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K-edge digital angiography using a flat panel detector with a pixel size of 50 μm

Eiichi Sato[a], Etsuro Tanaka[b], Hidezo Mori[c], Toshiaki Kawai[d], Takashi Inoue[e], Akira Ogawa[e], Kiyomi Takahashi[f], Shigehiro Sato[f] and Kazuyoshi Takayama[g]

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Abstract

The 100-μm-focus x-ray generator consists of a main controller for regulating the tube voltage and current and a tube unit with a high-voltage circuit and a fixed anode x-ray tube. The maximum tube voltage, current, and electric power were 105 kV, 0.5 mA, and 50 W, respectively. Using a 3-mm-thick aluminum filter, the x-ray intensity was 26.0 μGy/s at 1.0 m from the source with a tube voltage of 60 kV and a current of 0.50 mA. Because the peak photon energy was approximately 35 keV using the filter with a tube voltage of 60 kV, the bremsstrahlung x-rays were absorbed effectively by iodine-based contrast media with an iodine K-edge of 33.2 keV. Enhanced angiography was achieved with a flat panel detector with a pixel size of 50 μm using iodine-based microspheres 15 μm in diameter. In angiography of non-living animals, we observed fine blood vessels of approximately 100 μm with high contrasts.

Keywords: enhanced angiography, K-edge angiography, energy-selective imaging, flat panel detector, 50 μm pixel

1. Introduction

Monochromatic x-rays[1-8] are very useful for performing energy-selective radiography including mammography and enhanced K-edge angiography, [9-11] and these rays can be applied to perform x-ray fluorescent cancer diagnosis and cure utilizing a device delivery system. Therefore, we have developed monochromatic flash x-ray generators and steady state x-ray generators.

To perform enhanced K-edge angiography using iodine based contrast media, we have developed a

a Department of Physics, Iwate Medical University, 3-16-1 Honchodori, Morioka 020-0015, Japan
b Department of Nutritional Science, Faculty of Applied Bio-science, Tokyo University of Agriculture, 1-1-1 Sakuragaoka, Setagaya-ku 156-8502, Japan
c Department of Cardiac Physiology, National Cardiovascular Center Research Institute, 5-7-1 Fujishirodai, Suita, Osaka 565-8565, Japan
d Electron Tube Division #2, Hamamatsu Photonics K. K., 314-5 Shimokanzo, Iwata 438-0193, Japan
e Department of Neurosurgery, School of Medicine, Iwate Medical University, 19-1 Uchimaru, Morioka 020-8505, Japan
f Department of Microbiology, School of Medicine, Iwate Medical University, 19-1 Uchimaru, Morioka 020-8505, Japan
g Tohoku University Biomedical Engineering Research Organization, 2-1-1 Katahira, Sendai 980-8577, Japan

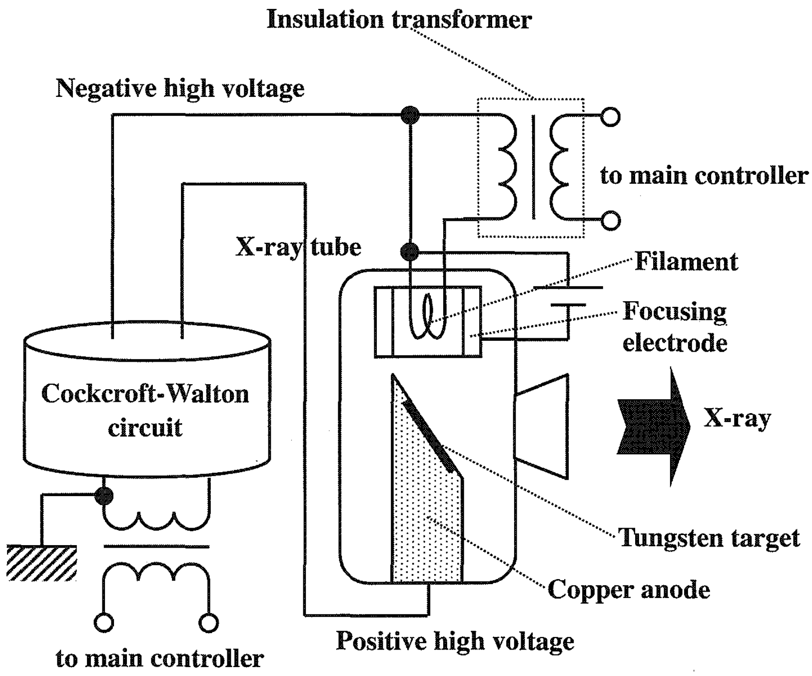

Fig. 1. Electric circuit of the x-ray generator.

cerium x-ray generator[12-14] because K-series characteristic x-rays from a cerium target are absorbed effectively by the iodine media. Subsequently, since we have also employed a conventional x-ray generator with a tungsten-target tube and have obtained narrow-photon-energy bremsstrahlung x-rays which are absorbed effectively by the media.

In cohesion radiography, the spatial resolution of an object is primarily limited by the resolution of digital radiography systems, such as, a computed radiography system (CR)[15] and a flat panel detector (FPD). The resolutions of the CR and the FPD are primarily determined by the sampling pitch and the pixel size, respectively. Although we usually employ the CR, the real-time radiography can be performed using the FPD.

In the present research, we employed the FPD with pixel sizes of $50 \times 50\ \mu$m, used to perform enhanced angiography by controlling bremsstrahlung x-ray spectra using an aluminum filter.

2. Experimental Setup

The x-ray generator consists of a main controller, an x-ray tube unit with a Cockcroft-Walton circuit, an insulation transformer, and a 100-μm-focus x-ray tube. The tube voltage, the current, and the exposure time can be controlled by the controller. The main circuit for producing x-rays is illustrated in Fig. 1, and employed the Cockcroft-Walton circuit in order to decrease the dimensions of the tube unit. In the x-ray tube, the positive and negative high voltages are applied to the anode and cathode electrodes, respectively. The filament heating current is supplied by an AC power supply in the controller in conjunction with an insulation transformer which is used for isolation from the high voltage from the Cockcroft-Walton circuit. In this experiment, the tube voltage applied was from 45 to 70 kV, and the tube current was regulated to within 0.50 mA (maximum current) by the filament temperature. The exposure time is controlled in order to obtain optimum x-ray intensity, and narrow-photon-energy bremsstrahlung x-rays are produced using a 3.0-mm-thick aluminum filter for absorbing soft x-rays.

3. Results and Discussion

3.1 X-ray intensity

The x-ray intensity was measured by a Victoreen 660 ionization chamber at 1.0 m from the x-ray source using the filter (Fig. 2). At a constant tube current of 0.50 mA, the x-ray intensity increased when the tube voltage was increased. At a tube voltage of 60 kV, the intensity with the filter was 26.0 μGy/s.

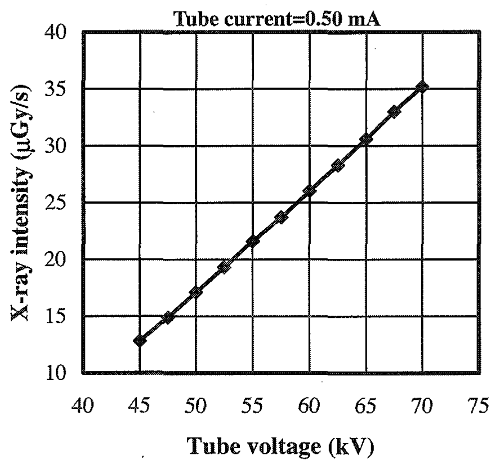

Fig. 2. X-ray intensity (μGy/s) as a function of tube voltage (kV) with a tube current of 0.50 mA.

3.2 X-ray Spectra

In order to measure x-ray spectra, we employed a cadmium telluride detector (XR-100T, Amptek) (Fig. 3). When the tube voltage was increased, the bremsstrahlung x-ray intensity increased, and both the maximum photon energy and the spectrum peak energy increased.

In order to perform K-edge angiography, bremsstrahlung x-rays of approximately 35 keV are useful, and the high-energy bremsstrahlung x-rays decrease the image contrast. Using this filter, because bremsstrahlung x-rays with energies higher than 60 keV were not absorbed easily, the tube voltage for angiography was determined as 60 kV by considering the filtering effect of radiographic objects.

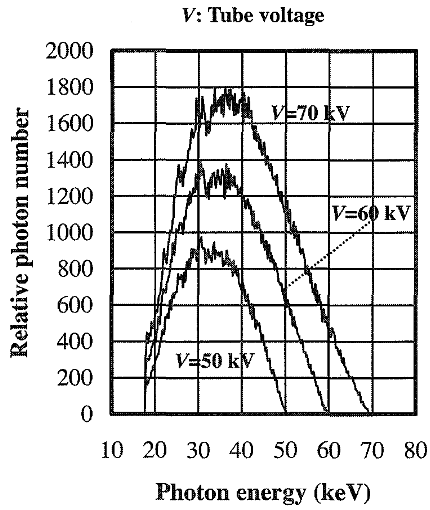

Fig. 3. Bremsstrahlung x-ray spectra measured using a cadmium telluride detector with changes in the tube voltage.

3.3 Enhanced Angiography

The cohesion radiography was performed using the FPD (C7921CA-02, Hamamatsu Photonics) and the filter at a tube voltage of 60 kV, and the distance between the x-ray source and the FPD was 1.0 m. First, the spatial resolution of cohesion radiography was measured using a lead test chart, and 83.3 μm lines (6 line pairs)

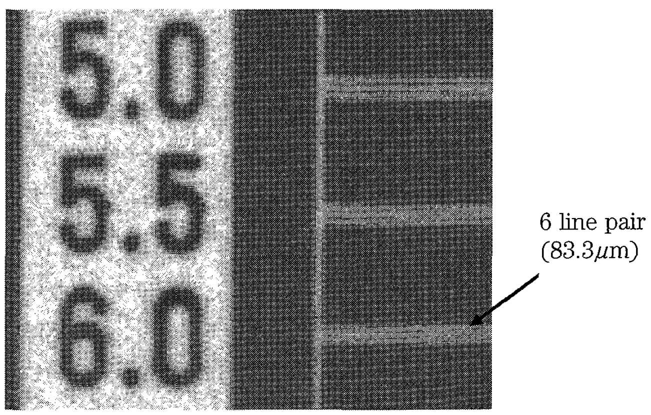

Fig. 4. Radiograms of a test chart for measuring the spatial resolution.

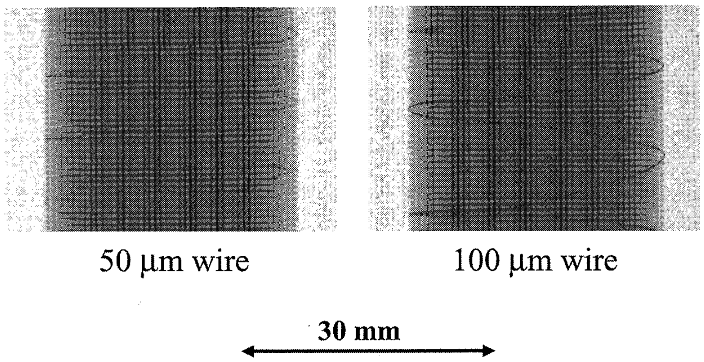

Fig. 5. Radiograms of tungsten wires coiled around PMMA rods.

were visible (Fig. 4). Subsequently, Fig. 5 shows radiograms of tungsten wires coiled around rods made of polymethyl methacrylate (PMMA). Although the image contrast decreased somewhat with decreases in the wire diameter, due to blurring of the image caused by the spatial resolution of 83.3 μm, a 50-μm-diameter wire could be observed.

Figure 6 shows the mass attenuation coefficients of iodine at the selected energies; the coefficient curve is discontinuous at the iodine K-edge. The effective bremsstrahlung x-ray spectra for K-edge angiography are shown above the iodine K-edge. Because iodine contrast media with a K-absorption edge of 33.2 keV absorb the rays easily, blood vessels were observed with high contrasts.

The angiography was performed at the same conditions using iodine microspheres of 15 μm in diameter, and the microspheres (containing 37% iodine by weight) are very useful for making phantoms of non-living animals used for angiography. Angiogram of a rabbit heart is shown in Fig. 7, and the coronary arteries are visible. Figure 8 shows angiograms of a larger dog heart using iodine spheres, and the coronary arteries of approximately 100 μm were observed.

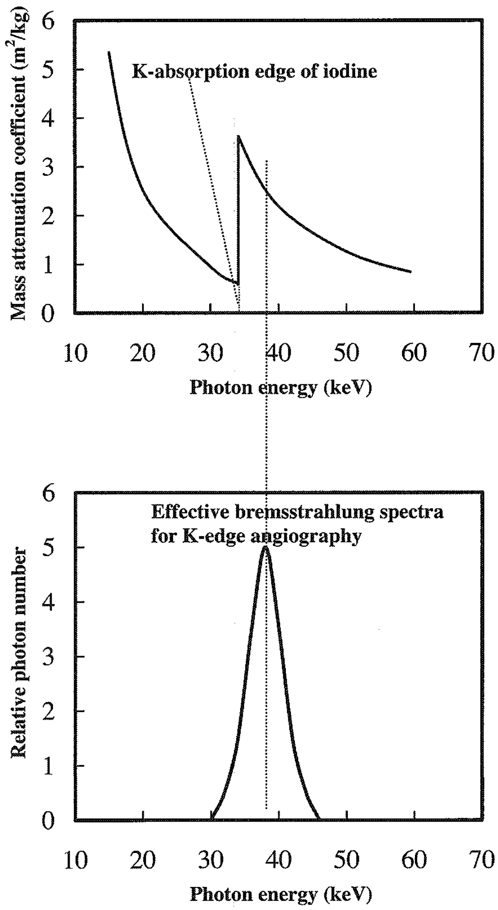

Fig. 6. Mass attenuation coefficients of iodine and effective bremsstrahlung x-rays for enhanced K-edge angiography.

4. Conclusion and Outlook

We employed an x-ray generator with a 100-μm-focus tungsten tube and performed enhanced K-edge angiography using narrow-photon-energy bremsstrahlung x-rays with a peak photon energy of

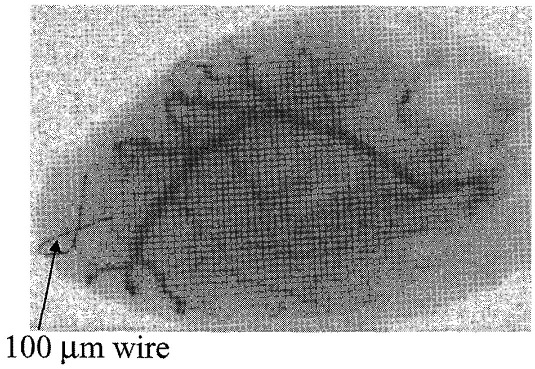

Fig. 7. Angiogram of an extracted rabbit heart using iodine microspheres.

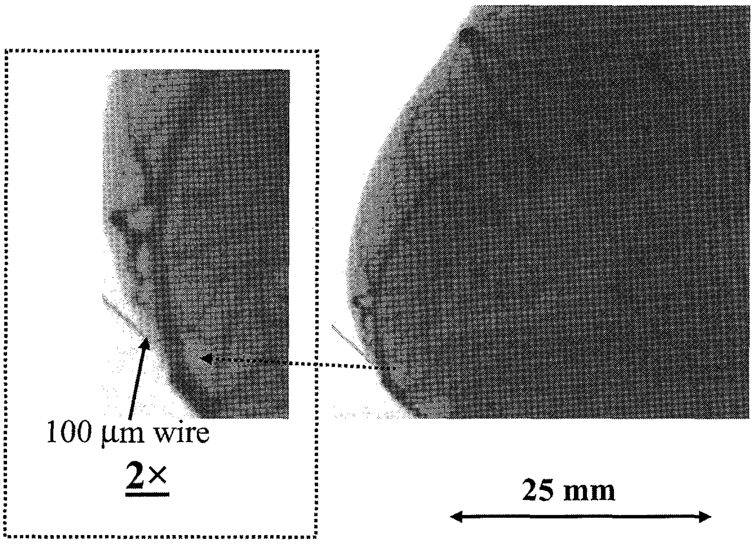

Fig. 8. Angiograms of an extracted dog heart.

approximately 35 keV, which can be absorbed easily by iodine-based contrast media. The bremsstrahlung x-ray intensity substantially increased with increases in the tube voltage, and the tube voltage was determined as 60 kV in order to increase the image contrast.

Because the pixel size of the FPD is 50 μm, we obtained spatial resolutions of approximately 80 μm using cohesion radiography even when a 100-μm-focus tube was employed. In order to observe fine blood vessels of less than 50 μm, the spatial resolution of the radiography system should be improved to approximately 20 μm using an x-ray CCD sensor, and the iodine density should be increased. Furthermore, the resolution can be improved easily utilizing magnification radiography, and the resolution improved with increases in the magnification ratio.

At a tube voltage of 60 kV and a current of 0.50 mA, the maximum number of photons was approximately 4×10^7 photons/($cm^2\cdot s$) at 1.0 m from the source, and the photon count rate can be increased easily using a rotating anode microfocus tube. In addition, a conventional x-ray generators can be employed, and the count rate can be increased easily by increasing the tube current.

Acknowledgments

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