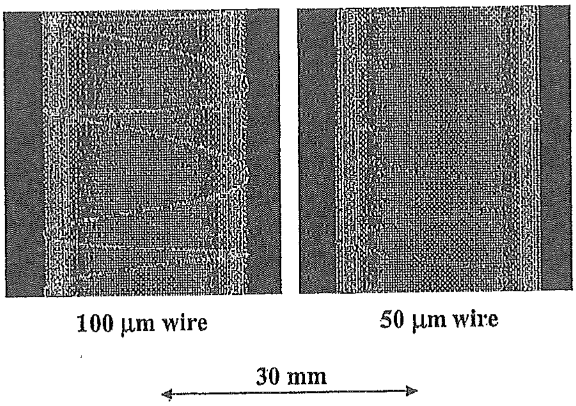

Figure 8: Radiograms of tungsten wires coiled around pipe made of polymethyl methacrylate.

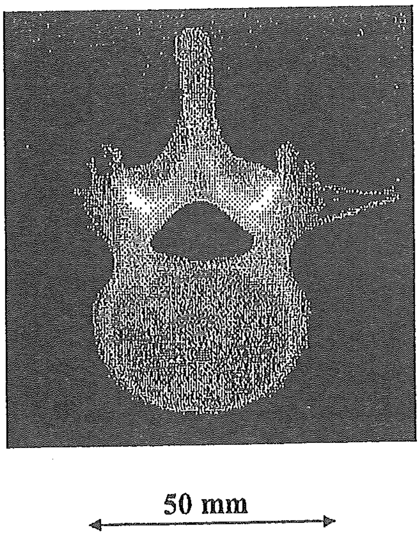

Figure 9: Radiogram of vertebra.

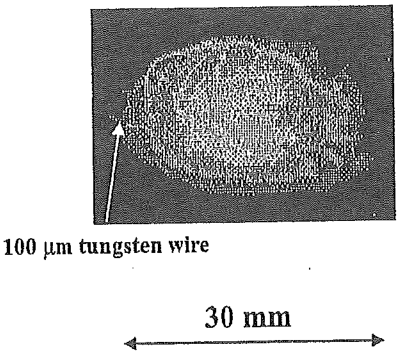

Figure 10: Angiograms of rabbit heart.

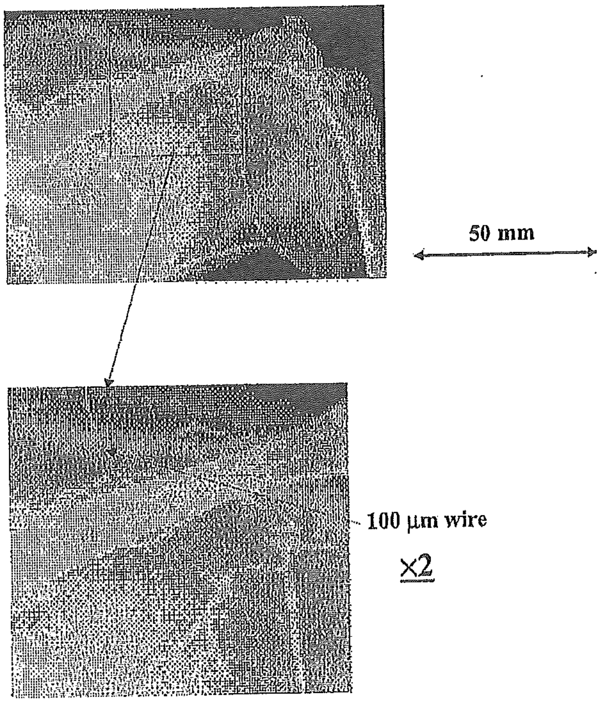

Figure 11: Angiograms of rabbit thigh.

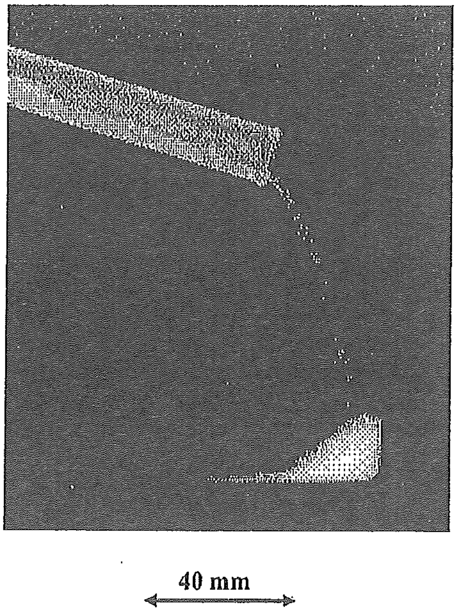

Figure 12:. Radiogram of aluminum grains falling into polypropylene beaker from glass test tube.

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

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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.

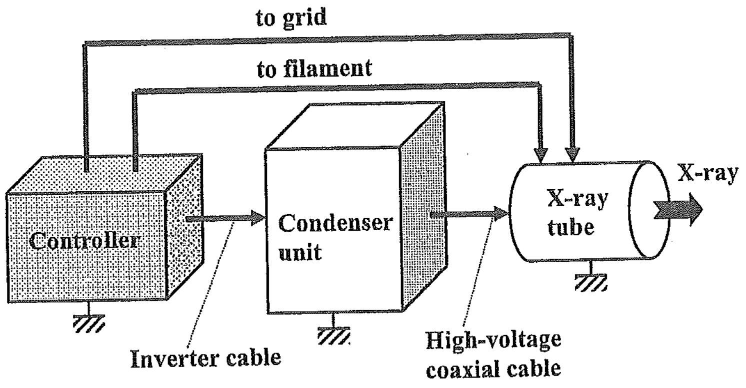


Figure 1: Block diagram of kilohertz-range stroboscopic x-ray generator.

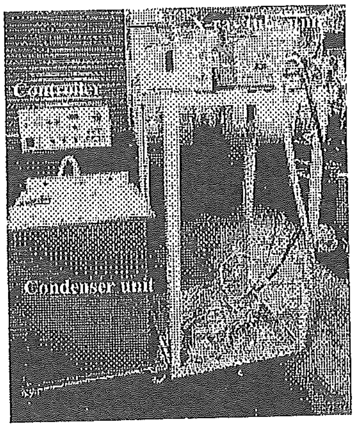


Figure 2: Stroboscopic x-ray generator.

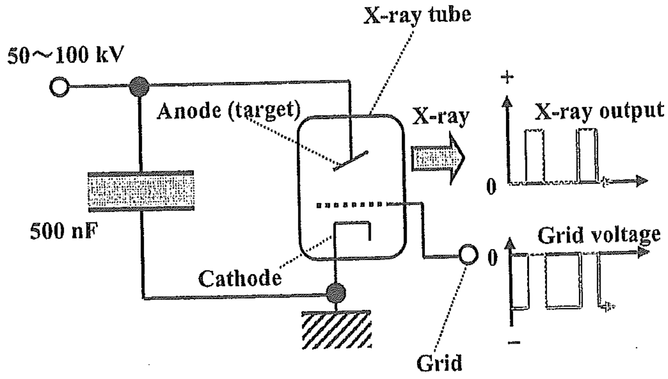


Figure 3: Main high-voltage circuit of x-ray generator.

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.

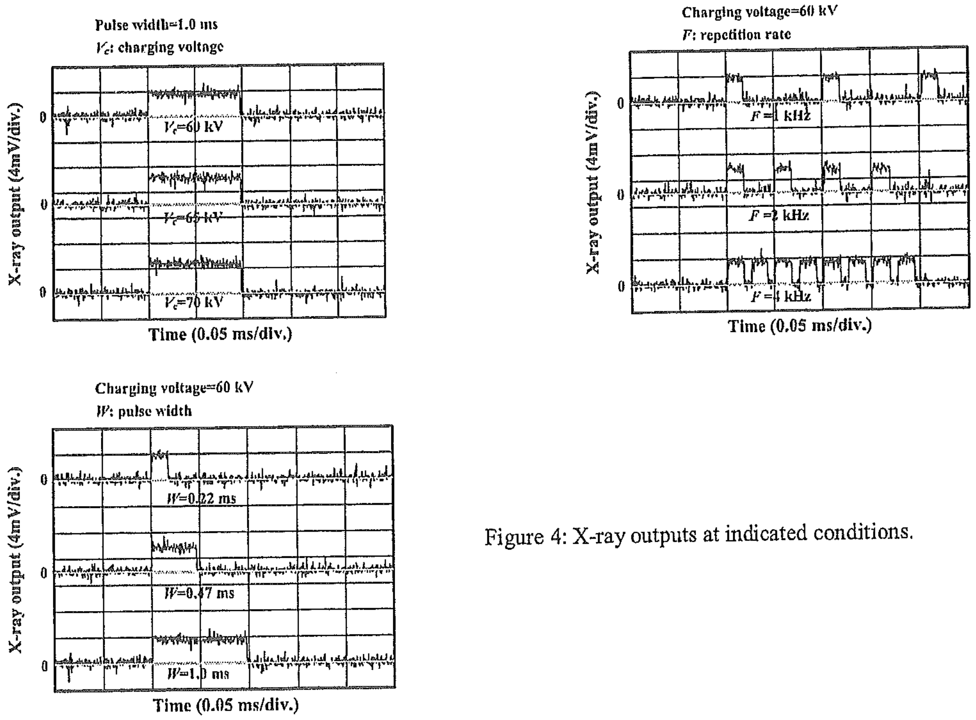


Figure 4: X-ray outputs at indicated conditions.

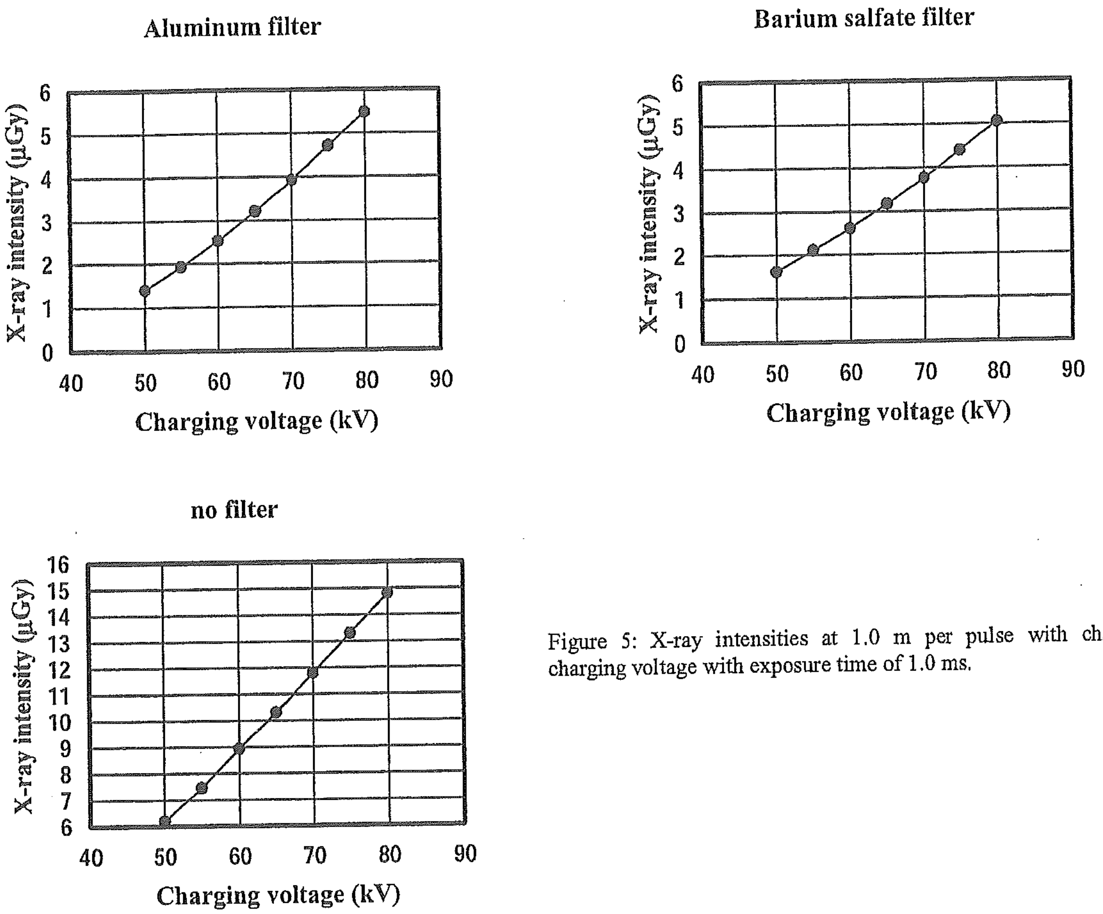


Figure 5: X-ray intensities at 1.0 m per pulse with changing charging voltage with exposure time of 1.0 ms.

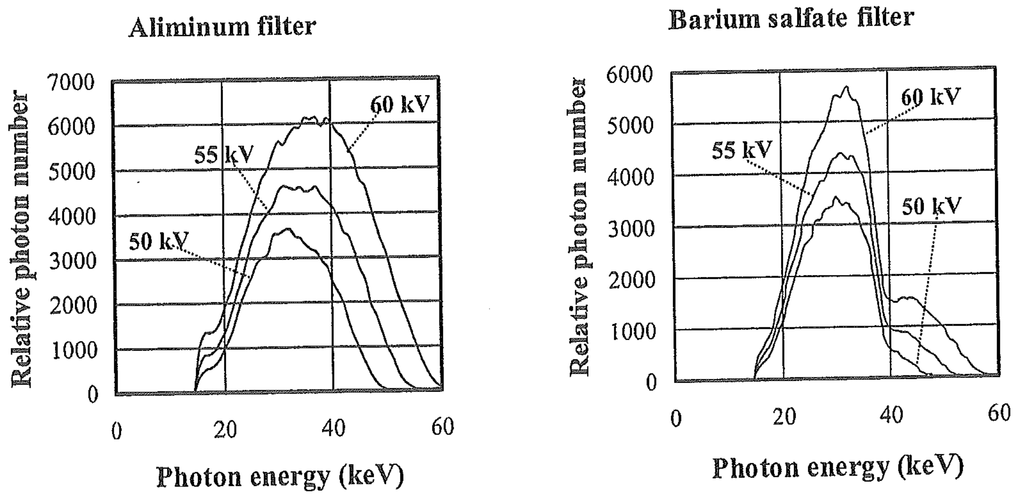


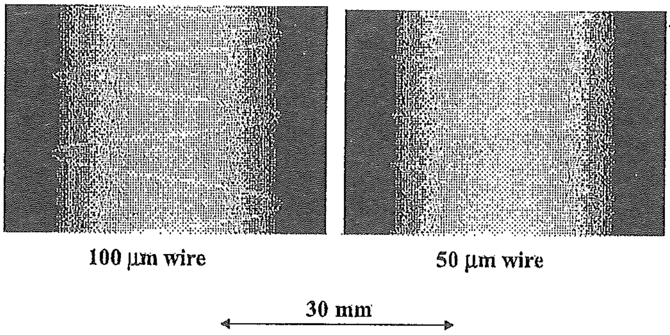
Figure 6: X-ray spectra at indicated conditions.

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.



100 µm wire **50 µm wire**

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

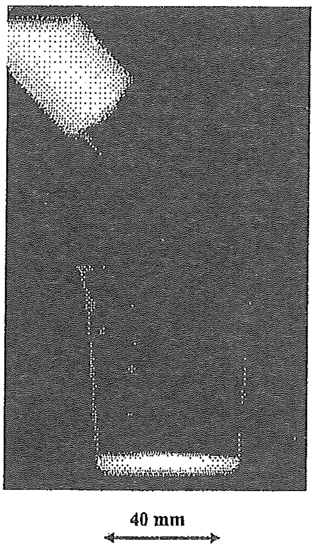


Figure 8: Radiogram of water spouted from injector using barium sulfate filter.

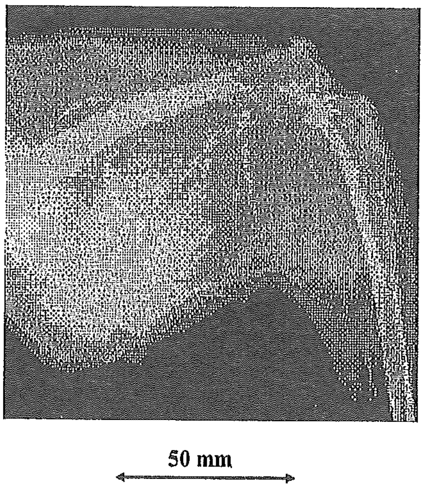


Figure 9: Angiograms of rabbit thigh achieved with barium sulfate filter.

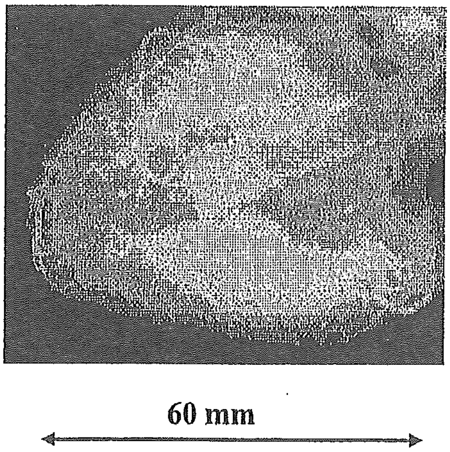


Figure 10: Angiogram of dog heart with aluminum filter.

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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Demonstration of flash K-edge angiography utilizing gadolinium-based contrast medium

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ABSTRACT

The high-voltage condensers in a polarity-inversion two-stage Marx surge generator are charged from −50 to −70 kV by a power supply, and the electric charges in the condensers are discharged to an x-ray tube after closing gap switches in the surge generator with a trigger device. The x-ray tube is a demountable diode, and the turbomolecular pump evacuates air from the tube with a pressure of approximately 1 mPa. Tungsten characteristic x rays can be produced, since the tube utilizes a disk cathode and a rod target, and bremsstrahlung rays are not emitted in the opposite direction to that of electron acceleration. At a charging voltage of −70 kV, the instantaneous tube voltage and current were 140 kV and 1.0 kA, respectively. The x-ray pulse widths were approximately 90 ns, and the estimated number of K photons was approximately 5×10^8 photons/cm^2 per pulse at 0.5 m from the source of 3.0 mm in diameter.

Keywords: angiography, gadolinium-based contrast media, characteristic x rays, quasi-monochromatic x rays, tungsten K lines

1. INTRODUCTION

So far, several different flash x-ray generators have been developed,[1] and soft generators[2-6] with photon energies of lower than 150 keV can be employed to perform biomedical radiography. In order to produce monochromatic x rays, plasma flash x-ray generators[7-11] are useful, since quite intense and sharp characteristic x rays such as lasers have been produced from weakly ionized linear plasmas of nickel, copper and molybdenum, while bremsstrahlung rays are hardly detected at all. Using these generators, the characteristic x-ray intensity substantially increased with corresponding increases in the charging voltage.

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Angiography using iodine-based contrast mediums is the current mainstay for observing blood vessels including coronary arteries. Conventional angiography uses an x-ray tube with a tungsten target, and bremsstrahlung x rays with just above the K-absorption edge (33.2 keV) are applied effectively, since the rays are absorbed easily by the iodine. Subsequently, synchrotrons have been used to form monochromatic parallel beams with photon energies of approximately 35 keV so as to perform enhanced K-edge angiography.[12-15]

Since K-series characteristic x rays from ytterbium, tantalum, and tungsten targets are absorbed effectively by gadolinium-based contrast media, these x rays are very useful for performing enhanced K-edge angiography. As compared with K-edge angiography using iodine-based contrast media with an iodine K-edge of 33.2 keV, the absorbed dose can be decreased easily in cases where the gadolinium media are employed.

In the present research, we developed an quasi-monochromatic flash x-ray generator with a tungsten target tube, and used it to perform a preliminary study on angiography achieved with tungsten K-series characteristic x rays.

2. PRINCIPLE OF K-EDGE ANGIOGRAPHY

Figure 1 shows the mass attenuation coefficients of gadolinium at the selected energies; the coefficient curve is discontinuous at the iodine K-edge. The average photon energy of the cerium Kα lines is shown just above the gadolinium K-edge. The average photon energy of tungsten Kα lines is 58.9 keV, and gadolinium contrast media with a K-absorption edge of 50.2 keV absorb the lines easily. Therefore, blood vessels were observed with high contrasts.

3. GENERATOR

3.1 High-voltage circuit

Block diagram of a compact monochromatic flash x-ray generator is shown in Fig. 2. This generator consists of the following components: a constant high-voltage power supply, a surge Marx generator with a capacity during main discharge of 425 pF, a thyratron trigger device for the surge generator, a turbomolecular pump, and a flash x-ray tube. Since the electric circuit of the high-voltage pulse generator employs a polarity-inversion two-stage Marx line (Fig. 3), 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.

3.2 X-ray tube

The x-ray tube is a demountable diode type, as illustrated in Fig. 4. This tube is connected to the turbomolecular pump with a pressure of about 1 mPa and consists of the following major devices: a rod-shaped tungsten 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 (Fig. 5), tungsten characteristic x rays can be produced.

4. CHARACTERISTICS

4.1 Tube voltage and current

Tube voltage and current were measured by 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 1.0 kA, respectively, at a charging voltage of −70 kV.

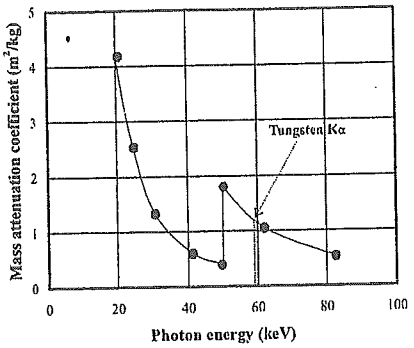


Figure 1: Relation between mass attenuation coefficient of iodine and average photon energy of tungsten Kα lines.

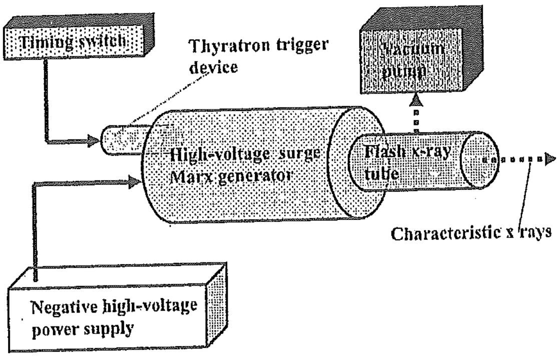


Figure 2: Block diagram of compact quasi-monochromatic flash x-ray generator.

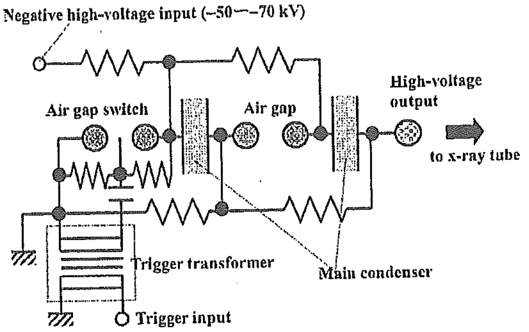


Figure 3: Circuit diagram of two-stage surge Marx generator.

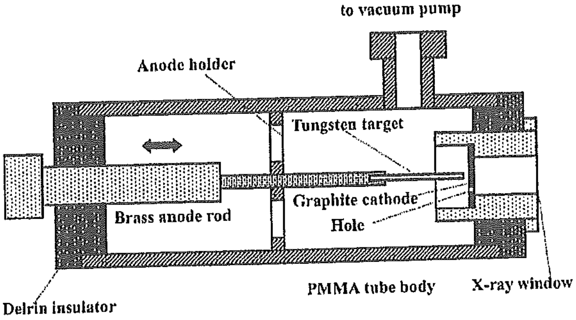


Figure 4: Schematic drawing of flash x-ray tube.

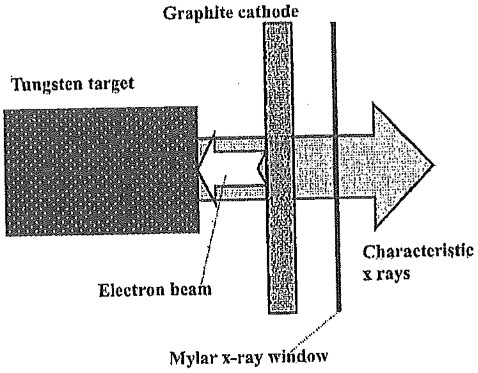


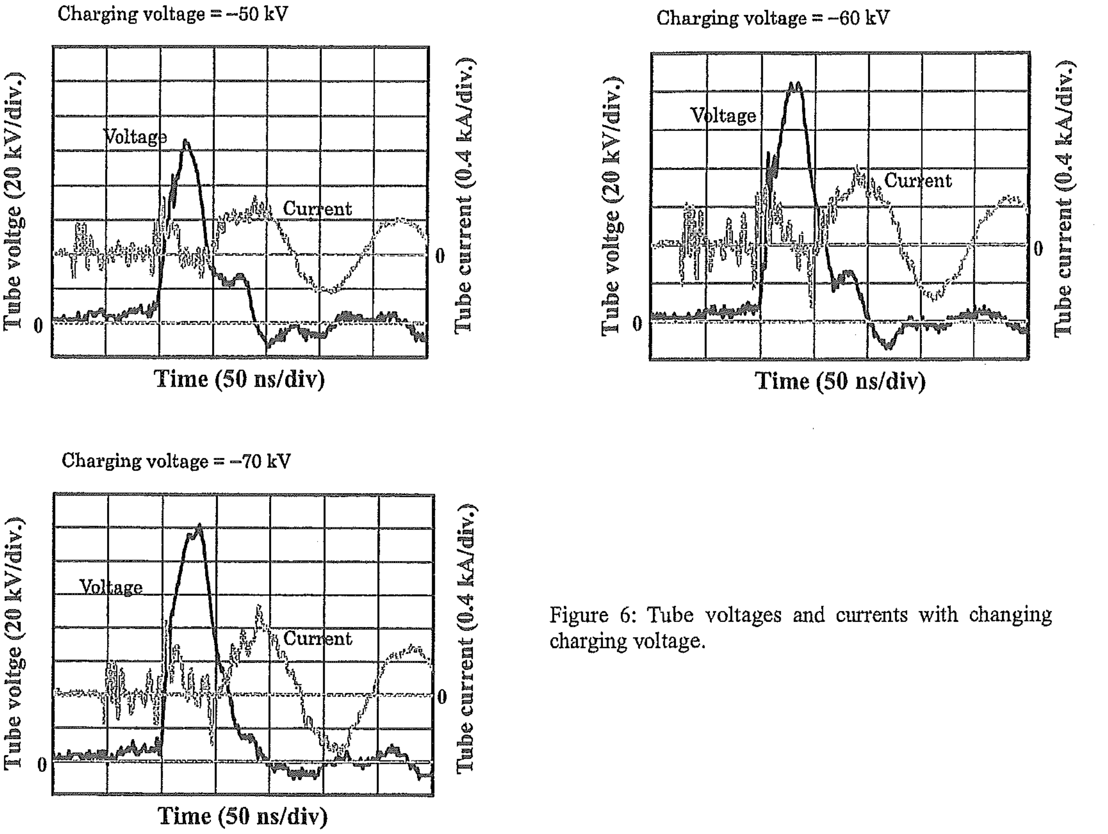
Figure 5: Irradiation of characteristic x rays.

4.2 X-ray output

X-ray output pulse was detected using a combination of a plastic scintillator and a photomultiplier (Fig. 7). When the charging voltage was increased, the pulse height increased, but the width seldom varied. The widths were about 90 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 an instantaneous value of approximately 5 μC/kg per pulse at 0.5 m from the x-ray source with a charging voltage of −70 kV.

4.3 X-ray source

In order to observe the x-ray source, we employed a 100-μm-diameter pinhole camera and an x-ray film (Polaroid XR-7) (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 about 3.0 mm.



Charging voltage = −50 kV

Charging voltage = −60 kV

Charging voltage = −70 kV

Figure 6: Tube voltages and currents with changing charging voltage.

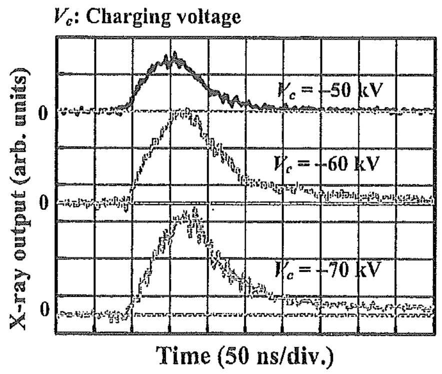


Figure 7: X-ray outputs at indicated conditions.

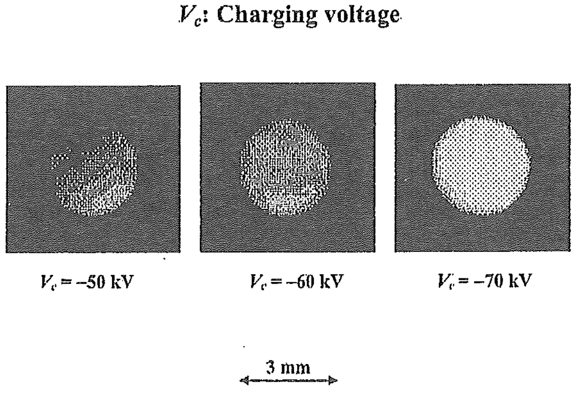


Figure 8: Images of the characteristic x-ray source with changes in charging voltage.

5. ANGIOGRAPHY

The flash angiography was performed by a computed radiography (CR) system (Konica Regius 150)[16] 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 9 shows radiograms of tungsten wires coiled around a rod made of polymethyl methacrylate. Although the image contrast increased with increases in the wire diameter, a 50 μm-diameter wire could be observed.

The image of plastic bullets falling into a polypropylene beaker from a glass test tube is shown in Fig. 10. Because the x-ray duration was approximately 100 ns, the stop-motion image of bullets could be obtained.

Angiograms of rabbit hearts are shown in Fig. 11. This image was obtained using iodine microspheres of 15 μm. Because the microspheres transmitted tungsten K-series characteristic x rays easily, the coronary arteries were barely visible. Figure 12 shows an angiogram of a polytetrafluoroethylene (Teflon) tube using a contrast medium which contains 7.5% gadolinium by weight, and a low contrast tube with an inside diameter of 1.0 mm is observed. Subsequently, a radiogram of gadolinium oxide powder in the Teflon tube is shown in Fig. 13, and the gadolinium oxide powder is visible. In cases where a gadolinium oxide suspension of 50% by weight is employed, high-contrast angiography of the tube could be performed (Fig. 14).

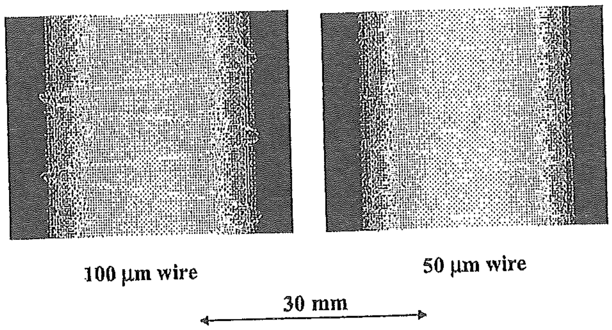

100 μm wire **50 μm wire**

Figure 9: Radiograms of tungsten wires coiled around a rod made of polymethyl methacrylate.

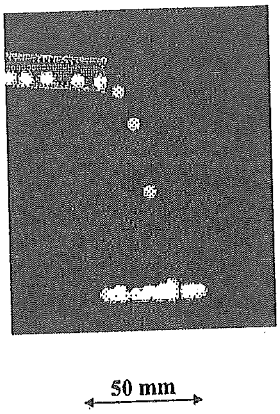


Figure 10: Radiogram of plastic bullets falling into polypropylene beaker from glass test tube.

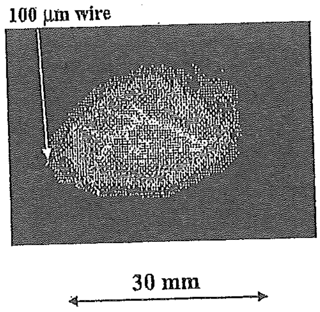


Figure 11: Angiograms of rabbit hearts using iodine microspheres.

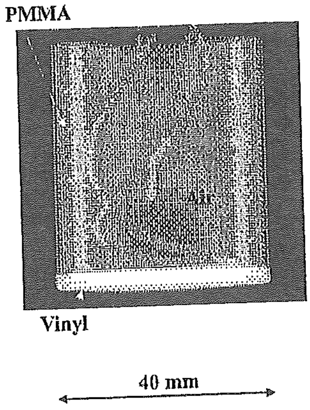


Figure 12: Angiograms of Teflon tube using gadolinium contrast medium of 7.5% by weight.

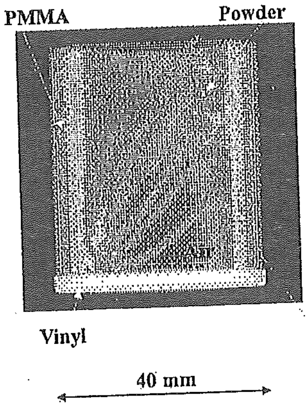


Figure 13: Radiography of gadolinium oxide powder in Teflon tube.

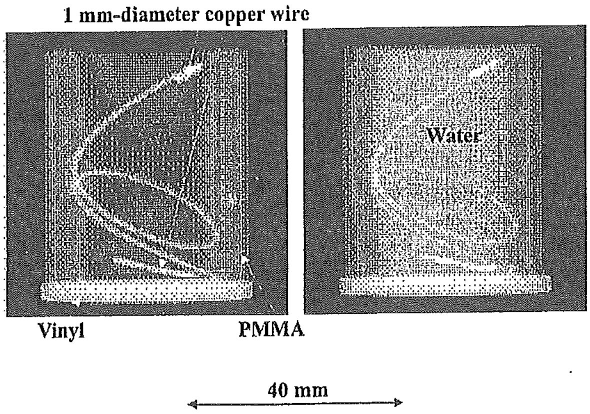


Figure 14: Angiography of Teflon tube using gadolinium oxide suspension of 50 % by weight.

6. DISCUSSION

Concerning the spectrum measurement, we have succeeded in measuring K-series characteristic x rays from a cerium target using a curved-crystal spectrometer. However, the tungsten K-series characteristic x rays could not be measured using the spectrometer utilizing a lithium fluoride crystal, because both the diffraction efficiency and the intensity substantially decreased with increases in photon energy. Therefore, optimum single crystal should be selected, and the measurements of the attenuation curve will be a conventional technique to confirm the irradiation of K-series characteristic x rays; the curve of transmittivity (logarithmic scale) vs absorber thickness is almost linear when bremsstrahlung x rays are not produced. In addition, L-series characteristic rays should be absorbed as much as possible before angiography using a tungsten or an ytterbium oxide filter. In these cases, the photon energies of the K-absorption edge of tungsten and ytterbium are 69.5 and 61.3 keV, respectively.

In this research, the generator produced instantaneous number of $K\alpha$ photons was approximately 5×10^{8} photons/cm^2 per pulse at 0.5 m from the source. Because the molybdenum plasma generator produced approximately 2×10^{9} photons/cm^2 per pulse at 0.5 m from the source, the x-ray intensity of $K\alpha$ lines had a lower value as compared with the plasma x-ray generator described above, which utilizes a large capacity condenser of approximately 200 nF.

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. In addition, steady-state monochromatic x rays for fluoroscopy can be produced by a similar tube using a constant high-voltage power supply. In conjunction with the fine focusing, these low-cost monochromatic x-ray generators will be employed to perform K-edge angiography and x-ray phase imaging for edge enhancement.

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Superposition of x-ray spectra using double-target plasma triode

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ABSTRACT

In the plasma flash x-ray generator, a 200 nF condenser is charged up to 50 kV by a power supply, and flash x rays are produced by the discharging. The x-ray tube is a demountable triode with a double target consisting of a copper and a molybdenum rods, and the turbomolecular pump evacuates air from the tube with a pressure of approximately 1 mPa. Target evaporation leads to the formation of weakly ionized linear plasma, consisting of metal ions and electrons, around the fine target, and intense characteristic x rays are produced. At a charging voltage of 50 kV, the maximum tube voltage was almost equal to the charging voltage of the main condenser, and the peak current was about 11 kA. When the charging voltage was increased, the linear plasma formed, and the molybdenum K-series characteristic x-ray intensities increased substantially. Although the intensities of copper Kα lines increased with increases in the charging voltage, hardly any clean Kβ lines were detected. The x-ray pulse widths were approximately 1.2 μs, and the time-integrated x-ray intensity was approximately 30 μC/kg at 1.0 m from the x-ray source with a charging voltage of 50 kV.

Keywords: flash x-ray, plasma x-ray, weakly ionized linear plasma, characteristic x rays, x-ray superposition

1. INTRODUCTION

Monochromatic x-ray computed tomography at two different energies has provided information about the electron density of human tissue.[1] In addition, a compact pulsed tunable monochromatic x-ray source has been designed, developed, and tested.[2] From the source, cone x-ray beams from 10 to 50 keV with pulse widths of 8 ps have been produced, and these beams are useful for biomedical imaging and protein crystallography.

Most flash x-ray generators utilize surge Marx generators[3,4] in conjunction with cold-cathode diodes and produce extremely short x-ray pulses with durations of less than 1 μs. In the surge generator, the output voltage is equal to the value of the condenser charging voltage multiplied by the stage number. Because the high-voltage durability substantially increased under the pulsed operation, the maximum photon energy of flash x rays has been increased to 1 MeV or beyond so as to perform military applications.

To perform biomedical radiography, we have developed several different soft flash x-ray generators[5-10] corresponding to specific radiographic objectives, and a major goal in our research is the development of an intense and clean

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monochromatic x-ray generator that can impact applications with biomedical radiography with photon energies of approximately 10 keV or beyond. In view of this situation, we confirmed irradiation of intense K-series characteristic x rays from the plasma axial direction by forming weakly ionized linear plasma.[11-15] On the other hand, we are very interested in the superposition of characteristic x rays in order to perform wide latitude radiography or energy subtraction radiography.

In this paper, we describe a plasma flash x-ray generator utilizing a double-target radiation tube, used to perform a preliminary experiment for the superposition of 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 200 nF, a turbomolecular pump, a krytron pulse generator as a trigger device, and a flash x-ray tube. In this generator, a low-impedance transmission line is employed in order to increase maximum tube current (Fig. 2). The high-voltage main condenser is charged up to 50 kV by the power supply, and electric charges in the condenser are discharged to the tube after triggering the cathode electrode with the trigger device. The plasma flash x rays are then produced.

2.2 X-ray tube

The x-ray tube is a demountable cold-cathode triode 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 pipe-shaped graphite cathode with a bore diameter of 10.0 mm, a trigger electrode made from copper wire, a brass focusing electrode, a stainless-steel vacuum chamber, a nylon insulator, a polyethylene terephthalate (Mylar) x-ray window 0.25 mm in thickness, and a double-rod target. The target is composed of a copper rod and a molybdenum rod each 2.0 mm in diameter, and the plasma length is primarily determined by the distance between the target tip and the graphite ring. The distance between the target and cathode electrodes is approximately 20 mm, and the trigger electrode is set in the cathode electrode. As electron beams from the cathode electrode are roughly converged to the target by the focusing electrode, evaporation leads to the formation of weakly ionized linear plasma, consisting of metal ions and electrons, around the fine target.

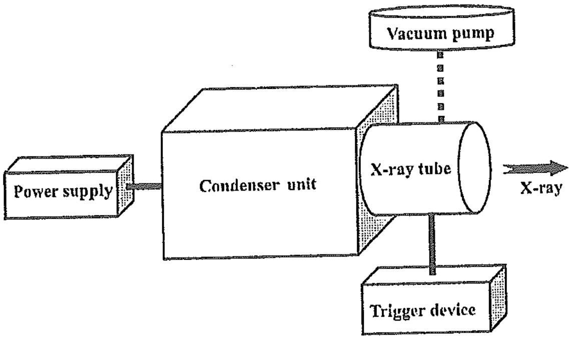

Figure 1: Block diagram of high-intensity plasma flash x-ray generator.

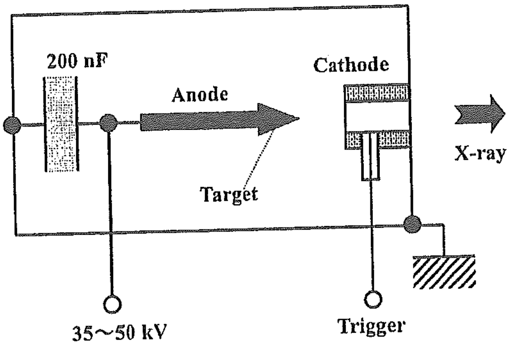

Figure 2: Circuit diagram of flash x-ray generator.

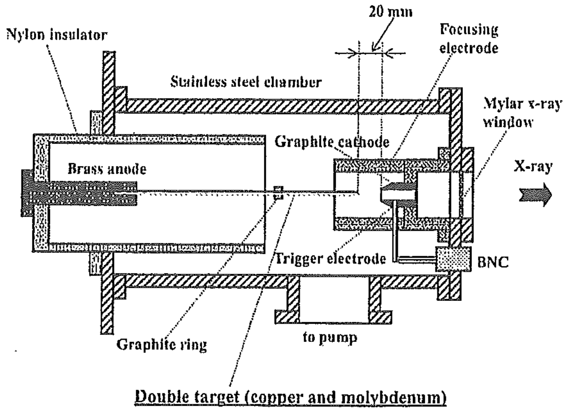

Figure 3: Schematic drawing of flash x-ray tube with double target.

3. CHARACTERISTICS

3.1 Tube voltage and current

Tube voltage and current were measured by a high-voltage divider with an input impedance of 1 GΩ and a current transformer, respectively. Figure 4 shows the time relation between the tube voltage and current. At the indicated charging voltages, they roughly displayed damped oscillations. When the charging voltage was increased, both the maximum tube voltage and current increased. At a charging voltage of 50 kV, the maximum tube voltage was almost equal to the charging voltage of the main condenser, and the maximum tube current was approximately 11 kA.

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 substantially increased with corresponding increases in the charging voltage. The x-ray pulse widths were about 1.2 μs, and the time-integrated x-ray intensity measured by a thermoluminescence dosimeter (Kyokko TLD Reader 1500 with MSO-S elements without energy compensation) had a value of approximately 30 μC/kg at 1.0 m from the x-ray source with a charging voltage of 50 kV.

3.3 X-ray source

In order to roughly observe images of the plasma x-ray source in the detector plane, we employed a 100-μm-diameter pinhole camera and an x-ray film (Polaroid XR-7) (Fig. 6). At a charging voltage of 35 kV, we observed two spots of the double target. 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 two targets, 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 from the plasma source 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[16] with a wide dynamic range, and relative x-ray intensity was calculated from Dicom digital data.

Figure 7 shows measured spectra near molybdenum K-series characteristic x rays. We observed sharp lines of K-series characteristic x rays of molybdenum. However bremsstrahlung rays were only detected slightly. The molybdenum characteristic x-ray intensity substantially increased with corresponding increases in the charging voltage. In the measurement of copper spectra (Fig. 8), although fairly clean Kα lines were observed, any sharp Kβ lines were hardly detected. In addition, we found lines of $0.5E_\alpha$, but $0.5E_\beta$ lines were not detected. Here, E_α and E_β are the average photon energies of molybdenum Kα and Kβ lines, respectively.