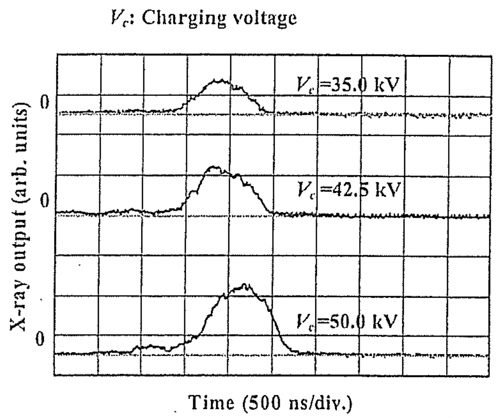


Figure 5: X-ray outputs at the indicated conditions.

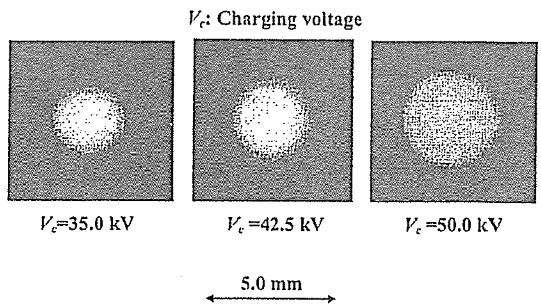


Figure 6: Images of plasma x-ray source.

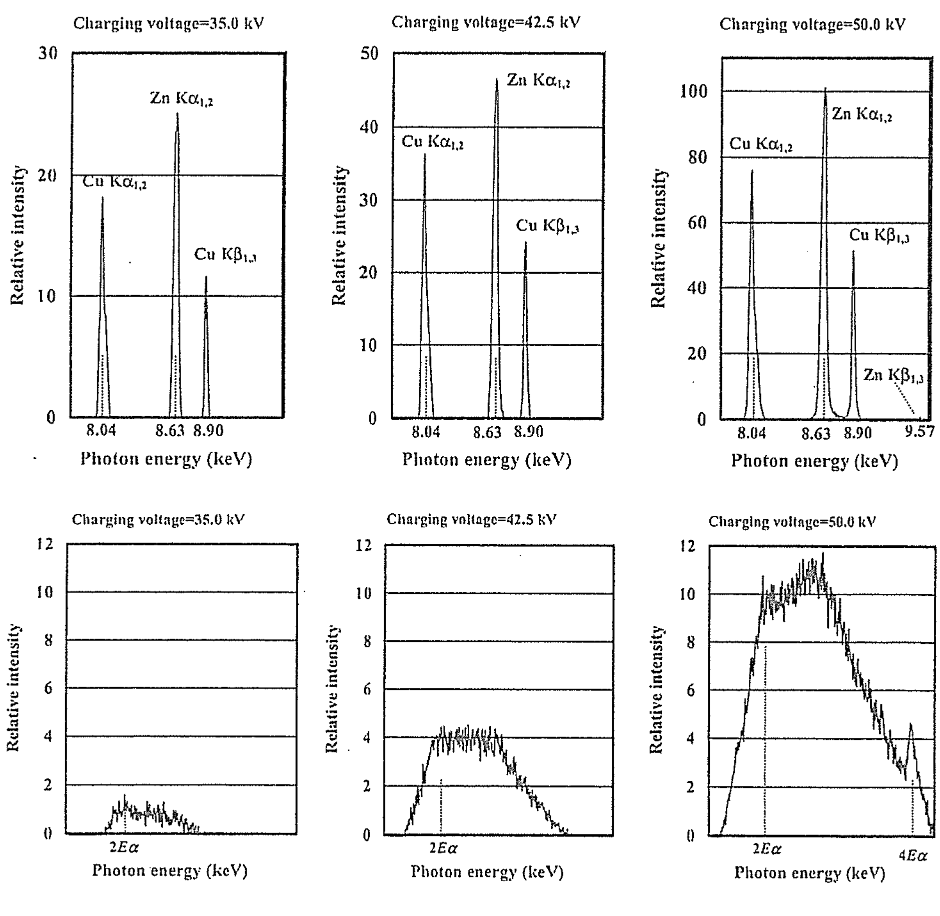


Figure 7: X-ray spectra at the indicated conditions.

3.3 X-ray source

In order to roughly observe images of the plasma x-ray source in the detector plane, 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 target, both the dimension and intensity decreased according to both increases in the thickness of a filter for absorbing x-rays and decreases in the pinhole diameter.

3.4 X-ray spectra

X-ray spectra from the plasma source were measured by a transmission-type spectrometer with a lithium fluoride curved crystal 0.5 mm in thickness. The spectra were taken by a computed radiography (CR) system[15] with a wide dynamic range, and relative x-ray intensity was calculated from Dicom digital data.

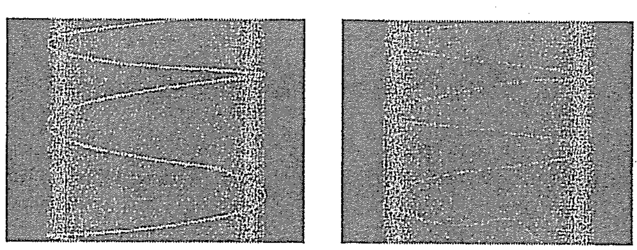
Figure 7 shows measured spectra from weakly ionized metal plasma. We observed sharp lines of K-series characteristic x- rays of copper Kα, copper Kβ and zinc Kα lines. However, zinc Kβ and bremsstrahlung rays were hardly detected. The characteristic x-ray intensity substantially increased with corresponding increases in the charging voltage. In the high-photon-energy region, higher harmonic hard x-rays with photon energies of approximately $2E_\alpha$ and $4E_\alpha$ were observed. Here, E_α is the average photon energies of copper Kα lines.

4. RADIOGRAPHY

The plasma radiography was performed by the CR system (Konica Regius 150) without using a filter, and the charging voltage and the distance (between the x-ray source and imaging plate) were 501 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. Next, the image of aluminum grains falling into a polypropylene beaker from a glass test tube is shown in Fig. 9. Because the x-ray duration was approximately 700 ns, the stop-motion image of grains could be obtained.

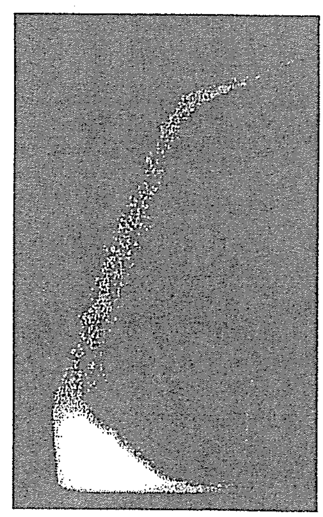
Figures 10 and 11 show angiograms of a rabbit heart and a thigh, respectively. In angiography, iodine-based microspheres of 15 μm in diameter were used, and fine blood vessels of about 100 μm are clearly visible.



100 μm wire　　50 μm wire

25 mm

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



40 mm

Figure 9: Radiogram of aluminum grains from a glass test tube.

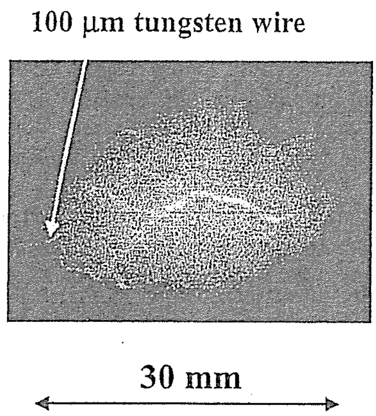


Figure 10: Angiogram of a rabbit heart.

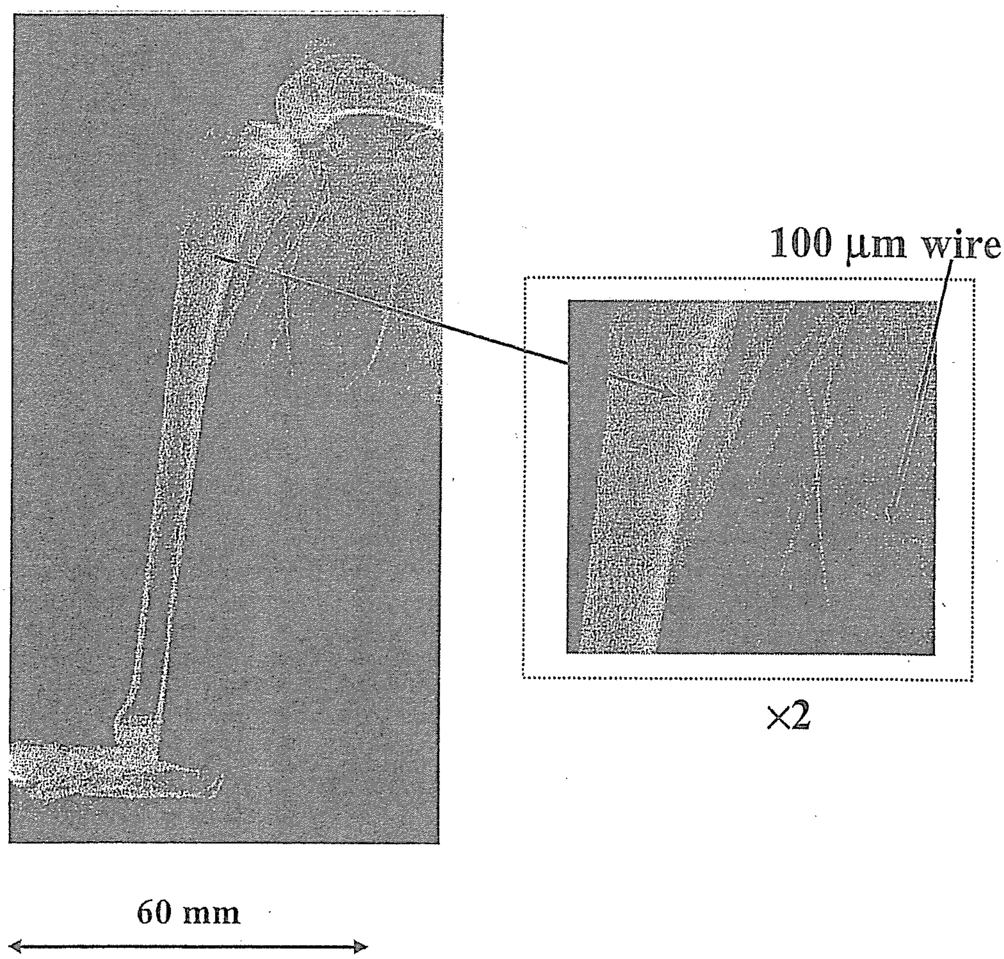


Figure 11: Angiogram of a rabbit thigh.

5. CONCLUSIONS AND OUTLOOK

Regarding the spectrum measurement, although we confirmed clean copper Kα, copper Kβ and zinc Kα lines, zinc Kβ lines were hardly observed. Because weakly ionized zinc plasma (ion) transmits zinc Kβ lines easily, the lines were absorbed by copper plasma. In high-photon-energy region, although we could not observe clean higher harmonics, bremsstrahlung x-rays with photon energies approximately $2E_\alpha$ and $4E_\alpha$ were left in cases where a high charging voltage of approximately 50 kV was applied.

From the experimental results, because the x-ray spectra with photon energies just beyond copper K edge are absorbed effectively by the copper plasma, zinc Kβ rays are useful to produce copper fluorescent rays. In addition, we are very interested in the results using a capillary-type target for forming weakly ionized linear plasma.

In this research, we obtained sufficient characteristic x-ray intensity per pulse for CR radiography, and the generator produced number of characteristic photons was approximately 1×10^8 photons/cm^2 at 1.0 m per pulse. In addition, since the photon energy of characteristic x-rays can be controlled by changing target elements, various quasi-monochromatic high-speed radiographies, such as flash energy subtraction radiography using a metal filter and wide-photon-energy radiography, will be possible.

ACKNOWLEDGMENT

This work was supported by Grants-in-Aid for Scientific Research (13470154, 13877114, 16591181, 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 the Keiryo Research Foundation, The Promotion and Mutual Aid Corporation for Private Schools of Japan, Japan Science and Technology Agency (JST), and the 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. 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. 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.

6. 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.

7. 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.

8. 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.

9. 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.

10. 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.

11. 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.

12. 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.
13. E. Sato, E. Tanaka, H. Mori, T. Kawai, T. Inoue, A. Ogawa, S. Sato, K. Takayama and H. Ido, "High-speed K-edge angiography achieved with tantalum K-series characteristic x rays," *SPIE*, **5745**, 810-817, 2005.
14. H. Obara, E. Sato, E. Tanaka, H. Mori, T. Kawai, S. Sato, H. Ojima, K. Takayama and H. Ido, "Superposition of x-ray spectra using a double-target plasma tube," *SPIE*, **5580**, 824-831, 2005.
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 and Sci.*, **35**, 13-23, 2000.
*obara@rad.cms.tohoku.ac.jp; phone +81-22-717-7941; fax +81-22-717-7944

Intense quasi-monochromatic flash x-ray generator utilizing molybdenum-target diode

Michiaki Sagae*[a], Eiichi Sato[a], Haruo Obara[b], Etsuro Tanaka[c], Hidezo Mori[d], Toshiaki Kawai[e], Shigehiro Sato[f], Hidenori Ojima[g], Kazuyoshi Takayama[g] and Hideaki Ido[h]

[a] Department of Physics, Iwate Medical University, 3-16-1 Honchodori, Morioka 020-0015, Japan
[b] Department of Radiological Technology, College of Medical Science, Tohoku University, 1-1 Seiryocho, Sendai 980-0872, Japan
[c] Department of Nutritional Science, Faculty of Applied Bio-science, Tokyo University of Agriculture, 1-1-1 Sakuragaoka, Setagaya-ku 156-8502, Japan
[d] Department of Cardiac Physiology, National Cardiovascular Center Research Institute, 5-7-1 Fujishirodai, Suita, Osaka 565-8565 Japan
[e] Electron Tube Division #2, Hamamatsu Photonics K. K., 314-5 Shimokanzo, Toyooka Village, Iwata-gun 438-0193, Japan
[f] Department of Microbiology, School of Medicine, Iwate Medical University, 19-1 Uchimaru, Morioka 020-8505, Japan
[g] Shock Wave Research Center, Institute of Fluid Science, Tohoku University, 2-1-1 Katahira, Sendai 980-8577, Japan
[h] Department of Applied Physics and Informatics, Faculty of Engineering, Tohoku Gakuin University, 1-13-1 Chuo, Tagajo 985-8537, Japan

ABSTRACT

In the flash x-ray generator, a 150 nF condenser is charged up to 80 kV by a power supply, and flash x rays are produced by the discharging. The x-ray tube is a demountable diode, and the turbomolecular pump evacuates air from the tube with a pressure of approximately 1 mPa. Since the electric circuit of the high-voltage pulse generator employs a cable transmission line, the high-voltage pulse generator produces twice the potential of the condenser charging voltage. At a charging voltage of 80 kV, the estimated maximum tube voltage and current were approximately 160 kV and 40 kA, respectively. When the charging voltage was increased, the K-series characteristic x-ray intensities of molybdenum increased. The K lines were clean and intense, and hardly any bremsstrahlung rays were detected at all. The x-ray pulse widths were approximately 100 ns, and the time-integrated x-ray intensity had a value of approximately 15 μC/kg at 1.0 m from the x-ray source with a charging voltage of 80 kV.

Keywords: flash x-ray, energy-selective radiography, characteristic x rays, quasi-monochromatic x rays, bremsstrahlung x-ray distribution

1. INTRODUCTION

In recent years, there have been several investigations dealing with the production of monochromatic x rays in radiology and cardiology. Particularly, monochromatic parallel beams using synchrotrons have been employed to perform enhanced K-edge angiography[1,2] and x-ray phase imaging.[3,4] In angiography, parallel beams with photon energies of approximately 35 keV have been employed, since these beams are absorbed effectively by an iodine-based contrast medium. Subsequently, in cases where phase imaging is employed, the spatial resolution can be improved, and the number of tissues which can be observed using x rays increases.

In order to perform biomedical radiography, we have developed several different soft flash x-ray generators[5-10] corresponding to specific radiographic objectives. Subsequently, electron impact flash x-ray sources can produce quasi-monochromatic x rays, because bremsstrahlung rays are not emitted in the opposite direction to that of electron

26th International Congress on High-Speed Photography and Photonics, edited by D. L. Paisley, S. Kleinfelder, D. R. Snyder, B. J. Thompson, Proc. of SPIE Vol. 5580 (SPIE, Bellingham, WA, 2005) · 0277-786X/05/$15 · doi: 10.1117/12.581246

acceleration.[11] Therefore, the sources will be conventional x-ray tubes for producing cone-beam K-series characteristic x rays, and monochromatic $K\alpha$ rays are obtained using a K-edge filter.

We have developed several different plasma flash x-ray generators[12-16] corresponding to specific radiographic objectives, and a major goal in our research is the development of an intense and sharp monochromatic x-ray generator that can impact applications with biomedical radiography. By forming weakly ionized linear plasma, because we have succeeded in producing fairly intense and clean K-series characteristic x rays. Without forming the linear plasma, characteristic x rays can be produced by considering the angle dependence of bremsstrahlung x rays. On the other hand, the electrostatic energy in the main discharge condenser should be increased as much as possible to increase the characteristic x-ray intensity.

In this paper, we describe an intense single flash x-ray generator utilizing a rod-target radiation tube, used to perform a preliminary experiment for generating intense and clean molybdenum K-series characteristic x rays.

2. GENERATOR

2.1 High-voltage circuit

Figure 1 shows a block diagram of a high-intensity plasma flash x-ray generator. The generator consists of the following essential components: a high-voltage power supply, a high-voltage condenser with a capacity of approximately 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 (Fig. 2).

2.2 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 molybdenum 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), molybdenum K-series characteristic x rays can be produced without using a filter.

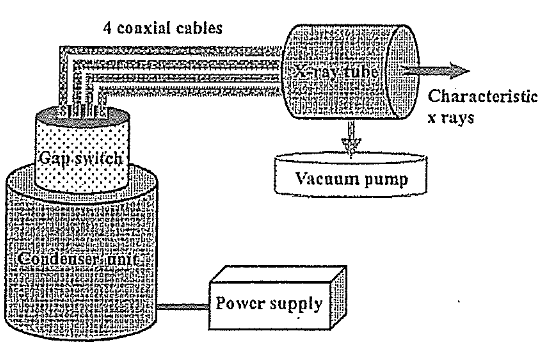


Figure 1: Block diagram of intense quasi-monochromatic flash x-ray generator.

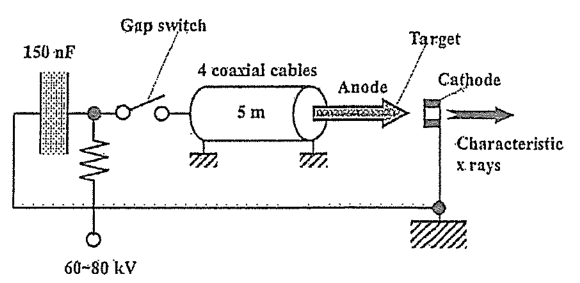


Figure 2: Circuit diagram of flash x-ray generator.

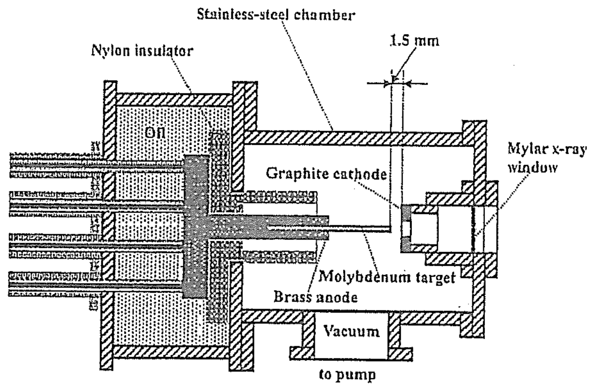


Figure 3: Schematic drawing of flash x-ray tube.

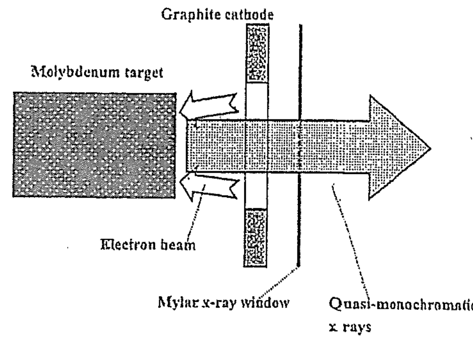


Figure 4: Irradiation of characteristic x rays.

3. CHARACTERISTICS

3.1 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 displayed 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.

3.2 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 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 15 μC/kg at 1.0 m from the x-ray source with a charging voltage of 80 kV.

3.3 X-ray source

In order to observe the characteristic 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.

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 by a computed radiography (CR) system (Konica Regius 150)[17] with a wide dynamic range, and relative x-ray intensity was calculated from Dicom digital data. Figure 7 shows measured spectra from the molybdenum 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.

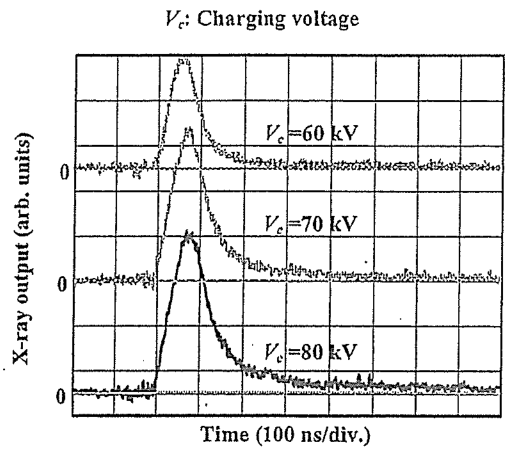


Figure 5: X-ray outputs at indicated conditions.

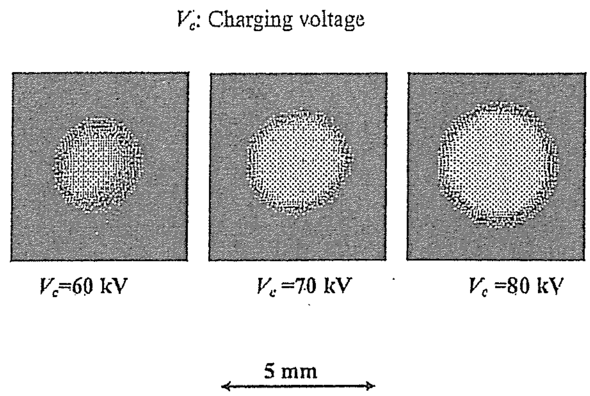


Figure 6: Images of characteristic x-ray source.

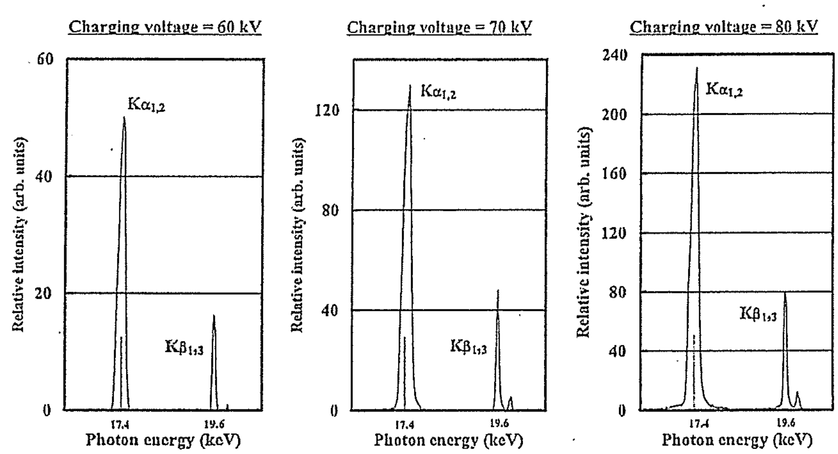


Figure 7: X-ray spectra from molybdenum target.

4. RADIOGRAPHY

The quasi-monochromatic flash radiography was performed by the CR system at 1.2 m from the x-ray source. Firstly, rough measurements of spatial resolution were made using wires. Figure 8 shows radiograms of tungsten wires coiled around a pipe made of polymethyl methacrylate with a charging voltage (V_c) of 70 kV. Although the image contrast increased with increases in the wire diameter, a 50-μm-diameter wire could be observed.

Figure 9 shows a radiogram of a vertebra with a V_c of 70 kV, and fine structures in the vertebra were observed. Figures 10 and 11 shows an angiogram of a rabbit heart (V_c=70 kV) and thigh (V_c=80 kV), respectively. In angiography, iodine-based microspheres of 15 μm in diameter were used, and fine blood vessels of about 100 μm were visible. Next, the image of aluminum grains falling into a polypropylene beaker from a glass test tube with a V_c of 80 kV is shown in Fig. 12. Because the x-ray duration was approximately 100 ns, the stop-motion image of grains could be obtained.

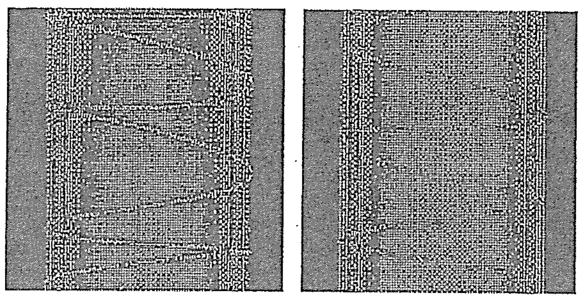


Figure 8: Radiograms of tungsten wires coiled around pipe made of polymethyl methacrylate.

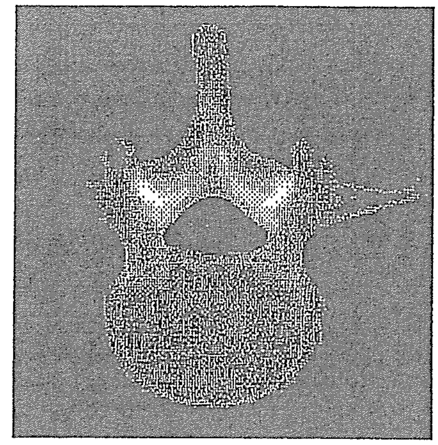


Figure 9: Radiogram of vertebra.

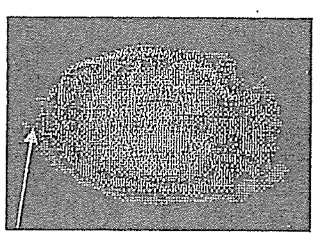


Figure 10: Angiograms of rabbit heart.

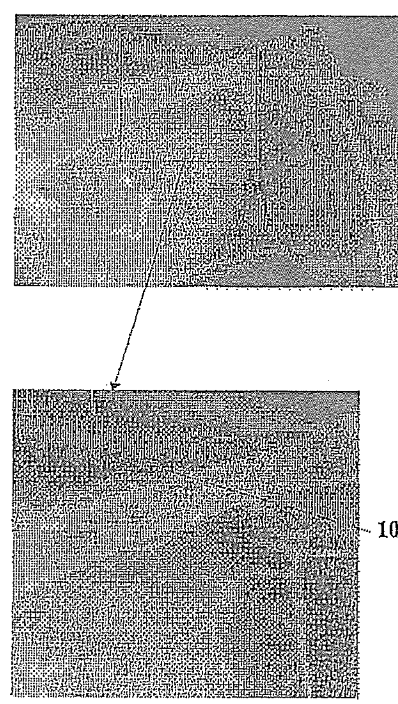


Figure 11: Angiograms of rabbit thigh.

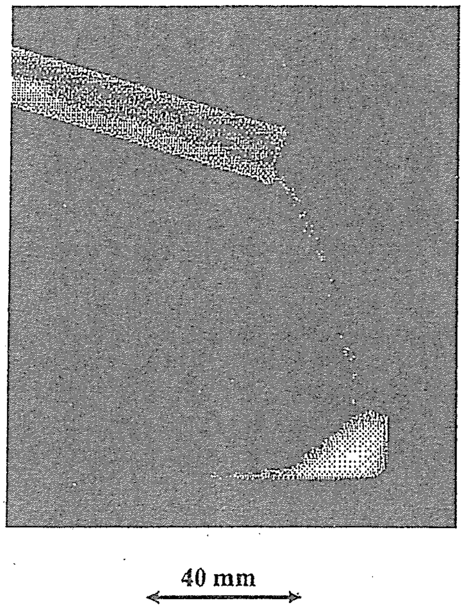


Figure 12:. Radiogram of aluminum grains falling into polypropylene beaker from glass test tube.

5. DISCUSSION

Concerning the spectrum measurement, we obtained fairly clean molybdenum Kα (17.4 keV) and Kβ (19.6 keV) lines. Therefore, we are very interested in the measurement the characteristic rays from nickel, copper, silver, cerium, and tungsten 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 enhanced K-edge angiography can be performed.

In this research, the generator produced instantaneous number of K photons was approximately 2×10^8 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 left using a 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. As compared with a steady-state x-ray generator, demonstrations of various monochromatic radiography will be accomplished easily, since the target element can be changed easily.

ACKNOWLEDGMENT

This work was supported by Grants-in-Aid for Scientific Research (13470154, 13877114, 16591181, 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. E. Sato, H. Isobe and F. Hoshino, "High intensity flash x-ray apparatus for biomedical radiography," *Rev. Sci. Instrum.*, **57**, 1399-1408, 1986.
6. 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.
7. E. Sato, M. Sagae, K. Takahashi, T. Oizumi, H. Ojima, K. Takayama, Y. Tamakawa, T. Yanagisawa, A. Fujiwara and K. Mitoya, "High-speed soft x-ray generators in biomedicine," *SPIE*, **2513**, pp. 649-667, 1994.
8. 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.
9. 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.
10. 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.
11. 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.
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. 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.
14. 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.
15. 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.
16. 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.
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.
*msagae@iwate-med.ac.jp; phone, phone +81-19-651-5111; fax +81-19-654-9282

Japanese Journal of Applied Physics
Vol. 44, No. 1A, 2005, pp. 446–449

Quasi-Monochromatic X-Ray Generator Utilizing Graphite Cathode Diode with Transmission-Type Molybdenum Target

Michiaki SAGAE, Eiichi SATO, Etsuro TANAKA[1], Yasuomi HAYASI, Hidezo MORI[2], Toshiaki KAWAI[3], Toshio ICHIMARU[4], Shigehiro SATO[5], Kazuyoshi TAKAYAMA[6] and Hideaki IDO[7]

Department of Physics, Iwate Medical University, 3-16-1 Honchodori, Morioka 020-0015, Japan
[1]*Department of Nutritional Science, Faculty of Applied Bio-science, Tokyo University of Agriculture, 1-1-1 Sakuragaoka, Setagaya-ku 156-8502, Japan*
[2]*Department of Cardiac Physiology, National Cardiovascular Center Research Institute, 5-7-1 Fujishiro-dai, Suita, Osaka 565-8565, Japan*
[3]*Electron Tube Division #2, Hamamatsu Photonics K.K., 314-5 Shimokanzo, Toyooka Village, Iwata-gun 438-0193, Japan*
[4]*Department of Radiological Technology, School of Health Sciences, Hirosaki University, 66-1 Honcho, Hirosaki 036-8564, Japan*
[5]*Department of Microbiology, School of Medicine, Iwate Medical University, 19-1 Uchimaru, Morioka 020-8505, Japan*
[6]*Shock Wave Research Center, Institute of Fluid Science, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai 980-8577, Japan*
[7]*Department of Applied Physics and Informatics, Faculty of Engineering, Tohoku Gakuin University, 1-13-1 Chuo, Tagajo 985-8537, Japan*

(Received June 19, 2004; accepted October 15, 2004; published January 11, 2005)

An X-ray generator consists of a negative high-voltage power supply and a field-emission-type cold-cathode X-ray tube. The tube is a glass-enclosed diode utilizing a transmission-type molybdenum target with a thickness of 20 μm, a needle graphite (carbon) cathode, a glass tube body, and a 0.5-mm-thick beryllium window. The tube current decreases gradually with time. After aging for 30 minutes, the tube current was approximately 0.2 mA with a tube voltage of 25 kV, and the focal-spot dimensions were 2.2×1.6 mm. Characteristic X-rays of molybdenum K-series were obtained after penetrating the molybdenum target and the beryllium window, and the K-absorption edge was observed clearly. The generator produced number of K photons was approximately 4×10^6 photons/cm^2·s at 1.0 m from the source. The average photon energies of Kα and Kβ lines were 17.4 and 19.6 keV, respectively, and quasi-monochromatic radiography was performed using a computed radiography system. [DOI: 10.1143/JJAP.44.446]

KEYWORDS: quasi-monochromatic X-rays, characteristic molybdenum X-rays, field emission, transmission target, quasi-monochromatic radiography

1. Introduction

Conventional medical X-ray tubes enable the observation of parts of the inside of the human body that cannot be seen by other ways. The X-ray images obtained with these tubes are exposed by both the bremsstrahlung and characteristic X-rays, unless monochromatic radiography is specifically performed. Monochromatic parallel X-ray beams are produced by synchrotrons using single crystals, and these beams have been employed to perform enhanced K-edge angiography[1–3] and X-ray phase imaging.[4,5] Subsequently, monochromatic X-ray computed tomography at two different energies has provided information on the electron density of human tissue.[6] In addition, a compact pulsed tunable monochromatic X-ray source has been designed, developed, and tested.[7] From the source, conical X-ray beams from 10 to 50 keV with pulse widths of 8 ps have been produced, and these beams are useful for biomedical imaging and protein crystallography.

Currently, flash X-ray generators[8–12] utilize cold-cathode radiation tubes and produce extremely high-dose-rate X-ray pulses with durations of less than 1 μs. In order to produce monochromatic X-rays, plasma flash X-ray generators are useful, since intense and sharp characteristic X-rays have been produced from weakly ionized linear plasmas of nickel,[13] copper[14] and molybdenum,[15] while bremsstrahlung rays are rarely detected.

In order to produce steady-state X-rays using a cold-cathode tube, the combination of the target and cathode electrodes is a very important factor. In view of the cathode, a carbon nanotube[16] is a useful field emitter and can be used as a cold cathode in an X-ray tube. Without using nanotubes, electrons can be emitted comparatively easily when lines of electric force are concentrated on a needle tip. Characteristic K-series X-rays have been obtained using a filter made of the same element as the target.

In the present research, we developed a cold-cathode X-ray tube with a needle-shaped graphite cathode, and applied it to produce characteristic molybdenum K-series X-rays by uisng a transmission target.

2. Generator

Figure 1 shows the block diagram of the X-ray generator, which consists of a negative high-voltage power supply (Model 500, −100 kV-3 mA, Pulse Electric Eng. Inc.) with dimensions of $450 \times 430 \times 150$ mm and an X-ray tube. In the X-ray tube, the negative high voltage is applied to the cathode electrode, and the anode (target) is connected to the ground potential.

The X-ray tube is a cold-cathode diode type, as illustrated in Fig. 2. In order to perform soft radiography, including mammography, we developed a quasi-monochromatic X-ray tube with a molybdenum target. This tube consists of the following major devices: a needle-shaped graphite cathode with a tip angle of 54° and a diameter of 3.0 mm, a

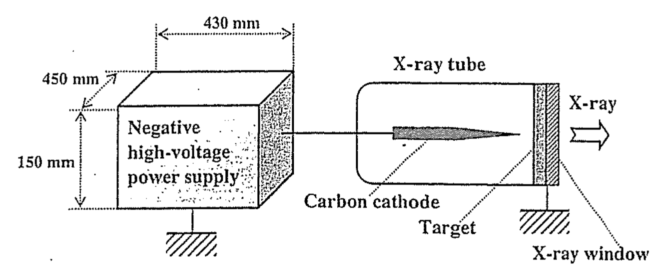


Fig. 1. Block diagram of quasi-monochromatic X-ray generator with cold-cathode diode.

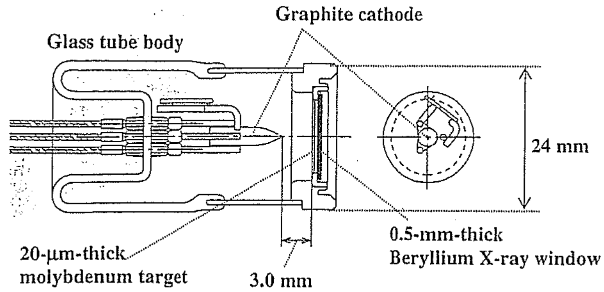


Fig. 2. Structure of X-ray tube.

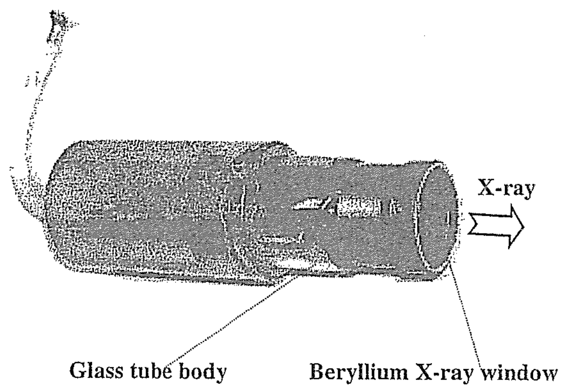


Fig. 3. Cold-cathode X-ray tube with transmission-type molybdenum target.

molybdenum disk target 20 μm thick, and a glass tube body. The target-cathode distance is 3.0 mm, and the transmission X-rays are obtained after the beam passes through the target and a 0.5-mm-thick beryllium X-ray window (Fig. 3). In this case, since the target plays the role of a K-edge filter for effectively absorbing bremsstrahlung X-rays with energies higher than the K-absorption edge, characteristic K-series X-rays are produced. The pressure in the glass-enclosed tube is primarily determined by the pressure when evacuation is stopped, and is approximately 1×10^{-4} Pa. The tube voltage is always constant and is regulated by the constant voltage power supply. Subsequently, the tube current is primarily determined by the tube voltage and the target-cathode distance, and increases with decreasing distance and increasing voltage.

In this experiment, the tube voltage applied was from 20 to 30 kV, and the exposure time was controlled in order to obtain optimum X-ray intensity for radiography.

3. Characteristics

3.1 X-ray intensity

In the field emission X-ray tube, it was very difficult to measure the X-ray intensity correctly, since the intensity gradually decreased during exposure, and small-scale vacuum breakdown may often occur. The X-ray intensity was measured using a Solidose 308 M ionization chamber for mammography at 1.0 m from the X-ray source with an exposure time of 10 s. Because the tube current increased when the tube voltage was increased, the X-ray intensity increased substantially with increasing tube voltage. In this measurement, the intensity rate with a tube voltage of 25 kV was approximately 0.3 μC/kg·s (=10 μJ/kg·s = 10 μGy/s) at 1.0 m from the source.

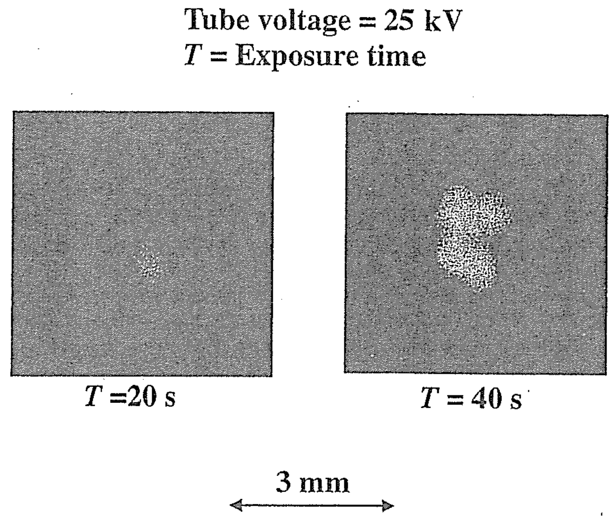


Fig. 4. Images of X-ray source with changes in exposure time.

3.2 X-ray source

In order to measure the images of the X-ray source, we employed a pinhole camera with a hole diameter of 100 μm in conjunction with a Polaroid XR-7 (film). When the exposure time was increased with a tube voltage of 25 kV, the spot intensity increased, but the spot dimensions seldom varied and had values of 2.2×1.6 mm (Fig. 4).

3.3 Cathode voltage and tube current

Cathode voltage and tube current were measured using a high-voltage divider and a resistor, respectively (Figs. 5 and 6). In this generator, the cathode voltage is −1 times the tube voltage, and we observed stable cathode voltages. Thereafter, the tube current increased exponentially with increasing tube voltage in a short time. In addition, the current was unstable, and decreased gradually with time.

3.4 X-ray spectra

X-ray spectra were measured using a transmission-type spectrometer with a curved lithium fluoride crystal 0.5 mm thick. The spectra were taken using a computed radiography (CR) system (Konica Regius 150)[17] with a wide dynamic range, and relative X-ray intensity was calculated from Dicom digital data. Figure 7 shows the measured spectra from the transmission-type molybdenum target. We observed lines of characteristic K-series X-rays and K-absorption edges of molybdenum. The characteristic X-ray intensity of the $K\alpha$ and $K\beta$ lines increased substantially when the tube voltage was increased.

4. Radiography

Radiography was performed using the CR system with a sampling pitch of 87.5 μm. The distance between the X-ray source and the imaging plate was 1.0 m.

Spatial resolution was roughly measured using wires. Radiograms of tungsten wires coiled around a pipe made of polymethyl methacrylate are shown in Fig. 8. Although the

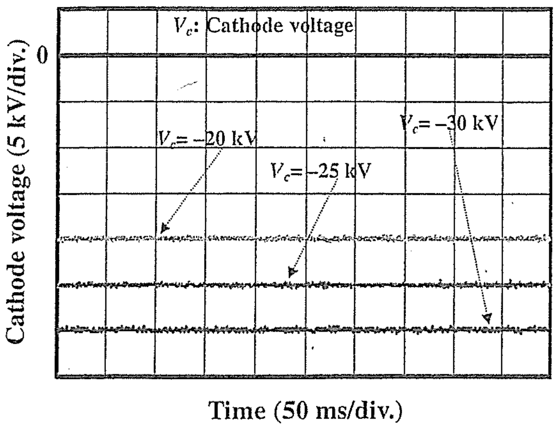


Fig. 5. Cathode voltages.

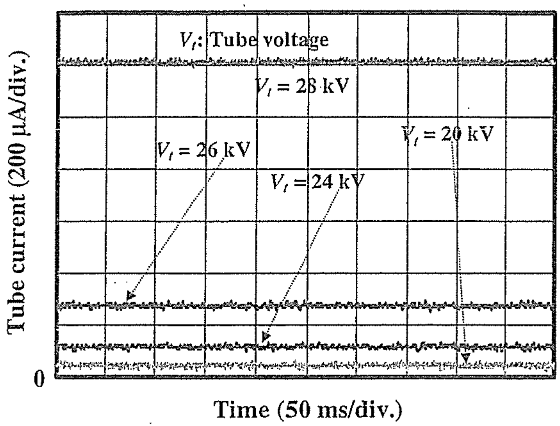


Fig. 6. Tube currents.

image contrast decreased somewhat with decreasing wire diameter due to blurring of the image caused by the sampling pitch, a 50-μm-diameter wire could be observed.

Figures 9 and 10 show angiograms of hearts. Iodine-based microspheres of 15 μm in diameter were used, and coronary

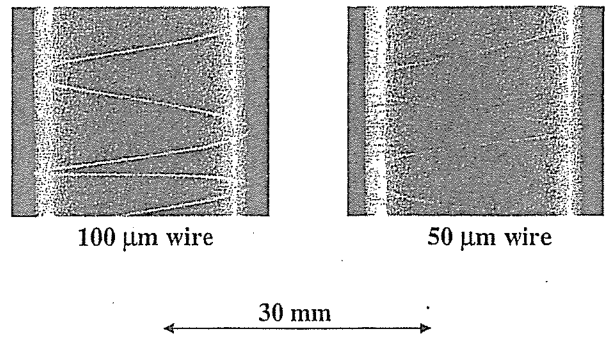


Fig. 8. Radiograms of tungsten wires of 50 and 100 μm diameter coiled around a pipe made of polymethyl methacrylate with tube voltage of 25 kV and exposure time of 20 s.

arteries and fine blood vessels of approximately 100 μm diameter were visible.

5. Discussion

In summary, we developed a simple X-ray generator with the cold-cathode diode and succeeded in producing characteristic molybdenum K-series X-rays using the transmission target as the K-edge filter. Subsequently, we confirmed the filtering effect of the target, and bremsstrahlung X-rays with photon energies higher than the edge were rarely detected with a tube voltage of 23 kV.

The current density J (A/cm^2) under field emission is written as:

$$J = 1.54 \times 10^{-6}(V/d)^2 \cdot \exp(-6.8 \times 10^7 \phi^{1.5} d/V)/\phi, \quad (1)$$

where V (V) is the tube voltage, d (cm) is the target-cathode distance, and ϕ (V) is the work function of the cathode element. Therefore, the current values in Fig. 6 corresponded qualitatively to eq. (1).

During the X-ray exposure, although the tube current decreases slightly due to ion sputtering, stable current flow can be obtained by selecting the appropriate cathode material and by controlling the radius of curvature of the cathode tip. In addition, the generator-produced number of

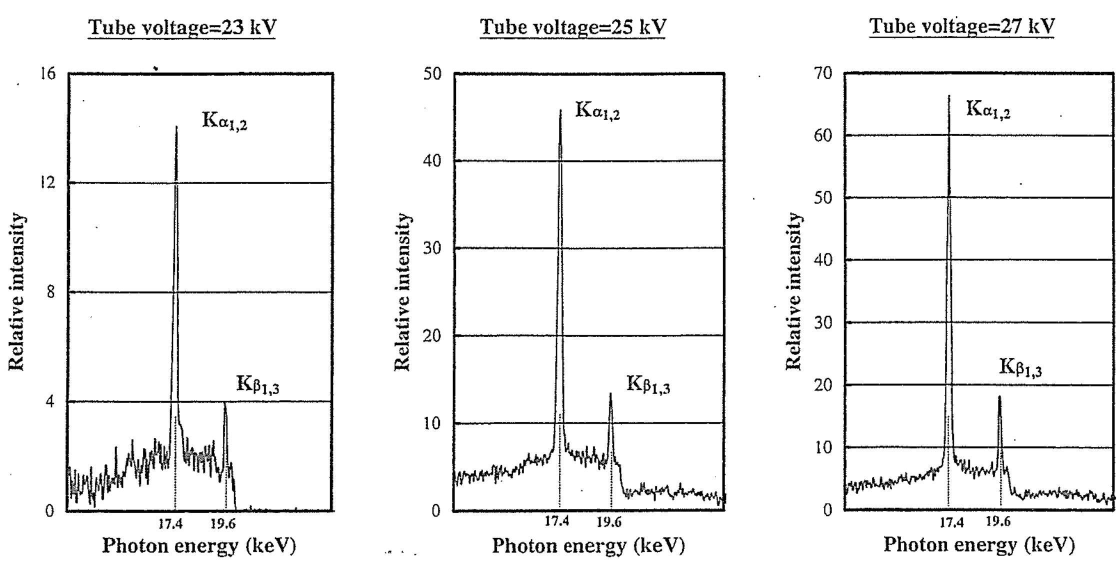


Fig. 7. X-ray spectra.

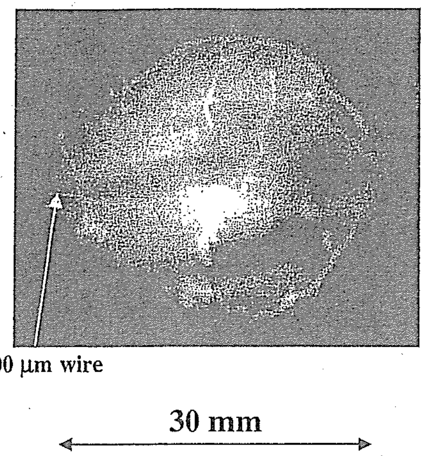


Fig. 9. Angiogram, using iodine microspheres, of extracted rabbit heart. Tube voltage and exposure time were 25 kV and 20 s, respectively.

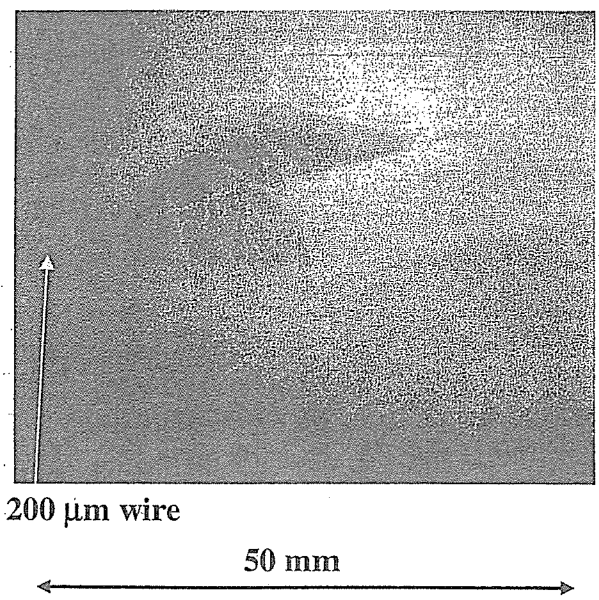


Fig. 10. Angiogram of extracted dog heart with tube voltage of 25 kV and exposure time of 60 s.

characteristic photons was approximately 4×10^6 photons/cm^2·s at 1.0 m from the source with a tube voltage of 25 kV, and the photon count rate could be increased easily by increasing the tube voltage and current.

The focal spot dimensions decrease with decreasing target-cathode space, and the distance between the X-ray source and the imaging plate should be increased as much as possible to improve the spatial resolution. In soft radiography achieved with characteristic molybdenum K-series X-rays, because an X-ray lens such as a polycapillary plate[18] can be employed, the spatial resolution may be improved by decreasing the inner capillary diameter.

Under the pulsed operation, the high-voltage durability increases substantially, and both the size of the X-ray tube and the diameter of the high-voltage coaxial cable can be decreased. In this case, because the time-average tube current is regulated by the pulse repetition rate, both the tube voltage and the current can be controlled without using a hot cathode.

Recently, we developed a cerium-target X-ray tube to perform enhanced K-edge angiography utilizing cerium Kα rays (34.6 keV), since the rays are absorbed effectively by iodine-based contrast media with a K-edge of 33.2 keV. In addition, Kα rays from ytterbium (52.0 keV), tantalum (57.1 keV), and tungsten (58.9 keV) targets are very useful for performing K-edge angiography using gadolinium-based contrast media with an edge of 50.2 keV. Hence, using these rays, because the absorbed dose can be decreased effectively, extremely low-dose angiography can 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, Grants from Keiryo Research Foundation, The Promotion and Mutual Aid Corporation for Private Schools of Japan, JST, NEDO, and MHLW (HLSRG, RAMT-nano-001, RHGTEFB-genome-005, and RGCD13C-1).

1) 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: Rev. Sci. Instrum. **63** (1992) 625.
2) H. Mori *et al.*: Radiology **201** (1996) 173.
3) K. Hyodo, M. Ando, Y. Oku, S. Yamamoto, T. Takeda, Y. Itai, S. Ohtsuka, Y. Sugishita and J. Tada: J. Synchrotron Rad. **5** (1998) 1123.
4) T. J. Davis, D. Gao, T. E. Gureyev, A. W. Stevenson and S. W. Wilkims: Nature **373** (1995) 595.
5) A. Momose, T. Takeda, Y. Itai and K. Hirano: Nature Medicine **2** (1996) 473.
6) M. Torikoshi, T. Tsunoo, M. Sasaki, M. Endo, Y. Noda, T. Kohno, K. Hyodo, K. Uesugi and N. Yagi: Phys. Med. Biol. **48** (2003) 673.
7) F. E. Carroll, M. H. Mendenhall, R. H. Traeger, C. Brau and J. W. Waters: Am. J. Roentgenol. **181** (2003) 1197.
8) R. Germer: J. Phys. E: Sci. Instrum. **12** (1979) 336.
9) E. Sato, H. Isobe and F. Hoshino: Rev. Sci. Instrum. **57** (1986) 1399.
10) A. Shikoda, E. Sato, M. Sagae, T. Oizumi, Y. Tamakawa and T. Yanagisawa: Rev. Sci. Instrum. **65** (1994) 850.
11) K. Takahashi, E. Sato, M. Sagae, T. Oizumi, Y. Tamakawa and T. Yanagisawa: Jpn. J. Appl. Phys. **33** (1994) 4146.
12) E. Sato, K. Takahashi, M. Sagae, S. Kimura, T. Oizumi, Y. Hayasi, Y. Tamakawa and T. Yanagisawa: Med. & Biol. Eng. & Comput. **32** (1994) 289.
13) E. Sato, Y. Hayasi, R. Germer, E. Tanaka, H. Mori, T. Kawai, T. Ichimaru, S. Sato, K. Takayama and H. Ido: J. Electron Spectrosc. & Related Phenom. **137–140** (2004) 713.
14) E. Sato, Y. Hayasi, R. Germer, E. Tanaka, H. Mori, T. Kawai, T. Ichimaru, K. Takayama and H. Ido: Rev. Sci. Instrum. **74** (2003) 5236.
15) E. Sato, Y. Hayasi, R. Germer, E. Tanaka, H. Mori, T. Kawai, H. Obara, T. Ichimaru, K. Takayama and H. Ido: Jpn. J. Med. Phys. **20** (2003) 123.
16) H. Sugie, M. Tanemura, V. Filip, K. Iwata, K. Takahashi and F. Okuyama: Appl. Phys. Lett. **78** (2000) 2578.
17) E. Sato, K. Sato and Y. Tamakawa: Ann. Rep. Iwate Med. Univ. Sch. Lib. Arts Sci. **35** (2000) 13.
18) E. Sato, Y. Hayasi, R. Germer, E. Tanaka, H. Mori, T. Kawai, T. Ichimaru, S. Sato, K. Takayama and H. Ido: J. Electron Spectrosc. Related Phenom. **137–140** (2004) 705.

Quasi-monochromatic cerium flash angiography

Eiichi Sato*[a], Rudolf Germer[b], Etsuro Tanaka[c], Hidezo Mori[d], Toshiaki Kawai[e], Toshio Ichimaru[f], Shigehiro Sato[g], Hidenori Ojima[h], Kazuyoshi Takayama[h] and Hideaki Ido[i]

[a] Department of Physics, Iwate Medical University, 3-16-1 Honchodori, Morioka 020-0015, Japan
[b] ITP, FHTW FB1 and TU-Berlin, Blankenhainer Str. 9, D 12249 Berlin, Germany
[c] Department of Nutritional Science, Faculty of Applied Bio-science, Tokyo University of Agriculture, 1-1-1 Sakuragaoka, Setagaya-ku 156-8502, Japan
[d] Department of Cardiac Physiology, National Cardiovascular Center Research Institute, 5-7-1 Fujishirodai, Suita, Osaka 565-8565 Japan
[e] Electron Tube Division #2, Hamamatsu Photonics K. K., 314-5 Shimokanzo, Toyooka Village, Iwata-gun 438-0193, Japan
[f] Department of Radiological Technology, School of Health Sciences, Hirosaki University, 66-1 Honcho, Hirosaki 036-8564, Japan
[g] Department of Microbiology, School of Medicine, Iwate Medical University, 19-1 Uchimaru, Morioka 020-8505, Japan
[h] Shock Wave Research Center, Institute of Fluid Science, Tohoku University, 2-1-1 Katahira, Sendai 980-8577, Japan
[i] Department of Applied Physics and Informatics, Faculty of Engineering, Tohoku Gakuin University, 1-13-1 Chuo, Tagajo 985-8537, Japan

ABSTRACT

The cerium target plasma flash x-ray generator is useful in order to perform high-speed enhanced K-edge angiography using cone beams because K-series characteristic x rays from the cerium target are absorbed effectively by iodine-based contrast mediums. In the flash x-ray generator, a 150 nF condenser is charged up to 80 kV by a power supply, and flash x rays are produced by the discharging. The x-ray tube is a demountable diode, and the turbomolecular pump evacuates air from the tube with a pressure of approximately 1 mPa. Since the electric circuit of the high-voltage pulse generator employs a cable transmission line, the high-voltage pulse generator produces twice the potential of the condenser charging voltage. At a charging voltage of 80 kV, the estimated maximum tube voltage and current were approximately 160 kV and 40 kA, respectively. When the charging voltage was increased, the K-series characteristic x-ray intensities of cerium increased. The K lines were clean and intense, and hardly any bremsstrahlung rays were detected at all. The x-ray pulse widths were approximately 100 ns, and the time-integrated x-ray intensity had a value of approximately 10 μC/kg at 1.0 m from the x-ray source with a charging voltage of 80 kV. In the angiography, we employed a film-less computed radiography (CR) system and iodine-based microspheres.

Keywords: flash x-ray, cerium target, characteristic x rays, bremsstrahlung x-ray distribution, K-edge angiography

1. INTRODUCTION

The potential of monochromatic parallel x-ray beams using a synchrotron and a monochrometor poses a major challenge to competing image acquisition technology, for example, x-ray phase imaging[1,2] and enhanced K-edge angiography.[3,4] Recently, cone-beam phase imaging[5] for the edge enhancement technique has been employed using a mini-focus x-ray tube. Subsequently, K-edge angiography has also been performed using cone beams of cerium Kα rays[6] of 34.6 keV, since K-series characteristic x rays from the cerium target are absorbed effectively by iodine-based contrast media.
Currently, most flash x-ray generators utilize cold-cathode x-ray tubes and produce extremely high-dose-rate pulse x rays with durations of less than 1 μs.[7] A number of flash x-ray generators have been developed in order to perform high-speed radiography, and the generators with maximum photon energies of less than 150 keV can be employed to

26th International Congress on High-Speed Photography and Photonics, edited by D. L. Paisley, S. Kleinfelder, D. R. Snyder, B. J. Thompson, Proc. of SPIE Vol. 5580 (SPIE, Bellingham, WA, 2005) · 0277-786X/05/$15 · doi: 10.1117/12.567575

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.

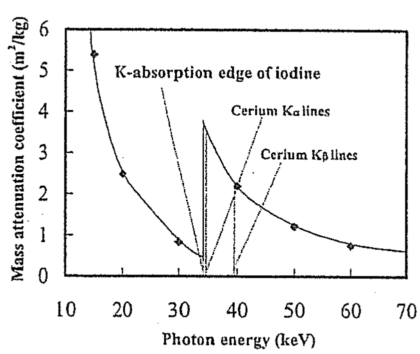


Figure 1: Relation between mass attenuation coefficient of iodine and average photon energies of cerium Kα and Kβ lines.

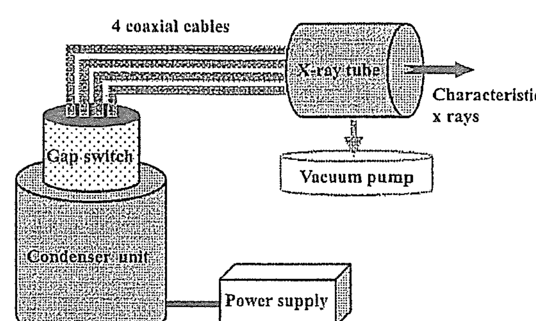


Figure 2: Block diagram of intense quasi-monochromatic flash x-ray generator.

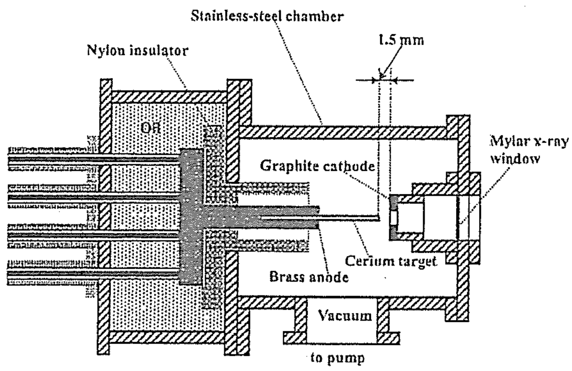


Figure 3: Schematic drawing of flash x-ray tube.

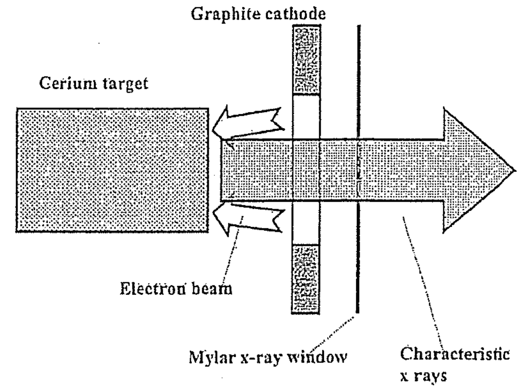


Figure 4: Irradiation of characteristic x rays.

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.

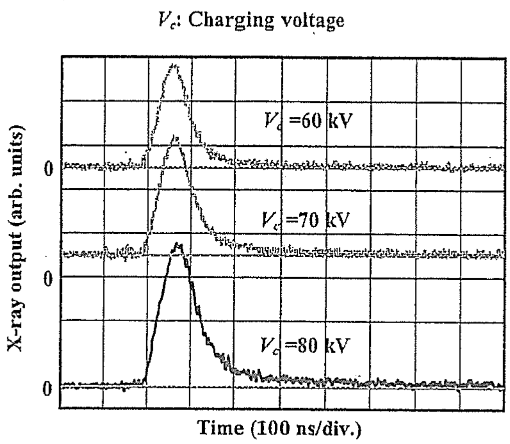


Figure 5: X-ray outputs at indicated conditions.

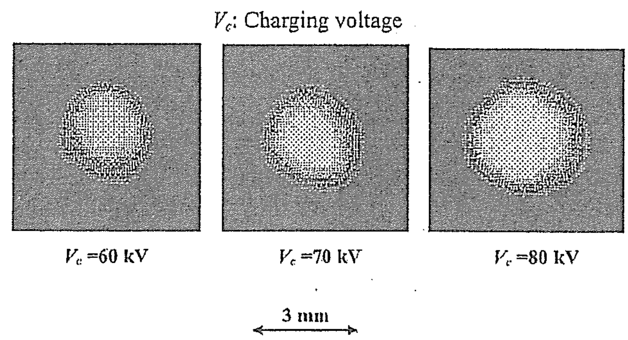


Figure 6: Images of characteristic x-ray source with changes in charging voltage.

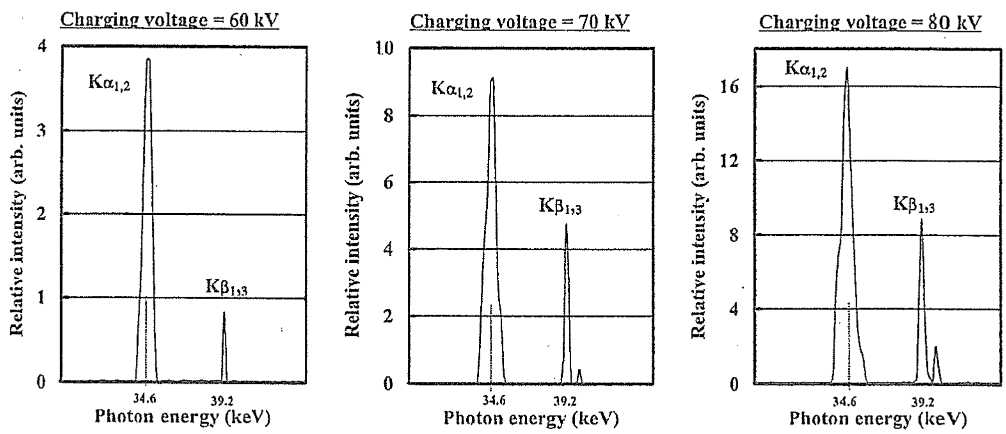


Figure 7: X-ray spectra from cerium target.

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).