direction. Without forming the linear plasma, because bremsstrahlung rays are not emitted in the opposite direction to that of electron acceleration, characteristic x rays can be produced by considering the angle dependence of bremsstrahlung x rays.[16] As compared with the plasma generator, the photon energy of the characteristic x rays can be increased by increasing the maximum output voltage, since a multistage Marx generator can be employed.

In this paper, we describe a compact flash x-ray generator utilizing a cold-cathode radiation tube, used to perform a preliminary experiment for generating clean copper Kα lines.

2. GENERATOR

2.1 High-voltage circuit

Figure 1 shows a block diagram of a compact monochromatic flash x-ray generator. This generator consists of the following components: a constant high-voltage power supply, a polarity-inversion two-stage surge Marx generator with a capacity during main discharge of 425 pF, a trigger device for the surge generator, a turbomolecular pump, and a flash x-ray tube. Since the electric circuit of the surge generator employs a polarity-inversion two-stage Marx line (Fig. 2), the surge generator produces twice the potential of the condenser charging voltage. When two condensers inside of the surge generator are charged from −50 to −70 kV, the ideal output voltage ranges from 100 to 140 kV.

2.2 X-ray tube

The x-ray tube is a demountable diode type, as illustrated in Fig. 3. This tube is connected to the turbomolecular pump with a pressure of approximately 1 mPa and consists of the following major devices: a rod-shaped copper target 3.0 mm in diameter, a disk cathode made of graphite, a polyethylene terephthalate (Mylar) x-ray window 0.25 mm in thickness, and a polymethyl methacrylate (PMMA) tube body. The target-cathode space was regulated to 1.25 mm from the outside of the x-ray tube by rotating the anode rod, and the transmission x rays are obtained through a 1.0-mm-thick graphite cathode and an x-ray window. Because bremsstrahlung rays are not emitted in the opposite direction to that of electron acceleration (Figs. 4 and 5), copper Kα rays can be produced using a 10-μm-thick nickel K-edge filter.

3. CHARACTERISTICS

3.1 Tube voltage and current

Tube voltage and current were measured using a high-voltage divider with an input impedance of 10 kΩ and a current transformer, respectively (Fig. 6). The voltage and current displayed roughly damped oscillations because the discharge resistance in the tube varied rapidly from infinity to approximately 0 Ω during the discharge. Thus, at the first quarter cycle of the oscillations, when the voltage decreased, the current increased. The instantaneous voltage and current increased with increases in the charging voltage, and the voltage and current were approximately 140 kV and 0.8 kA, respectively, at a charging voltage of −70 kV.

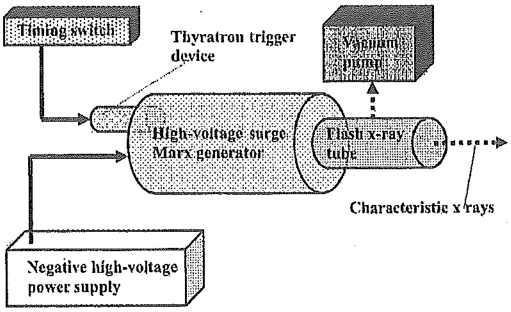

Figure 1: Block diagram of compact monochromatic flash x-ray generator.

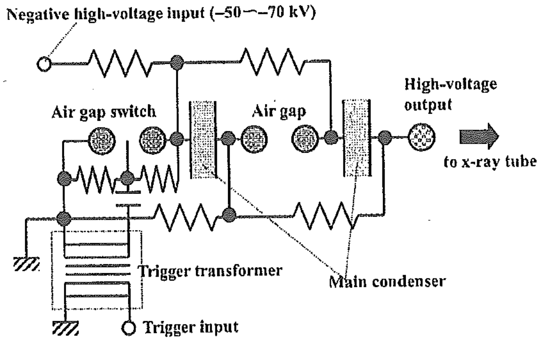

Figure 2: Circuit diagram of flash x-ray generator.

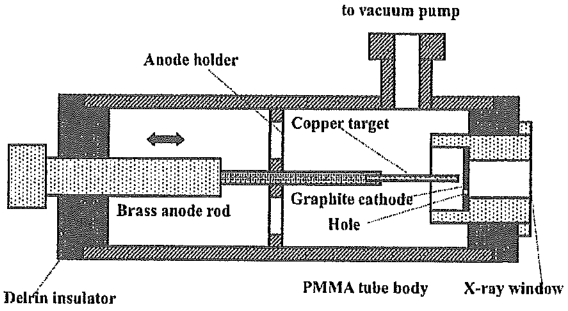

Figure 3: Schematic drawing of flash x-ray tube.

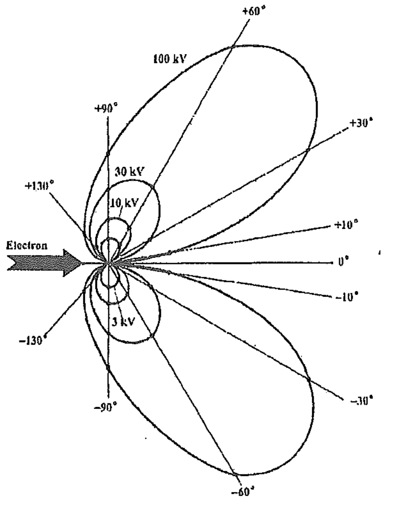

Figure 4: Bremsstrahlung x-ray intensity distribution vs angle.

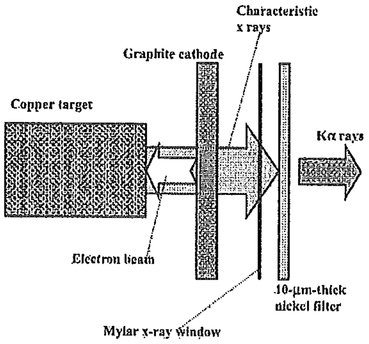

Figure 5: Characteristic x-ray irradiation.

3.2 X-ray output

X-ray output pulse was detected using a combination of a plastic scintillator, a photomultiplier, and the filter (Fig. 7). When the charging voltage was increased, the pulse height increased, but the width seldom varied. The widths were approximately 30 ns, and the time-integrated x-ray intensity measured using a thermoluminescence dosimeter (Kyokko TLD Reader 1500 having MSO-S elements without energy compensation) had a value of approximately 1.0 μC/kg per pulse at 0.5 m from the x-ray source with a charging voltage of −70 kV.

3.3 X-ray source

In order to observe the x-ray source, we employed a 100-μm-diameter pinhole camera, an x-ray film (Polaroid XR-7), and the filter (Fig. 8). When the charging voltage was increased, the spot intensity increased, and the intensities corresponded well to the x-ray pulse height. The dimension was almost equal to the target diameter and had a value of approximately 3.0 mm.

3.4 X-ray spectra

X-ray spectra were measured by a transmission-type spectrometer with a lithium fluoride curved crystal 0.5 mm in thickness. The spectra were taken using a computed radiography (CR) system[17] with a wide dynamic range, and relative x-ray intensity was calculated from Dicom digital data. Figure 9 shows the measured spectra from the copper target with the filter. We observed clean copper Kα lines, while bremsstrahlung rays were hardly detected at all. The Kα intensity increased with increases in the charging voltage.

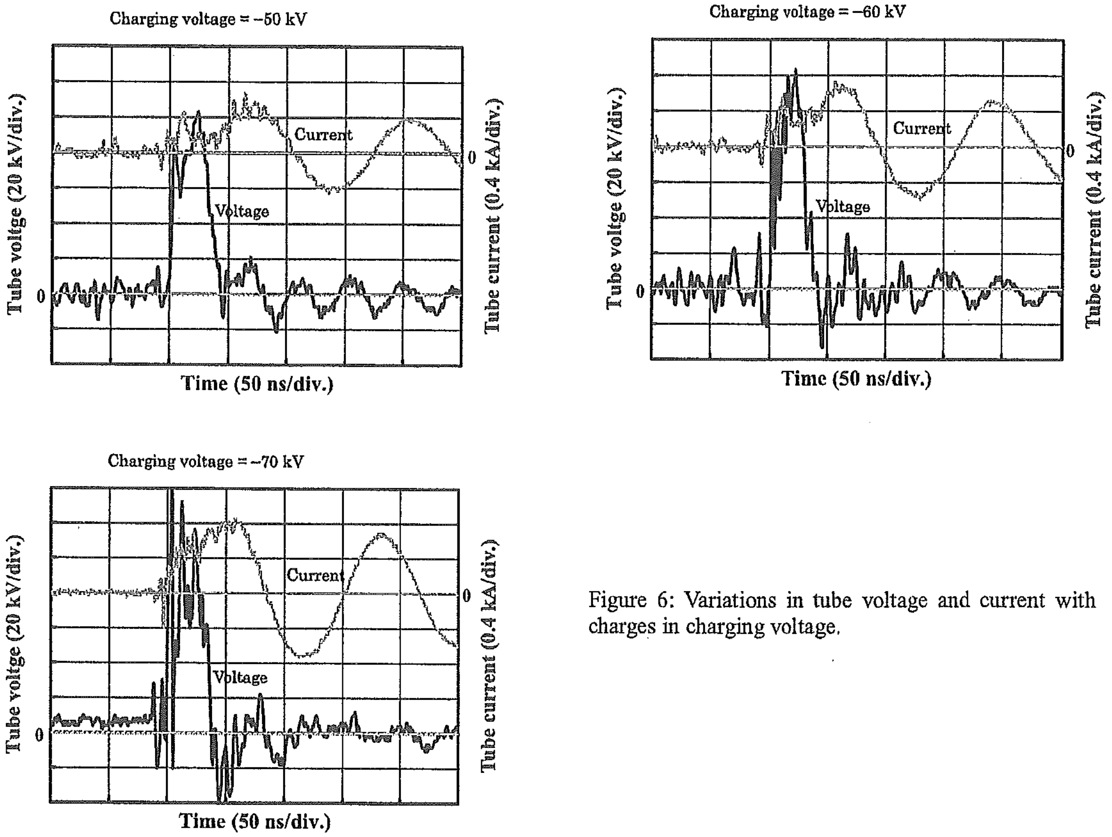

Figure 6: Variations in tube voltage and current with charges in charging voltage.

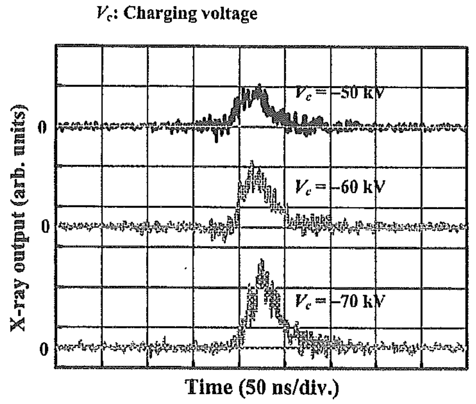

Figure 7: X-ray outputs according to changes charging voltage.

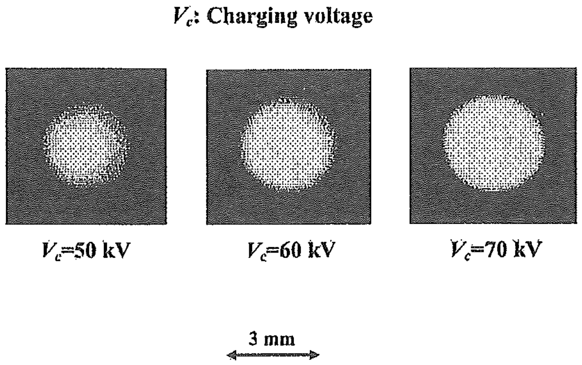

Figure 8: Images of x-ray source with changes in charging voltage.

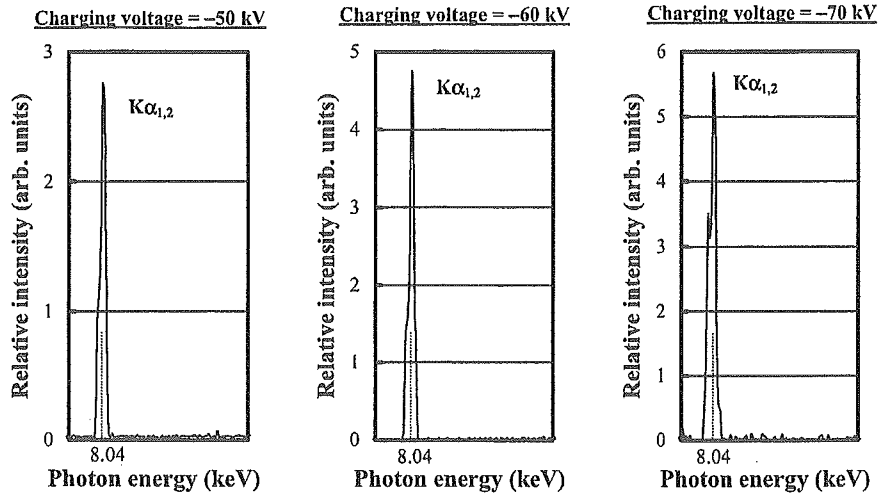

Figure 9: X-ray spectra from copper target according to changes in charging voltage.

4. RADIOGRAPHY

Flash radiography was performed using the CR system (Konica Regius 150) at 0.5 m from the x-ray source, and the charging voltage was −70 kV.

Firstly, rough measurements of spatial resolution were made using wires. Figure 10 shows radiograms of tungsten wires coiled around a pipe made of polymethyl methacrylate. Although the image contrast increased with increasing wire diameter, a 50-μm-diameter wire could be observed.

Figure 11 shows a radiogram of a vertebra, and fine structures in the vertebra were observed. The image of water falling into a polypropylene beaker from a plastic test tube is shown in Fig. 12. This image was taken with the slight addition of an iodine-based contrast medium. Because the x-ray duration was about 50 ns, the stop-motion image of water could be obtained. Figure 13 shows an angiogram of a rabbit heart; iodine-based microspheres of 15 μm in diameter were used, and fine blood vessels of approximately 100 μm were visible.

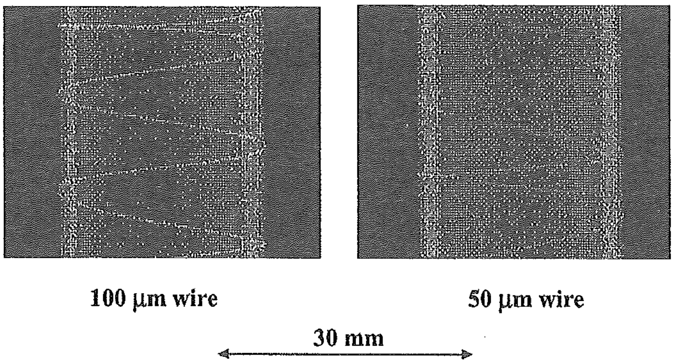
100 μm wire **50 μm wire**

Figure 10: Radiograms of tungsten wires of 50 and 100 μm in diameter coiled around pipe made of polymethyl methacrylate.

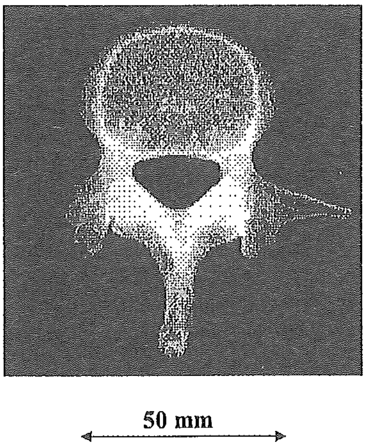

Figure 11: Radiogram of vertebra.

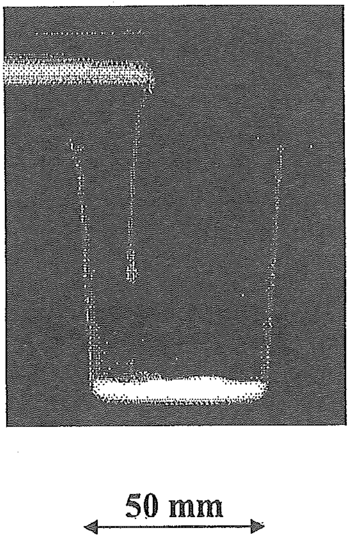

Figure 12: Radiogram of water falling into polypropylene beaker from plastic test tube.

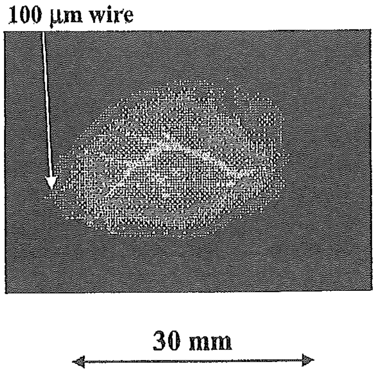

Figure 13: Angiograms of rabbit heart.

5. DISCUSSION

Concerning the spectrum measurement, we obtained fairly clean copper Kα rays (8.04 keV). Therefore, we are very interested in the measurement the Kα rays from cerium (34.6 keV), ytterbium (52.0 keV), tantalum (57.1 keV), and tungsten (58.9 keV) targets; the target element should be selected corresponding to the radiographic objectives. In medical applications, Kα rays of cerium are absorbed effectively by an iodine-based contrast medium with a K-edge of 33.2 keV, and K-edge angiography can be performed. In addition, since Kα rays from ytterbium, tantalum, and tungsten targets are absorbed effectively by gadolinium-based contrast media with a K-edge of 50.2 keV, these x rays are very useful for performing enhanced K-edge angiography.

In this research, the instantaneous number of generator-produced Kα photons was approximately 2.5×10^6 photons/cm^2 per pulse at 0.5 m from the source. However, the intensity can be increased by increasing the electrostatic energy in condensers in the surge generator, and quasi-monochromatic x rays of both Kα and Kβ (8.90 keV) lines are produced without using the nickel filter with a K-edge of 8.33 keV.

Using this flash x-ray generator, because the photon energy of characteristic x rays can be selected, a high-speed photon-counting radiography can be performed in order to decrease noise from radiograms. As compared with a steady-state x-ray generator, since the target element can be changed easily using this demountable PMMA tube, demonstrations of monochromatic radiography will be accomplished.

ACKNOWLEDGMENT

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Intense quasi-monochromatic flash x-ray generator utilizing molybdenum-target diode

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ABSTRACT

In the flash x-ray generator, a 150 nF condenser is charged up to 80 kV by a power supply, and flash x rays are produced by the discharging. The x-ray tube is a demountable diode, and the turbomolecular pump evacuates air from the tube with a pressure of approximately 1 mPa. Since the electric circuit of the high-voltage pulse generator employs a cable transmission line, the high-voltage pulse generator produces twice the potential of the condenser charging voltage. At a charging voltage of 80 kV, the estimated maximum tube voltage and current were approximately 160 kV and 40 kA, respectively. When the charging voltage was increased, the K-series characteristic x-ray intensities of molybdenum increased. The K lines were clean and intense, and hardly any bremsstrahlung rays were detected at all. The x-ray pulse widths were approximately 100 ns, and the time-integrated x-ray intensity had a value of approximately 15 μC/kg at 1.0 m from the x-ray source with a charging voltage of 80 kV.

Keywords: flash x-ray, energy-selective radiography, characteristic x rays, quasi-monochromatic x rays, bremsstrahlung x-ray distribution

1. INTRODUCTION

In recent years, there have been several investigations dealing with the production of monochromatic x rays in radiology and cardiology. Particularly, monochromatic parallel beams using synchrotrons have been employed to perform enhanced K-edge angiography[1,2] and x-ray phase imaging.[3,4] In angiography, parallel beams with photon energies of approximately 35 keV have been employed, since these beams are absorbed effectively by an iodine-based contrast medium. Subsequently, in cases where phase imaging is employed, the spatial resolution can be improved, and the number of tissues which can be observed using x rays increases.

In order to perform biomedical radiography, we have developed several different soft flash x-ray generators[5-10] corresponding to specific radiographic objectives. Subsequently, electron impact flash x-ray sources can produce quasi-monochromatic x rays, because bremsstrahlung rays are not emitted in the opposite direction to that of electron

26th International Congress on High-Speed Photography and Photonics, edited by D. L. Paisley, S. Kleinfelder, D. R. Snyder, B. J. Thompson, Proc. of SPIE Vol. 5580
(SPIE, Bellingham, WA, 2005) · 0277-786X/05/$15 · doi: 10.1117/12.581246

acceleration.[11] Therefore, the sources will be conventional x-ray tubes for producing cone-beam K-series characteristic x rays, and monochromatic $K\alpha$ rays are obtained using a K-edge filter.

We have developed several different plasma flash x-ray generators[12-16] corresponding to specific radiographic objectives, and a major goal in our research is the development of an intense and sharp monochromatic x-ray generator that can impact applications with biomedical radiography. By forming weakly ionized linear plasma, because we have succeeded in producing fairly intense and clean K-series characteristic x rays. Without forming the linear plasma, characteristic x rays can be produced by considering the angle dependence of bremsstrahlung x rays. On the other hand, the electrostatic energy in the main discharge condenser should be increased as much as possible to increase the characteristic x-ray intensity.

In this paper, we describe an intense single flash x-ray generator utilizing a rod-target radiation tube, used to perform a preliminary experiment for generating intense and clean molybdenum K-series characteristic x rays.

2. GENERATOR

2.1 High-voltage circuit

Figure 1 shows a block diagram of a high-intensity plasma flash x-ray generator. The generator consists of the following essential components: a high-voltage power supply, a high-voltage condenser with a capacity of approximately 150 nF, an air gap switch, a turbomolecular pump, a thyratron pulse generator as a trigger device, and a flash x-ray tube. In this generator, a coaxial cable transmission line is employed in order to increase maximum tube voltage using high-voltage reflection. The high-voltage main condenser is charged up to 80 kV by the power supply, and electric charges in the condenser are discharged to the tube through the four cables after closing the gap switch with the trigger device (Fig. 2).

2.2 X-ray tube

The x-ray tube is a demountable cold-cathode diode that is connected to the turbomolecular pump with a pressure of approximately 1 mPa (Fig. 3). This tube consists of the following major parts: a ring-shaped graphite cathode with an inside diameter of 4.5 mm, a stainless-steel vacuum chamber, a nylon insulator, a polyethylene terephthalate (Mylar) x-ray window 0.25 mm in thickness, and a rod-shaped molybdenum target 3.0 mm in diameter. The distance between the target and cathode electrodes can be regulated from the outside of the tube, and is set to 1.5 mm. As electron beams from the cathode electrode are roughly converged to the target by the electric field in the tube, evaporation leads to the formation of weakly ionized plasma, consisting of molybdenum ions and electrons, around the target. Because bremsstrahlung rays are not emitted in the opposite direction to that of electron acceleration (Fig. 4), molybdenum K-series characteristic x rays can be produced without using a filter.

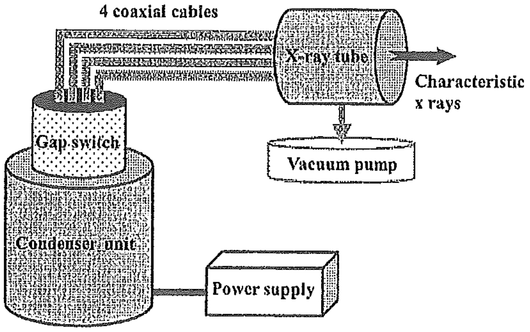

Figure 1: Block diagram of intense quasi-monochromatic flash x-ray generator.

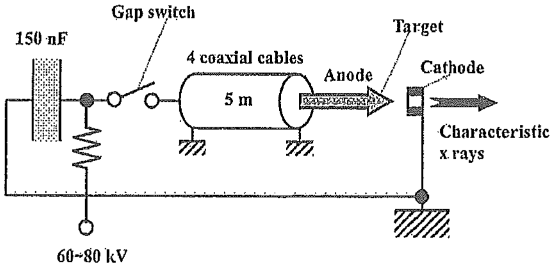

Figure 2: Circuit diagram of flash x-ray generator.

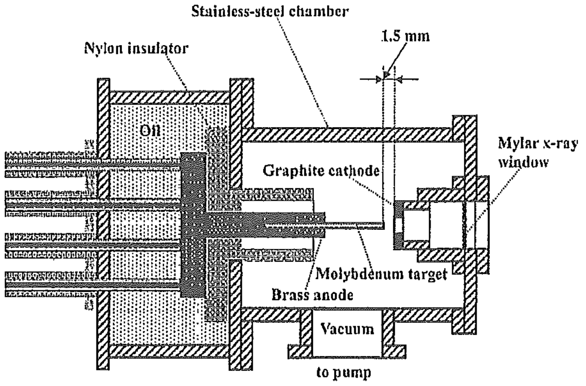

Figure 3: Schematic drawing of flash x-ray tube.

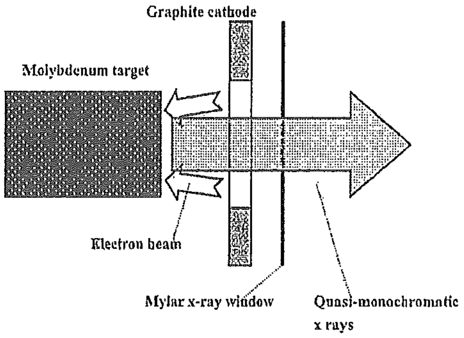

Figure 4: Irradiation of characteristic x rays.

3. CHARACTERISTICS

3.1 Tube voltage and current

In this generator, it was difficult to measure the tube voltage and current since the tube voltages were high, and there was no space to set a current transformer for measuring the tube current. Currently, the voltage and current roughly displayed damped oscillations. When the charging voltage was increased, both the maximum tube voltage and current increased. At a charging voltage of 80 kV, the estimated maximum values of the tube voltage and current were approximately 160 kV (2 times the charging voltage) and 40 kA, respectively.

3.2 X-ray output

X-ray output pulse was detected using a combination of a plastic scintillator and a photomultiplier (Fig. 5). The x-ray pulse height increased with corresponding increases in the charging voltage. The x-ray pulse widths were approximately 100 ns, and the time-integrated x-ray intensity measured by a thermoluminescence dosimeter (Kyokko TLD Reader 1500 having MSO-S elements without energy compensation) had a value of approximately 15 μC/kg at 1.0 m from the x-ray source with a charging voltage of 80 kV.

3.3 X-ray source

In order to observe the characteristic x-ray source, we employed a 100-μm-diameter pinhole camera and an x-ray film (Polaroid XR-7) (Fig. 6). When the charging voltage was increased, the plasma x-ray source grew, and both spot dimension and intensity increased. Because the x-ray intensity is the highest at the center of the spot, both the dimension and intensity decreased according to both increases in the thickness of a filter for absorbing x rays and decreases in the pinhole diameter.

3.4 X-ray spectra

X-ray spectra were measured by a transmission-type spectrometer with a lithium fluoride curved crystal 0.5 mm in thickness. The spectra were taken by a computed radiography (CR) system (Konica Regius 150)[17] with a wide dynamic range, and relative x-ray intensity was calculated from Dicom digital data. Figure 7 shows measured spectra from the molybdenum target. We observed clean K-series lines, while bremsstrahlung rays were hardly detected at all. The characteristic x-ray intensity substantially increased with increases in the charging voltage.

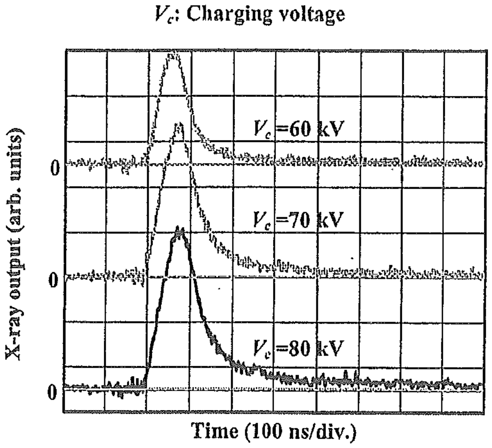

Figure 5: X-ray outputs at indicated conditions.

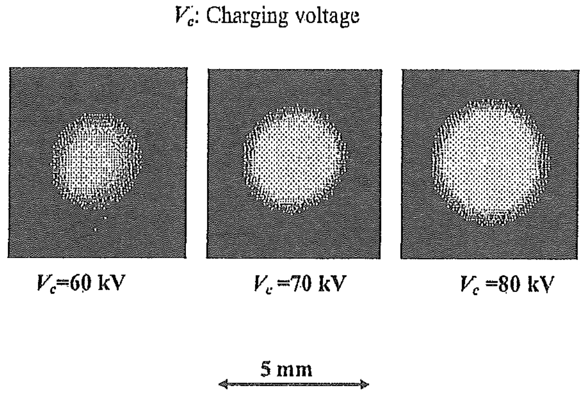

Figure 6: Images of characteristic x-ray source.

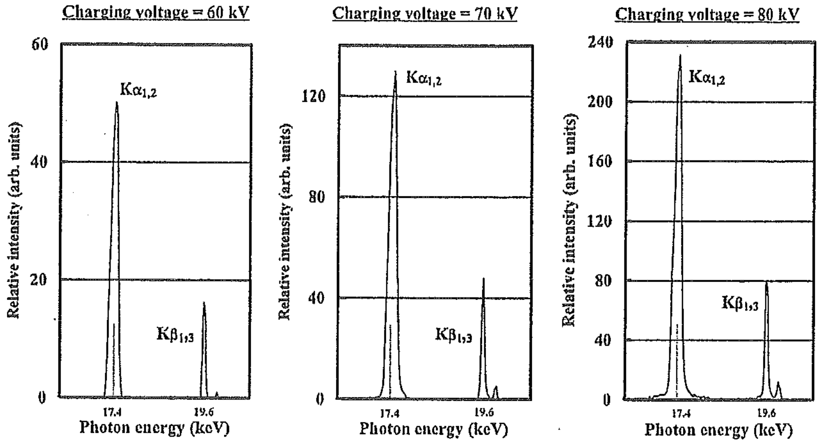

Figure 7: X-ray spectra from molybdenum target.

4. RADIOGRAPHY

The quasi-monochromatic flash radiography was performed by the CR system at 1.2 m from the x-ray source. Firstly, rough measurements of spatial resolution were made using wires. Figure 8 shows radiograms of tungsten wires coiled around a pipe made of polymethyl methacrylate with a charging voltage (V_c) of 70 kV. Although the image contrast increased with increases in the wire diameter, a 50-μm-diameter wire could be observed.

Figure 9 shows a radiogram of a vertebra with a V_c of 70 kV, and fine structures in the vertebra were observed. Figures 10 and 11 shows an angiogram of a rabbit heart (V_c=70 kV) and thigh (V_c=80 kV), respectively. In angiography, iodine-based microspheres of 15 μm in diameter were used, and fine blood vessels of about 100 μm were visible. Next, the image of aluminum grains falling into a polypropylene beaker from a glass test tube with a V_c of 80 kV is shown in Fig. 12. Because the x-ray duration was approximately 100 ns, the stop-motion image of grains could be obtained.

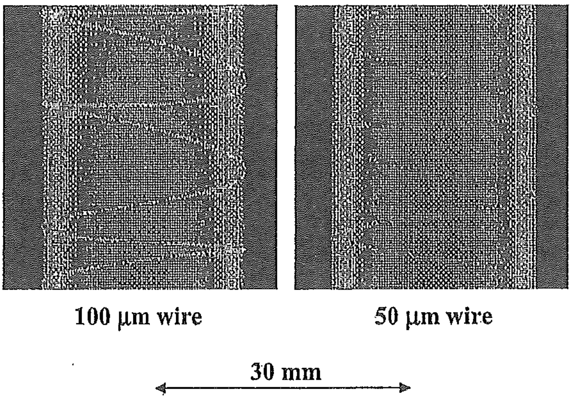

Figure 8: Radiograms of tungsten wires coiled around pipe made of polymethyl methacrylate.

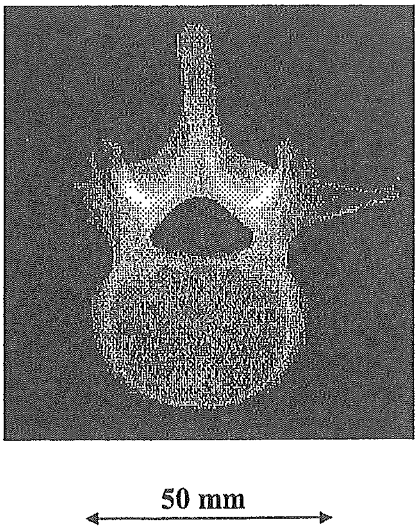

Figure 9: Radiogram of vertebra.

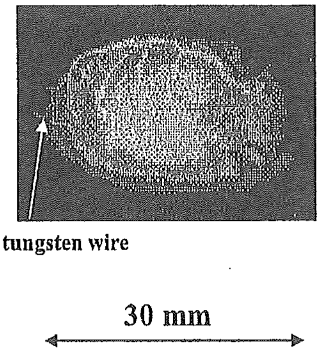

Figure 10: Angiograms of rabbit heart.

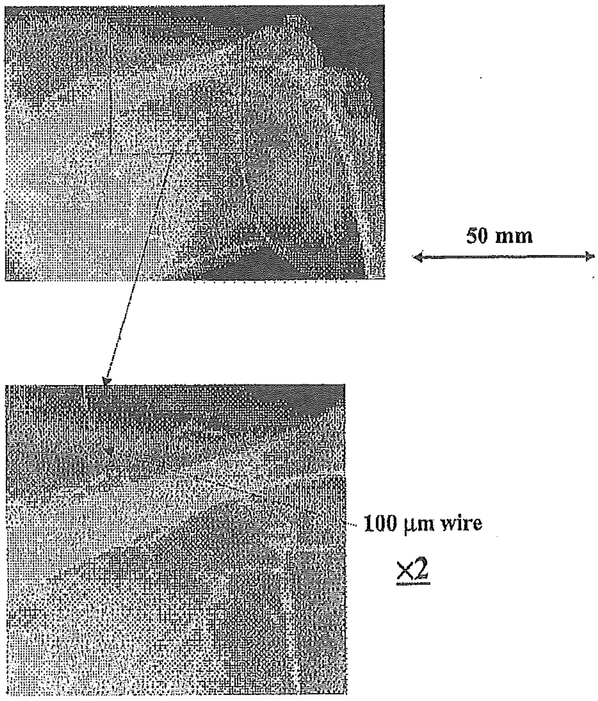

Figure 11: Angiograms of rabbit thigh.

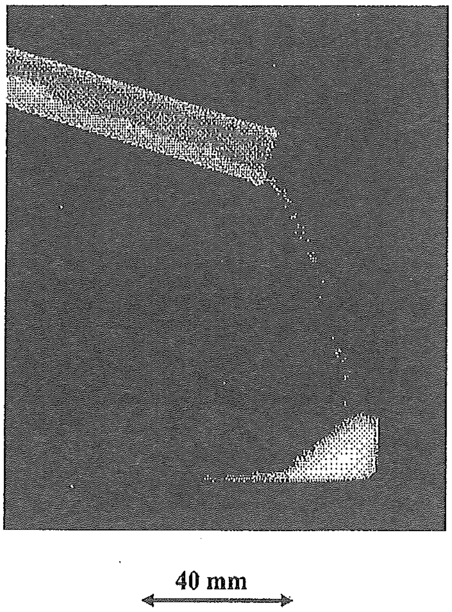

Figure 12:. Radiogram of aluminum grains falling into polypropylene beaker from glass test tube.

5. DISCUSSION

Concerning the spectrum measurement, we obtained fairly clean molybdenum Kα (17.4 keV) and Kβ (19.6 keV) lines. Therefore, we are very interested in the measurement the characteristic rays from nickel, copper, silver, cerium, and tungsten targets; the target element should be selected corresponding to the radiographic objectives. In a medical application, K-series characteristic x rays of cerium are absorbed effectively by an iodine-based contrast medium with a K-edge of 33.2 keV, and enhanced K-edge angiography can be performed.

In this research, the generator produced instantaneous number of K photons was approximately 2×10^8 photons/cm^2 per pulse at 1.0 m from the source. Subsequently, the intensity can be increased by increasing the electrostatic energy in condenser, and monochromatic Kα lines are left using a zirconium filter with a K-edge of 17.9 keV.

Using this flash x-ray generator, the photon energy of characteristic x rays can be selected, and we plan to design a high-speed photon-counting radiography system in order to decrease noise from radiograms. As compared with a steady-state x-ray generator, demonstrations of various monochromatic radiography will be accomplished easily, since the target element can be changed easily.

ACKNOWLEDGMENT

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Energy-selective high-speed radiography utilizing stroboscopic x-ray generator

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ABSTRACT

Energy-selective high-speed radiography utilizing a kilohertz-range stroboscopic x-ray generator and its application to high-speed angiography are described. This generator consists of the following major components: a main controller, a condenser unit with a Cockcroft-Walton circuit, and an x-ray tube unit in conjunction with a grid controller. The main condenser of about 500 nF in the unit is charged up to 100 kV by the circuit, and the electric charges in the condenser are discharged to the triode by the grid control circuit. Although the tube voltage decreased during the discharging for generating x rays, the maximum value was equal to the initial charging voltage of the main condenser. The maximum tube current and the repetition rate were approximately 0.5 A and 32 kHz, respectively. The x-ray pulse width ranged from 0.01 to 1.0 ms, and the maximum shot number had a value of 32. At a charging voltage of 80 kV and a width of 1.0 ms, the x-ray intensities obtained without filtering, using an aluminum filter, and using a barium sulfate filter were 14.8, 5.48 and 5.05 μGy per pulse, respectively, at 1.0 m, and the dimensions of the focal spot had values of 3.5 × 3.5 mm. Angiography was performed using both the aluminum and the barium sulfate filters at a charging voltage of 60 kV.

Keywords: energy-selective radiography, bremsstrahlung x rays, filtering, stroboscopic x-ray, pulse x-ray, angiography

1. INTRODUCTION

Modern high-speed x-ray generators are capable of producing short x-ray pulses with high dose rates, and have been applied to radiography in various fields. To produce hard flash x rays with maximum photon energies of approximately 1 MeV, multistage Marx surge generators have been developed.[1] Furthermore, induction linear accelerators[2] have been developed and improved to produce 10-MeV-order flash x rays. In contrast, 100-kV-order flash x-ray generators have been developed and applied to biomedicine.[3,4]

In the cases of multiple-shot and cine radiographies, we have developed several different repetitive-flash[5-8] and stroboscopic x-ray generators.[9-11] Although most flash x-ray generators have cold-cathode tubes, the stroboscopic generators utilize hot-cathode tubes. Particularly, although a 50 kHz stroboscopic generators have been manufactured, the repetition rate can be increased to MHz order.

Recently synchrotrons generate monochromatic parallel x-ray beams using a monochromator, and these beams have been employed to perform enhanced K-edge angiography[12,13] and x-ray phase imaging.[14,15] To perform angiography, the beams with photon energies of approximately 35 keV have been used, because iodine contrast mediums with a

26th International Congress on High-Speed Photography and Photonics, edited by D. L. Paisley, S. Kleinfelder, D. R. Snyder, B. J. Thompson, Proc. of SPIE Vol. 5580
(SPIE, Bellingham, WA, 2005) · 0277-786X/05/$15 · doi: 10.1117/12.568959

K-absorption edge of 33.155 keV absorb the beams effectively. In view of this situation, we have developed x-ray generators with cerium-target tubes[16,17] which can produce Kα rays of 34.6 keV.

In this research, we employed a tungsten-target x-ray tube and performed a preliminary study on high-speed angiography achieved with quasi-monochromatic x rays produced by filtering in conjunction with a computed radiography system.

2. GENERATOR

Figure 1 shows the block diagram of the kilohertz-range stroboscopic x-ray generator. This generator consists of the following major components: a main controller, a condenser unit with a Cockcroft-Walton circuit, and an x-ray tube unit in conjunction with a grid controller (Figs. 2 and 3). The main condenser of about 500 nF in the unit is charged up to 100 kV by the circuit, and the electric charges in the condenser are discharged to the triode by the grid control circuit. Although the tube voltage decreased during the discharging for generating x rays, the maximum value was equal to the initial charging voltage of the main condenser.

The x-ray tube is a glass-enclosed hot-cathode triode and is composed of the following major parts: an anode rod made of copper, a tungsten plate target, an iron focusing electrode, a tungsten hot cathode (filament), a tungsten grid, and a glass tube body. The electron beams from the cathode are accelerated between the anode and cathode electrodes and are converged to the target by the focusing electrode. The tube is set in the metal case filled with insulation oil, and the diaphragm regulates the radiation field.

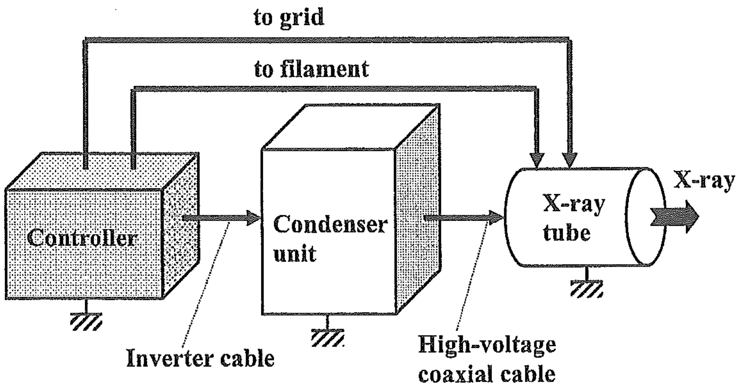


Figure 1: Block diagram of kilohertz-range stroboscopic x-ray generator.

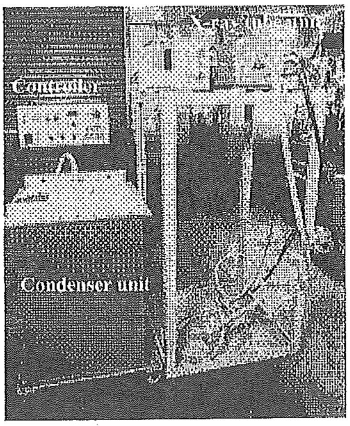


Figure 2: Stroboscopic x-ray generator.

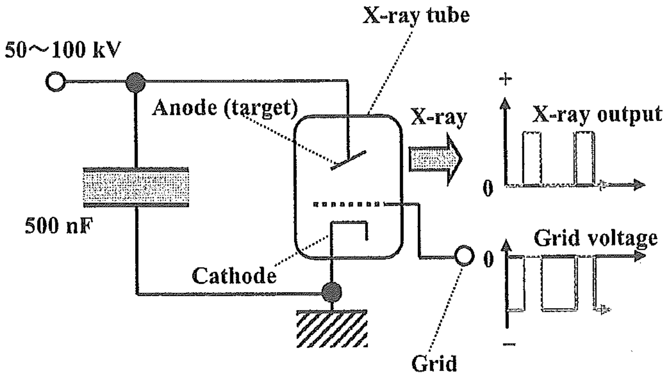


Figure 3: Main high-voltage circuit of x-ray generator.

3. CHARACTERISTICS

3.1 X-ray output

The x-ray output was detected by a pin diode, and the output voltages from the diode were measured by a digital storage scope (Fig. 4). Using this generator, the pulse width could be controlled correctly and ranged from 10 μs to 1.0 ms. The maximum repetition rate was approximately 50 kHz, and stable repetitive x-ray pulses were obtained. When the charging voltage was increased, the pulse height increased substantially.

3.2 Time-integrated x-ray intensity

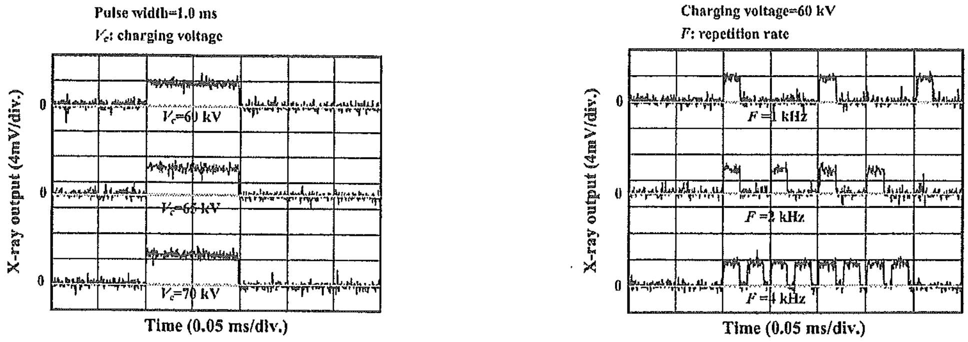
Figure 5 shows the time-integrated (absolute) value of the x-ray intensity (exposure) at 1.0 m per pulse measured by a Victoreen 660 ionization chamber. The intensity was proportional to the driving pulse width. At a constant pulse width of 1.0 ms, the intensity increased in proportion to approximately the second power of the charging voltage. At a charging voltage of 80 kV and a width of 1.0 ms, the x-ray intensity obtained without filtering, using an aluminum filter, and using a barium sulfate filter were 14.8, 5.48, and 5.05 μGy per pulse, respectively, at 1.0 m from the source.

3.3 X-ray source

The image of the x-ray source was measured using a pinhole camera with a hole diameter of 50 μm and a computed radiography (CR) system (Konica Regius 150)[18] with a sampling pitch of 87.5 μm. When the charging voltage was increased, the dimensions hardly varied, and were approximately 3.5×3.5 mm.

3.4 X-ray spectra

In order to measure x-ray spectra, we employed a cadmium tellurium detector (CDTE2020X, Hamamatsu Photonics Inc.) (Fig. 6). Compared with a germanium detector, this detector has a lower energy resolution of 1.7 keV.
When the charging voltage was increased, both the maximum photon energy and the intensities of bremsstrahlung x rays increased, and the photon energy of the spectrum peak also increased. The 3-mm-thick aluminum filter attenuated the low-photon-energy bremsstrahlung x rays. Subsequently, the barium sulfate filter, with a surface density of approximately 10 mg/cm^2, significantly attenuated the spectra above the barium K-edge of 37.4 keV. The areas under the spectral curves correlate closely to the total x-ray intensities shown in Fig. 4.



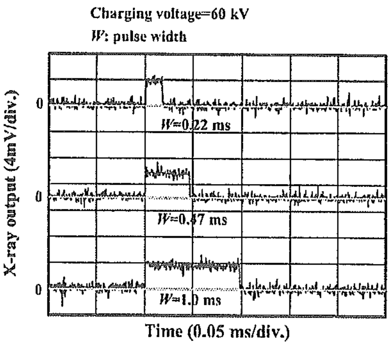
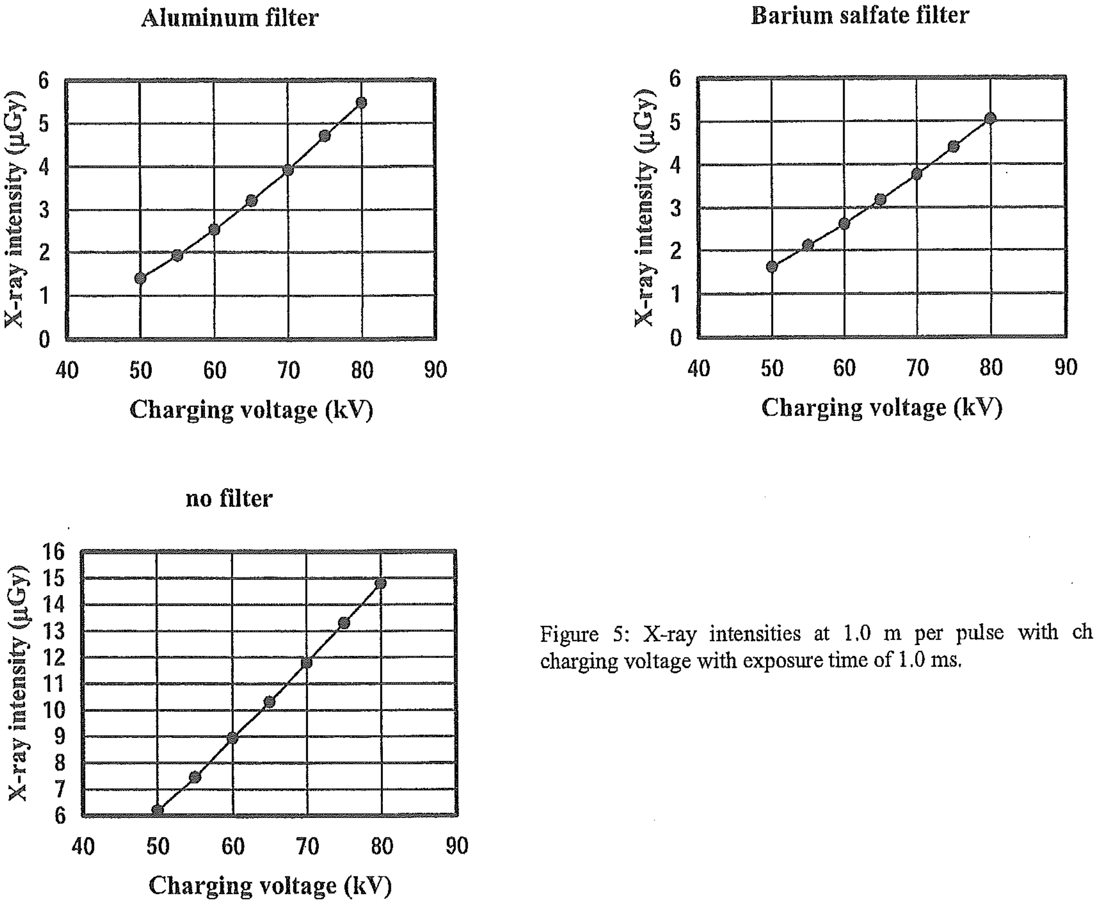


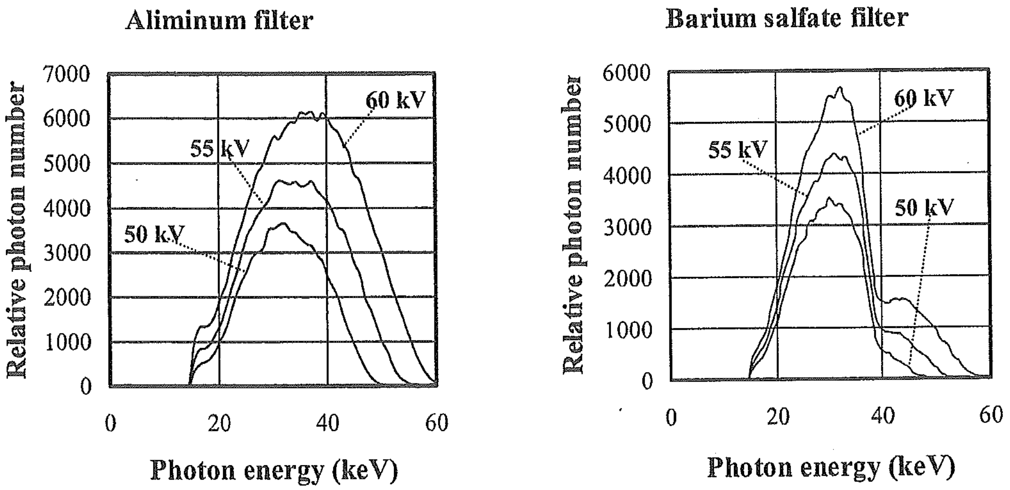
Figure 4: X-ray outputs at indicated conditions.


Aluminum filter

Barium salfate filter

no filter

Figure 5: X-ray intensities at 1.0 m per pulse with changing charging voltage with exposure time of 1.0 ms.


Aliminum filter

Barium salfate filter

Figure 6: X-ray spectra at indicated conditions.

4. RADIOGRAPHY

The angiography was performed by a CR system using the filters with a charging voltage of 60 kV, and the distance between the x-ray source and the imaging plate was 0.7 m. The image contrast hardly varied even when the filter was changed.

Figure 7 shows radiograms of tungsten wires coiled around a rod made of polymethyl methacrylate using the aluminum filter. Although the image contrast increased with increases in the wire diameter, a 50 μm-diameter wire could be observed.

The image of water spouted from an injector is shown in Fig. 8. This image was taken with the slight addition of an iodine-based contrast medium using the barium sulfate filter. Because the x-ray duration was 1 ms, the stop-motion image of water could be obtained. Figures 9 and 10 show angiograms of a rabbit thigh (barium sulfate filter) and a dog heart (aluminum filter), respectively. In angiography, iodine-based microspheres of 15 μm in diameter were used, and fine blood vessels of about 100 μm were visible.

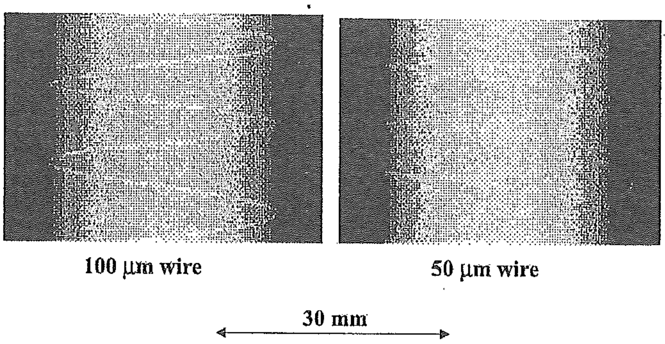


Figure 7: Radiograms of tungsten wires coiled around rod made of polymethyl methacrylate using aluminum filter.

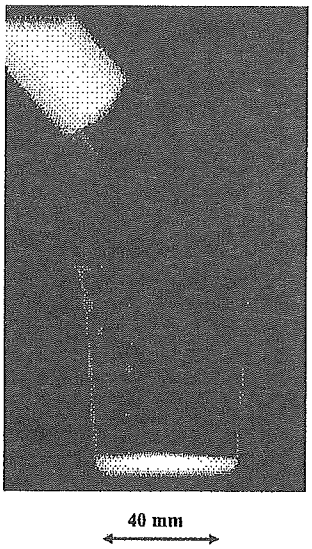


Figure 8: Radiogram of water spouted from injector using barium sulfate filter.

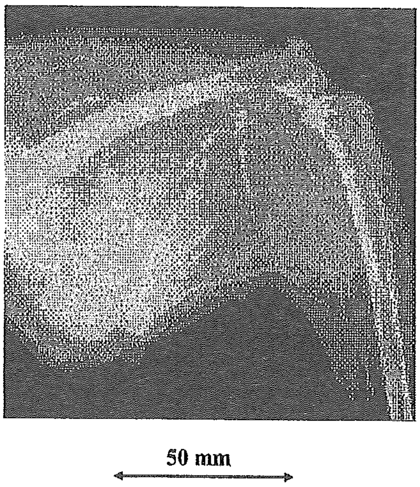


Figure 9: Angiograms of rabbit thigh achieved with barium sulfate filter.

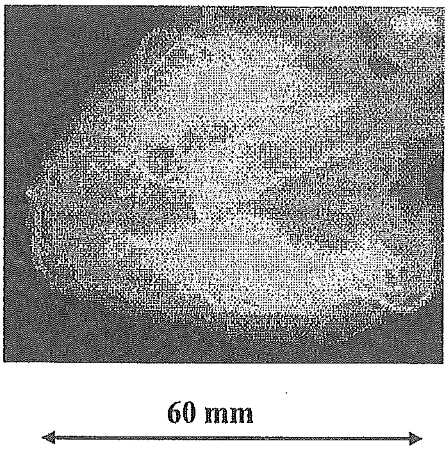


Figure 10: Angiogram of dog heart with aluminum filter.

5. DISCUSSION

Concerning the spectrum measurement, we obtained bremsstrahlung x rays with narrow energy latitudes using both the aluminum and the barium sulfate filters. When the aluminum filter was employed with a charging voltage of 60 kV, the peak photon energy of the spectra was approximately 35 kV. Therefore, the filter thickness should be increased in order to decrease bremsstrahlung x rays of lower than the K-absorption edge of iodine. Subsequently, using the barium sulfate filter, because the peak photon energy was nearly equal to the K-edge, aluminum filtering should be employed. In addition, a cerium oxide filter is also useful in order to increase the peak energy and to decrease low-photon-energy bremsstrahlung x rays.

Using these filters with a charging voltage of 60 kV and a pulse width (exposure time) of 1.0 ms, although we obtained the x-ray intensities of approximately 5 μGy at 1.0 m per pulse, the intensity should be maximized by increasing the tube current in order to improve the image quality using the CR system.

With recent advances in angiography using MRI, if the density of gadolinium-based contrast mediums increases, enhanced K-edge angiography utilizing monochromatic x-ray generators, which produce tungsten Kα rays, will be a useful technique to decrease the absorbed dose during angiography.

ACKNOWLEDGMENT

This work was supported by Grants-in-Aid for Scientific Research (13470154, 13877114, and 16591222) and Advanced Medical Scientific Research from MECSST, Health and Labor Sciences Research Grants(RAMT-nano-001, RHGTEFB-genome-005 and RHGTEFB-saisei-003), Grants from Keiryo Research Foundation, The Promotion and Mutual Aid Corporation for Private Schools of Japan, Japan Science and Technology Agency (JST), and New Energy and Industrial Technology Development Organization (NEDO, Industrial Technology Research Grant Program in '03).

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