4. RADIOGRAPHY

The angiography was performed by a CR system using the filters with a charging voltage of 60 kV, and the distance between the x-ray source and the imaging plate was 0.7 m. The image contrast hardly varied even when the filter was changed.
Figure 7 shows radiograms of tungsten wires coiled around a rod made of polymethyl methacrylate using the aluminum filter. Although the image contrast increased with increases in the wire diameter, a 50 μm-diameter wire could be observed.
The image of water spouted from an injector is shown in Fig. 8. This image was taken with the slight addition of an iodine-based contrast medium using the barium sulfate filter. Because the x-ray duration was 1 ms, the stop-motion image of water could be obtained. Figures 9 and 10 show angiograms of a rabbit thigh (barium sulfate filter) and a dog heart (aluminum filter), respectively. In angiography, iodine-based microspheres of 15 μm in diameter were used, and fine blood vessels of about 100 μm were visible.

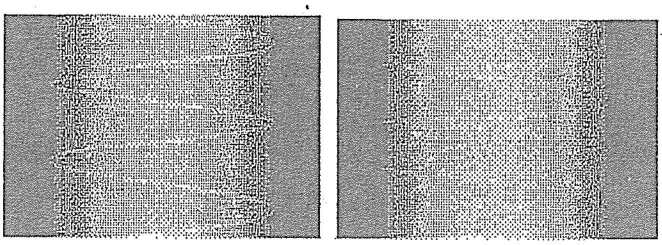

Figure 7: Radiograms of tungsten wires coiled around rod made of polymethyl methacrylate using aluminum filter.

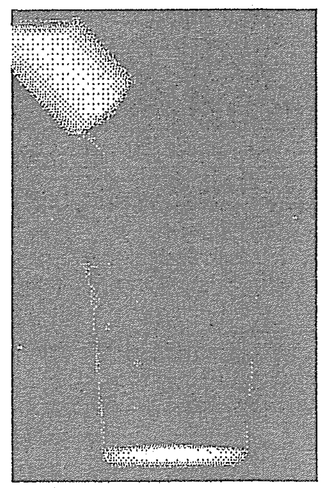

Figure 8: Radiogram of water spouted from injector using barium sulfate filter.

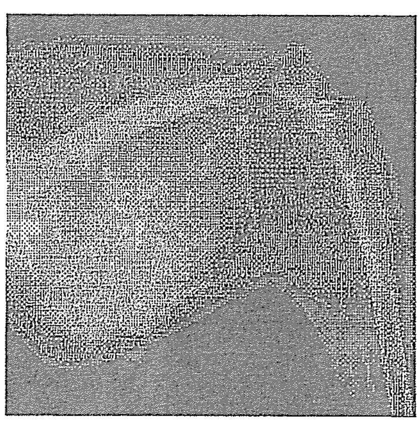

Figure 9: Angiograms of rabbit thigh achieved with barium sulfate filter.

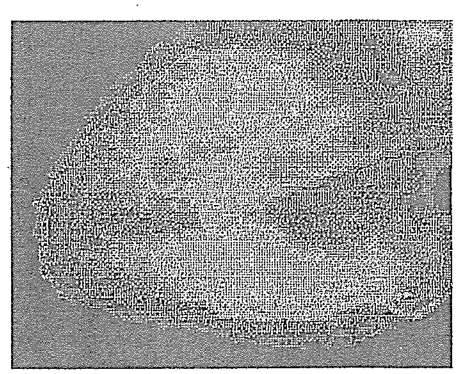

Figure 10: Angiogram of dog heart with aluminum filter.

5. DISCUSSION

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

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

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

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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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Clean monochromatic x-ray irradiation from weakly ionized linear copper plasma

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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 copper ions and electrons, around the fine target, and intense $K\alpha$ rays are produced using a 10-μm-thick nickel filter. At a charging voltage of 50 kV, the maximum tube voltage is almost equal to the charging voltage of the main condenser, and the peak current is about 15 kA. When the charging voltage is increased, the linear plasma forms, and the copper $K\alpha$ intensities substantially increase. The $K\alpha$ lines are quite clean and intense, and hardly any bremsstrahlung rays are detected at all. The x-ray pulse widths are approximately 700 ns, and the time-integrated x-ray intensity has a value of approximately 20 μC/kg at 1.0 m from the x-ray source with a charging voltage of 50 kV. [DOI: 10.1117/1.1882373]

Subject terms: flash x-ray; weakly ionized linear plasma; copper target; $K\alpha$ characteristic x-rays; monochromatic x-rays.

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1 Introduction

Flash x-rays have been produced by several different methods, and various generators have been developed corresponding to specific radiographic objectives.[1–3] Currently, maximum photon energy has been increased to approximately 1 MeV using multistage Marx pulse generators[1,2] to produce hard x-rays for military studies. In soft x-ray generators,[4–7] high-intensity single generators with large capacity condensers were originally developed. Subsequently, repetitive generators[8–12] have been developed, and the repetition rate has been increased to subkilohertz using a cold-cathode triode.

Recently, soft x-ray lasers have been produced by a gas-discharge capillary,[13–16] 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.

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We have developed several different plasma flash x-ray generators corresponding to specific radiographic objectives, and a major goal in our research is the development of an intense and clean monochromatic x-ray generator that can impact applications with biomedical radiography. By forming weakly ionized linear plasma,[17–20] because we have succeeded in producing fairly intense and clean quasi-monochromatic x-rays from the plasma axial direction, monochromatic x-rays should be produced using a K-edge filter.

We describe a plasma flash x-ray generator utilizing a new plasma x-ray tube, and used it to perform a preliminary experiment for generating clean monochromatic x-rays by forming a linear copper plasma cloud around a fine target.

2 Generator

2.1 *High-Voltage Circuit*

Figure 1 shows a block diagram of the high-intensity plasma flash x-ray generator. This 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

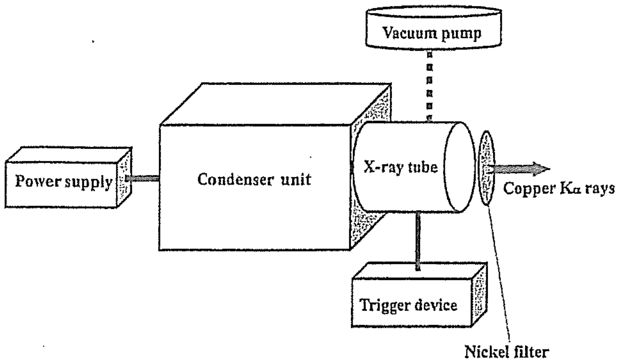

Fig. 1 Block diagram of high-intensity plasma flash x-ray generator.

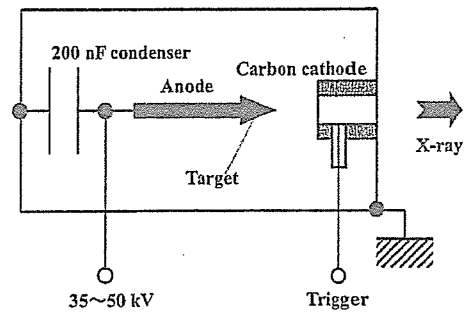

Fig. 2 Circuit diagram of generator.

generator as a trigger device, and a flash x-ray tube. In this generator, a low-impedance transmission line (Fig. 2) is employed to increase maximum tube current. The high-voltage main condenser is charged 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 hollow cylindrical carbon cathode with a bore diameter of 10.0 mm, a brass focusing electrode, 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 thick, and a rod-shaped copper target 3.0 mm in diameter with a tip angle of 60 deg. 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 a weakly ionized linear plasma, consisting of copper ions and electrons, around the fine target.

2.3 *Principle of Clean Kα-Ray Irradiation*

In the linear plasma, bremsstrahlung photons with energies higher than the K-absorption edge are effectively absorbed and are converted into fluorescent x-rays (Fig. 4). The plasma then transmits the fluorescent rays easily, and bremsstrahlung rays with energies lower than the K edge are also absorbed by the plasma. In addition, because bremsstrahlung rays are not emitted in the opposite direction to that of electron acceleration, intense characteristic x-rays are generated from the plasma-axial direction. Sub-

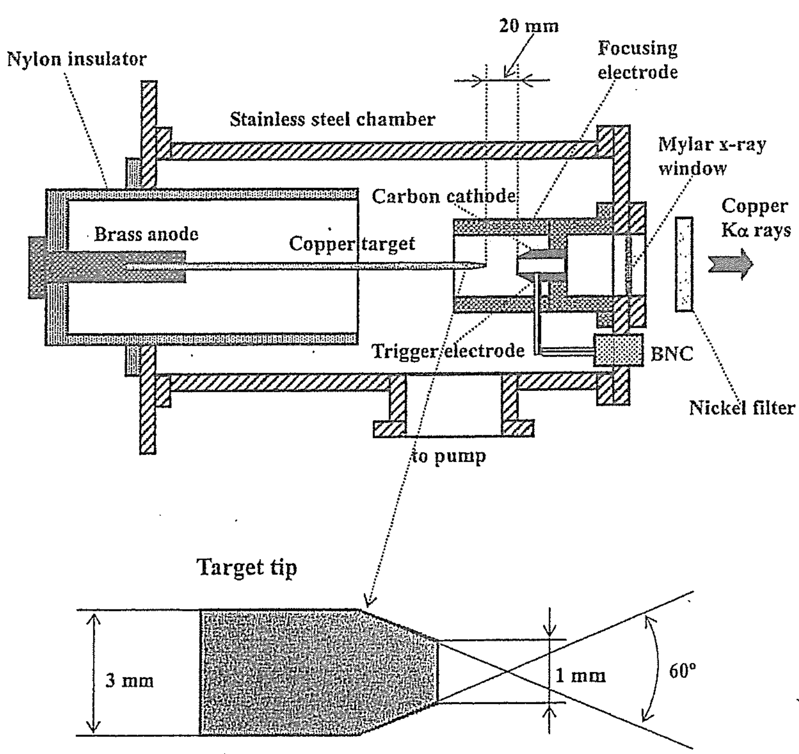

Fig. 3 Schematic drawing of flash x-ray tube with rod target.

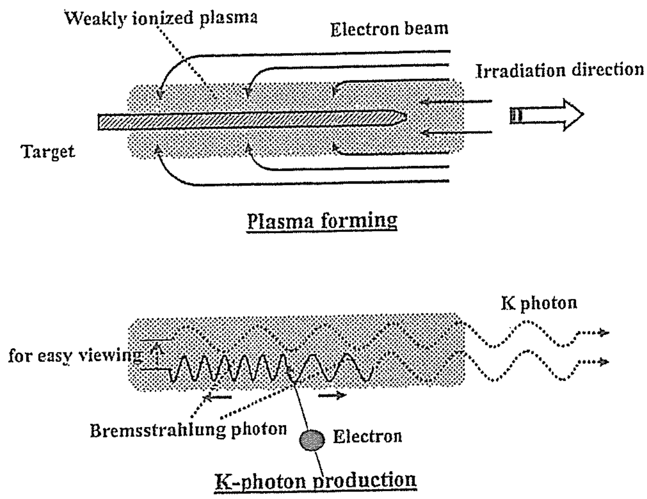

Fig. 4 K-photon irradiation from weakly ionized plasma.

sequently, $K\beta$ rays (8.90 keV) are absorbed effectively using a 10-μm-thick nickel K-edge filter with an edge of 8.33 keV, and quite clean $K\alpha$ rays (8.04 keV) are produced.

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 5 shows the time relation for 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 15 kA.

3.2 *X-Ray Output*

An x-ray output pulse was detected using a combination of a plastic scintillator and a photomultiplier using a 10-μm-thick monochromatic copper filter (Fig. 6). The x-ray pulse height substantially increased with corresponding increases in the charging voltage. The x-ray pulse widths were about 700 ns, and the time-integrated x-ray intensity per pulse measured by a thermoluminescence dosimeter (Kyokko TLD Reader 1500 utilizing MSO-S elements without energy compensation) had a value of about 20 μC/kg at 1.0 m from the x-ray source, with a charging voltage of 50 kV.

3.3 *X-Ray Source*

To measure images of the $K\alpha$ source, we employed a pinhole camera with a hole diameter of 100 μm (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 both increases in the thickness of a filter for absorbing x-rays and decreases in the pinhole diameter.

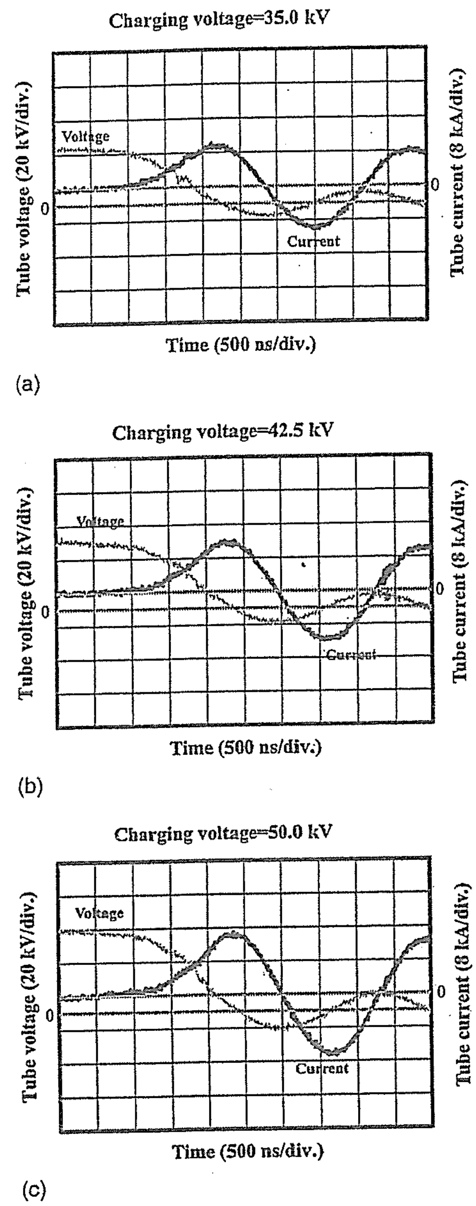

Fig. 5 Tube voltages and currents with charging voltage of (a) 35.0 kV, (b) 42.5 kV, and (c) 50.0 kV.

3.4 *X-Ray Spectra*

X-ray spectra from the plasma source were measured using a transmission-type spectrometer with a lithium fluoride

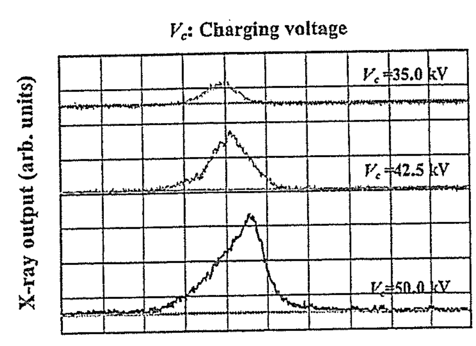

Fig. 6 X-ray outputs measured by plastic scintillator with changes in charging voltage.

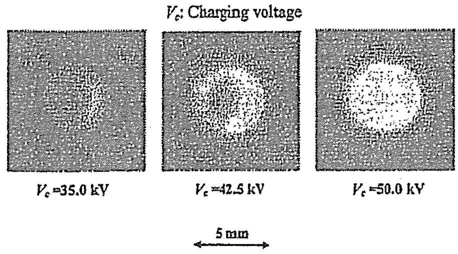

Fig. 7 Images of Kα x-ray source measured by pinhole of 100 μm from plasma axial direction.

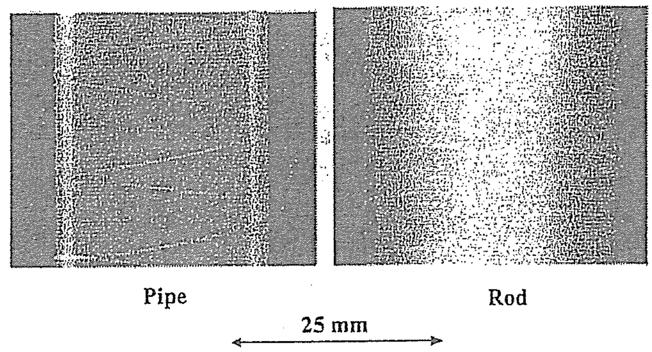

Fig. 9 Radiograms of tungsten wires 50 μm in diameter coiled around pipe, and rod made of polymethyl methacrylate.

curved crystal 0.5 mm in thickness. The spectra were taken by a computed radiography (CR) system[21] (Konica Regius 150) with a wide dynamic range, using the filter, and relative x-ray intensity was calculated from Dicom digital data. Figure 8 shows measured spectra from the copper target using the filter. In fact, we observed clean Kα lines such as lasers, and confirmed the significant filtering effect, while bremsstrahlung rays were hardly detected at all. The characteristic x-ray intensity of the Kα lines substantially increased with corresponding increases in the charging voltage, and the Kβ line was absorbed by the filter. Although this spectrometer has sufficient energy resolution for measuring Kα_1 and Kα_2 lines, we could observe only a single line.

4 Radiography

Plasma radiography was performed by the CR system without using the filter, and the distance between the x-ray source and imaging plate was 1.2 m.

First, rough measurements of image resolution were made using wires. Figure 9 shows radiograms of 50-μm-diam tungsten wires coiled around a pipe, and a rod made of polymethyl methacrylate with a charging voltage of 50 kV. Although the image contrast increased using the pipe, 50-μm-diam wires could be observed.

The image of water falling into a polypropylene beaker from a glass test tube is shown in Fig. 10. This image was taken with a charging voltage of 45 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 11 shows an angiogram of a rabbit heart; iodine-based microspheres of 15 μm in diameter were used with a charging voltage of 50 kV, and fine blood vessels of about 100 μm were visible.

5 Discussion

Concerning the spectrum measurement, we obtained fairly clean Kα lines from a weakly ionized linear plasma x-ray

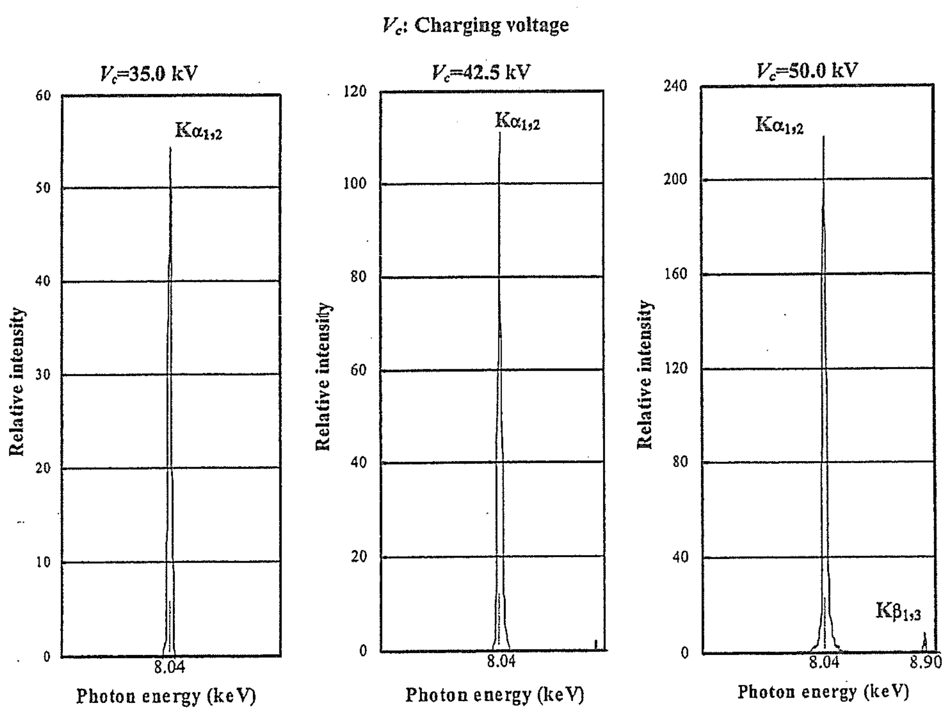

Fig. 8 X-ray spectra from weakly ionized copper plasma according to changes in charging voltage and to insertion of nickel K-edge filter.

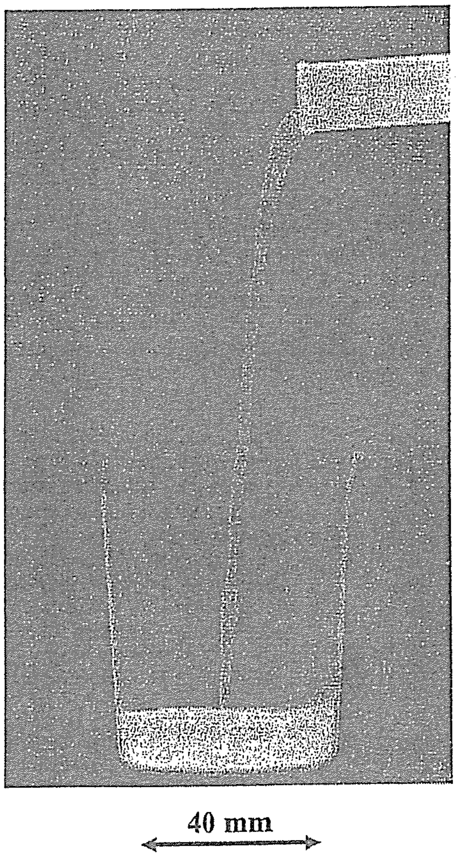

Fig. 10 Radiogram of water falling into polypropylene beaker from glass test tube.

source by absorbing Kβ lines using the K-edge filter. The lines are produced by x-ray enhancement by spontaneous emission, and the coherence can be increased by development of a resonator or by pulse laser irradiations from the plasma axial direction to produce higher harmonics. In a medical application, cerium Kα rays (34.6 keV) are absorbed effectively by an iodine-based contrast medium, and high contrast microangiography can be performed.

In this research, we obtained sufficient characteristic x-ray intensity per pulse for CR radiography using the filter, and the generator-produced number of characteristic Kα photons was approximately 5×10^{13} photons/cm$^2\cdot$s at 1.0 m from the source. In addition, since the photon energy of characteristic x-rays can be controlled by changing the target elements, various quasimonochromatic high-speed radiographies, such as high-contrast microangiography and parallel radiography using an x-ray lens, will be possible.

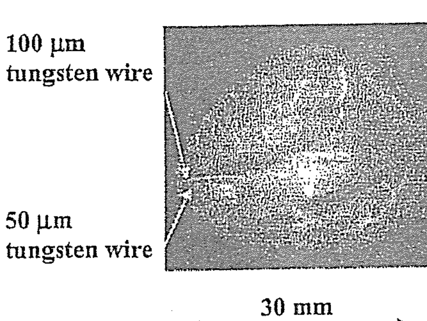

Fig. 11 Angiograms of rabbit heart.

Acknowledgments

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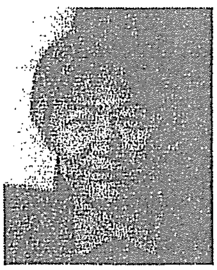

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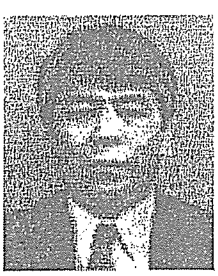

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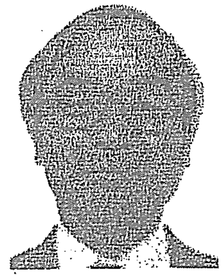

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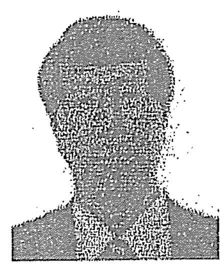

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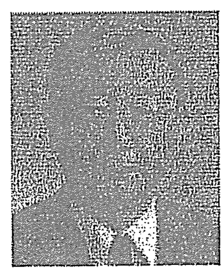

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High-speed enhanced K-edge angiography utilizing cerium plasma x-ray generator

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Abstract. The cerium target plasma flash x-ray generator is useful 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 plasma generator, a 200-nF condenser is charged up to 60 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 cerium ions and electrons, around the target, and intense flash x-rays are produced. At a charging voltage of 55 kV, the maximum tube voltage is almost equal to the charging voltage of the main condenser, and the maximum current is approximately 20 kA. When the charging voltage is increased, weakly ionized cerium plasma forms, and the K-series characteristic x-ray intensities increase. The x-ray pulse widths are about 500 ns, and the time-integrated x-ray intensity has a value of about 40 μC/kg at 1.0 m from the x-ray source with a charging voltage of 55 kV. In the angiography, we employ a filmless computed radiography (CR) system and iodine-based microspheres.

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Subject terms: plasma x-ray; cerium target; weakly ionized cerium plasma; characteristic x-ray; K-edge angiography.

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1 Introduction

Flash x-rays are useful to perform high-speed radiography, and various generators have been developed to correspond to specific radiographic objectives.[1–5] In the cases of multishot and cine radiographies, we have developed several different repetitive-flash[6–10] and stroboscopic x-ray generators.[11–17] Although most flash x-ray generators have cold-cathode tubes, the stroboscopic generators utilize hot-cathode tubes.

In conjunction with single crystals, synchrotrons generate monochromatic x-rays. These rays play important roles in parallel radiography and have been employed to perform high-contrast K-edge angiography[18] and x-ray phase imaging.[19,20] However, it is difficult to obtain sufficient machine times for various research projects, including medical applications.

As for angiography using iodine-based contrast mediums, K-series characteristic x-rays of cerium are extremely useful, since the rays are absorbed easily by iodine. In particular, since fairly intense and sharp characteristic x-rays have been produced from weakly ionized linear plasmas[21–24] of nickel, copper, and molybdenum, the development of a cerium-target x-ray tube for angiography is highly desirable.

In this research, we developed a single flash x-ray generator with a cerium-target plasma tube and performed a preliminary study on weakly ionized cerium plasma angiography.

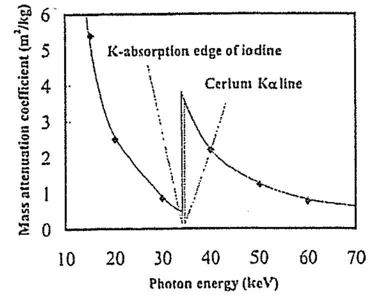

Fig. 1 Relation between mass attenuation coefficient of iodine and average photon energy of cerium $K\alpha$ lines.

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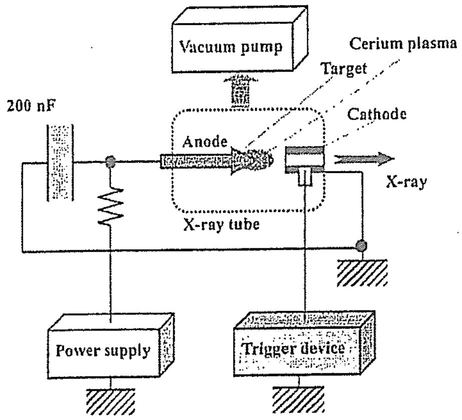

Fig. 2 Block diagram of high intensity plasma flash x-ray generator.

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 energy of the cerium Kα lines is shown just above the iodine K-edge. Cerium is a rare earth element and has a high reactivity; however, the average photon energy of Kα lines is 34.566 keV, and iodine contrast mediums with a K-absorption edge of 33.155 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. This generator consists of the following essential components: a high-voltage power supply, a high-voltage condenser with a capacity of about 200 nF, a turbomolecular pump, a krytron pulse generator as a trigger device, and a flash x-ray tube. The high-voltage main condenser is charged up to 60 kV by the power supply, and electric charges in the condenser are discharged to the tube after triggering the cathode electrode by the trigger device. The plasma flash x-rays are then produced.

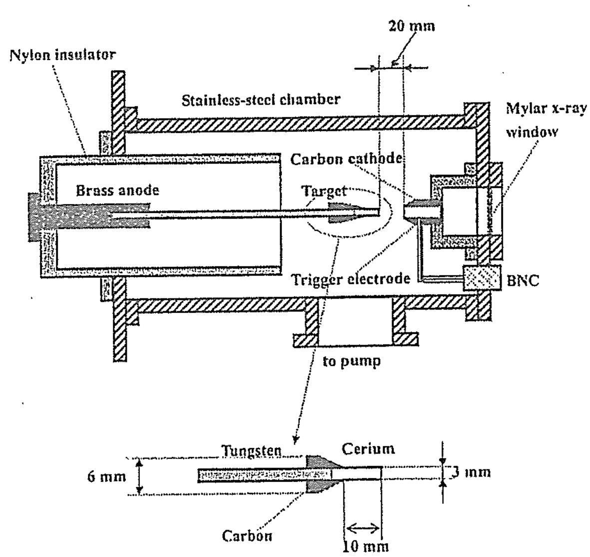

Fig. 3 Schematic drawing of flash x-ray tube.

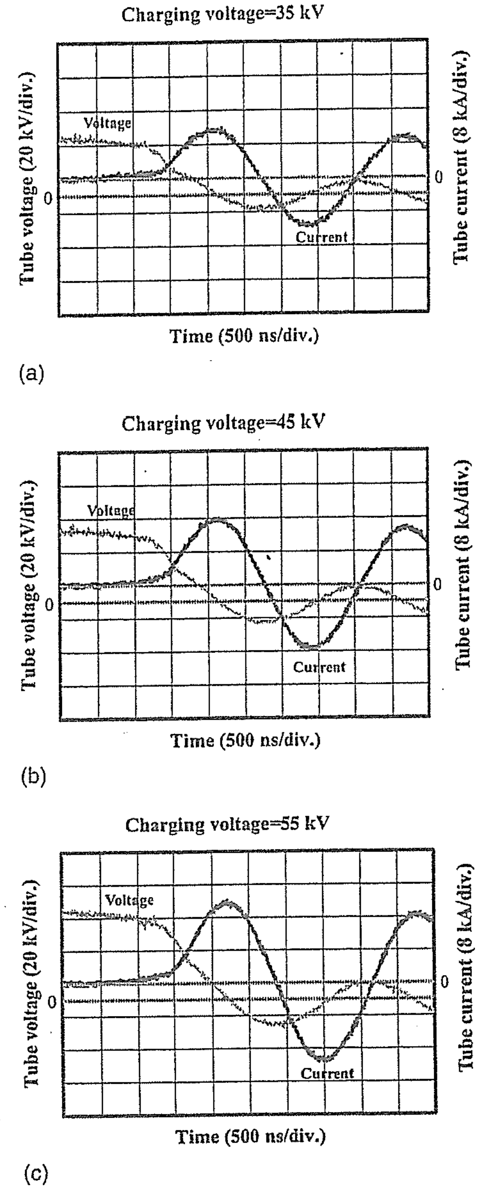

Fig. 4 Tube voltages and currents with charging voltage of (a) 35, (b) 45, and (c) 55 kV.

3.2 *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 hollow cylindrical carbon cathode with a bore diameter of 10.0 mm, a trigger electrode made from a copper wire, a stainless-steel vacuum chamber, a nylon insulator, a polyethylene terephthalate (Mylar) x-ray window of 0.25 mm, and a rod-shaped cerium target of 3.0 mm in diameter. The target tip is embedded in the carbon rod to absorb the characteristic x-rays of carbon by the window. The distance between the target and cathode electrodes is approximately 20 mm, and the trigger electrode is

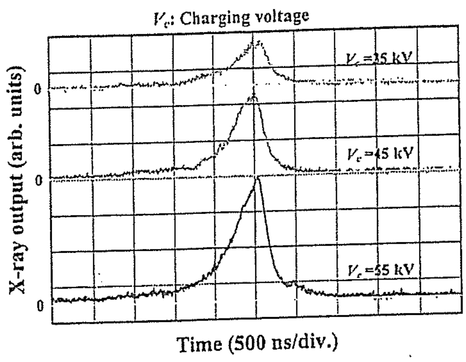

Fig. 5 X-ray outputs at indicated conditions.

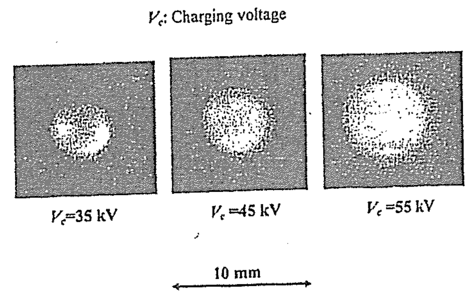

Fig. 6 Images of plasma x-ray source.

set in the cathode electrode. As electron beams from the cathode electrode are roughly converged to the target by an electric field in the tube, the weakly ionized plasma, which consists of cerium ions and electrons, forms around the target by evaporating.

4 Characteristics

4.1 *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 55 kV, the maximum tube voltage was almost equal to the charging voltage of the main condenser, and the maximum tube current was about 20 kA.

4.2 *X-Ray Output*

An x-ray output pulse was detected using a combination of a plastic scintillator and a photomultiplier. The x-ray pulse height substantially increased with corresponding increases in the charging voltage (Fig. 5). The x-ray pulse widths were about 500 ns, and the time-integrated x-ray intensity measured by a thermoluminescence dosimeter (Kyokko TLD Reader 1500 utilizing MSO-S elements without energy compensation) had a value of about 40 μC/kg at 1.0 m from the x-ray source with a charging voltage of 55 kV.

4.3 *X-Ray Source*

To measure images of the plasma x-ray source, we employed a pinhole camera with a hole diameter of 100 μm (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.

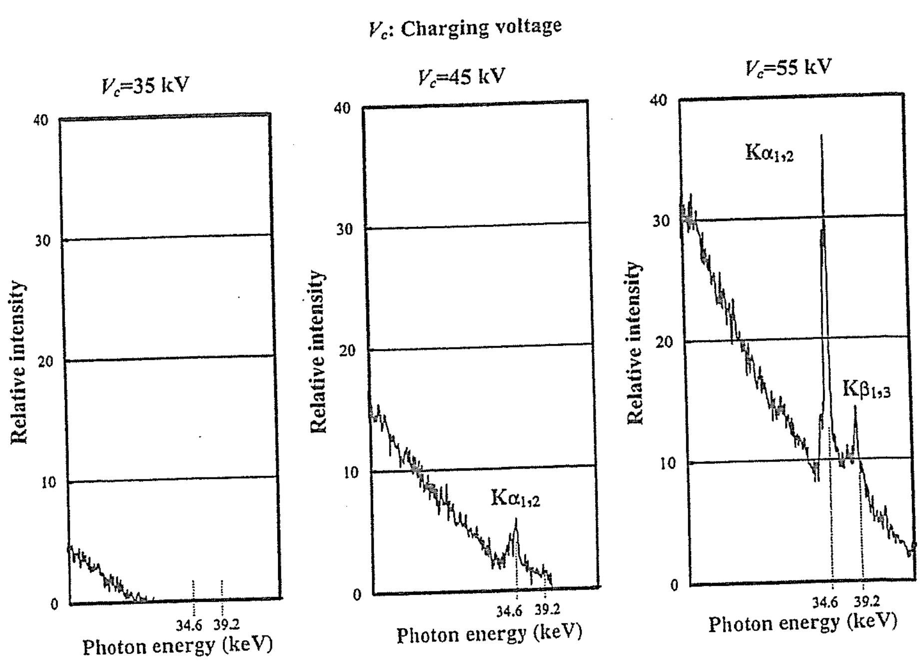

Fig. 7 X-ray spectra from weakly ionized cerium plasma.

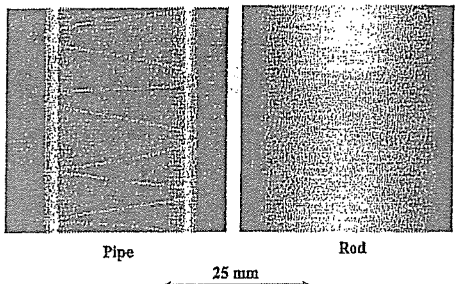

Fig. 8 Radiograms of tungsten wires of 50 μm in diameter coiled around pipe and rod made of PMMA.

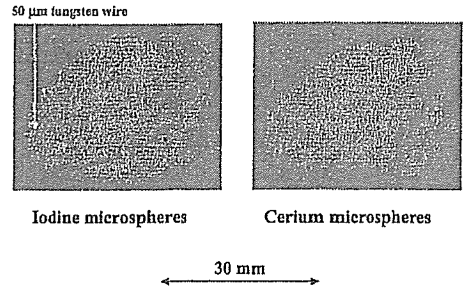

Fig. 10 Angiograms of rabbit hearts using iodine and cerium microspheres.

4.4 *X-Ray Spectra*

X-ray spectra from the plasma source were measured by a transmission-type spectrometer with a lithium fluoride curved crystal of 0.5 mm in thickness. The spectra were taken by a computed radiography (CR) system[25] (Konica Regius 150) having a wide dynamic range, and relative x-ray intensity was calculated from Dicom digital data. Figure 7 shows measured spectra from the cerium target. In this experiment, although we observed both the bremsstrahlung and characteristic x-rays, we could not observe characteristic x-rays with a charging voltage of 35 kV, because the critical excitation energy is 40.3 keV. Both intensities increased substantially with increases in the charging voltage.

5 Angiography

The plasma angiography was performed by the CR system without using a monochromatic filter, and the distance between the x-ray source and the imaging plate was 1.2 m. Subsequently, in angiography testing, we usually employ nonliving animal phantoms using microspheres.

First, rough measurements of image resolution were made using wires. Figure 8 shows radiograms of 50-μm-diam tungsten wires coiled around a pipe, and a rod made of polymethyl methacrylate (PMMA) with a charging voltage of 55 kV. Although the image contrast increased using the pipe, 50-μm-diam wires 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 a charging voltage of 55 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.

Angiograms of rabbit hearts are shown in Fig. 10. These two images were obtained using iodine and cerium microspheres of 15 μm, respectively, with a charging voltage of 55 kV. In cases where the cerium spheres were employed, the coronary arteries were barely visible. Figure 11 shows an angiogram of the external ear of a rabbit using iodine spheres with a charging voltage of 55 kV, and fine blood vessels of about 50 μm are visible. In angiography of a larger heart extracted from a dog, using iodine spheres, a PMMA plate was set in front of a heart facing x-ray source, and image contrast of coronary arteries improved with increases in the plate thickness (Fig. 12).

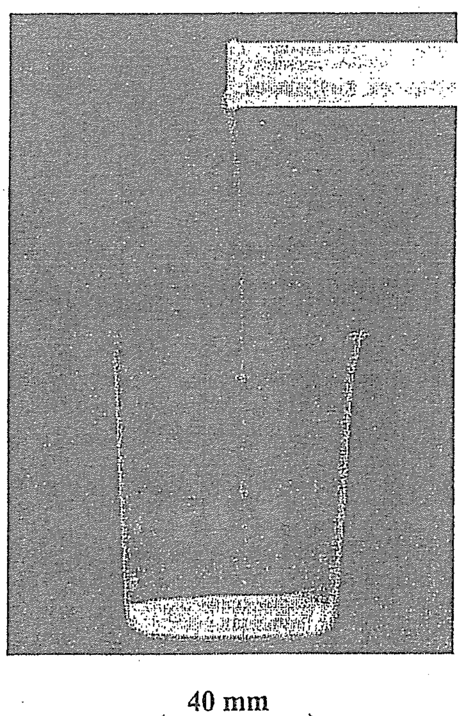

Fig. 9 Radiogram of water falling into a polypropylene beaker from a glass test tube.

6 Discussion

In an earlier experiment using a copper target,[24] bremsstrahlung x-rays were hardly observed at all, and we confirmed the irradiation of fairly clean K-series characteristic x-rays such as lasers. In the present work, although we confirmed intense characteristic x-rays with a higher charging voltage, bremsstrahlung x-rays were detected, since the bremsstrahlung intensity is proportional to the atomic num-

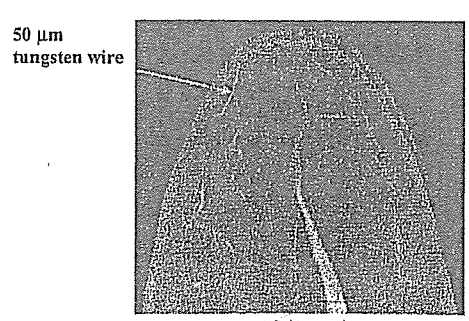

Fig. 11 Angiograms of external ear of rabbit.

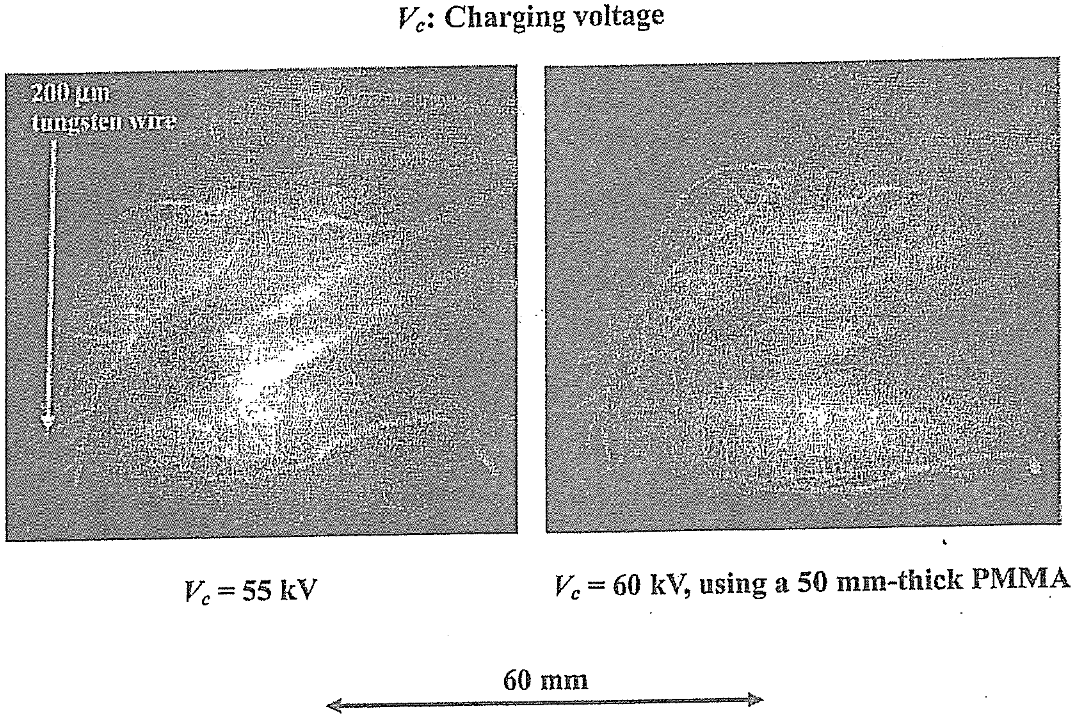

Fig. 12 Angiograms of extracted heart of dog.

ber of the target element, and high-photon-energy bremsstrahlung x-rays are not absorbed effectively in the plasma. Therefore, the condenser charging voltage should be raised as high as possible to increase the characteristic x-ray intensity. To decrease emission of bremsstrahlung x-rays from the carbon target holder, the target length should also be set as long as possible. Next, since the spheres easily transmit bremsstrahlung x-rays with energies lower than the edge, it is important that the rays be absorbed as much as possible before angiography to increase the image contrast.

In this research, we obtained sufficient x-ray intensity per pulse for CR radiography, and the generator produced high-dose-rate plasma x-rays of approximately 80 C/kg·s at 1.0 m with a charging voltage of 55 kV. In addition, because the x-ray intensity increases with increases in the electrostatic energy in the main discharge condenser, the flash x-rays from weakly ionized linear cerium plasma can be employed to perform high-speed angiography for cardiovascular disease.

Acknowledgments

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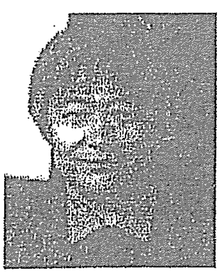

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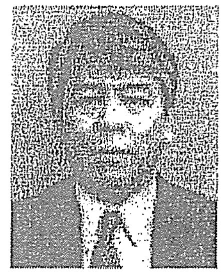

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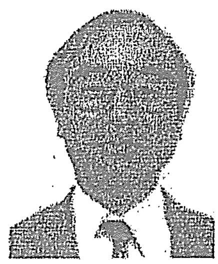

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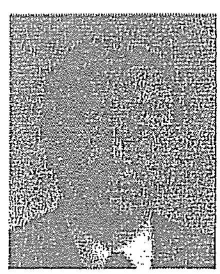

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Enhanced magnification angiography including phase-contrast effect using a 100-μm focus x-ray tube

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ABSTRACT

A microfocus x-ray tube is useful in order to perform magnification digital radiography including phase-contrast effect. The 100-μm-focus x-ray generator consists of a main controller for regulating the tube voltage and current and a tube unit with a high-voltage circuit and a fixed anode x-ray tube. The maximum tube voltage, current, and electric power were 105 kV, 0.5 mA, and 50 W, respectively. Using a 3-mm-thick aluminum filter, the x-ray intensity was 26.0 μGy/s at 1.0 m from the source with a tube voltage of 60 kV and a current of 0.50 mA. Because the peak photon energy was approximately 38 keV using the filter with a tube voltage of 60 kV, the bremsstrahlung x-rays were absorbed effectively by iodine-based contrast media with an iodine K-edge of 33.2 keV. Magnification angiography including phase-contrast effect was performed by three-time magnification imaging with a computed radiography system using iodine-based microspheres 15 μm in diameter. In angiography of non-living animals, we observed fine blood vessels of approximately 100 μm with high contrasts.

Keywords: high-contrast angiography, magnification digital radiography, microfocus x-ray tube, energy-selective imaging, phase-contrast effect

1. INTRODUCTION

Conventional flash x-ray generators utilizing condensers are useful in order to perform high-speed radiography including biomedical applications, and several different generators have been developed.[1-7] In particular, plasma flash x-ray generators[8-10] have been employed to produce clean K-series characteristic x-rays, and we have confirmed the irradiation of higher harmonic hard x-rays of Kα and Kβ lines. Without forming plasmas, demountable flash x-ray tubes can be employed to perform fundamental study on producing monochromatic x-rays,[11,12] and have succeeded in producing clean characteristic x-rays using angle dependence of bremsstrahlung x-ray distribution in Sommerfeld's theory. However, monochromatic flash radiography has had difficulties in increasing x-ray duration, and in performing magnification

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radiography including phase-contrast effect.

Synchrotrons are capable of producing high-dose-rate monochromatic parallel x-ray beams using a monochrocollimator, and the beams have been applied to phase-contrast radiography[13,14] and enhanced K-edge angiography.[15,16] In angiography, monochromatic x-rays with photon energies approximately 35 keV have been employed because the rays are absorbed effectively by iodine-based contrast media with an iodine K edge of 33.2 keV.

Without using synchrotrons, phase-contrast radiography for edge enhancement can be performed using a microfocus x-ray tube, and the enhancement have been applied in mammography achieved with a computed radiography (CR) system[17] using a 100-μm-focus molybdenum tube.[18] Subsequently, we have developed a cerium x-ray generator[19,20] to perform enhanced K-edge angiography using cone beams, and have succeeded in observing fine blood vessels and coronary arteries with high contrasts using cerium Kα rays of 34.6 keV. However, it is difficult to design the small focus cerium tube for angiography.

The magnification radiography is useful in order to improve the spatial resolution in digital radiography, and the phase contrast may come into effect in edge enhancement of comparatively large objects including thick blood vessels filled with low-density contrast media. Therefore, narrow photon energy bremsstrahlung x-rays with a peak energy of approximately 35 keV from a microfocus tungsten tube are useful to perform high-contrast high-resolution angiography. In the present research, we employed a 100-μm-focus tungsten tube, and performed enhanced magnification angiography including phase-contrast effect by controlling bremsstrahlung x-ray spectra using an aluminum filter.

2. PRINCIPLE OF ENHANCED 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 effective bremsstrahlung x-ray spectra for K-edge angiography are shown above the iodine K-edge. Because iodine contrast media with a K-absorption edge of 33.2 keV absorb the rays easily, blood vessels were observed with high contrasts.

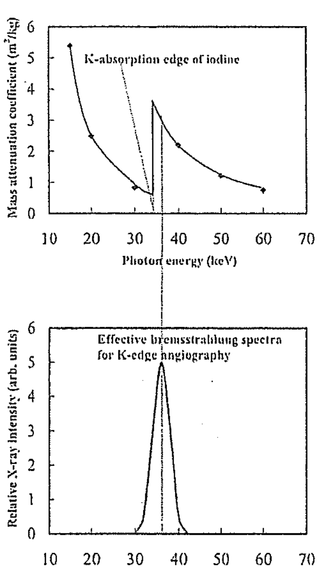

Figure 1: Mass attenuation coefficients of iodine and effective bremsstrahlung x-rays for enhanced K-edge angiography.

3. EXPERIMENTAL SETUP

Figure 2 shows the block diagram of a microfocus x-ray generator used in this experiment, and the generator consists of a main controller, an x-ray tube unit with a Cockcroft-Walton circuit, an insulation transfprmer, and a 100-μm-focus x-ray tube. The tube voltage, the current, and the exposure time can be controlled by the controlle. The main circuit for producing x-rays is illustrated in Fig. 3, and employed the Cockcroft-Walton circuit in order to decrease the dimensions of the tube unit. In the x-ray tube, the positive and negative high voltages are applied to the anode and cathode electrodes, respectively. The filament heating current is supplied by an AC power supply in the controller in conjunction with an insulation transformer which is used for isolation from the high voltage from the Cockcroft-Walton circuit. In this experiment, the tube voltage applied was from 45 to 70 kV, and the tube current was regulated to within 0.50 mA (maximum current) by the filament temperature. The exposure time is controlled in order to obtain optimum x-ray intensity, and narrow-photon-energy bremsstrahlung x-rays are produced using a 3.0-mm-thick aluminum filter for absorbing soft x-rays.

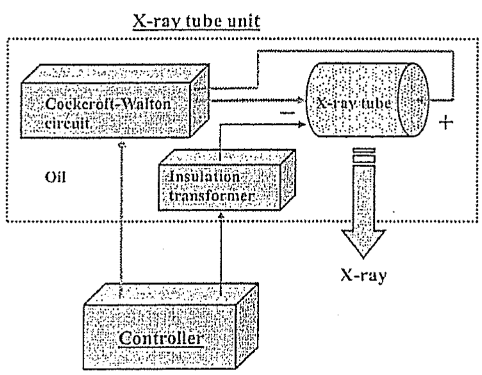

Figure 2: Block diagram of the x-ray generator.

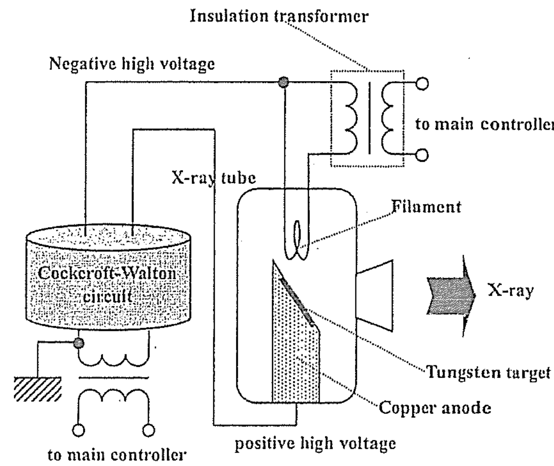

Figure 3: Electric circuit of the x-ray generator.

4 RESULTS

4.1 *X-ray intensity*

The x-ray intensity was measured by a Victoreen 660 ionization chamber at 1.0 m from the x-ray source using the filter (Fig. 4). At a constant tube current of 0.50 mA, the x-ray intensity increased when the tube voltage was increased. At a tube voltage of 60 kV, the intensity with the filter was 26.0 μGy/s.

4.2 *X-ray spectra*

In order to measure x-ray spectra, we employed a cadmium telluride detector (CDTE2020X, Hamamatsu Photonics K. K.) with a photon energy resolution of approximately 1.7 keV (Fig. 5). When the tube voltage was increased, the bremsstrahlung x-ray intensity increased, and both the maximum photon energy and the spectrum peak energy increased.

In order to perform K-edge angiography, bremsstrahlung x-rays of approximately 35 keV are useful, and the high-energy bremsstrahlung x-rays decrease the image contrast. Using this filter, because bremsstrahlung x-rays with energies higher than 60 keV were not absorbed easily, the tube voltage for angiography was determined as 60 kV.

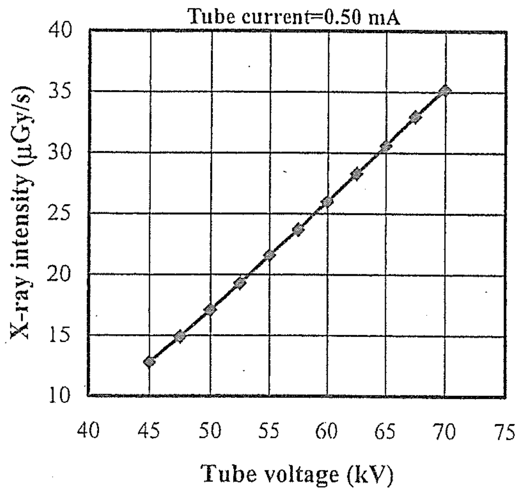

Figure 4: X-ray intensity (μGy/s) as a function of tube voltage (kV) with a tube current of 0.50 mA.

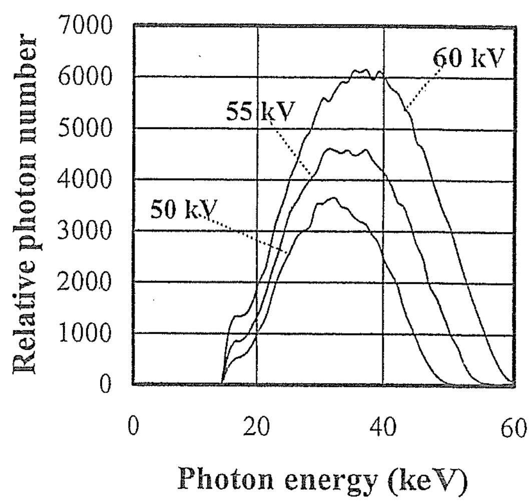

Figure 5. Bremsstrahlung x-ray spectra measured using a cadmium telluride detector with changes in the tube voltage.

4.3 *Magnification radiography*

The magnification radiography was performed by three-time magnification imaging using the CR system and the filter at a tube voltage of 60 kV, and the distance (between the x-ray source and the imaging plate) was 1.5 m (Fig. 6). Firstly, the spatial resolutions of conventional (cohesion) and magnification radiographies were made using a lead test chart. In the magnification radiography, 50 μm lines (10 line pairs) were clearly visible (Fig. 7). Subsequently, Fig. 8 shows radiograms of tungsten wires coiled around rods 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. Radiograms of one set of a bolt and a nut are shown in Fig. 9, the edge of a bubble in the bolt and the seam between the bolt and the nut are visible in magnification radiography.

4.4 *Enhanced magnification angiography*

The magnification angiography was performed at the same conditions using iodine microspheres of 15 μm in diameter, and the microspheres (containing 37% iodine by weight) are very useful for making phantoms of non-living animals used for angiography. Angiogram of a rabbit heart is shown in Fig. 10, and the coronary arteries are visible. Figure 11 shows angiograms of a larger dog heart using iodine spheres. Although the image contrast decreased slightly with increases in the thickness of the PMMA plate facing the x-ray source, the coronary arteries of approximately 100 μm were observed using a 100-mm-thick plate.

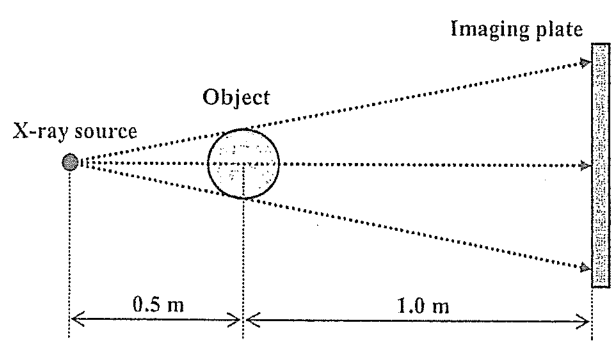

Figure 6. Three-time magnification imaging using an imaging plate in conjunction with a microfocus tube.

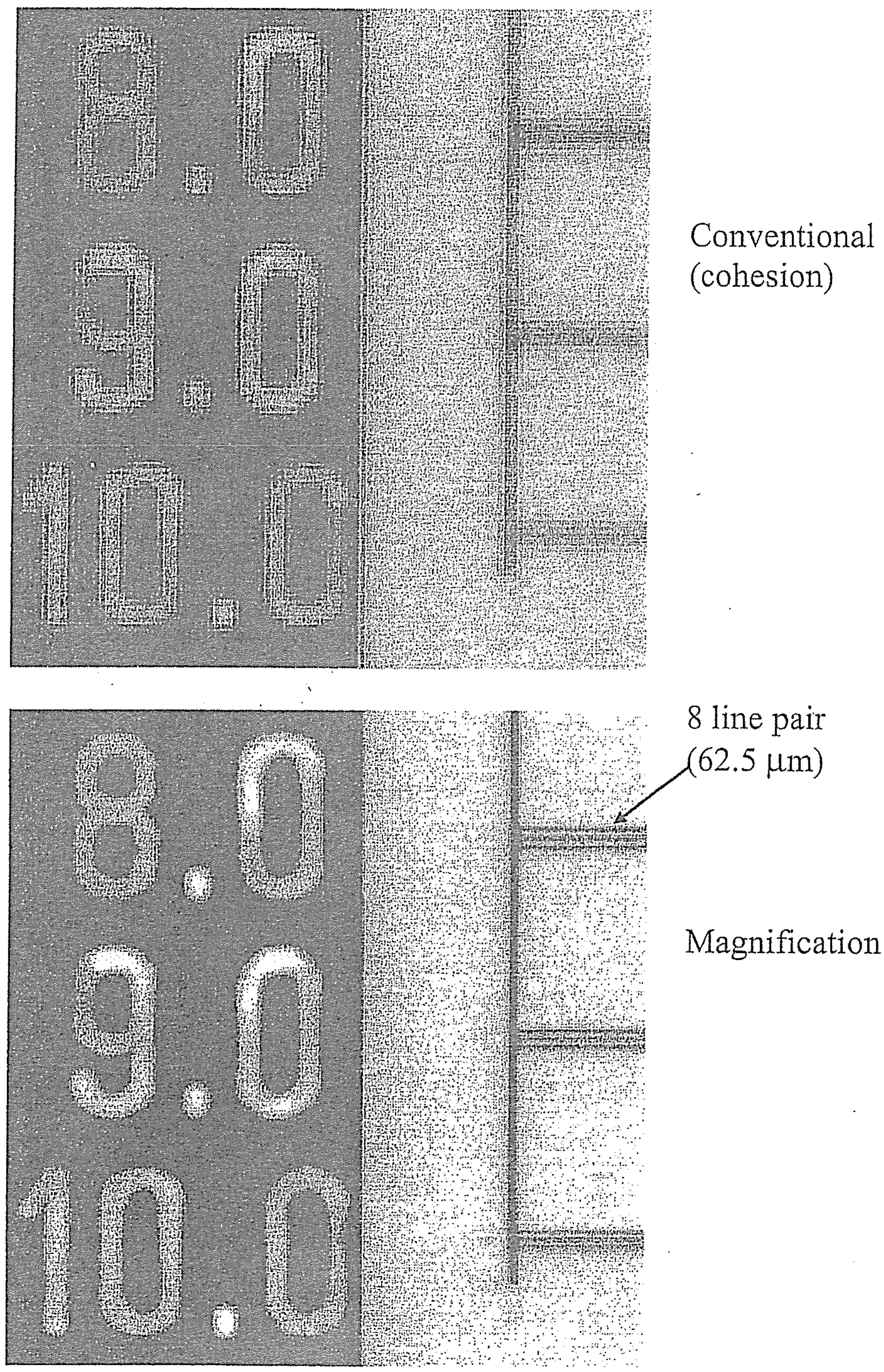

Figure 7. Radiogram of a test chart for measuring the spatial resolution.