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 μs 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-μm-thick tungsten filter was 9.88 μGy 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 μm and a computed radiography (CR) system (Konica Regius 150)[18] with a sampling pitch of 87.5 μm. When the charging voltage was increased, the dimensions hardly varied, and were approximately 1 × 1 mm.

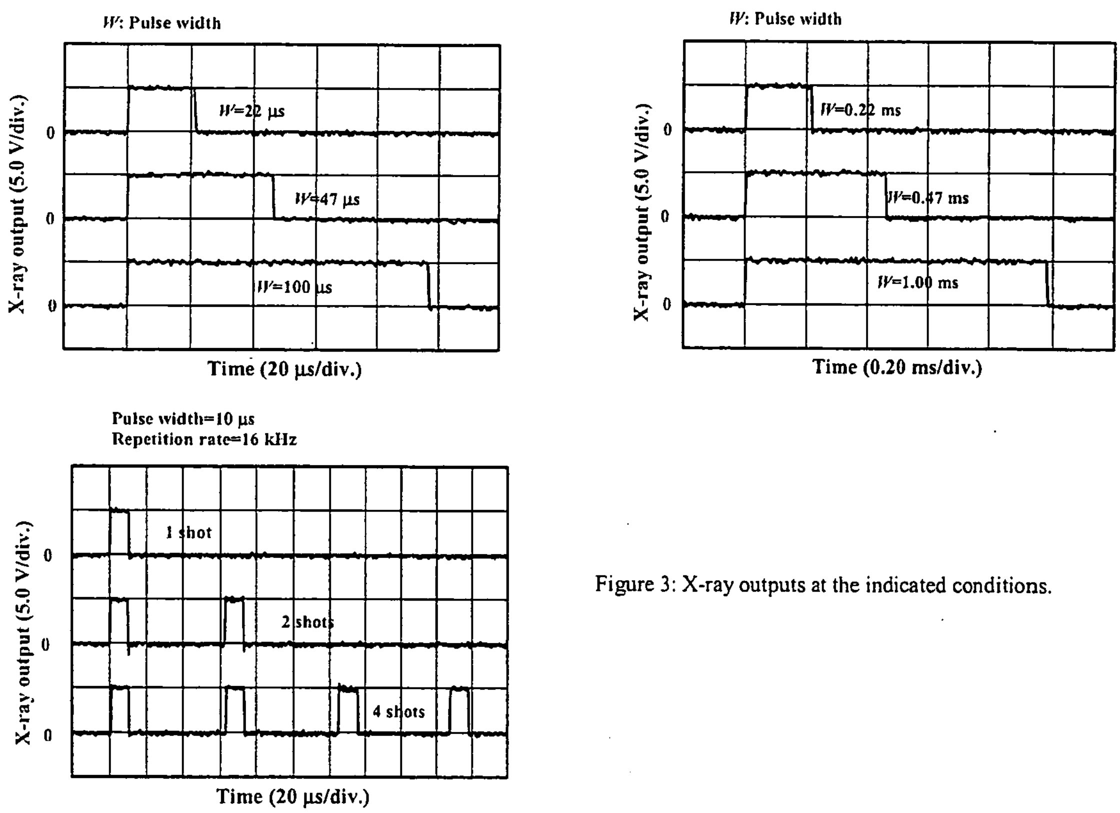

Figure 3: X-ray outputs at the indicated conditions.

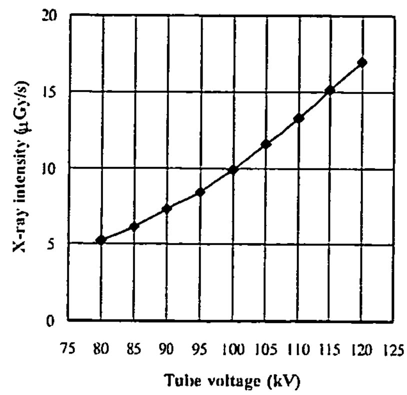

Figure 4: X-ray intensities at 1.0 m per pulse with changes in the charging voltage with an exposure time of 1.0 ms.

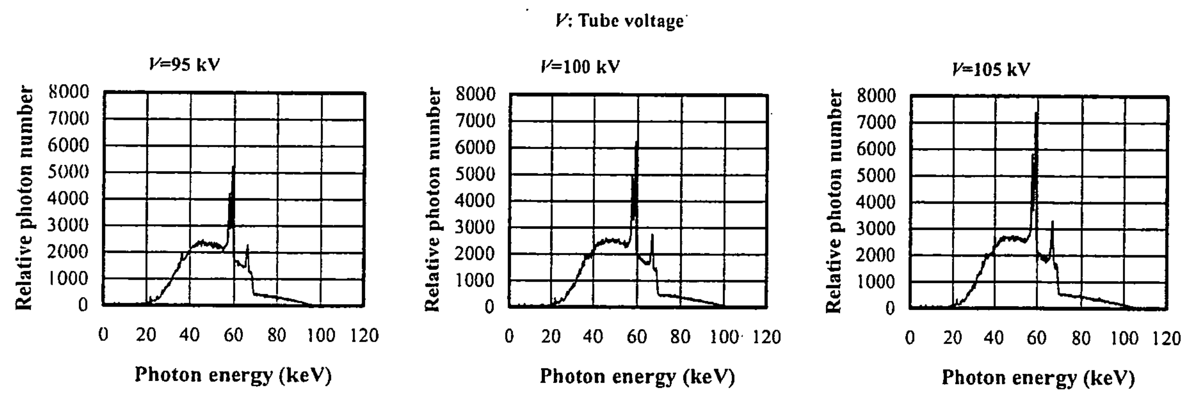

Figure 5: X-ray spectra at the indicated conditions.

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 Kα lines is shown just above the gadolinium K-edge. The average photon energy of tungsten Kα lines is 58.9 keV, and gadolinium contrast media with a K-absorption edge of 50.2 keV absorb the lines easily. Therefore, blood vessels were observed with high contrasts.

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.

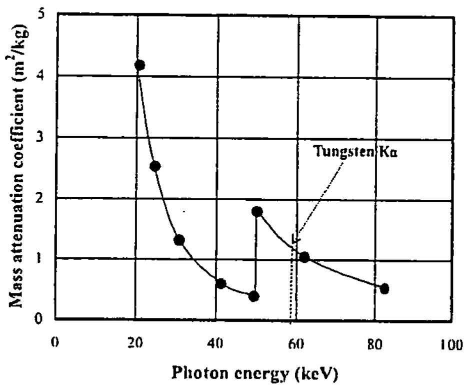

Figure 6: Mass attenuation coefficient of gadolinium and the average photon energy of tungsten Kα lines is shown above gadolinium K edge.

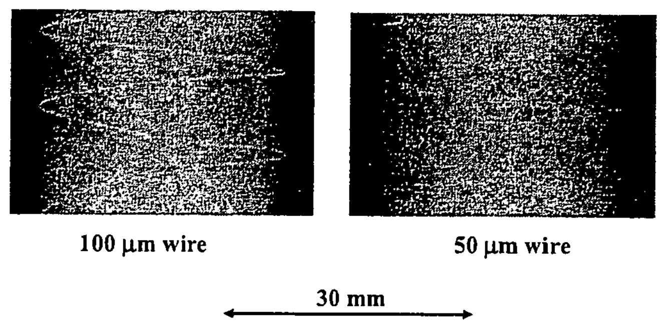

Figure 7: Radiograms of tungsten wires coiled around PMMA rods.

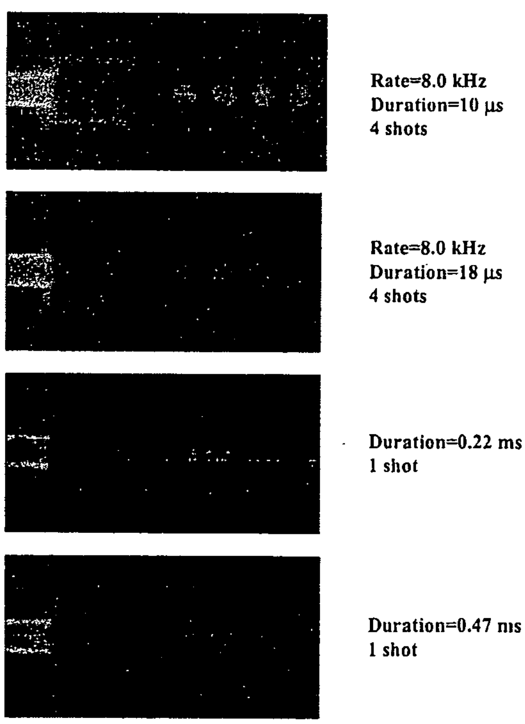

Figure 8: Radiograms of plastic bullets from an air gun at the indicated conditions.

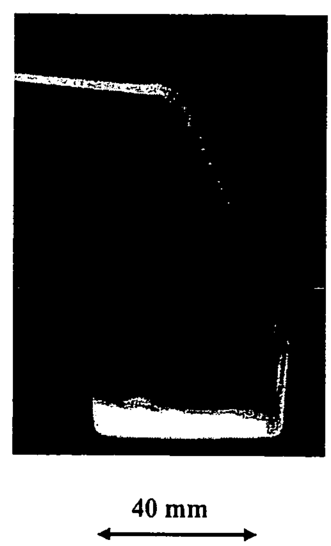

Figure 9: Radiogram of water falling into a polypropylene beaker from a glass test tube.

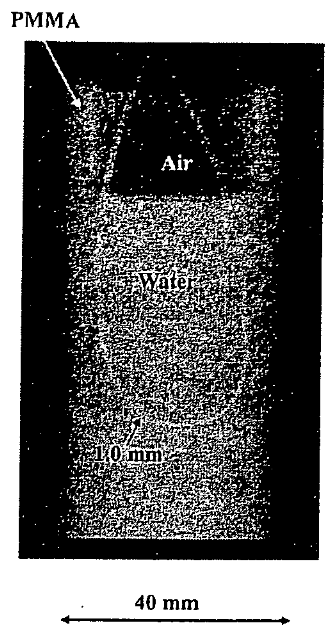

Figure 10: Angiography of a Teflon tube using a contrast medium which contains approximately 65% gadodiamidehydrate.

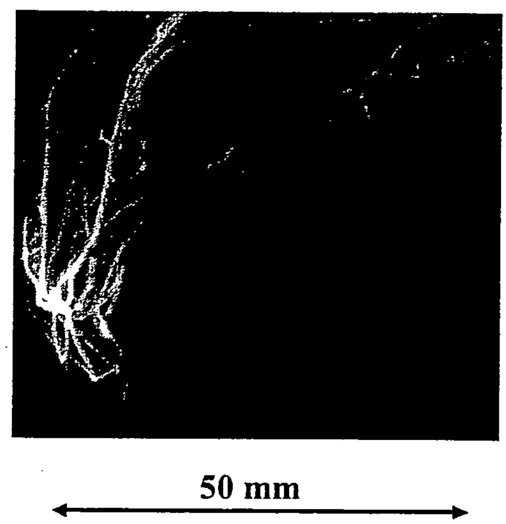

Figure 11: Angiography of a rabbit ear using gadolinium oxide powder.

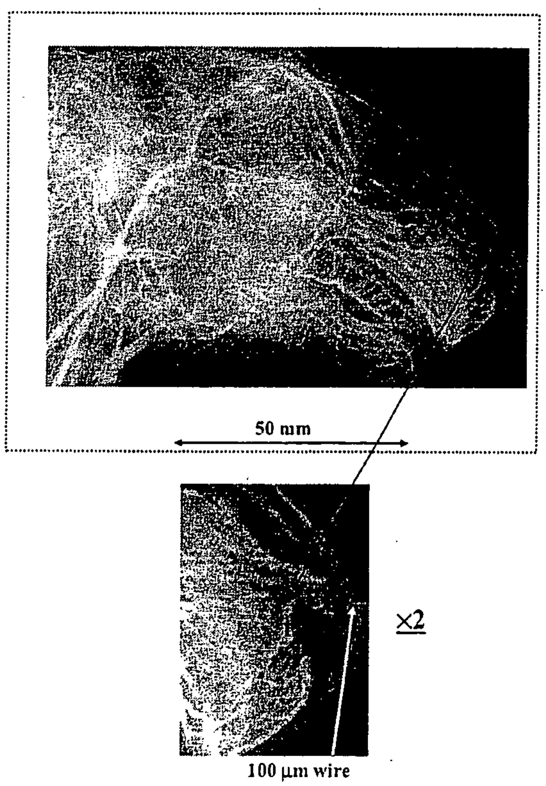

Figure 12: Angiography of a rabbit head using gadolinium oxide powder.

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, $K\beta$ 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 μGy at 1.0 m per pulse, the intensity should be maximized by increasing the tube current in order to improve the image quality using the CR system.
Nowadays, because flat panel detectors are very useful in order to perform real-time dynamic imaging with high spatial resolutions of 100 μm or less, stop-motion images of blood flows can be obtained using gadolinium media.

ACKNOWLEDGMENT

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Enhanced K-edge plasma angiography achieved with tungsten Kα rays utilizing gadolinium-based contrast media

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ABSTRACT

The tungsten plasma flash x-ray generator is useful in order to perform high-speed enhanced K-edge angiography using cone beams because Kα rays from the tungsten 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. 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 characteristic x-ray intensities of tungsten Kα lines increased. Using an ytterbium oxide filter, the Kα lines were clean, and hardly any Kβ lines and bremsstrahlung rays were detected. The x-ray pulse widths were approximately 60 ns, and the time-integrated x-ray intensity had a value of approximately 50 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 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, monochromatic x-rays, tungsten Kα rays

1. INTRODUCTION

Ultrafast X-Ray Detectors, High-Speed Imaging, and Applications, edited by Stuart Kleinfelder, Dennis L. Paisley, Zenghu Chang, Jean-Claude Kieffer, Jerome B. Hastings, Proc. of SPIE Vol. 5920 (SPIE, Bellingham, WA, 2005) · 0277-786X/05/$15 · doi: 10.1117/12.620212

Monochromatic parallel beams from synchrotron orbital radiation have been employed in phase-contrast radiography[1,2] and enhanced K-edge angiography.[3,4] In particular, the parallel beams with photon energies of approximately 35 keV have been employed to perform iodine K-edge 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,[5,6] and have performed cone-beam K-edge angiography achieved with cerium Kα rays of 34.6 keV.

Gadolinium-based contrast media with a K-edge of 50.2 keV have been employed to perform in MRA, 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 (57.1 keV) and tungsten (58.9 keV) are also useful to perform angiography.

In order to perform high-speed biomedical radiography, several different flash x-ray generators[7-10] with photon energies less than 150 keV have been developed, and plasma flash x-ray generators[11-13] have been developed to perform a preliminary experiment for producing hard x-ray lasers. From weakly ionized plasma, clean K-series characteristic x-rays of nickel and copper and their higher harmonic hard x-rays have been produced. Furthermore, high-photon-energy monochromatic flash x-ray generators[14-17] have been developed to produce K-series characteristic x-rays of molybdenum, cerium, ytterbium, tantalum, and tungsten, because bremsstrahlung rays are not emitted in the opposite direction to that of electron trajectory in Sommerfeld's theory.

In this article, we describe an intense monochromatic plasma flash x-ray generator with a tungsten target tube, and used it to perform a preliminary study on angiography achieved with tungsten Kα rays using an ytterbium oxide filter.

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 tungsten Kα lines is shown just above the gadolinium K-edge. The average photon energy of tungsten Kα lines is 58.9 keV, and gadolinium contrast media with a K-absorption edge of 50.2 keV absorb the lines easily. Therefore, blood vessels were observed with high contrasts.

3. GENERATOR

3.1 High-voltage circuit

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 tungsten 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 tungsten ions and electrons, around the target. Because bremsstrahlung rays are not emitted in the opposite direction to that of electron acceleration (Fig. 4), tungsten Kα rays can be produced using an ytterbium oxide filter with a surface density of 20 mg/cm^2.

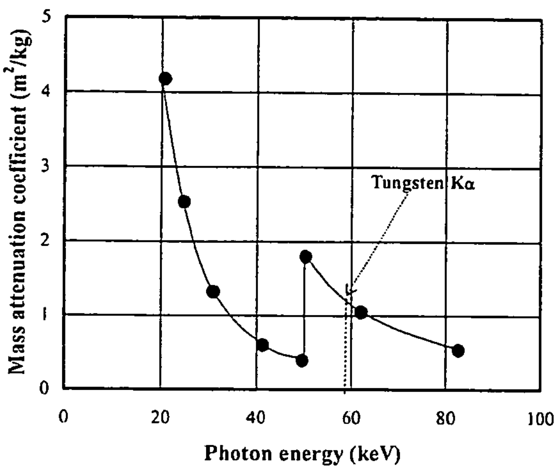

Figure 1: Mass attenuation coefficient of gadolinium and the average photon energy of tungsten Kα lines is shown above gadolinium K edge.

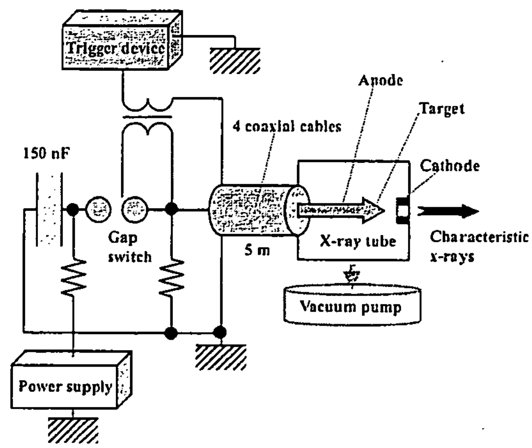

Figure 2: Block diagram including high-voltage circuit of the intense monochromatic plasma flash x-ray generator with a tungsten-target tube.

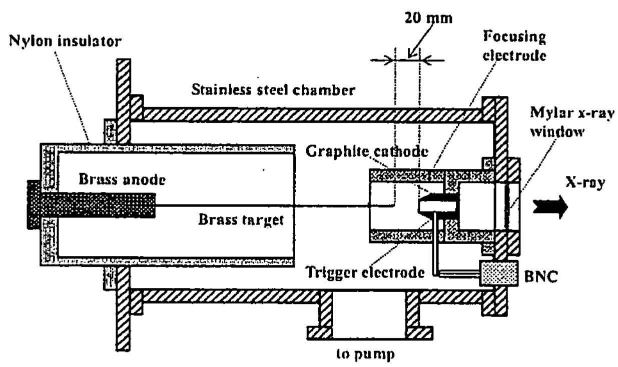

Figure 3: Schematic drawing of the flash x-ray tube with a rod-shaped tungsten target.

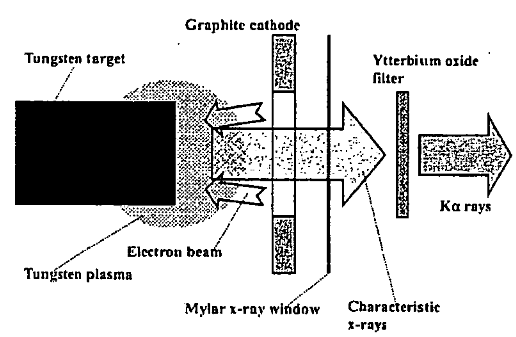

Figure 4: Irradiation of K-series characteristic x-rays of tungsten.

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 60 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 50 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 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 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[18] (Konica Minolta Regius 150) with a wide dynamic range, and relative x-ray intensity was calculated from Dicom original digital data corresponding to x-ray intensity; the data was scanned by Dicom viewer in the film-less CR system. Subsequently, the relative x-ray intensity as a function of the data was calibrated using a conventional x-ray generator, and we confirmed that the intensity was proportional to the exposure time. Figure 7 shows measured spectra from the tungsten target. We observed clean Kα lines, while Kβ lines and bremsstrahlung rays were hardly detected. The Kα intensity increased with increases in the charging voltage.

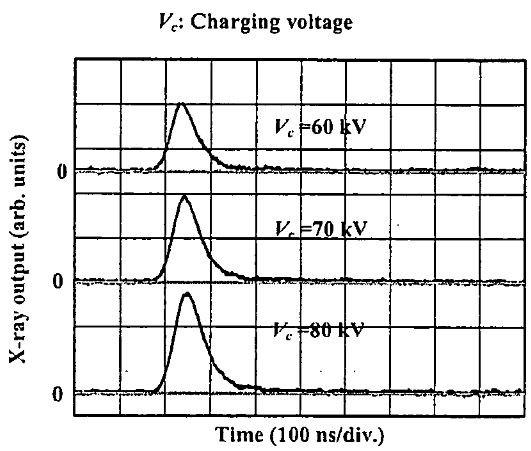

Figure 5: X-ray outputs detected using a combination of a plastic scintillator and a photomultiplier.

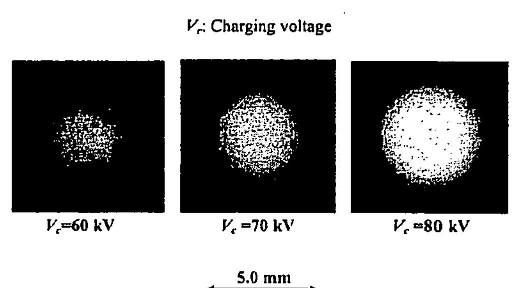

Figure 6: Images of Kα-ray source obtained using a pinhole camera with changes in the charging voltage.

5. ANGIOGRAPHY

The flash angiography was performed using the CR system and the filter 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 8 shows radiograms of tungsten wires in a rod made of polymethyl methacrylate (PMMA). 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 (20% gadolinium oxide suspension) falling into a polypropylene beaker from a plastic test tube is shown in Fig. 9. The diameter of gadolinium oxide powder ranges from 1 to 10 μm. Because the x-ray duration was about 60 ns, 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, 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, and fine blood vessels of approximately 100 μm were visible.

6. CONCLUSIONS AND OUTLOOK

We succeeded in producing tungsten Kα rays 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. In angiography, we employed tungsten Kα (58.9 keV) rays by absorbing Kβ rays (approximately 67 keV) using the ytterbium oxide filter, and L-series characteristic rays were also absorbed.

We obtained sufficient x-ray intensity per pulse for CR angiography with x-ray durations of approximately 60 ns, and the intensity can be increased by increasing the charging voltage at a constant target-cathode space. Currently, the x-ray duration increased with increases in the target-cathode space. In this research, the generator produced instantaneous number of Kα photons was approximately 1.5×10^8 photons/cm^2 per pulse at 1.0 m from the source.

Because the dimensions of the x-ray source are primarily determined by the target diameter, the diameter should be minimized in order to improve the spatial resolution, and can be reduced to approximately 0.5 mm. Because the x-ray intensity is the highest at the center of the spot, the effective focal spot size decreased during x-ray absorption in an object. Subsequently, the sampling pitch can be decreased to 43.8 μm using a CR system (Konica Minolta Regius 190) to observe fine blood vessels of approximately 50 μm in diameter.

Using this flash x-ray generator, enhanced K-edge angiography using iodine contrast media and a cerium target can be also performed. In addition, steady-state monochromatic x-rays can be produced by a similar tube utilizing a hot cathode and a constant high-voltage power supply. Using a tungsten or a molybdenum target, fine focusing can be realized, and these x-ray generators could be employed to perform quasi-monochromatic phase-contrast radiography for edge enhancement.

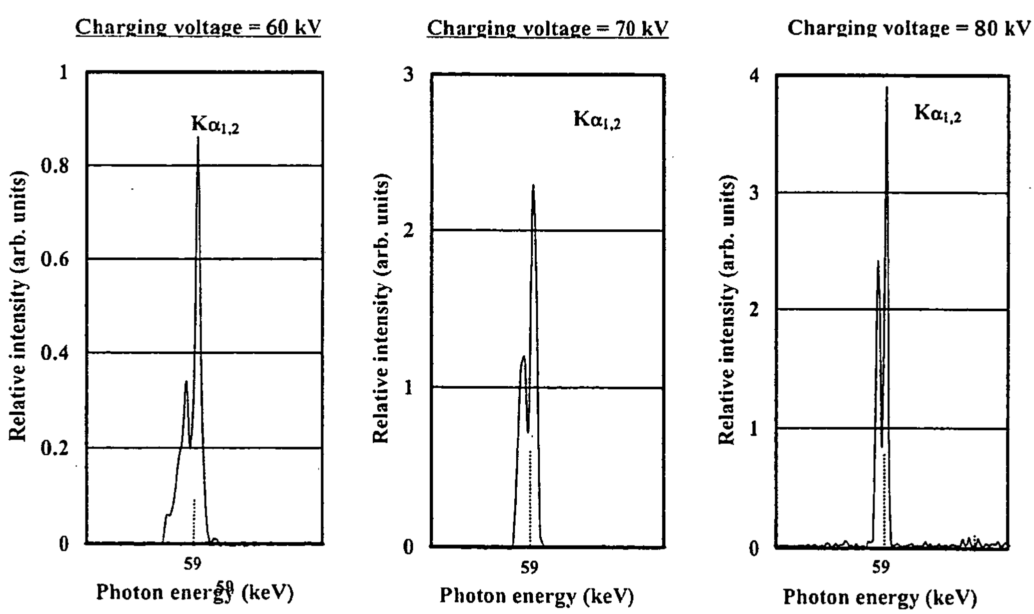

Figure 7: X-ray spectra from a tungsten target. The spectra were measured using a transmission type spectrometer with a lithium fluoride curved crystal.

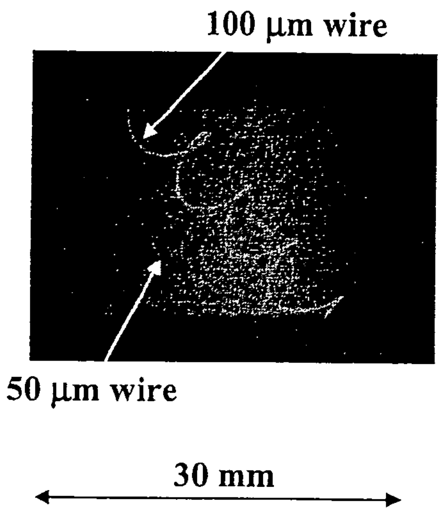

Figure 8: Radiograms of tungsten wires in a PMMA rod. gadodiamidehydrate.

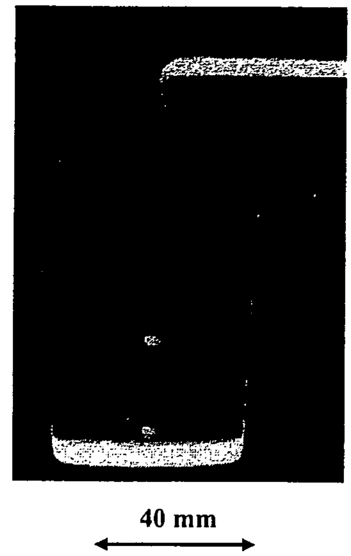

Figure 9: Radiogram of water falling into a polypropylene beaker from a glass test tube.

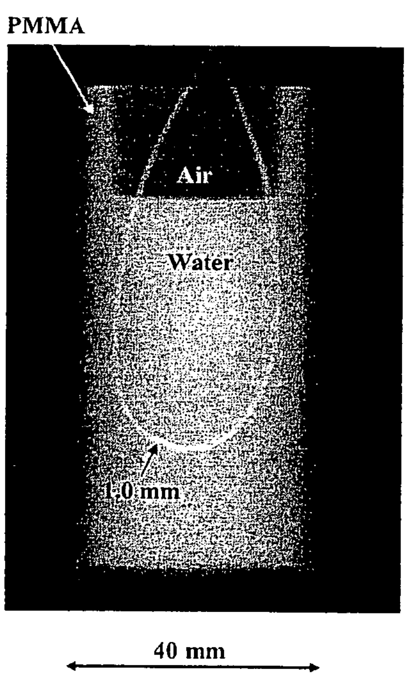

Figure 10: Angiography of a Teflon tube using a contrast medium which contains approximately 65% gadodiamidehydrate.

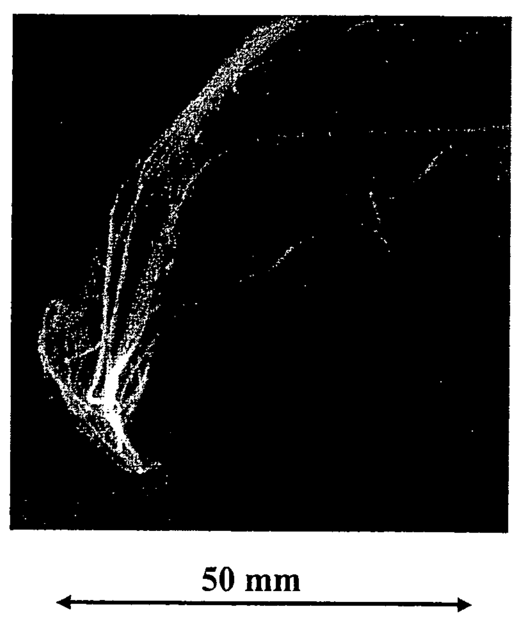

Figure 11: Angiography of a rabbit ear using gadolinium oxide powder.

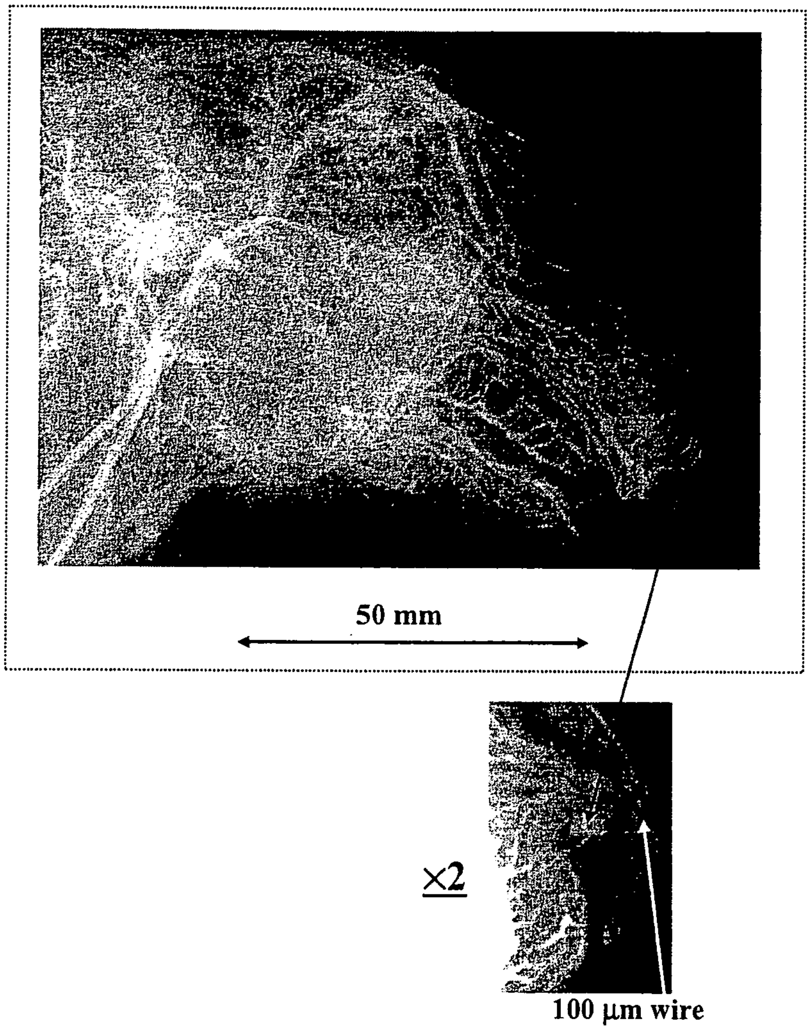

Figure 12: Angiography of a rabbit head using gadolinium oxide powder.

ACKNOWLEDGEMENTS

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Preliminary study for producing higher harmonic hard x-rays from weakly ionized copper plasma

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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 copper ions and electrons, around the fine target, and intense Kα 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 16 kA. The K-series characteristic x-rays were clean and intense, and higher harmonic x-rays were observed. The x-ray pulse widths were approximately 300 ns, and the time-integrated x-ray intensity had a value of approximately 1.5 mGy per pulse at 1.0 m from the x-ray source with a charging voltage of 50 kV.

Keywords: weakly ionized linear plasma, K-series characteristic x-rays, clean characteristic x-rays, higher harmonic hard x-rays

1. INTRODUCTION

In order to produce soft x-ray lasers, several different methods have been developed, and a discharge capillary[1-3] is very useful to increase the laser pulse energy with increases in the capillary length. However, it is difficult to increase the laser photon energy to 10 keV or beyond.

Using monochrocollimators, synchrotrons produce monochromatic parallel beams, which are fairly similar to monochromatic parallel laser beams, and the beams have been applied to various research project including

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phase-contrast radiography[4,5] and enhanced K-edge angiography.[6,7] 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 generators[8-13] have been developed, and plasma x-ray generators[14-17] 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. In this paper, we describe a recent plasma flash x-ray generator utilizing a rod target triode, used to perform a preliminary experiment for generating clean K-series characteristic x-rays and their higher harmonic hard x-rays by forming a plasma cloud around a fine target.

2. GENERATOR

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. 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.

The schematic drawing of the plasma x-ray tube is illustrated in Fig. 2. The x-ray tube is a demountable cold-cathode triode that is connected to the turbomolecular pump with a pressure of approximately 1 mPa. 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.

In the linear plasma, bremsstrahlung photons with energies 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 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 trajectory, intense characteristic x-rays are generated from the plasma-axial direction.

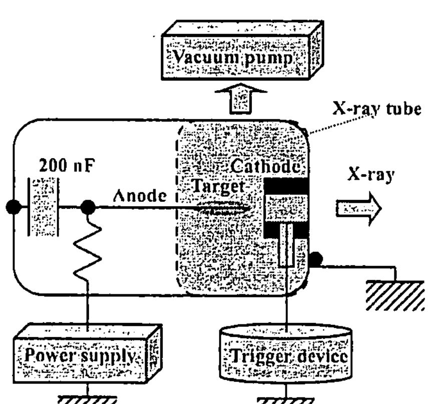


Figure 1: Block diagram including the electric circuit of the plasma flash x-ray generator.

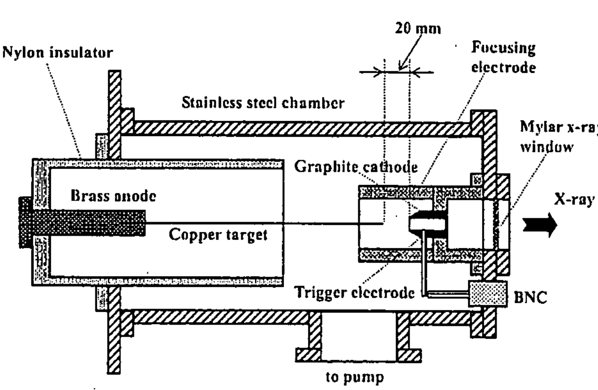


Figure 2: Schematic drawing of the flash x-ray tube with a rod copper target.

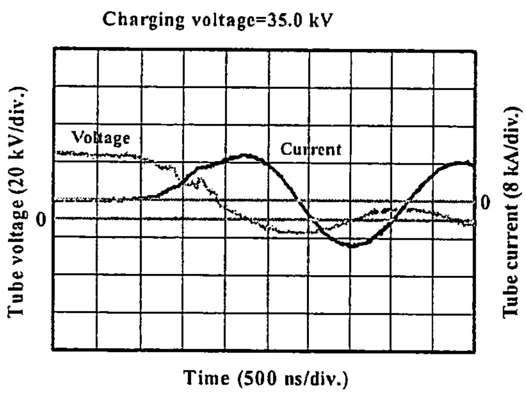
3. CHARACTERISTICS

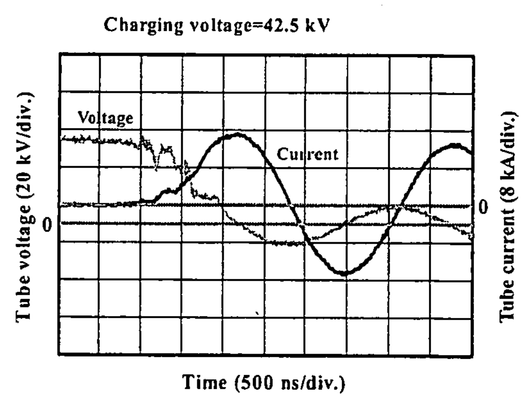
3.1 Tube voltage and current

Tube voltage and current were measured by a high-voltage divider with an input impedance of 1 GΩ and a current transformer, respectively. Figure 3 shows the time relation between the tube voltage and current. At the indicated charging voltages, they 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 16 kA.

3.2 X-ray output

X-ray output pulse was detected using a combination of a plastic scintillator and a photomultiplier (Fig. 4). The x-ray pulse height substantially increased with corresponding increases in the charging voltage. The x-ray pulse widths were about 300 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 1.5 mGy at 1.0 m from the x-ray source with a charging voltage of 50 kV.





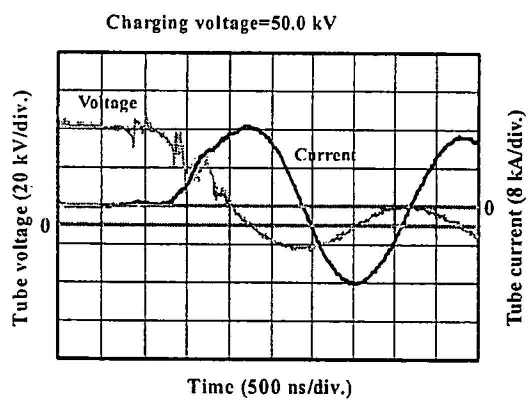


Figure 3: Tube voltages and currents with changes in the charging voltage.

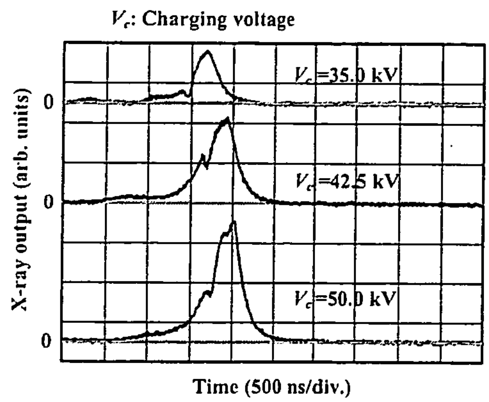


Figure 4: X-ray outputs at the indicated conditions.

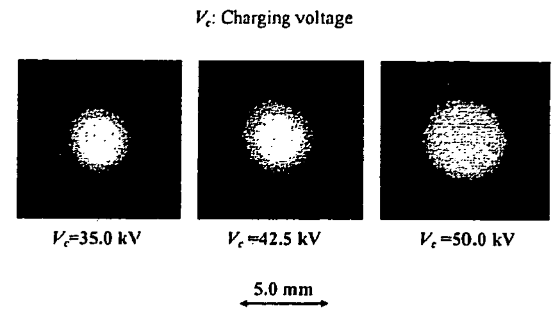


Figure 5: Images of the plasma x-ray source.

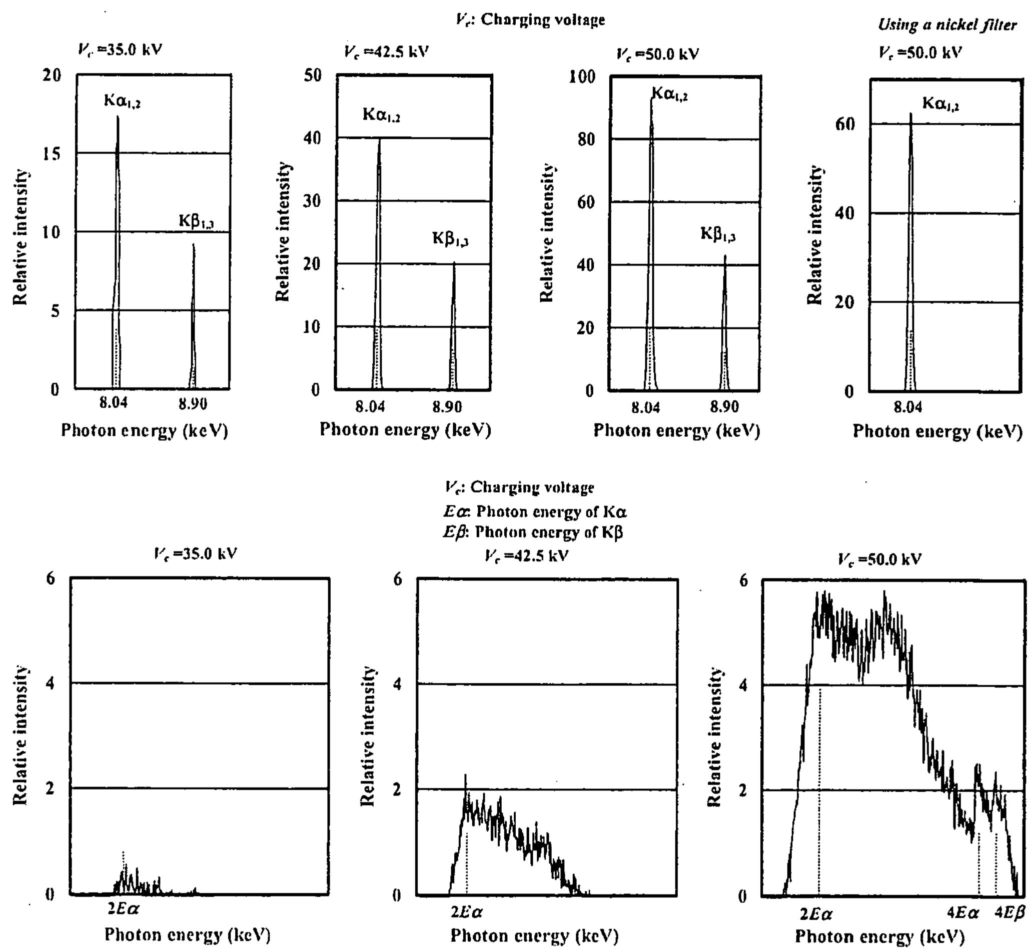


Figure 6: X-ray spectra from weakly ionized copper plasma at the indicated conditions.

3.3 X-ray source

In order to roughly observe images of the plasma x-ray source in the detector plane, we employed a pinhole camera with a hole diameter of 100 μm (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

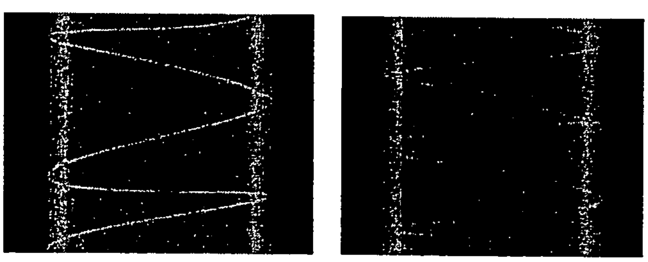
X-ray spectra from the plasma source were measured by a transmission-type spectrometer with a lithium fluoride curved crystal 0.5 mm in thickness. The spectra were taken by a computed radiography (CR) system[18] (Konica Regius 150) with a wide dynamic range, and relative x-ray intensity was calculated from Dicom digital data. Subsequently, the relative x-ray intensity as a function of the data was calibrated using a conventional x-ray generator, and we confirmed that the intensity was proportional to the exposure time. Figure 6 shows measured spectra from the copper target at the indicated conditions. In fact, we observed clean K lines such as lasers, and $K\alpha$ lines were left by absorbing $K\beta$ lines using a 10-μm-thick nickel filter. The characteristic x-ray intensity substantially increased with corresponding increases in the charging voltage, and higher harmonic hard x-rays were observed.

4. RADIOGRAPHY

The plasma radiography was performed by the CR system using the filter. The charging voltage and the distance between the x-ray source and imaging plate were 50 kV and 1.2 m, respectively.

Firstly, rough measurements of spatial resolution were made using wires. Figure 7 shows radiograms of tungsten wires coiled around pipes made of polymethyl methacrylate (PMMA). 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.

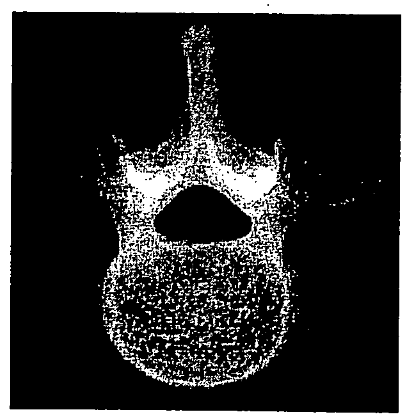
Figure 8 shows a radiogram of a vertebra, and fine structures in the vertebra were observed. Next, a radiogram of plastic bullets falling into a polypropylene beaker from a plastic test tube is shown in Fig. 9. Because the x-ray duration was about 0.5 μs, the stop-motion image of bullets could be obtained. Figure 10 shows an angiogram of a rabbit ear; iodine-based microspheres of 15 μm in diameter were used, and fine blood vessels of about 100 μm were visible.



100 μm wire   50 μm wire

25 mm

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



50 mm

Figure 8: Radiogram of a vertebra.

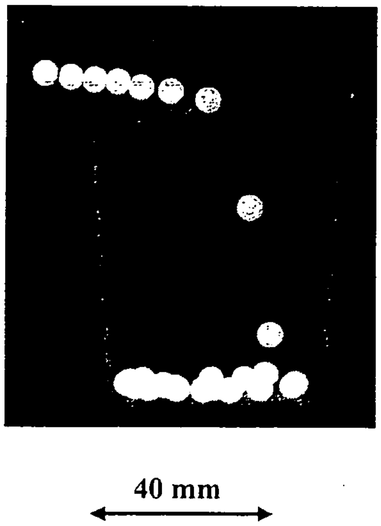


Figure 9: Radiogram of plastic bullets falling into polypropylene beaker from a plastic test tube.

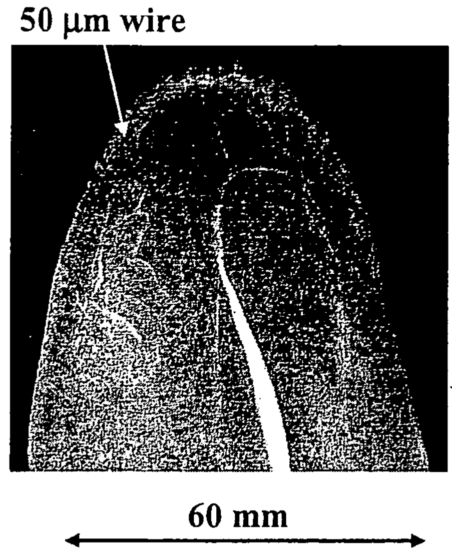


Figure 10: Angiogram of a rabbit ear.

5. CONCLUSIONS AND OUTLOOK

We obtained fairly intense and clean K lines from a weakly ionized linear plasma x-ray source, and Kα lines were left by absorbing Kβ lines using the nickel filter. In particular, the higher harmonic x-rays were produced from the plasma. Assuming that the harmonic rays are produced by the x-ray resonation (Fig. 11), the estimated spectra are shown in Fig. 12. In cases where a nickel target is employed, fractional harmonic x-rays are absorbed by the x-ray window and the air. In cases where weakly ionized linear plasma is employed, intense and clean K-series characteristic x-rays can be obtained. However, it is not easy to produce high-photon-energy K-series characteristic x-rays because the plasma transmits high-photon energy bremsstrahlung x-rays. Therefore, high-photon-energy plasma flash x-ray generator utilizing angle dependence of bremsstrahlung x-rays are very useful to produce K photons of molybdenum, silver, cerium, tantalum, and tungsten.

In this research, we obtained sufficient characteristic x-ray intensity per pulse for CR radiography, and the generator produced number of characteristic K photons was approximately 1×10^8 photons/cm^2 at 1.0 m per pulse. In addition, we are very interested in producing steady-state clean K rays and their higher harmonic hard x-rays using a similar tube in near future.

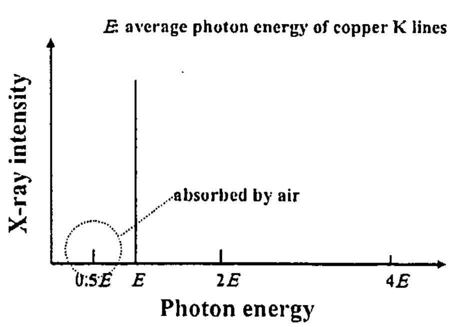


Figure 11: X-ray resonation without using a resonator.

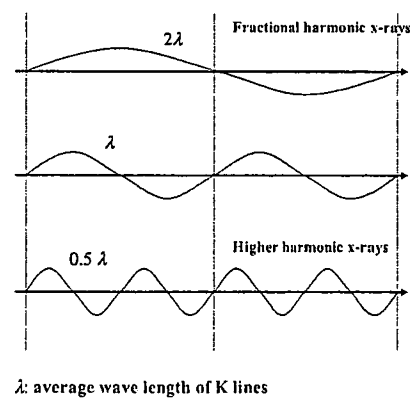


Figure 12: Estimated x-ray spectra under resonation.