed for systems based on a-Se that directly convert x-ray quanta in electron-hole pairs. Excellent image quality is claimed for systems that use CsI:Tl scintillator crystals to convert x-rays into light quanta, which then create charges in an a-Si photodiode.

New technology is in development at Agfa (Mortsel, Belgium) that will bring CR image quality at the same level as that of the best DR systems. Better image quality will be obtained by the use of a new excellent storage phosphor.

The characteristics of this new phosphor will be discussed. The detective quantum efficiency (DQE)

of CR systems using this phosphor will be calculated and the result will be compared with the DQE of DR systems.

STORAGE PHOSPHOR IMAGE PLATES

Needle Image Plate Versus Powder Image Plate

Conventional phosphor screens, used in film/screen radiography and the storage phosphor screens in the Agfa, Fuji (Kanagawa, Japan), and Kodak (Rochester, NY) CR systems, are powder screens. The active layer consists of microscopic phosphor crystals, held together by a binder.

The input screen in conventional image intensifiers is a CsI:Na needle screen.¹ It is an array of phosphor needles with a 5- to 10- μ m diameter and a 400- to 500- μ m length.

A needle screen leads to better image quality than a powder screen for two reasons. The needles act as light guides, thereby strongly reducing light spread in the phosphor layer. As a consequence, image sharpness is much higher at equal thickness. Also, no binder is present in a needle screen, which implies a higher phosphor packing density and, thus, a higher x-ray absorption.

CsBr:A Storage Phosphor

Two different storage phosphors are used in commercial CR systems: BaFBr_{1-x}I_x:Eu²⁺ and RbBr:Tl⁺.

The first phosphor is used in the plates of Agfa, Fuji, and Kodak, and now also Konica (Tokyo, Japan). It is an excellent storage phosphor with a high storage capacity² and a relatively high specific x-ray absorption. BaFBr_{1-x}I_x tends to decompose upon vapor deposition, which makes it difficult to grow it in needles.

RbBr:Tl⁺ is used in the chest-stands of Konica.

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It has a simple chemical composition and a cubic unit cell. As such, it can be easily grown in needles.³ Its specific x-ray absorption, for medical x-ray spectra, is, however, much lower than that of $\text{BaFBr}_{1-x}\text{I}_x$. As a consequence, RbBr:Tl^+ needle screens do not lead to better image quality than $\text{BaFBr}_{1-x}\text{I}_x\text{:Eu}^{2+}$ powder screens.

In a cooperation with SYMYX, a company specialized in combinatorial chemistry, Agfa discovered an excellent new storage phosphor, combining the strong points of $\text{BaFBr}_{1-x}\text{I}_x\text{:Eu}^{2+}$ and RbBr:Tl^+ .

Table 1 lists the relevant properties of the new storage phosphor, CsBr:A . Its cubic unit cell allows needle growth. Its chemical composition and density lead to a specific X-ray absorption that is similar to that of $\text{BaFBr}_{1-x}\text{I}_x$.

The new material has a quantum efficiency that is 1.5 times higher than that of $\text{BaFBr}_{1-x}\text{I}_x\text{:Eu}^{2+}$. A 40-keV x-ray quantum produces 600 defect centers for energy storage in CsBr:A versus only 400 for $\text{BaFBr}_{1-x}\text{I}_x\text{:Eu}^{2+}$.²

Finally, the stimulation energy of CsBr:A is $5 \mu\text{J}/\text{mm}^2$ versus $15 \mu\text{J}/\text{mm}^2$ for $\text{BaFBr}_{1-x}\text{I}_x\text{:Eu}^{2+}$. The low stimulation energy allows deeper read-out of the CsBr:A phosphor at equal laser power in a flying spot scanner.

Figure 1 shows the emission spectrum of the new phosphor. The blue emission allows efficient detection with both a PMT and a charge coupled device (CCD) detector. The stimulation spectrum (Fig 2) allows read-out with a cheap, compact diode laser.

IMAGE QUALITY OF CR SYSTEMS

Theory

DQE is a quantitative measure of a system's image quality. The DQE of a CR system has been calculated with the following equation⁴:

$$\text{DQE}(\nu) = \alpha / [1 + \beta + 1/(G \times \text{MTF}[\nu]^2)] \quad (1)$$

where α is the phosphor plate absorption, β is the noise excess factor, G is the gain of the system, and MTF is the modulation transfer function.

Equation 1 is a simplified equation, applicable in

Table 1. CsBr:A Physical Properties

Unit cell	Cubic, bcc
Density	4.44 g/cm ³
Quantum efficiency	15 Defect centers/keV*
Stimulation energy	5 $\mu\text{J}/\text{mm}^2$

*600 defect-centers per 40-keV x-ray quantum.

Abbreviation: bcc, base centered cubic.

Fig 1. Emission spectrum of CsBr:A .

the region where quantum noise predominates. Screen-structure noise and electronic noise are neglected, which is valid for CR systems in the medical x-ray dose range.

DQE of State-of-the-Art CR Systems

DQE for CR systems can be calculated, if the four parameters in equation 1 are known. The calculation is done for a 70-kVp x-ray spectrum, filtered by 20 mm of Al and at a dose of 0.3 mR. A commercial standard storage phosphor plate has an absorption, α , of approximately 55% under these irradiation conditions. According to our own measurements and according to Thoms,² the x-ray signal is amplified to 400 F-centers per absorbed x-ray quantum in a $\text{BaFBr}_{1-x}\text{I}_x\text{:Eu}^{2+}$ phosphor screen. In the read-out process, being relatively inefficient, only about 30% of the F-centers are

Fig 2. Stimulation spectrum of CsBr:A .

stimulated and produce an emission photon. Approximately 50% of the produced photons leave the screen at the detector side and, of these, only approximately 30% are collected by the optical fibers and are guided to the photomultiplier tube. In the PMT, which has a conversion efficiency of 25%, the 400 F-centers that are initially created by one x-ray quantum lead to only five photoelectrons ($400 \times 0.3 \times 0.5 \times 0.3 \times 0.25$). This number is the gain, G , of the system.

The origin of the noise excess factor, β , is the fact that different layers of the powder screen detector have different contributions to the signal^{4,5}. X-ray quanta absorbed in a top layer will give rise to a much larger number of photoelectrons in the PMT than X-ray quanta absorbed in a bottom layer of the screen. Based on data in the literature,⁴ β is assumed to be 0.7 for $\text{BaFBr}_{1-x}\text{I}_x\text{:Eu}^{2+}$ powder screens.

MTF values of 0.64, 0.26, and 0.15 were measured for the Agfa Compact CR system with the standard MD-10 screen at 1, 2 and 3 lp/mm, respectively.

When the parameters for α , β , G and MTF are introduced in equation 1, the DQE curve presented in Fig 3 is obtained. The result is in excellent agreement with the DQE curve obtained experimentally by Dobbins et al for the Fuji CR-system with the most recent generation of standard plates.⁶

DQE of CR Systems With CsBr:A Needle Image Plates

DQE is calculated for a 500- μm thick needle image plate. At this thickness, and for a filling factor of 90%, the absorption, α , is of the order of 85%. The gain of CR with CsBr:A needle IP will be higher for two reasons. First, the number of defect centers will be higher than for $\text{BaFBr}_{1-x}\text{I}_x\text{:Eu}^{2+}$, as indicated in Table 1. Second, due to the lower stimulation energy, 80% of the F-centers will be stimulated and produce photons versus only 30% in $\text{BaFBr}_{1-x}\text{I}_x\text{:Eu}^{2+}$ screens. As a result, the gain, G , will be 20 ($600 \times 0.8 \times 0.5 \times 0.3 \times 0.25$).

A needle screen being more transparent than a powder screen, the noise excess factor, β , is expected to be close to 0.2 as for a CsI:Tl screen used in direct radiography.⁷

The MTF values for a flying-spot scanner with a 500- μm CsBr:A needle IP have been measured and turn out to be similar to those of the Agfa Compact CR system with a standard MD-10 screen (Fig 4).

Based on the values for α , G , β , and MTF, the DQE as a function of spatial frequency has been calculated for a CR scanner with CsBr:A needle screen. The result is shown in Fig 3 in comparison with the DQE of two flat-panel DR systems. Lee et al obtained the DQE values for a 500- μm a-Se system under irradiation conditions that are similar to the conditions assumed in our calculation.⁸ The

Fig 3. DQE as a function of spatial frequency for CR and DR systems.

Fig 4. MTF as a function of spatial frequency for a 250- μm $\text{BaFBr}_{1-x}\text{I}_x\text{:Eu}$ powder screen and a 500- μm CsBr:A needle screen.

DQE values for a system based on a-Si in combination with a 160 mg/cm^2 CsI:Tl scintillator screen have been taken from Granfors.⁹ The DQE values were obtained for a 7-mm Al half value layer spectrum (equivalent to 70 kVp with 20-mm Al filtering) and a dose of 0.5 mR.

CONCLUSIONS

CsBr:A is an excellent storage phosphor. It has better phosphor characteristics than $\text{BaFBr}_{1-x}\text{I}_x\text{:Eu}^{2+}$ and it has the advantage that it can be grown in needles. The emission and stimulation spectra of CsBr:A are well suited for use in a CR system. CsBr:A has a higher conversion efficiency and a

lower stimulation energy, which makes deeper read-out possible at equal laser power.

CR performance can be improved significantly by using a needle screen instead of a powder screen. A needle screen yields images with acceptable resolution at higher coating weight and, therefore, higher x-ray absorption. A needle screen is less turbid than a powder screen, which leads to lower values for the noise excess factor.

Use of a CsBr:A needle screen in an existing CR system leads to significantly improved image quality. Image quality is equivalent to that offered by the best DR systems. This may offer the possibility to reduce x-ray dose in CR imaging.

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