

Figure 12: Angiography of a rabbit head using gadolinium oxide powder.

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Energy-selective gadolinium angiography utilizing a stroboscopic x-ray generator

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ABSTRACT

Energy-selective high-speed radiography utilizing a kilohertz-range stroboscopic x-ray generator and its application to high-speed angiography are described. This generator consists of the following major components: a main controller, a condenser unit with a Cockcroft-Walton circuit, and an x-ray tube unit in conjunction with a grid controller. The main condenser of about 500 nF in the unit is charged up to 120 kV by the circuit, and the electric charges in the condenser are discharged to the triode by the grid control circuit. Although the tube voltage decreased during the discharging for generating x-rays, the maximum value was equal to the initial charging voltage of the main condenser. The maximum tube current and the repetition rate were approximately 0.5 A and 50 kHz, respectively. The x-ray pulse width ranged from 0.01 to 1.0 ms, and the maximum shot number had a value of 32. At a charging voltage of 100 kV and a width of 1.0 ms, the x-ray intensity obtained using a 50- μ m-thick tungsten filter was 9.88 μ Gy at 1.0 m, and the dimensions of the focal spot had values of approximately 1×1 mm. Angiography was performed using the filter at a charging voltage of 100 kV.

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

1. INTRODUCTION

Flash x-ray generators are capable of producing high-dose rate short x-ray pulses, and have been applied to high-speed radiography in various fields.¹ To produce hard flash x-rays with maximum photon energies of approximately 1 MeV, multistage Marx surge generators have been developed. Furthermore, induction linear accelerators have been developed

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and improved to produce 10-MeV-order flash x-rays.² In contrast, 100-kV-order flash x-ray generators have been developed and applied to biomedicine. Subsequently, soft x-ray lasers have been produced using a gas-discharge capillary,³⁻⁵ and clean K-series characteristic x-rays⁶⁻⁹ and their higher harmonic hard x-rays have been produced from weakly ionized linear plasma.

In high-speed medical radiography, the repetition rate is one of the technical key parameters in real-time dynamic radiography. In view of this situation, we have developed two stroboscopic x-ray generators¹⁰ and have succeeded in producing repetitive x-rays with a maximum repetition rate of approximately 50 kHz. These generators employ 500 nF condensers and hot-cathode tungsten tubes, and the duration can be controlled from 10 μ s to 1.0 ms

Recently synchrotrons generate monochromatic parallel x-ray beams using a monochromator, and these beams have been employed to perform enhanced K-edge angiography.¹¹⁻¹³ To perform angiography, the beams with photon energies of approximately 35 keV have been used, because iodine contrast media with a K-absorption edge of 33.2 keV absorb the beams effectively. In view of this situation, we have developed x-ray generators with cerium-target tubes^{14,15} which can produce K α rays (34.6 keV). Subsequently, we have performed energy-selective high-speed angiography¹⁶ using quasi-monochromatic x-rays produced by the aluminum filtering.

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, K α rays of tantalum (57.1 keV)¹⁷ and tungsten (58.9 keV) are also useful to perform angiography, because the K α 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.

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

2. GENERATOR

Figure 1 shows the block diagram of the kilohertz-range stroboscopic x-ray generator. This generator consists of the following major components: a main controller, a condenser unit with a Cockcroft-Walton circuit, and an x-ray tube unit in conjunction with a grid controller (Fig. 2). The main condenser of approximately 500 nF in the unit is charged up to 120 kV by the circuit, and the electric charges in the condenser are discharged to the triode by the grid control circuit. Although the tube voltage decreased during the discharging for generating x-rays, the maximum value was equal to the initial charging voltage of the main condenser. In this generator, positive and negative high voltages are applied to the anode and cathode electrodes, respectively.

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

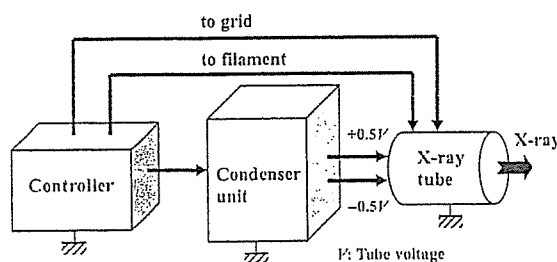


Figure 1: Block diagram of the kilohertz-range stroboscopic x-ray generator.

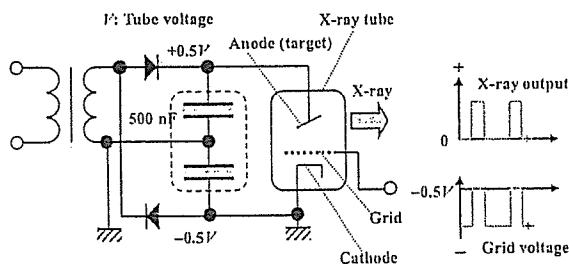


Figure 2: Main circuit of the kilohertz-range stroboscopic x-ray generator.

3. CHARACTERISTICS

3.1 X-ray output

The x-ray output signal was measured by a digital storage scope (Fig. 3) at the indicated conditions. Using this generator, the pulse width could be controlled correctly and ranged from 10 μ s to 1.0 ms. The maximum repetition rate was approximately 50 kHz, and stable repetitive x-ray pulses were obtained.

3.2 Time-integrated x-ray intensity

Figure 4 shows the time-integrated (absolute) value of the x-ray intensity at 1.0 m per pulse measured by a Victoreen 660 ionization chamber. The intensity was proportional to the driving pulse width. At a constant pulse width of 1.0 ms, the intensity increased with increases in the charging voltage. At a charging voltage of 100 kV and a width of 1.0 ms, the x-ray intensity obtained using a 50- μ m-thick tungsten filter was 9.88 μ Gy per pulse at 1.0 m from the source.

3.3 X-ray source

The image of the x-ray source was measured using a pinhole camera with a hole diameter of 50 μ m and a computed radiography (CR) system (Konica Regius 150)¹⁸ with a sampling pitch of 87.5 μ m. When the charging voltage was increased, the dimensions hardly varied, and were approximately 1 \times 1 mm.

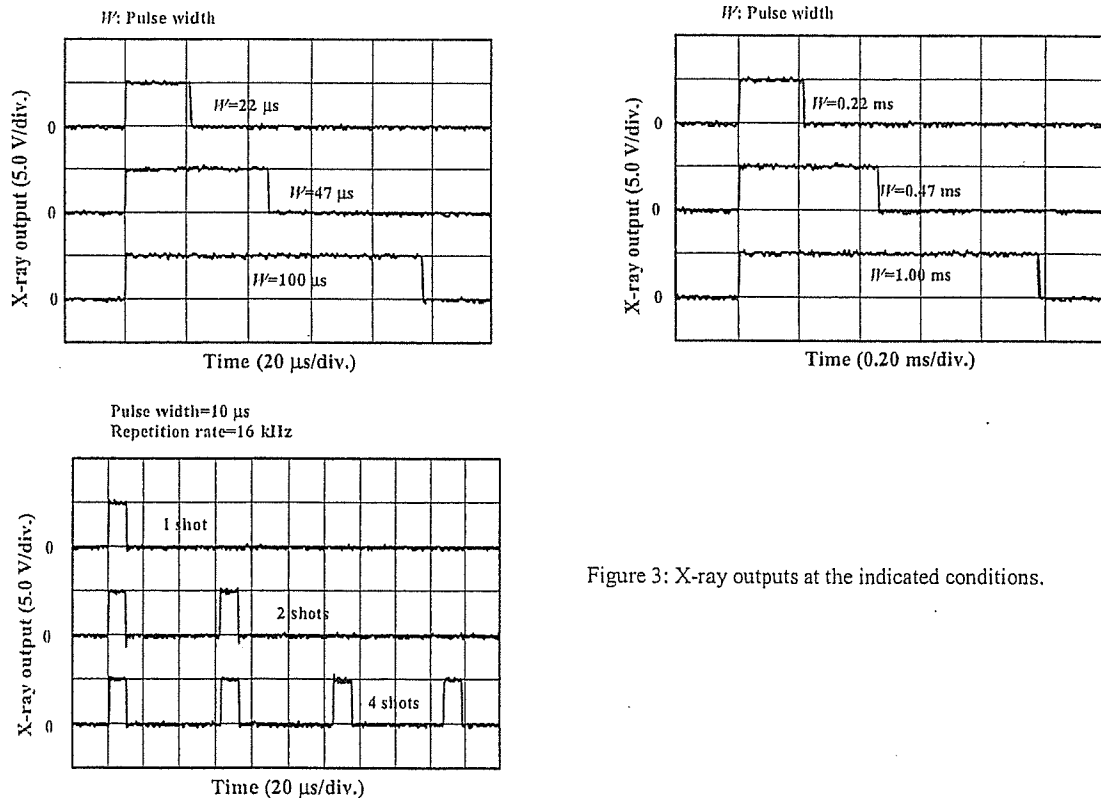


Figure 3: X-ray outputs at the indicated conditions.

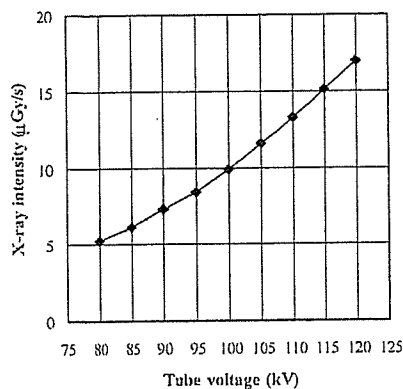


Figure 4: X-ray intensities at 1.0 m per pulse with changes in the charging voltage with an exposure time of 1.0 ms.

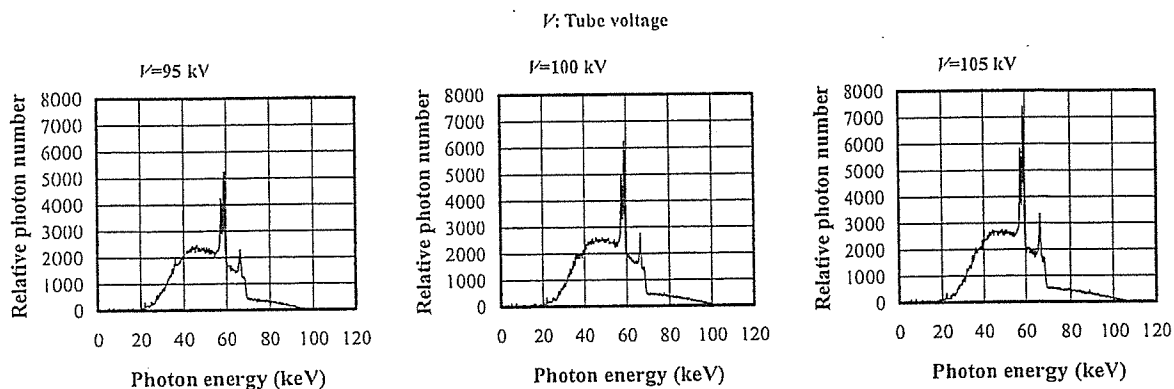


Figure 5: X-ray spectra at the indicated conditions.

3.4 X-ray spectra

In order to measure x-ray spectra with the filter, we employed a cadmium telluride detector (XR-100T, Amptek Inc.) (Fig. 5). When the charging voltage was increased, both the maximum photon energy and the intensities of bremsstrahlung x-rays increased, and the photon energy of the spectrum peak also increased. The areas under the spectral curves correlate closely to the total x-ray intensities shown in Fig. 4.

4. ANGIOGRAPHY

Figure 6 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 tungsten $K\alpha$ lines is shown just above the gadolinium K-edge. The average photon energy of tungsten $K\alpha$ lines is 58.9 keV, and gadolinium contrast media with a K-absorption edge of 50.2 keV absorb the lines easily. Therefore, blood vessels were observed with high contrasts. The radiography was performed by the CR system using the filter with a charging voltage of 100 kV, and the distance between the x-ray source and the imaging plate was 1.0 m. The image contrast hardly varied even when the filter was changed.

Firstly, rough measurements of spatial resolution were made using wires. Figure 7 shows radiograms of tungsten wires coiled around rods made of polymethyl methacrylate (PMMA). Although the image contrast increased with increases in the wire diameter, a 50 μm -diameter wire could be observed. Next, the time resolutions were roughly observed using a plastic bullet from an air gun. Although we obtained completely stop-motion images of a bullet utilizing multi-shot radiography with a duration of 10 μs , the average velocity could be measured with durations of sub-milliseconds (Fig. 8).

The image of water (20% gadolinium oxide suspension) falling into a polypropylene beaker from a plastic test tube is shown in Fig. 9. Because the x-ray duration was 1.0 ms, the stop-motion image of water could be obtained.

Figure 10 shows an angiogram of a polytetrafluoroethylene (Teflon) tube in a PMMA case using a contrast medium which contains approximately 65% gadodiamidehydrate with a duration of 1.0 ms, and a high-contrast tube with a bore diameter of 1.0 mm is observed. Figures 11 and 12 show angiograms of a rabbit ear and head using gadolinium oxide powder with a duration of 1.0 ms, and fine blood vessels of approximately 100 μm were visible.

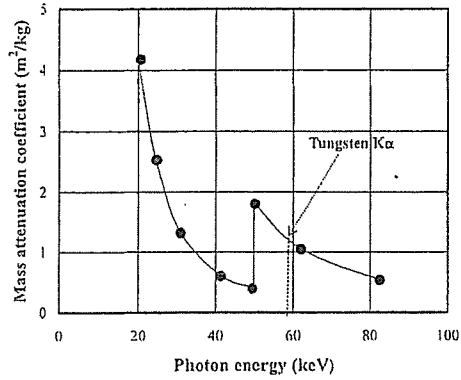


Figure 6: Mass attenuation coefficient of gadolinium and the average photon energy of tungsten K α lines is shown above gadolinium K edge.

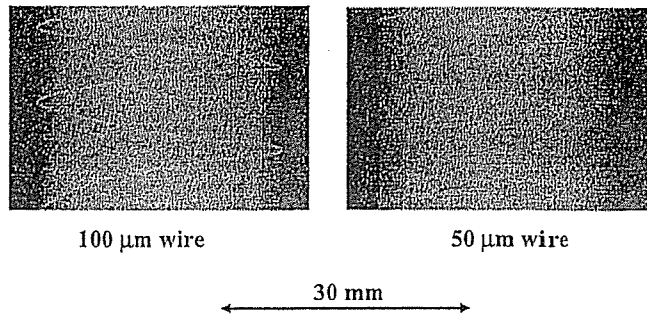
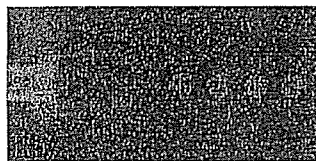
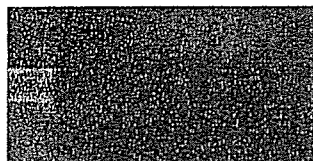


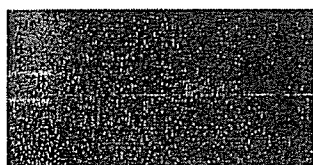
Figure 7: Radiograms of tungsten wires coiled around PMMA rods.



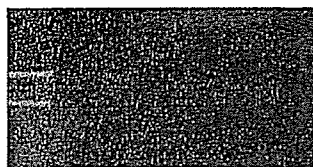
Rate=8.0 kHz
Duration=10 μs
4 shots



Rate=8.0 kHz
Duration=18 μs
4 shots



Duration=0.22 ms
1 shot



Duration=0.47 ms
1 shot

Figure 8: Radiograms of plastic bullets from an air gun at the indicated conditions.

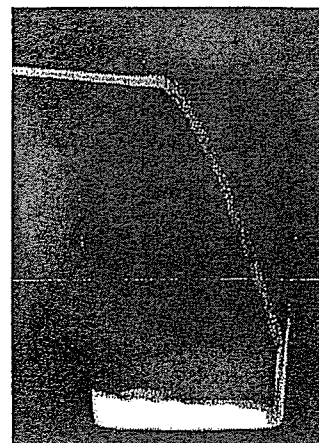
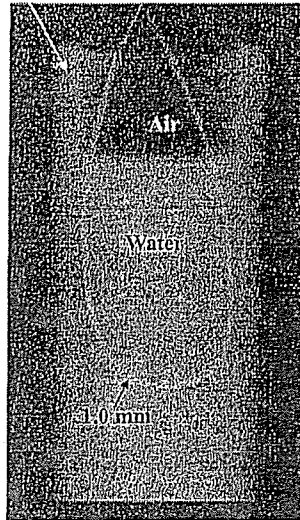


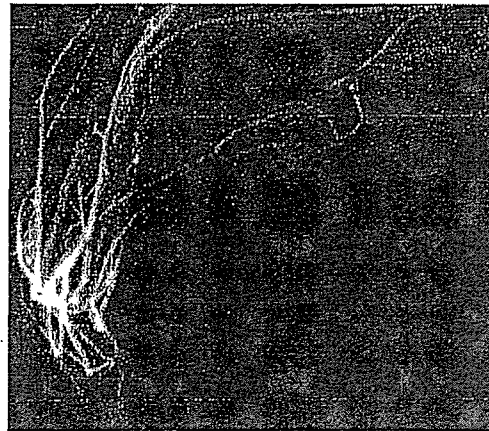
Figure 9: Radiogram of water falling into a polypropylene beaker from a glass test tube.

PMMA



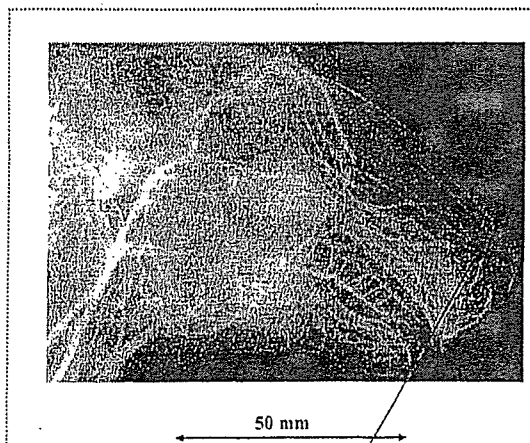
40 mm

Figure 10: Angiography of a Teflon tube using a contrast medium which contains approximately 65% gadodiamidehydrate.



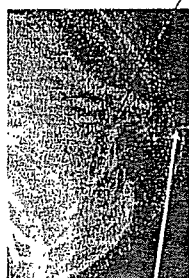
50 mm

Figure 11: Angiography of a rabbit ear using gadolinium oxide powder.



50 mm

Figure 12: Angiography of a rabbit head using gadolinium oxide powder.



100 μm wire

x2

5. DISCUSSION

In summary, we succeeded in performing high-speed enhanced angiography utilizing tungsten K-series characteristic x-rays and gadolinium contrast media. As compared with angiography using iodine media, the absorbed dose could be decreased utilizing angiography achieved with gadolinium media.

Concerning the spectrum measurement, we obtained K-series characteristic x-rays using the tungsten filter. When the filter was employed with a charging voltage of 100 kV, the peak photon energy of the spectra was approximately 50 kV. Therefore, the filter thickness should be increased in order to decrease bremsstrahlung x-rays with energies lower than the K-absorption edge of tungsten. In the imaging, we have to consider the filtering effect of human body. Subsequently, K β rays should be absorbed using an ytterbium oxide filter in order to improve the image contrast of blood vessels.

Using this filter with a charging voltage of 100 kV and a pulse width (exposure time) of 1.0 ms, although we obtained the x-ray intensities of approximately 10 μ Gy at 1.0 m per pulse, the intensity should be maximized by increasing the tube current in order to improve the image quality using the CR system.

Nowadays, because flat panel detectors are very useful in order to perform real-time dynamic imaging with high spatial resolutions of 100 μ m or less, stop-motion images of blood flows can be obtained using gadolinium media.

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

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ABSTRACT

The tantalum plasma flash x-ray generator is useful in order to perform high-speed K-edge angiography using cone beams because $K\alpha$ 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 $K\alpha$ 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 radiography¹⁻³ 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 $K\alpha$ 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 generators⁹⁻¹³ 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 generators¹⁴⁻¹⁶ 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 resonance 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 opposite 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 K α rays (52.0 keV) are useful for enhanced K-edge angiography, because the K α 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, K α 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 K α lines is shown above the gadolinium K-edge. The average photon energy of tantalum K α 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 thyatron 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.

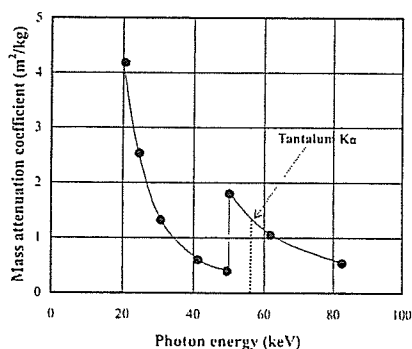


Figure 1: Relation between mass attenuation coefficient of gadolinium and average photon energy of tantalum K α lines.

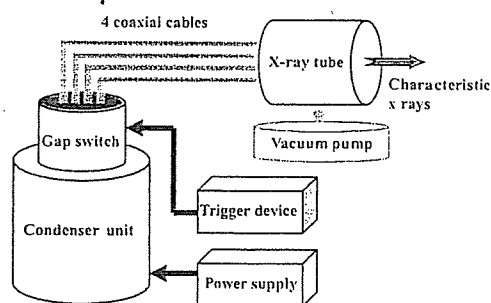


Figure 2: Block diagram of intense quasi-monochromatic flash x-ray generator.

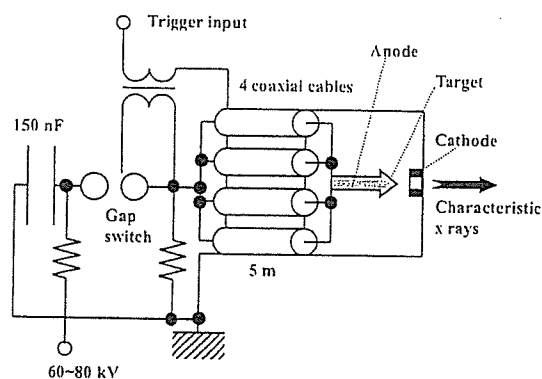


Figure 3: High-voltage circuit of flash x-ray generator.

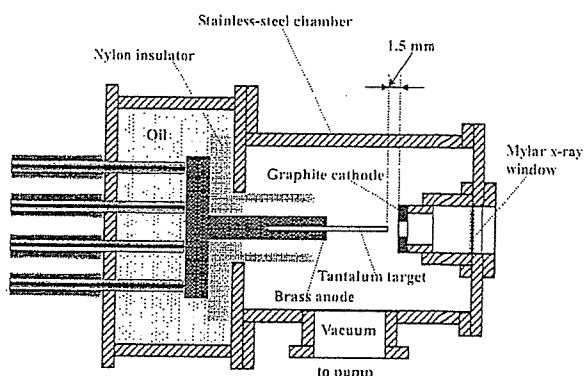


Figure 4: Schematic drawing of flash x-ray tube.

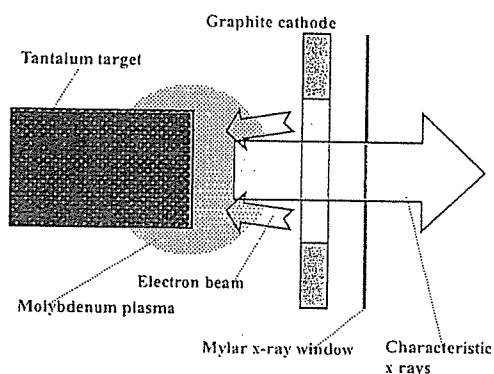


Figure 5: Irradiation of characteristic x rays.

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) system¹⁹ (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.

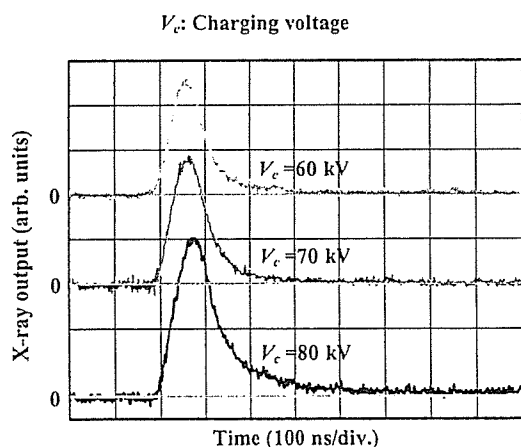


Figure 6: X-ray outputs at indicated conditions.

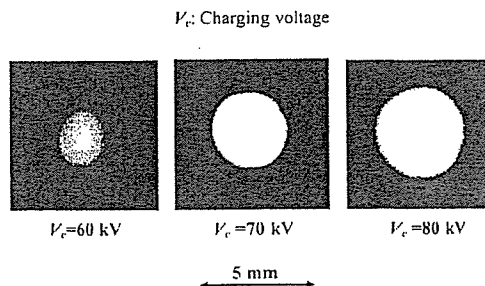


Figure 7: Images of characteristic x-ray source with changes in charging voltage.

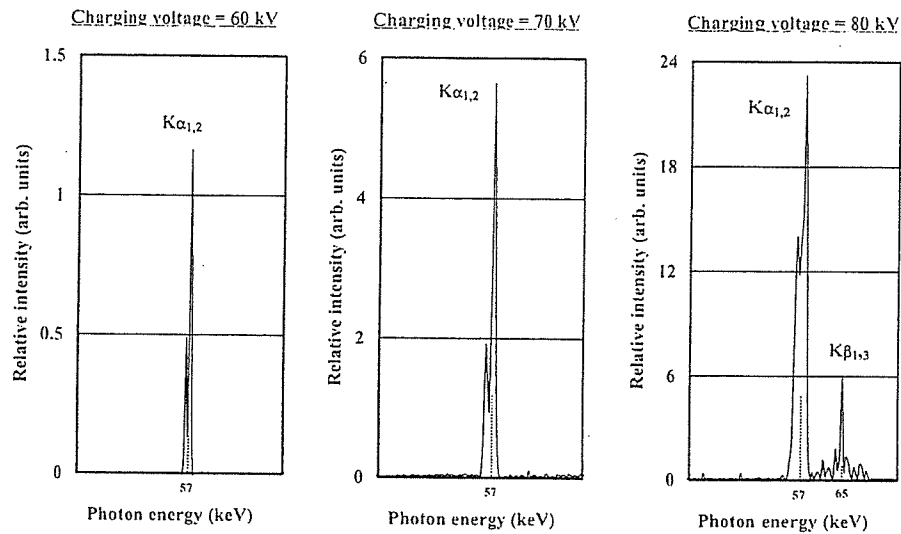


Figure 8: X-ray spectra from tantalum target.

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.

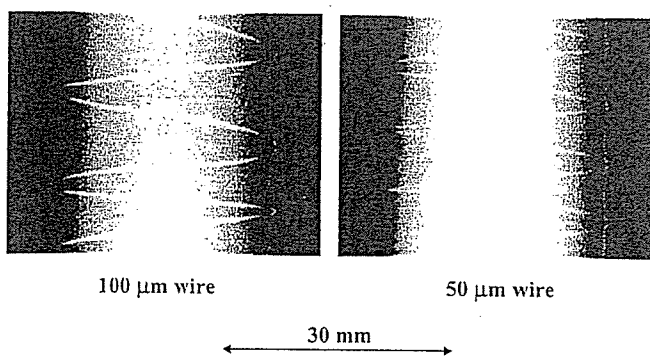


Figure 9: Radiograms of tungsten wires coiled around rod made of polymethyl methacrylate.

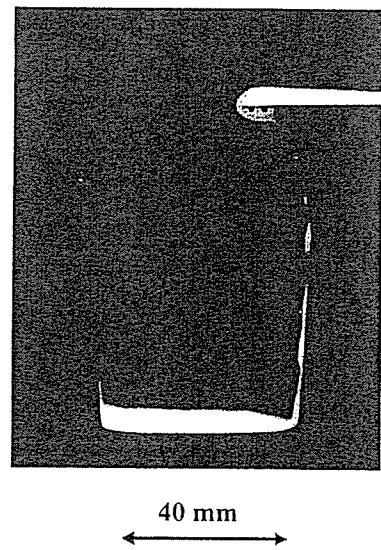


Figure 10: Radiogram of water falling into polypropylene beaker from plastic test tube.

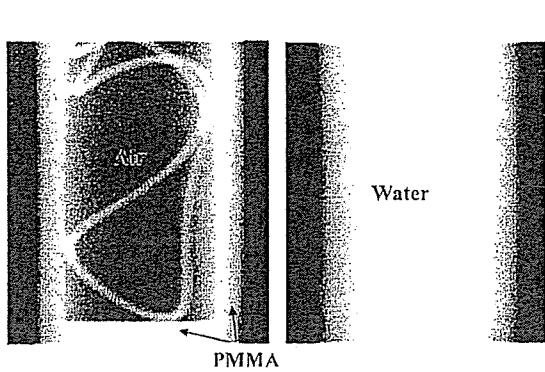


Figure 11: Angiograms of silicon tube using contrast medium of 32.3% gadodiamidehydrate.

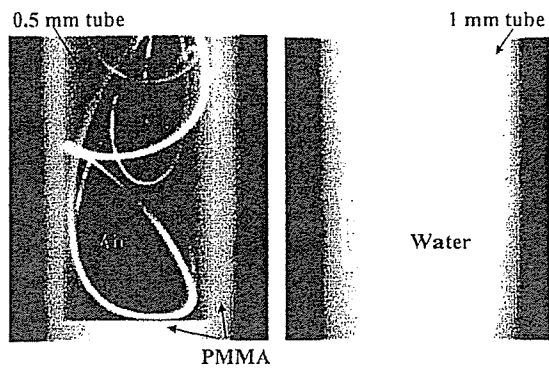


Figure 12: Angiography of silicon tube using gadolinium oxide suspension of 50%.

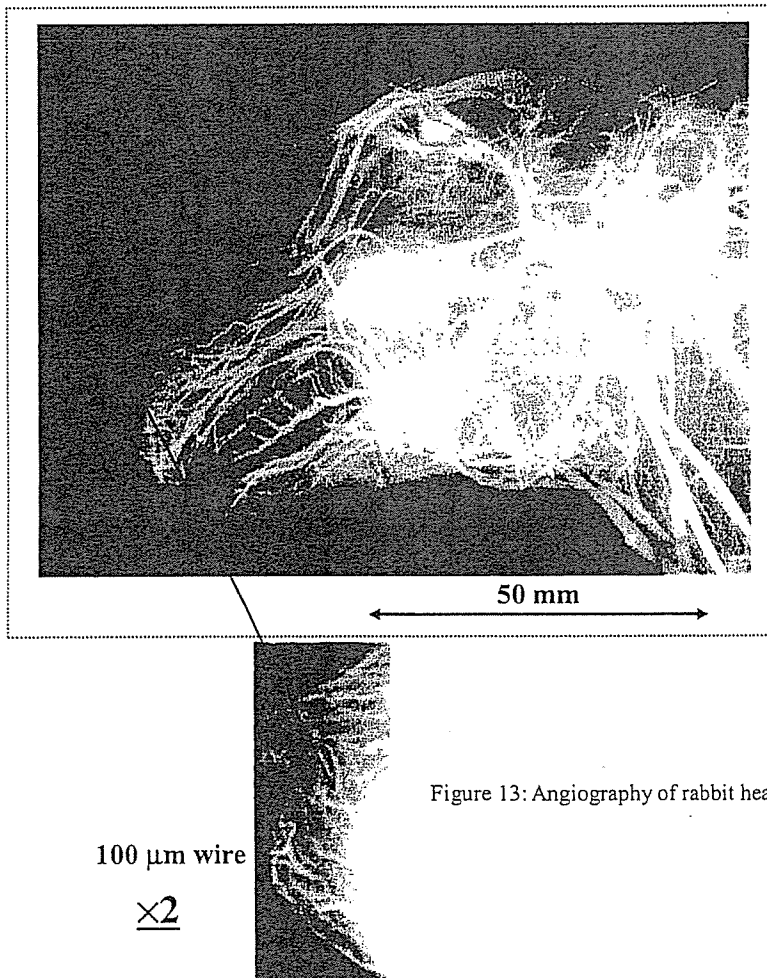


Figure 13: Angiography of rabbit head using gadolinium oxide powder.

6. DISCUSSION AND CONCLUSIONS

In summary, we succeeded in producing K-series characteristic x rays of tantalum and in performing K-edge angiography using gadolinium contrast media with a K-edge of 50.2 keV, and this K-edge angiography could be a useful technique to decrease the dose absorbed by patients. Although we employed tantalum $K\alpha$ (57.1 keV) and $K\beta$ (approximately 65 keV) rays, $K\beta$ rays should be absorbed using an ytterbium oxide filter with an ytterbium K edge of 61.3 keV in order to increase the image contrast of blood vessels.

To perform K-edge angiography using gadolinium media, although an ytterbium target with a $K\alpha$ energy of 52.0 keV is useful, the ytterbium has a high reactivity. If we assume that the ytterbium is employed, an alloy target should be developed. In this research, we obtained sufficient x-ray intensity per pulse for angiography, and the intensity can be increased by increasing the electrostatic energies in the high-voltage condenser. At a condenser capacity of 150 nF, the generator produced instantaneous number of K photons was approximately 1×10^9 photons/cm² per pulse at 1.0 m from the source.

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

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Weakly ionized linear plasma x-ray generator with molybdenum-target triode

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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 molybdenum ions and electrons, around the fine target, and intense characteristic x rays are produced. 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 16 kA. When the charging voltage was increased, the linear plasma formed, and the K-series characteristic x-ray intensities increased. The K lines were quite sharp and intense. The x-ray pulse widths were approximately 600 ns, and the time-integrated x-ray intensity had a value of approximately 65 $\mu\text{C/kg}$ at 1.0 m from the x-ray source with a charging voltage of 50 kV.

Keywords: flash x-ray, weakly ionized linear plasma, molybdenum characteristic x rays, quasi-monochromatic x rays, x-ray resonance

1. INTRODUCTION

In conjunction with monochromators, synchrotrons produce monochromatic parallel beams, which are fairly similar to monochromatic parallel laser beams, and the beams have been applied to enhanced K-edge angiography,^{1,2} phase imaging,^{3,4} and crystallography. Therefore, the production of coherent hard x-ray lasers for various research projects, including biomedical applications, has long been wished for.

Recently, soft x-ray lasers⁵⁻⁷ have been produced by a gas-discharge capillary, 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.

To apply flash x-ray generators to biomedicine, several different generators⁸⁻¹¹ have been developed, and plasma x-ray generators¹²⁻¹⁶ are useful for producing clean characteristic x rays in the low-photon-energy region of less than 20 keV. By forming weakly ionized linear plasma using rod targets, we confirmed irradiation of intense K-series characteristic x rays from the axial direction of the linear plasmas of nickel, copper, and molybdenum, since the bremsstrahlung x rays are absorbed effectively by the linear plasma; monochromatic clean $K\alpha$ rays were produced using K-edge filters. Subsequently, since high-photon-energy bremsstrahlung x rays are not absorbed effectively by the linear plasma due to attenuation coefficients, high-photon-energy quasi-monochromatic x-ray generators¹⁷ for producing characteristic x rays of molybdenum, silver, cerium, tantalum, and tungsten have been developed utilizing the angle dependence of bremsstrahlung x-ray intensity distribution.

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

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 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 up 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 pipe-shaped graphite cathode with a bore diameter of 10.0 mm, 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 molybdenum target 3.0 mm in diameter. 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 electric field in the tube, evaporation leads to the formation of weakly ionized linear plasma, consisting of molybdenum ions and electrons, around the fine target.

2.3 Principle of characteristic x-ray irradiation

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