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.

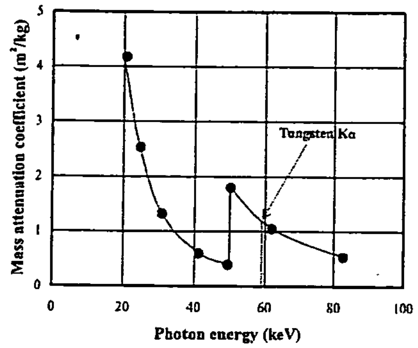

Figure 1: Relation between mass attenuation coefficient of iodine and average photon energy of tungsten Kα lines.

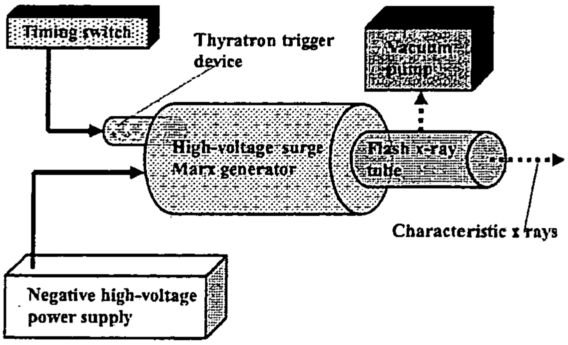

Figure 2: Block diagram of compact quasi-monochromatic flash x-ray generator.

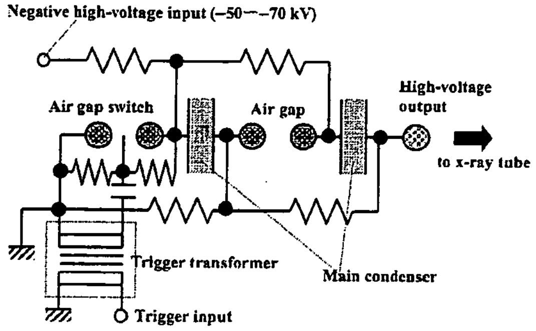

Figure 3: Circuit diagram of two-stage surge Marx generator.

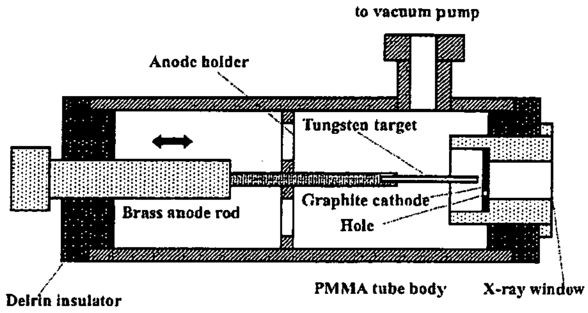

Figure 4: Schematic drawing of flash x-ray tube.

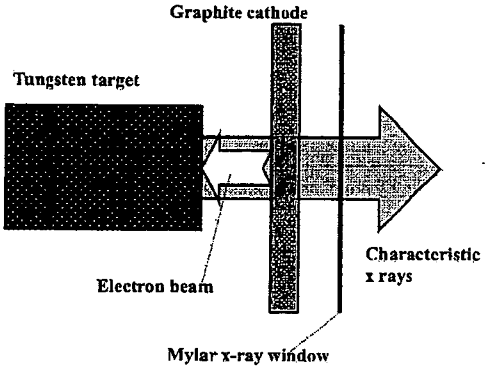

Figure 5: Irradiation of characteristic x rays.

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.

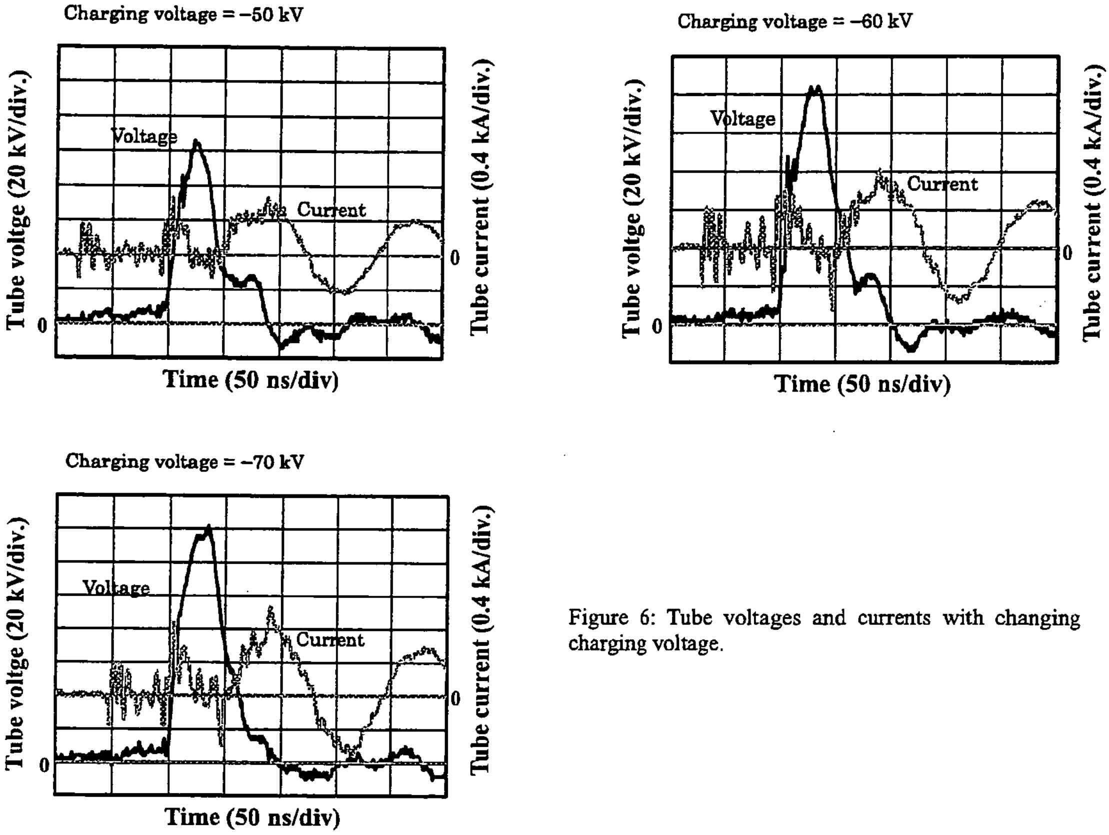

Figure 6: Tube voltages and currents with changing charging voltage.

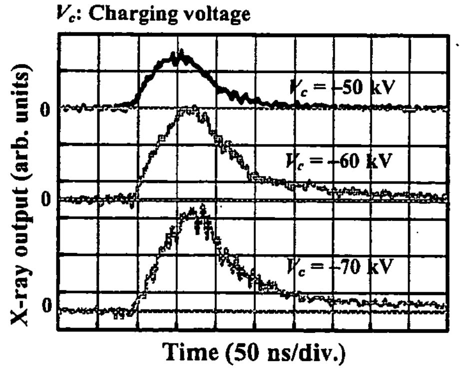

Figure 7: X-ray outputs at indicated conditions.

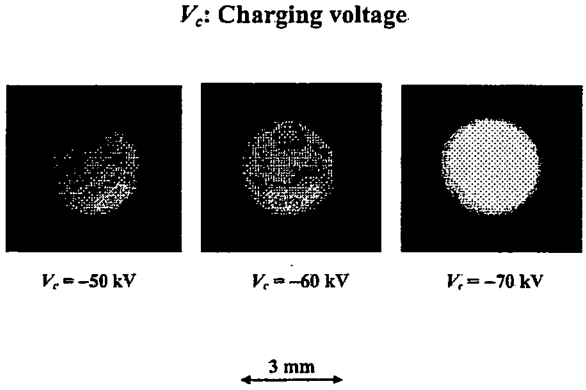

Figure 8: Images of the characteristic x-ray source with changes in charging voltage.

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).

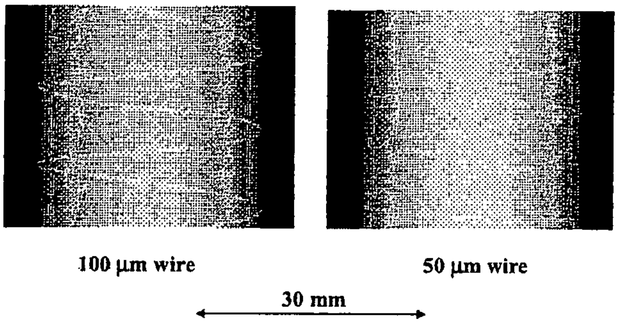

Figure 9: Radiograms of tungsten wires coiled around a rod made of polymethyl methacrylate.

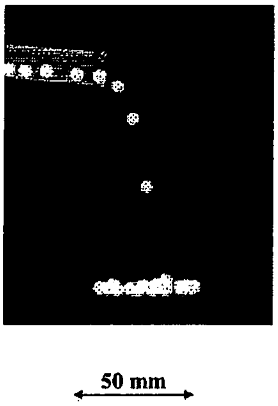

Figure 10: Radiogram of plastic bullets falling into polypropylene beaker from glass test tube.

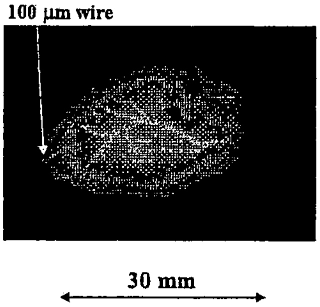

Figure 11: Angiograms of rabbit hearts using iodine microspheres.

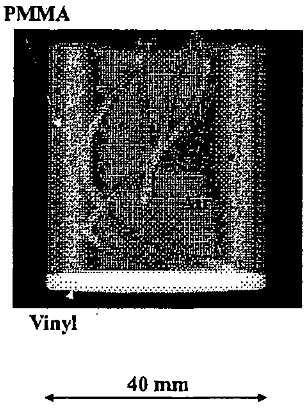

Figure 12: Angiograms of Teflon tube using gadolinium contrast medium of 7.5% by weight.

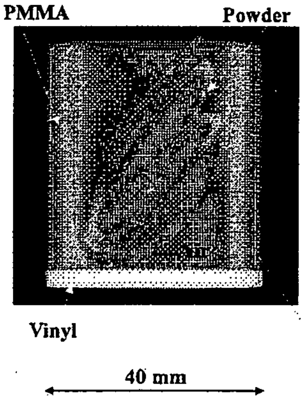

Figure 13: Radiography of gadolinium oxide powder in Teflon tube.

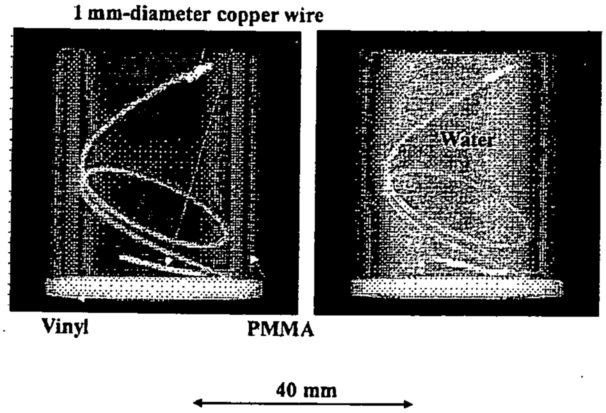

Figure 14: Angiography of Teflon tube using gadolinium oxide suspension of 50 % by weight.

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 Kα 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 Kα 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.

ACKNOWLEDGMENT

This work was supported by Grants-in-Aid for Scientific Research (13470154, 13877114, 16591181, 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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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

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: 10.1117/12.581235

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.

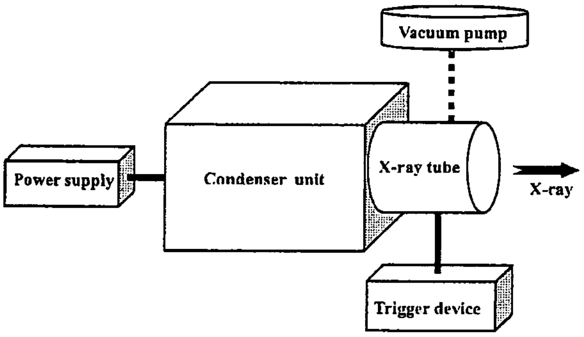


Figure 1: Block diagram of high-intensity plasma flash x-ray generator.

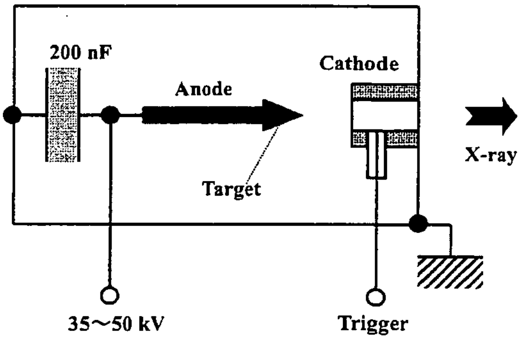


Figure 2: Circuit diagram of flash x-ray generator.

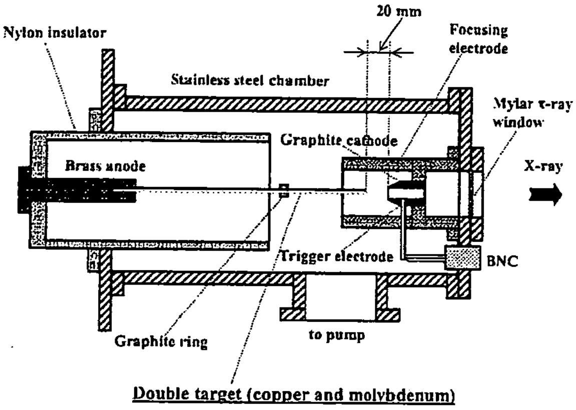


Figure 3: Schematic drawing of flash x-ray tube with double target.

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.

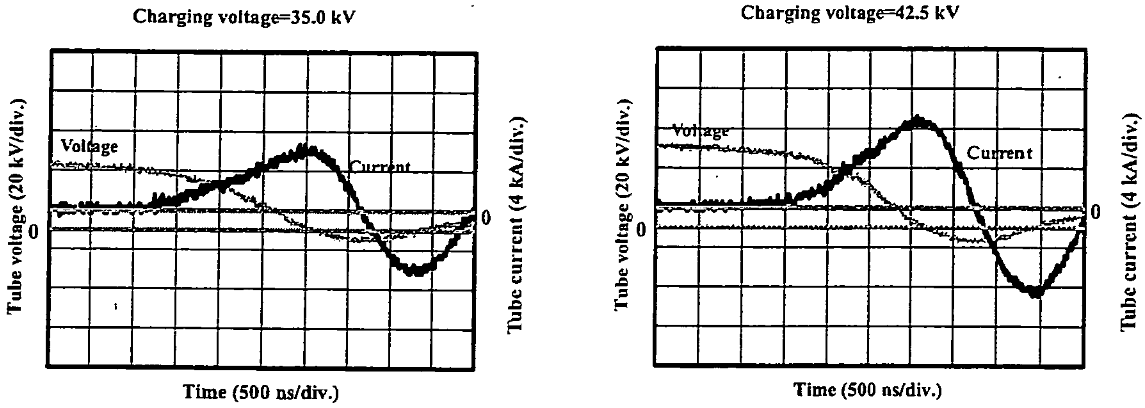
3.3 X-ray source

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.



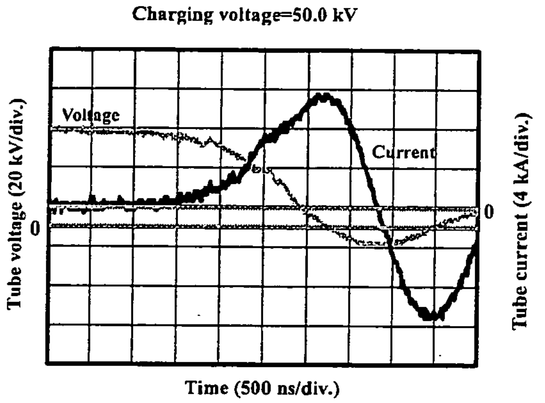


Figure 4: Tube voltages and currents with changing charging voltage.

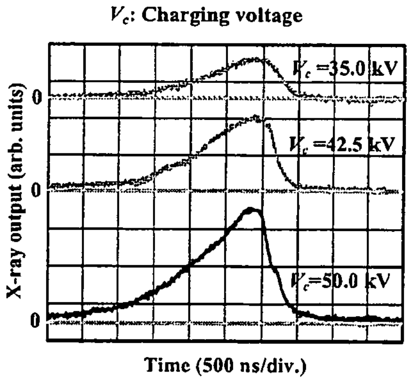


Figure 5: X-ray outputs at indicated conditions.

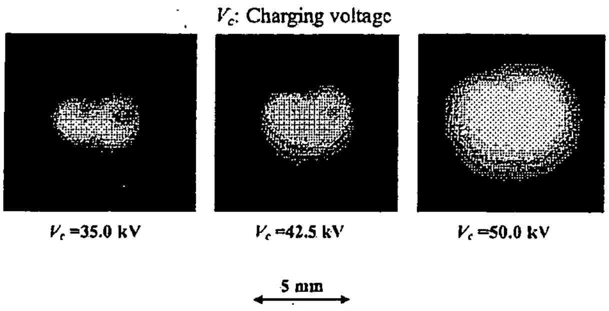


Figure 6: Images of plasma x-ray source of double target.

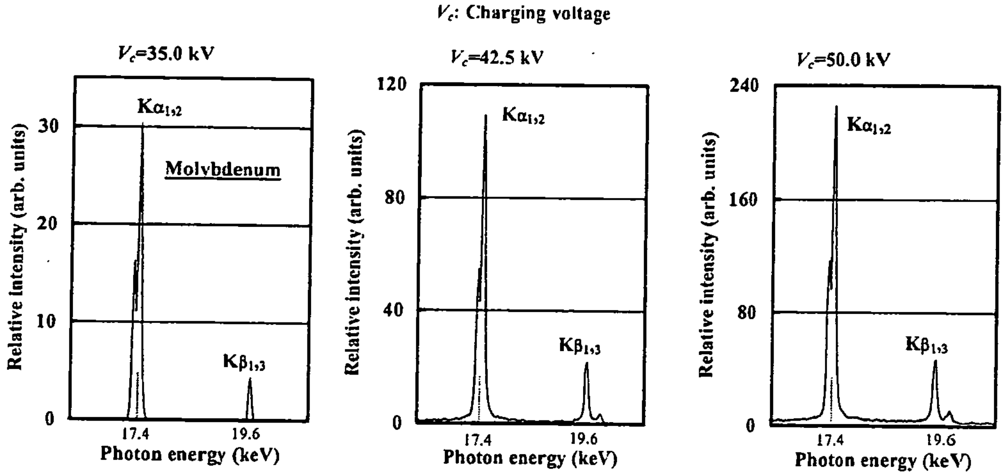


Figure 7: X-ray spectra near molybdenum K-series characteristic x rays.

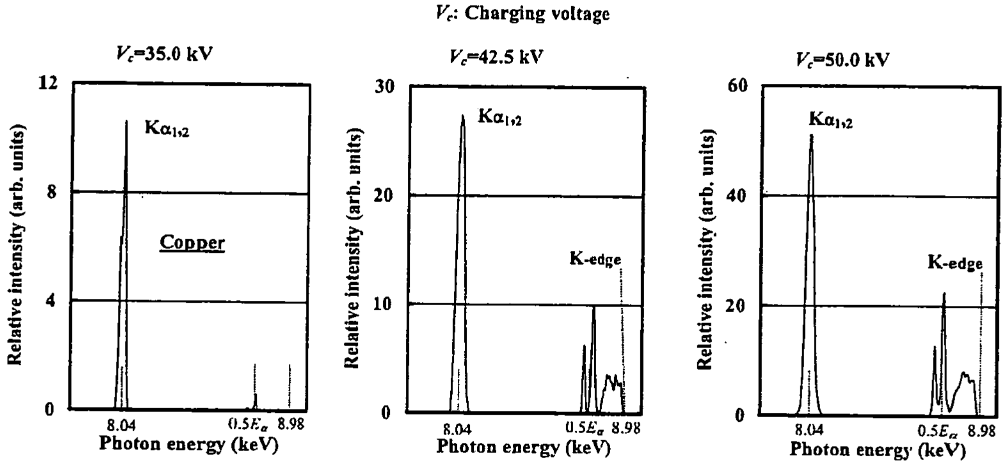


Figure 8: X-ray spectra near copper K-series characteristic x rays.

4. RADIOGRAPHY

The plasma radiography was performed by the CR system (Konica Regius 150) without using a filter, and the distance between the x-ray source and imaging plate was 1.2 m.

Figure 9 shows radiograms of tungsten wires coiled around a pipe made of polymethyl methacrylate with a charging voltage of 45 kV. Although the image contrast increased with increases in the wire diameter, a 50-μm-diameter wire could be observed. Next, the image of water falling into a polypropylene beaker from an glass test tube is shown in Fig. 10. This image was taken with a charging voltage of 50 kV, and an iodine-based contrast medium was added a little. Because the x-ray duration was about 1 μs, the stop-motion image of water was obtained. Figure 11 shows an angiogram of the external ear of a rabbit with a charging voltage (V_c) of 45 kV. In angiography, iodine-based microspheres of 15 μm in diameter were used, and fine blood vessels of about 100 μm are clearly visible. Figures 12 and 13 show angiograms of a rabbit heart (V_c=45 kV) and a thigh (V_c=50 kV), respectively, and fine blood vessels were visible.

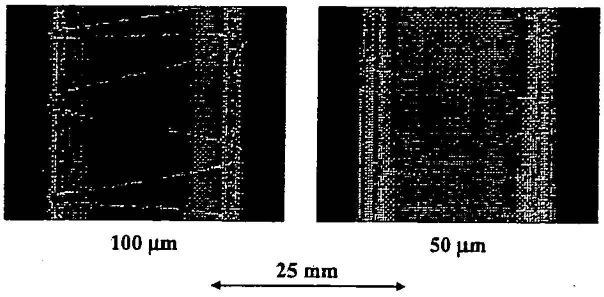


Figure 9: Radiograms of tungsten wires coiled around pipe made of polymethyl methacrylate.

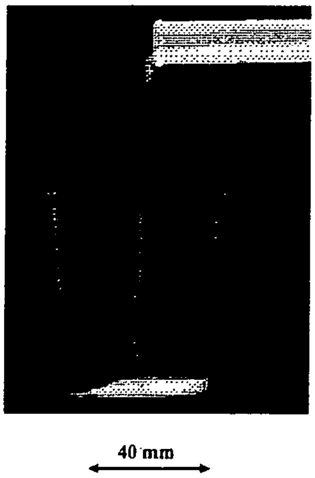


Figure 10: Radiogram of water from glass test tube.

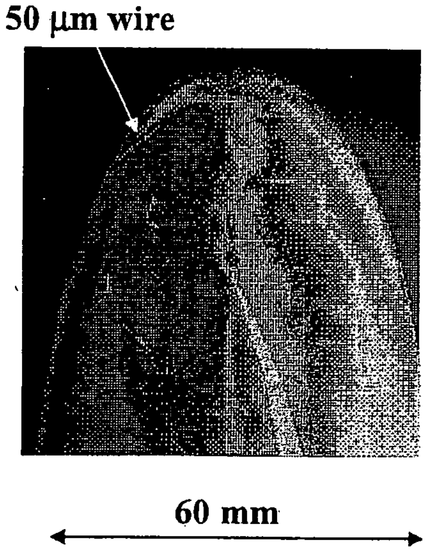


Figure 11: Angiogram of external ear.

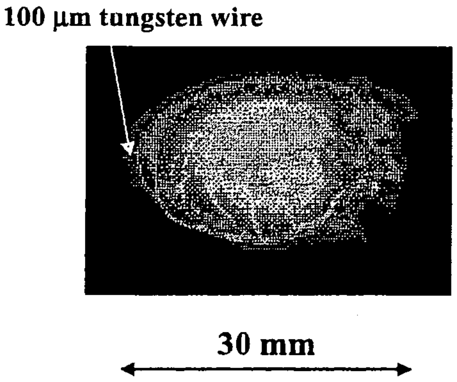


Figure 12: Angiogram of rabbit heart.

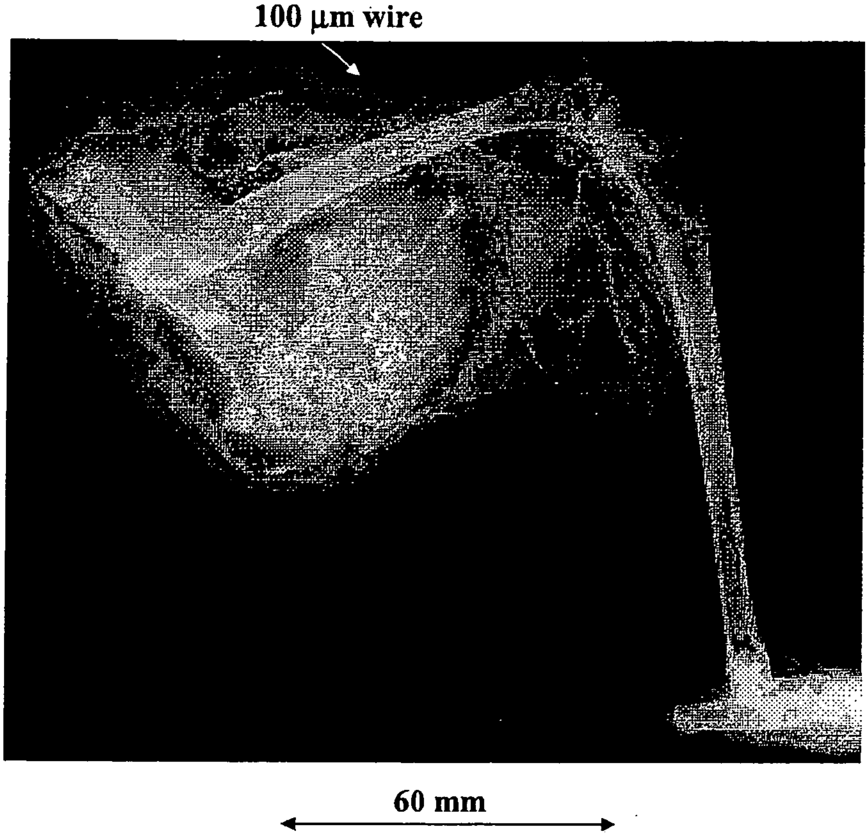


Figure 13: Angiogram of rabbit thigh.

5. DISCUSSION

Regarding the spectrum measurement, although we obtained intense and sharp molybdenum K-series lines, we could not observe copper Kβ lines. In addition, we observed $0.5E_{\alpha}$ lines and the copper K-absorption edge. If we assume that the $0.5E_{\alpha}$ lines are molybdenum Kα lines detected by the high order diffraction, the molybdenum Kβ lines, the copper Kβ lines, and the bremsstrahlung rays should be observed.

In this research, we obtained sufficient characteristic x-ray intensity per pulse for CR radiography without using a monochromatic filter, and the generator produced number of characteristic photons was approximately 4×10^8 photons/cm^2 at 1.0 m per pulse. In addition, since the photon energy of characteristic x rays can be controlled by changing target elements, various quasi-monochromatic high-speed radiographies, such as flash energy subtraction radiography using a metal filter and wide latitude radiography, will be possible.

ACKNOWLEDGMENT

This work was supported by Grants-in-Aid for Scientific Research (13470154, 13877114, 16591181and 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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Honorable Mention Poster Award

High-speed K-edge angiography achieved with tantalum K-series characteristic x rays

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ABSTRACT

The tantalum plasma flash x-ray generator is useful in order to perform high-speed K-edge angiography using cone beams because Kα rays from the tantalum target are absorbed effectively by gadolinium-based contrast media. 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. When the charging voltage was increased, the K-series characteristic x-ray intensities of tantalum increased. The K lines were clean and intense, and hardly any bremsstrahlung rays were detected. The x-ray pulse widths were approximately 100 ns, and the time-integrated x-ray intensity had a value of approximately 300 μGy at 1.0 m from the x-ray source with a charging voltage of 80 kV. Angiography was performed using a film-less computed radiography (CR) system and gadolinium-based contrast media. In angiography of non-living animals, we observed fine blood vessels of approximately 100 μm with high contrasts.

Keywords: angiography, gadolinium-based contrast media, characteristic x rays, quasi-monochromatic x rays, tantalum Kα photons

1. INTRODUCTION

The successful uses of monochromatic parallel beams from synchrotron orbital radiation in recent years have greatly increased the demand for phase-contrast radiography[1-3] and enhanced K-edge angiography.[4-6] In particular, the parallel beams with photon energies of approximately 35 keV have been employed to perform angiography, because the beams are absorbed effectively by iodine-based contrast media with a K-absorption edge of 33.2 keV. Without using a synchrotron, we have developed an x-ray generator utilizing a cerium-target tube, and have performed cone-beam K-edge angiography achieved with cerium Kα rays of 34.6 keV.[7] However, the x-ray intensity rate was limited because

Medical Imaging 2005: Physics of Medical Imaging, edited by Michael J. Flynn,
Proceedings of SPIE Vol. 5745 (SPIE, Bellingham, WA, 2005)
1605-7422/05/$15 · doi: 10.1117/12.601547

the thermal contact between the target and the anode was not good.

Although various flash x-ray generators have been developed,[8] we have developed flash x-ray generators[9-13] with photon energies of less than 150 keV in order to primarily perform high-speed biomedical radiography. Subsequently, we have developed plasma flash x-ray generators[14-16] to perform a preliminary experiment for producing hard x-ray lasers from weakly ionized linear plasma, and have succeeded in producing intense and clean K-series characteristic x rays using copper and nickel targets. In addition, we have confirmed the weak hard x-ray resonation verified from irradiation of weakly higher harmonic x rays. However, it is difficult to produce high-photon-energy characteristic x rays because the plasma transmits high-photon-energy bremsstrahlung x rays. Therefore, we developed a quasi-monochromatic flash x-ray generator[17,18] with a disk-cathode tube to produce high-energy characteristic x rays utilizing the angle dependence of bremsstrahlung x-ray distribution, because the bremsstrahlung rays are not emitted in the apposite direction to that of electron acceleration. Using this generator, we have succeeded in producing clean characteristic x rays from molybdenum, silver and cerium targets.

Gadolinium-based contrast media with a K-edge of 50.2 keV have been employed to perform angiography in MRI, and the gadolinium density has been increasing. In view of this situation, ytterbium Kα rays (52.0 keV) are useful for enhanced K-edge angiography, because the Kα rays are absorbed effectively by gadolinium media. As compared with angiography using iodine media, the absorbed dose can be decreased considerably utilizing angiography achieved with gadolinium media. However, because ytterbium is a lanthanide series element and has a high reactivity, Kα rays of tantalum and tungsten are also useful to perform angiography.

In this article, we describe an intense quasi-monochromatic plasma flash x-ray generator with a tantalum target tube, and used it to perform a preliminary study on angiography achieved with tantalum 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 gadolinium K-edge. The average photon energy of the tantalum Kα lines is shown above the gadolinium K-edge. The average photon energy of tantalum Kα lines is 57.1 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

Figure 2 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 (Fig. 3). 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.

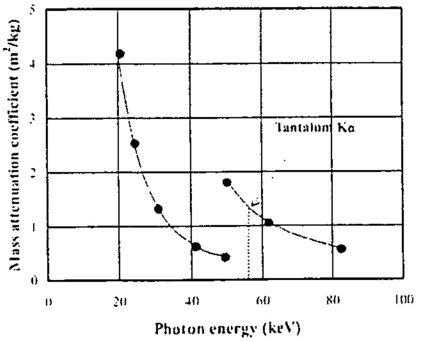

Figure 1: Relation between mass attenuation coefficient of gadolinium and average photon energy of tantalum Kα lines.

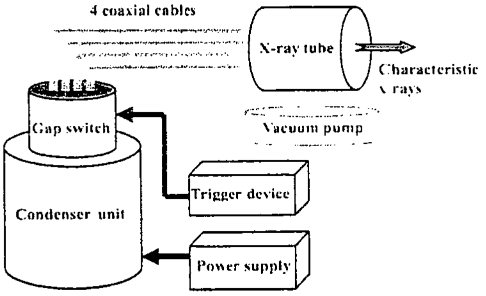

Figure 2: Block diagram of intense quasi-monochromatic flash x-ray generator.

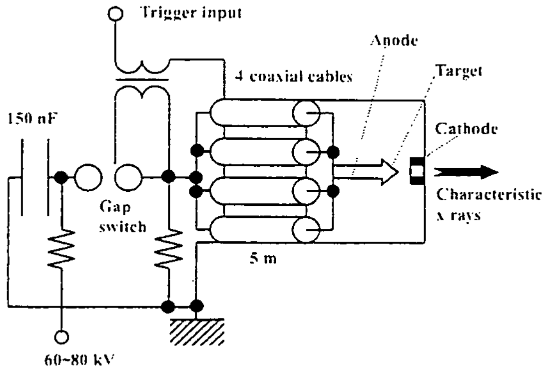

Figure 3: High-voltage circuit of flash x-ray generator.

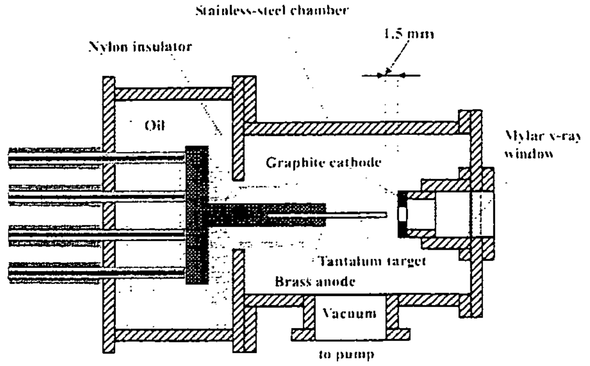

Figure 4: Schematic drawing of flash x-ray tube.

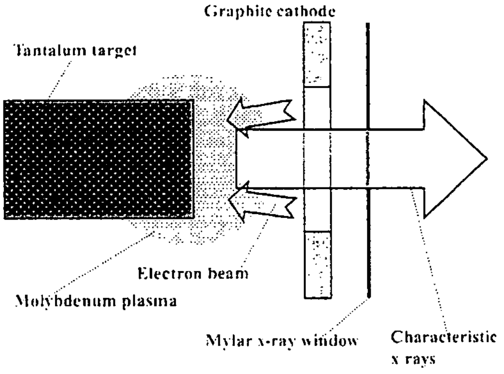

Figure 5: Irradiation of characteristic x rays.

3.2 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. 4). This tube consists of the following major parts: a ring-shaped graphite cathode with an bore 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 tantalum 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 tantalum ions and electrons, around the target. Because bremsstrahlung rays are not emitted in the opposite direction to that of electron acceleration (Fig. 5), tantalum K-series characteristic x rays can be produced without using a filter.

4. CHARACTERISTICS

4.1 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 display 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.

4.2 X-ray output

X-ray output pulse was detected using a combination of a plastic scintillator and a photomultiplier (Fig. 6). The x-ray pulse height substantially 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 300 μGy at 1.0 m from the x-ray source with a charging voltage of 80 kV.

4.3 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. 7). 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 decreases in the pinhole diameter.

4.4 X-ray spectra

X-ray spectra were measured using a transmission-type spectrometer with a lithium fluoride curved crystal 0.5 mm in thickness. The x-ray intensities of the spectra were detected by an imaging plate of a computed radiography (CR) system[19] (Konica Regius 150) with a wide dynamic range, and relative x-ray intensity was calculated from Dicom original digital data corresponding to x-ray intensity; the data was scanned by Dicom viewer in the film-less CR system. Subsequently, the relative x-ray intensity as a function of the data was calibrated using a conventional x-ray generator, and we confirmed that the intensity was proportional to the exposure time. Figure 8 shows measured spectra from the tantalum target. We observed clean K-series lines, while bremsstrahlung rays were hardly detected. The characteristic x-ray intensity substantially increased with increases in the charging voltage.

5. ANGIOGRAPHY

The flash angiography was performed by a computed radiography (CR) system (Konica Regius 150)[19] at 1.2 m from the x-ray source, and the charging voltage was 80 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 decreased somewhat with decreases in the wire diameter, due to blurring of the image caused by the sampling pitch of 87.5 μm, a 50 μm-diameter wire could be observed. Because the tungsten wires transmitted the characteristic x rays easily, low contrast radiograms were obtained.

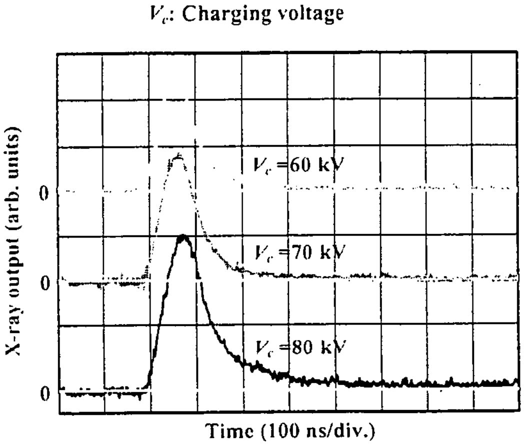

Figure 6: X-ray outputs at indicated conditions.

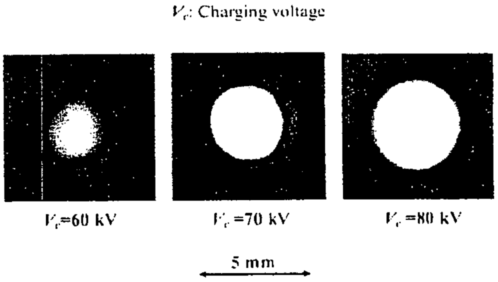

Figure 7: Images of characteristic x-ray source with changes in charging voltage.

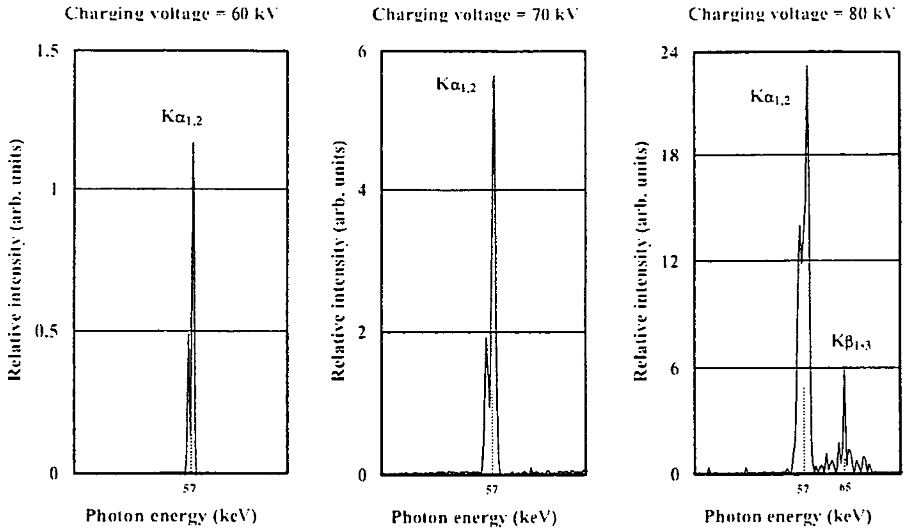

Figure 8: X-ray spectra from tantalum target.

The image of water (gadolinium oxide suspension of 20%) falling into a polypropylene beaker from a plastic test tube is shown in Fig. 10. The diameter of gadolinium oxide powder ranges from 1 to 10 µm. Because the x-ray duration was about 100 ns, the stop-motion image of water could be obtained.

Figure 11 shows an angiogram of a silicone rubber tube in a polymethyl methacrylate (PMMA) case using a contrast medium which contains 32.3% gadodiamidehydrate, and a low contrast tube with a bore diameter of 1.0 mm is observed. In cases where a gadolinium oxide suspension of 50% is employed, high-contrast angiography of the tubes (1.0 mm and 0.5 mm in bore diameter) could be performed (Fig. 12). Figure 13 shows an angiogram of a rabbit head using gadolinium oxide powder, and fine blood vessels of approximately 100 µm were visible.

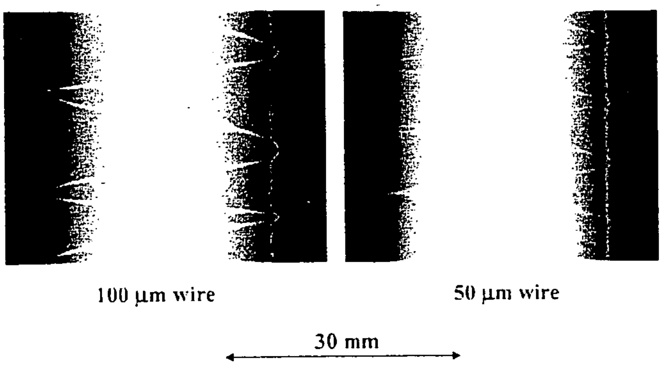

Figure 9: Radiograms of tungsten wires coiled around rod made of polymethyl methacrylate.

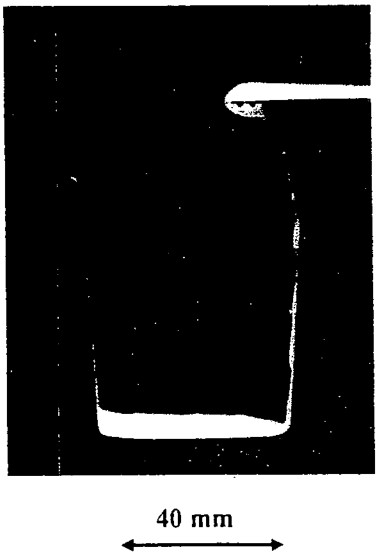

Figure 10: Radiogram of water falling into polypropylene beaker from plastic test tube.

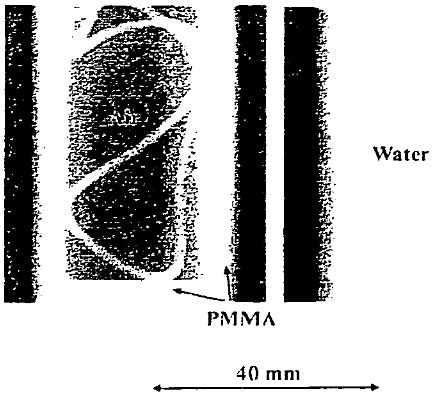

Figure 11: Angiograms of silicon tube using contrast medium of 32.3% gadodiamidehydrate.

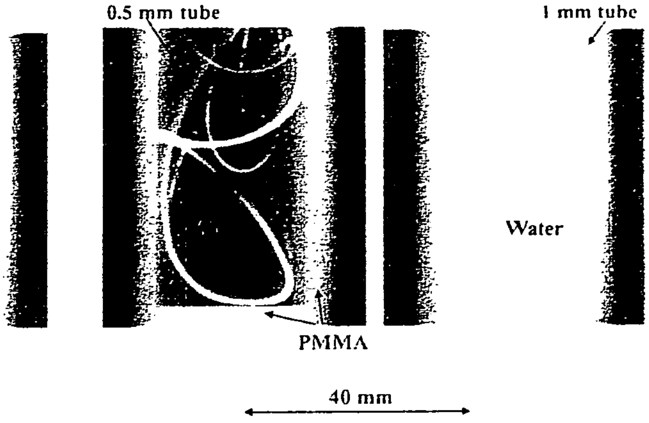

Figure 12: Angiography of silicon tube using gadolinium oxide suspension of 50%.

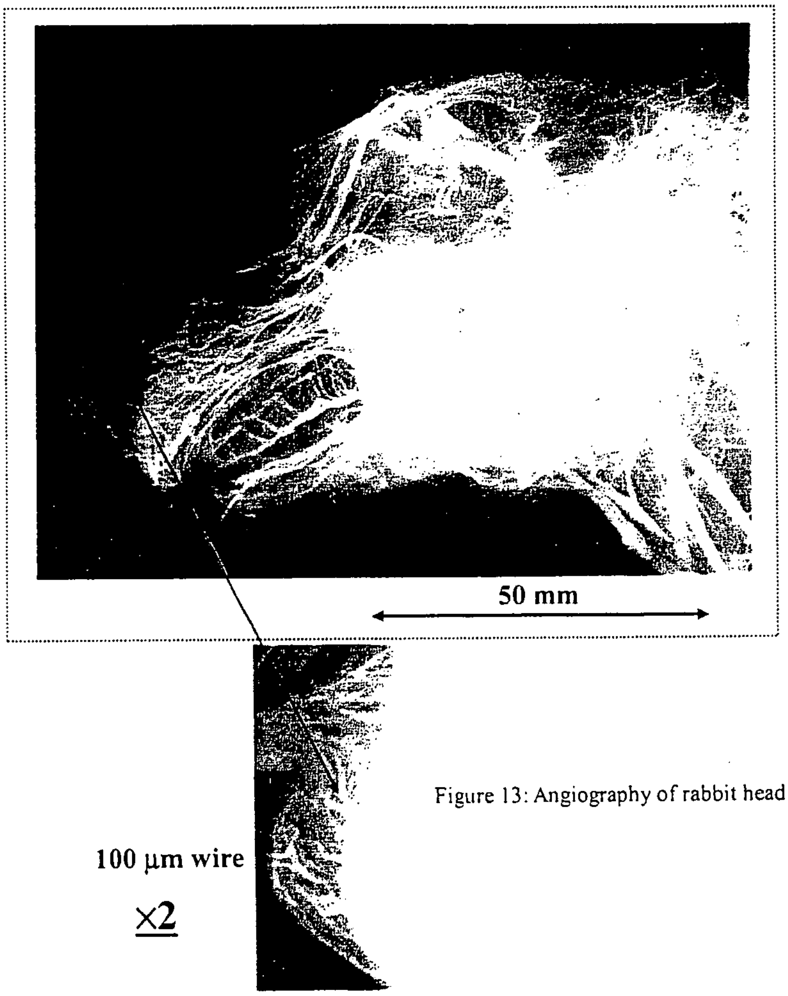

Figure 13: Angiography of rabbit head using gadolinium oxide powder.