perform soft radiography including biomedical applications.[8-12]

In a former experiment, we performed a preliminary experiment of high-speed K-edge angiography using a cerium plasma x-ray generator,[13] which produced both characteristic and bremsstrahlung x rays. As compared with a steady state x-ray generator with a constant tube voltage, the effective x-ray photon energies are lower, since both the tube voltage and current display damped oscillations; the tube current increases with decreasing tube voltage. Therefore, the condenser charging voltage should be increased as much as possible to increase the cerium characteristic x-ray intensity.

In the present research, we improved a plasma x-ray generator[14-18] with a cerium-target tube, and used it to perform a preliminary study on angiography achieved with cerium K-series characteristic x rays.

2. PRINCIPLE OF K-EDGE ANGIOGRAPHY

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

3. GENERATOR

3.1 High-voltage circuit

Figure 2 shows a block diagram of a high-intensity plasma flash x-ray generator. The generator consists of the following essential components: a high-voltage power supply, a high-voltage condenser with a capacity of approximately 150 nF, an air gap switch, a turbomolecular pump, a thyratron pulse generator as a trigger device, and a flash x-ray tube. In this generator, a coaxial cable transmission line is employed in order to increase maximum tube voltage using high-voltage reflection. The high-voltage main condenser is charged up to 80 kV by the power supply, and electric charges in the condenser are discharged to the tube through the four cables after closing the gap switch with the trigger device.

3.2 X-ray tube

The x-ray tube is a demountable cold-cathode diode that is connected to the turbomolecular pump with a pressure of approximately 1 mPa (Fig. 3). This tube consists of the following major parts: a ring-shaped graphite cathode with an inside diameter of 4.5 mm, a stainless-steel vacuum chamber, a nylon insulator, a polyethylene terephthalate (Mylar) x-ray window 0.25 mm in thickness, and a rod-shaped cerium target 3.0 mm in diameter. The distance between the target and cathode electrodes can be regulated from the outside of the tube, and is set to 1.5 mm. As electron beams from the cathode electrode are roughly converged to the target by the electric field in the tube, evaporation leads to the formation of weakly ionized plasma, consisting of molybdenum ions and electrons, around the target. Because bremsstrahlung rays are not emitted in the opposite direction to that of electron acceleration (Fig. 4), cerium K-series characteristic x rays can be produced without using a filter.

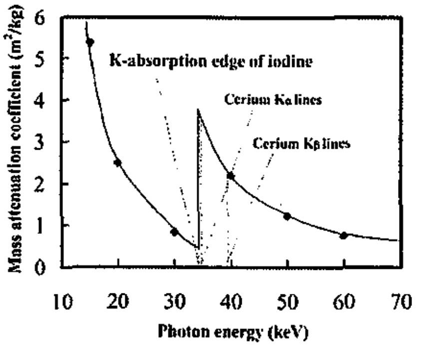

Figure 1: Relation between mass attenuation coefficient of iodine and average photon energies of cerium Kα and Kβ lines.

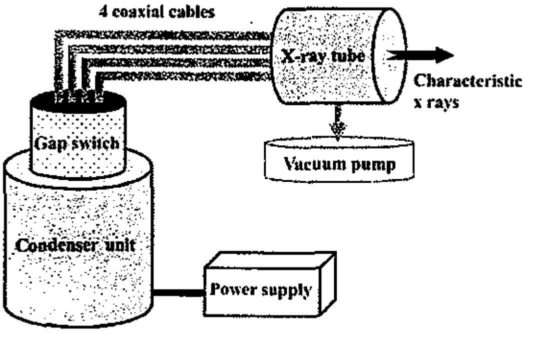

Figure 2: Block diagram of intense quasi-monochromatic flash x-ray generator.

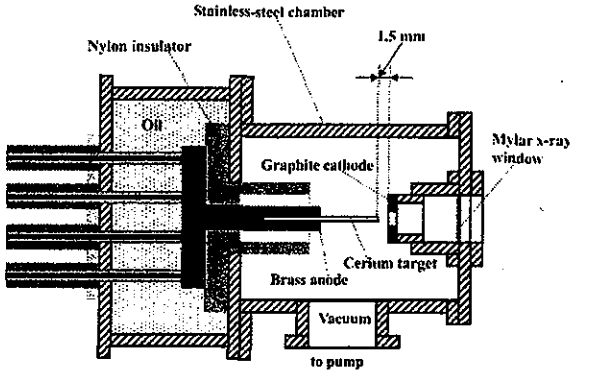

Figure 3: Schematic drawing of flash x-ray tube.

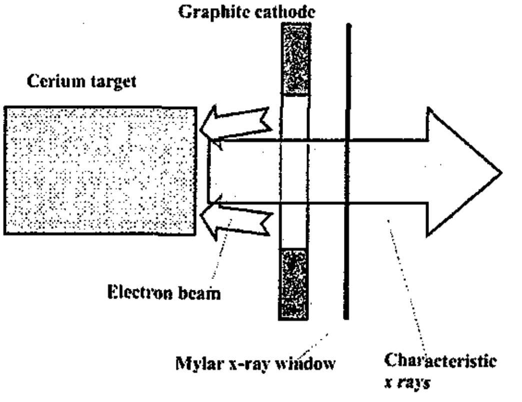

Figure 4: Irradiation of characteristic x rays.

4. CHARACTERISTICS

4.1 Tube voltage and current

In this generator, it was difficult to measure the tube voltage and current since the tube voltages were high, and there was no space to set a current transformer for measuring the tube current. Currently, the voltage and current roughly display damped oscillations. When the charging voltage was increased, both the maximum tube voltage and current increased. At a charging voltage of 80 kV, the estimated maximum values of the tube voltage and current were approximately 160 kV (2 times the charging voltage) and 40 kA, respectively.

4.2 X-ray output

X-ray output pulse was detected using a combination of a plastic scintillator and a photomultiplier (Fig. 5). The x-ray pulse height substantially increased with corresponding increases in the charging voltage. The x-ray pulse widths were approximately 100 ns, and the time-integrated x-ray intensity measured by a thermoluminescence dosimeter (Kyokko TLD Reader 1500 having MSO-S elements without energy compensation) had a value of approximately 10 μC/kg at 1.0 m from the x-ray source with a charging voltage of 80 kV.

4.3 X-ray source

In order to observe the Kα x-ray source, we employed a 100-μm-diameter pinhole camera and an x-ray film (Polaroid XR-7) (Fig. 6). When the charging voltage was increased, the plasma x-ray source grew, and both spot dimension and intensity increased. Because the x-ray intensity is the highest at the center of the spot, both the dimension and intensity decreased according to both increases in the thickness of a filter for absorbing x rays and decreases in the pinhole diameter.

4.4 X-ray spectra

X-ray spectra were measured by a transmission-type spectrometer with a lithium fluoride curved crystal 0.5 mm in thickness. The spectra were taken by a computed radiography (CR) system[19] with a wide dynamic range, and relative x-ray intensity was calculated from Dicom digital data. Figure 7 shows measured spectra from the cerium target. We observed clean K-series lines, while bremsstrahlung rays were hardly detected at all. The characteristic x-ray intensity substantially increased with increases in the charging voltage.

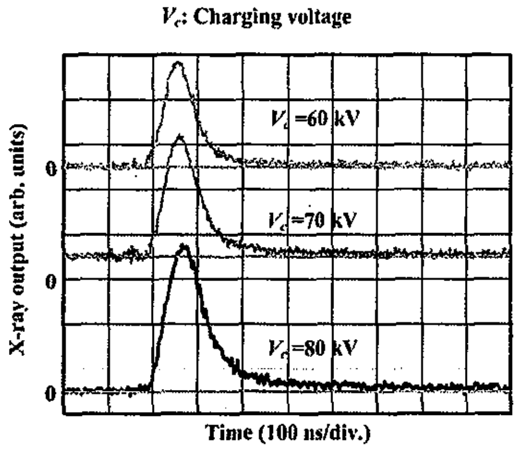

Figure 5: X-ray outputs at indicated conditions.

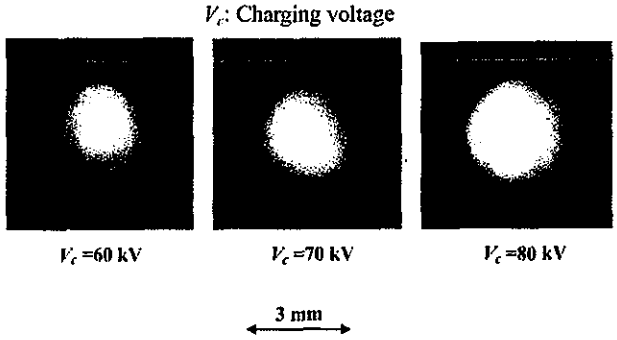

Figure 6: Images of characteristic x-ray source with changes in charging voltage.

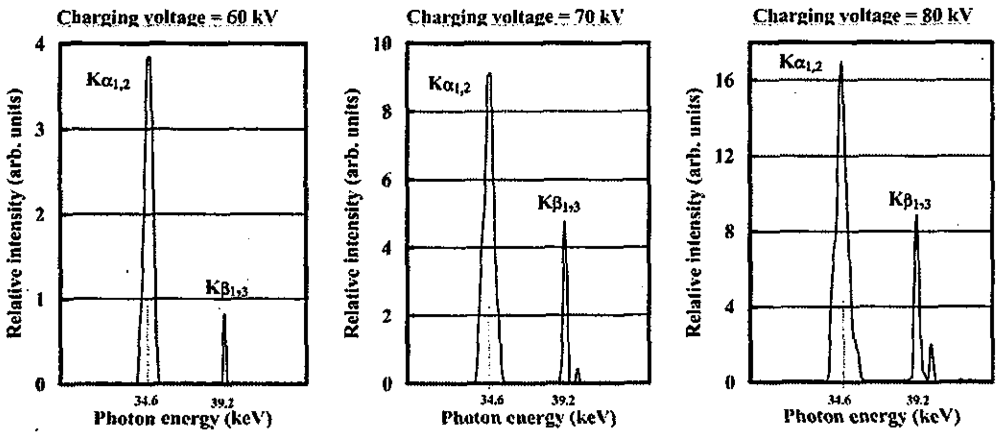

Figure 7: X-ray spectra from cerium target.

5. ANGIOGRAPHY

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

Figure 8 shows radiograms of tungsten wires coiled around a pipe made of polymethyl methacrylate. Although the image contrast increased with increases in the wire diameter, a 50 μm-diameter wire could be observed.

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

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

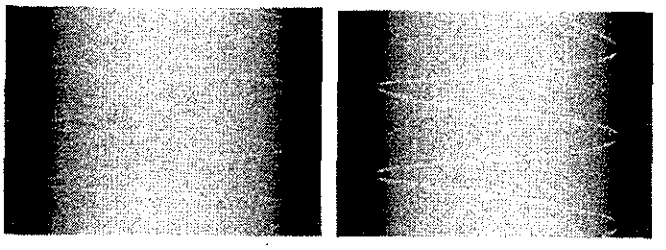

Figure 8: Radiograms of tungsten wires coiled around rod made of polymethyl methacrylate.

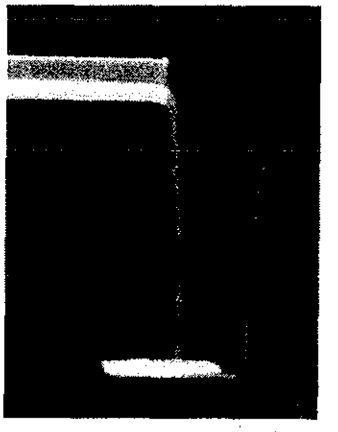

Figure 9: Radiogram of water falling into polypropylene beaker from glass test tube.

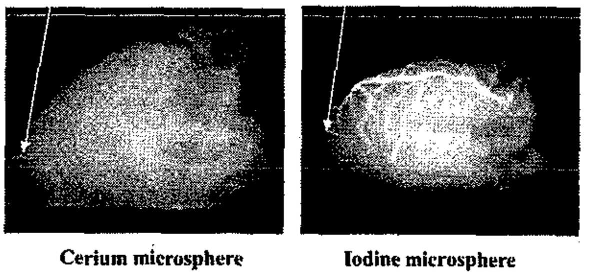

Figure 10: Angiograms of rabbit hearts using iodine and cerium microspheres.

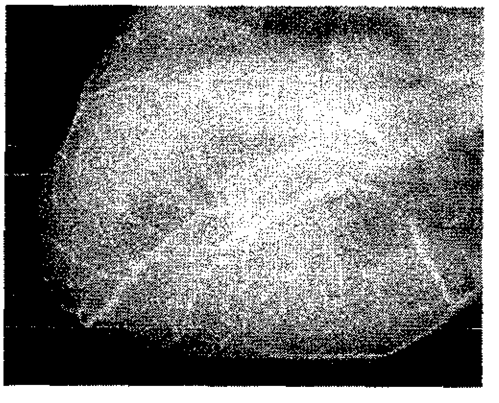

Fig. 11 Angiograms of extracted heart of dog.

6. DISCUSSION

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

In this research, the generator produced instantaneous number of K photons was approximately 5×10^8 photons/cm^2 per pulse at 1.0 m from the source. Subsequently, the intensity can be increased by increasing the electrostatic energy in condenser, and monochromatic Kα lines are produced using a barium oxide filter with a barium K-edge of 37.4 keV.

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

ACKNOWLEDGMENT

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).

REFERENCES

1. H. Mori, K. Hyodo, E. Tanaka, M. U. Mohammed, A. Yamakawa, Y. Shinozaki, H. Nakazawa, Y. Tanaka, T. Sekka, Y. Iwata, S. Honda, K. Umetani, H. Ueki, T. Yokoyama, K. Tanioka, M. Kubota, H. Hosaka, N. Ishizawa and M. Ando, "Small-vessel radiography in situ with monochromatic synchrotoron radiation," *Radiology*, **201**, 173-177, 1996.
2. K. Hyodo, M. Ando, Y. Oku, S. Yamamoto, T. Takeda, Y. Itai, S. Ohtsuka, Y. Sugishita and J. Tada, "Development of a two-dimensional imaging system for clinical applications of intravenous coronary angiography using intense synchrotron radiation produced by a multipole wiggler," *J. Synchrotron Rad.*, **5**, 1123-1126, 1998.
3. A. Momose, T. Takeda, Y. Itai and K. Hirano, "Phase-contrast x-ray computed tomography for observing biological soft tissues," *Nature Medicine*, **2**, 473-475, 1996.
4. M. Ando, A. Maksimenko, H. Sugiyama, W. Pattanasiriwisawa, K. Hyodo and C. Uyama, "A simple x-ray dark- and bright- field imaging using achromatic Laue optics, *Jpn. J. Appl. Phys.*, **41**, L1016-L1018, 2002.
5. A. Ishisaka, H. Ohara and C. Honda, "A new method of analyzing edge effect in phase contrast imaging with incoherent x-rays," *Opt. Rev.*, **7**, 566-572, 2000.
6. E. Sato, E. Tanaka, H. Mori, T. Kawai, T. Ichimaru, S. Sato, K. Takayama and H. Ido, "Demonstration of enhanced K-edge angiography using a cerium target x-ray generator," *Med. Phys*, **31**, 3017-3021, 2004.
7. R. Germer, "X-ray flash techniques," *J. Phys. E: Sci. Instrum.*, **12**, 336-350, 1979.
8. E. Sato, S. Kimura, S. Kawasaki, H. Isobe, K. Takahashi, Y. Tamakawa and T. Yanagisawa, "Repetitive flash x-ray generator utilizing a simple diode with a new type of energy-selective function," *Rev. Sci. Instrum.*, **61**, 2343-2348 1990.
9. A. Shikoda, E. Sato, M. Sagae, T. Oizumi, Y. Tamakawa and T. Yanagisawa, "Repetitive flash x-ray generator having a high-durability diode driven by a two-cable-type line pulser," *Rev. Sci. Instrum.*, **65**, 850-856, 1994.
10. E. Sato, K. Takahashi, M. Sagae, S. Kimura, T. Oizumi, Y. Hayasi, Y. Tamakawa and T. Yanagisawa, "Sub-kilohertz flash x-ray generator utilizing a glass-enclosed cold-cathode triode," *Med. & Biol. Eng. & Comput.*, **32**, 289-294, 1994.
11. K. Takahashi, E. Sato, M. Sagae, T. Oizumi, Y. Tamakawa and T. Yanagisawa, "Fundamental study on a long-duration flash x-ray generator with a surface-discharge triode," *Jpn. J. Appl. Phys.*, **33**, 4146-4151, 1994.
12. E. Sato, M. Sagae, E. Tanaka, Y. Hayasi, R. Germer, H. Mori, T. Kawai, T. Ichimaru, S. Sato, K. Takayama and H. Ido: Quasi-monochromatic flash x-ray generator utilizing a disk-cathode molybdenum tube, *Jpn. J. Appl. Phys.*, **43**, 7324-7328, 2004.
13. E. Sato, R. Germer, Y. Hayasi, K. Murakami, Y. Koorikawa, E. Tanaka, H. Mori, T. Kawai, T. Ichimaru, F. Obata, K. Takahashi, S. Sato, K. Takayama and Ido, H.: Weakly ionized cerium plasma radiography, *SPIE*, **5210**, 12-21, 2003.
14. E. Sato, Y. Hayasi, R. Germer, E. Tanaka, H. Mori, T. Kawai, H. Obara, T. Ichimaru, K. Takayama and H. Ido, "Intense characteristic x-ray irradiation from weakly ionized linear plasma and applications," *Jpn. J. Med. Imag. Inform. Sci.*, **20**, 148-155, 2003.
15. E. Sato, Y. Hayasi, R. Germer, E. Tanaka, H. Mori, T. Kawai, H. Obara, T. Ichimaru, K. Takayama and H. Ido, "Irradiation of intense characteristic x-rays from weakly ionized linear molybdenum plasma," *Jpn. J. Med. Phys.*, **23**, 123-131, 2003.
16. E. Sato, Y. Hayasi, R. Germer, E. Tanaka, H. Mori, T. Kawai, T. Ichimaru, K. Takayama and H. Ido, "Quasi-monochromatic flash x-ray generator utilizing weakly ionized linear copper plasma," *Rev. Sci. Instrum.*, **74**, 5236-5240, 2003.
17. E. Sato, R. Germer, Y. Hayasi, Y. Koorikawa, K. Murakami, E. Tanaka, H. Mori, T. Kawai, T. Ichimaru, F. Obata, K. Takahashi, S. Sato, K. Takayama and H. Ido: Weakly ionized plasma flash x-ray generator and its distinctive characteristics. *SPIE*, **5196**, 383-392, 2003.

18. E. Sato, Y. Hayasi, R. Germer, E. Tanaka, H. Mori, T. Kawai, T. Ichimaru, S. Sato, K. Takayama and H. Ido, "Sharp characteristic x-ray irradiation from weakly ionized linear plasma," *J. Electron Spectrosc. Related Phenom.*, **137-140**, 713-720, 2004.

19. E. Sato, K. Sato and Y. Tamakawa, "Film-less computed radiography system for high-speed imaging," *Ann. Rep. Iwate Med. Univ. Sch. Lib. Arts and Sci.*, **35**, 13-23, 2000.

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Monochromatic flash x-ray generator utilizing copper-target diode

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ABSTRACT

High-voltage condensers in a polarity-inversion two-stage Marx surge generator are charged from −50 to −70 kV using a power supply, and the electric charges in the condensers are discharged to an x-ray tube after closing the gap switches in the surge generator using 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 copper Kα lines are produced using a 10-μm-thick nickel 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. The peak tube voltage increased with increasing charging voltage. At a charging voltage of −70 kV, the peak tube voltage and current were 140 kV and 0.8 kA, respectively. The pulse widths were approximately 30 ns, and the maximum dimension of the x-ray source was 3.0 mm in diameter. The number of generator-produced Kα photons was approximately 2.5×10^6 photons/cm^2 at 0.5 m per pulse.

Keywords: flash x-ray, characteristic x rays, bremsstrahlung x-ray distribution, copper Kα lines, monochromatic radiography

1. INTRODUCTION

Flash radiography[1] is a major technique that uses high-voltage vacuum discharges to produce short x-ray pulses of less than 1 μs. Basically, although there are several different types of generators, the generator with a multistage Marx surge generator in conjunction with a cold-cathode x-ray tube is popular.[1,2] To apply the generator to biomedicine, several different flash x-ray generators[3-8] have been developed, and monochromatic or quasi-monochromatic generators are useful to perform energy-selective imaging, for example, enhanced K-edge angiography[9-11] using iodine-based contrast media; the angiography is specially performed using a synchrotron in conjunction with a monochromator.

In order to produce clean characteristic x rays with photon energies of less than 20 keV, weakly ionized linear plasma x-ray generators[12-15] are very useful, and intense quasi-monochromatic x rays are produced from the plasma axial direction. Without forming the linear plasma, because bremsstrahlung rays are not emitted in the opposite direction to that of electron acceleration, characteristic x rays can be produced by considering the angle dependence of bremsstrahlung x rays.[16] As compared with the plasma generator, the photon energy of the characteristic x rays can be increased by increasing the maximum output voltage, since a multistage Marx generator can be employed.

In this paper, we describe a compact flash x-ray generator utilizing a cold-cathode radiation tube, used to perform a preliminary experiment for generating clean copper Kα lines.

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 polarity-inversion two-stage surge Marx generator with a capacity during main discharge of 425 pF, a trigger device for the surge generator, a turbomolecular pump, and a flash x-ray tube. Since the electric circuit of the surge generator employs a polarity-inversion two-stage Marx line (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 copper target 3.0 mm in diameter, a disk cathode made of graphite, a polyethylene terephthalate (Mylar) x-ray window 0.25 mm in thickness, and a polymethyl methacrylate (PMMA) tube body. The target-cathode space was regulated to 1.25 mm from the outside of the x-ray tube by rotating the anode rod, and the transmission x rays are obtained through a 1.0-mm-thick graphite cathode and an x-ray window. Because bremsstrahlung rays are not emitted in the opposite direction to that of electron acceleration (Figs. 4 and 5), copper Kα rays can be produced using a 10-μm-thick nickel K-edge filter.

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. 6). The voltage and current displayed roughly damped oscillations because the discharge resistance in the tube varied rapidly from infinity to approximately 0 Ω during the discharge. Thus, at the first quarter cycle of the oscillations, when the voltage decreased, the current increased. The instantaneous voltage and current increased with increases in the charging voltage, and the voltage and current were approximately 140 kV and 0.8 kA, respectively, at a charging voltage of −70 kV.

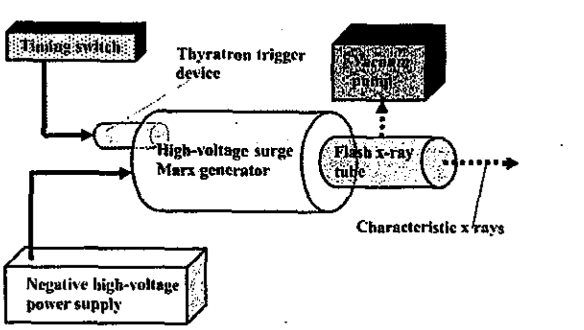

Figure 1: Block diagram of compact monochromatic flash x-ray generator.

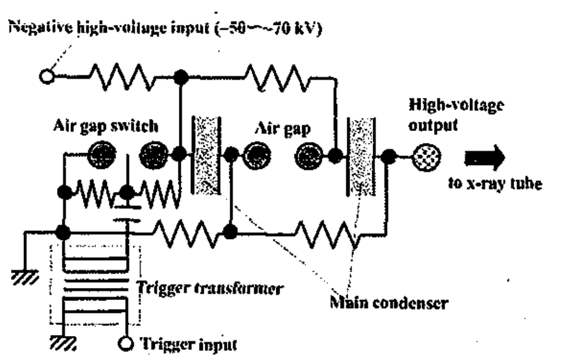

Figure 2: Circuit diagram of flash x-ray generator.

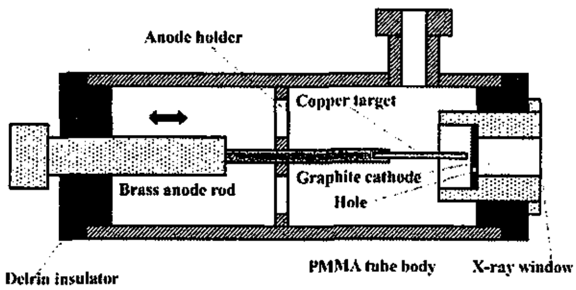

Figure 3: Schematic drawing of flash x-ray tube.

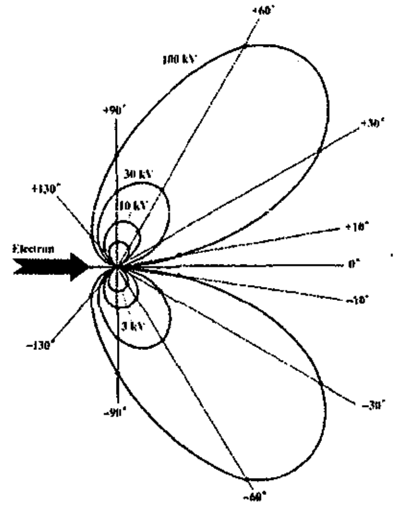

Figure 4: Bremsstrahlung x-ray intensity distribution vs angle.

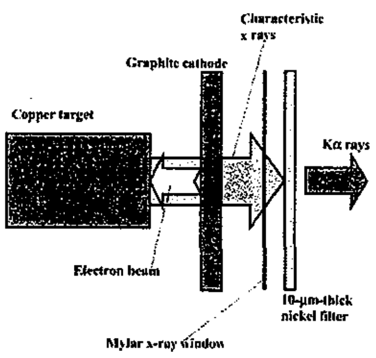

Figure 5: Characteristic x-ray irradiation.

3.2 X-ray output

X-ray output pulse was detected using a combination of a plastic scintillator, a photomultiplier, and the filter (Fig. 7). When the charging voltage was increased, the pulse height increased, but the width seldom varied. The widths were approximately 30 ns, and the time-integrated x-ray intensity measured using a thermoluminescence dosimeter (Kyokko TLD Reader 1500 having MSO-S elements without energy compensation) had a value of approximately 1.0 μC/kg per pulse at 0.5 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. 8). When the charging voltage was increased, the spot intensity increased, and the intensities corresponded well to the x-ray pulse height. The dimension was almost equal to the target diameter and had a value of 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] with a wide dynamic range, and relative x-ray intensity was calculated from Dicom digital data. Figure 9 shows the measured spectra from the copper target with the filter. We observed clean copper Kα lines, while bremsstrahlung rays were hardly detected at all. The Kα intensity increased with increases in the charging voltage.

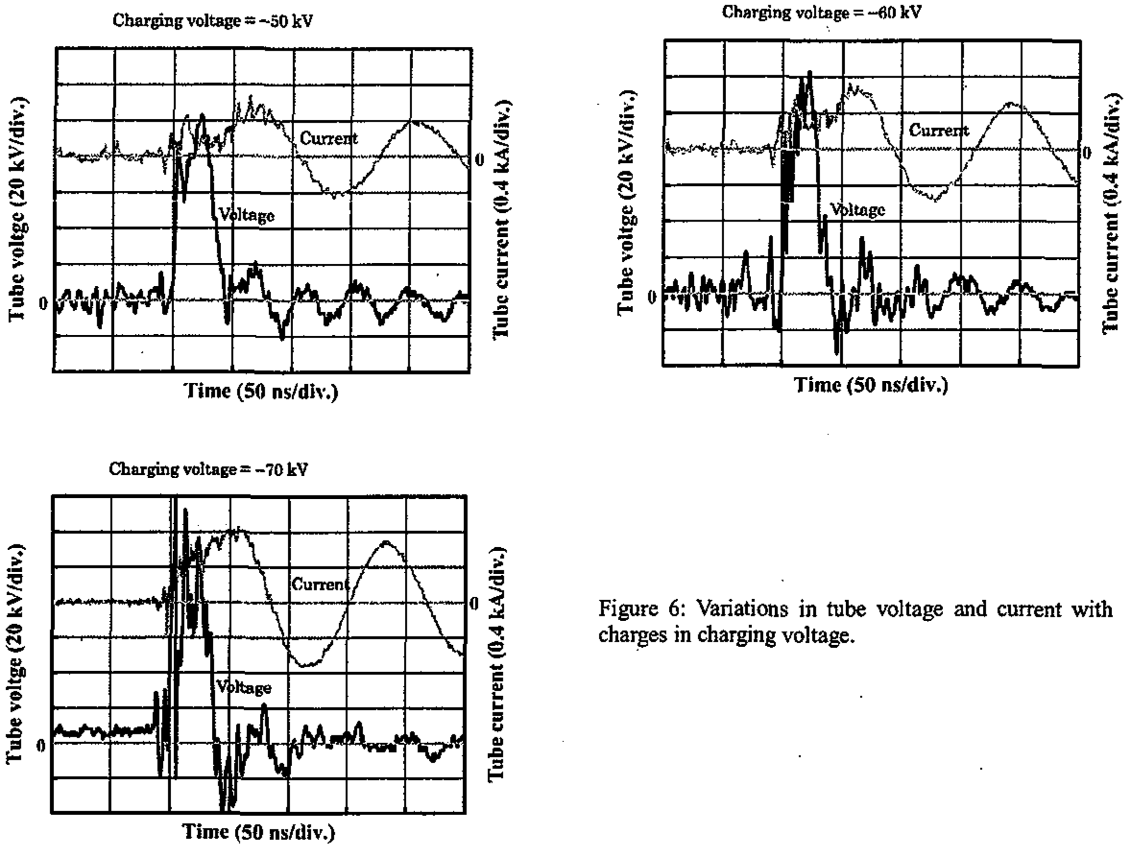

Figure 6: Variations in tube voltage and current with charges in charging voltage.

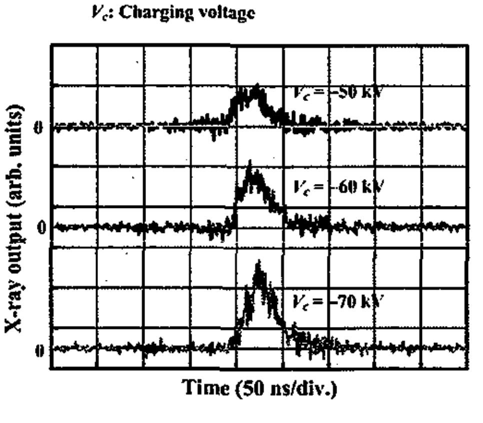

Figure 7: X-ray outputs according to changes charging voltage.

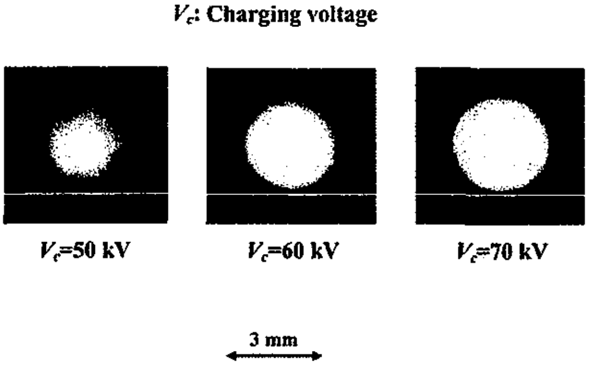

Figure 8: Images of x-ray source with changes in charging voltage.

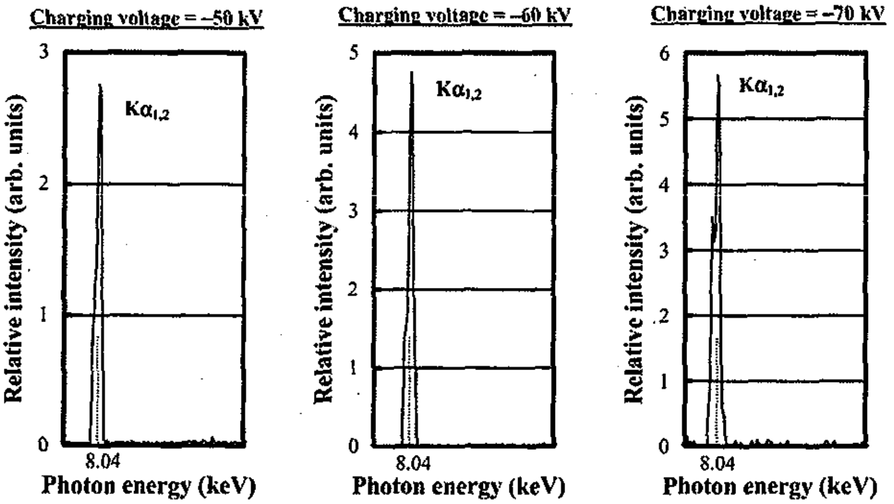

Figure 9: X-ray spectra from copper target according to changes in charging voltage.

4. RADIOGRAPHY

Flash radiography was performed using the CR system (Konica Regius 150) at 0.5 m from the x-ray source, and the charging voltage was −70 kV.

Firstly, rough measurements of spatial resolution were made using wires. Figure 10 shows radiograms of tungsten wires coiled around a pipe made of polymethyl methacrylate. Although the image contrast increased with increasing wire diameter, a 50-μm-diameter wire could be observed.

Figure 11 shows a radiogram of a vertebra, and fine structures in the vertebra were observed. The image of water falling into a polypropylene beaker from a plastic test tube is shown in Fig. 12. This image was taken with the slight addition of an iodine-based contrast medium. Because the x-ray duration was about 50 ns, the stop-motion image of water could be obtained. Figure 13 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.

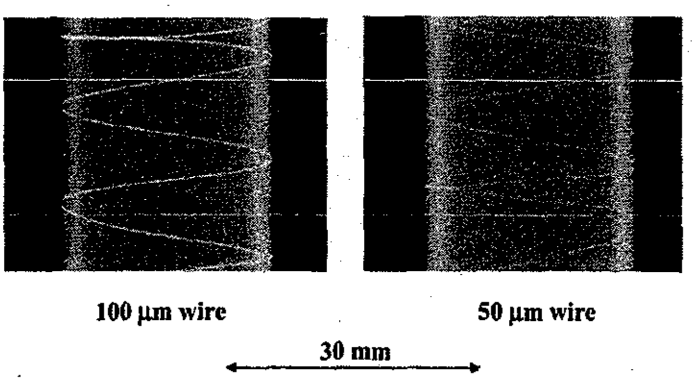

Figure 10: Radiograms of tungsten wires of 50 and 100 μm in diameter coiled around pipe made of polymethyl methacrylate.

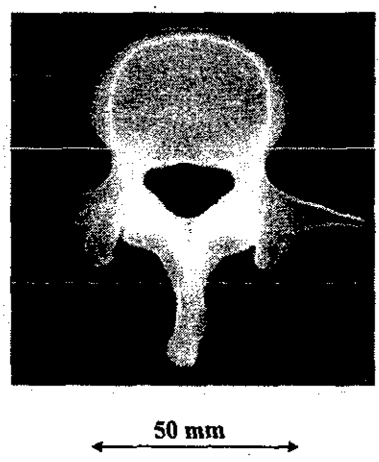

Figure 11: Radiogram of vertebra.

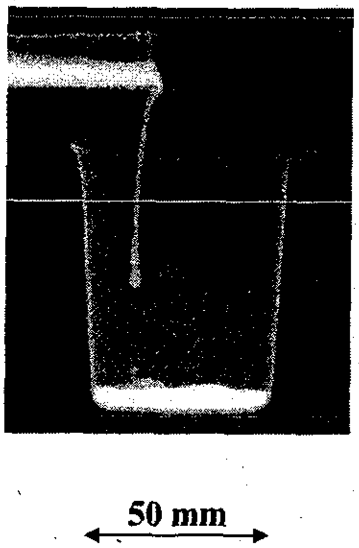

Figure 12: Radiogram of water falling into polypropylene beaker from plastic test tube.

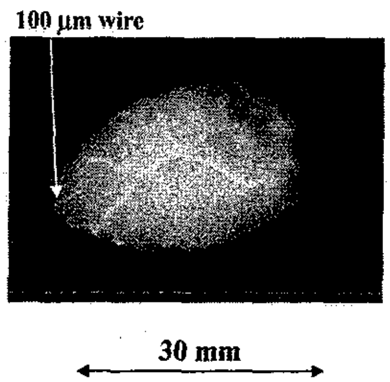

Figure 13: Angiograms of rabbit heart.

5. DISCUSSION

Concerning the spectrum measurement, we obtained fairly clean copper Kα rays (8.04 keV). Therefore, we are very interested in the measurement the Kα rays from cerium (34.6 keV), ytterbium (52.0 keV), tantalum (57.1 keV), and tungsten (58.9 keV) targets; the target element should be selected corresponding to the radiographic objectives. In medical applications, Kα 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 addition, since Kα rays from ytterbium, tantalum, and tungsten targets are absorbed effectively by gadolinium-based contrast media with a K-edge of 50.2 keV, these x rays are very useful for performing enhanced K-edge angiography.

In this research, the instantaneous number of generator-produced Kα photons was approximately 2.5×10^6 photons/cm^2 per pulse at 0.5 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 (8.90 keV) lines are produced without using the nickel filter with a K-edge of 8.33 keV.

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

ACKNOWLEDGMENT

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).

REFERENCES

1. R. Germer, "X-ray flash techniques," *J. Phys. E: Sci. Instrum.*, **12**, 336-350, 1979.
2. A. Mattsson, "Some characteristics of a 600 kV flash x-ray tube," *Physica Scripta*, **5**, 99-102, 1972.

3. E. Sato, H. Isobe and F. Hoshino, "High intensity flash x-ray apparatus for biomedical radiography," *Rev. Sci. Instrum.*, **57**, 1399-1408, 1986.

4. E. Sato, S. Kimura, S. Kawasaki, H. Isobe, K. Takahashi, Y. Tamakawa and T. Yanagisawa, "Repetitive flash x-ray generator utilizing a simple diode with a new type of energy-selective function," *Rev. Sci. Instrum.*, **61**, 2343-2348 1990.

5. A. Shikoda, E. Sato, M. Sagae, T. Oizumi, Y. Tamakawa and T. Yanagisawa, "Repetitive flash x-ray generator having a high-durability diode driven by a two-cable-type line pulser," *Rev. Sci. Instrum.*, **65**, 850-856, 1994.

6. E. Sato, K. Takahashi, M. Sagae, S. Kimura, T. Oizumi, Y. Hayasi, Y. Tamakawa and T. Yanagisawa, "Sub-kilohertz flash x-ray generator utilizing a glass-enclosed cold-cathode triode," *Med. & Biol. Eng. & Comput.*, **32**, 289-294, 1994.

7. K. Takahashi, E. Sato, M. Sagae, T. Oizumi, Y. Tamakawa and T. Yanagisawa, "Fundamental study on a long-duration flash x-ray generator with a surface-discharge triode," *Jpn. J. Appl. Phys.*, **33**, 4146-4151, 1994.

8. E. Sato, M. Sagae, A. Shikoda, K. Takahashi, T. Oizumi, M. Yamamoto, A. Takabe, K. Sakamaki, Y. Hayasi, H. Ojima K. Takayama and Y. Tamakawa, "High-speed soft x-ray techniques," *SPIE*, **2869**, 937-955, 1996.

9. H. Mori, K. Hyodo, E. Tanaka, M. U. Mohammed, A. Yamakawa, Y. Shinozaki, H. Nakazawa, Y. Tanaka, T. Sekka, Y. Iwata, S. Honda, K. Umetani, H. Ueki, T. Yokoyama, K. Tanioka, M. Kubota, H. Hosaka, N. Ishizawa and M. Ando, "Small-vessel radiography in situ with monochromatic synchrotoron radiation," *Radiology*, **201**, 173-177, 1996.

10. K. Hyodo, M. Ando, Y. Oku, S. Yamamoto, T. Takeda, Y. Itai, S. Ohtsuka, Y. Sugishita and J. Tada, "Development of a two-dimensional imaging system for clinical applications of intravenous coronary angiography using intense synchrotron radiation produced by a multipole wiggler," *J. Synchrotron Rad.*, **5**, 1123-1126, 1998.

11. E. Sato, E. Tanaka, H. Mori, T. Kawai, T. Ichimaru, S. Sato, K. Takayama and H. Ido, "Demonstration of enhanced K-edge angiography using a cerium target x-ray generator," *Med. Phys*, **31**, 3017-3021, 2004.

12. E. Sato, Y. Hayasi, R. Germer, E. Tanaka, H. Mori, T. Kawai, H. Obara, T. Ichimaru, K. Takayama and H. Ido, "Irradiation of intense characteristic x-rays from weakly ionized linear molybdenum plasma," *Jpn. J. Med. Phys.*, **23**, 123-131, 2003.

13. E. Sato, Y. Hayasi, R. Germer, E. Tanaka, H. Mori, T. Kawai, T. Ichimaru, K. Takayama and H. Ido, "Quasi-monochromatic flash x-ray generator utilizing weakly ionized linear copper plasma," *Rev. Sci. Instrum.*, **74**, 5236-5240, 2003.

14. E. Sato, R. Germer, Y. Hayasi, Y. Koorikawa, K. Murakami, E. Tanaka, H. Mori, T. Kawai, T. Ichimaru, F. Obata, K. Takahashi, S. Sato, K. Takayama and H. Ido: Weakly ionized plasma flash x-ray generator and its distinctive characteristics. *SPIE*, **5196**, 383-392, 2003.

15. E. Sato, Y. Hayasi, R. Germer, E. Tanaka, H. Mori, T. Kawai, T. Ichimaru, S. Sato, K. Takayama and H. Ido, "Sharp characteristic x-ray irradiation from weakly ionized linear plasma," *J. Electron Spectrosc. Related Phenom.*, **137-140**, 713-720, 2004.

16. E. Sato, M. Sagae, E. Tanaka, Y. Hayashi, R. Germer, H. Mori, T. Kawai, T. Ichimaru, S. Sato, K. Takayama and H. Ido: Quasi-monochromatic flash x-ray generator utilizing a disk-cathode molybdenum tube, *Jpn. J. Appl. Phys.*, **43**, 7324-7328, 2004.

17. E. Sato, K. Sato and Y. Tamakawa, "Film-less computed radiography system for high-speed imaging," *Ann. Rep. Iwate Med. Univ. Sch. Lib. Arts and Sci.*, **35**, 13-23, 2000.

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Energy-selective high-speed radiography utilizing stroboscopic x-ray generator

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ABSTRACT

Energy-selective high-speed radiography utilizing a kilohertz-range stroboscopic x-ray generator and its application to high-speed angiography are described. This generator consists of the following major components: a main controller, a condenser unit with a Cockcroft-Walton circuit, and an x-ray tube unit in conjunction with a grid controller. The main condenser of about 500 nF in the unit is charged up to 100 kV by the circuit, and the electric charges in the condenser are discharged to the triode by the grid control circuit. Although the tube voltage decreased during the discharging for generating x rays, the maximum value was equal to the initial charging voltage of the main condenser. The maximum tube current and the repetition rate were approximately 0.5 A and 32 kHz, respectively. The x-ray pulse width ranged from 0.01 to 1.0 ms, and the maximum shot number had a value of 32. At a charging voltage of 80 kV and a width of 1.0 ms, the x-ray intensities obtained without filtering, using an aluminum filter, and using a barium sulfate filter were 14.8, 5.48 and 5.05 μGy per pulse, respectively, at 1.0 m, and the dimensions of the focal spot had values of 3.5×3.5 mm. Angiography was performed using both the aluminum and the barium sulfate filters at a charging voltage of 60 kV.

Keywords: energy-selective radiography, bremsstrahlung x rays, filtering, stroboscopic x-ray, pulse x-ray, angiography

1. INTRODUCTION

Modern high-speed x-ray generators are capable of producing short x-ray pulses with high dose rates, and have been applied to radiography in various fields. To produce hard flash x rays with maximum photon energies of approximately 1 MeV, multistage Marx surge generators have been developed.[1] Furthermore, induction linear accelerators[2] have been developed and improved to produce 10-MeV-order flash x rays. In contrast, 100-kV-order flash x-ray generators have been developed and applied to biomedicine.[3,4]

In the cases of multiple-shot and cine radiographies, we have developed several different repetitive-flash[5-8] and stroboscopic x-ray generators.[9-11] Although most flash x-ray generators have cold-cathode tubes, the stroboscopic generators utilize hot-cathode tubes. Particularly, although a 50 kHz stroboscopic generators have been manufactured, the repetition rate can be increased to MHz order.

Recently synchrotrons generate monochromatic parallel x-ray beams using a monochromator, and these beams have been employed to perform enhanced K-edge angiography[12,13] and x-ray phase imaging.[14,15] To perform angiography, the beams with photon energies of approximately 35 keV have been used, because iodine contrast mediums with a

K-absorption edge of 33.155 keV absorb the beams effectively. In view of this situation, we have developed x-ray generators with cerium-target tubes[16,17] which can produce Kα rays of 34.6 keV.

In this research, we employed a tungsten-target x-ray tube and performed a preliminary study on high-speed angiography achieved with quasi-monochromatic x rays produced by filtering in conjunction with a computed radiography system.

2. GENERATOR

Figure 1 shows the block diagram of the kilohertz-range stroboscopic x-ray generator. This generator consists of the following major components: a main controller, a condenser unit with a Cockcroft-Walton circuit, and an x-ray tube unit in conjunction with a grid controller (Figs. 2 and 3). The main condenser of about 500 nF in the unit is charged up to 100 kV by the circuit, and the electric charges in the condenser are discharged to the triode by the grid control circuit. Although the tube voltage decreased during the discharging for generating x rays, the maximum value was equal to the initial charging voltage of the main condenser.

The x-ray tube is a glass-enclosed hot-cathode triode and is composed of the following major parts: an anode rod made of copper, a tungsten plate target, an iron focusing electrode, a tungsten hot cathode (filament), a tungsten grid, and a glass tube body. The electron beams from the cathode are accelerated between the anode and cathode electrodes and are converged to the target by the focusing electrode. The tube is set in the metal case filled with insulation oil, and the diaphragm regulates the radiation field.

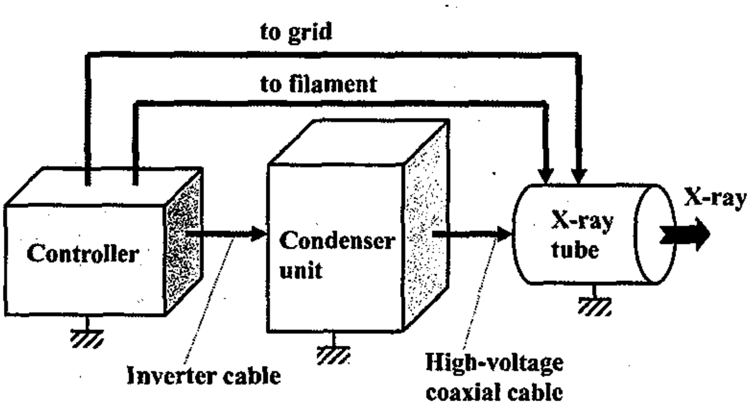


Figure 1: Block diagram of kilohertz-range stroboscopic x-ray generator.

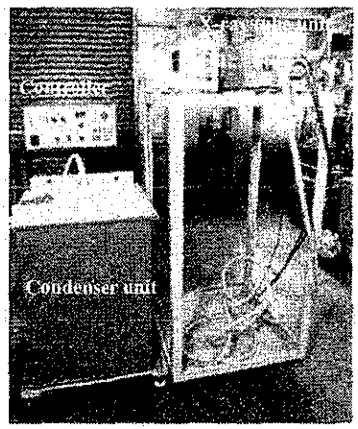


Figure 2: Stroboscopic x-ray generator.

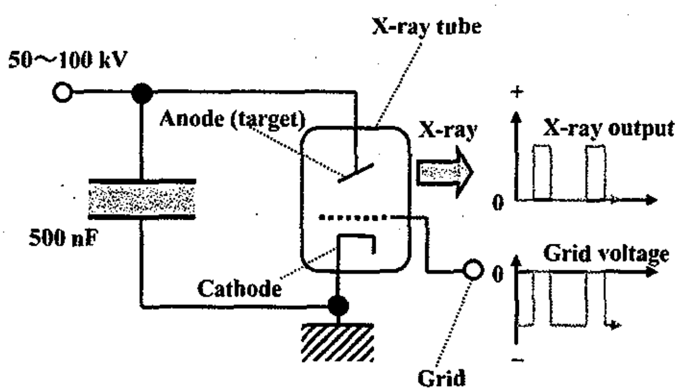


Figure 3: Main high-voltage circuit of x-ray generator.

3. CHARACTERISTICS

3.1 X-ray output

The x-ray output was detected by a pin diode, and the output voltages from the diode were measured by a digital storage scope (Fig. 4). Using this generator, the pulse width could be controlled correctly and ranged from 10 μs to 1.0 ms. The maximum repetition rate was approximately 50 kHz, and stable repetitive x-ray pulses were obtained. When the charging voltage was increased, the pulse height increased substantially.

3.2 Time-integrated x-ray intensity

Figure 5 shows the time-integrated (absolute) value of the x-ray intensity (exposure) at 1.0 m per pulse measured by a Victoreen 660 ionization chamber. The intensity was proportional to the driving pulse width. At a constant pulse width of 1.0 ms, the intensity increased in proportion to approximately the second power of the charging voltage. At a charging voltage of 80 kV and a width of 1.0 ms, the x-ray intensity obtained without filtering, using an aluminum filter, and using a barium sulfate filter were 14.8, 5.48, and 5.05 μGy per pulse, respectively, at 1.0 m from the source.

3.3 X-ray source

The image of the x-ray source was measured using a pinhole camera with a hole diameter of 50 μm and a computed radiography (CR) system (Konica Regius 150)[18] with a sampling pitch of 87.5 μm. When the charging voltage was increased, the dimensions hardly varied, and were approximately 3.5×3.5 mm.

3.4 X-ray spectra

In order to measure x-ray spectra, we employed a cadmium tellurium detector (CDTE2020X, Hamamatsu Photonics Inc.) (Fig. 6). Compared with a germanium detector, this detector has a lower energy resolution of 1.7 keV.

When the charging voltage was increased, both the maximum photon energy and the intensities of bremsstrahlung x rays increased, and the photon energy of the spectrum peak also increased. The 3-mm-thick aluminum filter attenuated the low-photon-energy bremsstrahlung x rays. Subsequently, the barium sulfate filter, with a surface density of approximately 10 mg/cm^2, significantly attenuated the spectra above the barium K-edge of 37.4 keV. The areas under the spectral curves correlate closely to the total x-ray intensities shown in Fig. 4.

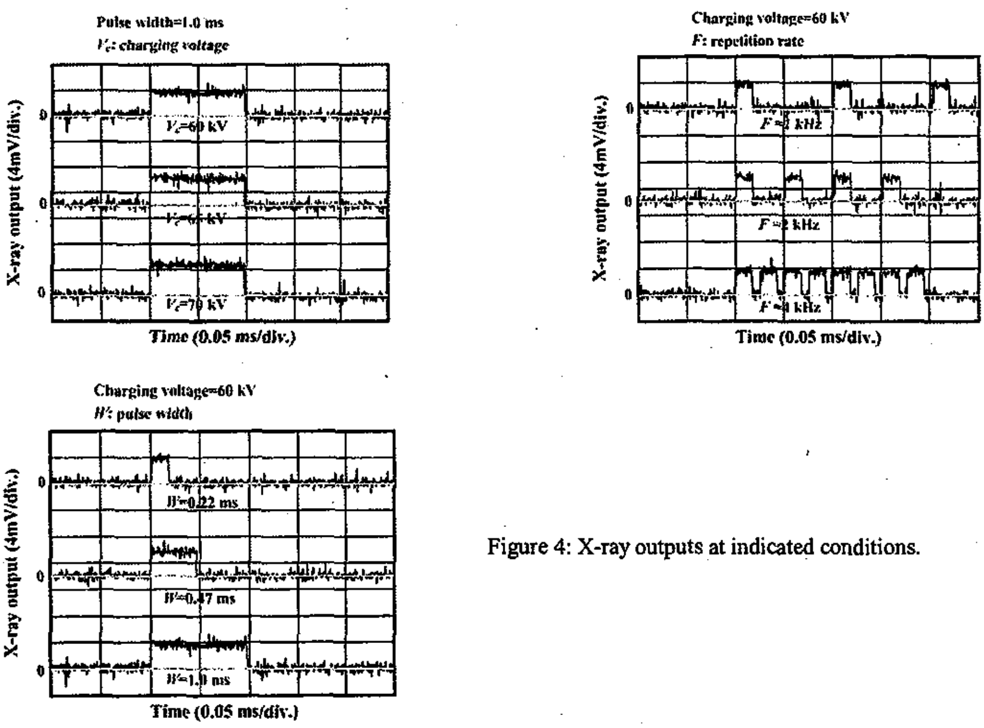
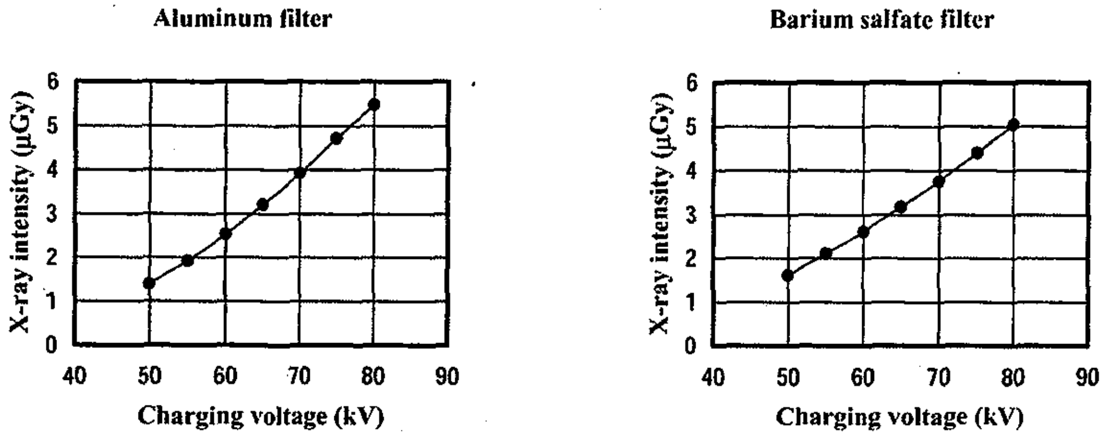


Figure 4: X-ray outputs at indicated conditions.



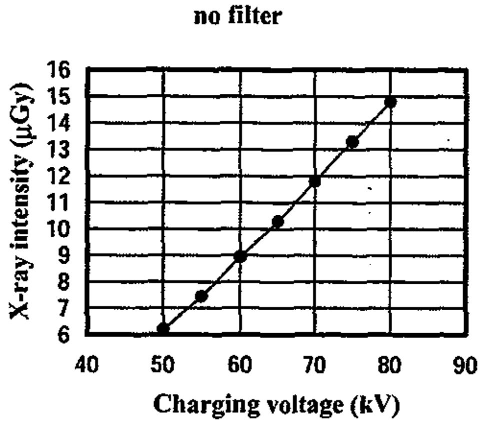


Figure 5: X-ray intensities at 1.0 m per pulse with changing charging voltage with exposure time of 1.0 ms.

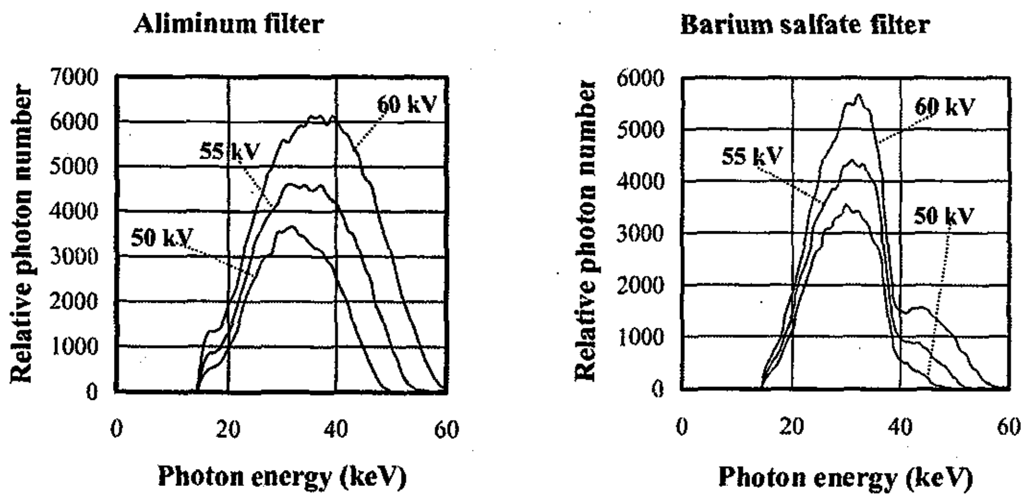


Figure 6: X-ray spectra at indicated conditions.

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.

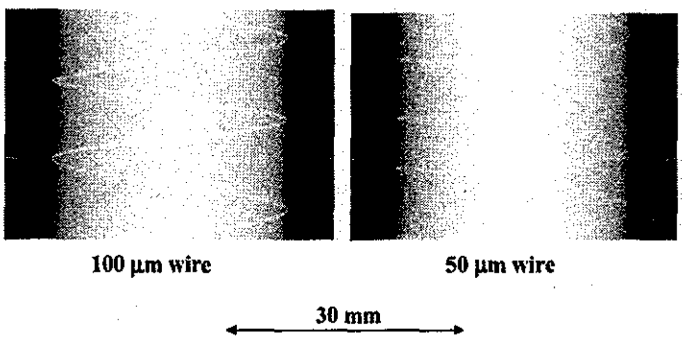


Figure 7: Radiograms of tungsten wires coiled around rod made of polymethyl methacrylate using aluminum filter.

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

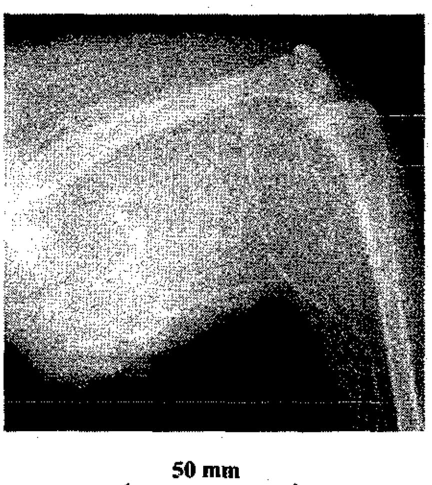


Figure 9: Angiograms of rabbit thigh achieved with barium sulfate filter.

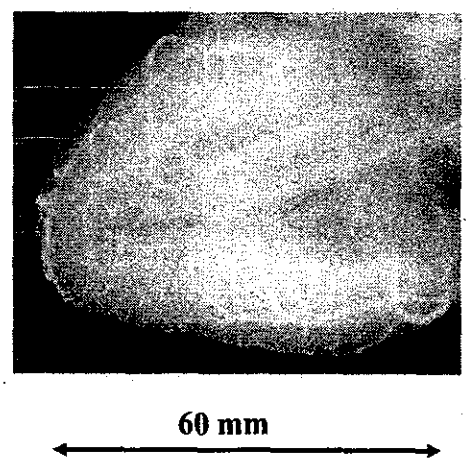


Figure 10: Angiogram of dog heart with aluminum filter.

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.

ACKNOWLEDGMENT

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REFERENCES

1. R. Germer, "X-ray flash techniques," *J. Phys. E: Sci. Instrum.*, **12**, 336-350, 1979.
2. C. Cavailler, "AIRIX- a new tool for flash radiography in detonics," *SPIE*, **4183**, 23-35, 2000.
3. E. Sato, M. Sagae, A. Shikoda, K. Takahashi, T. Oizumi, M. Yamamoto, A. Takabe, K. Sakamaki, Y. Hayasi, H. Ojima K. Takayama and Y. Tamakawa, "High-speed soft x-ray techniques," *SPIE*, **2869**, 937-955, 1996.
4. E. Sato, M. Sagae, E. Tanaka, Y. Hayasi, R. Germer, H. Mori, T. Kawai, T. Ichimaru, S. Sato, K. Takayama and H. Ido: Quasi-monochromatic flash x-ray generator utilizing a disk-cathode molybdenum tube, *Jpn. J. Appl. Phys.*, **43**, 7324-7328, 2004.
5. E. Sato, S. Kimura, S. Kawasaki, H. Isobe, K. Takahashi, Y. Tamakawa and T. Yanagisawa, "Repetitive flash x-ray generator utilizing a simple diode with a new type of energy-selective function," *Rev. Sci. Instrum.*, **61**, 2343-2348 1990.
6. A. Shikoda, E. Sato, M. Sagae, T. Oizumi, Y. Tamakawa and T. Yanagisawa, "Repetitive flash x-ray generator having a high-durability diode driven by a two-cable-type line pulser," *Rev. Sci. Instrum.*, **65**, 850-856, 1994.
7. E. Sato, K. Takahashi, M. Sagae, S. Kimura, T. Oizumi, Y. Hayasi, Y. Tamakawa and T. Yanagisawa, "Sub-kilohertz flash x-ray generator utilizing a glass-enclosed cold-cathode triode," *Med. & Biol. Eng. & Comput.*, **32**, 289-294, 1994.
8. K. Takahashi, E. Sato, M. Sagae, T. Oizumi, Y. Tamakawa and T. Yanagisawa, "Fundamental study on a long-duration flash x-ray generator with a surface-discharge triode," *Jpn. J. Appl. Phys.*, **33**, 4146-4151, 1994.
9. E. Sato, M. Sagae, K. Takahashi, A. Shikoda, T. Oizumi, Y. Hayasi, Y. Tamakawa and T. Yanagisawa, "10 kHz microsecond pulsed x-ray generator utilizing a hot-cathode triode with variable durations for biomedical radiography," *Med. & Biol. Eng. & Comput.*, **32**, 295-301, 1994.
10. E. Sato, T. Ichimaru, H. Obara, M. Zuguchi, H. Mori, E. Tanaka, T. Usuki, K. Sato, H. Ojima, K. Takayama, K. Sakamaki and Y. Tamakawa, "Condenser-discharge stroboscopic x-ray generator for medical radiography," *SPIE*, **4183**, p383-393, 2000.
11. E. Sato, H. Ojima, K. Takayama, M. Matsumasa, H. Obara, M. Zuguchi, T. Usuki, K. Sato, K. Sakamaki and Y. Tamakawa, "Observation of cavitation bubble cloud using a stroboscopic x-ray generator," *SPIE*, **4183**, 394-404, 2000.
12. H. Mori, K. Hyodo, E. Tanaka, M. U. Mohammed, A. Yamakawa, Y. Shinozaki, H. Nakazawa, Y. Tanaka, T. Sekka, Y. Iwata, S. Honda, K. Umetani, H. Ueki, T. Yokoyama, K. Tanioka, M. Kubota, H. Hosaka, N. Ishizawa and M. Ando, "Small-vessel radiography in situ with monochromatic synchrotoron radiation," *Radiology*, **201**, 173-177, 1996.

13. K. Hyodo, M. Ando, Y. Oku, S. Yamamoto, T. Takeda, Y. Itai, S. Ohtsuka, Y. Sugishita and J. Tada, "Development of a two-dimensional imaging system for clinical applications of intravenous coronary angiography using intense synchrotron radiation produced by a multipole wiggler," *J. Synchrotron Rad.*, **5**, 1123-1126, 1998.
14. A. Momose, T. Takeda, Y. Itai and K. Hirano, "Phase-contrast x-ray computed tomography for observing biological soft tissues," *Nature Medicine*, **2**, 473-475, 1996.
15. M. Ando, A. Maksimenko, H. Sugiyama, W. Pattanasiriwisawa, K. Hyodo and C. Uyama, "A simple x-ray dark- and bright- field imaging using achromatic Laue optics, *Jpn. J. Appl. Phys.*, **41**, L1016-L1018, 2002.
16. E. Sato, R. Germer, Y. Hayasi, K. Murakami, Y. Koorikawa, E. Tanaka, H. Mori, T. Kawai, T. Ichimaru, F. Obata, K. Takahashi, S. Sato, K. Takayama and Ido, H.: Weakly ionized cerium plasma radiography, *SPIE*, **5210**, 12-21, 2003.
17. E. Sato, E. Tanaka, H. Mori, T. Kawai, T. Ichimaru, S. Sato, K. Takayama and H. Ido, "Demonstration of enhanced K-edge angiography using a cerium target x-ray generator," *Med. Phys*, **31**, 3017-3021, 2004.
18. E. Sato, K. Sato and Y. Tamakawa, "Film-less computed radiography system for high-speed imaging," *Ann. Rep. Iwate Med. Univ. Sch. Lib. Arts and Sci.*, **35**, 13-23, 2000.

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