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Cerium X-ray Spectra without Filtering and their Application to High-contrast 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 media. The x-ray generator consists of a main controller, an x-ray tube unit with a high-voltage circuit and an insulation transformer, and a personal computer. The tube is a glass-enclosed diode with a cerium target and a 0.5-mm-thick beryllium window. The maximum tube voltage and current were 65 kV and 0.4 mA, respectively, and the focal-spot sizes were 1.2×0.8 mm. Sharp cerium K-series characteristic x rays were observed without using a filter, and the x-ray intensity was 209 μGy/s at 1.0 m from the source with a tube voltage of 60 kV and a current of 0.40 mA. Angiography was performed with 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, x-ray spectra, characteristic x rays, K-edge angiography, energy-selective radiography

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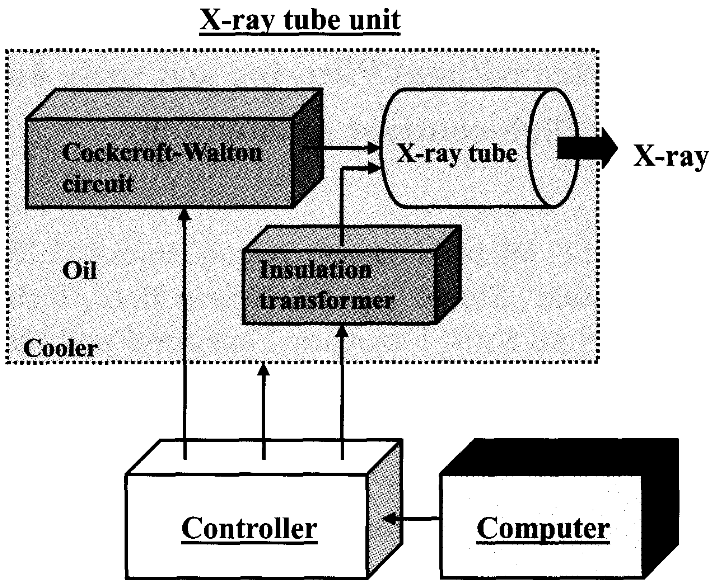

Fig. 1: Block diagram of compact x-ray generator with cerium-target radiation tube, which is used specially for K-edge angiography using iodine-based contrast media.

1. Introduction

The principle basis of quality assurance for enhanced K-edge angiography is the discontinuity of the absorption coefficient at the K-absorption edge of iodine-based contrast media, and angiography has been performed using monochromatic parallel x-ray beams with synchrotrons.[1-3] Subsequently, monochromatic x-ray computed tomography at two different energies has provided information on the electron density of human tissue.[4] In addition, a compact pulsed tunable monochromatic x-ray source has been designed, developed, and tested.[5] From the source, conical x-ray beams from 10 to 50 keV with pulse widths of 8 ps have been produced, and these beams are useful for biomedical imaging and protein crystallography.

In order to perform high-speed medical radiography, although several different flash x-ray generators[6-10] utilizing cold-cathode tubes have been developed, plasma flash x-ray generators[11-14] are useful to produce quasi-monochromatic x rays without using a K-edge filter. Therefore, we have performed a demonstration of cone-beam K-edge angiography[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, and have demonstrated enhanced K-edge angiography utilizing a barium sulfate filter.[15] In this research, Kα lines (34.6 keV) were left by absorbing Kβ lines (39.2 keV), and bremsstrahlung x rays with photon energies of lower than the barium K-edge (37.4 keV) were also observed. However, because cerium Kβ lines are also absorbed effectively by iodine, both Kα and Kβ lines should be selected to perform angiography. In measurements of x-ray spectra, although we usually employed a cadmium tellurium detector with a photon energy resolution of 1.7 keV, the resolution should be improved as much as possible to measure the characteristic x-ray intensity.

In the present research, we measured the x-ray spectra from a cerium-target tube using a germanium detector, and performed a preliminary study on cone-beam K-edge angiography achieved with cerium characteristic x rays without using a filter.

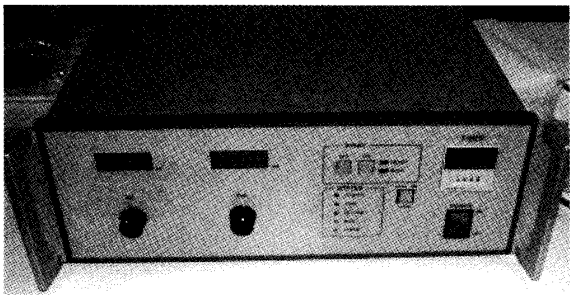

Fig. 2: Main controller.

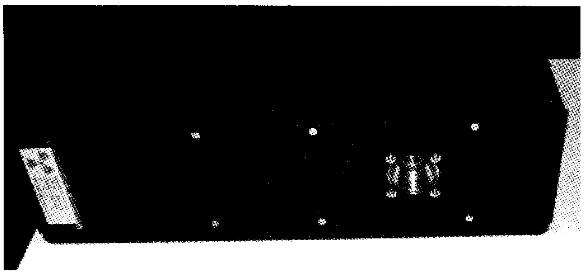

Fig. 3: X-ray tube unit.

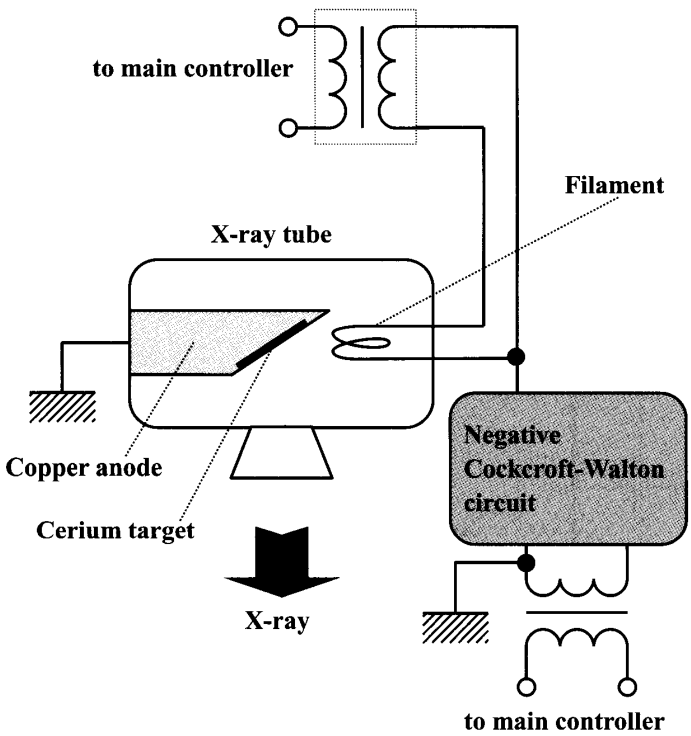

Fig. 4: Main circuit of x-ray generator.

2. Generator

Figure 1 shows the block diagram of the x-ray generator, which consists of a main controller (Fig. 2), a cerium-target x-ray tube unit (Fig. 3) with a Cockcroft-Walton circuit and an insulation transformer, and a personal computer. The tube voltage, the current, and the exposure time can be controlled by both the controller and the computer. The main circuit for producing x rays is illustrated in Fig. 4, and employs 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.

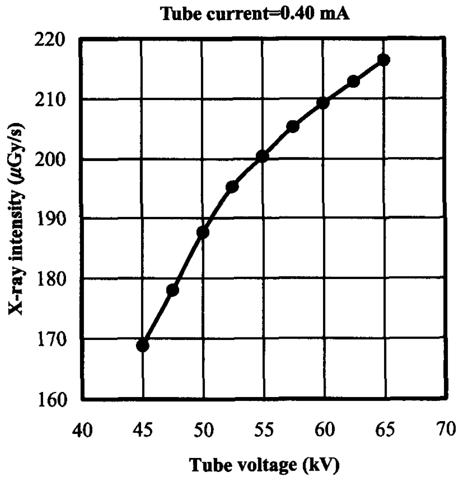

Fig. 5: X-ray intensity measured at 1.0 m from x-ray source according to changes in tube voltage.

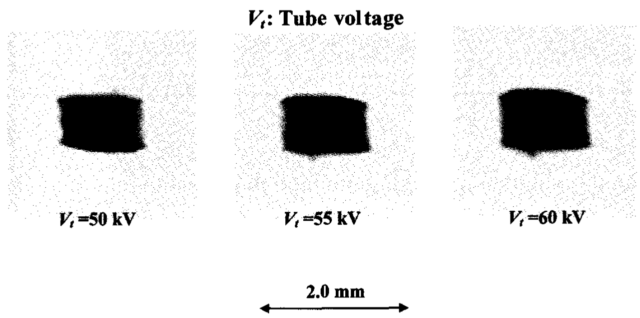

Fig. 6: Effective focal spots with changes in tube voltage.

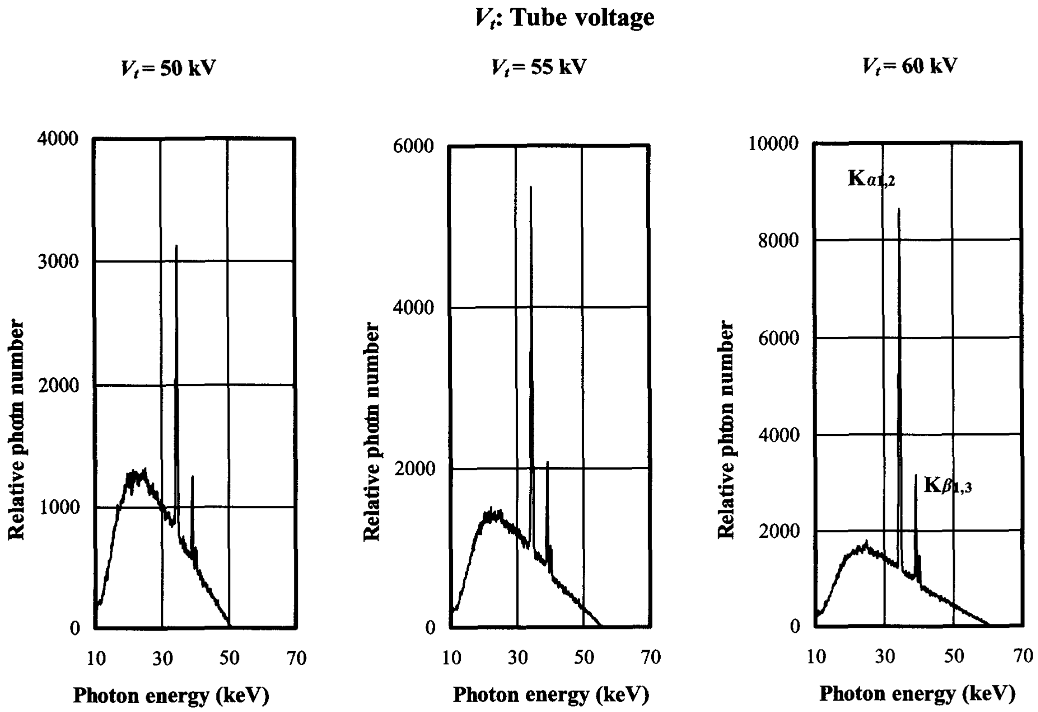

Fig. 7: X-ray spectra measured using germanium detector.

3. Characteristics

3.1 X-ray intensity

The x-ray intensity rate was measured by a Victoreen 660 ionization chamber at 1.0 m from the x-ray source (Fig. 5). At a constant tube current of 0.40 mA, the x-ray intensity increased when the tube voltage was increased. In this measurement, the intensity with a tube voltage of 60 kV and a current of 0.40 mA was 209 μGy/s with errors of less than 0.2%.

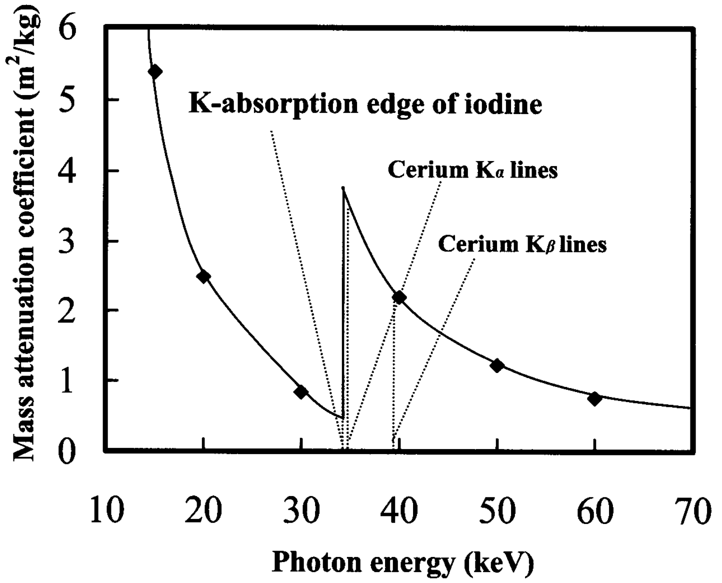

Fig. 8: Mass attenuation coefficients of iodine, and average photon energies of cerium Kα and Kβ lines.

3.2 Focal spot

In order to measure images of the x-ray source without 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[16] with a sampling pitch of 87.5 μm. When the tube voltage was increased, spot dimensions increased slightly and had values of 1.2 × 0.8 mm (Fig. 6).

3.3 X-ray spectra

In order to measure x-ray spectra, we employed a germanium detector (GLP-10180/07-P, Ortec Inc.) (Fig. 7). 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. Angiography

Figure 8 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) without using a 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 9 shows radiograms of tungsten wires in a rod made of polymethyl methacrylate with a tube voltage of 55 kV. Although the image contrast decreased somewhat with decreases in the wire diameter, due to blurring of the image caused by the sampling

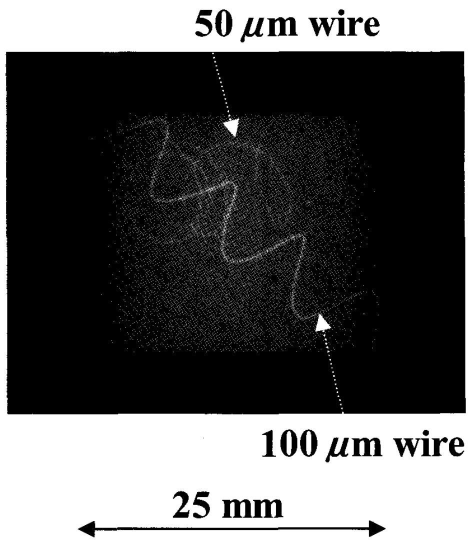

Fig. 9: Radiogram of tungsten wires in PMMA rod with tube voltage of 55 kV.

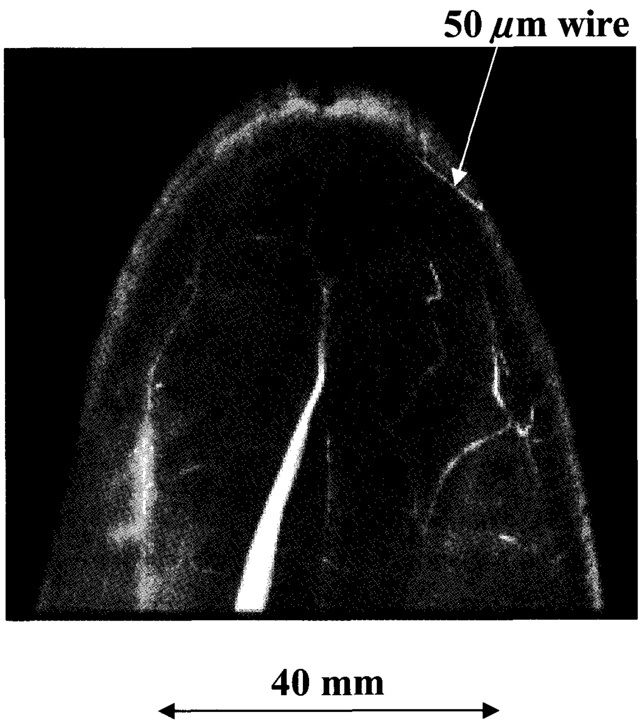

Fig. 10: Angiogram of rabbit ear with tube voltage of 50 kV.

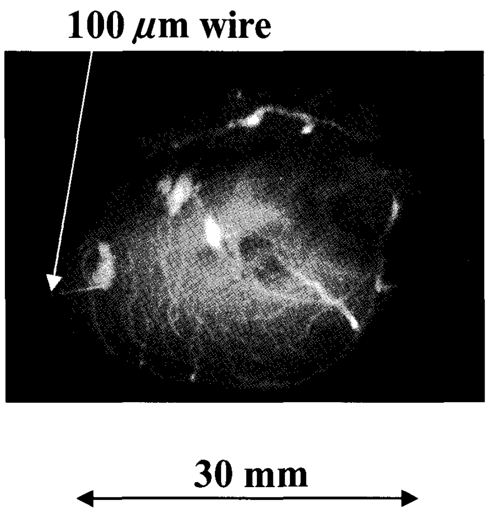

Fig. 11: Angiogram of extracted rabbit heart with tube voltage of 50 kV.

pitch of 87.5 μm, a 50 μm-diameter wire could be observed.

Figures 10 and 11 show angiograms of a rabbit ear and heart, respectively. These images were obtained using iodine microspheres of 15 μm in diameter at a tube voltage of 50 kV. Fine blood vessels in the ear and the coronary arteries in the heart were visible. Figure 12 shows an angiogram of a larger dog heart 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. 13). Using this imaging technique, fine blood vessels were not observed at all.

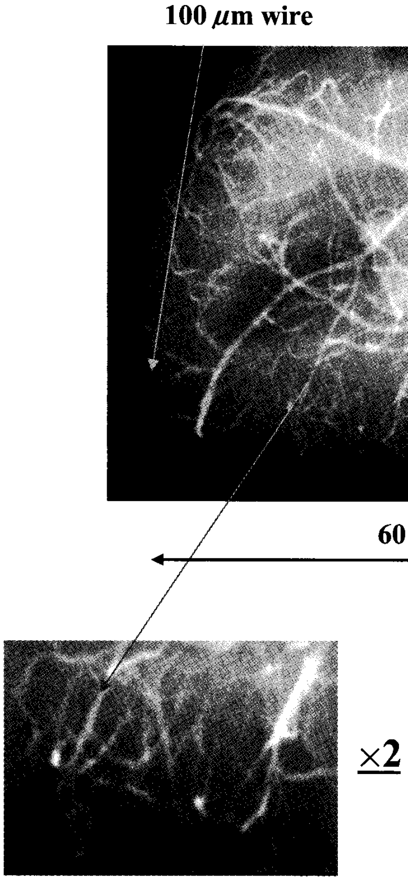

Fig. 12: Angiogram of extracted dog heart using iodine microspheres with tube voltage of 60 kV.

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

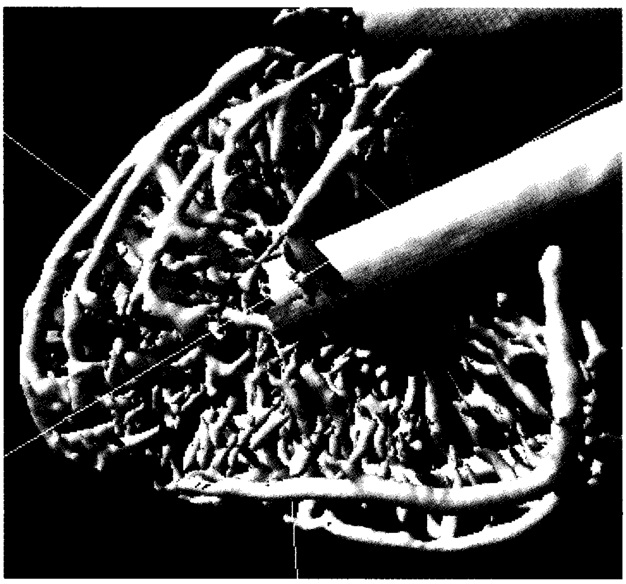

Fig. 13: 3-dimensional image of coronary arteries constructed from x-ray CT images by Pascal.

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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References

1. A. C. Thompson, H. D. Zeman, G. S. Brown, J. Morrison, P. Reiser, V. Padmanabahn, L. Ong, S. Green, J. Giacomini, H. Gordon and E. Rubenstein, "First operation of the medical research facility at the NSLS for coronary angiography," *Rev. Sci. Instrum.*, **63**, 625-628, 1992.
2. H. Mori, K. Hyodo, E. Tanaka, M. U. Mohammed, A. Yamakawa, Y. Shinozaki, H. Nakazawa, Y. Tanaka, T. Sekka, Y. Iwata, S. Honda, K. Umetani, H. Ueki, T. Yokoyama, K. Tanioka, M. Kubota, H. Hosaka, N. Ishizawa and M. Ando, "Small-vessel radiography in situ with monochromatic synchrotoron radiation," *Radiology*, **201**, 173-177, 1996.
3. K. Hyodo, M. Ando, Y. Oku, S. Yamamoto, T. Takeda, Y. Itai, S. Ohtsuka, Y. Sugishita and J. Tada, "Development of a two-dimensional imaging system for clinical applications of intravenous coronary angiography using intense synchrotron radiation produced by a multipole wiggler," *J. Synchrotron Rad.*, **5**, 1123-1126, 1998.
4. M. Torikoshi, T. Tsunoo, M. Sasaki, M. Endo, Y. Noda, T. Kohno, K. Hyodo, K. Uesugi and N. Yagi: "Electron density measurement with dual-energy x-ray CT using synchrotron radiation," *Phys. Med. Biol.*, **48**, 673-685, 2003.
5. F. E. Carroll, M. H. Mendenhall, R. H. Traeger, C. Brau and J. W. Waters, "Pulsed tunable monochromatic x-ray beams from a compact source: New opportunities," *Am. J. Roentgenol.*, **181**, 1197-1202, 2003.
6. E. Sato, H. Isobe and F. Hoshino, "High intensity flash x-ray apparatus for biomedical radiography," *Rev. Sci. Instrum.*, **57**, 1399-1408, 1986.
7. E. Sato, S. Kimura, S. Kawasaki, H. Isobe, K. Takahashi, Y. Tamakawa and T. Yanagisawa, "Repetitive flash x-ray generator utilizing a simple diode with a new type of energy-selective function," *Rev. Sci. Instrum.*, **61**, 2343-2348, 1990.
8. A. Shikoda, E. Sato, M. Sagae, T. Oizumi, Y. Tamakawa and T. Yanagisawa, "Repetitive flash x-ray

generator having a high-durability diode driven by a two-cable-type line pulser," *Rev. Sci. Instrum.*, **65**, 850-856, 1994.

9. E. Sato, K. Takahashi, M. Sagae, S. Kimura, T. Oizumi, Y. Hayasi, Y. Tamakawa and T. Yanagisawa, "Sub-kilohertz flash x-ray generator utilizing a glass-enclosed cold-cathode triode," *Med. & Biol. Eng. & Comput.*, **32**, 289-294, 1994.
10. E. Sato, M. Sagae, E. Tanaka, Y. Hayasi, R. Germer, H. Mori, T. Kawai, T. Ichimaru, S. Sato, K. Takayama and H. Ido, "Quasi-monochromatic flash x-ray generator utilizing a disk-cathode molybdenum tube," *Jpn. J. Appl. Phys.*, **43**, 7324-7328, 2004.
11. E. Sato, Y. Hayasi, R. Germer, E. Tanaka, H. Mori, T. Kawai, H. Obara, T. Ichimaru, K. Takayama and H. Ido, "Irradiation of intense characteristic x-rays from weakly ionized linear molybdenum plasma," *Jpn. J. Med. Phys.*, **23**, 123-131, 2003.
12. E. Sato, Y. Hayasi, R. Germer, E. Tanaka, H. Mori, T. Kawai, T. Ichimaru, K. Takayama and H. Ido, "Quasi-monochromatic flash x-ray generator utilizing weakly ionized linear copper plasma," *Rev. Sci. Instrum.*, **74**, 5236-5240, 2003.
13. E. Sato, R. Germer, Y. Hayasi, Y. Koorikawa, K. Murakami, E. Tanaka, H. Mori, T. Kawai, T. Ichimaru, F. Obata, K. Takahashi, S. Sato, K. Takayama and H. Ido, "Weakly ionized plasma flash x-ray generator and its distinctive characteristics," *SPIE*, **5196**, 383-392, 2003.
14. E. Sato, Y. Hayasi, R. Germer, E. Tanaka, H. Mori, T. Kawai, T. Ichimaru, S. Sato, K. Takayama and H. Ido, "Sharp characteristic x-ray irradiation from weakly ionized linear plasma," *J. Electron Spectrosc. Related Phenom.*, **137-140**, 713-720, 2004.
15. E. Sato, E. Tanaka, H. Mori, T. Kawai, T. Ichimaru, S. Sato, K. Takayama and H. Ido, "Demonstration of enhanced K-edge angiography using a cerium target x-ray generator," *Med. Phys*, **31**, 3017-3021, 2004.
16. E. Sato, K. Sato and Y. Tamakawa, "Film-less computed radiography system for high-speed imaging," *Ann. Rep. Iwate Med. Univ. Sch. Lib. Arts and Sci.*, **35**, 13-23, 2000.