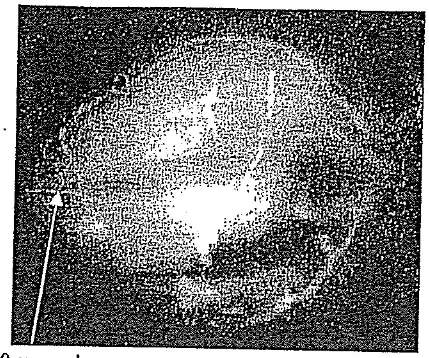

Fig. 9. Angiogram, using iodine microspheres, of extracted rabbit heart. Tube voltage and exposure time were 25 kV and 20 s, respectively.

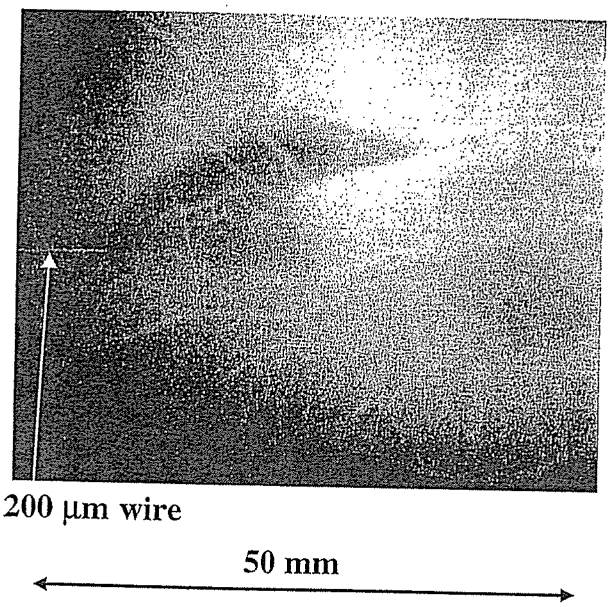

Fig. 10. Angiogram of extracted dog heart with tube voltage of 25 kV and exposure time of 60 s.

characteristic photons was approximately 4×10^6 photons/$cm^2 \cdot s$ at 1.0 m from the source with a tube voltage of 25 kV, and the photon count rate could be increased easily by increasing the tube voltage and current.

The focal spot dimensions decrease with decreasing target-cathode space, and the distance between the X-ray source and the imaging plate should be increased as much as possible to improve the spatial resolution. In soft radiography achieved with characteristic molybdenum K-series X-rays, because an X-ray lens such as a polycapillary plate[18] can be employed, the spatial resolution may be improved by decreasing the inner capillary diameter.

Under the pulsed operation, the high-voltage durability increases substantially, and both the size of the X-ray tube and the diameter of the high-voltage coaxial cable can be decreased. In this case, because the time-average tube current is regulated by the pulse repetition rate, both the tube voltage and the current can be controlled without using a hot cathode.

Recently, we developed a cerium-target X-ray tube to perform enhanced K-edge angiography utilizing cerium $K\alpha$ rays (34.6 keV), since the rays are absorbed effectively by iodine-based contrast media with a K-edge of 33.2 keV. In addition, $K\alpha$ rays from ytterbium (52.0 keV), tantalum (57.1 keV), and tungsten (58.9 keV) targets are very useful for performing K-edge angiography using gadolinium-based contrast media with an edge of 50.2 keV. Hence, using these rays, because the absorbed dose can be decreased effectively, extremely low-dose angiography can be accomplished.

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Quasi-monochromatic cerium flash angiography

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ABSTRACT

The cerium target plasma flash x-ray generator is useful in order to perform high-speed enhanced K-edge angiography using cone beams because K-series characteristic x rays from the cerium target are absorbed effectively by iodine-based contrast mediums. 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 cerium 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 10 μC/kg at 1.0 m from the x-ray source with a charging voltage of 80 kV. In the angiography, we employed a film-less computed radiography (CR) system and iodine-based microspheres.

Keywords: flash x-ray, cerium target, characteristic x rays, bremsstrahlung x-ray distribution, K-edge angiography

1. INTRODUCTION

The potential of monochromatic parallel x-ray beams using a synchrotron and a monochrometor poses a major challenge to competing image acquisition technology, for example, x-ray phase imaging[1,2] and enhanced K-edge angiography.[3,4] Recently, cone-beam phase imaging[5] for the edge enhancement technique has been employed using a mini-focus x-ray tube. Subsequently, K-edge angiography has also been performed using cone beams of cerium Kα rays[6] of 34.6 keV, since K-series characteristic x rays from the cerium target are absorbed effectively by iodine-based contrast media.
Currently, most flash x-ray generators utilize cold-cathode x-ray tubes and produce extremely high-dose-rate pulse x rays with durations of less than 1 μs.[7] A number of flash x-ray generators have been developed in order to perform high-speed radiography, and the generators with maximum photon energies of less than 150 keV can be employed to

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perform soft radiography including biomedical applications.[8-12]
In a former experiment, we performed a preliminary experiment of high-speed K-edge angiography using a cerium plasma x-ray generator,[13] which produced both characteristic and bremsstrahlung x rays. As compared with a steady state x-ray generator with a constant tube voltage, the effective x-ray photon energies are lower, since both the tube voltage and current display damped oscillations; the tube current increases with decreasing tube voltage. Therefore, the condenser charging voltage should be increased as much as possible to increase the cerium characteristic x-ray intensity.
In the present research, we improved a plasma x-ray generator[14-18] with a cerium-target tube, and used it to perform a preliminary study on angiography achieved with cerium K-series characteristic x rays.

2. PRINCIPLE OF K-EDGE ANGIOGRAPHY

Figure 1 shows the mass attenuation coefficients of iodine at the selected energies; the coefficient curve is discontinuous at the iodine K-edge. The average photon energies of the cerium Kα and Kβ lines are shown above the iodine K-edge. Cerium is a rare earth element and has a high reactivity; however, the average photon energy of Kα and Kβ lines are 34.6 and 39.2 keV, respectively, and iodine contrast media with a K-absorption edge of 33.2 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. 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.

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. 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 cerium 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), cerium K-series characteristic x rays can be produced without using a filter.

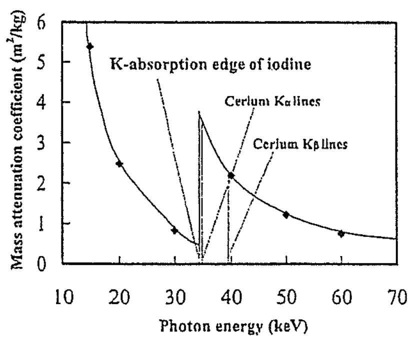


Figure 1: Relation between mass attenuation coefficient of iodine and average photon energies of cerium Kα and Kβ lines.

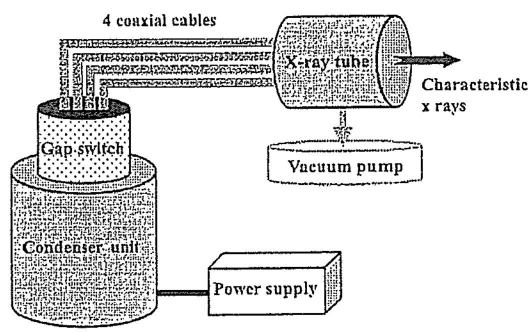


Figure 2: Block diagram of intense quasi-monochromatic flash x-ray generator.

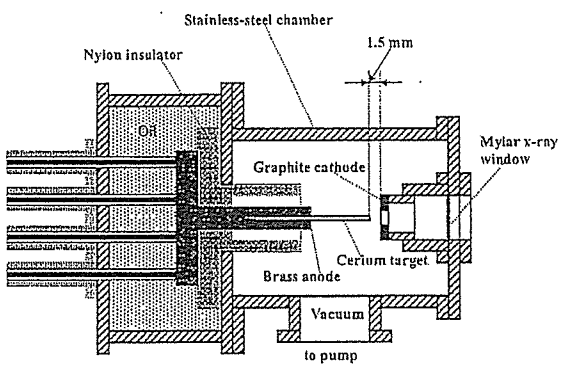


Figure 3: Schematic drawing of flash x-ray tube.

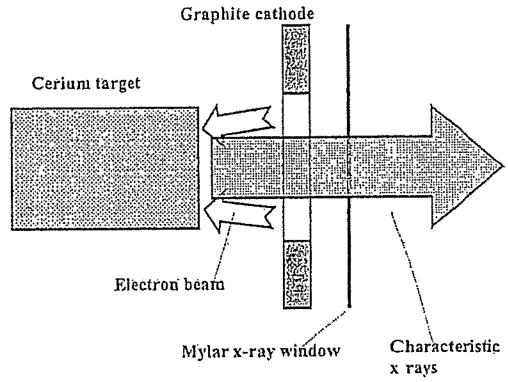


Figure 4: Irradiation of characteristic x rays.

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. 5). 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 10 μC/kg 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 Kα 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.

4.4 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[19] with a wide dynamic range, and relative x-ray intensity was calculated from Dicom digital data. Figure 7 shows measured spectra from the cerium 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.

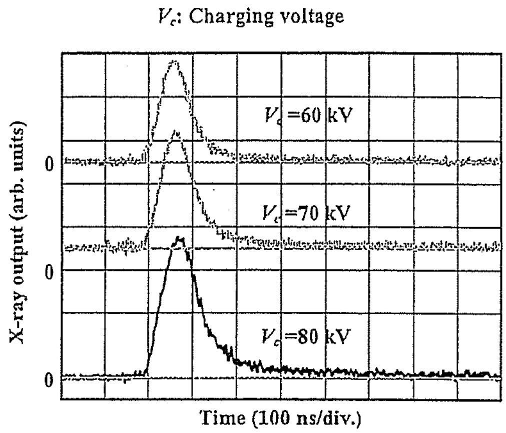


Figure 5: X-ray outputs at indicated conditions.

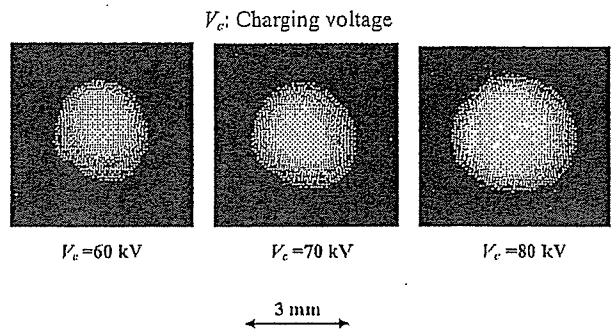


Figure 6: Images of characteristic x-ray source with changes in charging voltage.

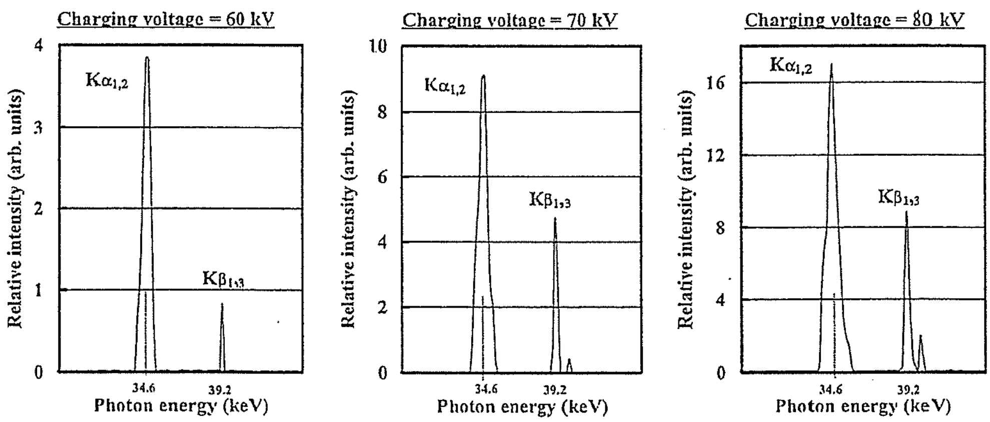


Figure 7: X-ray spectra from cerium target.

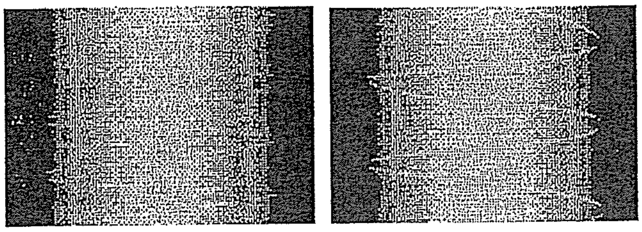
5. ANGIOGRAPHY

The plasma angiography was performed by the CR system (Konica Regius 150) without using a monochromatic filter, and the charging voltage and the distance between the x-ray source and the imaging plate were 70 kV and 1.2 m, respectively.

Figure 8 shows radiograms of tungsten wires coiled around a pipe 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 water falling into a polypropylene beaker from a glass test tube is shown in Fig. 9. This image was taken with the slight addition of an iodine-based contrast medium. Because the x-ray duration was about 100 ns, the stop-motion image of water could be obtained.

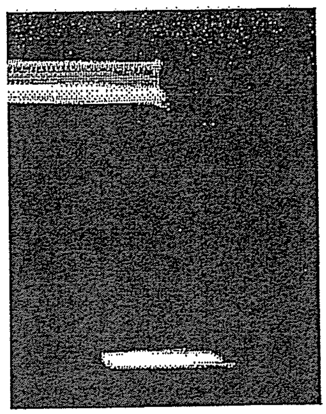
Angiograms of rabbit hearts are shown in Fig. 10. These two images were obtained using iodine and cerium microspheres of 15 μm, respectively. In case where the cerium spheres were employed, the coronary arteries were barely visible. In angiography of a larger heart extracted from a dog using iodine spheres, fine blood vessels of approximately 100 μm were visible (Fig. 11).



50 μm 100 μm

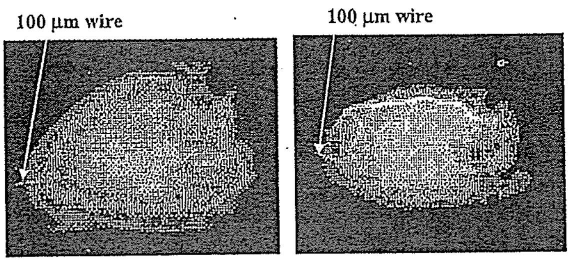
25 mm

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



40 mm

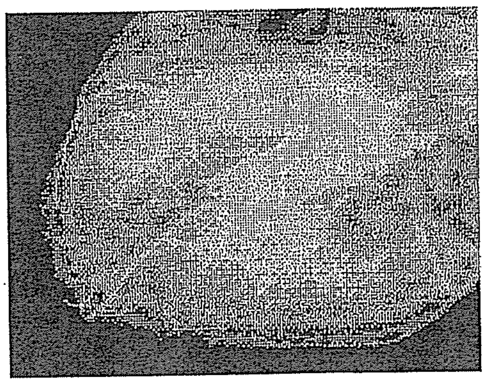
Figure 9: Radiogram of water falling into polypropylene beaker from glass test tube.



Cerium microsphere Iodine microsphere

30 mm

Figure 10: Angiograms of rabbit hearts using iodine and cerium microspheres.



60 mm

Fig. 11 Angiograms of extracted heart of dog.

6. DISCUSSION

Concerning the spectrum measurement, we obtained fairly clean cerium Kα and Kβ lines. Therefore, we are very interested in the measurement the characteristic rays from nickel, copper, molybdenum, silver, and tungsten targets; the target element should be selected corresponding to the radiographic objectives.

In this research, the generator produced instantaneous number of K photons was approximately 5×10^8 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 produced using a barium oxide filter with a barium K-edge of 37.4 keV.

Using this flash x-ray generator, as high output voltages can be produced using cables, high-photon-energy K-series characteristic x rays can be produced by increasing the atomic number of the target element. With recent advances in angiography using MRI, if the density of gadolinium-based contrast media increases, enhanced K-edge angiography utilizing monochromatic x-ray generators, which produce Kα rays from ytterbium, tantalum, and tungsten targets, will be a useful technique to decrease the absorbed dose during angiography.

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Monochromatic flash x-ray generator utilizing a disk-cathode silver tube

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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. Clean silver $K\alpha$ lines are produced using a 30-μm-thick palladium filter, 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 are 90 kV and 0.8 kA, respectively. The x-ray pulse widths are approximately 80 ns, and the instantaneous number of generator-produced $K\alpha$ photons is approximately 4×10^{7}photons/cm^{2} per pulse at 0.3 m from the source 3.0 mm in diameter. [DOI: 10.1117/1.2049248]

Subject terms: x-ray source; x-ray tube; x-ray spectra; rapid imaging; x-ray beam filtration; monochromatic x-rays.

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1 Introduction

Energy-selective monochromatic radiography is a useful method for medical radiography, and quasimonochromatic x-rays have been produced using a K-edge filter when conventional medical x-ray tubes are employed. In contrast, monochromatic parallel x-ray beams have been produced using synchrotrons in conjunction with silicon single crystals, and have been applied effectively to enhanced K-edge angiography,[1–3] achieved with x-rays with a photon energy of approximately 35 keV.

In high-speed radiography, we have developed several different flash x-ray generators[4–9] utilizing cold cathode x-ray tubes, and intense and clean K-series characteristic x-rays have been produced from the axial direction of weakly ionized linear plasma[10–14] of nickel and copper using a plasma flash x-ray generator. In the plasma, bremsstrahlung spectra with photon energies of higher than the K-absorption edge are effectively absorbed and are converted into fluorescent x-rays. The plasma then transmits the fluorescent rays easily. Subsequently, the photon ener-

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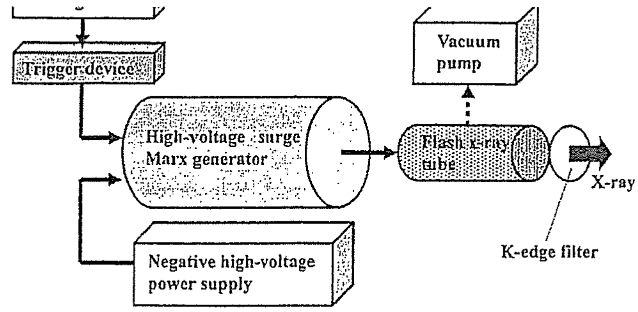

Fig. 1 Block diagram of the compact quasimonochromatic flash x-ray generator.

gies of the characteristic x-rays are determined by the target element, and the tube voltage should be increased in cases where the high-photon-energy characteristic x-rays are selected. However, it is difficult to increase the photon energies, since the maximum tube voltage is approximately 60 kV without using a high-voltage gap switch.

To increase the maximum tube voltage, a multistage surge Marx generator[15,16] is useful, because the output voltage is equal to the value of the condenser charging voltage multiplied by the stage number. In addition, characteristic x-rays can be produced by considering the angle dependence of bremsstrahlung x-rays when a cold cathode diode, in conjunction with the surge generator, is employed.

In this study, we developed a compact flash x-ray generator utilizing a silver-target radiation tube, and used it to perform a preliminary experiment for producing clean monochromatic x-rays.

2 Experimental Setup

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 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

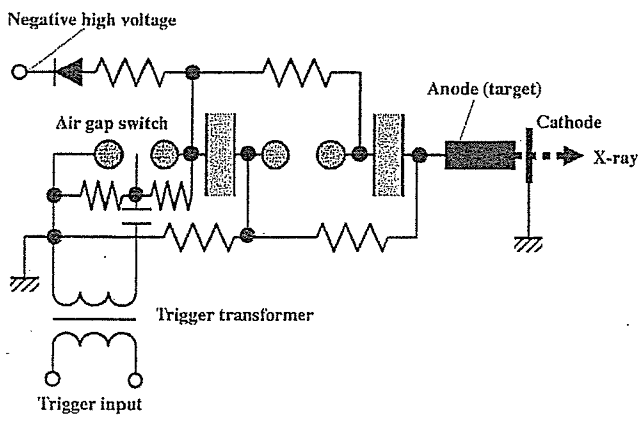

Fig. 2 Circuit diagram of the flash x-ray generator.

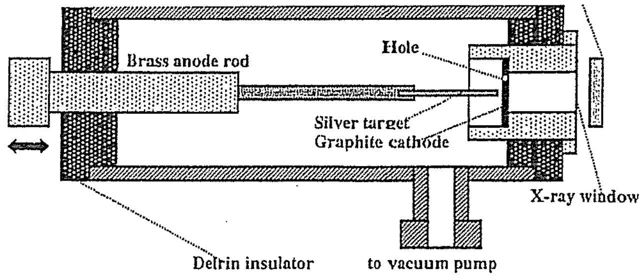

Fig. 3 Schematic drawing of the flash x-ray tube.

employs a polarity-inversion two-stage Marx line[13,14] (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 silver 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 1.0 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. In Sommerfeld's theory,[17] because bremsstrahlung rays are not emitted in the opposite direction to that of electron trajectory (Fig. 4), silver Kα rays can be produced using a 30-μm-thick palladium K-edge filter. In the K-series characteristic x-ray irradiation, Kα rays are left by absorbing Kβ rays to perform the preliminary experiment for producing clean monochromatic x-rays and to confirm the filtering effect.

3 Results and Discussion

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

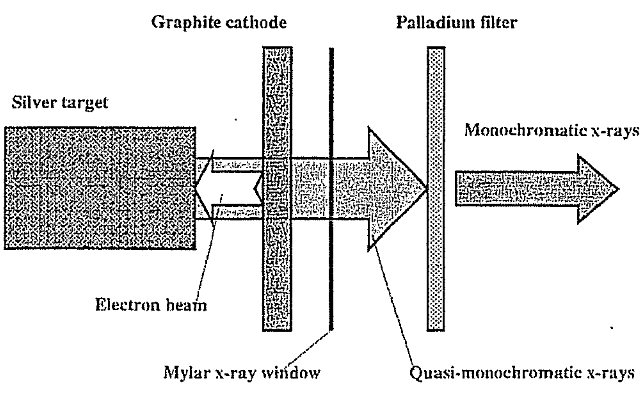

Fig. 4 Irradiation of silver Kα rays using a palladium K-edge filter.

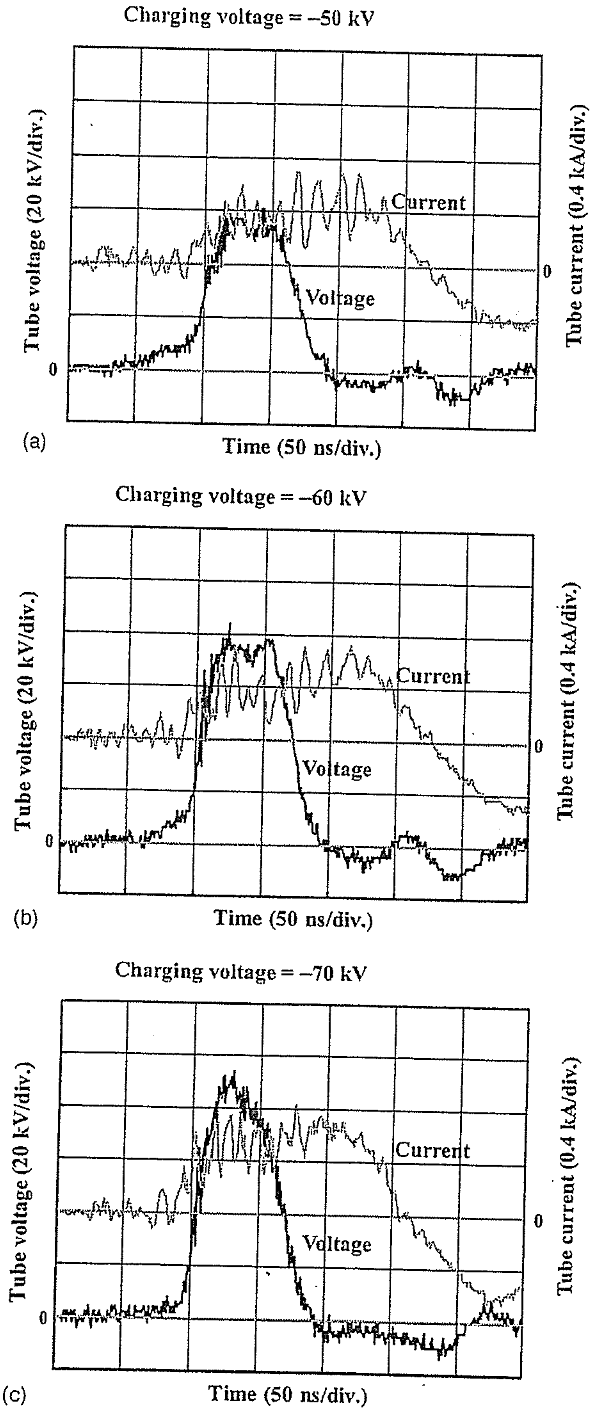

Fig. 5 Variations in tube voltage and current with charging voltages of (a) –50 kV, (b) –60 kV, and (c) –70 kV.

current transformer, respectively (Fig. 5). 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. Within twice the potential of the condenser charging voltage, the instantaneous voltage increases according to increases in the charging voltage and

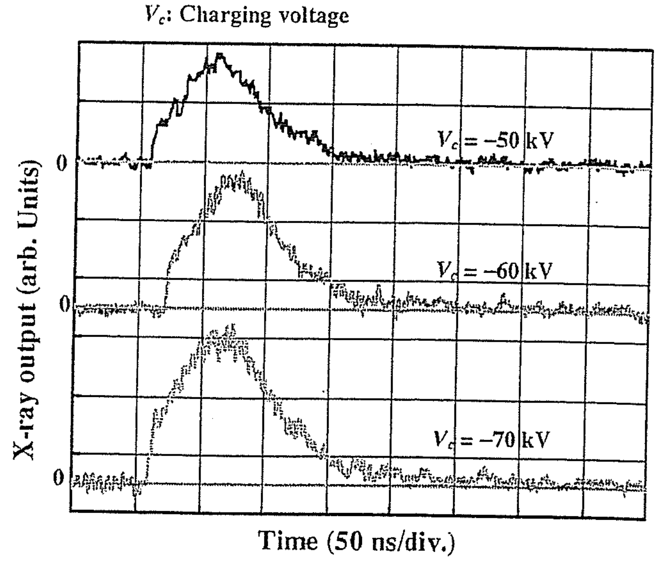

Fig. 6 X-ray outputs at the indicated conditions using the filter.

to increases in the target-cathode space. On the other hand, the instantaneous current increases with increases in the charging voltage and decreases in the space. At a space of 1.0 mm, the instantaneous voltage and current increased with increases in the charging voltage, and the voltage and current were approximately 90 kV and 0.8 kA, respectively, at a charging voltage of –70 kV.

3.2 *X-ray Output*

An x-ray output pulse was detected using a combination of a plastic scintillator, a photomultiplier, and the filter (Fig. 6). When the charging voltage was increased, the pulse height increased, but the width seldom varied. The widths were approximately 80 ns, and the time-integrated x-ray dose measured using a thermoluminescence dosimeter (Kyokko TLD Reader 1500 having MSO-S elements without energy compensation) had a value of approximately 90 μGy per pulse at 0.3 m from the x-ray source with a charging voltage of –70 kV. In the dose measurement, five elements (detectors) with a diameter of 2.0 mm and a length of 11 mm were set at 0.3 m from the x-ray source, and the dose was the average value of ten shots of flash

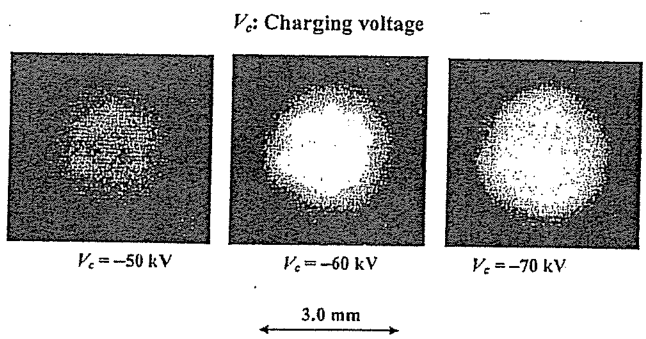

Fig. 7 Images of x-ray sources of Kα lines with changes in the charging voltage.

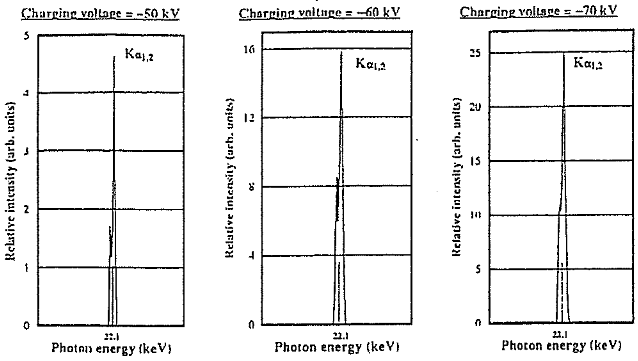

Fig. 8 X-ray spectra from a silver target with the filter.

x-rays and five elements. Using this high-voltage pulse generator, the maximum repetition rate of flash x-rays was approximately 50 Hz. At a charging voltage of −70 kV and the maximum rate, the electric power of the flash x-ray generator and the dose rate are estimated at approximately 200 W and 400 μGy/s at 1.0 m, respectively.

3.3 *X-ray Source*

To observe the x-ray source, we employed a 100-μm-diam pinhole camera, an x-ray film (Polaroid XR-7), and the filter (Fig. 7). 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 thick. The spectra were taken using a computed radiography (CR) system[18] (Konica Regius 150) with a wide dynamic range, and relative x-ray intensity was calculated from Dicom digital data. Figure 8 shows the measured spectra from the silver target with the filter. We observed clean Kα lines, while bremsstrahlung rays were hardly detected. When the charging voltage was increased, the instantaneous tube voltage and current increased, and the Kα intensity substantially increased.

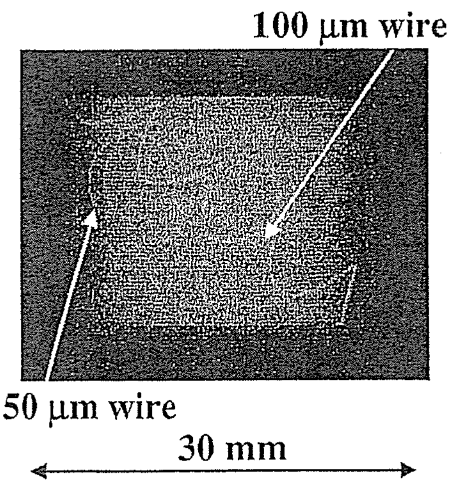

Fig. 9 Radiograms of tungsten wires of 50 and 100 μm in a rod made of polymethyl methacrylate.

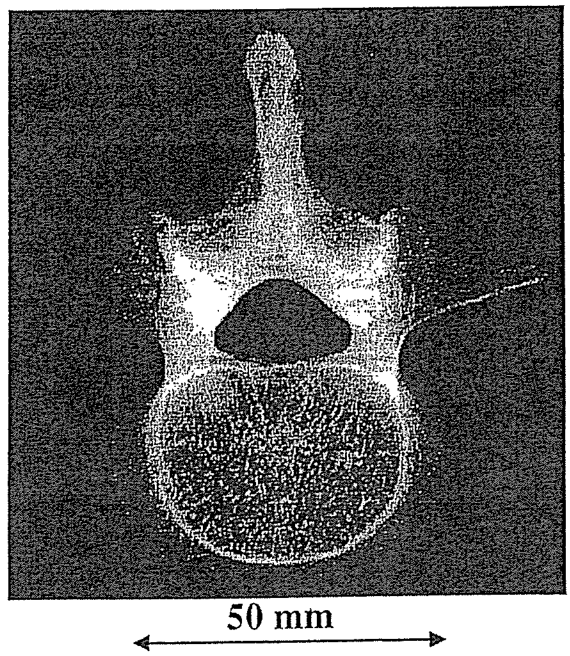

Fig. 10 Radiogram of a vertebra.

3.5 *Radiography*

Monochromatic flash radiography was performed using the CR system 0.3 m from the x-ray source with the filter, and the charging voltage was −70 kV. First, rough measure-

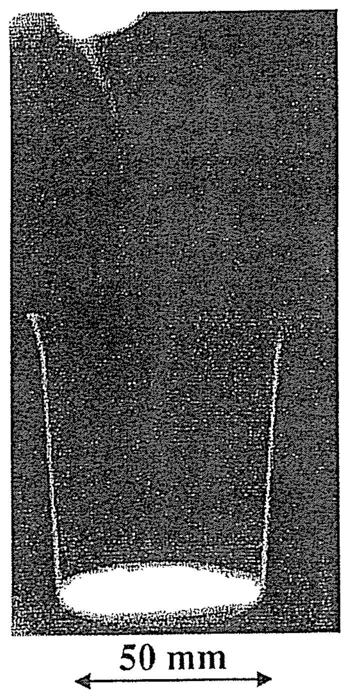

Fig. 11 Radiogram of water falling into a polypropylene beaker from a glass test tube.

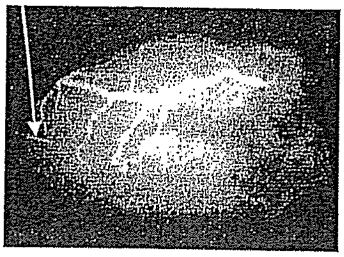

Fig. 12 Angiogram of a rabbit heart.

ments of spatial resolution were made using wires. Figure 9 shows radiograms of tungsten wires in a rod made of polymethyl methacrylate. Although the image contrast increased with increases in the wire diameter, a 50-μm-diam wire could be observed.

Figure 10 shows a radiogram of a vertebra, and fine structures in the vertebra are observed. Next, the image of water falling into a polypropylene beaker from an injector is shown in Fig. 11. This image was taken with the slight addition of an iodine-based contrast medium. Because the x-ray duration was approximately 80 ns, the stop-motion image of water could be obtained. Figure 12 shows an angiogram of a rabbit heart; iodine-based microspheres 15 μm in diameter were used, and fine blood vessels of approximately 100 μm were visible.

4 Conclusion and Outlook

Concerning the spectrum measurement, we obtained fairly clean silver $K\alpha$ rays (22.1 keV). Therefore, we are very interested in the measurement of the $K\alpha$ rays from cerium (34.6 keV) and tungsten (58.9 keV) targets. The target element should be selected corresponding to the radiographic objectives. In medical applications, 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 K-edge angiography can be performed.

In this research, the instantaneous number of generator-produced $K\alpha$ photons was approximately 4×10^7 photons/cm^2 per pulse 0.3 m from the source. However, the intensity can be increased by increasing the electrostatic energy in condensers in the surge generator, and quasimonochromatic x-rays of both $K\alpha$ and $K\beta$ (24.9 keV) lines are produced without using the palladium filter with a K-edge of 24.3 keV.

Using this flash x-ray generator, because the photon energy of characteristic x-rays can be selected, a high-speed photon-counting radiography system can be performed 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 easily.

Acknowledgment

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Enhanced K-edge plasma angiography achieved with tungsten Kα rays utilizing gadolinium-based contrast media

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ABSTRACT

The tungsten plasma flash x-ray generator is useful in order to perform high-speed enhanced K-edge angiography using cone beams because Kα rays from the tungsten 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. 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 characteristic x-ray intensities of tungsten Kα lines increased. Using an ytterbium oxide filter, the Kα lines were clean, and hardly any Kβ lines and bremsstrahlung rays were detected. The x-ray pulse widths were approximately 60 ns, and the time-integrated x-ray intensity had a value of approximately 50 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 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, monochromatic x-rays, tungsten Kα rays

1. INTRODUCTION

Ultrafast X-Ray Detectors, High-Speed Imaging, and Applications, edited by Stuart Kleinfelder, Dennis L. Paisley, Zenghu Chang, Jean-Claude Kieffer, Jerome B. Hastings, Proc. of SPIE Vol. 5920 (SPIE, Bellingham, WA, 2005) · 0277-786X/05/$15 · doi: 10.1117/12.620212

Monochromatic parallel beams from synchrotron orbital radiation have been employed in phase-contrast radiography[1,2] and enhanced K-edge angiography.[3,4] In particular, the parallel beams with photon energies of approximately 35 keV have been employed to perform iodine K-edge 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,[5,6] and have performed cone-beam K-edge angiography achieved with cerium Kα rays of 34.6 keV.

Gadolinium-based contrast media with a K-edge of 50.2 keV have been employed to perform in MRA, 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 (57.1 keV) and tungsten (58.9 keV) are also useful to perform angiography.

In order to perform high-speed biomedical radiography, several different flash x-ray generators[7-10] with photon energies less than 150 keV have been developed,. and plasma flash x-ray generators[11-13] have been developed to perform a preliminary experiment for producing hard x-ray lasers. From weakly ionized plasma, clean K-series characteristic x-rays of nickel and copper and their higher harmonic hard x-rays have been produced. Furthermore, high-photon-energy monochromatic flash x-ray generators[14-17] have been developed to produce K-series characteristic x-rays of molybdenum, cerium, ytterbium, tantalum, and tungsten, because bremsstrahlung rays are not emitted in the opposite direction to that of electron trajectory in Sommerfeld's theory.

In this article, we describe an intense monochromatic plasma flash x-ray generator with a tungsten target tube, and used it to perform a preliminary study on angiography achieved with tungsten Kα rays using an ytterbium oxide filter.

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 tungsten 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

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. 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.

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. 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 tungsten 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 tungsten ions and electrons, around the target. Because bremsstrahlung rays are not emitted in the opposite direction to that of electron acceleration (Fig. 4), tungsten Kα rays can be produced using an ytterbium oxide filter with a surface density of 20 mg/cm^2.

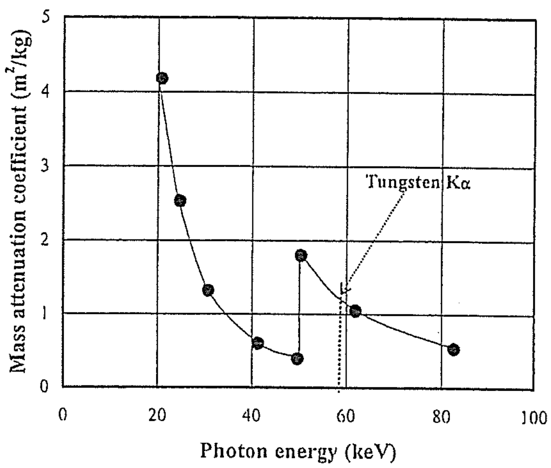

Figure 1: Mass attenuation coefficient of gadolinium and the average photon energy of tungsten Kα lines is shown above gadolinium K edge.

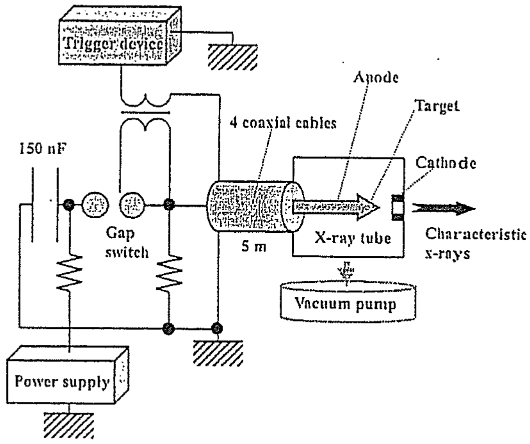

Figure 2: Block diagram including high-voltage circuit of the intense monochromatic plasma flash x-ray generator with a tungsten-target tube.

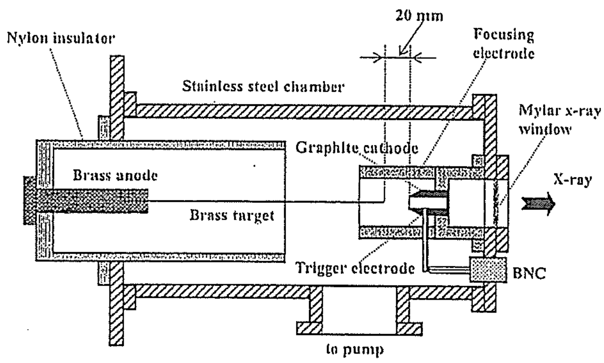

Figure 3: Schematic drawing of the flash x-ray tube with a rod-shaped tungsten target.

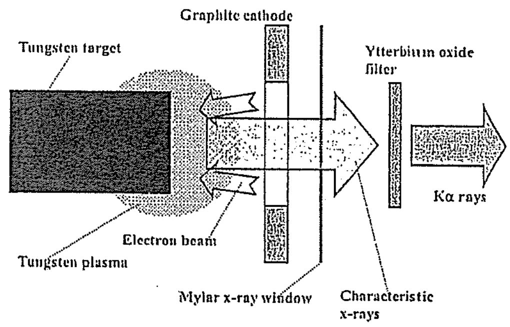

Figure 4: Irradiation of K-series characteristic x-rays of tungsten.

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. 5). The x-ray pulse height substantially increased with corresponding increases in the charging voltage. The x-ray pulse widths were approximately 60 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 50 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 Kα 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.

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[18] (Konica Minolta 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 7 shows measured spectra from the tungsten target. We observed clean Kα lines, while Kβ lines and bremsstrahlung rays were hardly detected. The Kα intensity increased with increases in the charging voltage.

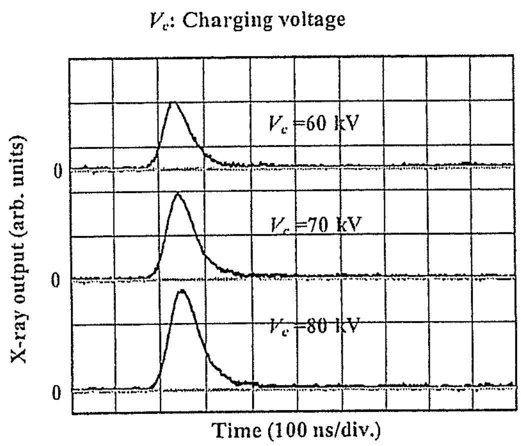

Figure 5: X-ray outputs detected using a combination of a plastic scintillator and a photomultiplier.

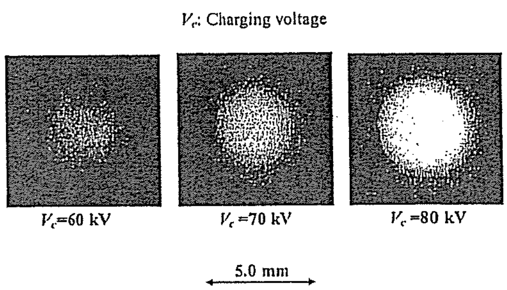

Figure 6: Images of Kα-ray source obtained using a pinhole camera with changes in the charging voltage.

5. ANGIOGRAPHY

The flash angiography was performed using the CR system and the filter 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 8 shows radiograms of tungsten wires in a rod made of polymethyl methacrylate (PMMA). Although the image contrast decreased somewhat with decreases in the wire diameter, due to blurring of the image caused by the sampling pitch of 87.5 μm, a 50 μm-diameter wire could be observed.

The image of water (20% gadolinium oxide suspension) falling into a polypropylene beaker from a plastic test tube is shown in Fig. 9. The diameter of gadolinium oxide powder ranges from 1 to 10 μm. Because the x-ray duration was about 60 ns, the stop-motion image of water could be obtained.

Figure 10 shows an angiogram of a polytetrafluoroethylene (Teflon) tube in a PMMA case using a contrast medium which contains approximately 65% gadodiamidehydrate, and a high-contrast tube with a bore diameter of 1.0 mm is observed. Figures 11 and 12 show angiograms of a rabbit ear and head using gadolinium oxide powder, and fine blood vessels of approximately 100 μm were visible.

6. CONCLUSIONS AND OUTLOOK

We succeeded in producing tungsten Kα rays and in performing K-edge angiography using gadolinium contrast media with a K-edge of 50.2 keV, and this K-edge angiography could be a useful technique to decrease the dose absorbed by patients. In angiography, we employed tungsten Kα (58.9 keV) rays by absorbing Kβ rays (approximately 67 keV) using the ytterbium oxide filter, and L-series characteristic rays were also absorbed.

We obtained sufficient x-ray intensity per pulse for CR angiography with x-ray durations of approximately 60 ns, and the intensity can be increased by increasing the charging voltage at a constant target-cathode space. Currently, the x-ray duration increased with increases in the target-cathode space. In this research, the generator produced instantaneous number of Kα photons was approximately 1.5×10^8 photons/cm^2 per pulse at 1.0 m from the source.

Because the dimensions of the x-ray source are primarily determined by the target diameter, the diameter should be minimized in order to improve the spatial resolution, and can be reduced to approximately 0.5 mm. Because the x-ray intensity is the highest at the center of the spot, the effective focal spot size decreased during x-ray absorption in an object. Subsequently, the sampling pitch can be decreased to 43.8 μm using a CR system (Konica Minolta Regius 190) to observe fine blood vessels of approximately 50 μm in diameter.

Using this flash x-ray generator, enhanced K-edge angiography using iodine contrast media and a cerium target can be also performed. In addition, steady-state monochromatic x-rays can be produced by a similar tube utilizing a hot cathode and a constant high-voltage power supply. Using a tungsten or a molybdenum target, fine focusing can be realized, and these x-ray generators could be employed to perform quasi-monochromatic phase-contrast radiography for edge enhancement.

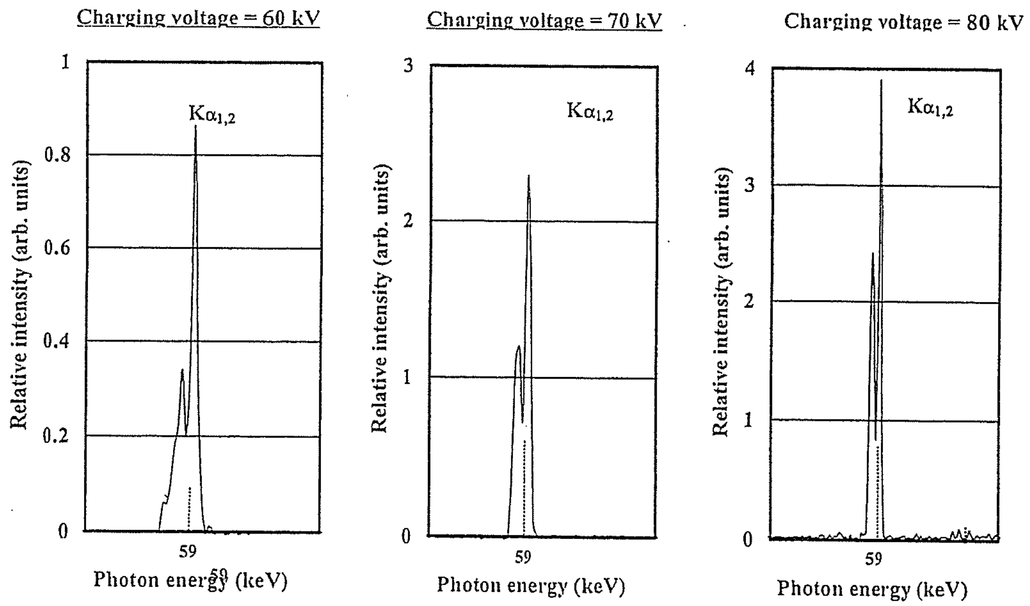

Figure 7: X-ray spectra from a tungsten target. The spectra were measured using a transmission type spectrometer with a lithium fluoride curved crystal.

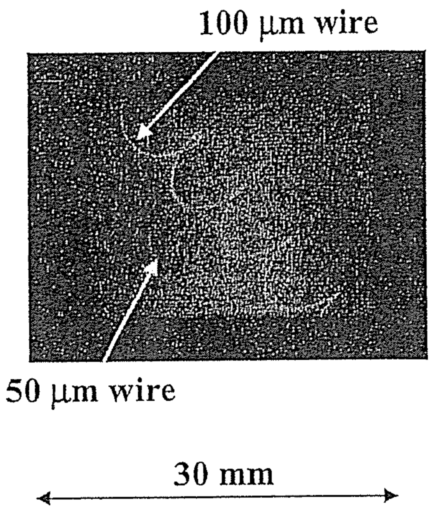

Figure 8: Radiograms of tungsten wires in a PMMA rod. gadodiamidehydrate.

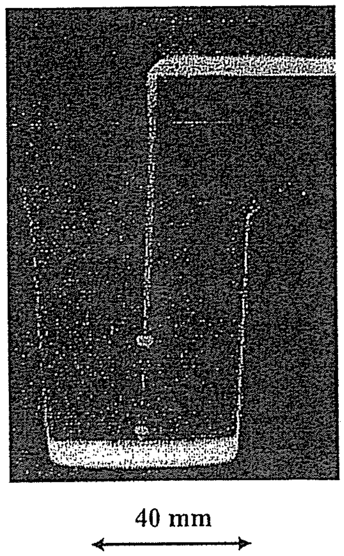

Figure 9: Radiogram of water falling into a polypropylene beaker from a glass test tube.

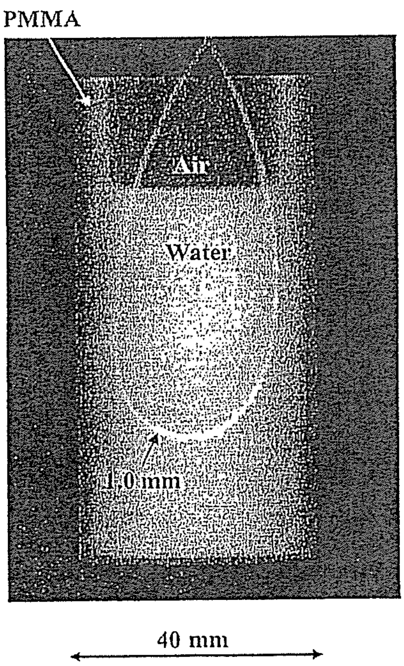

Figure 10: Angiography of a Teflon tube using a contrast medium which contains approximately 65% gadodiamidehydrate.

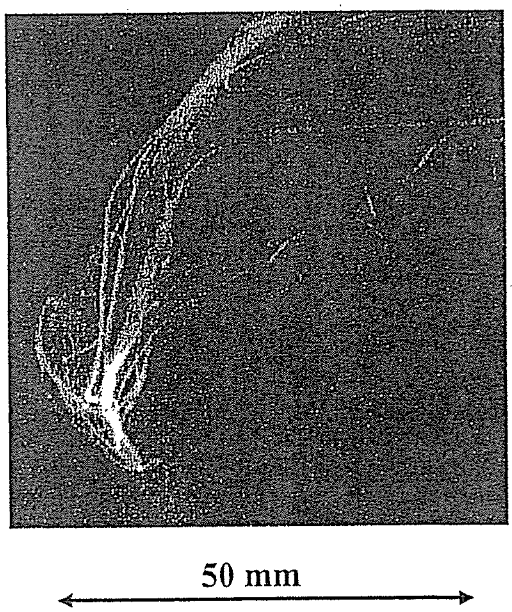

Figure 11: Angiography of a rabbit ear using gadolinium oxide powder.