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Obtaining low energy γ dose with CMOS sensors*

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A method is established for measuring low energy γ-rays dose by using CMOS sensors without any X-/γ-ray converters. Gamma-ray source of ^{241}Am and ^{152}Eu are used to test the system. Based on gray value, an analysis method is proposed to obtain the γ-ray dose. Cumulative dose is determined by correlating the gray value to the dose readings of standard dosimeters. The relationship between gray value and the cumulative dose of γ-rays are trained by using back propagation neural network with BFGS algorithm. After comparison, it shows that BFGS algorithm trainings are suitable for different γ-ray sources under higher error condition. These indicate the feasibility of measuring low energy γ-ray dose by using common CMOS image sensors.

Keywords: CMOS image sensor, Low energy γ-ray detection, Image processing, BP neural network, BFGS algorithm

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I. INTRODUCTION

CMOS (complementary metal oxide semi-conductor) image sensor is advantageous in its low power consumption, low price and good radiation resistance [1–3]. In recent years, CMOS image sensors have been widely used in detecting X- and γ-rays. Using a scintillating material as converters for X-ray to visible light photons, the CMOS image sensors are used in X-ray imaging detectors for medical imaging applications [4]. However, the use of converters narrows the dynamic range [5]. The CMOS sensors are also used in γ-ray detection and classification [6]. In this paper, we explore the possibility of measuring low energy γ-ray dose using CMOS sensor without any converters. Results of dosimetry measurements using ^{241}Am and ^{152}Eu γ-ray sources are presented and discussed. The article is organized as follows. Fundamentals of low energy γ-rays detection by using CMOS are described in Sec. II. In Sec. III, the gray value analysis method is introduced and fit the correlation between the energy of γ-rays and the cumulative gray value, and a network model based on back propagation (BP) neural network and the Broyden-Fletcher-Goldfarb-Shanno (BFGS) algorithm is adopted to reduce the detection error and the convergence speed. A summary is presented in Section IV.

II. METHODS

The key parts used in this experiment are the UPA1021 CMOS digital image sensors produced by Philips. The CMOS image sensor is composed of an image array of

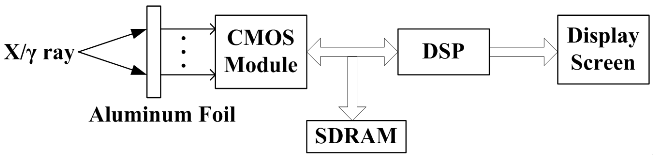

Fig. 1. Schematic diagram of the system.

307200 (640 × 480) pixels, plus an on-pixel amplifier, timing and control circuits, dual 8 bit A/D and video port, and signal processing unit [7]. The pixel size of the sensor is 2.2 µm × 2.2 µm, and optical size is 1/10 inches. The sensors are kept in black environment to reduce the interference by visible light in measurements. Besides, the CMOS image sensor is covered by an aluminum foil to prevent the α particles. Fig. 1 is a schematic diagram of the system [8, 9].

The CMOS pixel unit is composed of a photodiode, an electrical signal conversion unit, a signal transmission transistors and a signal amplifier [10]. X- or γ-ray photons produce photoelectric effect inside the photodiode. The photocurrent is proportional to the luminance component of CMOS.

The digital signal processor (DSP) produces the driving signal for CMOS, and controls working condition of the CMOS. Also, it transforms the received signals into 2D images, calculates the cumulative dose of γ-rays, and sends the image and cumulative doses to the display screen. The SDRAM improves the image processing speed.

A. Gray value analysis

Gray value analysis is applied to analyze the results in this work. Gray value is brightness of an image or degree of color shades. Generally, gray value of pixel is acquired before complex image processing. Gray value analysis is widely used in satellite images, aerial photographs, geophysical observations, etc. [11]. If the color values of a certain pixel in an

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original image are (Red, $Green$, $Blue$), the gray value is calculated by [12]

$$h = 0.299Red + 0.587Green + 0.114Blue. \quad (1)$$

One γ photon usually hits some adjacent pixels at the instant of imaging. Besides, crosstalk in CMOS image sensor always happens in adjacent pixels because of closeness of the pixels [13]. Then, cumulative gray value of CMOS pixels irradiated by the photons can be used to detect the γ-rays. The gray value of one pixel is called as $h(x, y)$, where (x, y) denotes the coordinate of pixels around the brightest one in the light spot. The cumulative gray value can be calculated by:

$$H = \sum h(x, y). \quad (2)$$

III. BFGS ALGORITHM

BP (back propagation) neural network is a multilayer feed forward network based on the error BP algorithm and is used to approach any continuous function in arbitrary precision. Theoretically, a neural network with combinations of different training functions, nodes and layer numbers can fit any input and output nonlinear functions [14]. Many improved learning algorithm are proposed based on classical BP algorithm. In numerical optimization, BFGS is an iterative method to solve the unconstrained nonlinear optimization problems [15, 16]. As an improved the Newton's method, it performs nicely even for non-smooth optimizations. In the MATLAB optimization toolbox, the BFGS algorithm is implemented by *trainbfg* [17].

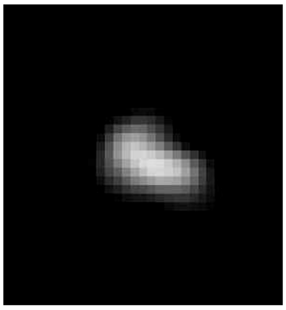
IV. EXPERIMENTS

A. The gray level response of ^{241}Am

The CMOS image sensors were irradiated by ^{241}Am (1.26×10^5 Bq, 4.0534×10^4 γ/s) source at Shanghai Institute of Applied Physics, Chinese Academy of Science. In its α decay nuclide, ^{241}Am, emits 59.5 keV and 26 keV γ-rays. The CMOS chip was covered by an aluminum foil to prevent the α particles.

First, the system was set in a radiation-free environment and the gray value response of ^{241}Am on CMOS is analyzed to test the background before the experiment. The results show the background gray value is 22.

Next, the ^{241}Am source was placed at 30 cm to the CMOS image sensor, and the γ-rays were recorded at a rate of 30 fps. A typical image is shown in Fig. 2, where the pixel units not exposed by γ-rays are kept black. The gray values of the lighted units were calculated by MATLAB, and plotted in Fig. 2. The light spot is composed of units with different gray values, some of which are lower than the background due to crosstalk in adjacent pixels.



22	21	22	23	22	22	24	23	18	17	21	24	24
17	19	27	28	24	22	24	24	23	21	21	21	20
19	23	28	24	18	19	19	21	25	26	23	20	17
27	28	24	21	22	29	21	18	22	26	25	21	19
30	25	20	36	60	61	41	23	20	24	25	23	22
26	18	19	58	105	94	63	32	21	22	24	24	25
24	18	27	58	89	118	119	91	45	19	22	25	17
22	18	21	38	56	67	74	66	42	27	25	23	14
22	21	19	21	25	23	32	37	34	29	25	21	17
24	25	22	19	17	18	18	22	25	24	20	21	28
25	24	23	22	21	27	22	20	22	21	18	21	23
23	19	20	21	21	26	23	23	24	23	21	21	20
20	19	22	22	18	24	24	24	22	22	24	23	25

Fig. 2. Typical image of a ^{241}Am γ photon acquired by CMOS and gray values of the lighted spots.

B. Dose measurement

The γ photon response on the CMOS image sensor can be denoted by cumulating the gray values of all pixels. A standard dosimeter was used to record the radiation dose. The gray values obtained by CMOS and the standard doses were used to deduce the correlation. The dose on the dosimeter were recorded every three minutes, while the video of γ-rays on CMOS was recorded continuously. Each frame of images was analyzed because the cumulative doses are denoted by the cumulative gray value of each γ photon.

The largest gray value of each frame was compared with the background. If the largest gray value exceeds background, the frame would be abandoned. Otherwise, the pixels of largest gray value were selected and the gray values of pixels around the largest one were accumulated. The procedures were repeated with other images and the cumulative dose of ^{241}Am was denoted by the accumulated gray value of all the images, which is called as H'.

It was found that the cumulative gray values (H') changes with sizes of the pixel matrix. To determine a proper size of the matrix, 13×13, 11×11 and 9×9 matrices were compared. A two-tier BP neural network (5 nodes in the input layer, 1 node in the output layer with the expected error 10^{-5}) was created. The accumulated gray values (H') were used as inputs, and the dose values recorded on the standard dosimeter were used as outputs. Thirty-two sets of sampling data were used to train the network by the BFGS algorithm.

The correlation between the accumulated gray values (H') and the cumulative dose for the ^{241}Am source is plotted in Fig. 3(a). The cumulative dose and accumulated gray value are in good correlation for all the three matrices. The H' is larger with a larger matrix under the same cumulative dose.

The best method with proper matrix is selected by global consistency comparison. Data not used for training are often used as the testing data to estimate the global consistency, which is characterized by the dose error. Six sets of testing data were taken as the inputs of the trained network and the corresponding cumulative dose was the actual output. The actual dose (a) was acquired by the network and the expected dose (e) was measured by the standard dosimeter. Relative error of the dose (Δ) is calculated by

$$\Delta = [(a - e)/e] \times 100\%. \quad (3)$$

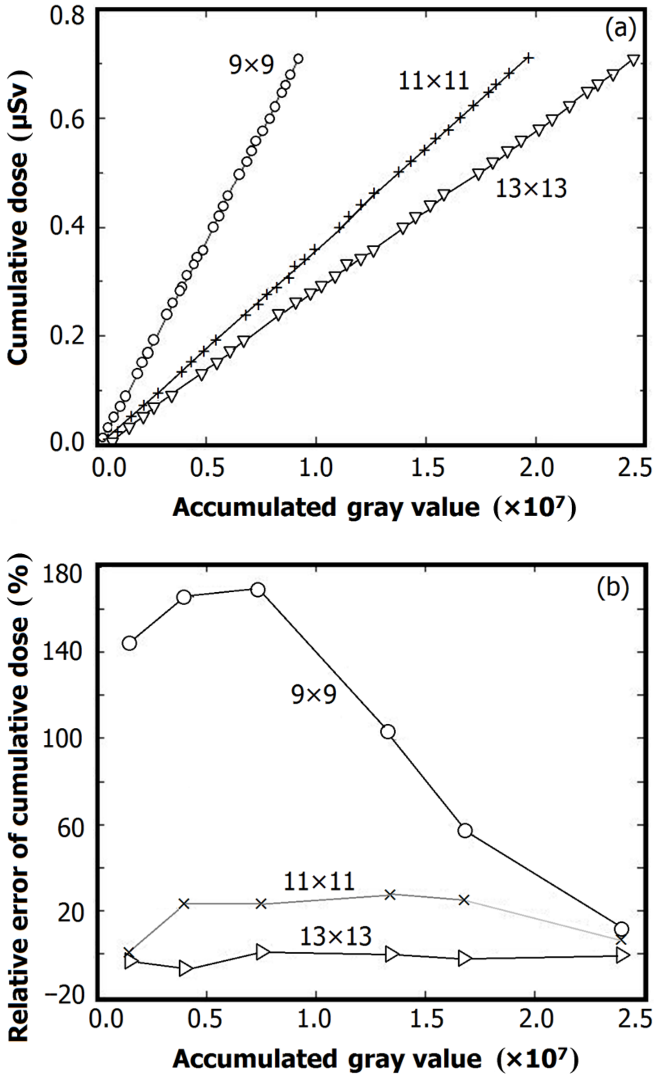


Fig. 3. The correlation for ^{241}Am between the H' and cumulative doses (a) and relative error of the cumulative dose (b), using the BP networks with BFGS trained by the data of 13×13, 11×11 and 9×9 matrices.

The dose errors using the three matrices are shown in Fig. 3(b). The dose error of the 9×9 matrix is the highest of all matrices, and the error of 13×13 matrix is the lowest of all matrices. Therefore, 13×13 matrix pixels are of better global convergence, and are chosen in the following analysis within the precision allowed.

C. Comparison between different sources

^{152}Eu (9.97 kBq) is an important radionuclide for energy and efficiency calibration of γ spectrometers [18]. ^{152}Eu has a complex decay scheme, 27.9% by β^- emission and 72.1% by electron capture. It emits over 140 γ-rays ranging from 122 keV to 1408 keV. For comparison, ^{152}Eu γ-rays were measured, with aluminum foil to block off the β particles.

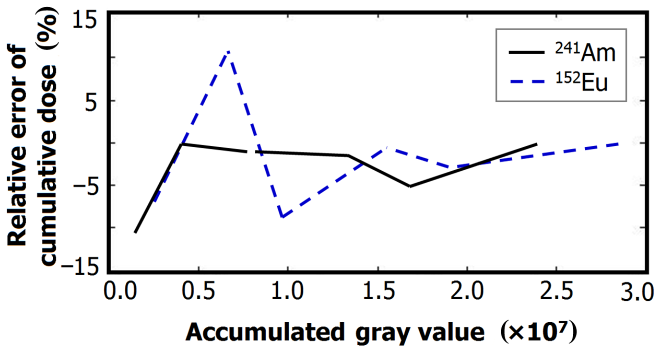


Fig. 4. (Color online) The testing dose error of the networks trained by data of 13×13 matrix of the ^{152}Eu and ^{241}Am γ sources.

The same method was used to obtain the cumulative dose of ^{152}Eu. The 13×13 matrix pixels were used as the statistical. Testing dose error of the networks trained by data from the ^{152}Eu and ^{241}Am source are plotted in Fig. 4.

It can be seen from Fig. 4 that the correlation between H' and the cumulative dose trained for the ^{241}Am source by the BP network is also suitable for ^{152}Eu source, and the ^{241}Am has a lower testing dose error. The BFGS algorithm is employed to compensate for the energy loss and reduce the measurement error in this experiment. Besides, the number of sampling points and the corresponding H' increase with the dose. This can offset some errors of the energy loss. Therefore, the error decreases as the accumulated gray value increases.

From Fig. 4, the testing dose error of ^{241}Am differs from ^{152}Eu, due to the different response in CMOS pixels. In this work, the cumulative dose is measured with the known source type.

D. Radiation damage analysis

The performance (especially dark current) of CMOS is always characterized by the gray value of dark images [19]. Radiation damage is analyzed by comparing the gray value of images acquired before and after the irradiation. The images were collected every three minutes. The largest gray value of each image was picked from pre-test and post-test of the experiment, and the results were both 22. After two days irradiation by ^{241}Am and ^{152}Eu, only one dead pixel is found on the CMOS image sensor. The gray value of the dead pixel is less than 40. Experiment results showed that the dead pixels did not influence the dose error. Therefore, that exposure to small doses of radiation over short periods of time does not damage the CMOS or its functionality.

V. SUMMARY

In summary, a method is proposed to obtain the cumulative dose of ^{241}Am and ^{152}Eu using common CMOS sensor without any converters, while the type of γ source will not be distinguished. The gray value analysis of the recorded images is adopted as the image preprocessing. The BP neural network and the BFGS algorithm are used to train the network and fit the correlation between the cumulative gray value and cumulative dose. Experimental results show that the γ dose is calibrated in this method. The error of ^{152}Eu is lower than ^{241}Am in the experiments. The simulation results show that the cumulative dose of low energy γ-rays (^{241}Am and ^{152}Eu) detection is completed. The irradiation experiments show that the irradiation damage is very little and can be ignored. Based on the experimental results, it is proposed that the general CMOS image sensors can be used to measure the cumulative dose of low energy γ rays in the case of knowing the source type.

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