6. DISCUSSION AND CONCLUSIONS

In summary, we succeeded in producing K-series characteristic x rays of tantalum 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. Although we employed tantalum Kα (57.1 keV) and Kβ (approximately 65 keV) rays, Kβ rays should be absorbed using an ytterbium oxide filter with an ytterbium K edge of 61.3 keV in order to increase the image contrast of blood vessels.

To perform K-edge angiography using gadolinium media, although an ytterbium target with a Kα energy of 52.0 keV is useful, the ytterbium has a high reactivity. If we assume that the ytterbium is employed, an alloy target should be developed. In this research, we obtained sufficient x-ray intensity per pulse for angiography, and the intensity can be increased by increasing the electrostatic energies in the high-voltage condenser. At a condenser capacity of 150 nF, the generator produced instantaneous number of K photons was approximately 1×10^9 photons/cm^2 per pulse at 1.0 m from the source.

In the flash x-ray tube, bremsstrahlung x rays with energies higher than the K-edge are absorbed effectively by the weakly ionized plasma and are converted into fluorescent (characteristic) x rays. In conjunction with this property, because the bremsstrahlung x rays are not emitted in the opposite direction to that of electron acceleration, clean characteristic x rays are produced. Using this flash x-ray generator, with which the photon energy of characteristic x rays can be selected, quasi-monochromatic imaging such as enhanced K-edge angiography using iodine contrast media and mammography can be performed.

ACKNOWLEDGMENT

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*dresato@iwate-med.ac.jp; phone +81-19-651-5111; fax +81-19-654-9282

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

Eiichi Sato, MEMBER SPIE
Iwate Medical University
Department of Physics
Morioka 020-0015, Japan
E-mail: dresato@iwate-med.ac.jp

Etsuro Tanaka
Tokyo University of Agriculture
Department of Nutritional Science
Faculty of Applied Bioscience
Setagaya-ku 156-8502, Japan

Hidezo Mori
National Cardiovascular Center Research Institute
Department of Cardiac Physiology
Osaka 565-8565, Japan

Toshiaki Kawai, MEMBER SPIE
Hamamatsu Photonics Incorporated
Electron Tube Division #2
Iwata-gun 438-0193, Japan

Shigehiro Sato
Iwate Medical University
Department of Microbiology
School of Medicine
Morioka 020-8505, Japan

Kazuyoshi Takayama, MEMBER SPIE
Tohoku University
Shock Wave Research Center
Institute of Fluid Science
Sendai 980-8577, Japan

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 were about 500 ns, and the time-integrated x-ray intensity had 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.

2 Principle of K-Edge Angiography

Figure 1 shows the mass attenuation coefficients of iodine at the selected energies; the coefficient curve is discontinu-

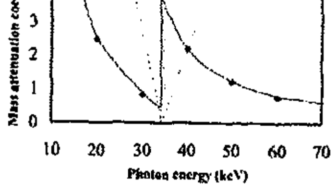


Fig. 1 Relation between mass attenuation coefficient of iodine and average photon energy of cerium Kα lines.

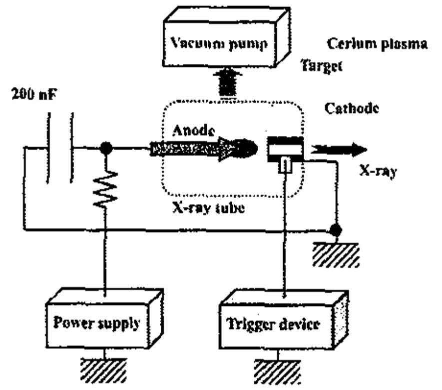


Fig. 2 *Block diagram of high intensity plasma flash x-ray generator.*

ous 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.

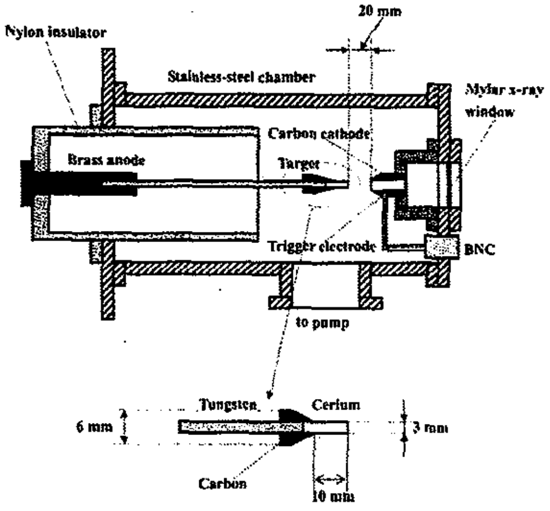
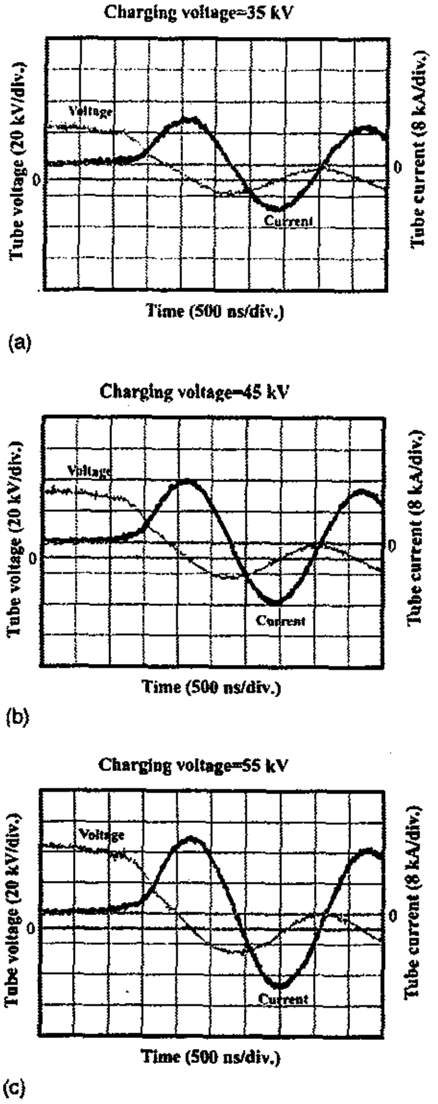


Fig. 3 Schematic drawing of flash x-ray tube.



(a)

(b)

(c)

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 set in the cathode electrode. As electron beams from the cathode electrode are roughly converged to the target by an

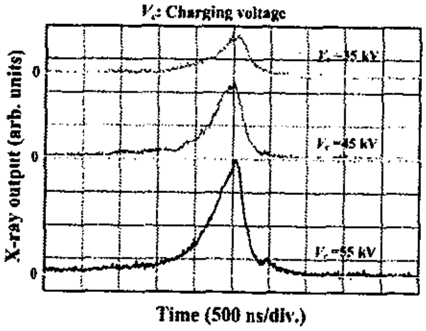


Fig. 5 X-ray outputs at indicated conditions.

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.

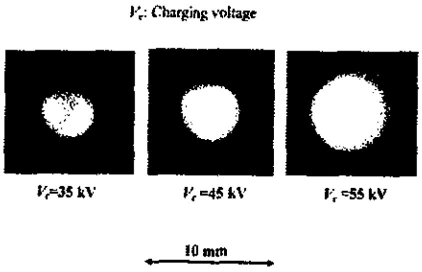


Fig. 6 Images of plasma x-ray source.

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.

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

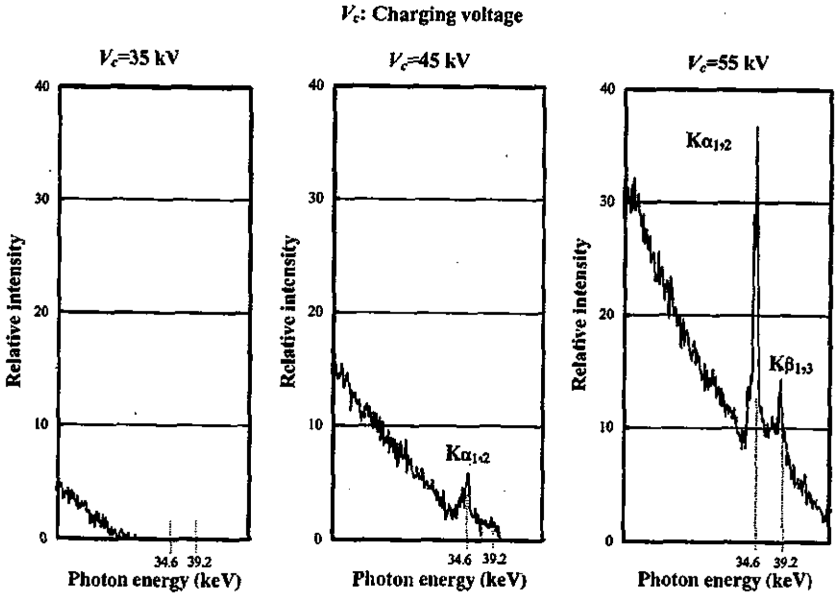


Fig. 7 X-ray spectra from weakly ionized cerium plasma.

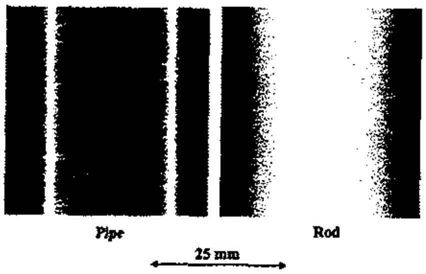


Fig. 8 Radiograms of tungsten wires of 50 μm in diameter coiled around pipe and rod made of PMMA.

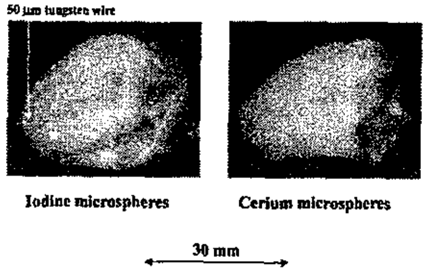


Fig. 10 *Angiograms of rabbit hearts using iodine and cerium microspheres.*

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.

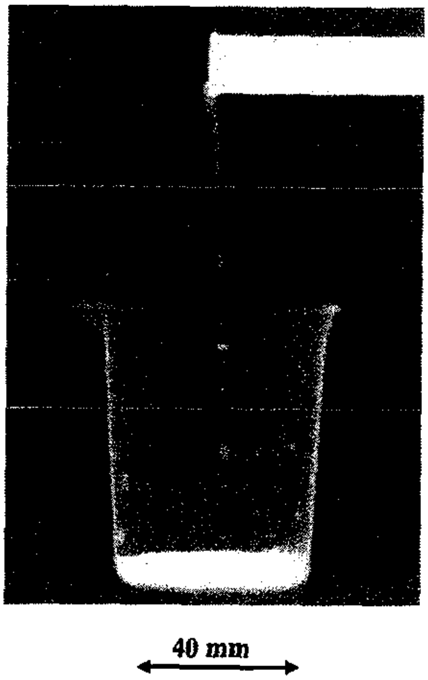


Fig. 9 *Radiogram of water falling into a polypropylene beaker from a glass test tube.*

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).

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 number 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

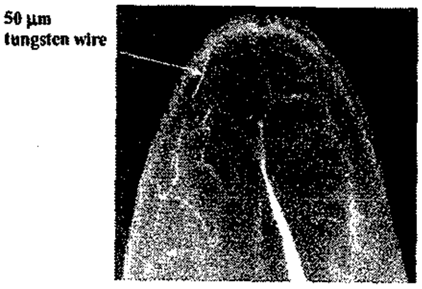


Fig. 11 Angiograms of external ear of rabbit.

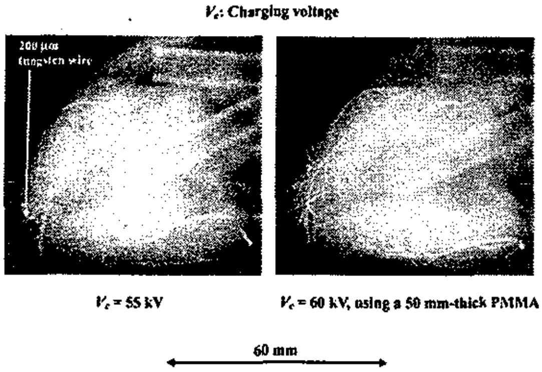


Fig. 12 Angiograms of extracted heart of dog.

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

Eiichi Sato, MEMBER SPIE
Iwate Medical University
Department of Physics
Morioka 020-0015, Japan
E-mail: dresato@iwate-med.ac.jp

Etsuro Tanaka
Tokyo University of Agriculture
Department of Nutritional Science
Faculty of Applied Bioscience
Setagaya-ku 156-8502, Japan

Hidezo Mori
National Cardiovascular Center Research Institute
Department of Cardiac Physiology
Osaka 565-8565, Japan

Toshiaki Kawai, MEMBER SPIE
Hamamatsu Photonics Incorporated
Electron Tube Division #2
Iwata-gun 438-0193, Japan

Shigehiro Sato
Iwate Medical University
Department of Microbiology
School of Medicine
Morioka 020-8505, Japan

Kazuyoshi Takayama, MEMBER SPIE
Tohoku University
Shock Wave Research Center
Institute of Fluid Science
Sendai 980-8577, Japan

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 Kα 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 Kα intensities substantially increase. The Kα 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. *© 2005 Society of Photo-Optical Instrumentation Engineers.* [DOI: 10.1117/1.1882373]

Subject terms: flash x-ray; weakly ionized linear plasma; copper target; Kα 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,[4–8] high-intensity single generators with large capacity condensers were originally developed. Subsequently, repetitive generators[9–12] 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.

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 sharp quasimonochromatic 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 generator as a trigger device, and a flash x-ray tube. In this generator, a low-impedance transmission line (Fig. 2) is

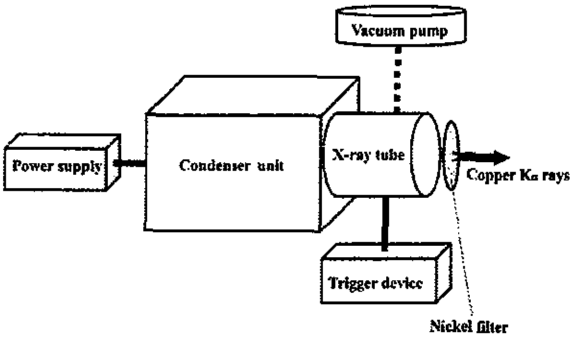

Fig. 1 Block diagram of high-intensity plasma flash x-ray generator.

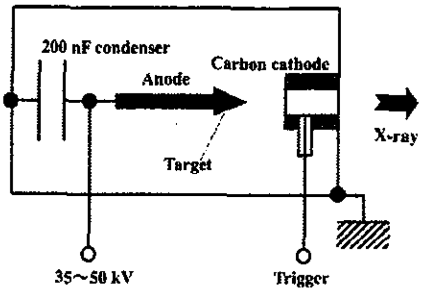

Fig. 2 Circuit diagram of generator.

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. Subsequently, Kβ rays (8.90 keV) are absorbed effectively us-

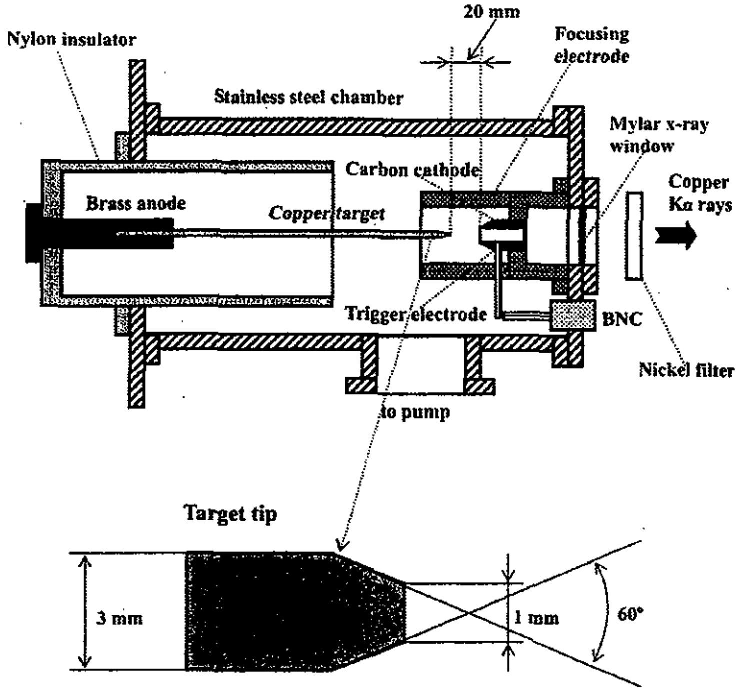

Fig. 3 Schematic drawing of flash x-ray tube with rod target.

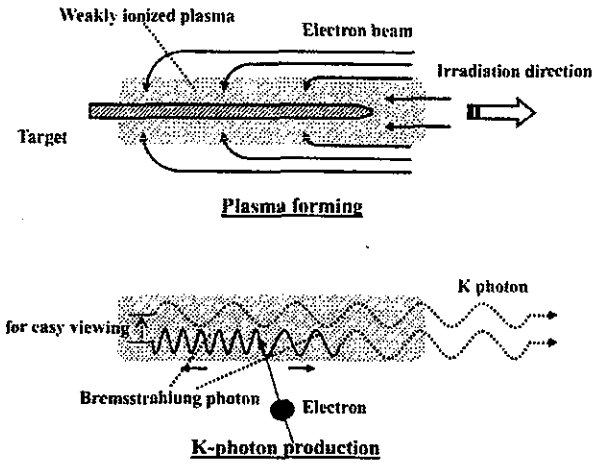

Fig. 4 K-photon irradiation from weakly ionized plasma.

ing a 10-μm-thick nickel K-edge filter with an edge of 8.33 keV, and quite clean Kα 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 Kα 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.

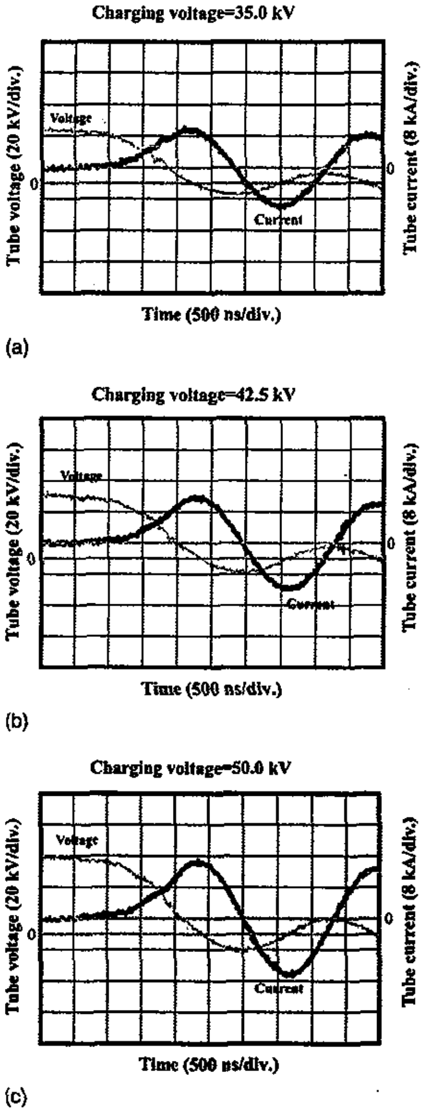

Fig. 5 Tube voltages and currents with charging voltage of (a) 35.0 kV, (b) 42.5 kV, and (c) 50.0 kV.

3.4 *X-Ray Spectra*

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

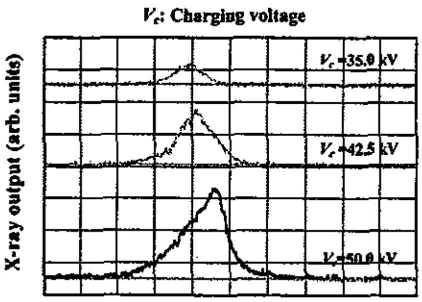

Fig. 6 X-ray outputs measured by plastic scintillator with changes in charging voltage.

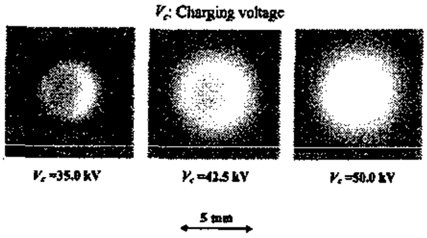

Fig. 7 Images of Kα x-ray source measured by pinhole of 100 μm from plasma axial direction.

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.

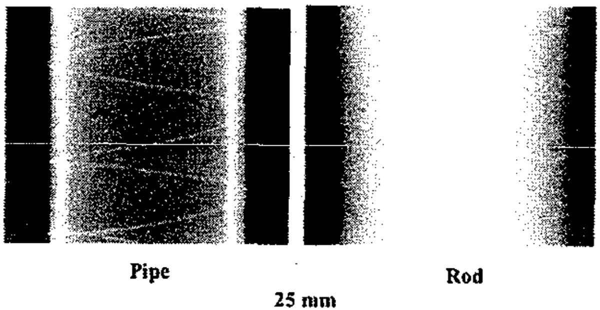

Fig. 9 Radiograms of tungsten wires 50 μm in diameter coiled around pipe, and rod made of polymethyl methacrylate.

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

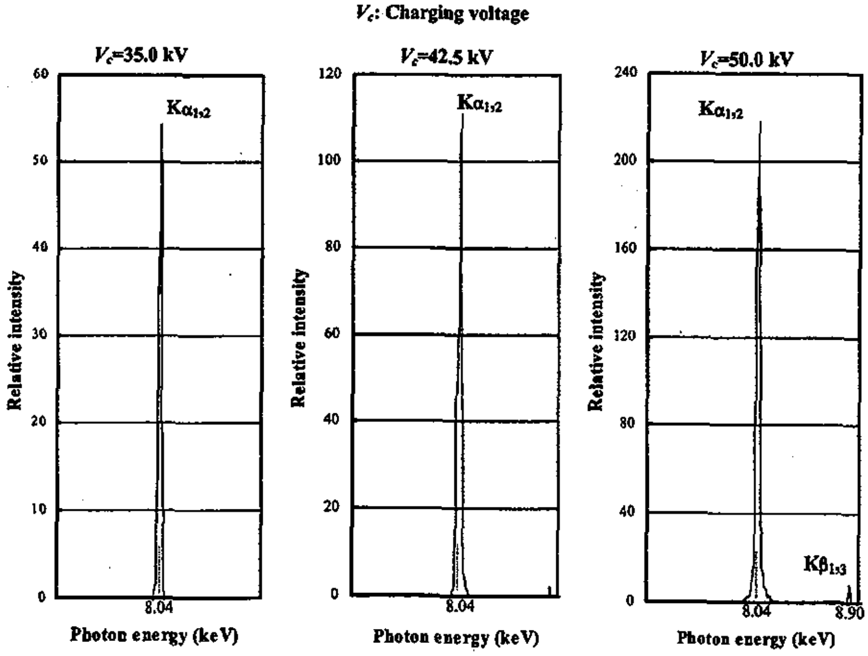

Fig. 8 X-ray spectra from weakly ionized copper plasma according to changes in charging voltage and to insertion of nickel K-edge filter.

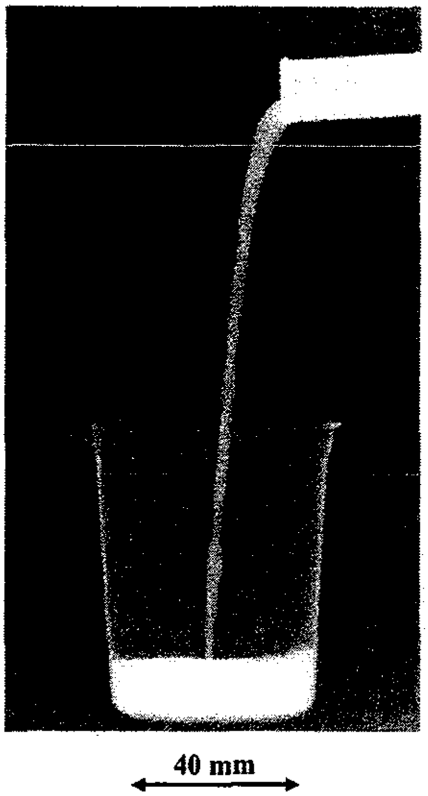

Fig. 10 Radiogram of water falling into polypropylene beaker from glass test tube.

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 high 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.

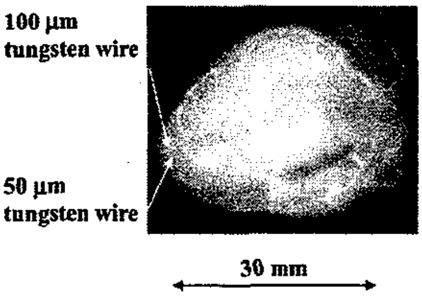

Fig. 11 Angiograms of rabbit heart.

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Cerium x-ray spectra without filtering and their application to high-contrast angiography

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Eiichi Sato[a], Akira Yamadera[b], Michiaki Sagae[a], Toshio Ichimaru[b], Norihiko Morino[b],
Motoki Ikeda[b], Chie Sasaki[b], Etsuro Tanaka[c], Hidezo Mori[d], Toshiaki Kawai[e],
Fumihito Ito[f], Shigehiro Sato[g], Kazuyoshi Takayama[h] and Hideaki Ido[i]

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Abstract

The cerium-target x-ray tube is useful in order to perform cone-beam K-edge angiography because K-series characteristic x rays from the cerium target are absorbed effectively by iodine-based contrast media. The x-ray generator consists of a main controller, an x-ray tube unit with a high-voltage circuit and an insulation transformer, and a personal computer. The tube is a glass-enclosed diode with a cerium target and a 0.5-mm-thick beryllium window. The maximum tube voltage and current were 65 kV and 0.4 mA, respectively, and the focal-spot sizes were 1.2×0.8 mm. Sharp cerium K-series characteristic x rays were observed without using a filter, and the x-ray intensity was 209 μGy/s at 1.0 m from the source with a tube voltage of 60 kV and a current of 0.40 mA. Angiography was performed 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: x-ray tube, cerium target, x-ray spectra, characteristic x rays, K-edge angiography, energy-selective radiography

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[a] Department of Physics, Iwate Medical University, 3-16-1 Honchodori, Morioka 020-0015, Japan
[b] Department of Radiological Technology, School of Health Sciences, Hirosaki University, 66-1 Honcho, Hirosaki 036-8564, Japan
[c] Department of Nutritional Science, Faculty of Applied Bio-science, Tokyo University of Agriculture, 1-1-1 Sakuragaoka, Setagaya-ku 156-8502, Japan
[d] Department of Cardiac Physiology, National Cardiovascular Center Research Institute, 5-7-1 Fujishirodai, Suita, Osaka 565-8565, Japan
[e] Electron Tube Division #2, Hamamatsu Photonics K. K., 314-5 Shimokanzo, Toyooka Village, Iwata-gun 438-0193, Japan
[f] Digital Culutre Technology Corp., Kanno The 2nd Bldg., 3-17-7 Chuodori, Morioka 020-0021, Japan
[g] Department of Microbiology, School of Medicine, Iwate Medical University, 19-1 Uchimaru, Morioka 020-8505, Japan
[h] Shock Wave Research Center, Institute of Fluid Science, Tohoku University, 2-1-1 Katahira, Sendai 980-8577, Japan
[i] Department of Applied Physics and Informatics, Faculty of Engineering, Tohoku Gakuin University, 1-13-1 Chuo, Tagajo 985-8537, Japan

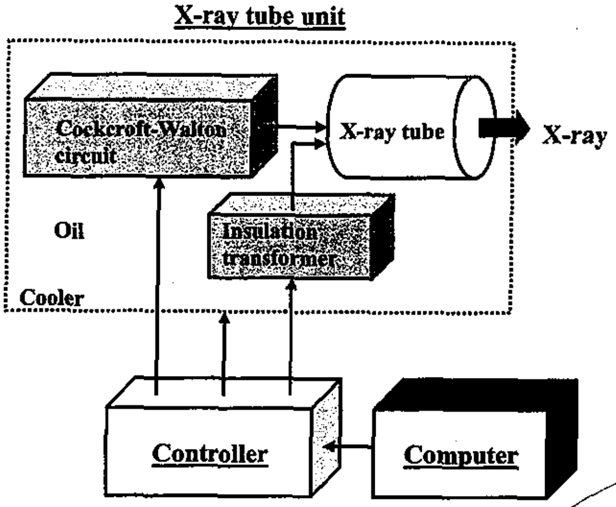

Fig. 1: Block diagram of compact x-ray generator with cerium-target radiation tube, which is used specially for K-edge angiography using iodine-based contrast media.

1. Introduction

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The principle basis of quality assurance for enhanced K-edge angiography is ~~based on~~ the discontinuity of the absorption coefficient at the K-absorption edge of iodine-based contrast media, and ~~the~~ angiography has been performed using monochromatic parallel x-ray beams with synchrotrons.[1-3] Subsequently, monochromatic x-ray computed tomography at two different energies has provided information on the electron density of human tissue.[4] In addition, a compact pulsed tunable monochromatic x-ray source has been designed, developed, and tested.[5] From the source, conical x-ray beams from 10 to 50 keV with pulse widths of 8 ps have been produced, and these beams are useful ~~for~~ biomedical imaging and protein crystallography.

In order to perform high-speed medical radiography, although several different flash x-ray generators[6-10] utilizing cold-cathode tubes have been developed, plasma flash x-ray generators[11-14] are useful to produce quasi-monochromatic x rays without using a K-edge filter. Therefore, we have performed a demonstration of cone-beam K-edge angiography[10] utilizing a cerium plasma generator, since K-series characteristic x rays from the cerium target are absorbed effectively by iodine.

Recently, we have developed a steady-state x-ray generator utilizing a cerium-target tube, and have demonstrated enhanced K-edge angiography utilizing a barium sulfate filter.[15] In this research, Kα lines (34.6 keV) were left by absorbing Kβ lines (39.2 keV), and bremsstrahlung x rays with photon energies of lower than the barium K-edge (37.4 keV) were also observed. However, because cerium Kβ lines are also absorbed effectively by iodine, both Kα and Kβ lines should be selected to perform angiography. In measurements of x-ray spectra, although we usually employed a cadmium tellurium detector with a photon energy resolution of 1.7 keV, the resolution should be improved as much as possible to measure the characteristic x-ray intensity.

In the present research, we measured the x-ray spectra from a cerium-target tube using a germanium detector, and performed a preliminary study on cone-beam K-edge angiography achieved with cerium characteristic x rays without using a filter.

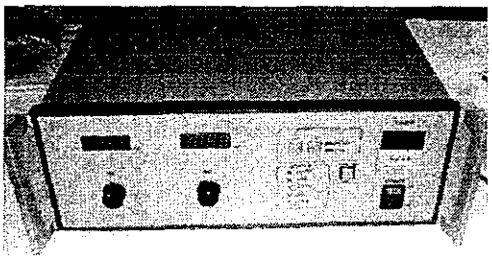

Fig. 2: Main controller.

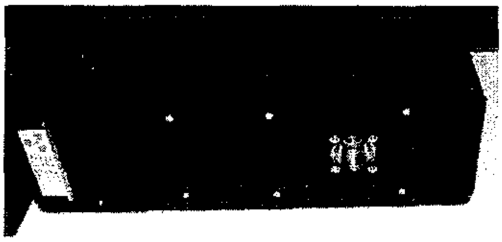

Fig. 3: X-ray tube unit.

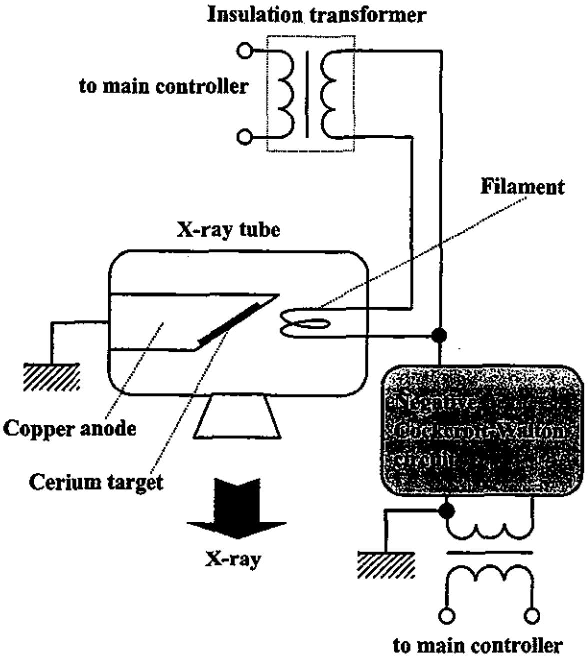

Fig. 4: Main circuit of x-ray generator.

2. Generator

Figure 1 shows the block diagram of the x-ray generator, which consists of a main controller (Fig. 2), a cerium-target x-ray tube unit (Fig. 3) with a Cockcroft-Walton circuit and an insulation transformer, and a personal computer. The tube voltage, the current, and the exposure time can be controlled by both the controller and the computer. The main circuit for producing x rays is illustrated in Fig. 4, and employs the Cockcroft-Walton circuit in order to decrease the dimensions of the tube unit. In the x-ray tube, the negative high-voltage is applied to the cathode electrode, and the anode (target) is connected to the tube unit case (ground potential) to cool the anode and the target effectively. The filament heating current is supplied by an AC power supply in the controller in conjunction with an insulation transformer. In this experiment, the tube voltage applied was from 45 to 65 kV, and the tube current was regulated to within 0.40 mA (maximum current) by the filament temperature. The exposure time is controlled in order to obtain optimum x-ray intensity.

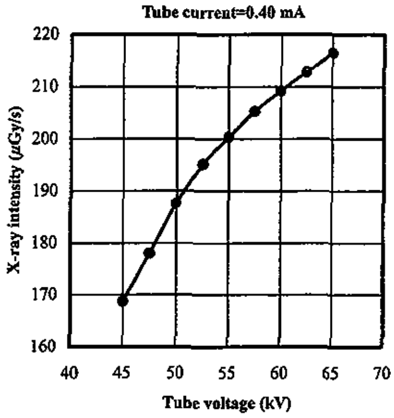

Fig. 5: X-ray intensity measured at 1.0 m from x-ray source according to changes in tube voltage.

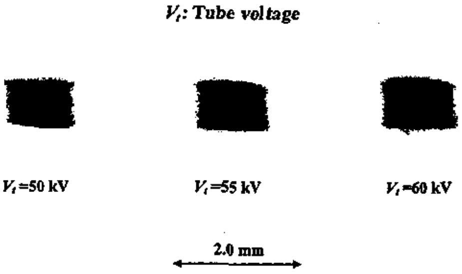

Fig. 6: Effective focal spots with changes in tube voltage.

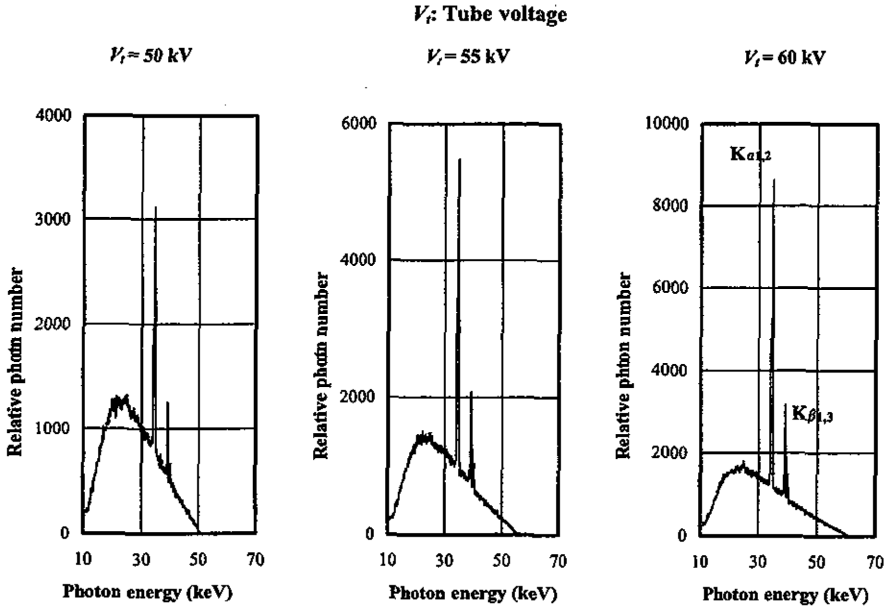

Fig. 7: X-ray spectra measured using germanium detector.

3. Characteristics

3.1 X-ray intensity

The x-ray intensity rate was measured by a Victoreen 660 ionization chamber at 1.0 m from the x-ray source (Fig. 5). At a constant tube current of 0.40 mA, the x-ray intensity increased when the tube voltage was increased. In this measurement, the intensity with a tube voltage of 60 kV and a current of 0.40 mA was 209 μGy/s with errors of less than 0.2%.

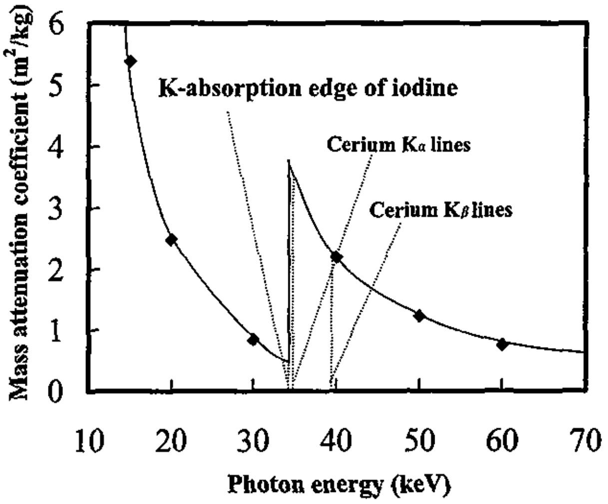

Fig. 8: Mass attenuation coefficients of iodine, and average photon energies of cerium Kα and Kβ lines.

3.2 Focal spot

In order to measure images of the x-ray source without filtration, we employed a pinhole camera with a hole diameter of 50 μm (magnification ratio of 1:2) in conjunction with a Computed Radiography (CR) system[16] with a sampling pitch of 87.5 μm. When the tube voltage was increased, spot dimensions increased slightly and had values of 1.2 × 0.8 mm (Fig. 6).

3.3 X-ray spectra

In order to measure x-ray spectra, we employed a germanium detector (GLP-10180/07-P, Ortec Inc.) (Fig. 7). When the tube voltage was increased, the characteristic x-ray intensities of Kα and Kβ lines substantially increased, and both the maximum photon energy and the intensities of bremsstrahlung x rays increased.

4. Angiography

Figure 8 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 and Kβ lines are shown just above the iodine K-edge. Cerium is a rare earth element and has a high reactivity; however, the average photon energies of Kα and Kβ lines are 34.6 and 39.2 keV, respectively, 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.

The angiography was performed by the CR system (Konica Regius 150) without using a filter, and the distance (between the x-ray source and the imaging plate) was 1.5 m. Firstly, rough measurements of spatial resolution were made using wires. Figure 9 shows radiograms of tungsten wires in a rod made of polymethyl methacrylate with a tube voltage of 55 kV. Although the image contrast decreased somewhat with decreases in the wire diameter, due to blurring of the image caused by the sampling

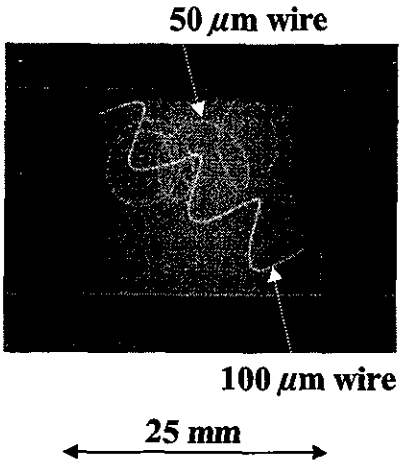

Fig. 9: Radiogram of tungsten wires in PMMA rod with tube voltage of 55 kV.

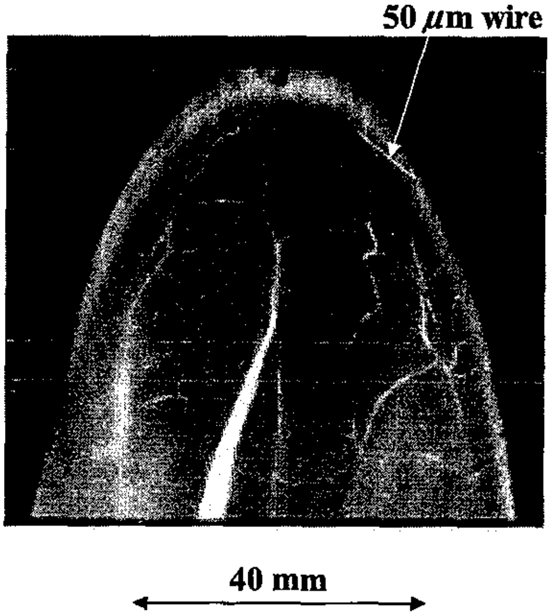

Fig. 10: Angiogram of rabbit ear with tube voltage of 50 kV.

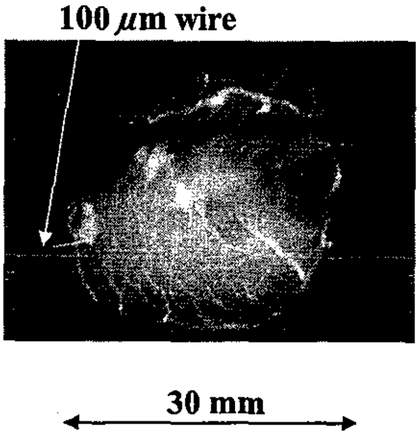

Fig. 11: Angiogram of extracted rabbit heart with tube voltage of 50 kV.

pitch of 87.5 μm, a 50 μm-diameter wire could be observed.

Figures 10 and 11 show angiograms of a rabbit ear and heart, respectively. These images were obtained using iodine microspheres of 15 μm in diameter at a tube voltage of 50 kV. Fine blood vessels in the ear and the coronary arteries in the heart were visible. Figure 12 shows an angiogram of a larger dog heart at a tube voltage of 60 kV using iodine spheres. For comparison, we show 3-dimensional image of the coronary arteries constructed from x-ray CT images by Pascal (Digital Culture Tech. Corp.) with a tungsten x-ray tube (Fig. 13). Using this imaging technique, fine blood vessels were not observed at all.