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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Demonstration of flash K-edge angiography utilizing gadolinium-based contrast medium

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ABSTRACT

The high-voltage condensers in a polarity-inversion two-stage Marx surge generator are charged from −50 to −70 kV by a power supply, and the electric charges in the condensers are discharged to an x-ray tube after closing gap switches in the surge generator with a trigger device. The x-ray tube is a demountable diode, and the turbomolecular pump evacuates air from the tube with a pressure of approximately 1 mPa. Tungsten characteristic x rays can be produced, since the tube utilizes a disk cathode and a rod target, and bremsstrahlung rays are not emitted in the opposite direction to that of electron acceleration. At a charging voltage of −70 kV, the instantaneous tube voltage and current were 140 kV and 1.0 kA, respectively. The x-ray pulse widths were approximately 90 ns, and the estimated number of K photons was approximately 5×10^8 photons/cm^2 per pulse at 0.5 m from the source of 3.0 mm in diameter.

Keywords: angiography, gadolinium-based contrast media, characteristic x rays, quasi-monochromatic x rays, tungsten K lines

1. INTRODUCTION

So far, several different flash x-ray generators have been developed,[1] and soft generators[2-6] with photon energies of lower than 150 keV can be employed to perform biomedical radiography. In order to produce monochromatic x rays, plasma flash x-ray generators[7-11] are useful, since quite intense and sharp characteristic x rays such as lasers have been produced from weakly ionized linear plasmas of nickel, copper and molybdenum, while bremsstrahlung rays are hardly detected at all. Using these generators, the characteristic x-ray intensity substantially increased with corresponding increases in the charging voltage.

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Angiography using iodine-based contrast mediums is the current mainstay for observing blood vessels including coronary arteries. Conventional angiography uses an x-ray tube with a tungsten target, and bremsstrahlung x rays with just above the K-absorption edge (33.2 keV) are applied effectively, since the rays are absorbed easily by the iodine. Subsequently, synchrotrons have been used to form monochromatic parallel beams with photon energies of approximately 35 keV so as to perform enhanced K-edge angiography.[12-15]

Since K-series characteristic x rays from ytterbium, tantalum, and tungsten targets are absorbed effectively by gadolinium-based contrast media, these x rays are very useful for performing enhanced K-edge angiography. As compared with K-edge angiography using iodine-based contrast media with an iodine K-edge of 33.2 keV, the absorbed dose can be decreased easily in cases where the gadolinium media are employed.

In the present research, we developed an quasi-monochromatic flash x-ray generator with a tungsten target tube, and used it to perform a preliminary study on angiography achieved with tungsten K-series characteristic x rays.

2. PRINCIPLE OF K-EDGE ANGIOGRAPHY

Figure 1 shows the mass attenuation coefficients of gadolinium at the selected energies; the coefficient curve is discontinuous at the iodine K-edge. The average photon energy of the cerium Kα lines is shown just above the gadolinium K-edge. The average photon energy of tungsten Kα lines is 58.9 keV, and gadolinium contrast media with a K-absorption edge of 50.2 keV absorb the lines easily. Therefore, blood vessels were observed with high contrasts.

3. GENERATOR

3.1 High-voltage circuit

Block diagram of a compact monochromatic flash x-ray generator is shown in Fig. 2. This generator consists of the following components: a constant high-voltage power supply, a surge Marx generator with a capacity during main discharge of 425 pF, a thyratron trigger device for the surge generator, a turbomolecular pump, and a flash x-ray tube. Since the electric circuit of the high-voltage pulse generator employs a polarity-inversion two-stage Marx line (Fig. 3), 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.

3.2 X-ray tube

The x-ray tube is a demountable diode type, as illustrated in Fig. 4. This tube is connected to the turbomolecular pump with a pressure of about 1 mPa and consists of the following major devices: a rod-shaped tungsten 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 (Fig. 5), tungsten characteristic x rays can be produced.

4. CHARACTERISTICS

4.1 Tube voltage and current

Tube voltage and current were measured by 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 1.0 kA, respectively, at a charging voltage of −70 kV.

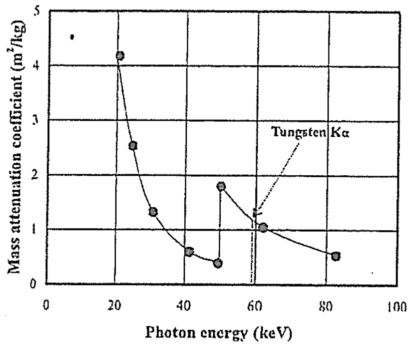


Figure 1: Relation between mass attenuation coefficient of iodine and average photon energy of tungsten Kα lines.

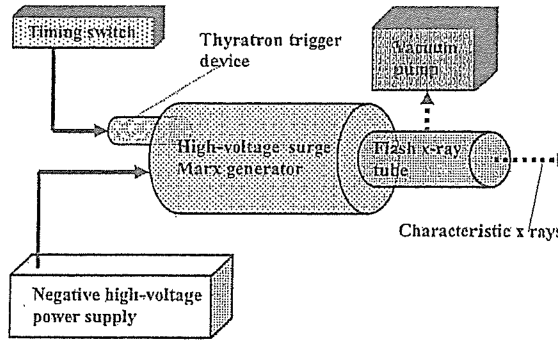


Figure 2: Block diagram of compact quasi-monochromatic flash x-ray generator.

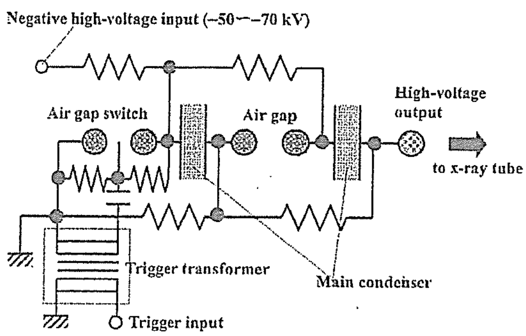


Figure 3: Circuit diagram of two-stage surge Marx generator.

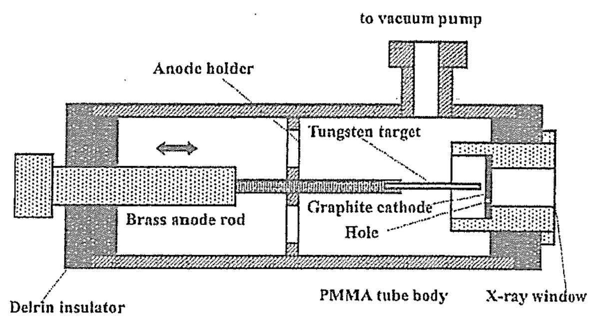


Figure 4: Schematic drawing of flash x-ray tube.

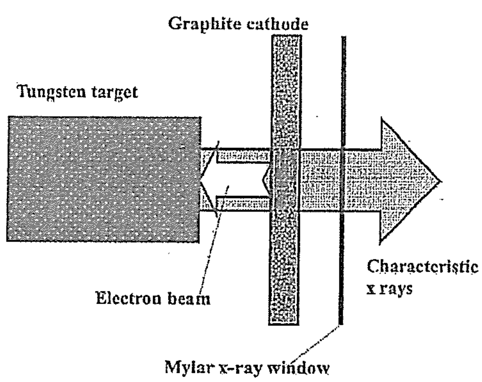


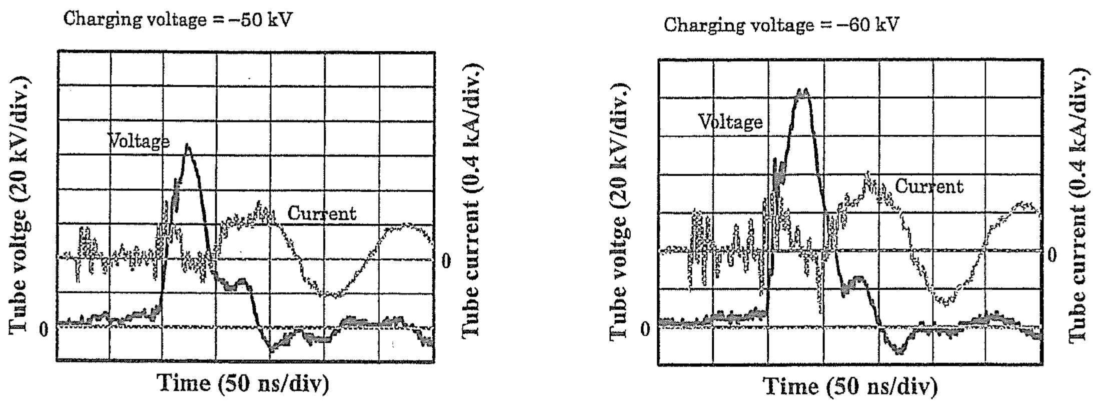
Figure 5: Irradiation of characteristic x rays.

4.2 X-ray output

X-ray output pulse was detected using a combination of a plastic scintillator and a photomultiplier (Fig. 7). When the charging voltage was increased, the pulse height increased, but the width seldom varied. The widths were about 90 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 an instantaneous value of approximately 5 μC/kg per pulse at 0.5 m from the x-ray source with a charging voltage of −70 kV.

4.3 X-ray source

In order to observe the x-ray source, we employed a 100-μm-diameter pinhole camera and an x-ray film (Polaroid XR-7) (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 about 3.0 mm.



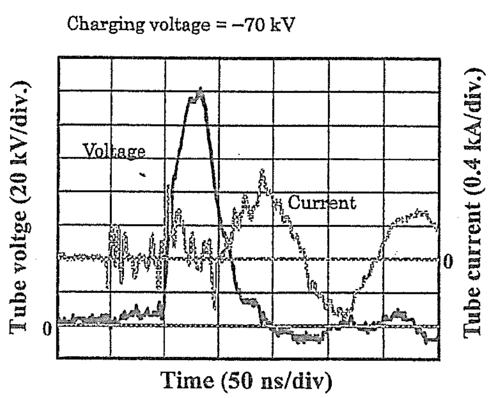


Figure 6: Tube voltages and currents with changing charging voltage.

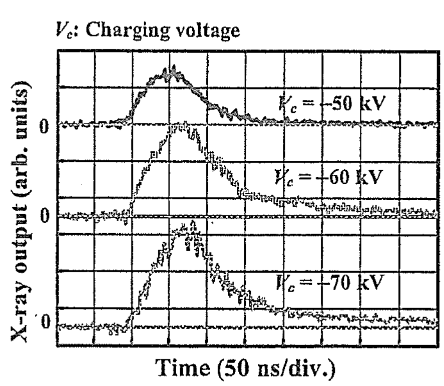


Figure 7: X-ray outputs at indicated conditions.

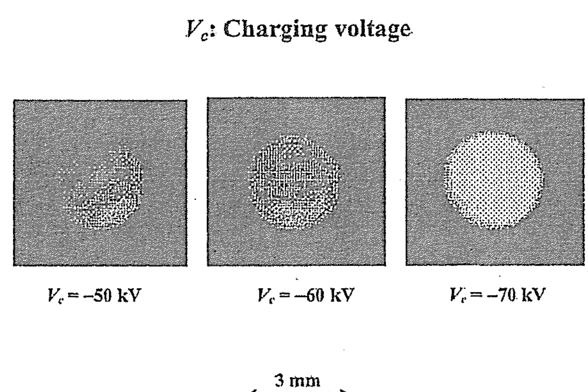


Figure 8: Images of the characteristic x-ray source with changes in charging voltage.

5. ANGIOGRAPHY

The flash angiography was performed by a computed radiography (CR) system (Konica Regius 150) [16] 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 9 shows radiograms of tungsten wires coiled around a rod 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 plastic bullets falling into a polypropylene beaker from a glass test tube is shown in Fig. 10. Because the x-ray duration was approximately 100 ns, the stop-motion image of bullets could be obtained.

Angiograms of rabbit hearts are shown in Fig. 11. This image was obtained using iodine microspheres of 15 μm. Because the microspheres transmitted tungsten K-series characteristic x rays easily, the coronary arteries were barely visible. Figure 12 shows an angiogram of a polytetrafluoroethylene (Teflon) tube using a contrast medium which contains 7.5% gadolinium by weight, and a low contrast tube with an inside diameter of 1.0 mm is observed. Subsequently, a radiogram of gadolinium oxide powder in the Teflon tube is shown in Fig. 13, and the gadolinium oxide powder is visible. In cases where a gadolinium oxide suspension of 50% by weight is employed, high-contrast angiography of the tube could be performed (Fig. 14).

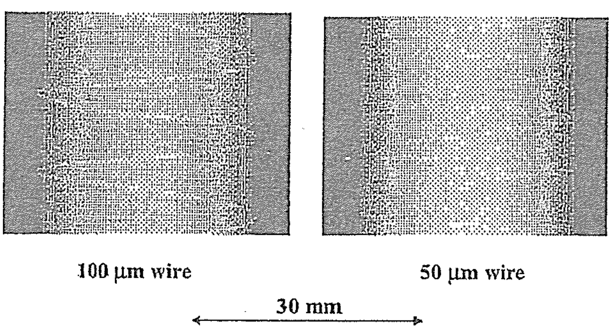


Figure 9: Radiograms of tungsten wires coiled around a rod made of polymethyl methacrylate.

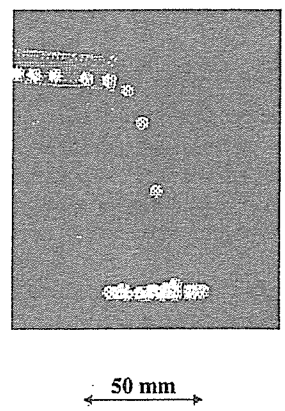


Figure 10: Radiogram of plastic bullets falling into polypropylene beaker from glass test tube.

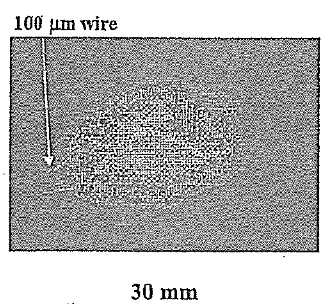


Figure 11: Angiograms of rabbit hearts using iodine microspheres.

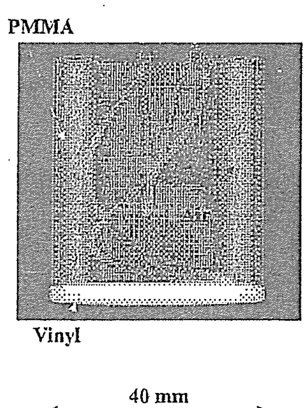


Figure 12: Angiograms of Teflon tube using gadolinium contrast medium of 7.5% by weight.

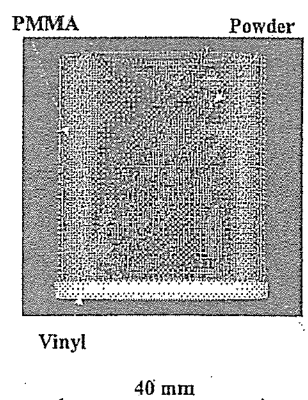


Figure 13: Radiography of gadolinium oxide powder in Teflon tube.

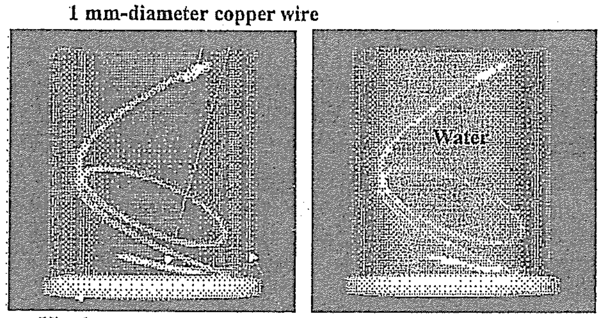


Figure 14: Angiography of Teflon tube using gadolinium oxide suspension of 50 % by weight.

6. DISCUSSION

Concerning the spectrum measurement, we have succeeded in measuring K-series characteristic x rays from a cerium target using a curved-crystal spectrometer. However, the tungsten K-series characteristic x rays could not be measured using the spectrometer utilizing a lithium fluoride crystal, because both the diffraction efficiency and the intensity substantially decreased with increases in photon energy. Therefore, optimum single crystal should be selected, and the measurements of the attenuation curve will be a conventional technique to confirm the irradiation of K-series characteristic x rays; the curve of transmittivity (logarithmic scale) vs absorber thickness is almost linear when bremsstrahlung x rays are not produced. In addition, L-series characteristic rays should be absorbed as much as possible before angiography using a tungsten or an ytterbium oxide filter. In these cases, the photon energies of the K-absorption edge of tungsten and ytterbium are 69.5 and 61.3 keV, respectively.

In this research, the generator produced instantaneous number of $K\alpha$ photons was approximately 5×10^8 photons/cm^2 per pulse at 0.5 m from the source. Because the molybdenum plasma generator produced approximately 2×10^9 photons/cm^2 per pulse at 0.5 m from the source, the x-ray intensity of $K\alpha$ lines had a lower value as compared with the plasma x-ray generator described above, which utilizes a large capacity condenser of approximately 200 nF.

Using this flash x-ray generator, the photon energy of characteristic x rays can be selected, and we plan to design a high-speed photon-counting radiography system in order to decrease noise from radiograms. In addition, steady-state monochromatic x rays for fluoroscopy can be produced by a similar tube using a constant high-voltage power supply. In conjunction with the fine focusing, these low-cost monochromatic x-ray generators will be employed to perform K-edge angiography and x-ray phase imaging for edge enhancement.

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REFERENCES

1. R. Germer, "X-ray flash techniques," *J. Phys. E: Sci. Instrum.*, **12**, 336-350, 1979.
2. 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.
3. 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.
4. 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.
5. 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.
6. 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.
7. 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.
8. 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.
9. 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.
10. 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.
11. 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.
12. A. C. Thompson, H. D. Zeman, G. S. Brown, J. Morrison, P. Reiser, V. Padmanabahn, L. Ong, S. Green, J. Giacomini, H. Gordon and E. Rubenstein, "First operation of the medical research facility at the NSLS for coronary angiography," *Rev. Sci. Instrum.*, **63**, 625-628, 1992.
13. 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.
14. 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.
15. 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.
16. 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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Compact monochromatic flash x-ray generator utilizing a disk-cathode molybdenum tube

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The high-voltage condensers in a polarity-inversion two-stage Marx surge generator are charged from −50 to −70 kV by a power supply, and the electric charges in the condensers are discharged to an x-ray tube after closing gap switches in the surge generator with a trigger device. The x-ray tube is a demountable diode, and the turbo molecular pump evacuates air from the tube with a pressure of approximately 1 mPa. Clean molybdenum Kα lines are produced using a 20 μm-thick zirconium filter, since the tube utilizes a disk cathode and a rod target, and bremsstrahlung rays are not emitted in the opposite direction to that of electron acceleration. At a charging voltage of −70 kV, the instantaneous tube voltage and current were 120 kV and 1.0 kA, respectively. The x-ray pulse widths were approximately 70 ns, and the generator produced instantaneous number of Kα photons was approximately 3×10^7 photons/cm^2 per pulse at 0.5 m from the source of 3.0 mm in diameter. © *2005 American Association of Physicists in Medicine.* [DOI: 10.1118/1.1829247]

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

I. INTRODUCTION

In recent years, many valuable discoveries have been made in laser technology, and soft x-ray lasers of neonlike argon (46.9 nm, 26.4 eV) have been produced using a gas-discharge capillary.[1–3] In these experiments, the laser energy increased with increases in the capillary length, and these kinds of first discharges can generate hot and dense plasma columns with aspect ratios of 1000:1. However, it is difficult to increase the laser photon energy to 10 keV or beyond.

We have developed several different soft flash x-ray generators[4–8] 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 medical radiography. In view of this situation, we confirmed irradiation of intense K-series characteristic x rays from the plasma axial direction by forming weakly ionized linear plasma.[9–12] In the plasma, bremsstrahlung spectra with photon energies of higher than the K-absorption edge are effectively absorbed and are converted into fluorescent x rays, and the plasma then transmits the fluorescent rays easily. However, the bremsstrahlung x rays are produced using a molybdenum target,[11] since high photon energy bremsstrahlung x rays are not absorbed effectively in the linear plasma.

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. As compared with the plasma generator, the photon

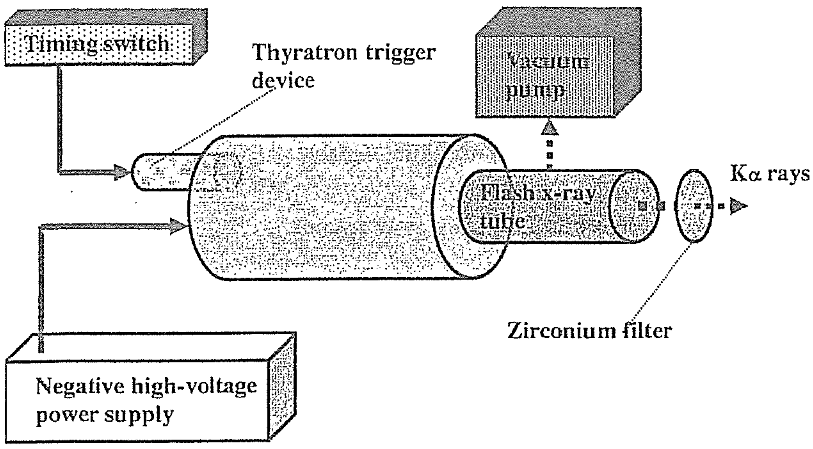

FIG. 1. Block diagram of the compact quasimonochromatic flash x-ray generator with a cold-cathode monochromatic diode.

energy of the characteristic x rays can be increased by increasing the maximum output voltage of the pulse generator, since a multistage Marx generator[13,14] can be employed. In this case, the output voltage is equal to the value of the condenser charging voltage multiplied by the stage number.

In this article, we describe a compact flash x-ray generator utilizing a molybdenum-target radiation tube, used to perform a preliminary experiment for producing clean monochromatic x rays.

II. GENERATOR

A. High-voltage circuit

Figure 1 shows a block diagram of a compact monochromatic flash x-ray generator. This generator consists of the following components: a constant high-voltage power supply, a surge Marx generator with a capacity during main discharge of 425 pF, a thyratron trigger device of the surge generator, a turbo molecular pump, and a flash x-ray tube. Since the electric circuit of the high-voltage pulse generator employs a polarity-inversion two-stage Marx line[13,14] (Fig. 2), the surge generator produces twice the potential of the condenser charging voltage. When two condensers inside of the surge generator are charged from −50 to −70 kV, the ideal output voltage ranges from 100 to 140 kV.

B. X-ray tube

The x-ray tube is a demountable diode type, as illustrated in Fig. 3. This tube is connected to the turbo molecular pump with a pressure of about 1 mPa and consists of the following major devices: a rod-shaped molybdenum 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 tube body. The target-cathode space was regulated to 1.0 mm from the outside of the x-ray tube by rotating the anode rod, and the transmission x rays are obtained through a 1.0 mm-thick graphite cathode and an x-ray window. Because bremsstrahlung rays are not emitted in the opposite direction to that of electron acceleration (Fig. 4), molybdenum $K\alpha$ rays can be produced using a 20 μm-thick zirconium K-edge filter.

III. CHARACTERISTICS

A. Tube voltage and current

Tube voltage and current were measured by a high-voltage divider with an input impedance of 10 kΩ and a current transformer, respectively (Fig. 5). The voltage and current displayed roughly damped oscillations because the discharge resistance in the tube varied rapidly from infinity

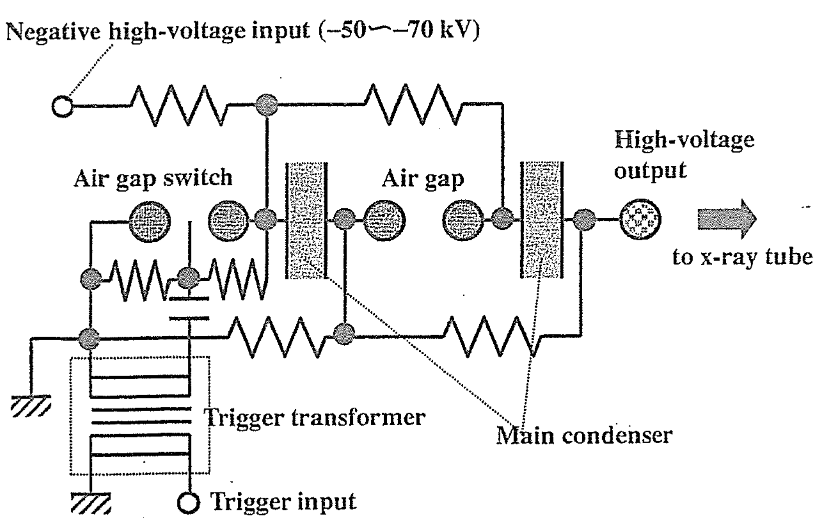

FIG. 2. Circuit diagram of the two-stage surge Marx generator. The generator produces twice the potential of the condenser charging voltage.

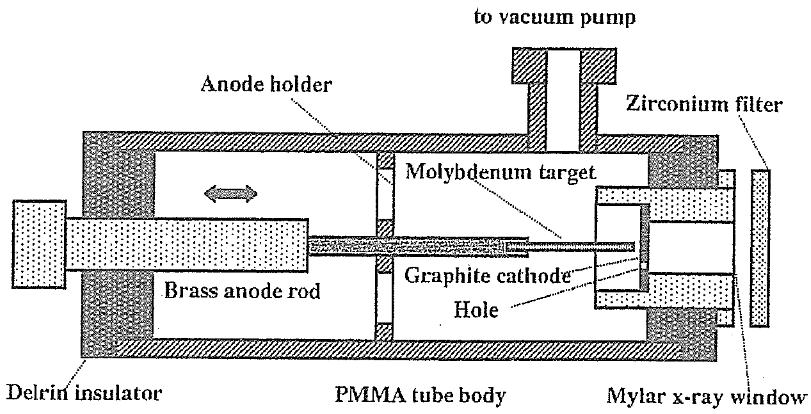

FIG. 3. Schematic drawing of the flash x-ray tube with a rod-shaped molybdenum target and a disk graphite cathode.

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 120 kV and 1.0 kA, respectively, at a charging voltage of -70 kV.

B. X-ray output

X-ray output pulse was detected using a combination of a plastic scintillator, a photomultiplier, and the filter (Fig. 6). When the charging voltage was increased, the pulse height increased, but the width seldom varied. The widths were about 70 ns, and the time-integrated x-ray dose measured by a thermoluminescence dosimeter (Kyokko TLD Reader 1500 having MSO-S elements without energy compensation) had an instantaneous value of approximately 70 μGy per pulse at 0.5 m from the x-ray source with a charging voltage of -70 kV.

C. X-ray source

In order to observe the Kα x-ray source, we employed a 100 μm-diameter pinhole camera, an x-ray film (Polaroid XR-7), and the filter (Fig. 7). When the charging voltage was increased, the spot intensity increased, and the intensities corresponded well to the x-ray pulse height. The dimension was almost equal to the target diameter and had a value of about 3.0 mm.

D. X-ray spectra

X-ray spectra were measured using a transmission-type spectrometer[11] with a lithium fluoride curved crystal 0.5 mm in thickness. The x-ray intensities of the spectra were detected by an imaging plate of a computed radiography (CR) system[15] (Konica Regius 150) with a wide dynamic range, and relative x-ray intensity was calculated from Dicom original digital data corresponding to x-ray intensity; the data was scanned by Dicom viewer in the film-less CR system. Subsequently, the relative x-ray intensity as a function of the data was calibrated using a conventional x-ray generator, and we confirmed that the intensity was proportional to the exposure time. Figure 8 shows measured spectra from the molybdenum target with the filter. In fact, we observed clean Kα lines, while bremsstrahlung rays were hardly detected at all. The Kα intensity substantially increased with increases in the charging voltage.

IV. RADIOGRAPHY

The monochromatic flash radiography was performed by the CR system at 0.5 m from the x-ray source with the filter, and the charging voltage was -70 kV.

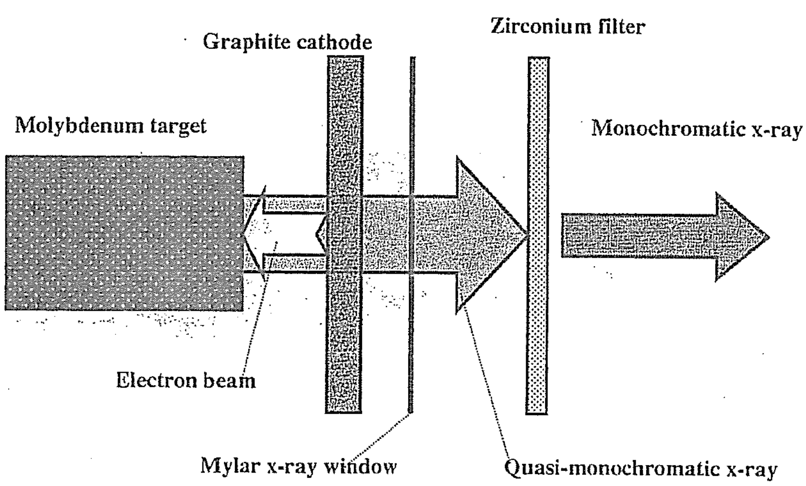

FIG. 4. Irradiation of Kα rays using a monochromatic zirconium filter. Bremsstrahlung rays are not emitted in the opposite direction to that of electron acceleration, and molybdenum Kα rays are left using a zirconium filter.

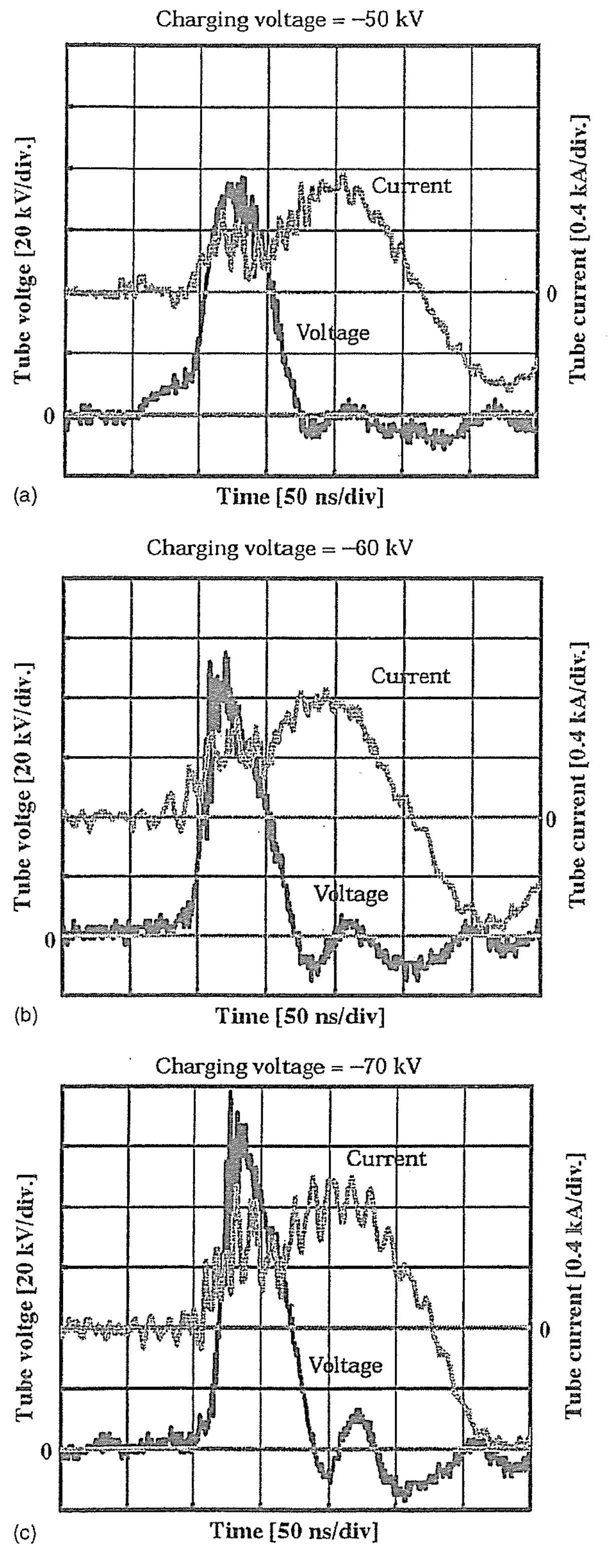

FIG. 5. Variations in the tube voltage and current with a charging voltage of (a) −50 kV, (b) −60 kV, and (c) −70 kV.

First, rough measurements of spatial resolution were made using wires. Figure 9 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.

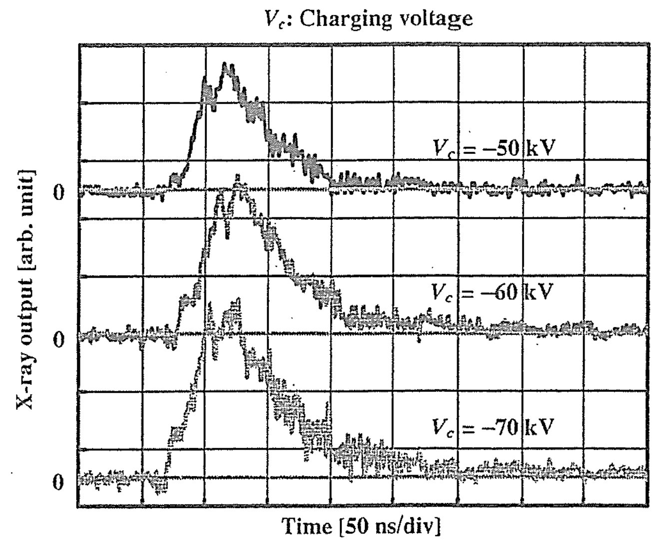

FIG. 6. X-ray outputs detected using a combination of a plastic scintillator, a photomultiplier, and the zirconium filter.

Figure 10 shows a radiogram of a vertebra, and fine structures in the vertebra were observed. Next, the image of water falling into a polypropylene beaker from a glass test tube is shown in Fig. 11. This image was taken with the slight addition of an iodine-based contrast medium. Because the x-ray duration was about 70 ns, the stop-motion image of water could be obtained. Figure 12 shows an angiogram of a rabbit heart; iodine-based microspheres of 15 μm in diameter were used, and fine blood vessels of about 100 μm were visible.

V. DISCUSSION

Concerning the spectrum measurement, we obtained fairly clean molybdenum Kα rays (17.4 keV). Therefore, we are very interested in the measurement the Kα rays from nickel (7.47 keV), copper (8.04 keV), silver (22.1 keV), cerium (34.6 keV), and tungsten (58.9 keV) targets; the target element should be selected corresponding to the radiographic objectives. In a medical application, K-series characteristic x rays of cerium are absorbed effectively by an iodine-based contrast medium with a K-edge of 33.2 keV, and high contrast microangiography can be performed.

In this research, the generator produced instantaneous number of Kα photons was approximately 3×10^7

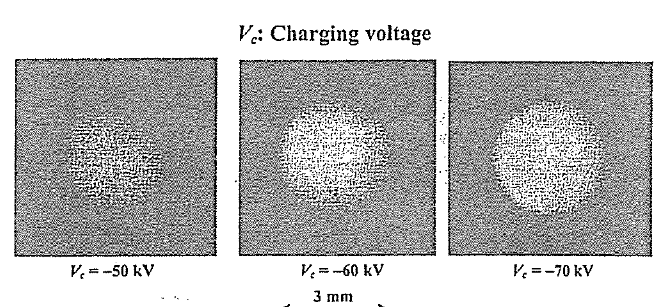

FIG. 7. Images of the x-ray source of Kα lines obtained using a pinhole camera with changes in the charging voltage.

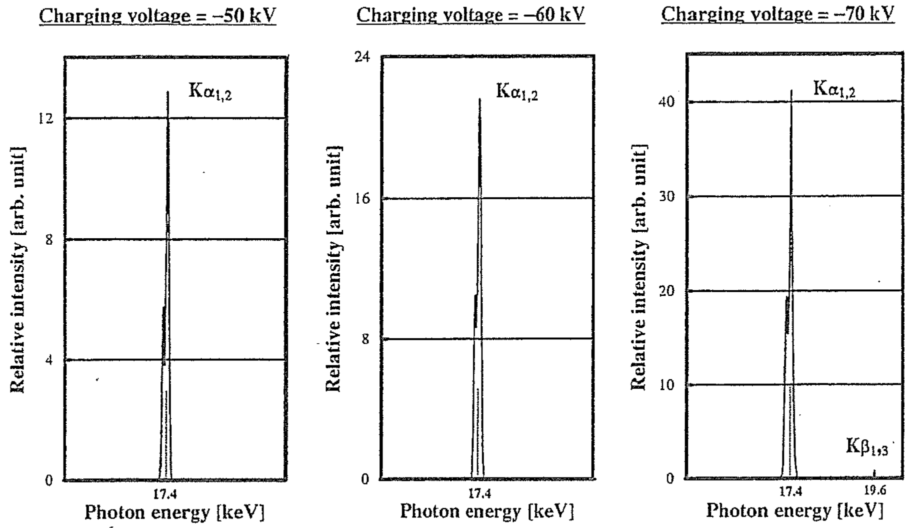

FIG. 8. X-ray spectra from the molybdenum target with the filter. The spectra were measured using a transmission type spectrometer with a lithium fluoride curved crystal.

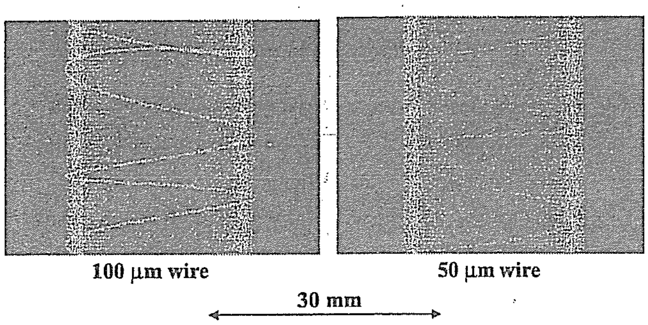

FIG. 9. Radiograms of tungsten wires of 50 and 100 μm in diameter coiled around a pipe made of polymethyl methacrylate. A 50 μm-diameter wire could be observed.

photons/cm^2 per pulse at 0.5 m from the source. Because the molybdenum plasma generator produced approximately 5 $\times 10^8$ photons/cm^2 per pulse at 1.0 m from the source, the x-ray intensity of Kα lines had a lower value as compared with the plasma x-ray generator[11] described above, which utilizes a large capacity condenser of approximately 200 nF. 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 (19.6 keV) lines are produced without using the zirconium filter with a K-edge of 17.9 keV.

Using this flash x-ray generator, the photon energy of characteristic x rays can be selected, and we plan to design a high-speed photon-counting radiography system in order to decrease noise from radiograms. In addition, steady-state

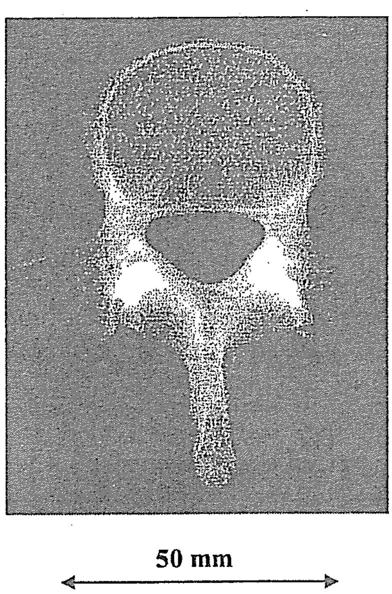

FIG. 10. Radiogram of a vertebra. Fine structure of the vertebra were visible.

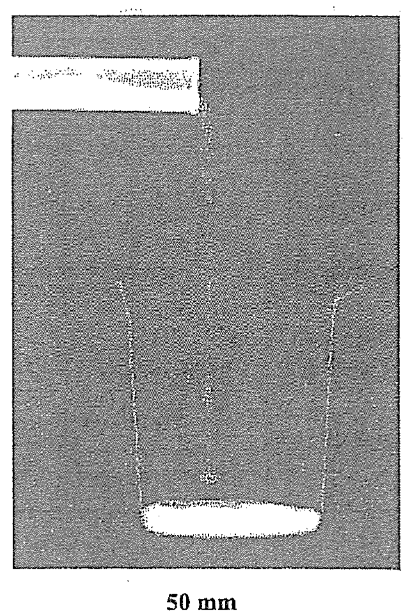

FIG. 11. Radiogram of water falling into a polypropylene beaker from a glass test tube. The stop-motion image of water was obtained by monochromatic flash radiography.

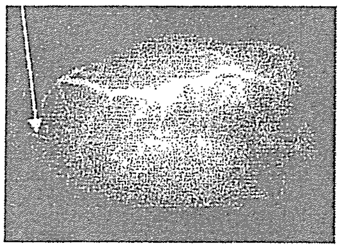

FIG. 12. Angiograms of a rabbit heart. Fine blood vessels of approximately 100 μm were visible.

monochromatic x rays for fluoroscopy can be produced by a similar tube using a constant high-voltage power supply. In conjunction with the fine focusing, these low-cost monochromatic x-ray generators will be employed to perform K-edge angiography and x-ray phase imaging for edge enhancement.[16]

ACKNOWLEDGMENTS

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[1]J. J. Rocca, V. Shlyaptsev, F. G. Tomasel, O. D. Cortazar, D. Hartshorn, and J. L. A. Chilla, "Demonstration of a discharge pumped table-top soft x-ray laser," Phys. Rev. Lett. **73**, 2192–2195 (1994).
[2]J. J. Rocca, D. P. Clark, J. L. A. Chilla, and V. N. Shlyaptsev, "Energy extraction and achievement of the saturation linit in a discharge-pumped table-top soft x-ray amplifier," Phys. Rev. Lett. **77**, 1476–1479 (1996).
[3]C. D. Macchietto, B. R. Benware, and J. J. Rocca, "Generation of millijoule-level soft-x-ray laser pulses at a 4-Hz repetition rate in a highly saturated tabletop capillary discharge amplifier," Opt. Lett. **24**, 1115–1117 (1999).
[4]E. Sato, H. Isobe, and F. Hoshino, "High intensity flash x-ray apparatus for biomedical radiography," Rev. Sci. Instrum. **57**, 1399–1408 (1986).
[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., Part 1 **33**, 4146–4151 (1994).
[8]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).
[9]E. Sato, R. Germer, Y. Hayasi, E. Tanaka, H. Mori, T. Kawai, T. Usuki, K. Sato, H. Obara, M. Zuguchi, T. Ichimaru, H. Ojima, K. Takayama, and H. Ido, "Plasma flash x-ray generator (PFXG-02)," Proc. SPIE **4948**, 604–609 (2002).
[10]E. Sato, Y. Hayasi, R. Germer, E. Tanaka, H. Mori, T. Kwai, T. Ichimaru, K. Takayama, and Hideaki Ido, "Quasi-monochromatic flash x-ray generator utilizing weakly ionized linear copper plasma," Rev. Sci. Instrum. **74**, 5236–5240 (2003).
[11]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).
[12]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).
[13]A. Mattsson, "Some characteristics of a 600 kV flash x-ray tube," Phys. Scr. **5**, 99–102 (1972).
[14]R. Germer, "X-ray flash techniques," J. Phys. E **12**, 336–350 (1979).
[15]E. Sato, K. Sato, and Y. Tamakawa, "Film-less computed radiography system for high-speed imaging," Ann. Rep. Iwate Med. Univ. Sch. Lib. Arts Sci. **35**, 13–23 (2000).
[16]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).

Monochromatic x-ray generator utilizing angle dependence of bremsstrahlung x-ray distribution

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ABSTRACT

This generator consists of the following components: a constant high-voltage power supply, a filament power supply, a turbomolecular pump, and an x-ray tube. The x-ray tube is a demountable diode which is connected to the turbomolecular pump and consists of the following major devices: a molybdenum rod target, a tungsten hairpin cathode (filament), a focusing (Wehnelt) electrode, a polyethylene terephthalate x-ray window 0.25 mm in thickness, and a stainless-steel tube body. In the x-ray tube, the positive high voltage is applied to the anode (target) electrode, and the cathode is connected to the tube body (ground potential). In this experiment, the tube voltage applied was from 22 to 36 kV, and the tube current was regulated to within 100 μA by the filament temperature. The exposure time is controlled in order to obtain optimum x-ray intensity. The electron beams from the cathode are converged to the target by the focusing electrode, and clean Kα rays are produced through the focusing electrode using a 20-μm-thick zirconium filter. The x-ray intensity was 12.1 μGy/s at 1.0 m from the x-ray source with a tube voltage of 30 kV and a tube current of 100 μA, and monochromatic radiography was performed using a computed radiography system.

Keywords: demountable x-ray tube, electron-impact source, monochromatic x-rays, Kα rays, Sommerfeld's theory

1. INTRODUCTION

Recently, we have developed several different flash x-ray generators[1-6] corresponding to specific radiographic objectives, and the plasma x-ray source has been growing with increases in the electrostatic energy in the condenser. By forming weakly ionized linear plasma[7-10] using rod targets, we confirmed irradiation of clean K-series characteristic x-rays such as hard x-ray lasers from the plasma axial direction using a table-top flash x-ray generator. This super fluorescence has been employed to perform cone-beam monochromatic radiography such as iodine K-edge angiography.[11] Furthermore, because higher harmonic hard x-rays have been produced from the copper plasma, we have to confirm the irradiations of higher harmonics with charges in the target element.

At present, brilliant monochromatic parallel x-ray beams from synchrotron radiation are used in various fields including medical imaging,[12-15] and large-scale x-ray free electron laser sources are constructing as a new-generation radiation

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source for producing monochromatic coherent x-rays. In contrast, small-scale steady-state monochromatic parallel and cone beams can be employed to perform medical imaging including phase-contrast radiography and K-edge angiography[16,17] in hospitals.

In this paper, we developed a monochromatic x-ray generator, used to perform a preliminary experiment for generating clean molybdenum Kα rays by angle dependence of the bremsstrahlung x-rays.

2. GENERATOR

Figure 1 shows a block diagram of a compact monochromatic x-ray generator. This generator consists of the following components: a constant high-voltage power supply (SL150, Spellman Inc.), a DC filament power supply, a turbomolecular pump, and an x-ray tube. The structure of the x-ray tube is illustrated in Fig. 2. The x-ray tube is a demountable diode which is connected to the turbomolecular pump with a pressure of approximately 0.5 mPa and consists of the following major devices: a molybdenum rod target 3.0 mm in diameter, a tungsten hairpin cathode (filament), a focusing (Wehnelt) electrode, a polyethylene terephthalate x-ray window 0.25 mm in thickness, and a stainless-steel tube body. In the x-ray tube, the positive high voltage is applied to the anode (target) electrode, and the cathode is connected to the tube body (ground potential). In this experiment, the tube voltage applied was from 22 to 36 kV, and the tube current was regulated to within 100 μA by the filament temperature. The exposure time is controlled in order to obtain optimum x-ray intensity. The electron beams from the cathode are converged to the target by the focusing electrode, and x-rays are produced through the focusing electrode. Because bremsstrahlung rays are not emitted in the opposite direction to that of electron trajectory (Fig. 3), clean molybdenum Kα rays can be produced using a 20-μm-thick zirconium filter.

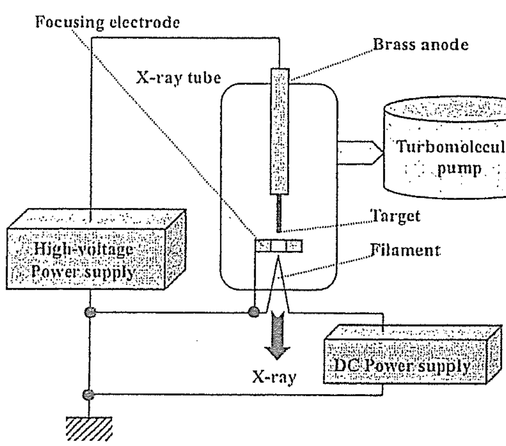

Figure 1: Block diagram including the main transmission line of the compact x-ray generator with a monochromatic diode.

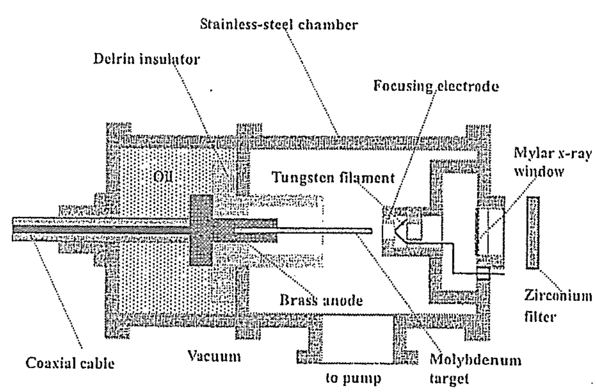

Figure 2: Schematic drawing of the monochromatic x-ray tube.

3. CHARACTERISTICS

3.1 X-ray intensity

X-ray intensity was measured by a Victoreen 660 ionization chamber at 1.0 m from the x-ray source (Fig. 4). At a constant tube current of 100 μA, the x-ray intensity increased when the tube voltage was increased. In this measurement, the intensity with a tube voltage of 30 kV and a current of 100 μA was 12.1 μGy/s at 1.0 m from the source.

3.2 X-ray source

In order to measure images of the x-ray source, we employed a pinhole camera with a hole diameter of 100 μm in conjunction with a computed radiography (CR) system[18] (Fig. 5). When the tube voltage was increased, the spot diameter slightly increased and had a maximum value of approximately 2.3 mm.

3.3 X-ray spectra

X-ray spectra were measured using a transmission-type spectrometer with a lithium fluoride curved crystal 0.5 mm in thickness. The x-ray intensities of the spectra were detected by an imaging plate of the CR system (Konica Minolta Regius 150) with a wide dynamic range, and relative x-ray intensity was calculated from Dicom original digital data corresponding to x-ray intensity; the data was scanned by Dicom viewer in the film-less CR system. Subsequently, the relative x-ray intensity as a function of the data was calibrated using a conventional x-ray generator, and we confirmed that the intensity was proportional to the exposure time. Figure 6 shows measured spectra from the molybdenum target using the filter. We observed clean Kα lines, while bremsstrahlung rays were hardly detected. The Kα intensity substantially increased with increases in the tube voltage.

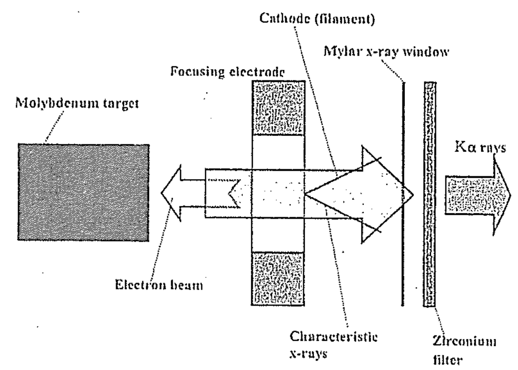

Figure 3: K-photon irradiation from the x-ray tube.

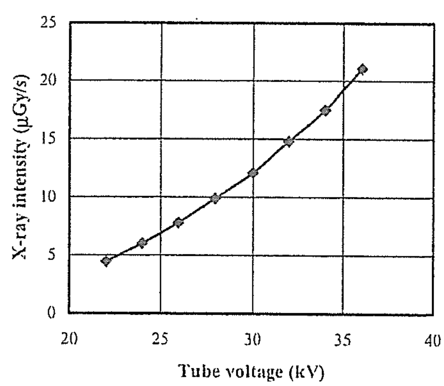

Figure 4: X-ray intensity at 1.0 m from the x-ray source according to changes in the tube voltage.

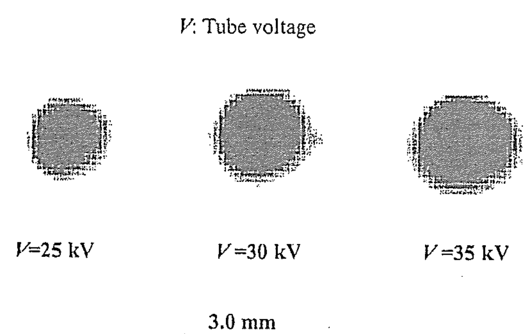

Figure 5: Images of the characteristic x-ray source obtained using a pinhole camera with changes in the tube voltage.

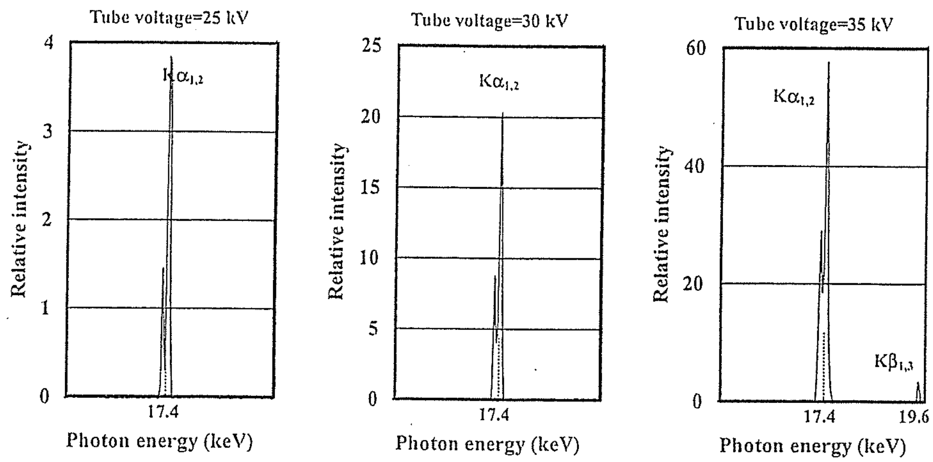

Figure 6: X-ray spectra from the molybdenum target. The spectra were measured using a transmission type spectrometer with a lithium fluoride curved crystal.

4. RADIOGRAPHY

The monochromatic radiography was performed by the CR system at 1.0 m from the x-ray source with the filter, and the tube voltage was 30 kV.
Firstly, rough measurements of image resolution were made using wires. Figure 7 shows radiograms of tungsten wires coiled around pipes made of polymethyl methacrylate (PMMA). Although the image contrast increased with increases in the wire diameter, a 50 μm-diameter wire could be observed.
A radiogram of a vertebra is shown in Fig. 8, and the fine structure of the vertebra was observed. Next, angiography was performed using iodine microspheres of 15 μm in diameter. Figures 9 and 10 show angiograms of a rabbit heart and thigh, respectively, and we could obtained high contrast images of coronary arteries and fine blood vessels.

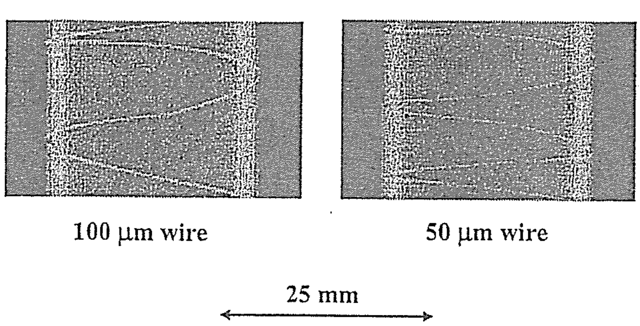

Figure 7: Radiograms of tungsten wires of 50 and 100 μm in diameter coiled around pipes made of polymethyl methacrylate. A 50 μm-diameter wire could be observed.

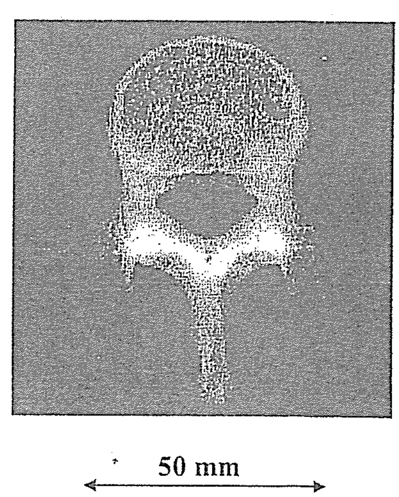

Figure 8: Radiogram of a vertebra. Fine structure of the vertebra were visible.

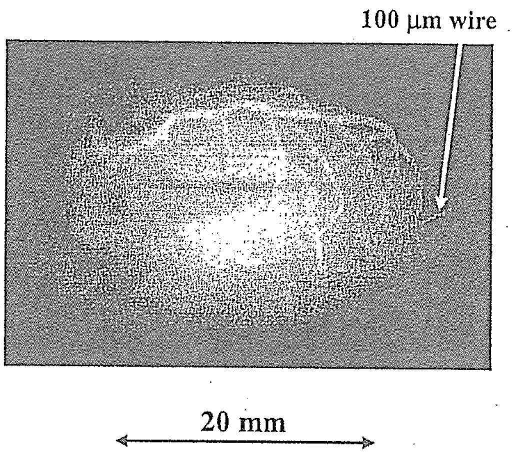

Figure 9: Angiograms of a rabbit heart. Coronary arteries were visible.

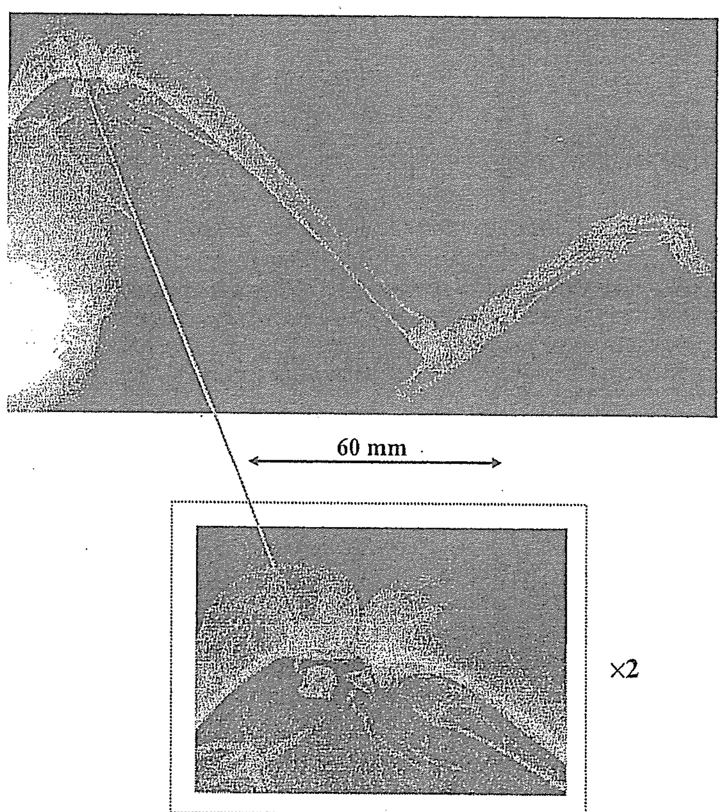

Figure 10: Angiogram of a rabbit thigh. Fine blood vessels of approximately 100 μm in diameter were visible.

5. CONCLUSIONS AND OUTLOOK

We developed a new monochromatic x-ray generator with a molybdenum-target tube and succeeded in producing clean molybdenum $K\alpha$ lines. The $K\alpha$ intensity increased with increases in the tube voltage, and monochromatic $K\alpha$ rays were left by the zirconium filter. Without using the filter, bremsstrahlung x-rays were hardly observed.

In this experiment, although the maximum tube voltage and current were 36 kV and 0.10 mA, the voltage and current could be increased to 100 kV and 1.0 mA, respectively. Under the pulsed operation, the current can be increased to approximately 1 A without considering the target evaporation. Subsequently, the maximum number of characteristic photons was approximately 5×10^6 photons/cm^2· s at 1.0 m from the source, and the photon count rate can be increased easily by increasing the current.

The molybdenum K-series characteristic x-rays are useful for mammography, and the photon energies of characteristic x-rays can be selected by the target element. In particular, enhanced K-edge angiography can be performed using a cerium target because cerium $K\alpha$ rays (34.6 keV) are absorbed easily by iodine-based contrast media with an iodine K-edge of 33.2 keV. Furthermore, low-dose enhanced K-edge angiography can be performed utilizing a tungsten target in conjunction with gadolinium media.

Using these angiographies, coronary arteries and fine blood vessels formed in regenerative medicine may be observed with high contrasts. Furthermore, a flat panel detector is useful to observe blood flows for cases of cardiovascular disease.

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REFERENCES

1. 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.

2. 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.

3. 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.

4. 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.

5. 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.

6. E. Sato, E. Tanaka, H. Mori, T. Kawai, T. Ichimaru, S. Sato, K. Takayama and H. Ido, "Compact monochromatic flash x-ray generator utilizing a disk-cathode molybdenum tube," *Med. Phys.*, **32**, 49-54, 2005.

7. 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.

8. 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.

9. 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.

10. E. Sato, E. Tanaka, H. Mori, T. Kawai,S. Sato and K. Takayama, "Clean monochromatic x-ray irradiation from weakly ionized linear copper plasma," *Opt. Eng.*, 44, 049002-1-6, 2005.

11. E. Sato, R. Germer, E. Tanaka, H. Mori, T. Kawai, T. Ichimaru, S. Sato, H. Ojima, K. Takayama and H. Ido, "Quasi-monochromatic cerium flash angiography," *SPIE*, **5580**, 146-152, 2005.

12. T. J. Davis, D. Gao, T. E. Gureyev, A. W. Stevenson and S. W. Wilkins, "Phase-contrast imagimg of weakly