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Monte Carlo simulation-based feasibility study of novel indirect flat panel detector system for removing scatter radiation

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ABSTRACT

The purpose of this study is to investigate the feasibility of a novel indirect flat panel detector (FPD) system for removing scatter radiation. The substrate layer of our FPD system has a Pb net-like structure that matches the ineffective area and blocks the scatter radiation such that only primary X-rays reach the effective area on a thin-film transistor. To evaluate the performance of the proposed system, we used Monte Carlo simulations to derive the scatter fraction and contrast. The scatter fraction of the proposed system is lower than that of a parallel grid system, and the contrast is superior to that of a system without a grid. If the structure of the proposed FPD system is optimized with respect to the specifications of a specific detector, the purpose of the examination, and the energy range used, the FPD can be useful in diagnostic radiology.

Introduction

In plain radiography, the behavior of primary rays from the X-ray tube can be classified according to whether they penetrate without any change in direction, are completely absorbed inside the patient, or interact with the patient and scatter, which is commonly known as scatter radiation or scatter photons [1]. Scatter radiation reaches the detector together with the primary rays and generates an electrical signal in the X-ray detection system, which degrades the image contrast. In a previous study, more than seven times as many scatter photons as incident X-rays were generated in a 20-cm-thick water phantom [2]. There have been many attempts to reduce scatter radiation, and the International Commission on Radiological Protection recommended that in diagnostic radiology, the scatter radiation generated in patients should be removed using a "material with a low attenuation coefficient" [3].

The recent trend in plain radiography is away from film/screen systems and toward digital systems such as storage phosphor systems and indirect/direct flat panel detectors (FPDs) [4]. The grid structure has been used to remove scatter radiation in film/screen systems since the early 1900s [5] and in digital radiography without any new innovative changes except for using a different interspace material and high-density grids. The existing grid system has several shortcomings. First, the shadow of the grid on the detector can cause a grid artifact to appear on the acquired image [6,7]. To avoid this problem, the grid can be moved by motors; however, for a compact system design, a stationary grid system with a high density of 60 lines/cm or more is preferred [8]. The grid pattern caused by grid shadow rarely appeared once the high-density grid began to be used in digital radiography. However, optimization of grid frequency (lines/cm) and of the sampling pitch of the digital radiography system is required to avoid the aliasing artifact [9].

Indirect FPDs have a thin film transistor (TFT) for each pixel size [10]; and hence, the scatter radiation signal would not enter the effective area on the pixel. Therefore, if the Pb in the grid does not block the effective area on the TFT layer, the grid artifact as an aliasing error is not seen. Furthermore, the image quality is improved by adapting the existing grid system, but the exposure dose must be increased to obtain the same image quality. The exposure dose could be reduced if there are no obstructions above the effective area on the pixel, so that the intact effective area is maintained.

We studied the feasibility of a novel CsI-based FPD system with a Pb net-like structure in the substrate layer that matches the

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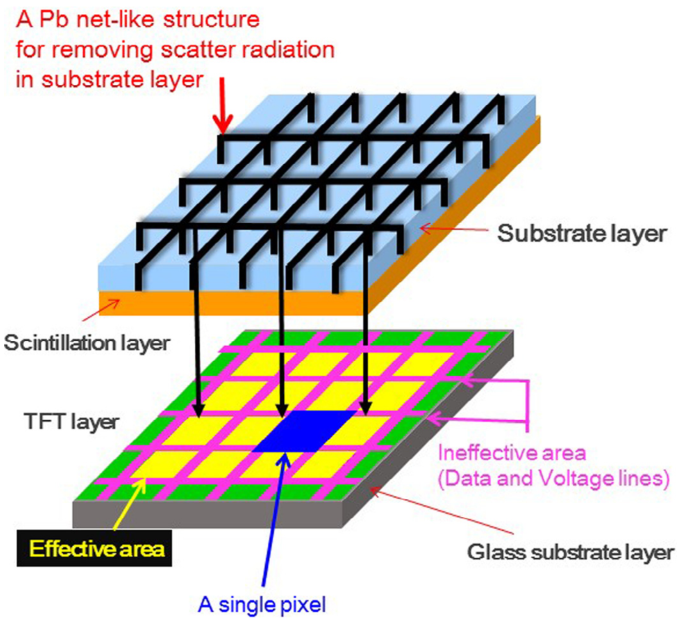

Figure 1. Schematic illustration of the novel CsI-based FPD for removing scatter radiation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

ineffective area and blocks the scatter radiation such that only primary X-rays reach the effective area.

Materials and methods

Concept of the CsI-based indirect FPD system

The indirect FPD comprises three layers: substrate, scintillation layer, and TFT [11]. In most indirect FPDs, there are two different ways to align the scintillation on the top of the CMOS or CCD. One is by direct deposition of the scintillation layer on the CMOS or CCD [12] and the other is by optical coupling of the scintillation layer that is deposited on another substrate such as graphite or an Al plate. Direct deposition is much easier with respect to the fabrication process; however, most manufacturers use the optical coupling technique at present [13]. There have been several studies on the use of the structured scintillation layer in imaging applications [14–16]. Some studies aimed to develop an indirect FPD system with a net-like pixelated CsI scintillation layer meant to enhance spatial resolution and detection efficiency. However, this approach induces scattered light in the scintillation layer. Meanwhile, the TFT layer is a matrix of pixels [17] and ineffective areas where voltage and data lines cross the space between the pixels, and only the effective area of a single pixel can detect the signals [18]. We devised a new FPD system with a Pb net-like structure in the substrate layer that matches the ineffective area in the TFT and blocks the scatter radiation by using the concept of an antiscatter grid so that only primary X-rays reach the effective area (Fig. 1).

Monte Carlo simulation to investigate the feasibility of the FPD system

To investigate the feasibility of our FPD system, we performed Monte Carlo simulations by using MCNPX 2.6.0 software (Los Alamos National Laboratory, Los Alamos, NM, USA) [19]. In addition, SRS-78 software [20] was used to simulate the continuous X-ray spectrum with the following conditions: a tungsten (W) anode, a 12° target angle for the anode, and an additional 0.5-mm-thick copper filter. We calculated the scatter fractions under five simulation conditions: no grid, a parallel grid (Mitaya Manufacturing, Co., Ltd., Saitama, Japan), and three indirect FPD systems. The parallel grid had an 8:1 grid ratio, 60 lines/cm strip density, 0.96-mm-thick Pb septum, and 100-cm focusing distance. Table 1 presents the specifications of the three simulated indirect FPD systems. In this simulation study, the substrate layer was graphite ($_6$C), the density and thickness of which were 2.15 g/cm^3 and 572 µm, respectively. The scintillation layer was CsI (density: 4.51 g/cm^3, thickness: 600 µm), in which the ratio of $_{55}$Cs to $_{53}$I was 1:1. Tally 8 (pulse height tally) was used to record the result of photon absorption in each pixel of the simulated detector; based on the tally option, the energy cutoff was set to 50 eV. The default cross sections of photon interaction were set by using an LCA card and a photon physics card (Phys:P). Because the energy used in this study was in the range of 10–140 keV, a range generally used in diagnostic radiology, we did not modify any physics models in the simulation. Point source radiation was used, and the exposure area was set to cover the entire limited detection area of 2 cm × 2 cm. The source-to-detector distance (SDD) was fixed at 100 cm in all simulation systems. In clinical situations, it is impossible to remove the gap the between the grid and the detector in the parallel grid system. Therefore, for the simulation, we set the air gap between the parallel grid and the detector at 2 cm. The electrons induced by photon interactions were not included as transport particles in this study. In addition, we did not include the results of the simulated optical light photons because this study was about improving the performance of the novel FPD system, not about evaluating the capacity of the CsI used as the scintillation material. The number of histories was controlled to maintain a statistical error <5% [19,21].

Index for evaluating the performance of the novel indirect FPD system: scatter fraction

In diagnostic radiology, the X-rays that reach the detector after passing through the patient consist of a primary component and a scatter radiation component. To investigate the effect of scatter radiation on image quality, it is necessary to determine the values of these two components, I_s and I_p. The effect of scatter radiation on image quality may be in terms of scatter fraction [22]. Scatter fraction is the fraction of total radiation that results from scatter radiation. The performance of the novel indirect FPD system was evaluated using the scatter fraction value. Scatter radiation reduces image contrast, so a low scatter fraction (%) means better image quality. However, it is difficult to measure only the primary or only the scatter radiation under real conditions, although some studies

Table 1
Specifications of three simulated novel indirect FPD systems with different pixel size, thickness of Pb, and effective area of each pixel.

	Simulation #1	Simulation #2	Simulation #3
Matrix size	129 × 129	129 × 129	129 × 129
Total pixel size	153 µm × 153 µm	153 µm × 153 µm	163 µm × 163 µm
Thickness of Pb (ineffective area, µm)	10	20	20
Effective area of each pixel (µm)	143 µm × 143 µm	133 µm × 133 µm	143 µm × 143 µm
Thickness of CsI (µm)	600	600	600

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