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, 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.

Proc. KEK

Enhanced K-edge angiography utilizing cerium-target diode

Eiichi Sato[a], Akira Yamadera[b], Toshio Ichimaru[b], Etsuro Tanaka[c], Hidezo Mori[d], Toshiaki Kawai[e], Shigehiro Sato[f], 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, School of Health Sciences, Hirosaki University, 66-1 Honcho, Hirosaki 036-8564, Japan
[c] Department of Nutritional Science, Faculty of Applied Bio-science, Tokyo University of Agriculture, 1-1-1 Sakuragaoka, Setagaya-ku 156-8502, Japan
[d] Department of Cardiac Physiology, National Cardiovascular Center Research Institute, 5-7-1 Fujishirodai, Suita, Osaka 565-8565, Japan
[e] Electron Tube Division #2, Hamamatsu Photonics K. K., 314-5 Shimokanzo, Toyooka Village, Iwata-gun 438-0193, Japan
[f] 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

The cerium-target x-ray tube is useful in order to perform cone-beam K-edge angiography because Kα rays from the cerium target are absorbed effectively by iodine-based contrast mediums. The x-ray generator consists of a main controller, an x-ray tube unit with a high-voltage circuit and an insulation transformer, and a personal computer. The tube is a glass-enclosed diode with a cerium target and a 0.5-mm-thick beryllium window. The maximum tube voltage and current were 65 kV and 0.4 mA, respectively, and the focal-spot sizes were approximately 1×1 mm. Sharp cerium Kα lines were left using a barium sulfate filter, and the x-ray intensity was 16.8 μGy/s at 1.0 m from the source with a tube voltage of 60 kV and a current of 0.40 mA. Angiography was performed with an x-ray film (Fuji IX 100) using iodine-based microspheres 15 μm in diameter. In angiography of non-living animals, we observed fine blood vessels of 100 μm or less with high contrasts.

Keywords: x-ray tube, cerium target, x-ray spectra, Kα rays, K-edge angiography, monochromatic x rays

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.[1-3] Subsequently, monochromatic x-ray computed tomography at two different energies has provided information on the electron density of human tissue.[4] In addition, a compact pulsed tunable monochromatic x-ray source has been designed, developed, and tested.[5] From the source, conical x-ray beams from 10 to 50 keV with pulse widths of 8 ps have been produced, and these beams are useful for biomedical imaging and protein crystallography.

In order to perform high-speed medical radiography, although several different flash x-ray generators[6-10] utilizing cold-cathode tubes have been developed, plasma flash x-ray generators[11-14] are useful to produce quasi-monochromatic x rays without using a K-edge filter. Therefore, we have performed a demonstration of cone-beam K-edge angiography[15] utilizing a cerium plasma generator, since K-series characteristic x rays from the cerium target are absorbed effectively by iodine.

Recently, we have developed a steady-state x-ray generator utilizing a cerium-target tube, and have demonstrated enhanced K-edge angiography utilizing a barium sulfate filter.[16] In this research, Kα lines (34.6 keV) were left by absorbing Kβ lines (39.2 keV), and bremsstrahlung x rays with photon energies of lower than the barium K-edge (37.4 keV) were also observed. To perform angiography, the spatial resolution was primarily determined by the sampling pitch (87.5 μm) of a computed radiography (CR) system.[17] In measurements of x-ray spectra, although we usually employed a cadmium tellurium detector with a photon energy resolution of 1.7 keV, the resolution should be improved as much as possible to measure the characteristic x-ray spectra.

In the present research, we measured the x-ray spectra from a cerium-target tube using a germanium detector, and performed a preliminary study on cone-beam K-edge angiography achieved with cerium Kα rays using a barium sulfate filter and an x-ray film.

2. Generator

Figure 1 shows the block diagram of the x-ray generator, which consists of a main controller (Fig. 2), a cerium-target x-ray tube unit (Fig. 3) with a Cockcroft-Walton circuit and an insulation transformer, and a personal computer. The tube voltage, the current, and the exposure time can be controlled by both the controller and the computer. The main circuit for producing x rays is illustrated in Fig. 4, and employed the Cockcroft-Walton circuit in order to decrease the dimensions of the tube unit. In the x-ray tube, the negative high-voltage is applied to the cathode electrode, and the anode (target) is connected to the tube unit case (ground potential) to cool the anode and the target effectively. The filament heating current is supplied by an AC power supply in the controller in conjunction with an insulation transformer. In this experiment, the tube voltage applied was from 45 to 65 kV, and the tube current was regulated to within 0.40 mA (maximum current) by the filament temperature. The exposure time is controlled in order to obtain optimum x-ray intensity. Monochromatic Kα lines were left using a 5-mm-thick barium sulfate filter in which barium sulfate powder was mixed with polymethyl methacrylate (PMMA) resin, since both the bremsstrahlung and the Kβ rays were absorbed effectively by the filter. In designing the filter, the surface density of the barium sulfate powder is important, since the x rays are absorbed effectively by the powder as compared with the PMMA resin. In this case, the density was approximately 10 mg/cm^2.

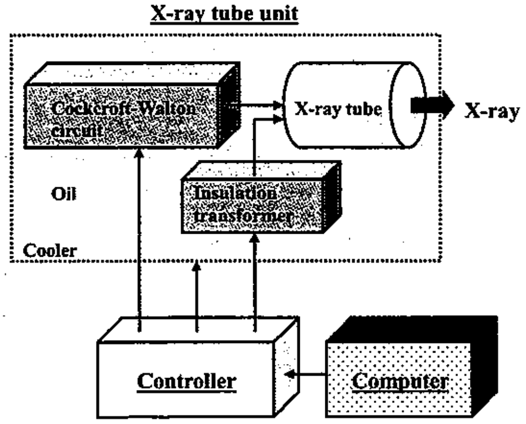

Fig. 1: Block diagram of compact x-ray generator with cerium-target radiation tube, which is used specially for K-edge angiography using iodine-based contrast media.

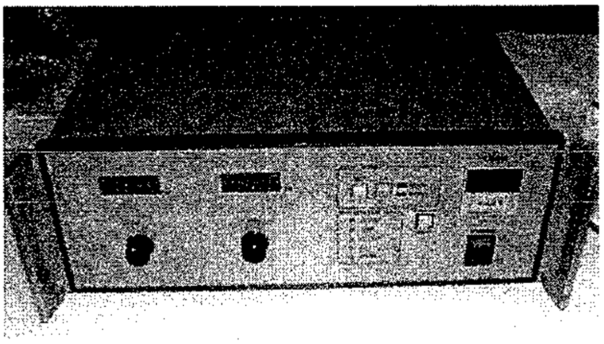

Fig. 2: Main controller.

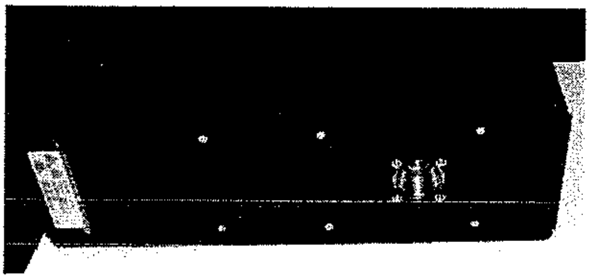

Fig. 3: X-ray tube unit.

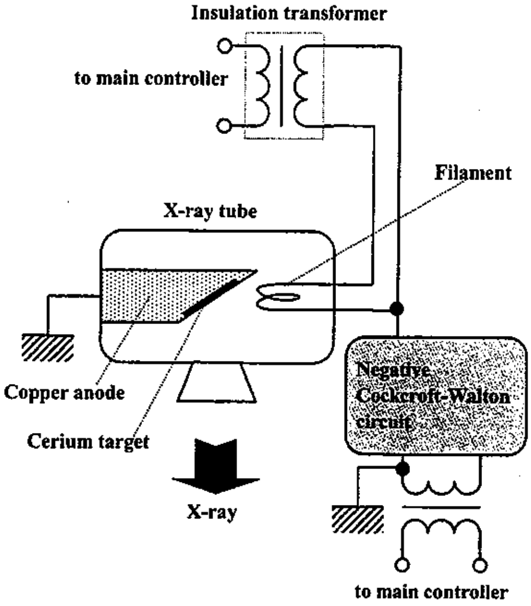

Fig. 4: Main circuit of x-ray generator.

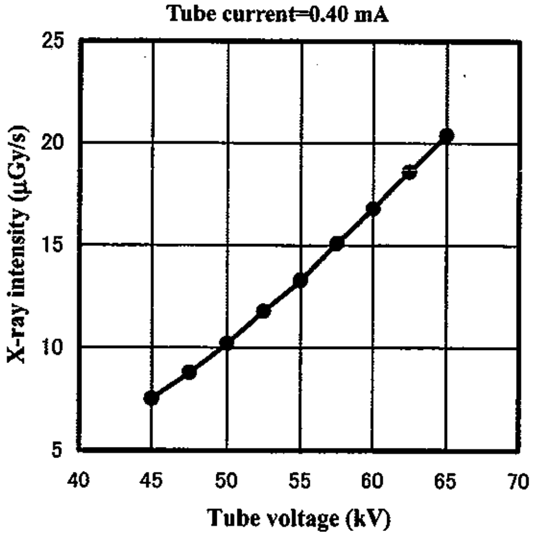

Fig. 5: X-ray intensity measured at 1.0 m from x-ray source according to changes in tube voltage using barium sulfate filter.

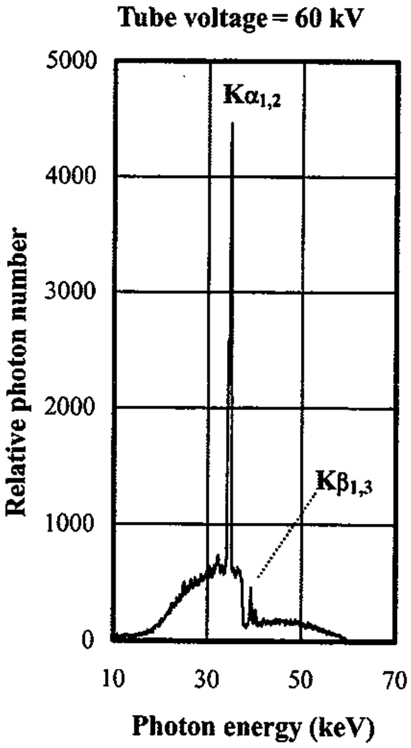

Fig. 6: X-ray spectra measured using germanium detector and filter.

3. *Characteristics*

3.1 X-ray intensity

The x-ray intensity rate was measured by a Victoreen 660 ionization chamber at 1.0 m from the x-ray source (Fig. 5). At a constant tube current of 0.40 mA, the x-ray intensity increased when the tube voltage was increased. In this measurement, the intensity with a tube voltage of 60 kV and a current of 0.40 mA was 16.8 μGy/s with errors of less than 0.2%.

3.2 Focal spot

In order to measure images of the x-ray source, we employed a pinhole camera with a hole diameter of 50 μm (magnification ratio of 1:2) in conjunction with a Computed Radiography (CR) system[16] with a sampling pitch of 87.5 μm. When the tube voltage was increased, spot dimensions increased slightly and had values of approximately 1×1 mm.

3.3 X-ray spectra

In order to measure x-ray spectra, we employed a germanium detector (GLP-10180/07-P, Ortec Inc.) (Fig. 6). When the tube voltage was increased, the Kα intensity substantially increased, and both the maximum photon energy and the intensities of bremsstrahlung x rays increased.

4. Angiography

Figure 7 shows the mass attenuation coefficients of iodine at the selected energies; the coefficient curve is discontinuous at the iodine K-edge. The average photon energy of the cerium Kα lines is shown just above the iodine K-edge. Cerium is a rare earth element and has a high reactivity; however, the average photon energy of Kα is 34.6 keV, and iodine contrast mediums with a K-absorption edge of 33.155 keV absorb the lines easily. Therefore, blood vessels were observed with high contrasts.

The angiography was performed using an x-ray film (Fuji IX 100), iodine microspheres of 15 μm in diameter, and the filter. The distance (between the x-ray source and the imaging plate) was 1.5 m, and the tube voltage was 60 kV. Firstly, rough measurements of spatial resolution were made using wires. Figure 8 shows radiograms of tungsten wires in a rod made of polymethyl methacrylate. Although the image contrast hardly varied with decreases in the wire diameter, a 50-μm-diameter wire could be observed clearly.

Figures 9 and 10 show angiograms of a rabbit heart and a thigh, respectively. The coronary arteries in the heart and fine blood vessels in the thigh were visible. Figure 11 shows an angiogram of a larger dog heart. Because the size of the dog heart is almost the same as human heart, human coronary arteries can be observed.

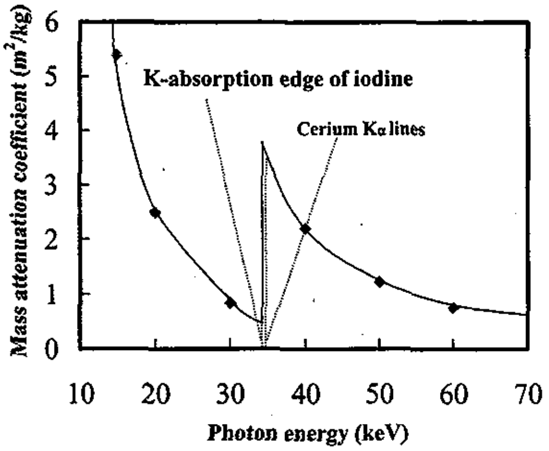

Fig. 7: Mass attenuation coefficients of iodine, and average photon energy of cerium Kα lines.

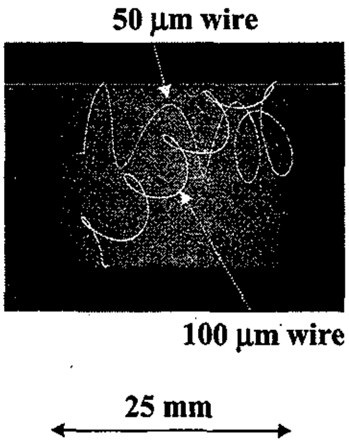

Fig. 8: Radiogram of tungsten wires in PMMA rod.

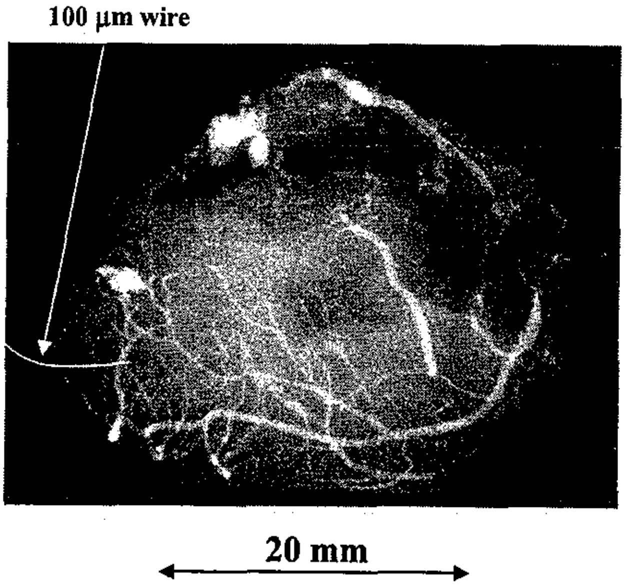

Fig. 9: Angiogram of rabbit heart.

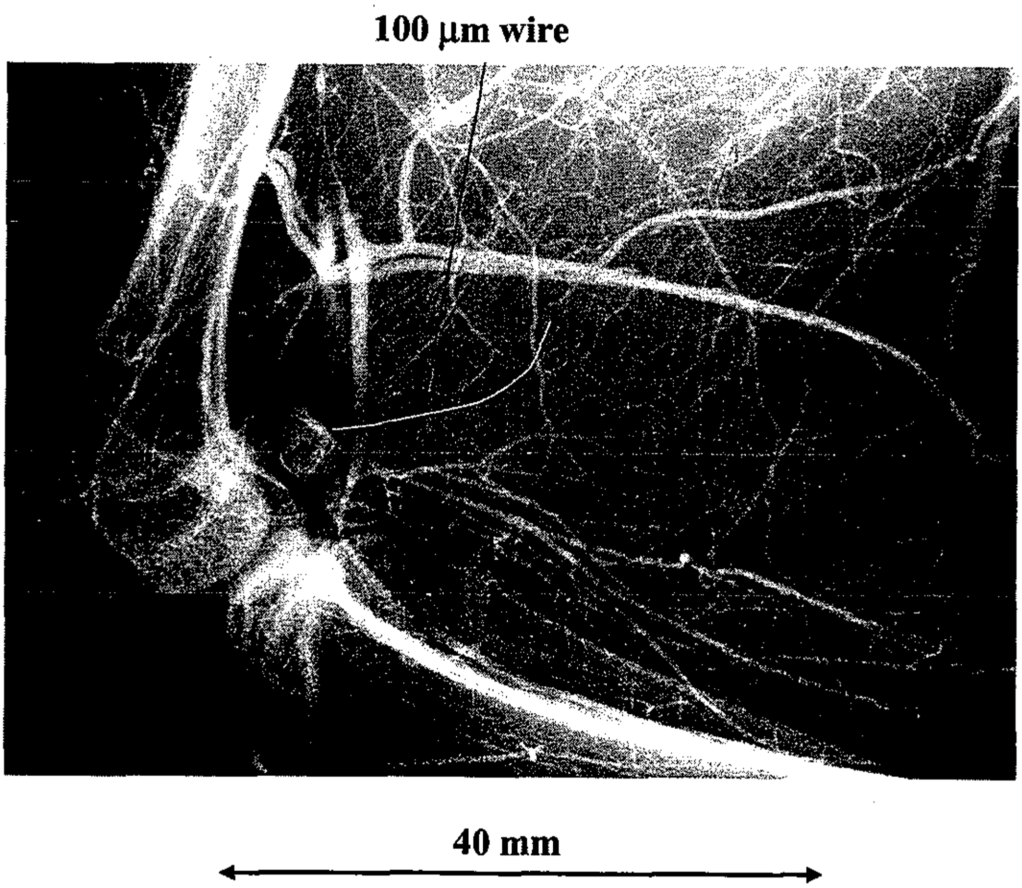

Fig. 10: Angiogram of extracted rabbit thigh.

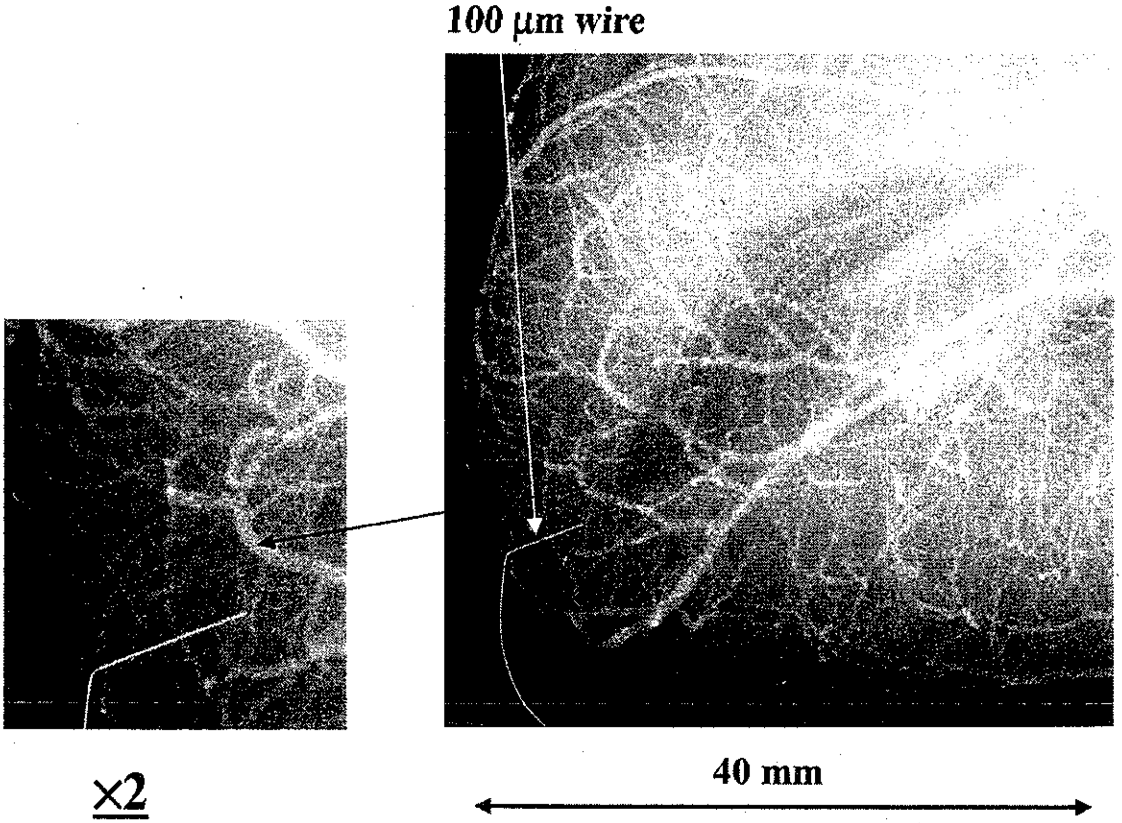

Fig. 11: Angiogram of extracted dog heart using iodine microspheres.

5. Discussion and results

In summary, we developed a new x-ray generator with a cerium-target tube and succeeded in producing cerium Kα lines, which can be absorbed easily by iodine-based contrast mediums. Both the characteristic and bremsstrahlung x-ray intensities increased with increases in the tube voltage, and Kβ lines were absorbed effectively by the barium sulfate filter. Without using the filter, bremsstrahlung intensity can be decreased effectively by considering the angle dependence, since bremsstrahlung rays are not emitted in the opposite direction to that of electron acceleration.

The x-ray intensity was limited because the thermal contact between the target and the anode was not good. However, the intensity can be increased by welding the target or using a cerium-alloy target. In addition, a rotation anode tube can be developed by sputtering of cerium. In this preliminary experiment, although the maximum tube voltage and current were 65 kV and 0.40 mA, respectively, the voltage and current could be increased. Subsequently, the generator produced maximum number of characteristic photons was approximately 3×10^7 photons/cm^2·s at 1.0 m from the source, and the photon count rate can be increased easily by improving the target.

In the former research, we employed a CR system for performing angiography with a spatial resolution of approximately 100 μm. In cases where the film is employed, the x-ray exposure time increases due to the sensitivity of the film. However, because the spatial resolution is improved, fine blood vessels can be observed with high contrasts.

Acknowledgment

This work was supported by Grants-in-Aid for Scientific Research (13470154, 13877114, and 16591222) and Advanced

Medical Scientific Research from MECSST, Health and Labor Sciences Research Grants (RAMT-nano-001, RHGTEFB-genome-005 and RHGTEFB-saisei-003), Grants from Keiryo Research Foundation, The Promotion and Mutual Aid Corporation for Private Schools of Japan, Japan Science and Technology Agency (JST), and New Energy and Industrial Technology Development Organization (NEDO, Industrial Technology Research Grant Program in '03).

References

1. 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.
2. 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.
3. 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.
4. M. Torikoshi, T. Tsunoo, M. Sasaki, M. Endo, Y. Noda, T. Kohno, K. Hyodo, K. Uesugi and N. Yagi: "Electron density measurement with dual-energy x-ray CT using synchrotron radiation," *Phys. Med. Biol.*, **48**, 673-685, 2003.
5. F. E. Carroll, M. H. Mendenhall, R. H. Traeger, C. Brau and J. W. Waters, "Pulsed tunable monochromatic x-ray beams from a compact source: New opportunities," *Am. J. Roentgenol.*, **181**, 1197-1202, 2003.
6. E. Sato, H. Isobe and F. Hoshino, "High intensity flash x-ray apparatus for biomedical radiography," *Rev. Sci. Instrum.*, **57**, 1399-1408, 1986.
7. 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.
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. 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, 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, 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.
13. 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.
14. 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.
15. E. Sato, R. Germer, Y. Hayasi, K. Murakami, Y. Koorikawa, E. Tanaka, H. Mori, T. Kawai, T. Ichimaru, F. Obata, K. Takahashi, S. Sato, K. Takayama and H. Ido, "Weakly ionized cerium plasma radiography," *SPIE*, **5210**, 12-21, 2003.
16. 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.
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.

Proc. KEK

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

Eiichi Sato[a], Michiaki Sagae[a], Yasuomi Hayasi[a], Etsuro Tanaka[b], Hidezo Mori[c], Toshiaki Kawai[d], Toshio Ichimaru[e], Shigehiro Sato[f], 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 Nutritional Science, Faculty of Applied Bio-science, Tokyo University of Agriculture, 1-1-1 Sakuragaoka, Setagaya-ku 156-8502, Japan
[c] Department of Cardiac Physiology, National Cardiovascular Center Research Institute, 5-7-1 Fujishirodai, Suita, Osaka 565-8565 Japan
[d] Electron Tube Division #2, Hamamatsu Photonics K. K., 314-5 Shimokanzo, Toyooka Village, Iwata-gun 438-0193, Japan
[e] Department of Radiological Technology, School of Health Sciences, Hirosaki University, 66-1 Honcho, Hirosaki 036-8564, 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 plasma flash x-ray generator, a 200 nF condenser is charged up to 50 kV by a power supply, and flash x rays are produced by the discharging. The x-ray tube is a demountable triode with a trigger electrode, and the turbomolecular pump evacuates air from the tube with a pressure of approximately 1 mPa. Target evaporation leads to the formation of weakly ionized linear plasma, consisting of copper ions and electrons, around the fine target, and intense $K\alpha$ lines are left using a 10-μm-thick nickel filter. At a charging voltage of 50 kV, the maximum tube voltage was almost equal to the charging voltage of the main condenser, and the peak current was about 15 kA. When the charging voltage was increased, the linear plasma formed, and the $K\alpha$ intensity increased. The $K\alpha$ lines were clean and intense, and hardly any bremsstrahlung rays were detected at all. The x-ray pulse widths were approximately 700 ns, and the time-integrated x-ray intensity had a value of approximately 20 μC/kg at 1.0 m from the x-ray source with a charging voltage of 50 kV.

Keywords: flash x-ray, weakly ionized linear plasma, copper target, $K\alpha$ rays, monochromatic x rays

1. Introduction

Flash x rays have been produced by several different methods, and various generators have been developed corresponding to specific radiographic objectives.[1-3] Currently, the maximum photon energy has been increased to approximately 1 MeV using multiple-stage Marx pulse generators[1,2] in order to produce hard x rays for military studies. In soft x-ray generators,[4-8] high-intensity single generators with large capacity condensers were originally developed. Subsequently, repetitive generators[9-12] have been developed, and the repetition rate has been increased to sub-kilohertz using a cold-cathode triode.

Recently, soft x-ray lasers have been produced by a gas-discharge capillary,[13-16] and the laser pulse energy substantially increased in proportion to the capillary length. These kinds of fast discharges can generate hot and dense plasma columns with aspect ratios approaching 1000:1. However, it is difficult to increase the laser photon energy to 10 keV or beyond.

Because there are no x-ray resonators in the high-photon-energy region, new methods for increasing coherence will be desired in the future.

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

In this paper, we describe a plasma flash x-ray generator utilizing a rod-target radiation tube, used to perform a preliminary experiment for generating intense and clean monochromatic x rays by forming a linear copper plasma cloud around a fine target.

2. Generator

2.1 High-voltage circuit

Figure 1 shows a block diagram of the high-intensity plasma flash x-ray generator. This generator consists of the following essential components: a high-voltage power supply, a high-voltage condenser with a capacity of approximately 200 nF, a turbomolecular pump, a krytron pulse generator as a trigger device, and a flash x-ray tube. In this generator, a low-impedance transmission line is employed in order to increase maximum tube current. The high-voltage main condenser is charged to 50 kV by the power supply, and electric charges in the condenser are discharged to the tube after triggering the cathode electrode with the trigger device. The plasma flash x rays are then produced.

2.2 X-ray tube

The x-ray tube is a demountable cold-cathode triode that is connected to the turbomolecular pump with a pressure of approximately 1 mPa (Fig. 2). This tube consists of the following major parts: a hollow cylindrical carbon cathode with a bore diameter of 10.0 mm, a brass focusing electrode, a trigger electrode made from copper wire, a stainless steel vacuum chamber, a nylon insulator, a polyethylene terephthalate (Mylar) x-ray window 0.25 mm in thickness, and a rod-shaped copper target 3.0 mm in diameter with a tip angle of 60°. The distance between the target and cathode electrodes is approximately 20 mm, and the trigger electrode is set in the cathode electrode. As electron beams from the cathode electrode are roughly converged to the target by the focusing electrode, evaporation leads to the formation of a weakly ionized linear plasma, consisting of copper ions and electrons, around the fine target.

2.3 Characteristic x-ray irradiation

In the linear plasma, bremsstrahlung photons with energies higher than the K-absorption edge are effectively absorbed and are converted into fluorescent x rays (Fig. 3). The plasma then transmits the fluorescent rays easily, and bremsstrahlung rays with energies lower than the K-edge are also absorbed by the plasma. In addition, because bremsstrahlung rays are not emitted in the opposite direction to that of electron acceleration, intense characteristic x rays are generated from the plasma-axial direction.

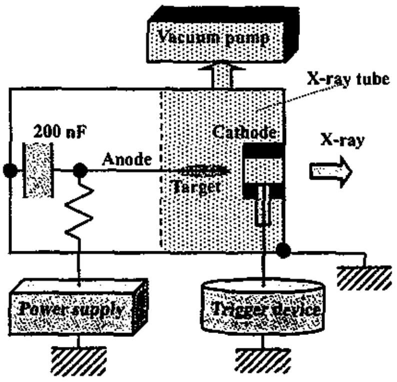

Fig. 1: Block diagram including electric circuit of plasma flash x-ray generator.

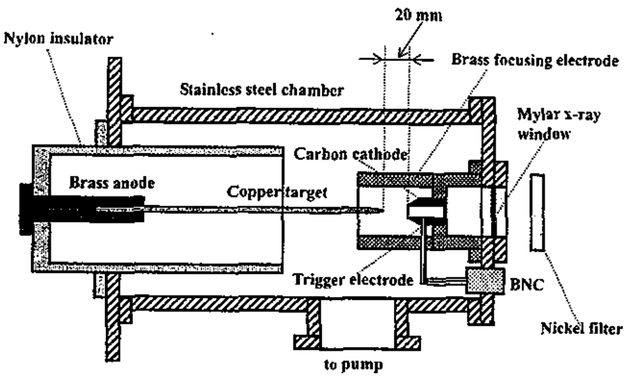

Fig. 2: Schematic drawing of flash x-ray tube with rod target.

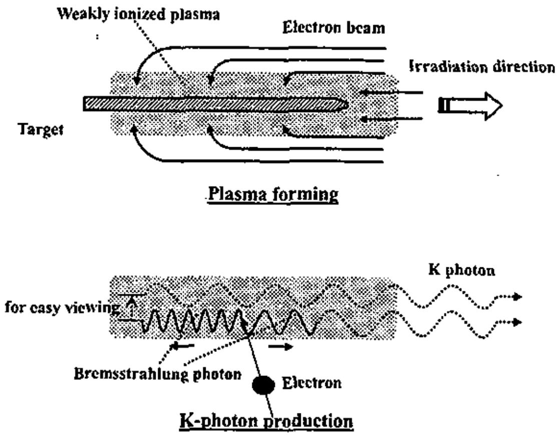

Fig. 3: K-photon irradiation from plasma.

3. Characteristics

3.1 Tube voltage and current

Tube voltage and current were measured by a high-voltage divider with an input impedance of 1 GΩ and a current transformer, respectively. Figure 4 shows the time relation for the tube voltage and current. The tube 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 50 kV, the maximum tube voltage was almost equal to the charging voltage of the main condenser, and the maximum tube current was approximately 15 kA.

3.2 X-ray output

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

3.3 X-ray source

In order to measure images of the plasma x-ray source, we employed a pinhole camera with a hole diameter of 100 μm and the filter (Fig. 5). 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 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[21] (Konica Regius 150) with a wide dynamic range, using the filter, and relative x-ray intensity was calculated from Dicom digital data. Figure 6 shows measured spectra from the copper target. In fact, we observed sharp lines of Kα rays such as lasers, while bremsstrahlung rays were hardly detected at all. The characteristic x-ray intensity of the Kα line substantially increased with corresponding increases in the charging voltage.

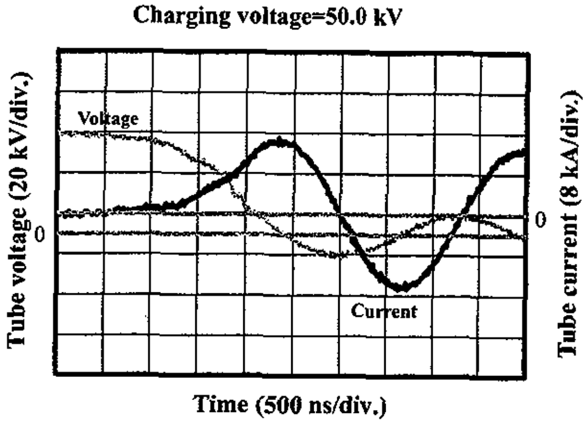

Fig. 4: Tube voltages and currents with charging voltage of 50.0 kV.

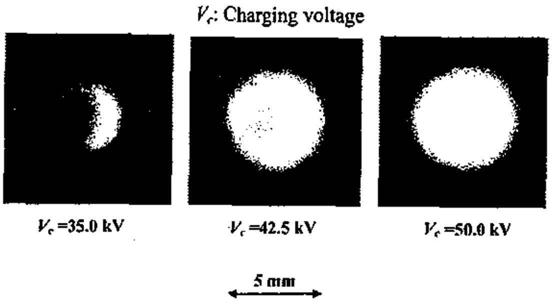

Fig. 5: Images of plasma x-ray source measured by pinhole of 100 μm from plasma axial direction.

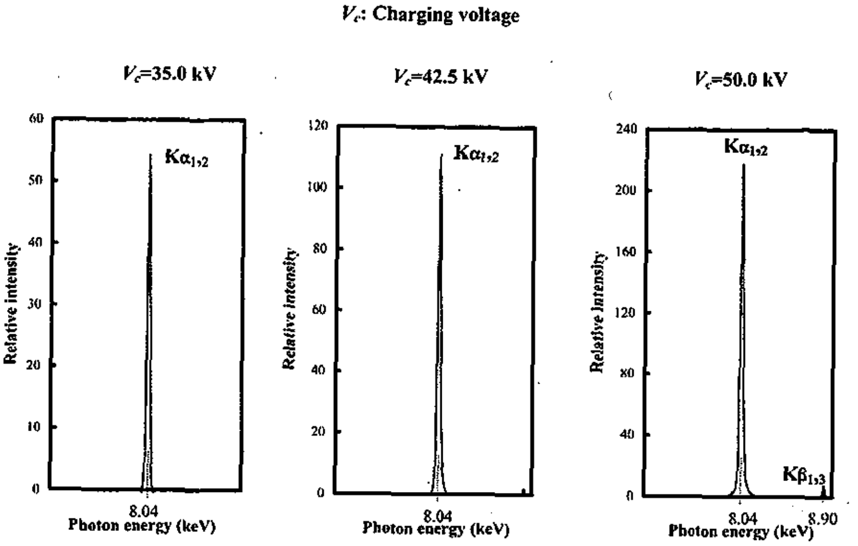

Fig. 6: X-ray spectra from weakly ionized copper plasma according to changes in charging voltage and to insertion of nickel filter.

4. Radiography

The plasma radiography was performed by the CR system using the filter, and the distance between the x-ray source and imaging plate was 1.2 m.

Firstly, rough measurements of image resolution were made using wires. Figure 7 shows radiograms of tungsten wires in a rod made of PMMA with a charging voltage of 45 kV. Although the image contrast decreased somewhat with decreases in the wire diameter, due to blurring of the image caused by the sampling pitch of 87.5 μm, a 50-μm-diameter wire could be observed. The image of water falling into a polypropylene beaker from a plastic test tube is shown in Fig. 8. This image was taken with a charging voltage of 45 kV, with the slight addition of an iodine-based contrast medium. Because the x-ray duration was about 1 μs, the stop-motion image of water could be obtained.

Figure 9 shows an angiogram of a rabbit heart; iodine-based microspheres of 15 μm in diameter were used with a charging voltage of 50 kV, and fine blood vessels of about 100 μm were visible.

5. Discussion

Concerning the spectrum measurement, we obtained fairly intense and clean Kα lines from a weakly ionized linear plasma x-ray source by absorbing Kβ lines using the monochromatic filter. In a medical application, cerium Kα rays are absorbed effectively by an iodine-based contrast medium, and high contrast microangiography can be performed.

In this research, we obtained sufficient characteristic x-ray intensity per pulse for CR radiography using a monochromatic filter, and the generator produced number of characteristic Kα photons was approximately 5×10^7 photons/cm^2 at 1.0 m per pulse. In addition, since the photon energy of characteristic x rays can be controlled by changing the target elements, various quasi-monochromatic high-speed radiographies, such as high-contrast microangiography and parallel radiography using an x-ray lens, will be possible.

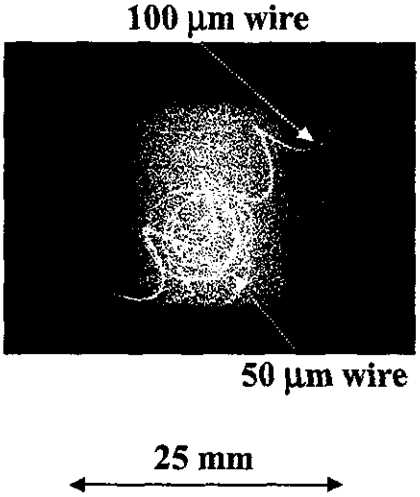

Fig. 7: Radiograms of tungsten wires in rod made of polymethyl methacrylate.

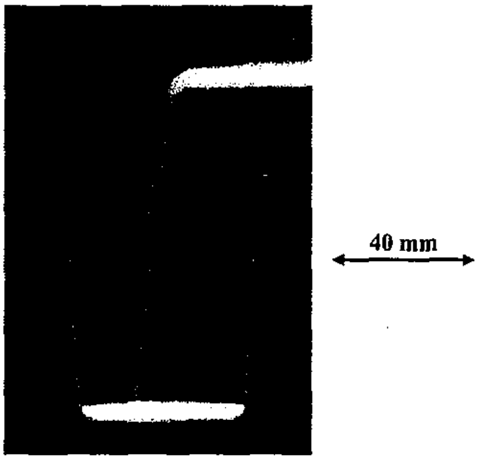

Fig. 8: Radiogram of water falling into polypropylene beaker from plastic test tube.

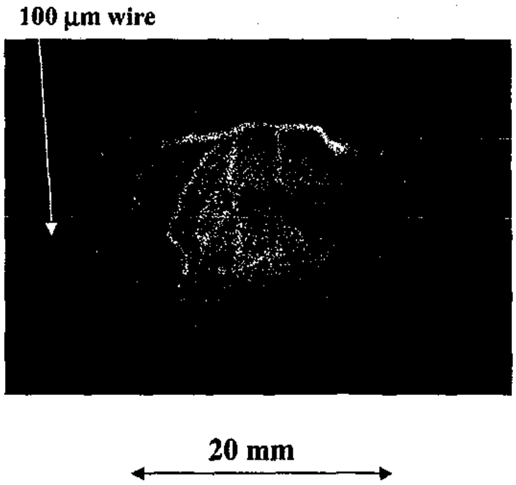

Fig. 9: Angiograms of rabbit heart.

Acknowledgment

This work was supported by Grants-in-Aid for Scientific Research (13470154, 13877114, and 16591222) and Advanced

Medical Scientific Research from MECSST, Health and Labor Sciences Research Grants(RAMT-nano-001, RHGTEFB-genome-005 and RHGTEFB-saisei-003), Grants from Keiryo Research Foundation, The Promotion and Mutual Aid Corporation for Private Schools of Japan, Japan Science and Technology Agency (JST), and New Energy and Industrial Technology Development Organization (NEDO, Industrial Technology Research Grant Program in '03).

References

1. A. Mattsson, "Some characteristics of a 600 kV flash x-ray tube," *Physica Scripta*, **5**, 99-102, 1972.
2. R. Germer, "X-ray flash techniques," *J. Phys. E: Sci. Instrum.*, **12**, 336-350, 1979.
3. C. Cavailler, "AIRIX- a new tool for flash radiography in detonics," *Proc. SPIE*, **4183**, 23-35, 2000.
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. 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," *Proc. SPIE*, **2513**, 649-667, 1994.
6. E. Sato, M. Sagae, K. Takahashi, A. Shikoda, T. Oizumi, H. Ojima, K. Takayama, Y. Tamakawa, T. Yanagisawa, A. Fujiwara and K. Mitoya, "Dual energy flash x-ray generator," *Proc. SPIE*, **2513**, 723-735, 1994.
7. 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," *Proc. SPIE*, **2869**, 937-955, 1996.
8. E. Sato, S. Kimura, S. Kawasaki, H. Isobe, K. Takahashi, Y. Tamakawa and T. Yanagisawa, "Repetitive flash x-ray generator utilizing a simple diode with a new type of energy-selective function," *Rev. Sci. Instrum.*, **61**, 2343-2348, 1990.
9. S. Kimura, E. Sato, M. Sagae, A. Shikoda, T. Oizumi, K. Takahashi, Y. Tamakawa and T. Yanagisawa, "Disk-cathode flash x-ray tube driven by a repetitive two-stage Marx pulser," *Med. & Biol. Eng. & Comput.*, **31**, S37-S43, 1993.
10. 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.
11. 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.
12. 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.
13. 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," *Proc. Phys. Lev. Lett.*, **73**, 2192-2195, 1994.
14. J.J. Rocca, D.P. Clark, J.L.A. Chilla and V.N. Shlyaptsev, "Energy Extration and achievement of the saturation limit in a discharge-pumped table-top soft x-ray amplifier," *Phys. Lev. Lett.*, **77**, 1476-1479, 1996.
15. 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.
16. J.J.G. Rocca, J.L.A. Chilla, S. Sakadzic, A. Rahman, J. Filevich, E. Jankowska, E.C. Hammarsten, B.M. Luther, H.C. Kapteyn, M. Murnane and V.N. Shlyapsev, "Advances in capillary discharge soft x-ray laser research," *Proc. SPIE*, **4505**, 1-6 2001.
17. E. Sato, Y. Suzuki, Y. Hayashi, E. Tanaka, H. Mori, T. Kawai, K. Takayama, H. Ido and Y. Tamakawa, "High-intensity quasi-monochromatic x-ray irradiation from the linear plasma target," *Proc. SPIE*, **4505**, 154-164, 2001.
18. E. Sato, Y. Hayasi, E. Tanaka, H. Mori, T. Kawai, T. Usuki, K. Sato, H. Obara, T. Ichimaru, K. Takayama, H. Ido and Y. Tamakawa, "Quasi-monochromatic radiography using a high-intensity quasi-x-ray laser generator," *Proc. SPIE*, **4682**, 538-548, 2002.
19. 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.
20. 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.*, **20**, 123-131, 2003.
21. 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.

High-speed K-edge angiography achieved with tantalum K-series characteristic x rays

Eiichi Sato*[a], Etsuro Tanaka[b], Hidezo Mori[c], Toshiaki Kawai[d], Takashi Inoue[e], Akira Ogawa[e], Shigehiro Sato[f], 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 Nutritional Science, Faculty of Applied Bio-science, Tokyo University of Agriculture, 1-1-1 Sakuragaoka, Setagaya-ku 156-8502, Japan
[c] Department of Cardiac Physiology, National Cardiovascular Center Research Institute, 5-7-1 Fujishirodai, Suita, Osaka 565-8565, Japan
[d] Electron Tube Division #2, Hamamatsu Photonics K. K., 314-5 Shimokanzo, Toyooka Village, Iwata-gun 438-0193, Japan
[e] Department of Neurosurgery, School of Medicine, Iwate Medical University, 19-1 Uchimaru, Morioka 020-8505, 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

The tantalum plasma flash x-ray generator is useful in order to perform high-speed K-edge angiography using cone beams because Kα rays from the tantalum target are absorbed effectively by gadolinium-based contrast media. 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. When the charging voltage was increased, the K-series characteristic x-ray intensities of tantalum increased. The K lines were clean and intense, and hardly any bremsstrahlung rays were detected. The x-ray pulse widths were approximately 100 ns, and the time-integrated x-ray intensity had a value of approximately 300 μGy at 1.0 m from the x-ray source with a charging voltage of 80 kV. Angiography was performed using a film-less computed radiography (CR) system and gadolinium-based contrast media. In angiography of non-living animals, we observed fine blood vessels of approximately 100 μm with high contrasts.

Keywords: angiography, gadolinium-based contrast media, characteristic x rays, quasi-monochromatic x rays, tantalum Kα photons

1. INTRODUCTION

The successful uses of monochromatic parallel beams from synchrotron orbital radiation in recent years have greatly increased the demand for phase-contrast radiography[1-3] and enhanced K-edge angiography.[4-6] In particular, the parallel beams with photon energies of approximately 35 keV have been employed to perform angiography, because the beams are absorbed effectively by iodine-based contrast media with a K-absorption edge of 33.2 keV. Without using a synchrotron, we have developed an x-ray generator utilizing a cerium-target tube, and have performed cone-beam K-edge angiography achieved with cerium Kα rays of 34.6 keV.[7] However, the x-ray intensity rate was limited because the thermal contact between the target and the anode was not good.

Although various flash x-ray generators have been developed,[8] we have developed flash x-ray generators[9-13] with photon energies of less than 150 keV in order to primarily perform high-speed biomedical radiography. Subsequently, we have developed plasma flash x-ray generators[14-16] to perform a preliminary experiment for producing hard x-ray lasers from weakly ionized linear plasma, and have succeeded in producing intense and clean K-series characteristic x rays using copper and nickel targets. In addition, we have confirmed the weak hard x-ray resonation verified from irradiation of weakly higher harmonic x rays. However, it is difficult to produce high-photon-energy characteristic x rays because the plasma transmits high-photon-energy bremsstrahlung x rays. Therefore, we developed a quasi-monochromatic flash x-ray generator[17,18] with a disk-cathode tube to produce high-energy characteristic x rays utilizing the angle dependence of bremsstrahlung x-ray distribution, because the bremsstrahlung rays are not emitted in the apposite direction to that of electron acceleration. Using this generator, we have succeeded in producing clean characteristic x rays from molybdenum, silver and cerium targets.

Gadolinium-based contrast media with a K-edge of 50.2 keV have been employed to perform angiography in MRI, and the gadolinium density has been increasing. In view of this situation, ytterbium Kα rays (52.0 keV) are useful for enhanced K-edge angiography, because the Kα rays are absorbed effectively by gadolinium media. As compared with angiography using iodine media, the absorbed dose can be decreased considerably utilizing angiography achieved with gadolinium media. However, because ytterbium is a lanthanide series element and has a high reactivity, Kα rays of tantalum and tungsten are also useful to perform angiography.

In this article, we describe an intense quasi-monochromatic plasma flash x-ray generator with a tantalum target tube, and used it to perform a preliminary study on angiography achieved with tantalum 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 gadolinium K-edge. The average photon energy of the tantalum Kα lines is shown above the gadolinium K-edge. The average photon energy of tantalum Kα lines is 57.1 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

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 (Fig. 3). 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.

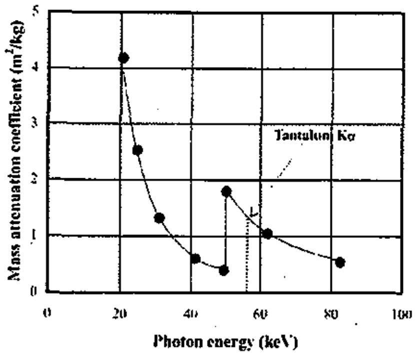

Figure 1: Relation between mass attenuation coefficient of gadolinium and average photon energy of tantalum Kα lines.

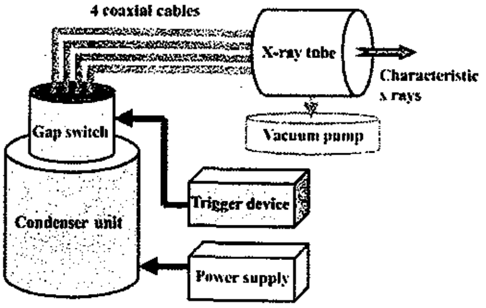

Figure 2: Block diagram of intense quasi-monochromatic flash x-ray generator.

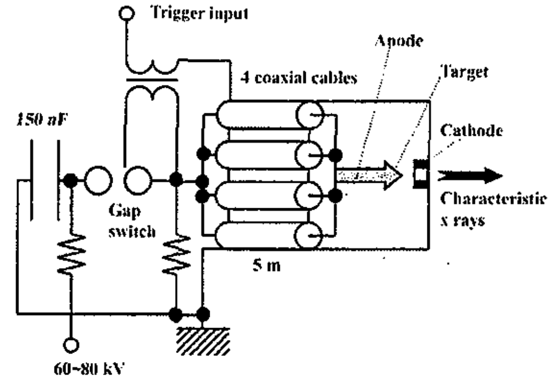

Figure 3: High-voltage circuit of flash x-ray generator.

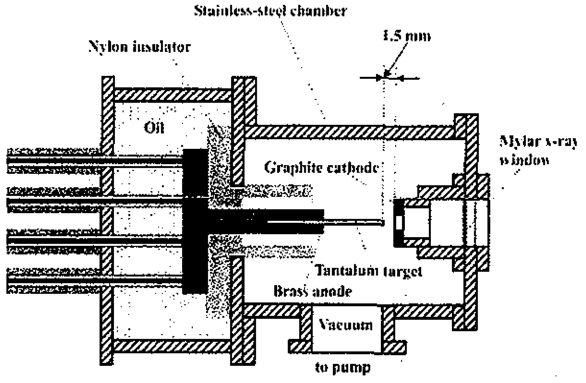

Figure 4: Schematic drawing of flash x-ray tube.

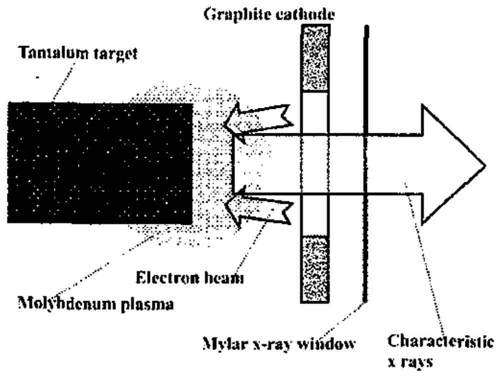

Figure 5: Irradiation of characteristic x rays.

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. 4). This tube consists of the following major parts: a ring-shaped graphite cathode with an bore 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 tantalum 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 tantalum ions and electrons, around the target. Because bremsstrahlung rays are not emitted in the opposite direction to that of electron acceleration (Fig. 5), tantalum K-series characteristic x rays can be produced without using a filter.

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. 6). 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 300 μGy 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 characteristic x-ray source, we employed a 100-μm-diameter pinhole camera and an x-ray film (Polaroid XR-7) (Fig. 7). When the charging voltage was increased, the plasma x-ray source grew, and both spot dimension and intensity increased. Because the x-ray intensity is the highest at the center of the spot, both the dimension and intensity decreased according to decreases in the pinhole diameter.

4.4 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 a computed radiography (CR) system[19] (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 tantalum target. We observed clean K-series lines, while bremsstrahlung rays were hardly detected. The characteristic x-ray intensity substantially increased with increases in the charging voltage.

5. ANGIOGRAPHY

The flash angiography was performed by a computed radiography (CR) system (Konica Regius 150)[19] at 1.2 m from the x-ray source, and the charging voltage was 80 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 decreased somewhat with decreases in the wire diameter, due to blurring of the image caused by the sampling pitch of 87.5 μm, a 50 μm-diameter wire could be observed. Because the tungsten wires transmitted the characteristic x rays easily, low contrast radiograms were obtained.

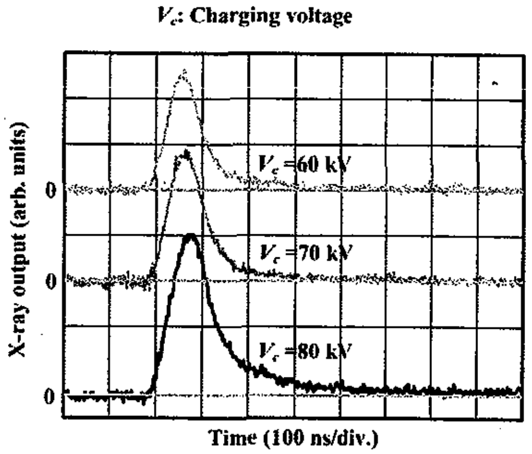

Figure 6: X-ray outputs at indicated conditions.

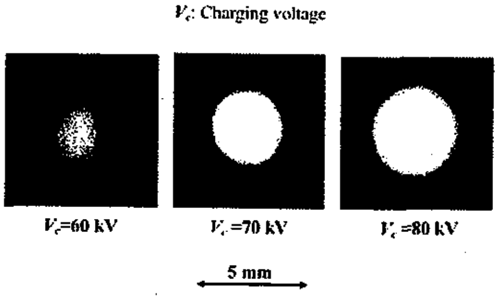

Figure 7: Images of characteristic x-ray source with changes in charging voltage.

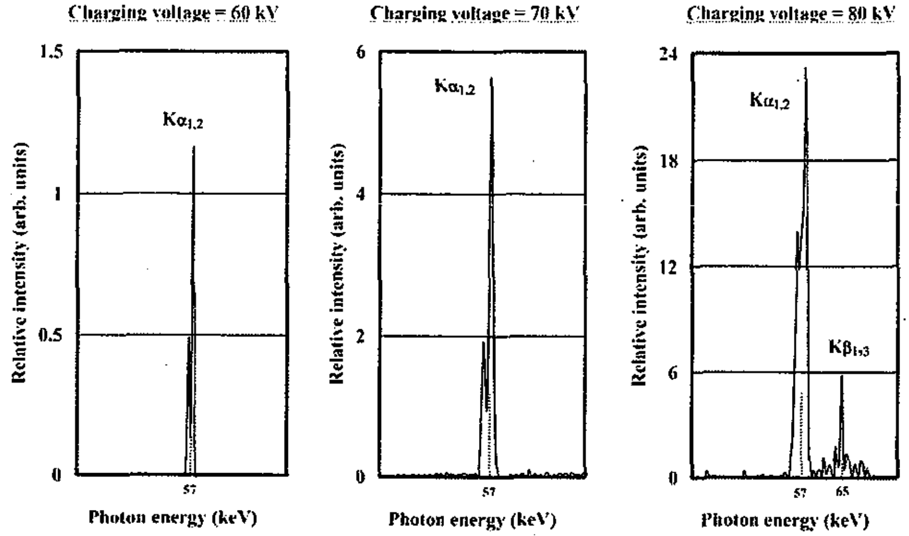

Figure 8: X-ray spectra from tantalum target.

The image of water (gadolinium oxide suspension of 20%) falling into a polypropylene beaker from a plastic test tube is shown in Fig. 10. The diameter of gadolinium oxide powder ranges from 1 to 10 μm. Because the x-ray duration was about 100 ns, the stop-motion image of water could be obtained.

Figure 11 shows an angiogram of a silicone rubber tube in a polymethyl methacrylate (PMMA) case using a contrast medium which contains 32.3% gadodiamidehydrate, and a low contrast tube with a bore diameter of 1.0 mm is observed. In cases where a gadolinium oxide suspension of 50% is employed, high-contrast angiography of the tubes (1.0 mm and 0.5 mm in bore diameter) could be performed (Fig. 12). Figure 13 shows an angiogram of a rabbit head using gadolinium oxide powder, and fine blood vessels of approximately 100 μm were visible.

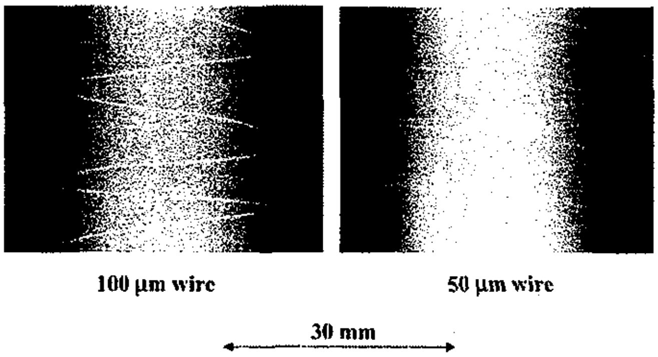

Figure 9: Radiograms of tungsten wires coiled around rod made of polymethyl methacrylate.

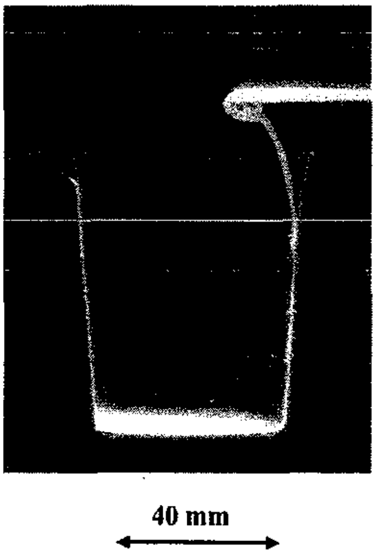

Figure 10: Radiogram of water falling into polypropylene beaker from plastic test tube.

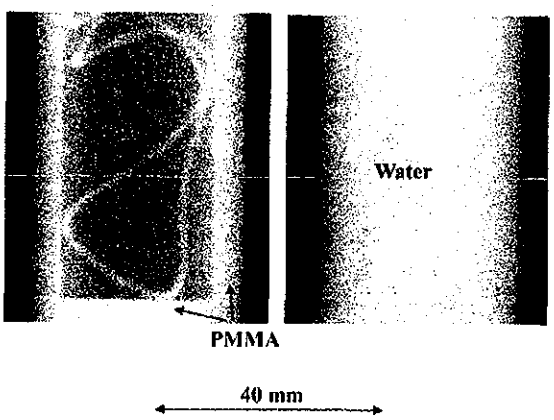

Figure 11: Angiograms of silicon tube using contrast medium of 32.3% gadodiamidehydrate.

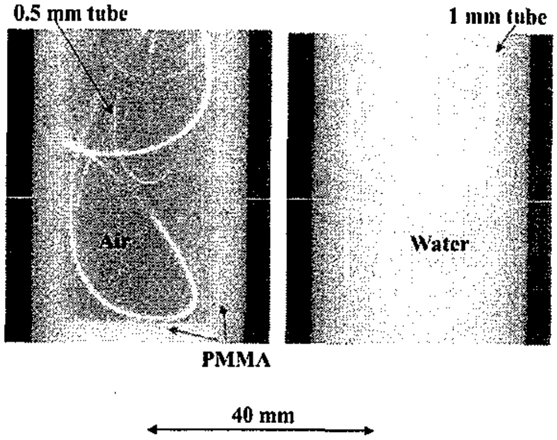

Figure 12: Angiography of silicon tube using gadolinium oxide suspension of 50%.

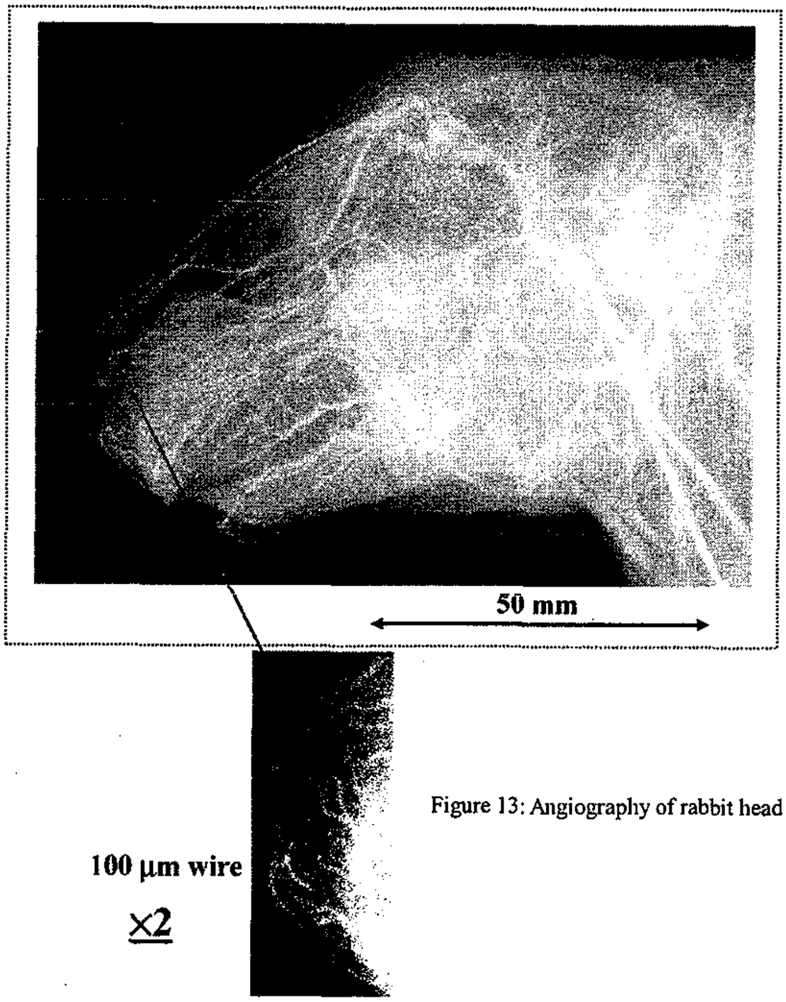

Figure 13: Angiography of rabbit head using gadolinium oxide powder.