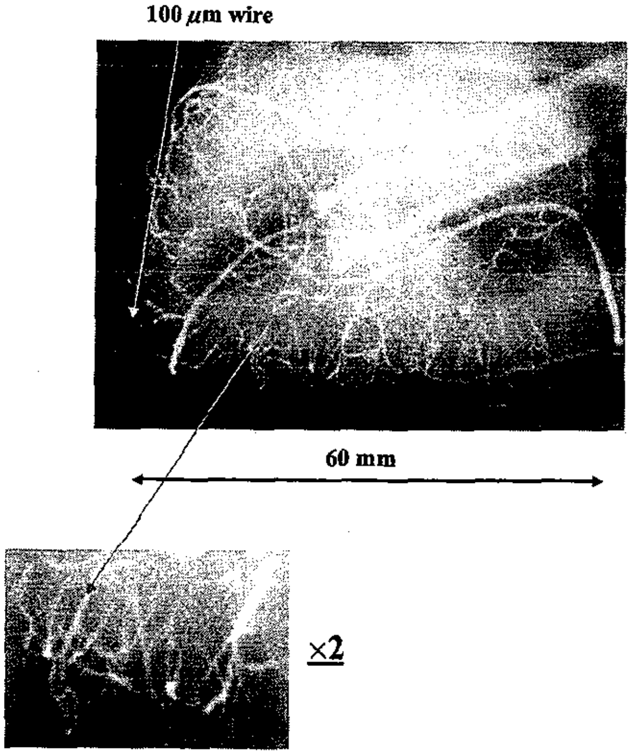

Fig. 12: Angiogram of extracted dog heart using iodine microspheres with tube voltage of 60 kV.

5. Discussion and results

In summary, we employed an x-ray generator with a cerium-target tube and succeeded in producing cerium characteristic x rays, which can be absorbed easily by iodine-based contrast media. Both the characteristic and the bremsstrahlung x-ray intensities increased with increases in the tube voltage, low-photon-energy bremsstrahlung x rays with energies of less than the iodine K edge should be absorbed by filtering to perform angiography. 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

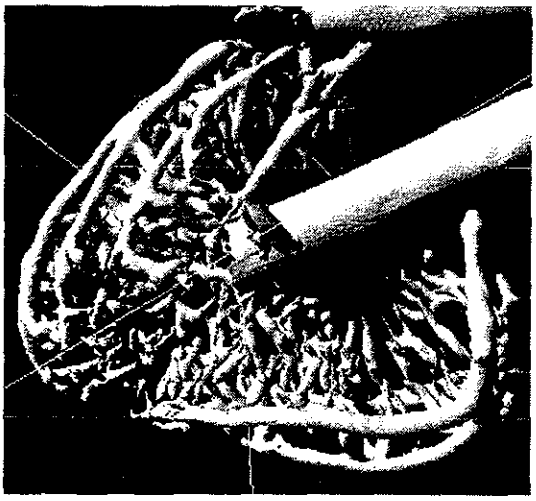

Fig. 13: 3-dimensional image of coronary arteries constructed from x-ray CT images by Pascal.

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.

As compared with 3-dimensional blood images constructed from x-ray CT images by Pascal, fine blood vessels were visible. Because the sampling pitch of the CR system is 87.5 μm, we obtained spatial resolutions of approximately 100 μm. In order to observe fine blood vessels of less than 100 μm, the spatial resolution of the CR system should be improved.

Acknowledgment

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Bremsstrahlung x-ray spectra for enhanced K-edge angiography

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Abstract

Energy-selective enhanced K-edge angiography utilizing a conventional x-ray generator is described. The x-ray generator is SOFRON NST-1005, and the maximum tube voltage and current are 100 kV and 5 mA, respectively. In the present research, the tube voltage ranged from 45 to 65 kV, and the tube current was regulated to optimum values. The exposure time is controlled in order to obtain optimum x-ray intensity. At a charging voltage of 60 kV, the x-ray intensity rate obtained using an aluminum and a barium sulfate filters were 58.4 and 51.6 μGy/s at 0.7 m per pulse, respectively, and the dimensions of the focal spot were approximately 1 × 1 mm. Angiography was performed using both the aluminum and the barium sulfate filters with a charging voltage of 60 kV.

Keywords: angiography, aluminum filtering, barium sulfate filtering, quasi-monochromatic x rays, iodine-based contrast medium

1. Introduction

μ μ

Monochromatic parallel radiography using a synchrotron in conjunction with single crystals continues to be the major tool used in x-ray phase imaging[1,2] and enhanced K-edge angiography.[3,4] In cases where the phase imaging is employed, the spatial resolution can be improved, and the number of tissues which can be observed using x rays increases.

To perform high-speed radiography, several different flash x-ray generators have been developed,[5] and soft generators[6-10] with photon energies of lower than 150 keV can be employed to perform biomedical

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Fig. 4: X-ray tube unit with coolers.

radiography. In order to produce monochromatic x rays, plasma flash x-ray generators[11-15] are useful, since quite intense and sharp characteristic x rays such as lasers have been produced from weakly ionized linear plasmas of nickel, copper and molybdenum.

Parallel beams with photon energies of approximately 35 keV have been employed so as to perform angiography, since these beams are absorbed effectively by an iodine-based contrast medium. Subsequently, K-series characteristic x rays with energies of approximately 35 keV are also useful, and fine blood vessels were observed with high contrasts. In view of this situation, we have developed x-ray generators with cerium-target tubes[16, 17] which can produce $K\alpha$ rays of 34.6 keV. Because bremsstrahlung x rays of approximately 35 keV also useful in order to perform high-contrast angiography, the development of optimum filters for producing narrow-energy-latitude bremsstrahlung x rays are desired in cases where a conventional tungsten target is employed.

In this research, we employed a tungsten-target x-ray tube and performed a preliminary study on enhanced angiography achieved with bremsstrahlung x rays with narrow-photon-energy latitudes produced by filtering in conjunction with a computed radiography (CR) system.[18]

2. Principle of K-edge angiography

Figure 1 shows the mass attenuation coefficients of iodine at the selected energies; the coefficient curve is discontinuous at the iodine K-edge. The effective bremsstrahlung x-ray spectra for K-edge angiography are shown above the iodine K-edge. Because iodine contrast mediums with a K-absorption edge of 33.2 keV absorb the rays easily, blood vessels were observed with high contrasts.

3. Experimental setup

A steady state x-ray generator (SOFRON NST-1005) is shown in Fig. 2, and the maximum tube voltage and current are 100 kV and 5 mA, respectively. In this experiment, the tube voltage applied was from 45 to 65 kV, and the tube current was regulated to within 5.0 mA (maximum current) by the filament

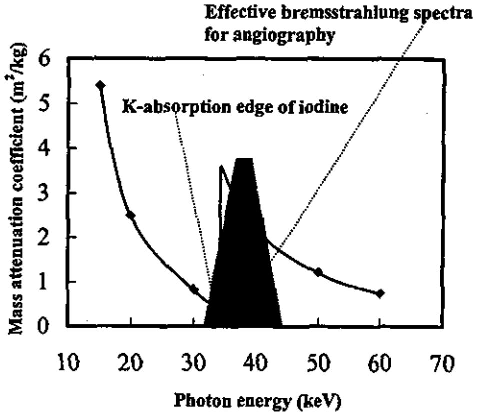


Fig. 1: Mass attenuation coefficients of iodine and effective bremsstrahlung x rays for enhanced K-edge angiography.

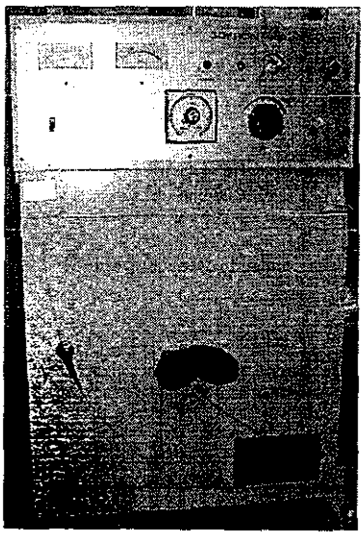
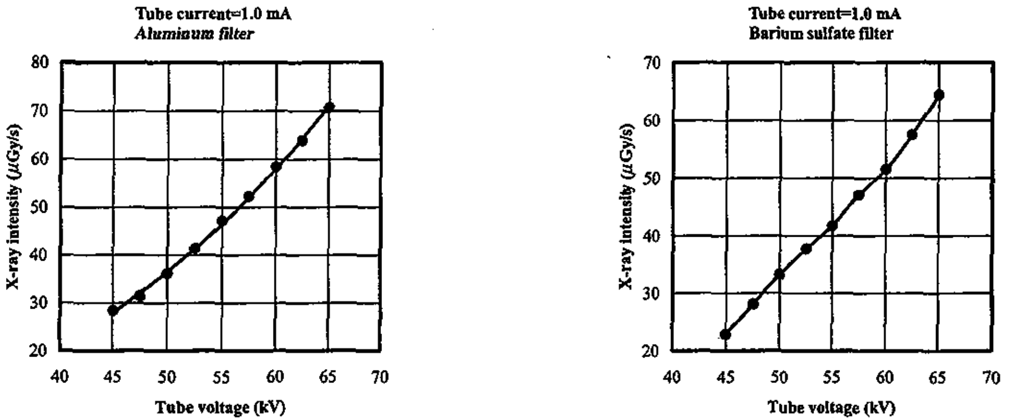
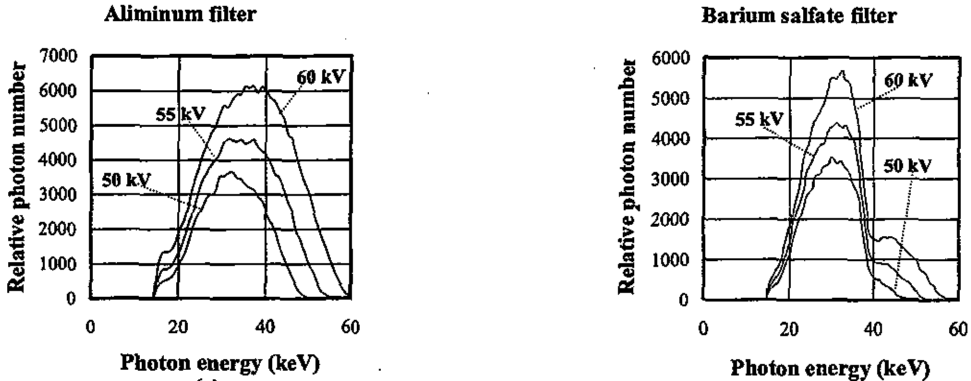


Fig. 2: X-ray generator.



(a) (b)

Fig. 3: X-ray intensity at 1.0 m per pulse with changing charging voltage (a) using aluminum filter and (b) using barium sulfate filter.



(a) (b)

Fig. 4: X-ray spectra using (a) aluminum filter and (b) barium sulfate filter.

temperature. The exposure time is controlled in order to obtain optimum x-ray intensity. 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.

4. Characteristics

4.1 X-ray intensity

Figure 3 shows the x-ray intensity at 0.7 m per pulse measured by a Victoreen 660 ionization chamber. The x-ray intensity increased with increasing the tube voltage. At a tube voltage of 60 kV, the x-ray intensities obtained using an aluminum filter and a barium sulfate filter were 58.4 and 51.6 μGy/s, respectively, at 0.7 m from the x-ray source.

4.2 X-ray spectra

In order to measure x-ray spectra, we employed a cadmium tellurium detector (CDTE2020X, Hamamatsu Photonics K.K.) (Fig. 4). Compared with a germanium detector, this detector has a lower energy resolution of 1.7 keV. When the tube 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 3-mm-thick aluminum filter attenuated the low-photon-energy bremsstrahlung x rays. The barium sulfate filter, with a surface density of approximately 10 mg/cm^2, significantly attenuate the spectra above the barium K-edge energy of 37.4 keV. The areas under the spectral curves correlate closely to the total x-ray intensities shown in Fig. 3

5. Angiography

The angiography was performed by the CR system (Konica Regius 150) using the filters with a tube voltage of 60 kV, and the distance between the x-ray source and the imaging plate was 0.7 m. The image contrast hardly varied even when the filter was changed.

Figure 5 shows radiograms of tungsten wires coiled around a rod made of polymethyl methacrylate using the aluminum filter. Although the image contrast increased with increases in the wire diameter, a 50-μm-diameter wire could be observed.

Figures 6 and 7 show angiograms of a rabbit thigh (barium sulfate filter) and a dog heart (aluminum filter), respectively. In angiography, iodine-based microspheres of 15 μm in diameter were used, and fine blood vessels of approximately 100 μm were visible.

6. Discussion

Concerning the spectrum measurement, we obtained bremsstrahlung x rays with narrow energy latitudes using both the aluminum and the barium sulfate filters. When the aluminum filter was employed with a tube voltage of 60 kV, the peak photon energy of spectra was approximately 35 kV.

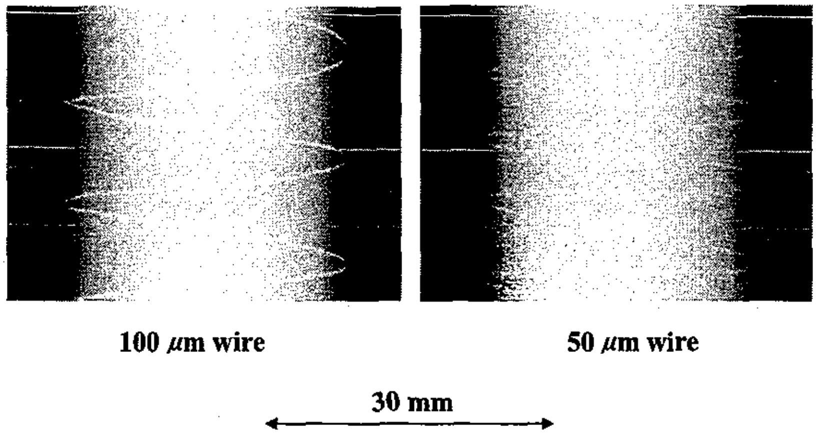


Fig. 5: Radiograms of tungsten wires coiled around rod made of polymethyl methacrylate using aluminum filter.

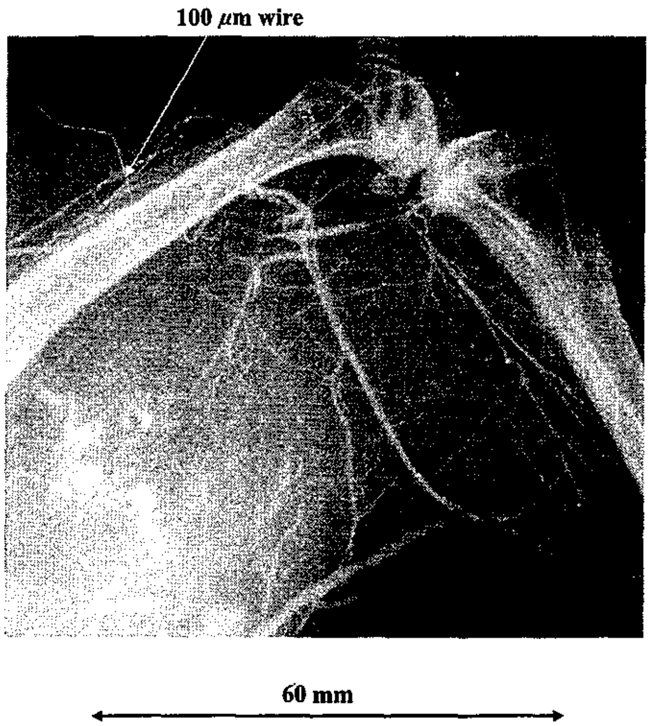


Fig. 6: Angiograms of rabbit thigh achieved with barium sulfate filter

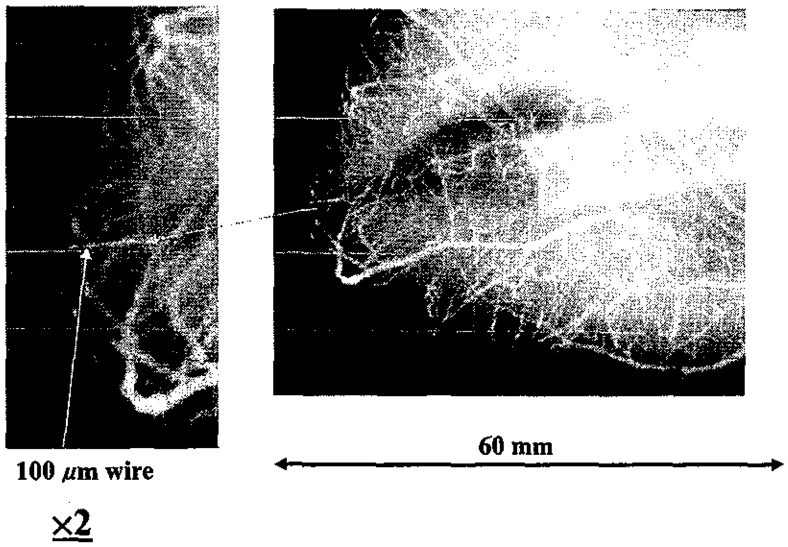


Fig. 7: Angiogram of dog heart with aluminum filter.

Therefore, the filter thickness should be increased as much as possible to decrease bremsstrahlung x rays of lower than K-absorption edge of iodine. Subsequently, using the barium sulfate filter, because the peak photon energy was nearly equal to the K-edge, aluminum filtering should be employed. In addition, cerium oxide filter is also useful in order to increase the peak energy and to decrease the low-photon-energy bremsstrahlung x rays.

In the present research, we employed a low-dose-rate x-ray generator in order to measure the x-ray spectra using a semiconductor detector. However, conventional medical x-ray generators with high dose rates can be employed to increase the tube current and to decrease the exposure time at a constant tube voltage.

With recent advances in angiography using MRI, if the density of gadolinium-based contrast media increases, enhanced K-edge angiography utilizing monochromatic x-ray generators, which produce Kα rays of ytterbium, tantalum, and tungsten, will be fairly useful technique to decrease the absorbed dose during angiography.

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Extremely soft x-ray generator and its applications

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ABSTRACT

The development of an extremely soft x-ray generator with a tungsten-target tube and its applications to radiography and disinfection are described. This generator consists of a high-voltage power supply, a filament power supply, and an x-ray tube. Negative high voltages are applied to the cathode electrode in the x-ray tube, and the tube voltage and current are regulated by the input of a transformer and the filament voltage, respectively. The x-ray tube is a glass-enclosed double-focus diode with a tungsten target and a 0.2 mm-thick beryllium window. The maximum tube voltage and electric power were 60 kV and 400 W, respectively. The focal-spot sizes were 4×4 (large) and 1×1 mm (small), respectively. Extremely soft radiography was performed with a computed radiography system, and we observed fine blood vessels of about 100 μm with high contrasts. Using this generator, we performed the disinfection achieved with extremely soft x rays.

Keywords: extremely soft x-ray, thin beryllium window, soft x-ray disinfection, soft radiography

1. INTRODUCTION

Synchrotrons generate high-dose-rate bremsstrahlung x rays with wide photon energy latitudes, and monochromatic x-ray beams have been produced using single crystals. These rays have been employed to perform K-edge angiography[1-3] and phase imaging.[4-6] However, it is difficult to increase the irradiation field, due to the parallel beam, or to obtain sufficient machine times for various research projects, including medical applications.

Conventional medical x-ray generators produce both bremsstrahlung and characteristic x rays, and quasi-monochromatic x rays have been produced using K-edge filters. In contrast, flash x-ray generators utilize cold-cathode tubes, and the generators[7-13] with photon energies of lower than 150 keV can be employed to perform biomedical radiography. In order to produce monochromatic x rays, plasma flash x-ray generators[14-18] are useful, since quite intense and sharp characteristic x rays such as lasers have been produced from weakly ionized linear plasmas.

In order to produce monochromatic parallel beams using a hot-cathode x-ray tube in conjunction with the crystals, high-dose-rate bremsstrahlung x rays are needed, and the x-ray photon energy is selected by Bragg's angle. Therefore,

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the thickness of the x-ray window of the tube should be decreased as much as possible so as to increase the x-ray dose rate and to produce soft bremsstrahlung x rays. In addition, soft x rays are useful to image soft-tissue objects, including biomedical objects, and the rays may be used to perform disinfection of various fungi, including anthrax, because the x rays are absorbed easily by fungi.

In the present research, we developed an extremely soft x-ray generator with a tungsten-target tube, and used it to perform preliminary studies on extremely soft radiography and disinfection.

2. GENERATOR

Figure 1 shows the block diagram of the x-ray generator, which consists of a high-voltage power supply (Fig. 2), an x-ray tube unit (Fig. 3), and a filament power supply. The negative high voltage is applied to the cathode electrode, and the anode (target) is connected to the ground potential. The x-ray tube is a glass-enclosed diode with a tungsten target and a 0.2 mm-thick beryllium window. In this experiment, the peak tube voltage was regulated from 10 to 15 kV using an auto transformer, and the peak tube current was regulated within 15 mA by the filament voltage (temperature). The exposure time is controlled in order to obtain optimum x-ray intensity, and the x-ray tube is a double-focus type with focal-spot dimensions of approximately 4×4 (large spot) and 1×1 mm (small spot), respectively.

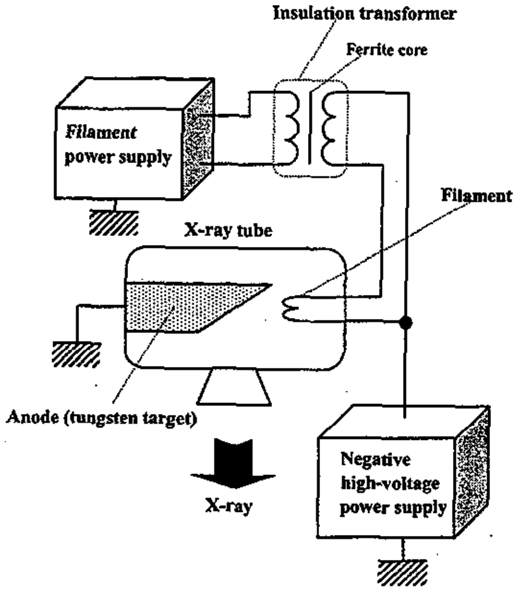


Fig. 1. Block diagram of extremely soft x-ray generator.

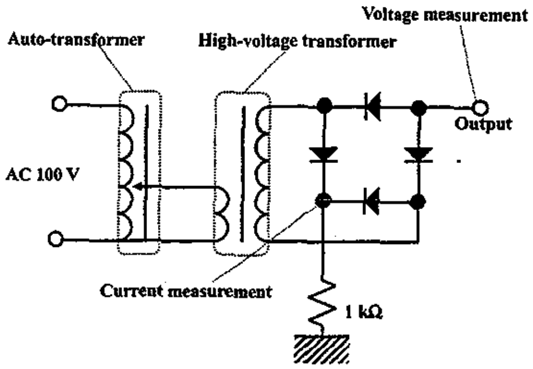


Fig. 2. Circuit diagram of high voltage power supply.

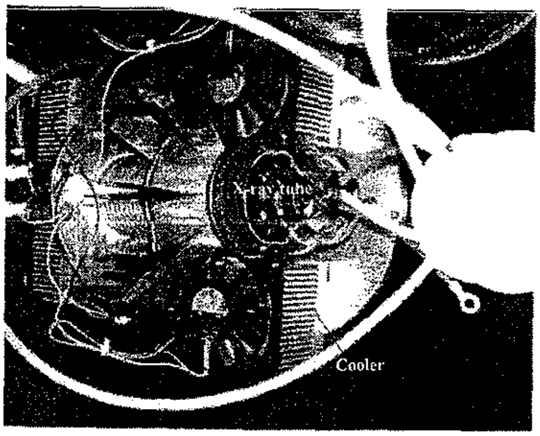


Fig. 3. X-ray tube unit with coolers.

3. CHARACTERISTICS

3.1 Cathode voltage and current

The cathode voltage and current were measured by a high-voltage divider and a resistor, respectively, and the tube voltage was −1 times the cathode voltage. Figure 4 shows variations in the voltage and current. The negative peak voltage increased when the input voltage from an auto transformer was increased. Next, the peak tube current was regulated constantly by the filament voltage.

3.2 X-ray source

In order to measure images of the x-ray source, we employed a pinhole camera with a hole diameter of 50 μm in conjunction with a Computed Radiography (CR) system.[19] The dimensions of small and large spots seldom varied and had values of approximately 1 × 1 and 4 × 4mm, respectively.

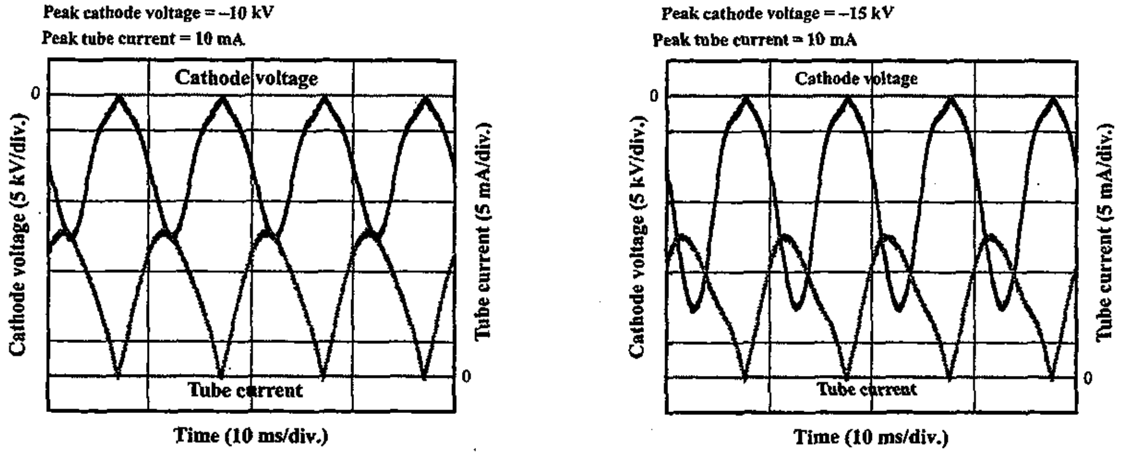


Fig. 4. Cathode voltages and tube currents at indicated conditions.

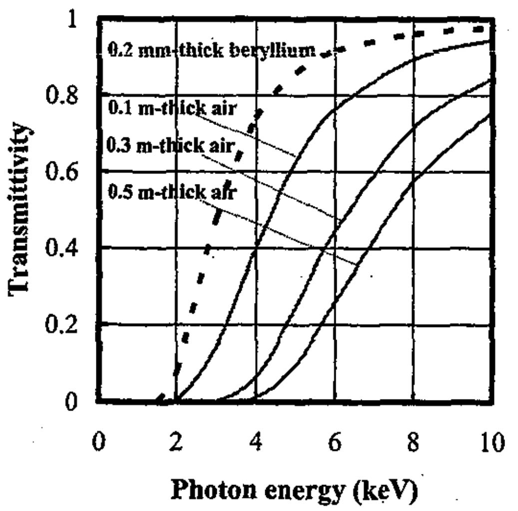


Fig. 5. Transmittivity of x rays with photon energy.

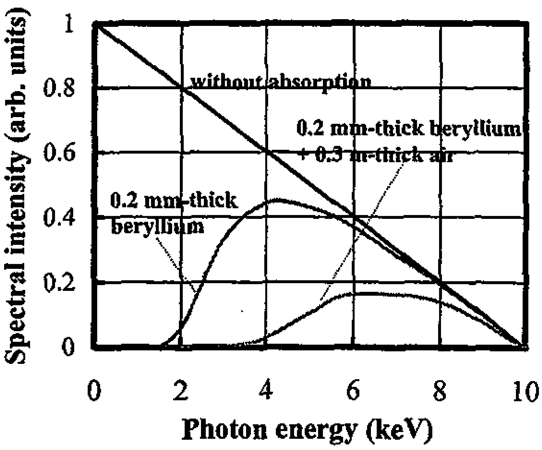


Fig. 6. Calculated bremsstrahlung spectra at indicated conditions.

3.3 X-ray spectra

Figure 5 shows transmittivity of beryllium and dry air with changes in the photon energy. When a 0.2 mm-thick beryllium window is employed, x-ray spectra with energies of lower than 2 keV are absorbed effectively. Subsequently, 0.5 m-thick air transmit x rays with energies of higher than 4 keV.

The bremsstrahlung x-ray spectra were calculated by the mass attenuation coefficients of the beryllium and the dry air at a constant tube voltage of 10 kV (Fig. 6). As shown in this figure, the soft x rays of lower than 2 keV were primarily absorbed by the beryllium x-ray window, and the rays were also absorbed by the air. Therefore, the distance should be decreased as much as possible in order to obtain soft x rays.

4. RADIOGRAPHY

The radiography was performed using the CR system (Konica Regius 150) and the small spot, and the distance between the x-ray source and imaging plate was 0.5 m. Next, the peak current (I_p) and the exposure time were 10 mA and 10 s, respectively. Figure 7 shows radiograms of tungsten wires coiled around pipes made of polymethyl methacrylate with a peak tube voltage V_p of 15 kV. Although the image contrast increased with increases in the wire diameter, a 50 μm-diameter wire could be observed.

A radiogram of a thin film for food wrapping is shown in Fig. 8. The V_p was 15 kV, and the image of a folded film is visible. Next, angiograms of rabbit hearts recorded using iodine microspheres of 15 μm in diameter are shown in Fig. 9. These two images were obtained using a 1.0 mm-thick aluminum filter and without using the filter at a V_p of 15 kV. In the case where the filter was not employed, the coronary arteries were barely visible, since the heart did not transmit extremely soft x rays. Finally, Fig. 10 shows an angiogram of the external ear of a rabbit; iodine-based microspheres of 15 μm in diameter were used at a V_p of 10 kV, and fine blood vessels of about 50 μm were clearly visible.

5. DISINFECTION

Figure 11 shows the experimental setup for disinfection using soft x rays. Fungi were enclosed in an envelope and were exposed to soft x rays using the large spot, and we performed disinfection of three fungi with changes in the exposure time using a copper box with a V_p of 15 kV and an I_p of 10 mA. In these experiments, the complete disinfection times for Bacillus subtilis and staphylococcus were approximately 15 and 3 hours, respectively, and the time for B-coli was less than 1 hour (Tables 1-3).

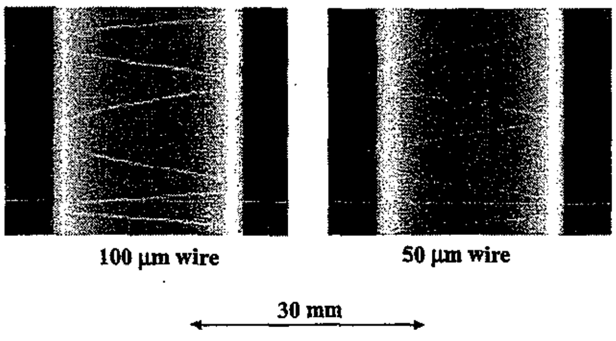

100 μm wire 50 μm wire

Fig. 7. Radiograms of tungsten wires of 50 and 100 μm in diameter coiled around pipes made of polymethyl methacrylate.

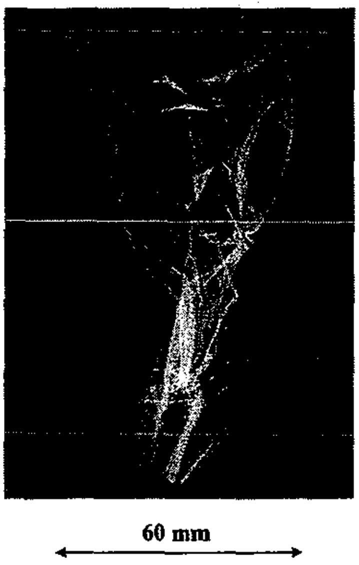
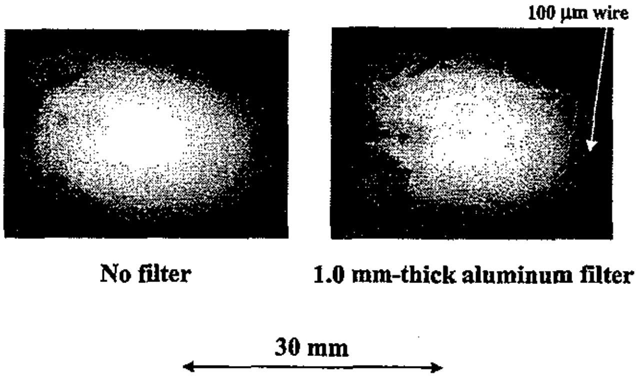


Fig. 8. Radiogram of film.



No filter 1.0 mm-thick aluminum filter

Fig. 9. Angiograms of rabbit hearts.

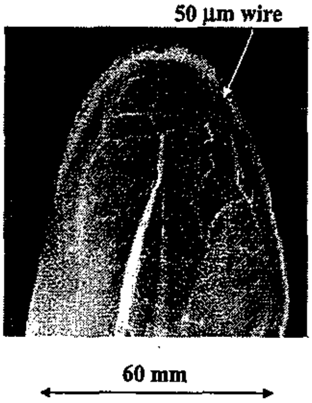


Fig. 10. Angiograms of external ear of rabbit.

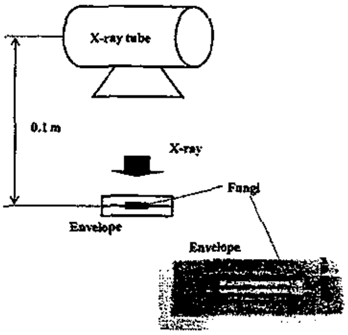


Fig. 11. Experimental setup for disinfection.

Table 1. Disinfection test for Bacillus subtilis.

Exposure time (hour) \ Culture time (day)	1	2	3	4
6	+	+	+	+
12	–	–	+	+
18	–	–	–	–
24	–	–	–	–

Table 2. Disinfection test for staphylococcus.

Exposure time (hour) \ Culture time (day)	1	2	3	4
1	–	+	+	+
2	–	+	+	+
3	–	–	–	–
4	–	–	–	–

Table 3. Disinfection test for B-coli.

Exposure time (hour) \ Culture time (day)	1	2	3	4
1	–	–	–	–
2	–	–	–	–
3	–	–	–	–
4	–	–	–	–

6. DISCUSSION

In the present work, we succeeded in generating extremely soft x rays using a 0.2 mm-thick beryllium window in conjunction with a tungsten target. By the calculation of bremsstrahlung x rays, x rays with energies higher than 2 keV are produced. However, it is very difficult to measure the x-ray dose because there are no dosimeters with constant energy sensitivities.

In radiography, the image quality hardened in response to increases in the thickness of the aluminum filter, because the low-photon-energy x rays of the spectra were absorbed easily by the filter. Using this x-ray generator, although K-series characteristic x rays of tungsten are not produced, due to the tube voltage, the photon energies of the characteristic x rays can be selected by the target element.

In the disinfection, the distance between the x-ray source and fungi should be decreased as much as possible to decrease the absorbed x-ray dose by air. Subsequently, because the air is dissociated greatly, ion beams will also be a useful technique for the disinfection and the excluding of static electricity from semiconductor devices.

Because it is possible to produce low-photon-energy x rays and to perform extremely soft radiography and x-ray disinfection, and to exclude electricity, this system can be applied in various fields.

ACKNOWLEDGMENTS

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Compact x-ray generator utilizing cerium-target tube for angiography

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ABSTRACT

The cerium-target x-ray tube is useful in order to perform cone beam K-edge angiography because K-series characteristic x rays from the cerium target are absorbed effectively by iodine-based contrast mediums. The x-ray generator consists of a main controller and a unit with a high-voltage circuit and a fixed anode x-ray tube. 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 1.3×0.9 mm. Cerium K-series characteristic x rays were left using a 3.0 mm-thick aluminum filter, and the x-ray intensity was 0.59 μC/kg at 1.0 m from the source with a tube voltage of 60 kV, a current of 0.40 mA, and an exposure time of 1.0 s. Angiography was performed with a computed radiography system using iodine-based microspheres 15 μm in diameter. In angiography of non-living animals, we observed fine blood vessels of approximately 100 μm with high contrasts.

Key words: x-ray tube, cerium target, quasi-monochromatic x rays, characteristic x rays, K-edge angiography

1. INTRODUCTION

Monochromatic parallel x-ray beams are the basis of radiography using synchrotrons in conjunction with single crystals, and these beams have been employed to perform enhanced K-edge angiography[1-3] and x-ray phase imaging.[4-6] In angiography, the beams with photon energies of approximately 35 keV are absorbed effectively by iodine-based contrast mediums. However, it is difficult to obtain sufficient machine times for various research projects, including medical applications.

In order to perform high speed medical radiography, although several different flash x-ray generator[7-13] utilizing

Ray Sources and Optics, edited by C. A. MacDonald, A. T. Macrander,
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SPIE, Bellingham, WA, 2004) · 0277-786X/04/$15 · doi: 10.1117/12.560534

cold-cathode tubes have been developed, plasma flash x-ray generators[14-18] 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[19] 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,[20] and have demonstrated enhanced K-edge angiography utilizing a barium sulfate filter. In the spectrum measurement, although Kα lines were produced, bremsstrahlung x rays with photon energies of lower than the barium K-edge (37.4 keV) were also observed. Therefore, optimum filtering for K-edge angiography should be selected to increase image contrast of fine blood vessels.

In the present research, we employed a compact x-ray generator with a cerium target tube, and used it to perform a preliminary study on cone beam K-edge angiography achieved with cerium characteristic x rays utilizing an aluminum filter.

2. GENERATOR

Figure 1 shows the block diagram of the x-ray generator, which consists of a main controller and an x-ray tube unit with a Cockcroft-Walton circuit and a cerium-target tube. The tube voltage, the current, and the exposure time can be controlled by the controller. The main circuit for producing x rays is illustrated in Fig. 2, 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. Quasi-monochromatic x rays are produced using a 3.0 mm-thick aluminum filter for absorbing soft bremsstrahlung rays.

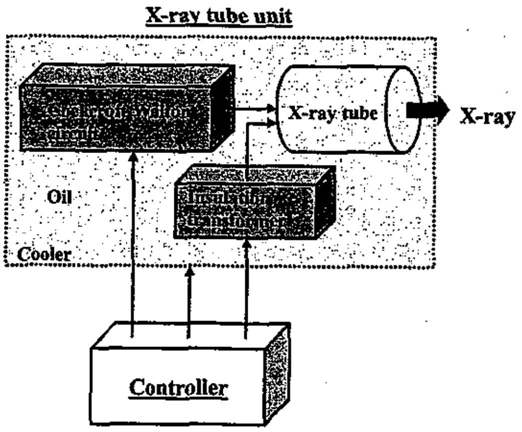

Fig. 1. Block diagram of compact x-ray generator with cerium-target radiation tube, which is used specially for K-edge angiography using iodine-based contrast mediums.

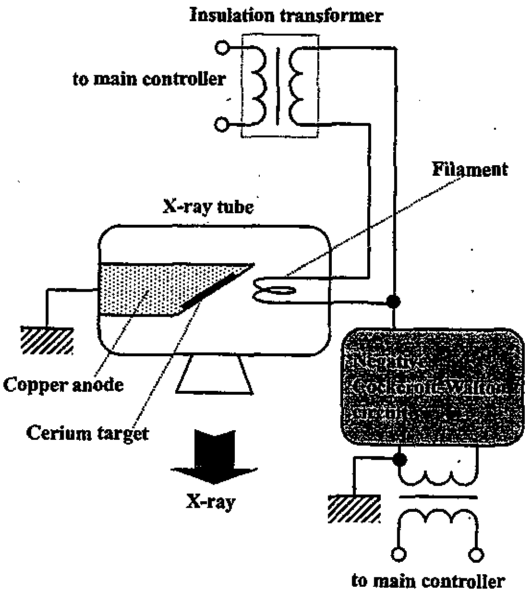

Fig. 2. Main circuit of x-ray generator.

3. CHARACTERISTICS

3.1 X-ray intensity

X-ray intensity was measured by a Victoreen 660 ionization chamber at 1.0 m from the x-ray source using the filter with an exposure time of 1.0 s (Fig. 3). 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 0.59 μC/kg at 1.0 m from the source with errors of less than 0.2%.

3.2 Focal spot

In order to measure images of the x-ray source after the aluminum filtration, 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[21] with a sampling pitch of 87.5 μm. When the tube voltage was increased, spot dimensions increased slightly and had values of 1.3×0.9 mm (Fig. 4).

3.3 X-ray spectra

In order to measure x-ray spectra, we employed a cadmium tellurium detector (CDTE2020X, Hamamatsu Photonics Inc.) (Fig. 5). Compared with a germanium detector, this detector has a lower energy resolution of 1.7 keV. When the tube voltage was increased, the characteristic x-ray intensities of Kα and Kβ lines increased, and both the maximum photon energy and the intensities of bremsstrahlung x rays increased.

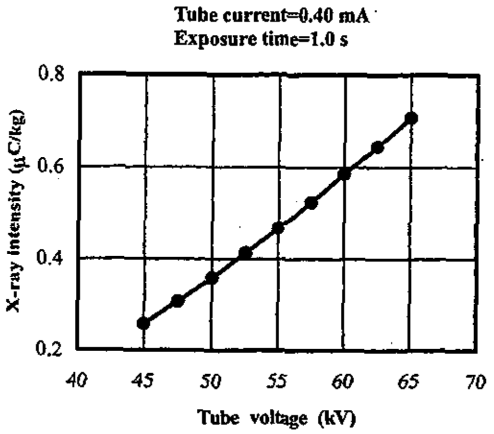

Fig. 3. X-ray intensity measured at 1.0 m from x-ray source according to changes in tube voltage.

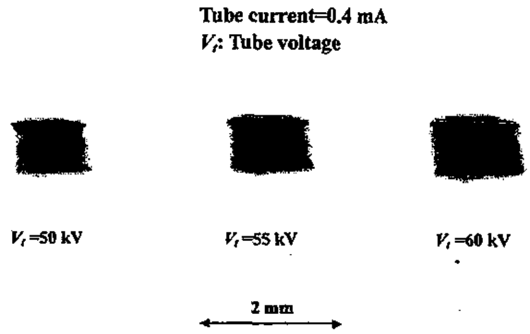

Fig. 4. Effective focal spots with changes in tube voltage.

4. ANGIOGRAPHY

Figure 6 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 and Kβ lines are shown just above the iodine K-edge. Cerium is a rare earth element and has a high reactivity; however, the average photon energies of Kα and Kβ lines are 34.6 and 39.2 keV, respectively, 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 by the CR system (Konica Regius 150) using the filter, and the distance (between the x-ray source and the imaging plate) was 1.5 m. Firstly, rough measurements of spatial resolution were made using wires. Figure 7 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.

Angiograms of rabbit hearts are shown in Fig. 8. These two images were obtained using iodine and cerium microspheres of 15 μm in diameter at a tube voltage of 60 kV. In the case where the cerium spheres were employed, the coronary arteries were barely visible. Figure 9 shows an angiogram of a larger dog heart using the cerium target at a tube voltage of 60 kV using iodine spheres. For comparison, we show 3-dimensional image of the coronary arteries constructed from x-ray CT images by Pascal (Digital Culture Tech. Corp.) with a tungsten x-ray tube (Fig. 10). Using this imaging technique, fine blood vessel were not observed at all.