Annual Report of Iwate Medical University
School of Liberal Arts and Sciences
No. 41 (2006), 9 - 16.

Angular dependence of x-ray spectra from a demountable x-ray tube with a copper target

Eiichi Sato[a], Etsuro Tanaka[b], Hidezo Mori[c], Toshiaki Kawai[d], Takashi Inoue[e], Akira Ogawa[e], Kiyomi Takahashi[f], Shigehiro Sato[f] and Kazuyoshi Takayama[g]

(Received November 6, 2006)

Abstract

The x-ray 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 tungsten hairpin cathode (filament), a focusing electrode, a polyethylene terephthalate x-ray window 0.25 mm in thickness, a stainless-steel tube body, and a rod target. 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 12 to 18 kV, and the tube current was regulated to within 0.10 mA by the filament temperature. The electron beams from the cathode are converged to the target by the focusing electrode, and x-rays are produced from the target plane. The x-ray spectra were measured from two directions with angles between the electron trajectory and the x-ray beam axis of 180° and 90°. As compared with the x-ray spectra with an angle of 90°, the bremsstrahlung x-ray intensity decreased slightly with an angle of 180° (opposite direction to that of electron trajectory).

Keywords: demountable x-ray tube, electron-impact source, copper target, x-ray spectra, bremsstrahlung x-ray distribution

1. Introduction

Monochromatic radiography can be performed using monochromatic x-ray generators, and various monochromatic generators have been developed corresponding to specific radiographic objectives. In

---

[a] Department of Physics, Iwate Medical University, 3-16-1 Honchodori, Morioka 020-0015, Japan
[b] Department of Nutritional Science, Faculty of Applied Bio-science, Tokyo University of Agriculture, 1-1-1 Sakuragaoka, Setagaya-ku 156-8502, Japan
[c] Department of Cardiac Physiology, National Cardiovascular Center Research Institute, 5-7-1 Fujishirodai, Suita, Osaka 565-8565, Japan
[d] Electron Tube Division #2, Hamamatsu Photonics K. K., 314-5 Shimokanzo, Iwata 438-0193, Japan
[e] Department of Neurosurgery, School of Medicine, Iwate Medical University, 19-1 Uchimaru, Morioka 020-8505, Japan
[f] Department of Microbiology, School of Medicine, Iwate Medical University, 19-1 Uchimaru, Morioka 020-8505, Japan
[g] Tohoku University Biomedical Engineering Research Organization, 2-1-1 Katahira, Sendai 980-8577, Japan

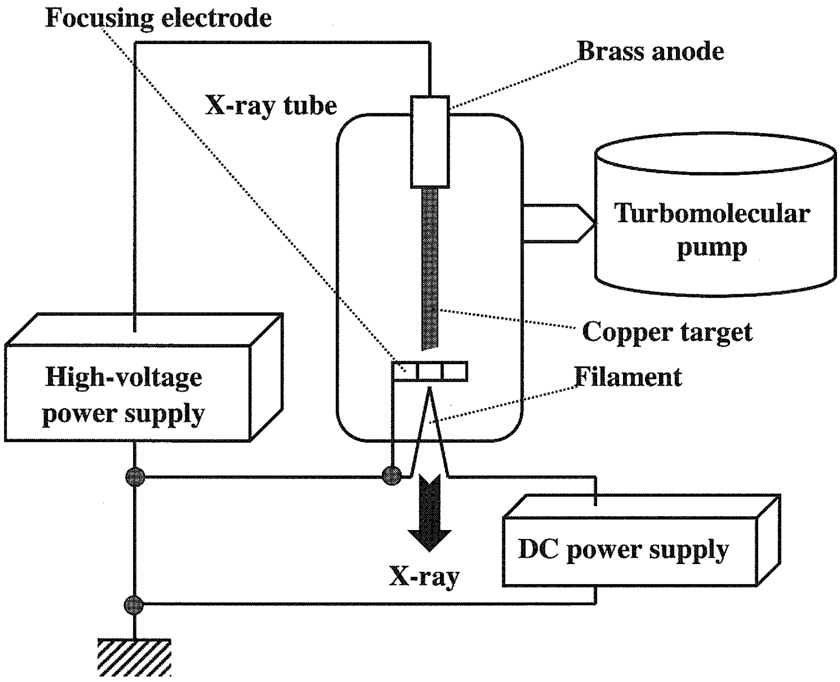

Fig. 1. Block diagram including the main transmission line of the compact x-ray generator with a demountable diode.

particular, plasma flash x-ray generators[1-7] produce extremely clean K-series characteristic x-rays such as lasers with x-ray durations of less than 1μs, and it is possible to generate low-photon-energy flash K-rays utilizing angle dependence of the bremsstrahlung x-ray intensity distribution, because the bremsstrahlung x-rays are not emitted in the opposite direction to that of electron trajectory in an empirical theory. In addition, we have developed a steady-state characteristic x-ray generator[8] utilizing the angle dependence, and clean molybdenum K lines have been produced using a molybdenum target. To observe fine blood vessels of approximately 100 μm or less, enhanced K-edge angiography systems[9-11] have been developed using synchrotrons in conjunction with single silicon crystals. However, it is difficult to obtain sufficient machine times for various researches including micro-angiography. In view of this situation, we have developed a cerium x-ray generator[12-14] and have succeeded in performing demonstrations of enhanced iodine-K-edge angiography by the filtering for absorbing bremsstrahlung rays. Because bremsstrahlung x-ray intensity is proportion to the atomic number of the target element, it is difficult to produce steady-state clean cerium K lines without using a filter.

Using a spectrometer utilizing a lithium fluoride curved crystal[15] in conjunction with an imaging plate,[16] bremsstrahlung x-rays were not observed at all from a characteristic x-ray generator with a molybdenum target. However, low-intensity bremsstrahlung rays were observed using a cadmium telluride semiconductor device.[15] Subsequently, we are very interested in the bremsstrahlung x-ray intensity according to changes in the angle between the electron trajectory and the x-ray beam axis.

In this research, we employed an x-ray generator with a demountable diode, used to perform a preliminary experiment for measuring the x-ray spectra.

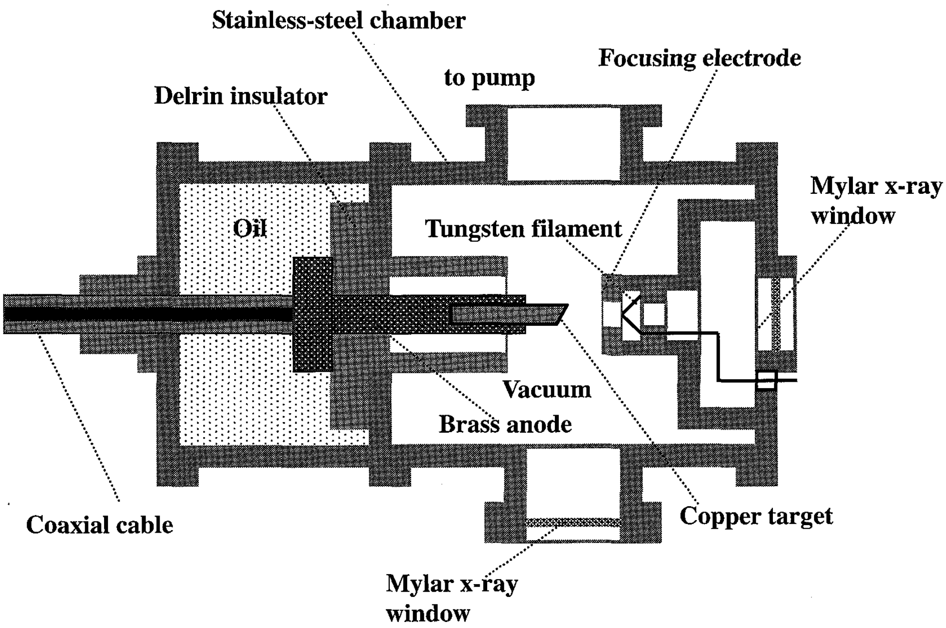

Fig. 2. Schematic drawing of the characteristic x-ray tube with a copper target.

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), a DC filament power supply, a turbomolecular pump, and an x-ray tube. The structures of the x-ray tube are illustrated in Figs. 2 and 3. 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 tungsten hairpin cathode (filament), a focusing electrode, a polyethylene terephthalate x-ray window 0.25 mm in thickness, a stainless-steel tube body, and a rod copper target of 5.0 mm in diameter. 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 12 to 18 kV, and the tube current was regulated to within 0.10 mA by the filament temperature. The electron beams from the cathode are converged to the target by the focusing electrode, and the exposure time is controlled in order to obtain optimum x-ray intensity.

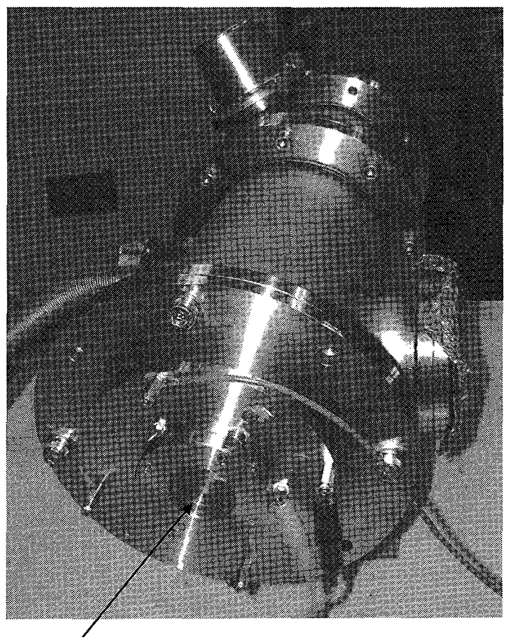

Fig. 3. Demountable x-ray tube.

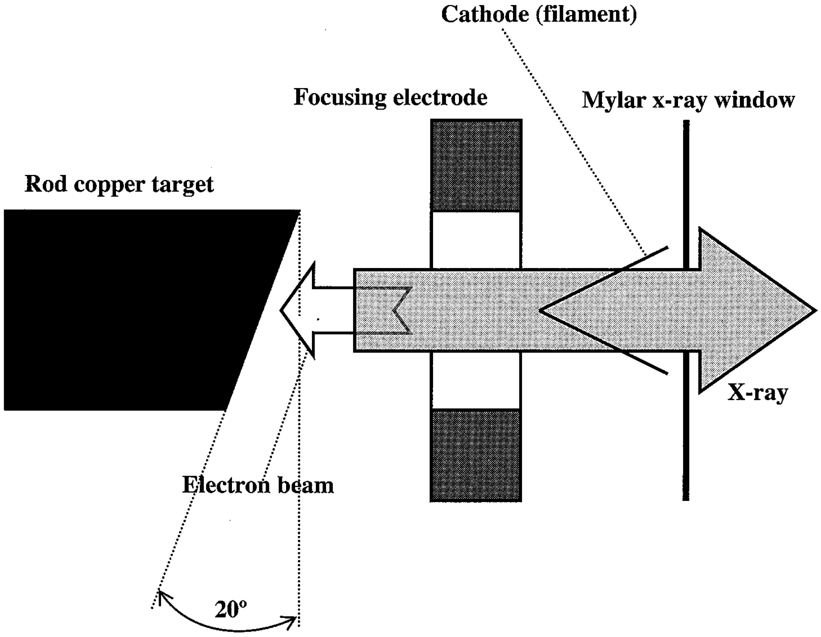

Fig. 4. X-ray irradiation at an angle of 180°.

3. X-ray spectra

X-ray spectra were measured from two directions with angles between the electron trajectory and the x-ray beam axis of 180° and 90° (Figs. 4 and 5) using a silicon detector (XR-100CR, Amptek) (Fig. 6). We observed sharp K lines, and the characteristic x-ray intensities substantially increased with increases in the tube voltage (Figs. 7 and 9). Clean K lines were left by a 10-μm-thick copper filter, and the Kα lines were selected out by absorbing Kβ lines using a 10-μm-thick nickel filter (Figs. 8 and 10). As compared with the x-ray spectra with an angle of 90°, the bremsstrahlung x-ray intensity decreased slightly with an angle of 180°.

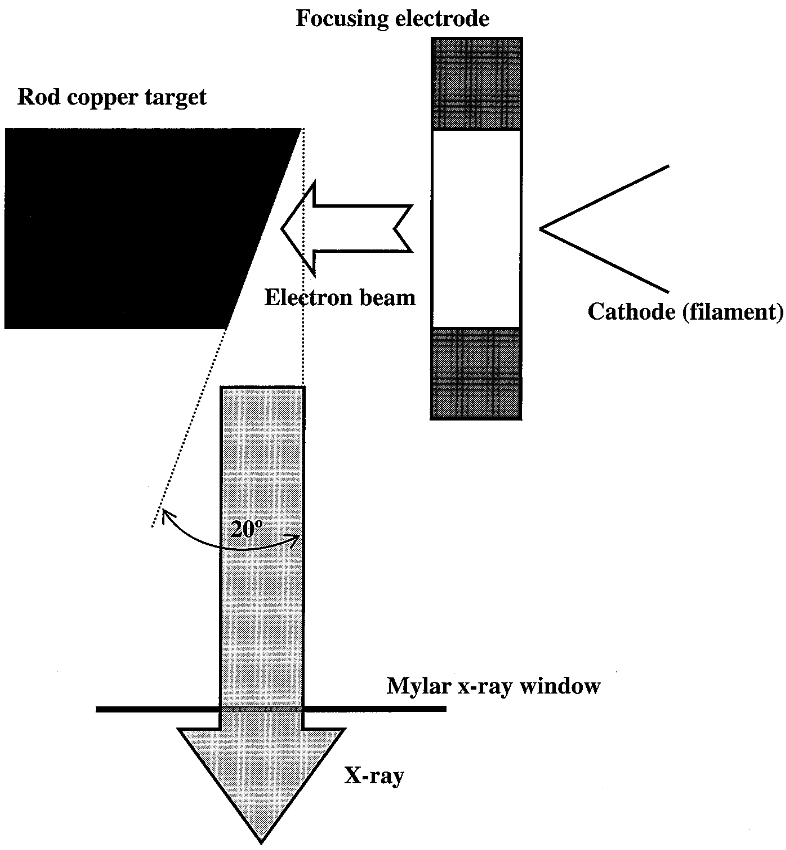

Fig. 5. X-ray irradiation at an angle of 90°.

4. Conclusions and Outlook

We developed an x-ray generator with the demountable diode with a hot cathode, and measured the x-ray spectra from two directions. At an angle of 180°, comparatively clean K lines were observed using the detector, and the K-ray intensity increased with increases in the tube voltage, and monochromatic Kα lines were left by the nickel filter.

In the spectrum measurements, we usually employ a silicon detector and a lithium fluoride curved crystal. The detector is useful for measuring 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. Using the crystal in conjunction with a computed radiography system, we observed clean copper K lines.

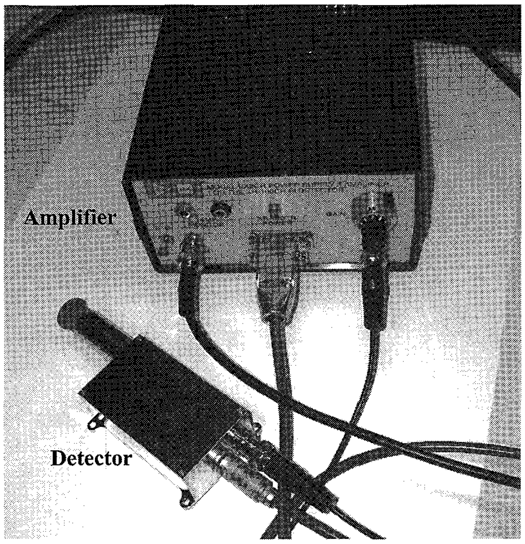

Fig. 6. Silicon x-ray detector (XR-100CR, Amptek).

In this preliminary experiment, although the maximum tube voltage and current were 18 kV and 0.10 mA, the voltage and current could be increased to 100 kV and 1.0 mA, respectively. At an angle of 180° and a tube current of 1.0 mA, the generator produced maximum number of characteristic photons from the rod target was approximately 1×10^6 photons/(cm^2 · s) at 1.0 m from the source, and the photon count rate can be increased easily by increasing the current.

Currently, the copper K-series characteristic x-rays are useful for extremely soft radiography, and the photon energies of characteristic x-rays can be selected by the target element. In particular, the pipe target is useful for forming monochromatic line beams by decreasing the bore diameter.

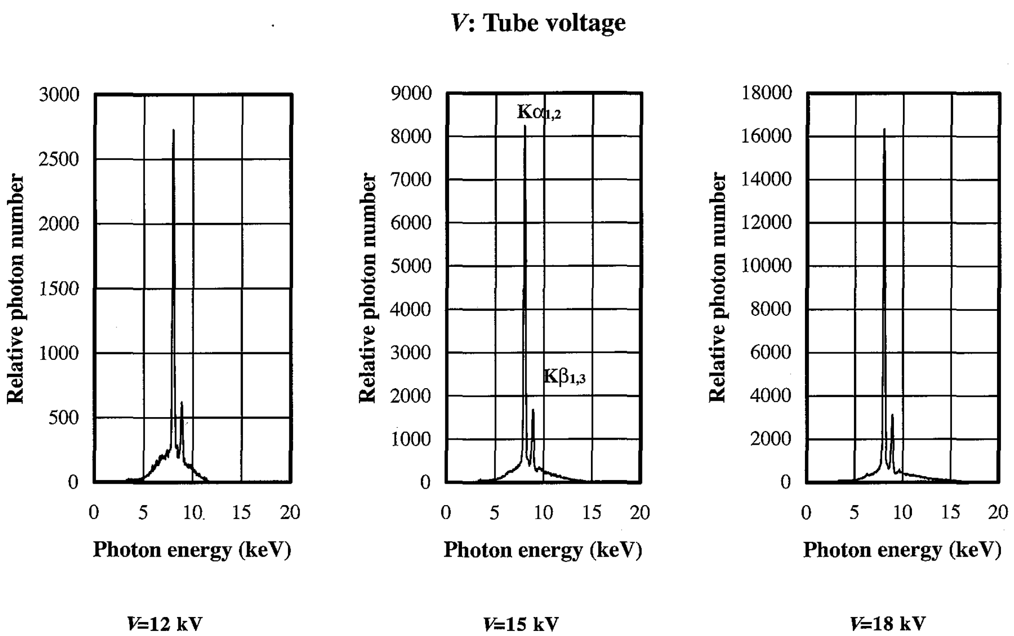

Fig. 7. X-ray spectra at an angle of 180° without using a filter.

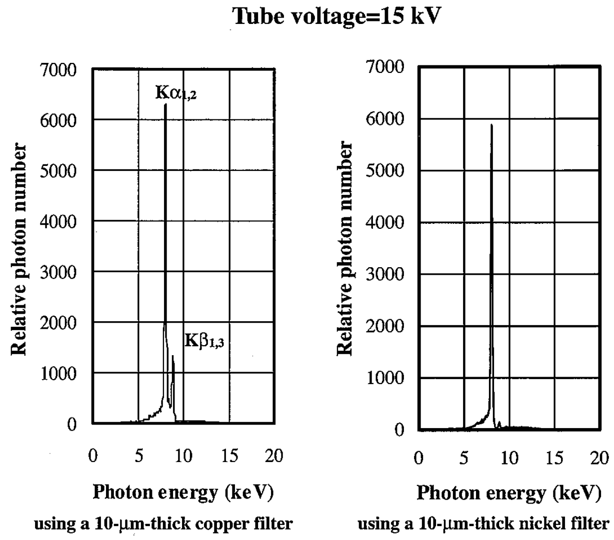

Fig. 8. X-ray spectra at an angle of 180° using monochromatic K-edge filters.

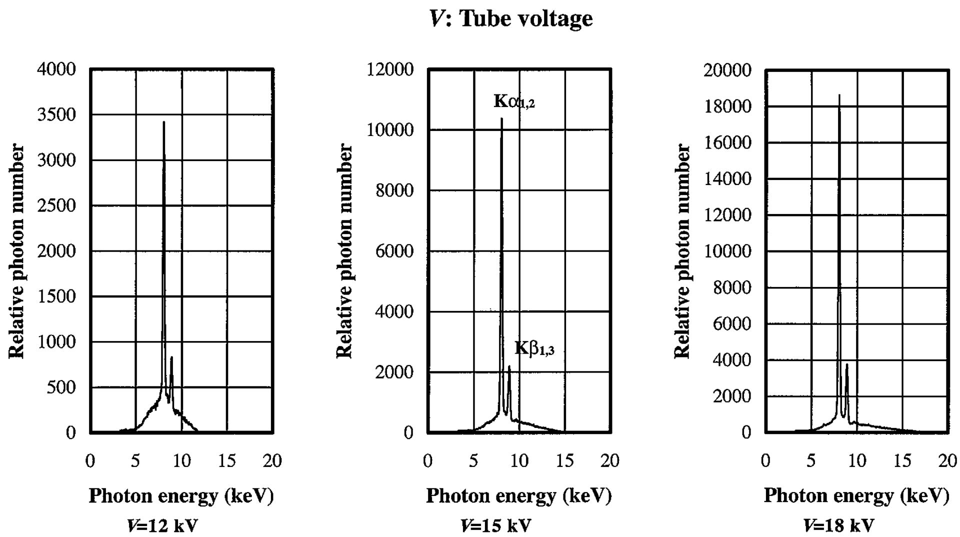

Fig. 9. X-ray spectra at an angle of 90° without using a filter..

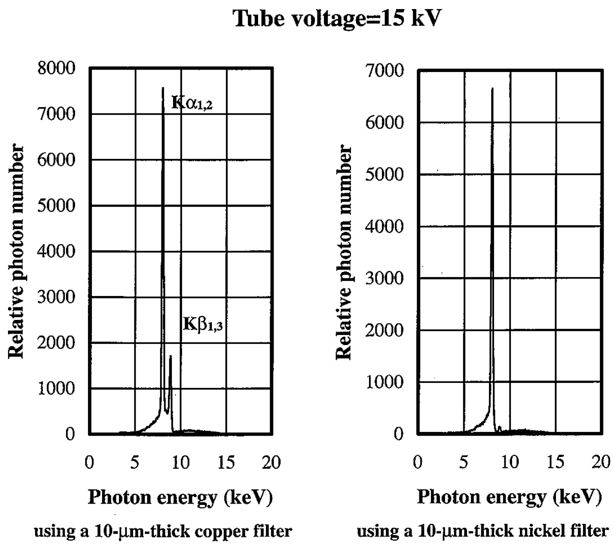

Fig. 10. X-ray spectra at an angle of 90° using the filters.

Acknowledgments

This work was supported by Grants-in-Aid for Scientific Research (13470154, 13877114, 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), and grants from the Keiryo Research Foundation, Promotion and Mutual Aid Corporation for Private Schools of Japan, Japan Science and Technology Agency (JST), and New Energy and Industrial Technology Development Organization (NEDO, Industrial Technology Research Grant Program in '03).

References

1. 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.
2. 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.
3. E. Sato, Y. Hayasi, K. Kimura, E. Tanaka, H. Mori, T. Kawai, T. Inoue, A. Ogawa, S. Sato, K. Takayama, J. Onagawa and H. Ido, "Enhanced K-edge angiography utilizing tantalum plasma x-ray generator in conjunction with gadolium-based contrast media," *Jpn. J. Appl. Phys.*, **44**, 8716-8721, 2005.
4. E. Sato, E. Tanaka, H. Mori, T. Kawai, S. Sato and K. Takayama, "Clean monochromatic x-ray irradiation from weakly ionized linear copper plasma," *Opt. Eng.*, **44**, 049002-1-6, 2005.
5. E. Sato, Y. Hayasi, E. Tanaka, H. Mori, T. Kawai, T. Inoue, A. Ogawa, S. Sato, K. Takayama and H. Ido, "K-edge angiography utilizing a tungsten plasma X-ray generator in conjunction with gadolinium-based contrast media," *Rad. Phys. Chem.*, **75**, 1841-1849, 2006.
6. E. Sato, Y. Hayasi, R. Germer, E. Tanaka, H. Mori, T. Kawai, T. Inoue, A. Ogawa, S. Sato, K. Takayama and J. Onagawa, "X-ray spectra from weakly ionized linear copper plasma," *Jpn. J. Appl. Phys.*, **45**, 5301-5306, 2006.
7. E. Sato, Y. Hayasi, E. Tanaka, H. Mori, T. Kawai, T. Inoue, A. Ogawa, S. Sato, K. Takayama, J. Onagawa and H. Ido, "Preliminary study for producing higher harmonic hard x-rays from weakly ionized nickel plasma," *Rad. Phys. Chem.*, **75**, 1812-1818, 2006.
8. E. Sato, E. Tanaka, H. Mori, T. Kawai, T. Inoue, A. Ogawa, S. Sato, K. Takayama and J. Onagawa, "Characteristic x-ray generator utilizing angle dependence of bremsstrahlung x-ray distribution," *Jpn. J. Appl. Phys.*, **45**, 2845-2849, 2006.
9. 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.
10. 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.
11. 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.

12. 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.
13. E. Sato, A. Yamadera, E. Tanaka, H. Mori, T. Kawai, F. Ito, T. Inoue, A. Ogawa, S. Sato, K. Takayama, J. Onagawa and H. Ido, "X-ray spectra from a cerium target and their application to cone beam K-edge angiography," *Opt. Eng.*, **44**, 096502-1-6, 2005.
14. E. Sato, E. Tanaka, H. Mori, T. Kawai, T. Inoue, A. Ogawa, A. Yamadera, S. Sato, F. Ito, K. Takayama, J. Onagawa and H. Ido, "Variations in cerium x-ray spectra and enhanced K-edge angiography," *Jpn. J. Appl. Phys.*, **44**, 8204-8209, 2005.
15. E. Sato, E. Tanaka, H. Mori, T. Kawai, T. Inoue, A. Ogawa, K. Takahashi, S. Sato and K. Takayama, "X-ray spectra from a characteristic x-ray generator with a molybdenum tube," *Ann. Rep. Iwate Med. Univ. Sch. Lib. Arts Sci.*, **40**, 1-7, 2005.
16. E. Sato, K. Sato, T. Usuki 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.