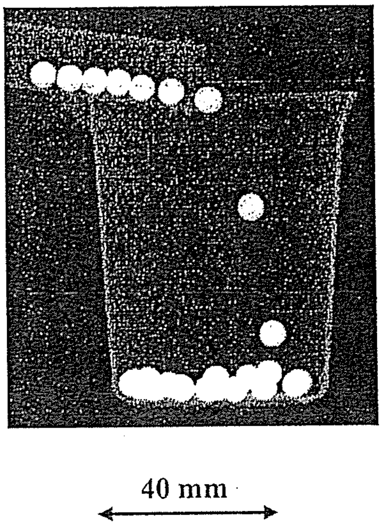

Figure 9: Radiogram of plastic bullets falling into polypropylene beaker from a plastic test tube.

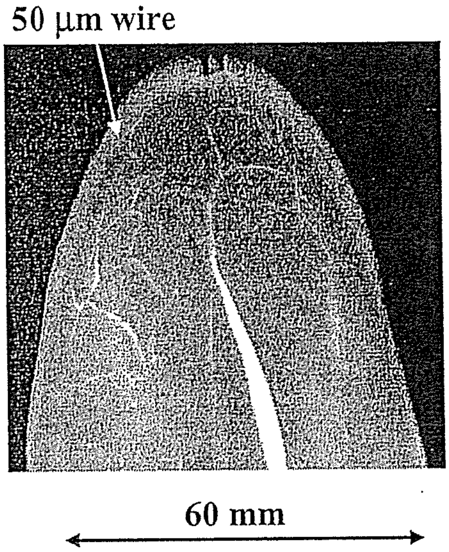

Figure 10: Angiogram of a rabbit ear.

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.

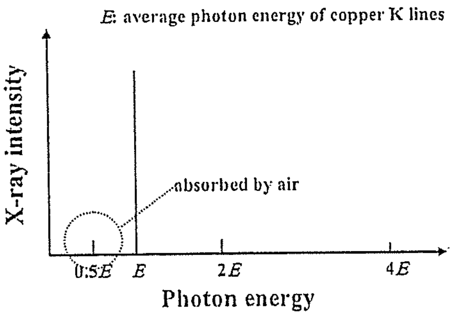

Figure 11: X-ray resonation without using a resonator.

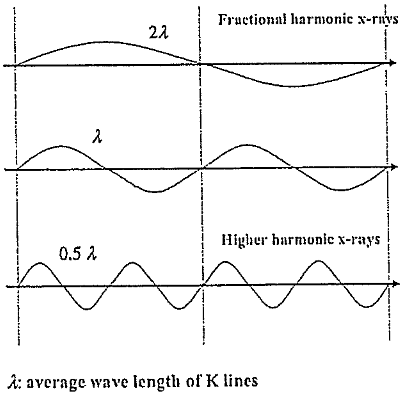

Figure 12: Estimated x-ray spectra under resonation.

ACKNOWLEDGMENTS

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Annual Report of Iwate Medical University
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No. 40 (2005), 1 - 7.

X-ray Spectra from a Characteristic X-ray Generator with a Molybdenum Tube

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(Received October 31, 2005)

Abstract

This generator consists of the following components: a constant high-voltage power supply, a filament power supply, a turbomolecular pump, and an x-ray tube. The x-ray tube is a demountable diode which is connected to the turbomolecular pump and consists of the following major devices: a molybdenum rod target, a tungsten hairpin cathode (filament), a focusing electrode, a polyethylene terephthalate x-ray window 0.25 mm in thickness, and a stainless-steel tube body. In the x-ray tube, the positive high voltage is applied to the anode (target) electrode, and the cathode is connected to the tube body (ground potential). In this experiment, the tube voltage applied was from 22 to 36 kV, and the tube current was regulated to within 100 μA by the filament temperature. The exposure time is controlled in order to obtain optimum x-ray intensity. The electron beams from the cathode are converged to the target by the focusing electrode, and x-rays are produced through the focusing electrode. Using a lithium fluoride curved crystal, clean K-series characteristic x-rays were observed without using a filter. However, bremsstrahlung x-rays were observed using a cadmium telluride detector.

Keywords: demountable x-ray tube, quasi-monochromatic x-rays, K-series characteristic x-rays, Sommerfeld's theory, curved crystal, cadmium telluride detector

1. Introduction

Most flash x-ray generators employ high-voltage condensers and cold-cathode x-ray tubes,[1-6] and the plasma x-ray source has been growing with increases in the electrostatic energy in the condenser. By

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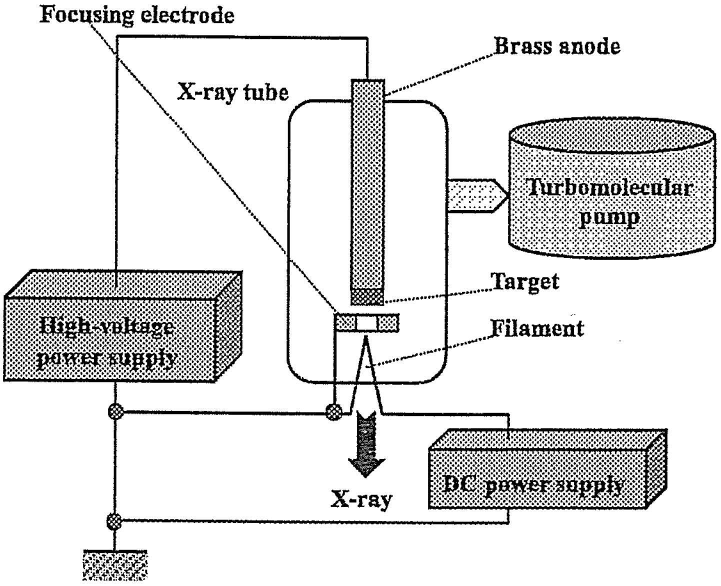

Fig. 1: Block diagram including the main transmission line of the compact x-ray generator with a quasi-monochromatic diode.

forming weakly ionized linear plasma[6-9] using a rod-target triode, we confirmed irradiation of clean K-series characteristic x-rays such as hard x-ray lasers and their higher harmonic hard x-rays from the plasma axial direction. Because the plasma transmits high-photon-energy bremsstrahlung x-rays, it is difficult to produce high-photon-energy characteristic x-rays. In view of this situation, we have developed a super-fluorescent x-ray generator[10-13] by forming weakly ionized plasma at the target tip and have succeeded in producing comparatively clean K-series characteristic x-rays of molybdenum, cerium, tantalum, and tungsten. In particular, the cerium target is useful for performing iodine K-edge angiography, and gadolinium K-edge angiography can be performed using tantalum and tungsten targets.

Steady-state K-series characteristic x-rays left by filters have been employed to perform mammography using a molybdenum target and to perform K-edge angiography[14-17] using a cerium target. In addition, the rays are also useful for performing real-time radiography achieved with a flat panel detector. Because the characteristic x-ray intensity decreases with increases in the filter thickness, the development of a characteristic x-ray generator utilizing the angle dependence of bremsstrahlung x-rays has been wished for.

In the spectrum measurements, we employ a cadmium telluride detector and a lithium fluoride curved crystal. The detector is useful to measure the total spectra including scattering beams. On the other hand, the spectra from only the x-ray source can be measured using the crystal by selecting Bragg's angle.

In this paper, we describe an x-ray generator developed and used to perform a preliminary experiment for generating clean K-series characteristic x-rays by angle dependence of the bremsstrahlung x-rays and measurement of the x-ray spectra using two methods.

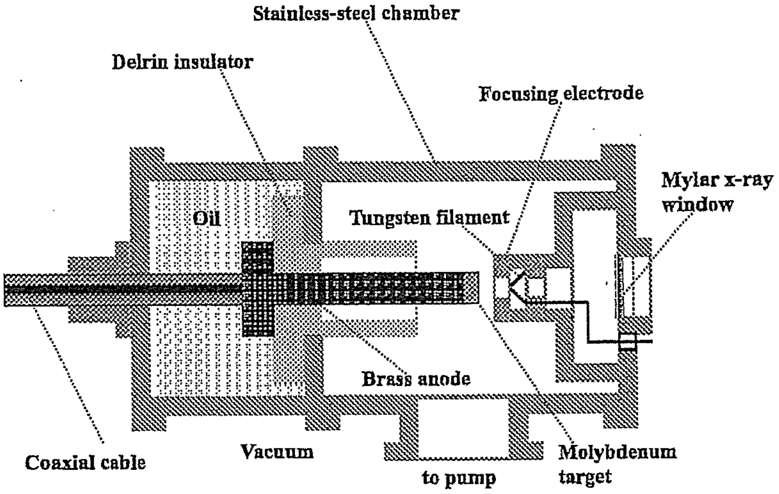

Fig. 2: Schematic drawing of the quasi-monochromatic x-ray tube.

2. Generator

Figure 1 shows a block diagram of a compact characteristic (quasi-monochromatic) x-ray generator. This generator consists of the following components: a constant high-voltage power supply (SL150, Spellman Inc.), a DC filament power supply, a turbomolecular pump, and an x-ray tube. The structure of the x-ray tube is illustrated in Fig. 2. The x-ray tube is a demountable diode which is connected to the turbomolecular pump with a pressure of approximately 0.5 mPa and consists of the following major devices: a molybdenum plate target, a tungsten hairpin cathode (filament), a focusing electrode, a polyethylene terephthalate x-ray window 0.25 mm in thickness, and a stainless-steel tube body. In the x-ray tube, the positive high voltage is applied to the anode (target) electrode, and the cathode is connected to the tube body (ground potential). In this experiment, the tube voltage applied was from 22 to 36 kV, and the tube current was regulated to within 100 μA by the filament temperature. The exposure time is controlled in order to obtain optimum x-ray intensity. The electron beams from the cathode are converged to the target by the focusing electrode, and x-rays are produced through the focusing electrode. Because bremsstrahlung rays are not emitted in the opposite direction to that of electron trajectory, clean molybdenum K-series x-rays can be produced without using a filter.

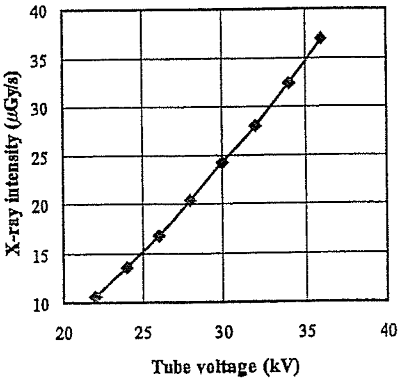

Fig. 3: X-ray intensity at 1.0 m from the x-ray source according to changes in the tube voltage.

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 (Fig. 3). At a constant tube current of 100 μA, the x-ray intensity increased when the tube voltage was

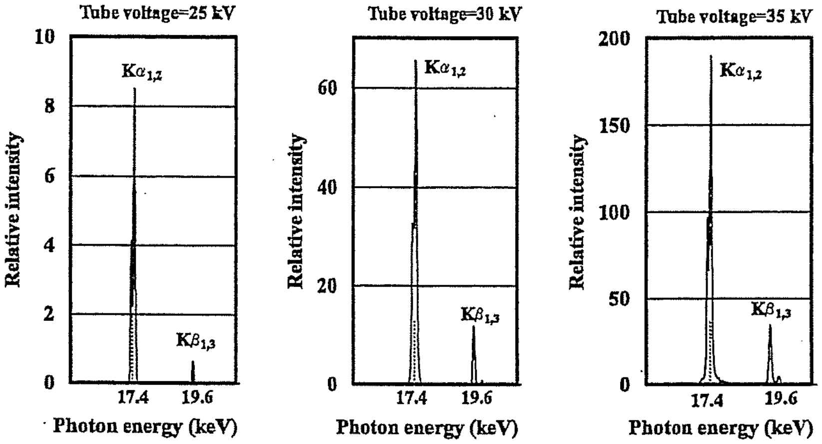

Fig. 4: X-ray spectra from the molybdenum target measured using a transmission type spectrometer with a lithium fluoride curved crystal.

increased. In this measurement, the intensity with a tube voltage of 30 kV and a current of 100 μA was 24.2 μGy/s at 1.0 m from the source.

3.2 X-ray spectra

First, 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 the 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. Figure 4 shows measured spectra from the molybdenum target. We observed clean K lines, while bremsstrahlung

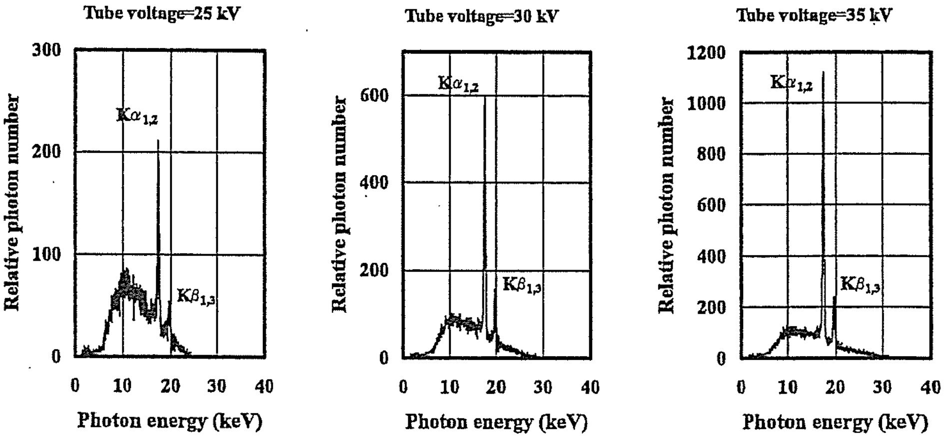

Fig. 5: X-ray spectra from the molybdenum target measured using a cadmium telluride detector.

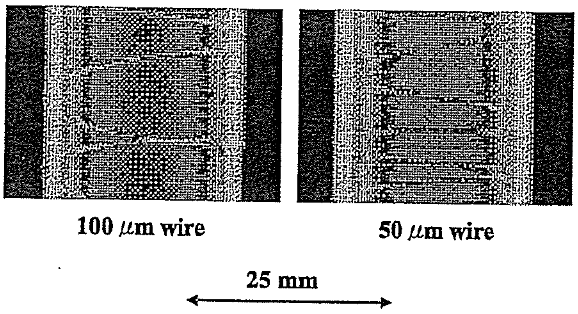

Fig. 6: Radiograms of tungsten wires of 50 and 100 μm in diameter coiled around pipes made of polymethyl methacrylate. A 50-μm-diameter wire could be observed.

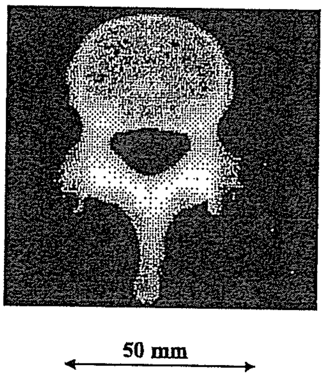

Fig. 7: Radiogram of a vertebra. Fine structure of the vertebra were visible.

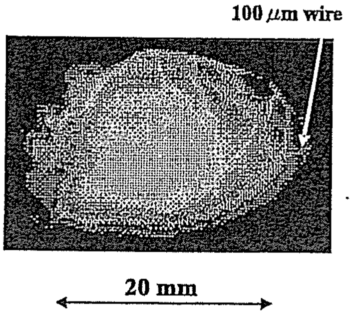

Fig. 8: Angiograms of a rabbit heart. Coronary arteries were visible.

rays were hardly detected. The characteristic x-ray intensity substantially increased with increases in the tube voltage.

The measured spectra using a cadmium telluride detector are shown in Fig. 5. Using the detector, we observed low intensity continuous x-rays. When the tube voltage was increased, both the characteristic x-ray intensity and the maximum photon energy increased.

4. Radiography

The monochromatic radiography was performed by the CR system at 1.0 m from the x-ray source with the filter, and the tube voltage was 30 kV.

First, rough measurements of image resolution were made using wires. Figure 6 shows radiograms of tungsten wires coiled around pipes made of polymethyl methacrylate (PMMA). Although the image contrast increased with increases in the wire diameter, a 50-μm-diameter wire could be observed.

A radiogram of a vertebra is shown in Fig. 7, and the fine structure of the vertebra was observed. Next, angiography was performed using iodine microspheres of 15 μm in diameter. Figure 8 shows an angiogram of a rabbit heart, and we obtained high contrast images of coronary arteries and fine blood vessels.

5. Conclusions and Outlook

In summary, we developed a new characteristic x-ray generator with a molybdenum-target tube and measured clean molybdenum K lines using the crystal spectrometer. However, continuous x-rays were detected using the detector. In both measurements, the characteristic x-ray intensity increased with increases in the tube voltage, and monochromatic Kα lines were left by a zirconium filter. Because we could measure bremsstrahlung x-rays[19] from a transmission-type molybdenum target using the crystal, the bremsstrahlung intensity was low as compared with that obtained using conventional molybdenum tubes.

In this preliminary experiment, although the maximum tube voltage and current were 36 kV and 100 μA, the voltage and current could be increased to 100 kV and 1.0 mA, respectively. Under the pulsed operation, the current can be increased to approximately 1 A without considering the target evaporation. Subsequently, the generator produced maximum number of characteristic photons was approximately 1×10^8 photons/(cm$^2 \cdot$ s) at 1.0 m from the source, and the photon count rate can be increased easily by increasing the current.

Using this x-ray generator, because it is not easy to produce high-photon-energy K-series characteristic x-rays, we are very interested in increasing the energy by changing the electrode configuration between the target, cathode, and focusing electrodes.

Acknowledgments

This work was supported by Grants-in-Aid for Scientific Research (13470154, 13877114, 16591181, and 16591222) and Advanced Medical Scientific Research from MECSST, Health and Labor Sciences Research Grants (RAMT-nano-001, RHGTEFB-genome-005 and RHGTEFB-saisei-003), Grants from the Keiryo Research Foundation, The Promotion and Mutual Aid Corporation for Private Schools of Japan, Japan Science and Technology Agency (JST), and The New Energy and Industrial Technology Development Organization (NEDO, Industrial Technology Research Grant Program in '03).

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No. 40 (2005), 9-15.

Measurement of Cerium X-ray Spectra Using a Cerium Oxide Powder Filter and Enhanced K-edge Angiography

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Akira Ogawa[c], Kiyomi Takahashi[f], Shigehiro Sato[f] and Kazuyoshi Takayama[g]

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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 media. 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 70 kV and 0.40 mA, respectively, and the focal-spot sizes were approximately 1×1 mm. Cerium K-series characteristic x-rays were left using a cerium oxide powder filter, and the x-ray intensity was 14.3 μGy/s 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.

Keywords: x-ray tube, cerium target, cerium oxide filter, powder filter, characteristic x-rays, K-edge angiography

1. Introduction

Flash x-ray generators are useful for performing high-speed radiography,[1] and several different generators with maximum photon energies of 150 keV[2-5] have been applied to biomedical radiography. By forming weakly ionized linear plasma[6-9] using a cold-cathode triode, we have succeeded in producing K-series characteristic x-rays of nickel and copper. Subsequently, we have developed super-fluorescent

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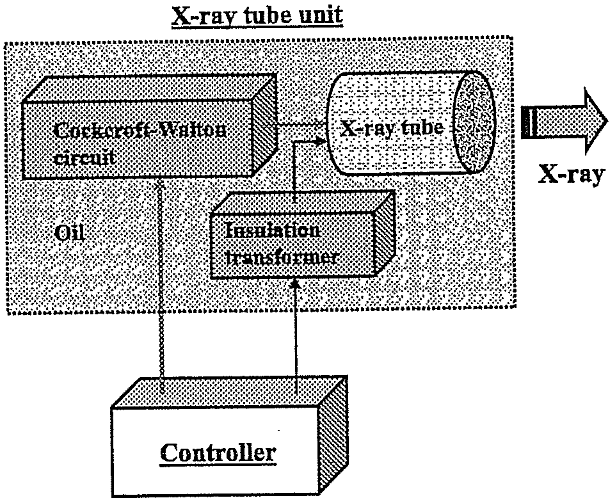

Fig. 1: Block diagram of the compact x-ray generator with a cerium-target radiation tube, which is used specially for K-edge angiography using iodine-based contrast media.

x-ray generator[10-13] to produce comparatively clean high-photon-energy characteristic x-rays of cerium and tungsten.

To produce steady state x-rays, synchrotrons generate high-dose-rate bremsstrahlung x-rays, and monochromatic parallel beams are formed using single crystals. In particular, x-rays of approximately 35 keV have been applied to perform enhanced K-edge angiography[14,15] and phase-contrast radiography,[16,17] including dark-field imaging using an analyzer crystal. Using these imaging, although the spatial resolution has been improved, it is difficult to increase the irradiation field due to the parallelity. Recently, we have developed a steady-state x-ray generator utilizing a cerium-target tube[18-20] and have demonstrated enhanced K-edge angiography utilizing a barium sulfate filter. In this research, $K\alpha$ lines (34.6 keV) were left by absorbing $K\beta$ lines (39.2 keV), and bremsstrahlung x-rays with photon energies lower than the barium K-edge (37.4 keV) were also observed. However, because cerium $K\beta$ lines are also absorbed effectively by iodine, both $K\alpha$ and $K\beta$ lines should be selected to perform angiography.

In the present research, we measured the x-ray spectra from a cerium-target tube using a new cadmium telluride detector, and performed a preliminary study on cone-beam K-edge angiography achieved with cerium characteristic x-rays using a cerium oxide powder 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

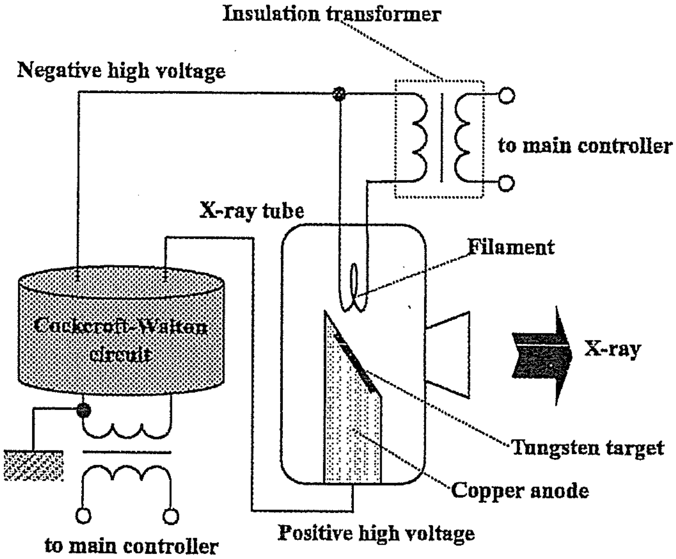

Fig. 2: Main circuit of the x-ray generator.

conjunction with an insulation transformer. In this experiment, the tube voltage applied was from 45 to 70 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 cerium oxide power filter with a surface density of 30 mg/cm^2.

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 14.3 μGy/s at 1.0 m from the source.

3.2 Focal spot

In order to measure images of the x-ray source after the 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)

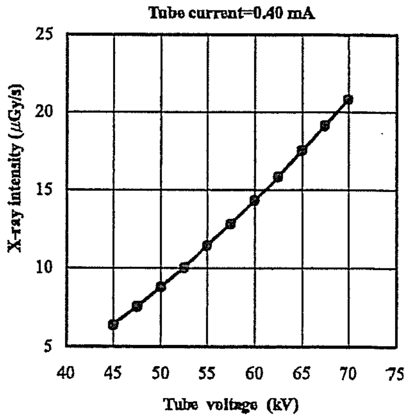

Fig. 3: X-ray intensity measured at 1.0 m from the x-ray source according to changes in the tube voltage.

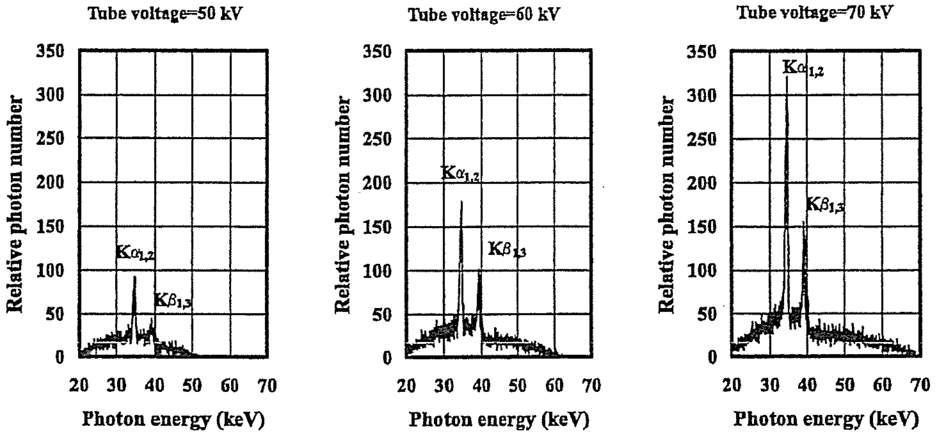

Fig. 4: X-ray spectra measured using a cadmium telluride detector with changes in the tube voltage.

system[21] with a sampling pitch of 87.5 μm. When the tube voltage was increased, spot dimensions increased slightly and had values of approximately 1×1 mm.

3.3 X-ray spectra

In order to measure x-ray spectra, we employed a cadmium telluride detector (XR-100T, Amptek Inc.) (Fig. 4). When the tube voltage was increased, the characteristic x-ray intensities of Kα and Kβ lines substantially increased, and both the maximum photon energy and the intensities of bremsstrahlung x-rays increased.

4. K-edge Angiography

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 media with a K-absorption edge of

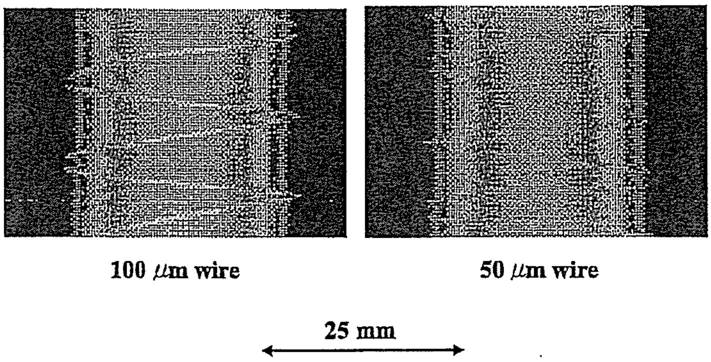

Fig. 5: Radiograms of tungsten wires coiled around PMMA rods.

33.2 keV absorb the lines easily. Therefore, blood vessels were observed with high contrasts.

The angiography was performed by the CR system[21] (Konica Regius 150) using the filter with a tube voltage of 60 kV, and the distance (between the x-ray source and the imaging plate) was 1.5 m. First, rough measurements of spatial resolution were made using wires. Figure 5 shows radiograms of tungsten wires coiled around rods 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.

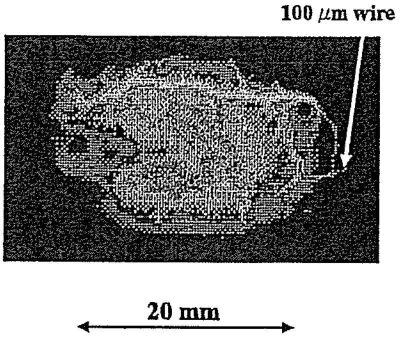

Fig. 6: Angiograms of an extracted rabbit heart using iodine microspheres.

An angiograms of a rabbit heart is shown in Fig. 6. This image was obtained using iodine microspheres of 15 μm in diameter. Fine blood vessels in the coronary arteries in the heart were visible. Figure 7 shows an angiogram of a larger dog heart using iodine spheres, and blood vessels of approximately 100 μm in diameter were visible.

5. Discussion

In summary, we employed an x-ray generator with a cerium-target tube and succeeded in producing cerium K-series characteristic x-rays, which can be absorbed easily by iodine-based contrast media. In the spectrum measurement, high-photon-energy bremsstrahlung x-rays beyond cerium K-edge (40.4 keV) were absorbed effectively.

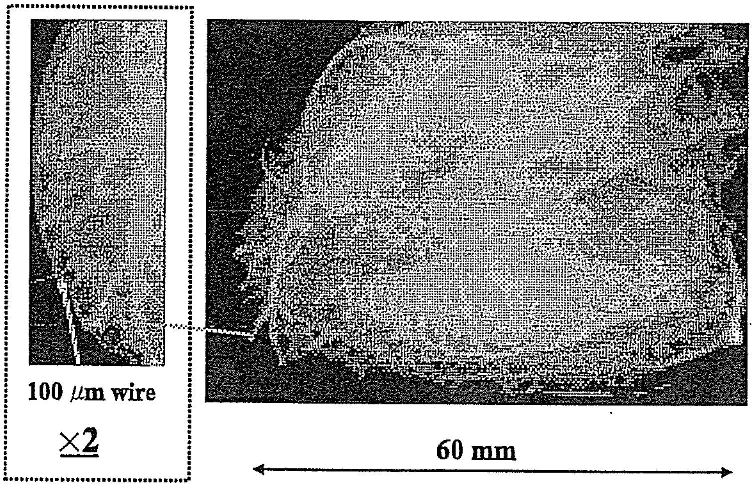

Fig. 7: Angiograms of an extracted dog heart using iodine microspheres.

In angiography, fine blood vessels were observed with high contrast with a spatial resolution of approximately 100 μm; the resolution was almost equal to the sampling pitch (87.5 mm) of the CR system. Therefore, the pith should be minimized, and magnification digital radiography including phase-contrast effect should be employed in order to improve the spatial resolution.

Although the cerium x-ray generator used in this research produces both the characteristic and the bremsstrahlung x-rays, bremsstrahlung intensity can be decreased effectively by considering the angle dependence without using the filter, since bremsstrahlung rays are not emitted in the opposite direction to that of electron trajectory. Subsequently, the generator produced maximum number of estimated characteristic photons was approximately 5×10^7 photons / ($\mathrm{cm}^2 \cdot \mathrm{s}$) at 1.0 m from the source, and the photon count rate can be increased easily by improving the target.

Acknowledgment

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Variations in Cerium X-ray Spectra and Enhanced K-Edge Angiography

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A cerium-target X-ray tube is useful in performing cone-beam K-edge angiography because K-series characteristic X-rays from the cerium target are absorbed effectively by iodine-based contrast media. 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 1.0-mm-focus 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. Cerium Kα rays were selected out using a barium sulfate filter, and the X-ray intensities without filtering and with a barium sulfate filter were 209 and 16.8 µGy/s, respectively, at 1.0 m from the source with a tube voltage of 60 kV and a current of 0.40 mA. Angiography was performed with an X-ray film using the filter and iodine-based microspheres 15 µm in diameter. In the angiography of nonliving animals, we observed fine blood vessels approximately 100 µm in diameter with high contrasts. [DOI: 10.1143/JJAP.44.8204]

KEYWORDS: X-ray tube, cerium target, monochromatic X-rays, Kα rays, K-edge angiography

1. Introduction

Monochromatic parallel X-ray beams have been used to perform enhanced K-edge angiography[1–4] using iodine-based contrast media because the X-rays with photon energies of approximately 35 keV are absorbed easily by iodine with a K-edge of 33.2 keV. In conjunction with a high-resolution camera, fine blood vessels of approximately 50 µm can be observed.[3] Although the parallel beams have also been employed to perform phase-contrast radiography,[5–7] weakly absorbing materials have been observed with high contrasts.

Flash radiography of biomedical tissues has been investigated for a number of years, and several different flash X-ray generators have been developed corresponding to specific radiographic objectives.[8–11] The advantages of flash radiography include the use of K-series characteristic X-rays and their relatively good imaging contrast. However, monochromatic flash radiography[12–15] has encountered difficulties in increasing X-ray duration, and in performing X-ray computed tomography (CT).

Recently, a steady-state X-ray generator utilizing a cerium-target tube[16] has been developed, and has been employed to perform enhanced K-edge angiography achieved with cerium Kα rays and iodine-based contrast media, since Kα rays (34.6 keV) are absorbed effectively by iodine. In this case, because the sampling pitch of a computed radiography system (Konica Minolta Regius 150)[17] is 87.5 µm, a spatial resolution of approximately 100 µm has been obtained. Therefore, the resolution should be minimized by using a film or decreasing the pitch.

In the above-mentioned preliminary experiment,[16] we employed a cadmium tellurium detector with a photon energy resolution of 1.7 keV to measure X-ray spectra from the cerium target. However, the resolution should be minimized to measure the characteristic X-ray intensity and to confirm the K-edge effect of a barium sulfate filter for absorbing Kβ and bremsstrahlung X-rays, because the photon energy width of the K-series lines is approximately 1 keV.

In the present research, we measured the X-ray spectra from a cerium target tube using a germanium detector with a photon energy resolution of 0.12 keV and performed a preliminary study on enhanced K-edge angiography achieved with cerium Kα rays.

2. Generator

Figure 1 shows a block diagram of the X-ray generator, which consists of a main controller and an X-ray tube unit

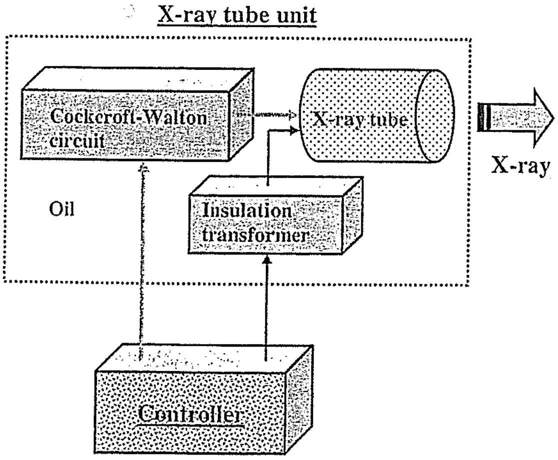

Fig. 1. Block diagram of compact X-ray generator with cerium-target radiation tube, which is used particularly for K-edge angiography using iodine-based contrast media.

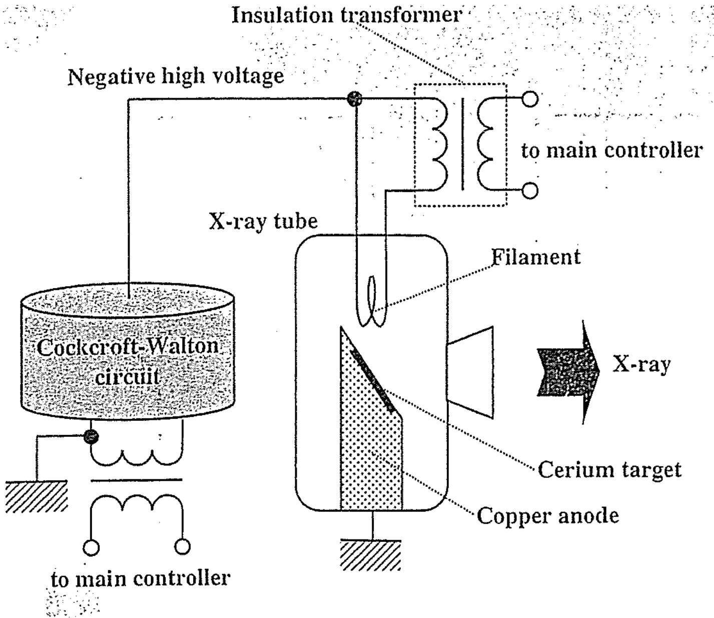

Fig. 2. Main circuit of X-ray generator.

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 it employed the Cockcroft–Walton circuit in order to decrease the dimensions of the tube unit. In the X-ray tube, a high negative 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. The tube is a conventional diode with a plate cerium target, a 1.0 mm focus, a take-off angle of 22°, and a 0.5-mm-thick beryllium window. In this experiment, the tube voltage was from 45 to 65 kV, and the tube current was regulated to within 0.40 mA (maximum current) by the filament temperature. The exposure time is controlled in order to obtain optimum X-ray intensity. Monochromatic Kα rays are selected out using a barium sulfate filter for absorbing bremsstrahlung and Kβ rays. 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 poly(methyl methacrylate) (PMMA) resin. In this case, the density was approximately 30 mg/cm^2.

3. Characteristics

3.1 *X-ray intensity*

The X-ray intensity rate was measured by a Victoreen 660 ionization chamber at 1.0 m from the X-ray source (Fig. 3). At a constant tube current of 0.40 mA, the X-ray intensity increased when the tube voltage was increased. At a tube voltage of 60 kV and a current of 0.40 mA, the intensities without filtering and with the filter were 208 and 16.8 μGy/s, respectively, with errors of less than 0.2%. The X-ray intensity was limited because the thermal contact between the target and the anode was not good.

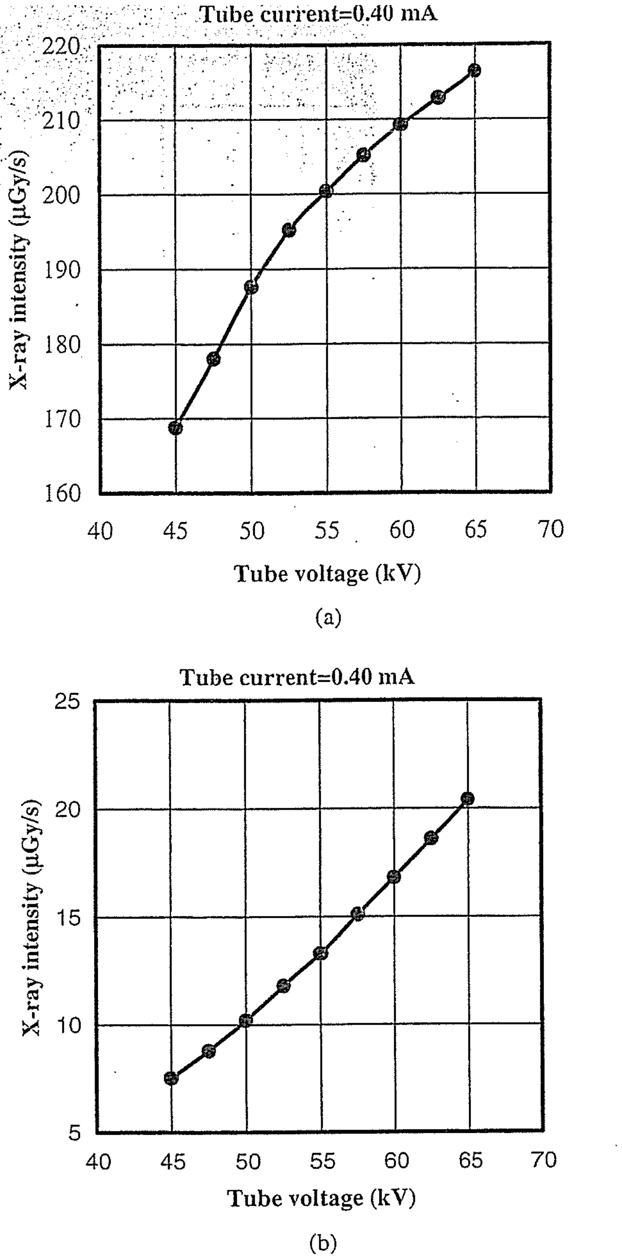

Fig. 3. X-ray intensity measured at 1.0 m from X-ray source according to changes in tube voltage (a) without filtering and (b) using barium-sulfate filter.

3.2 *X-ray spectra*

In order to measure X-ray spectra, we employed a germanium detector (GLP-10180/07-P, Ortec Inc.) (Fig. 4). Without filtering, when the tube voltage was increased, the X-ray intensities of cerium K-series characteristic lines increased, and both the maximum photon energy and the bremsstrahlung X-ray intensity increased. Using the filter, both the Kβ lines and the bremsstrahlung X-rays with photon energies higher than the barium K-edge of 37.4 keV were absorbed effectively, and sharp Kα lines were left. With increases in the tube voltage, the Kα intensity substantially increased, and the maximum photon energy increased.

In order to perform K-edge angiography, the Kα rays are useful, and the high-energy bremsstrahlung X-rays decrease the image contrast. Using the filter, because bremsstrahlung X-rays with energies higher than 60 keV were not absorbed easily, the tube voltage for angiography was determined to be 60 kV. Subsequently, low-energy bremsstrahlung rays

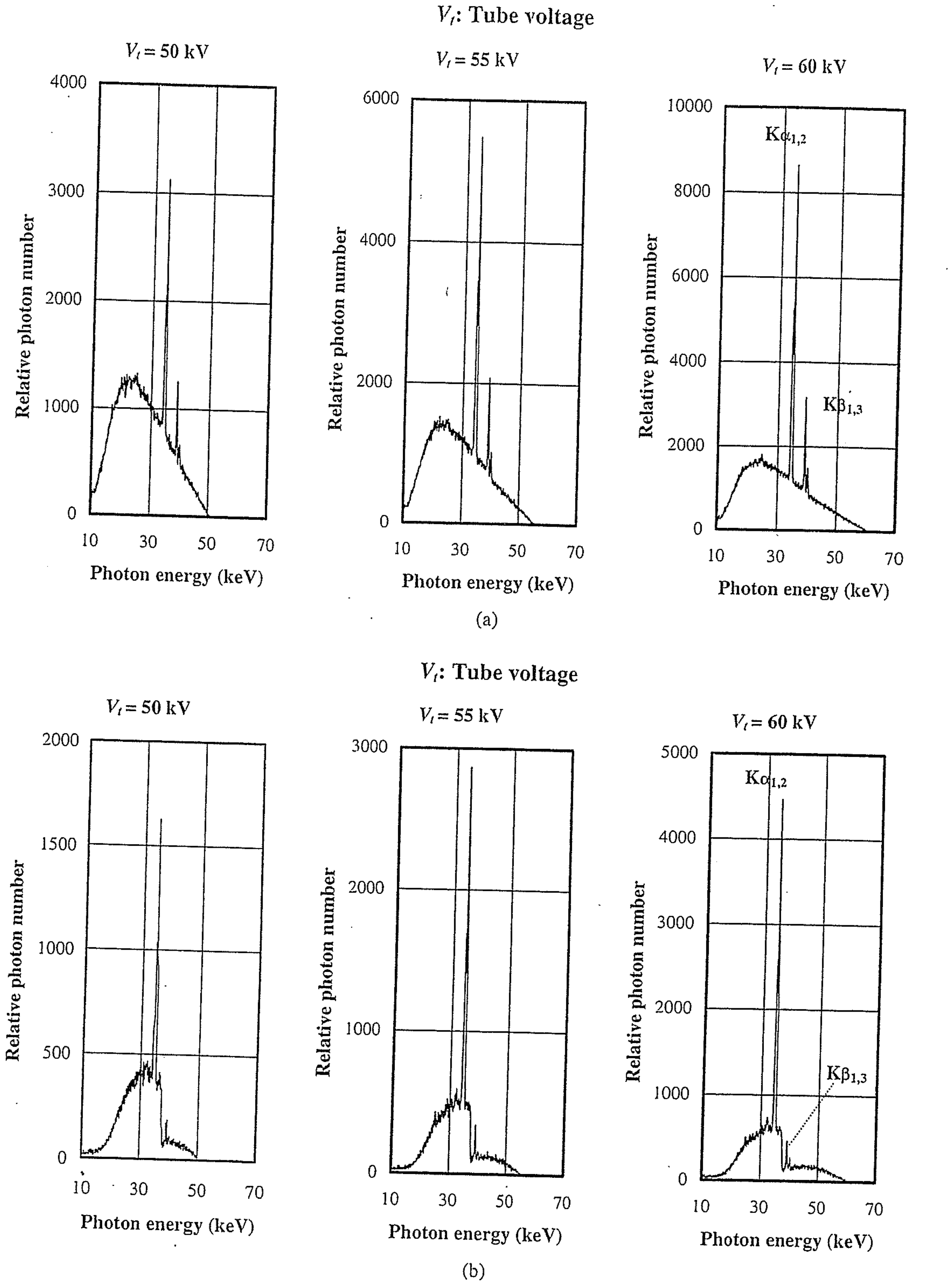

Fig. 4. X-ray spectra measured using germanium detector with changes in tube voltage (a) without filtering and (b) using barium sulfate filter.

with energies lower than the K-edge should be minimized using the filter or an aluminum filter to increase the blood-vessel contrast, since the iodine contrast media transmit the rays easily.

4. K-edge Angiography

Because the average photon energy of Kα is 34.6 keV, iodine contrast media with a K-absorption edge of 33.2 keV absorb the Kα lines easily. Therefore, blood vessels were observed with high contrasts. In order to observe fine blood vessels approximately 50 µm in diameter, the angiography was performed using an X-ray film (Fuji IX 100), iodine microspheres 15 µm in diameter, and the filter. The distance between the X-ray source and the imaging plate was 1.5 m, and the tube voltage was 60 kV. First, rough measurements of spatial resolution were made using wires. Figure 5 shows radiograms of tungsten wires coiled around rods made of PMMA with an X-ray exposure time of 300 s. Although the

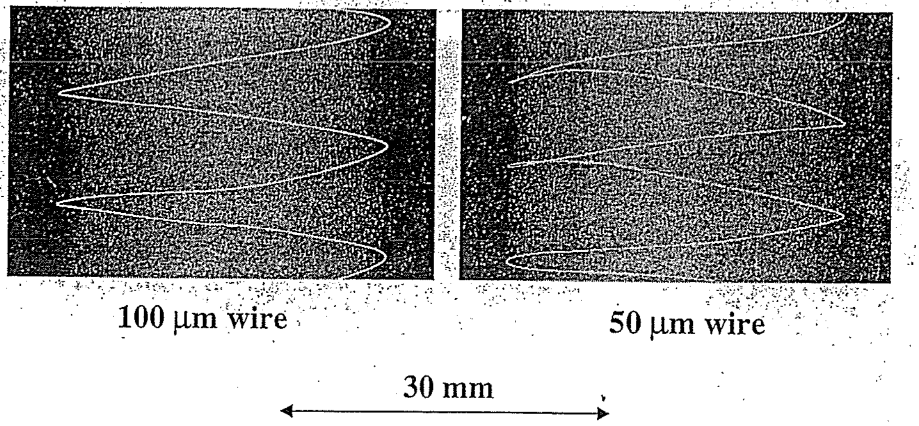

Fig. 5. Radiograms of tungsten wires coiled around PMMA rods.

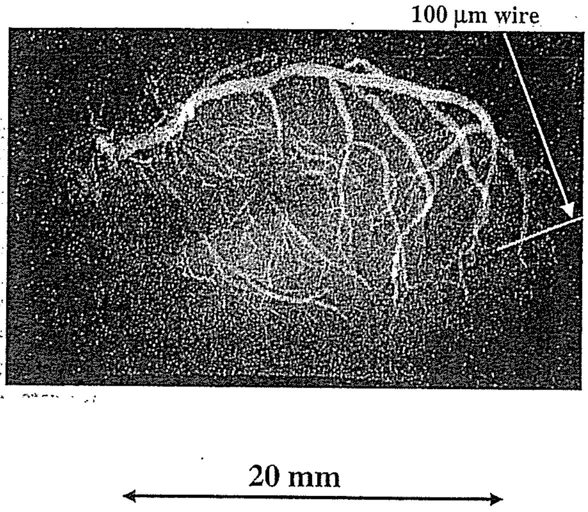

Fig. 6. Angiograms of extracted rabbit heart using iodine microspheres.

image contrast hardly varied with decreases in the wire diameter, a 50-μm-diameter wire could be observed clearly.

Figures 6 and 7 show angiograms of a rabbit heart and a thigh, respectively, with an exposure time of 300 s. The coronary arteries in the heart and fine blood vessels in the thigh with diameters of approximately 100 μm were visible. Figure 8 shows an angiogram of a dog heart in a 100-mm-thick water phantom with an exposure time of 1,500 s. Because the size of the dog heart is almost the same as that of a human heart, human coronary arteries can be observed. For comparison, we show a three-dimensional (3D) image of the coronary arteries constructed from X-ray CT images taken by Pascal (Digital Culture Tech. Corp.) with a tungsten X-ray tube (Fig. 9). This heart was the same as that used in K-edge angiography and was observed from the same direction by rotating the three-dimensional (3D) image; CT angiography was performed without using the water phantom. Using this 3D angiography achieved with a multislice helical CT, fine blood vessels were not observed at all.

5. Discussion

In the present research, 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 bremsstrahlung X-ray intensities increased with tube voltage

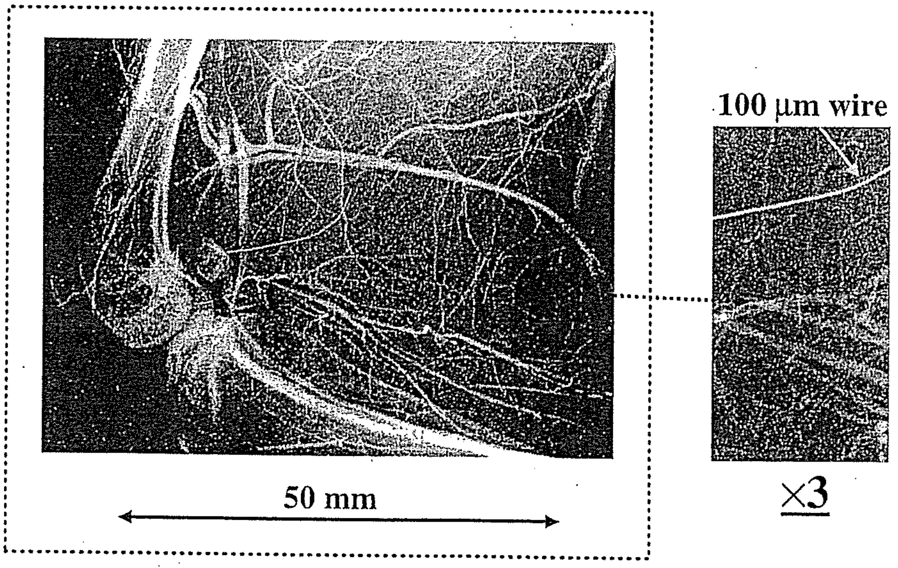

Fig. 7. Angiogram of rabbit thigh using iodine microspheres.