5. DISCUSSION

In summary, we employed an x-ray generator with a cerium-target tube and succeeded in producing cerium characteristic x rays, which can be absorbed easily by iodine-based contrast mediums. The characteristic x-ray intensities increased with increases in the tube voltage, and low-photon-energy bremsstrahlung rays were absorbed effectively by the filter. Although the cerium x-ray generator used in this research produces both the characteristic and the bremsstrahlung x rays, bremsstrahlung intensity can be decreased effectively by considering the angle dependence without using the filter, since bremsstrahlung rays are not emitted in the opposite direction to that of electron acceleration. Subsequently, the generator produced maximum number of characteristic photons was approximately 35M photons/$cm^2 \cdot s$ at 1.0 m from the source, and the photon count rate can be increased easily by improving the target.

As compared with 3-dimensional blood images constructed from x-ray CT images by Pascal, fine blood vessels were visible. Because the sampling pitch of the CR system is 87.5 μm, we obtained spatial resolutions of approximately 100 μm. In order to observe fine blood vessels of less than 100 μm, the spatial resolution of the CR system should be improved as much as possible.

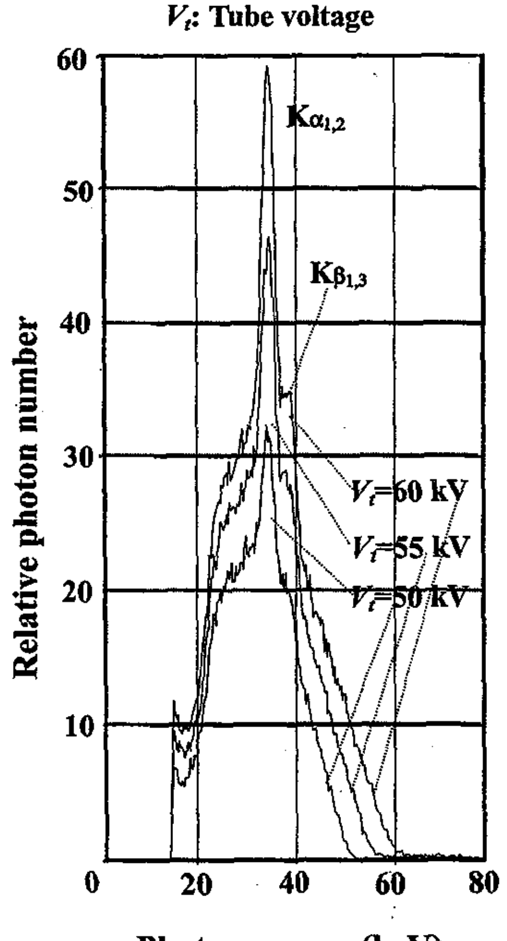

Fig. 5. X-ray spectra measured using cadmium tellurium detector with changes in tube voltage.

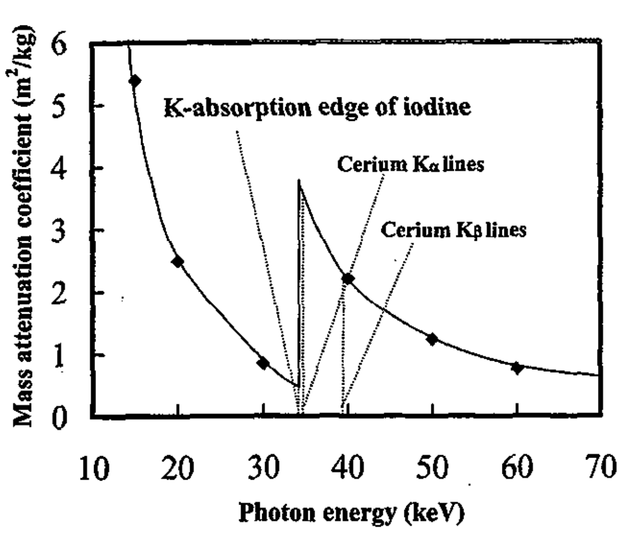

Fig. 6. Mass attenuation coefficients of iodine, and average photon energies of cerium Kα and Kβ lines.

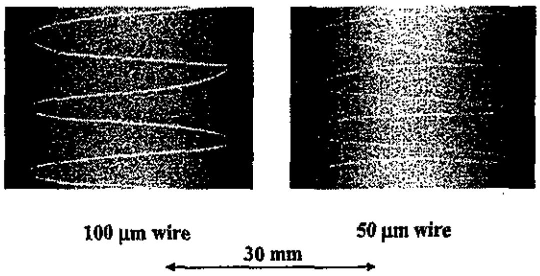

Fig. 7. Radiograms of tungsten wires in PMMA rod with tube voltage of 60 kV.

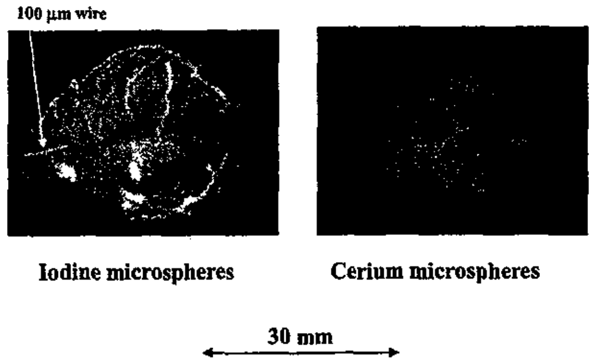

Fig. 8. Angiograms of extracted rabbit hearts using iodine and cerium microspheres with tube voltage of 60 kV.

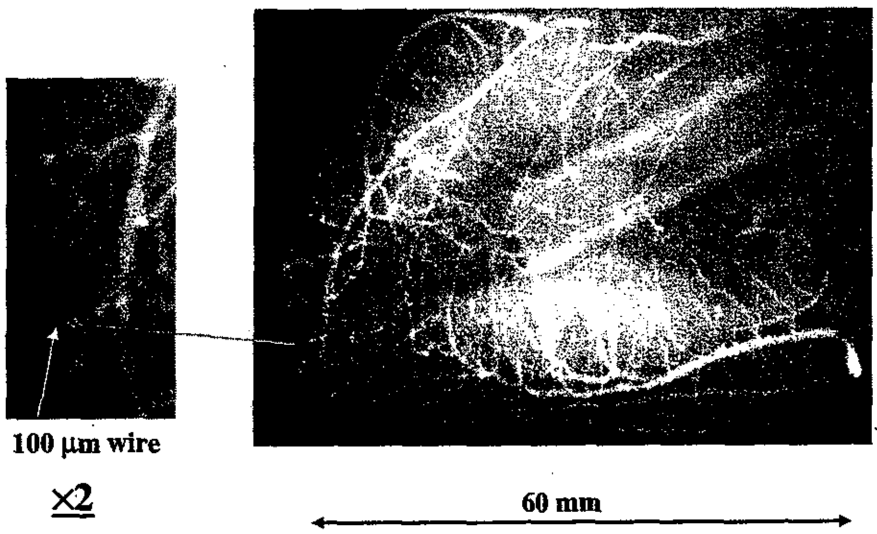

Fig. 9. Angiograms of extracted dog heart using iodine microspheres with tube voltage of 60 kV.

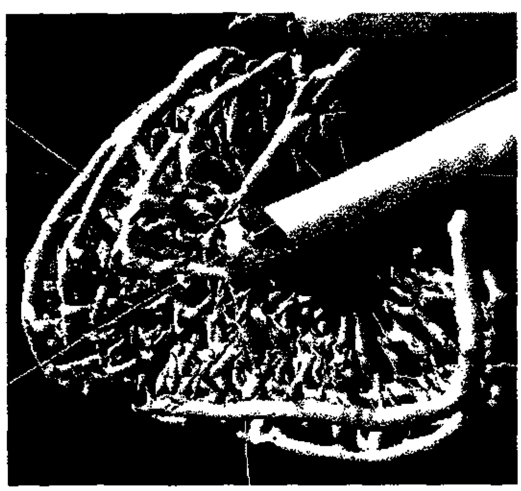

Fig. 10. 3-dimensional image of coronary arteries constructed from x-ray CT images by Pascal.

ACKNOWLEDGMENTS

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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Monochromatic flash x-ray generator utilizing 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 Kα 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 were 90 kV and 0.8 kA, respectively. The x-ray pulse widths were approximately 80 ns, and the instantaneous number of generator-produced Kα photons was approximately 40 M photons/cm^2 per pulse at 0.3 m from the source of 3.0 mm in diameter.

Key words: x-ray source, x-ray tube, x-ray spectra, rapid imaging, x-ray beam filtration, monochromatic x rays

1. INTRODUCTION

Energy-selective monochromatic radiography is a useful method for the medical radiography, and quasi-monochromatic x rays have been produced using a K-edge filter when conventional medical x-ray tube 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 fairly intense and clean characteristic x rays have been produced from the axial direction of weakly ionized linear plasma[10-14] 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, and the plasma then transmits the fluorescent rays easily. However, it is difficult to increase the photon energies of the characteristic x rays,

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(SPIE, Bellingham, WA, 2004) · 0277-786X/04/$15 · doi: 10.1117/12.560537

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. GENERATOR

2.1 High-voltage circuit

Figure 1 shows a block diagram of a compact monochromatic flash x-ray generator. This generator consists of the following components: a constant high-voltage power supply, a 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[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. Because bremsstrahlung rays are not emitted in the opposite direction to that of electron acceleration (Fig. 4), silver Kα rays can be produced using a 30 μm-thick palladium K-edge filter.

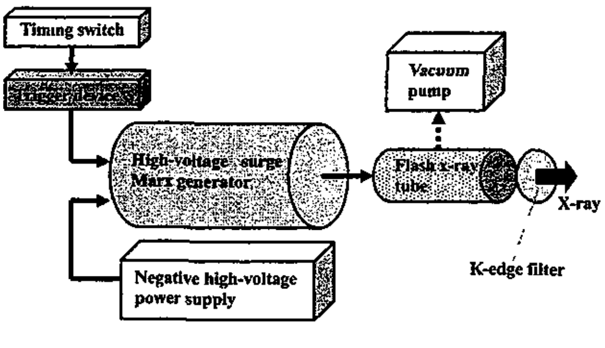


Fig. 1. Block diagram of compact quasi-monochromatic flash x-ray generator.

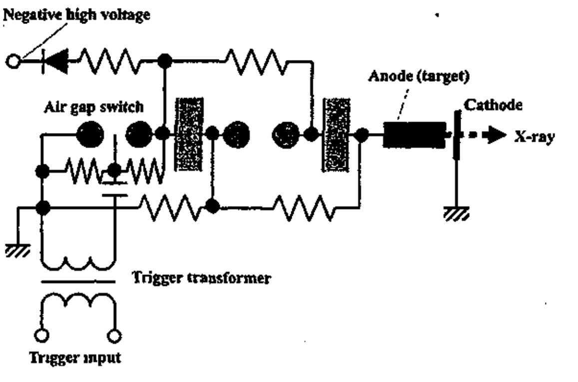


Fig. 2. Circuit diagram of flash x-ray generator.

3. CHARACTERISTICS

3.1 Tube voltage and current

Tube voltage and current were measured using a high-voltage divider with an input impedance of 10 kΩ and a current transformer, respectively (Fig. 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. 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.

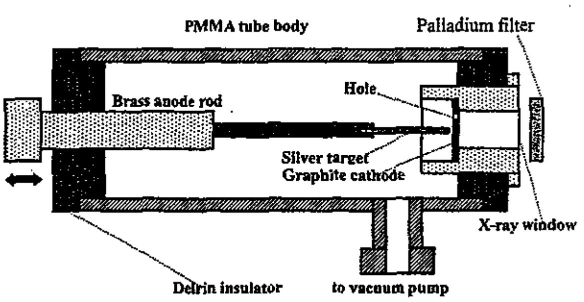


Fig. 3. Schematic drawing of flash x-ray tube.

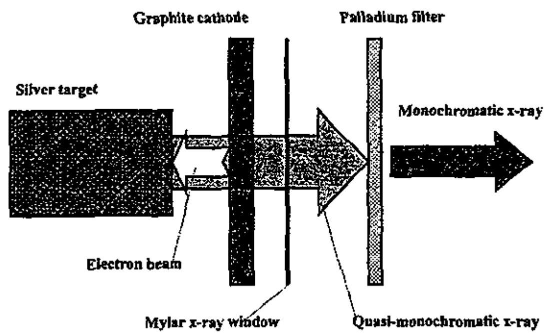
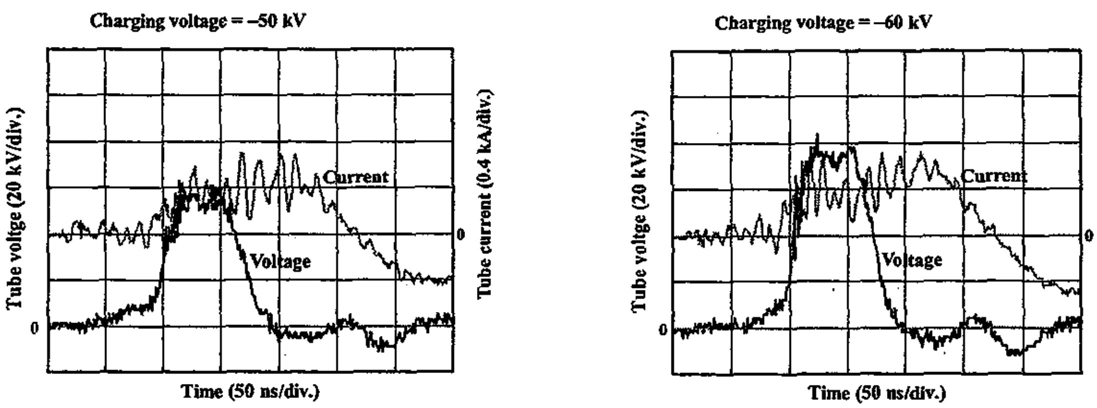


Fig. 4. Irradiation of silver Kα rays using palladium K-edge filter.



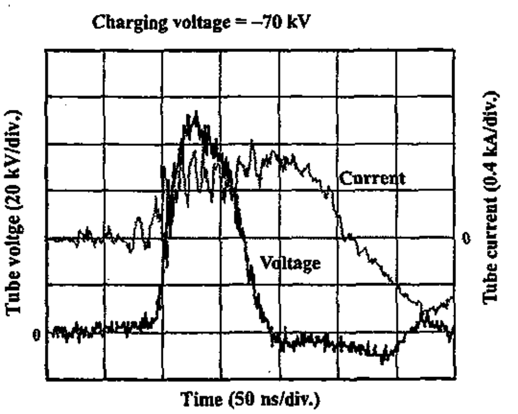


Fig. 5. Variations in tube voltage and current with charges in charging voltage.

3.2 X-ray output

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 an instantaneous value of approximately 90 μGy per pulse at 0.3 m from the x-ray source with a charging voltage of −70 kV.

3.3 X-ray source

In order to observe the x-ray source, we employed a 100 μm-diameter pinhole camera, an x-ray film (Polaroid XR-7), and the filter (Fig. 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 in thickness. The spectra were taken using a computed radiography (CR) system[17] (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 at all. The Kα intensity substantially increased with increases in the charging voltage.

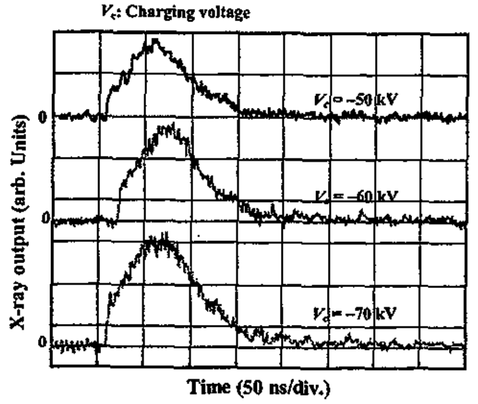


Fig. 6. X-ray outputs at indicated conditions using monochromatic filter.

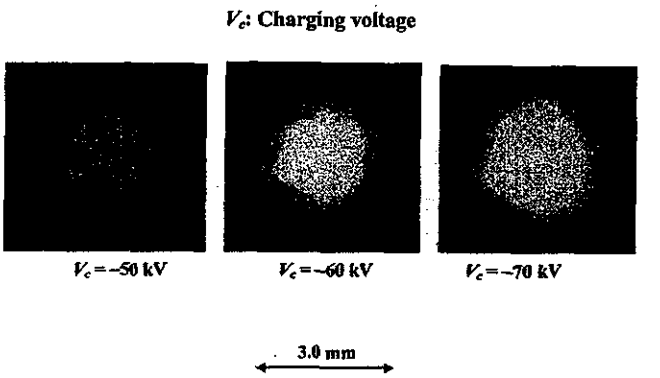


Fig. 7. Images of x-ray source of Kα lines with changes in charging voltage.

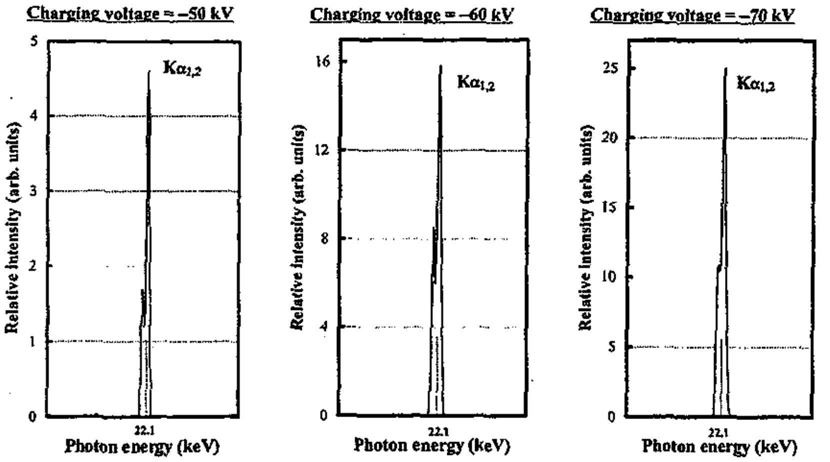


Fig. 8. X-ray spectra from silver target with palladium filter.

4. RADIOGRAPHY

Monochromatic flash radiography was performed using the CR system at 0.3 m from the x-ray source with the filter, and the charging voltage was –70 kV. Firstly, rough measurements 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 increasing wire diameter, a 50 μm-diameter wire could be observed.

Figure 10 shows a radiogram of a vertebra, and fine structures in the vertebra were 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 of 15 μm in diameter were used, and fine blood vessels of approximately 100 μm were visible.

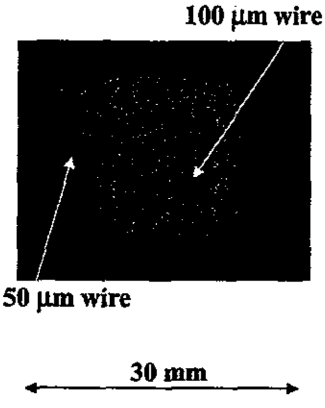
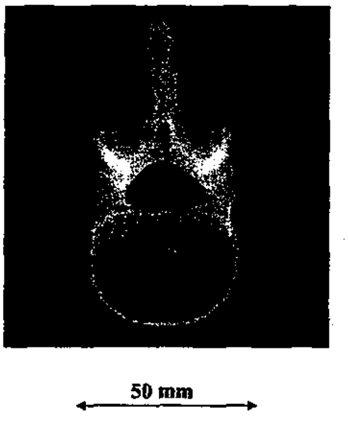


Fig. 9. Radiograms of tungsten wires of 50 and 100 μm in diameter coiled around pipe made of polymethyl methacrylate.



.Fig. 10. Radiogram of vertebra.

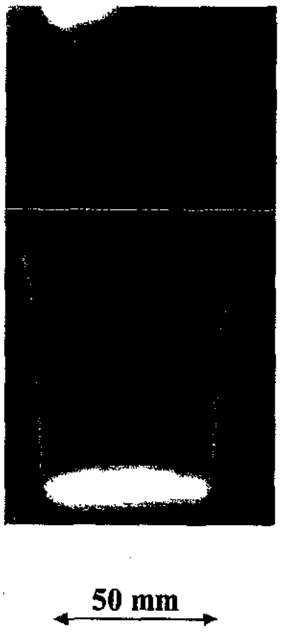


Fig. 11. Radiogram of water falling into polypropylene beaker from glass test tube.

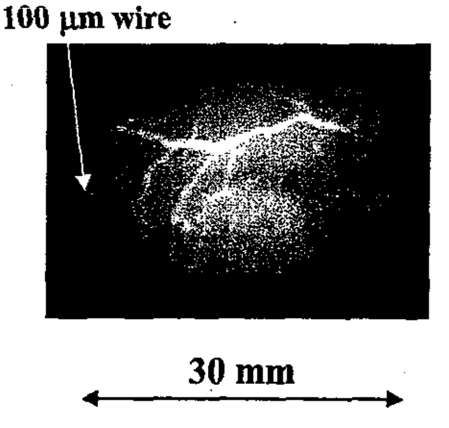


Fig. 12. Angiograms of rabbit heart.

5. DISCUSSION

Concerning the spectrum measurement, we obtained fairly clean silver Kα rays (22.1 keV). Therefore, we are very interested in the measurement the Kα 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 Kα photons was approximately 40 M photons/cm^2 per pulse at 0.3 m from the source. However, the intensity can be increased by increasing the electrostatic energy in condensers in the surge generator, and quasi-monochromatic x rays of both Kα and Kβ (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 in order to decrease noise from radiograms. As compared with a steady state x-ray generator, since the target element can be changed easily using this demountable PMMA tube, demonstrations of monochromatic radiography will be accomplished easily.

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Weakly ionized linear plasma x-ray generator with molybdenum-target 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 trigger electrode, 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 molybdenum 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 16 kA. When the charging voltage was increased, the linear plasma formed, and the K-series characteristic x-ray intensities increased. The K lines were quite sharp and intense. The x-ray pulse widths were approximately 600 ns, and the time-integrated x-ray intensity had a value of approximately 65 μC/kg at 1.0 m from the x-ray source with a charging voltage of 50 kV.

Keywords: flash x-ray, weakly ionized linear plasma, molybdenum characteristic x rays, quasi-monochromatic x rays, x-ray resonation

1. INTRODUCTION

In conjunction with monochromators, synchrotrons produce monochromatic parallel beams, which are fairly similar to monochromatic parallel laser beams, and the beams have been applied to enhanced K-edge angiography,[1,2] phase imaging,[3,4] and crystallography. Therefore, the production of coherent hard x-ray lasers for various research projects, including biomedical applications, has long been wished for.

Recently, soft x-ray lasers[5-7] have been produced by a gas-discharge capillary, and the laser pulse energy substantially increased in proportion to the capillary length. These kinds of fast discharges can generate hot and dense plasma columns with aspect ratios approaching 1000:1. However, it is difficult to increase the laser photon energy to 10 keV or beyond. Because there are no x-ray resonators in the high-photon-energy region, new methods for increasing coherence will be desired in the future.

To apply flash x-ray generators to biomedicine, several different generators[8-11] have been developed, and plasma x-ray generators[12-16] are useful for producing clean characteristic x rays in the low-photon-energy region of less than 20 keV. By forming weakly ionized linear plasma using rod targets, we confirmed irradiation of intense K-series characteristic x rays from the axial direction of the linear plasmas of nickel, copper, and molybdenum, since the bremsstrahlung x rays are absorbed effectively by the linear plasma; monochromatic clean Kα rays were produced using K-edge filters. Subsequently, since high-photon-energy bremsstrahlung x rays are not absorbed effectively by the linear plasma due to attenuation coefficients, high-photon-energy quasi-monochromatic x-ray generators[17] for producing characteristic x rays of molybdenum, silver, cerium, tantalum, and tungsten have been developed utilizing the angle dependence of bremsstrahlung x-ray intensity distribution.

In this paper, we describe a recent plasma flash x-ray generator utilizing a rod-target radiation tube, used to perform a preliminary experiment for generating intense and sharp quasi-monochromatic x rays under resonating conditions by forming a linear molybdenum plasma cloud around a fine target.

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. 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. 2). 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 stainless-steel vacuum chamber, a nylon insulator, a polyethylene terephthalate (Mylar) x-ray window 0.25 mm in thickness, and a rod-shaped molybdenum target 3.0 mm in diameter. The distance between the target and cathode electrodes 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 electric field in the tube, evaporation leads to the formation of weakly ionized linear plasma, consisting of molybdenum ions and electrons, around the fine target.

2.3 Principle of characteristic x-ray irradiation

In weakly ionized linear 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, and bremsstrahlung rays with energies of lower than the K-edge are also absorbed by the plasma. In addition, because bremsstrahlung rays are not emitted in the direction opposite to electron acceleration, intense characteristic x rays are generated from the plasma-axial direction.

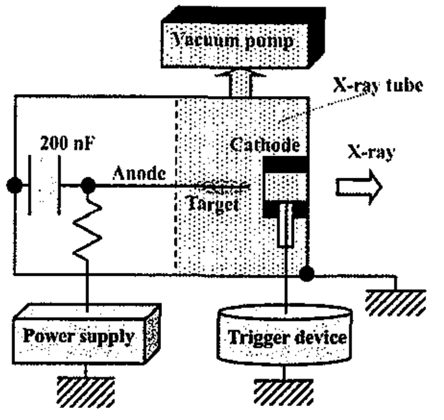

Figure 1: Block diagram of high-intensity plasma flash x-ray generator.

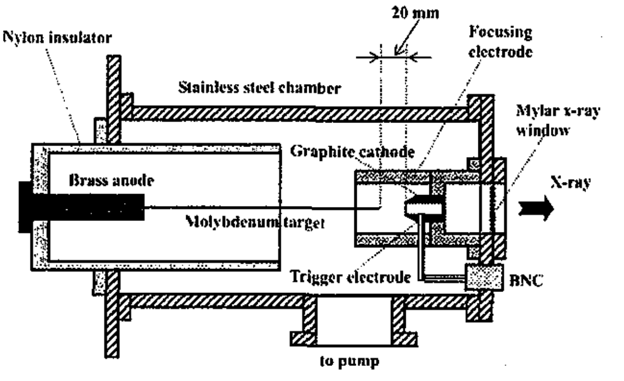

Figure 2: Schematic drawing of flash x-ray tube with rod target.

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 3 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 16 kA.

3.2 X-ray output

X-ray output pulse was detected using a combination of a plastic scintillator and a photomultiplier (Fig. 4). The x-ray pulse height substantially increased with corresponding increases in the charging voltage. The x-ray pulse widths were about 600 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 65 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 pinhole camera with a hole diameter of 100 μm and an x-ray film (Polaroid XR-7) (Fig. 5). When the charging voltage was increased, the plasma x-ray source grew, and both spot dimension and intensity increased. Because the x-ray intensity is the highest at the center of the spot, both the dimension and intensity decreased according to both increases in the thickness of a filter for absorbing x rays and decreases in the pinhole diameter.

3.4 X-ray spectra

X-ray spectra 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[18] with a wide dynamic range, and relative x-ray intensity was calculated from Dicom digital data. Figure 6 shows measured spectra from the molybdenum target. In fact, we observed quite sharp lines of K-series characteristic x rays, and bremsstrahlung rays were detected slightly at a high charging voltage of approximately 50 kV. The characteristic x-ray intensity substantially increased with corresponding increases in the charging voltage. We found high-intensity lines with a photon energy of $0.5E_\alpha$ corresponding to Kα lines with an average photon energy of E_α. Although lines of $0.5E_\beta$, corresponding to Kβ lines with an average photon energy of E_β, were also detected, hardly any bremsstrahlung x rays were detected at all.

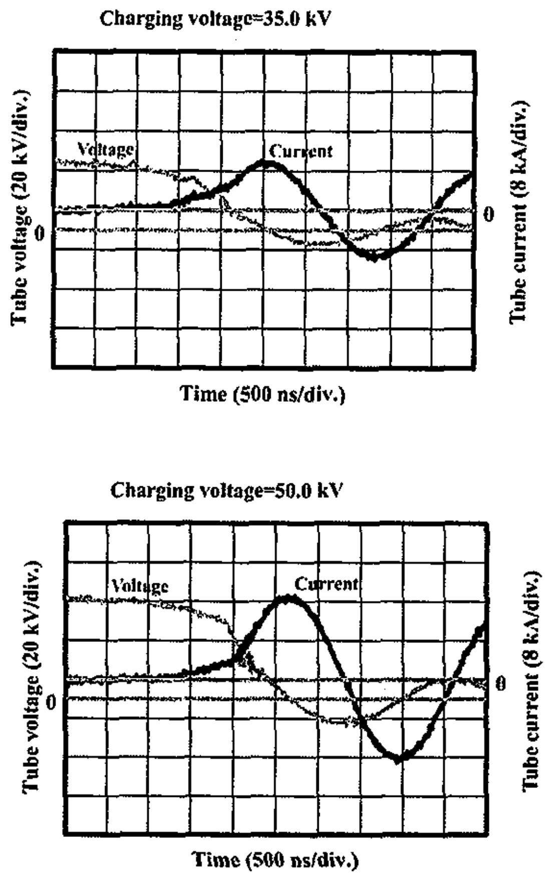

Figure 3: Tube voltages and currents with changing charging voltage.

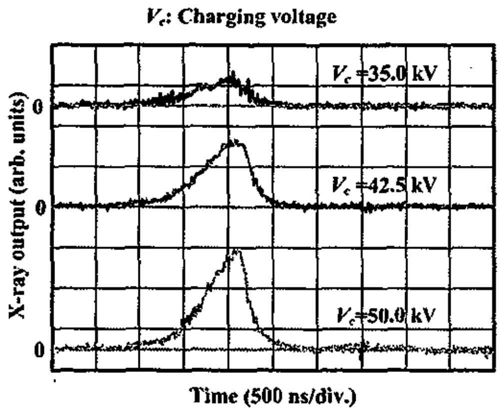

Figure 4: X-ray outputs at indicated conditions.

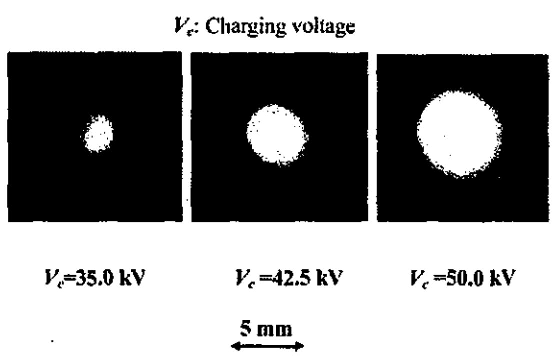

Figure 5: Images of plasma x-ray source.

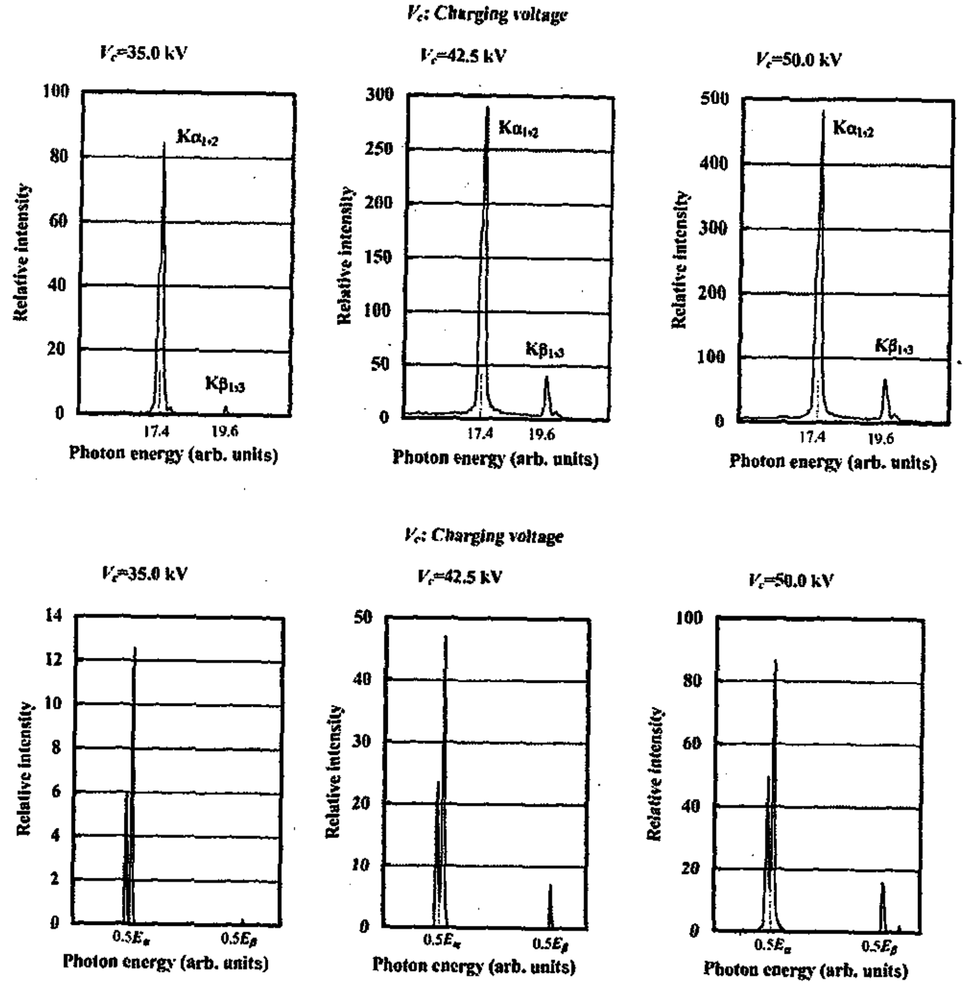

Figure 6: X-ray spectra from molybdenum plasma.

4. RADIOGRAPHY

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

Firstly, rough measurements of image resolution were made using wires. Figure 7 shows radiograms of tungsten wires coiled around a pipe made of polymethyl methacrylate with a tube voltage of 50 kV. 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 falling into a polypropylene beaker from a plastic test tube is shown in Fig. 8. This image was taken with a charging voltage of 50 kV, with the slight addition of an iodine-based contrast medium. Because the x-ray duration was about 1 μs, the stop-motion image of water could be obtained.

Figure 9 shows a radiogram of a vertebra with a charging voltage of 45 kV, and fine structures in the vertebra were observed. Figure 10 shows an angiogram of a rabbit heart with a charging voltage of 50 kV. In angiography, iodine-based microspheres of 15 μm in diameter were used, and fine blood vessels of about 100 μm were visible.

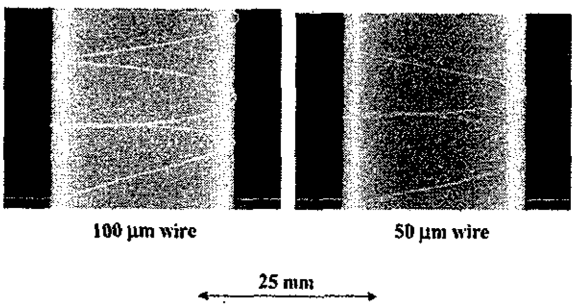

Figure 7: Radiograms of tungsten wires in PMMA rod.

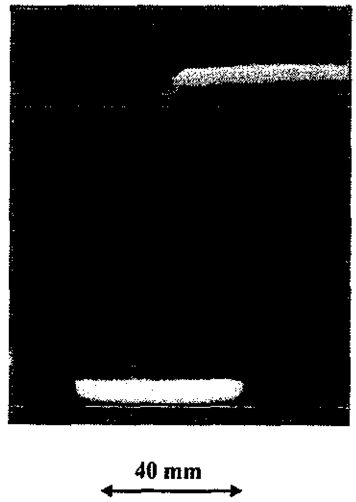

Figure 8: Radiogram of water falling into polypropylene beaker from glass test tube.

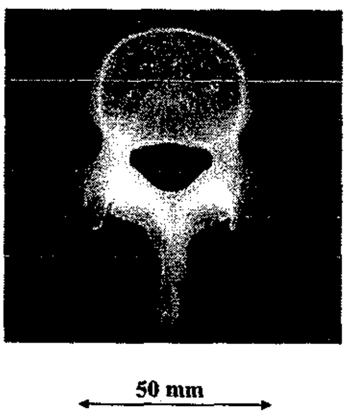

Figure 9: Radiogram of vertebra.

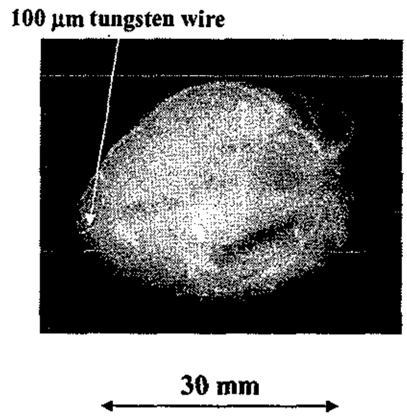

Figure 10: Angiograms of rabbit heart.

5. DISCUSSION

Regarding the spectrum measurement, although we obtained quite intense and sharp K-series lines by forming a linear plasma x-ray source, bremsstrahlung x rays were observed slightly at charging voltages of approximately 50 kV. In addition, we observed fairly intense and clean lines with photon energies of $0.5E_\alpha$. Because bremsstrahlung x rays were hardly observed, we thought that the $0.5E_\alpha$ and $0.5E_\beta$lines were not characteristic x rays reflected by the high order diffraction and were produced by the hard x-ray resonation (oscillation) without using a resonator (Figs. 11 and 12). If we assume that x-ray intensities of the two lines and bremsstrahlung rays are signal and noise, respectively, the signal to noise ratio is higher than 1000:1, and this value is almost equal to those of soft x-ray lasers produced by the gas-discharge capillary.

In this research, we obtained sufficient x-ray intensity per pulse for CR radiography without using a monochromatic filter, and the generator produced number of characteristic photons was approximately 1×10^9 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 high-contrast micro angiography and dual-energy subtraction radiography, will be possible.

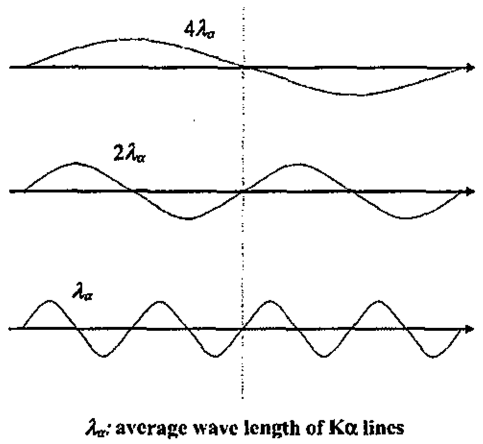

Figure 11: Assumption of hard x-ray resonation without using resonator.

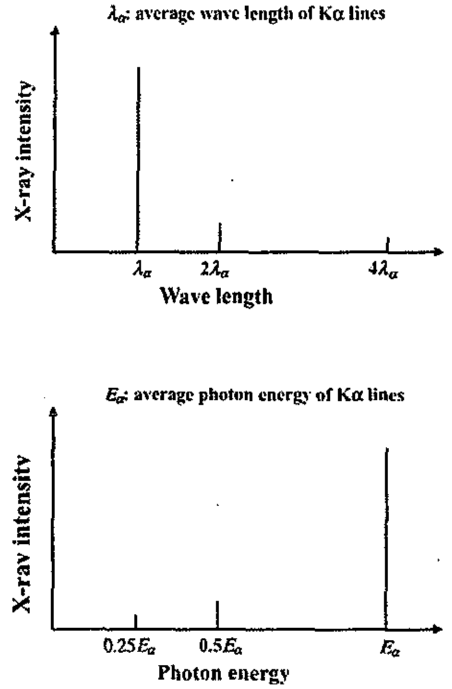

Figure 12: Estimated x-ray spectra under resonation.

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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