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Development of a Rotating X-ray Shutter for Coronary Angiography Using Synchrotron Radiation

Yasunari Oku,[a,b]* Kazuyuki Hyodo,[a,c] Masami Ando[a,c] and Junichiro Tada[d]†

[a]The Graduate University for Advanced Studies, KEK, Tsukuba, Ibaraki 305, Japan, [b]Kanto Technical Institute, Kawasaki Heavy Industries Ltd, Noda, Chiba 278, Japan, [c]Institute of Materials Structure Science, High Energy Accelerator Research Organization, Tsukuba, Ibaraki 305, Japan, and [d]Safety Control Division, JASRI, Kamigori, Ako, Hyogo 678-12, Japan. E-mail: oku_yasunari@now.khi.co.jp

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The first clinical examination using a two-dimensional imaging system of coronary angiography with monochromated synchrotron radiation was carried out at the National Laboratory for High Energy Physics in May 1996. A rotating X-ray shutter was developed to produce a pulsed X-ray beam with 2–6 ms of beam spill to suppress image blurring, at a frequency of 30 Hz. A performance test of the X-ray shutter using synchrotron radiation was carried out, and it was verified that the shutter had satisfactory specifications for clinical applications. With this X-ray shutter the monitored radiation dose in clinical examinations was consistent with theoretical expectations and kept within a reasonable level of radiation protection.

Keywords: coronary angiography; dynamic imaging; radiation dose; pulsed X-ray beams; clinical examinations.

1. Introduction

Studies of coronary angiography with monochromated synchrotron radiation are being carried out throughout the world. In the USA, Germany and Russia, a sheet-type beam coupled to a linear position detector is used, so that patients are moved vertically in synchronization with contrast agent flow in coronaries (Rubenstein *et al.*, 1986; Dix *et al.*, 1989; Dementyev *et al.*, 1989). On the other hand, in this study, a two-dimensional imaging system is used (Hyodo *et al.*, 1991) at the High Energy Accelerator Research Organization (KEK). Upon termination of basic studies in July 1995, construction of a system for clinical applications was started in May 1996 (Hyodo *et al.*, 1998). The first clinical application using the two-dimensional imaging system with synchrotron radiation was carried out at the TRISTAN accumulation ring (AR) of KEK as a collaboration between KEK and the University of Tsukuba (Ohtsuka *et al.*, 1998). An image intensifier and TV (II-TV) system was adopted as an X-ray detector. The TV system reads one image in a period of 1/30 s; on the other hand, the irradiation period of X-rays per image must be in the range 2–6 ms because motional blur of images due to the heart beating must be avoided. Thus, an X-ray shutter, a system to produce a periodically pulsed X-ray beam, is necessary for clinical applications. The shutter must also prevent the passage of unnecessary radiation (Zeman *et al.*, 1983). We have developed a rotating X-ray shutter which allows X-rays to pass through for 2–6 ms and interrupts their passage during other ineffective periods. Readout of the TV system starts with the trigger pulse of the shutter so as to synchronize the timing of the X-ray pulse.

† Previous affiliation: Institute for Basic Medical Sciences, University of Tsukuba, Tsukuba, Japan.

2. Principle

Iodine, whose *K*-edge energy is 33.17 keV, is generally used in angiography, and is also used as the contrast material for coronary angiography with synchrotron radiation. Monochromatic X-rays, of energy just above that of the *K*-edge of iodine, are used, because the difference between the mass-attenuation coefficients of iodine and soft tissue or bone is greater at this energy. In order to make two-dimensional images for coronary angiography, an asymmetric diffraction monochromator is employed (Hyodo *et al.*, 1991) to magnify the vertical X-ray beam size. We arranged the rotating X-ray shutter in front of the monochromator in order to make the hole of the X-ray shutter as small as possible. This X-ray shutter consists of a drum with a radial hole that rotates at 15 rev s^{-1}. X-rays can pass through the hole for 2–6 ms, at a frequency of 30 Hz. The X-ray shutter also generates trigger pulses. We employed three different types of sensors for generating trigger pulses: a photoelectric sensor, a proximity sensor and a digital encoder. Any of these sensors would be sufficient in an extreme case if radiation damage or other mechanical trouble occurred.

3. Design

The shape of the hole in the transaxial plane of the drum is shown in Fig. 1. The design of the shape is described in the following. At the beginning of the irradiation period, t_e, phase (*a*) in Fig. 1, the plane of the hole wall of the drum is parallel to the synchrotron radiation beam axis. Phase (*c*) is the end of the irradiation period. At the end of the transition period, t_t, phase (*d*), synchrotron radiation is completely interrupted by the shutter drum. The shape shown in Fig. 2 is determined so that the X-ray path length in the attenuation material of the drum is as long as possible in the transition period between phase (*c*) and phase (*d*) in Fig. 1. The energy of the X-rays that we used was high and they must be effectively attenuated. By orienting the axis of rotation of the drum perpendicular to the synchrotron radiation beam, effective attenuation of the X-rays is possible, as in the rotation disc shutter designed by LeGrand *et al.* (1989). The effects are that the transition period is halved, and that a large amount of metal can be used to block the beam, rather than the case of setting the axis of rotation parallel to the X-ray beam. The detailed design of the drum is as follows. As the rotating angle in

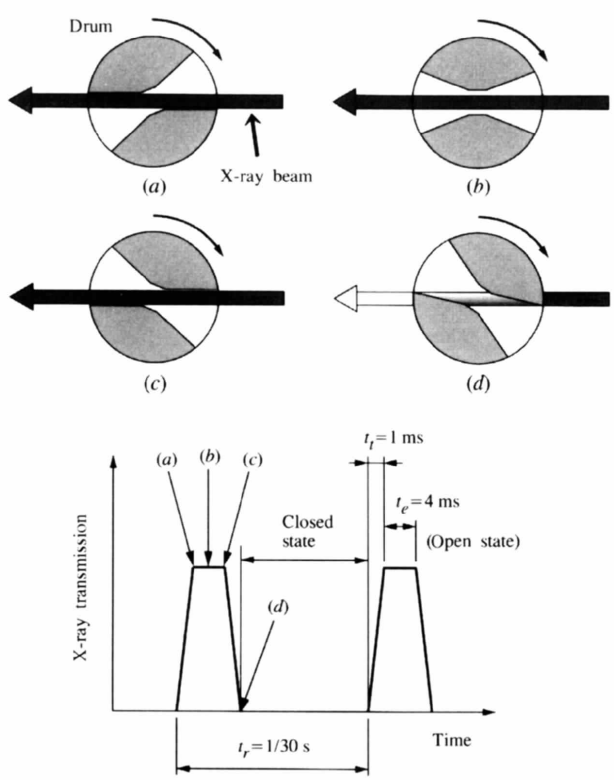

Figure 1
Time-sequence drum rotation. (*a*) Beginning of the irradiation period; (*b*) centre; (*c*) end; (*d*) end of the transition and beginning of complete closing. t_r is the repetitive period of drum half rotation, t_e is the irradiation period of the X-rays, and t_t is the transition period between X-ray passing and stopping.

the transition period, t_t, between phases (*c*) and (*d*) in Fig. 1 is twice the beam-covering angle, θ_b, in Fig. 2, and the rotating angle in the repetitive period, t_r, is π, θ_b is related to t_t and the repetitive period, t_r, as

$$2\theta_b = t_t\pi/t_r. \tag{1}$$

The radius of the drum, R, is related to θ_b and the synchrotron radiation beam vertical width, h_b, by

$$R = h_b/2\sin\theta_b. \tag{2}$$

The opening angle of the drum, θ_o, in Fig. 2 is related to θ_b, the irradiation period, t_e, and t_r by

$$2\theta_o = t_e\pi/t_r + 2\theta_b. \tag{3}$$

The opening height of the drum, h_o, is

$$h_o = 2R\sin\theta_o. \tag{4}$$

After a rotation of $\theta_o - \theta_b$ clockwise from the state shown in Fig. 2 (see also Fig. 1*b*), the edge of the drum is parallel to the beam axis (Fig. 1*c*). Thus, the cutting angle of the drum, θ_c, is

$$\theta_c = \theta_o - \theta_b. \tag{5}$$

The medical requirements for the rotating X-ray shutter are as follows: (*a*) the time structure of the X-ray beam is pulsed with a beam spill of either 2, 4 or 6 ms at 30 Hz so that the irradiation is synchronized with the timing of the imaging system; (*b*) in the closed state, the intensity of the 33.17 and 99.51 keV X-rays must be attenuated to less than 10^{-8} of the original photons; (*c*) the transition period, t_t, between the irradiation period and closed state should be less than 1 ms, to ensure that X-rays do not contribute during this period to the images; and (*d*) trigger pulses (TTL signal) should be generated at the start of the irradiation period.

From requirement (*a*), the repetitive period of synchrotron radiation passing through the X-ray shutter, t_r, should be 1/30 s and the irradiation period, t_e, is selected to be 2 ms here. On the other hand, from requirement (*c*), the transition period, t_t, was assumed to be 1 ms.

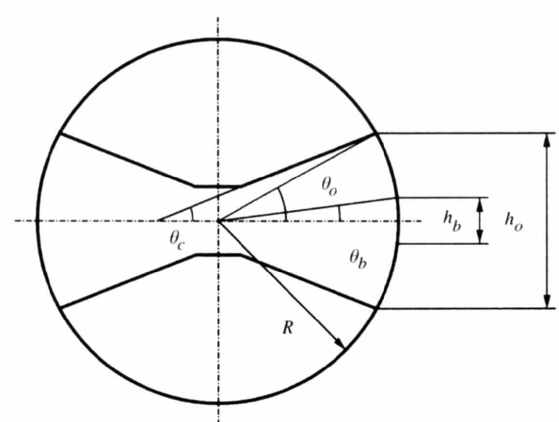

Figure 2
Design parameters of the X-ray shutter drum; see equations (1)–(5).

With the above parameters and the vertical beam width (h_b = 7 mm) of synchrotron radiation of the NE1 beamline at the AR of KEK, the design parameters of the drum were obtained from equations (1)–(5) as follows: $2\theta_b = 3\pi/100$ rad = 5.4°, R = 75 mm, $2\theta_o$ = 0.282 rad = 16.2°, h_o = 21.2 mm, θ_c = 5.4°. As the horizontal beam width was ~80 mm, the opening width of the drum was designed to be 90 mm. Two other types of drum for 4 and 6 ms pulse widths were also designed. We employed stainless steel SUS304 as the material for the drum. Passing through this drum, the 33.17 keV X-rays attenuated to less than 10^{-100}, and the third harmonic at 99.51 keV is attenuated to less than 2.2×10^{-18} in the closed state. The third harmonic arises from the (311) reflection from the silicon-crystal monochromator (Konishi *et al.*, 1985). The arrangement of the system including motors and sensors is shown in Fig. 3. The rotation of the drum is driven by a variable-speed motor. In order to synchronize the readout start timing of the CCD camera of the II-TV system with the start timing of the X-rays passing through the X-ray shutter, the trigger pulses must be generated by the X-ray shutter controller. As noted above, three sensors are used for generating trigger pulses. The photoelectric sensor intercepts a laser beam which passes through a radial hole in the disc. The proximity sensor identifies a recess cut on the edge of the disc. These discs are attached to both sides of the drum as shown in Fig. 3. Both sensors provide a signal just before the opening position of the X-ray shutter. A pulse motor (Fig. 3) rotates the shutter drum to the closed state when the X-ray shutter is stopped. Even if the X-ray shutter system is stopped by mechanical accidents, the shutter drum must be closed promptly in order to avoid unnecessary irradiation to the patients.

4. Safety analysis for thermal load

Analysis of the drum for an accidental thermal load had to be carried out in order to confirm its safety. The thermal investigation was carried out using the program code *ANSYS* (SAS IP, Inc.) for finite-element analysis. Con-

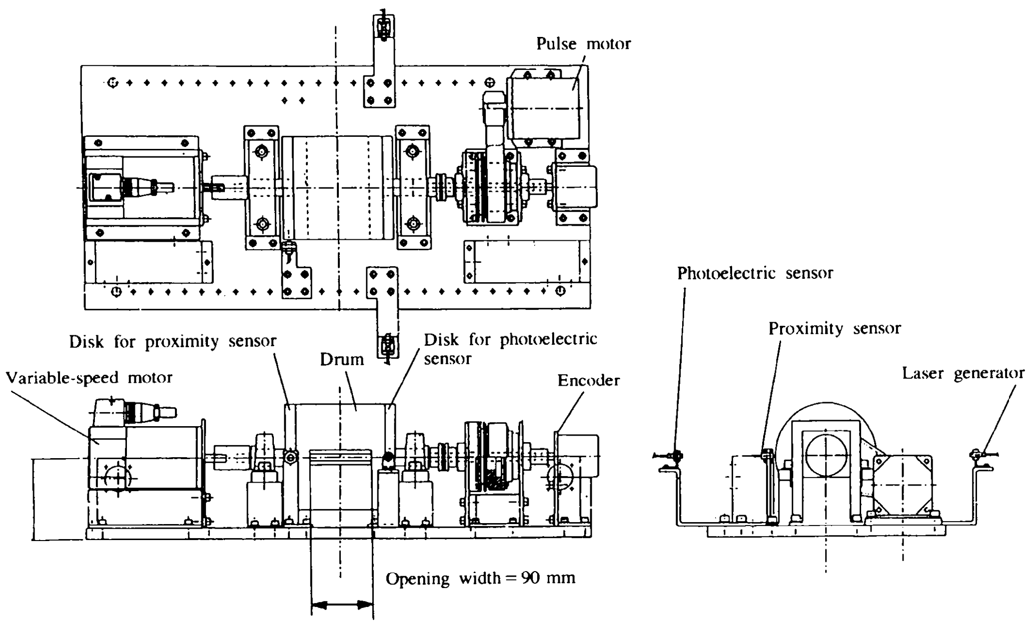

Figure 3
The rotating X-ray shutter system.

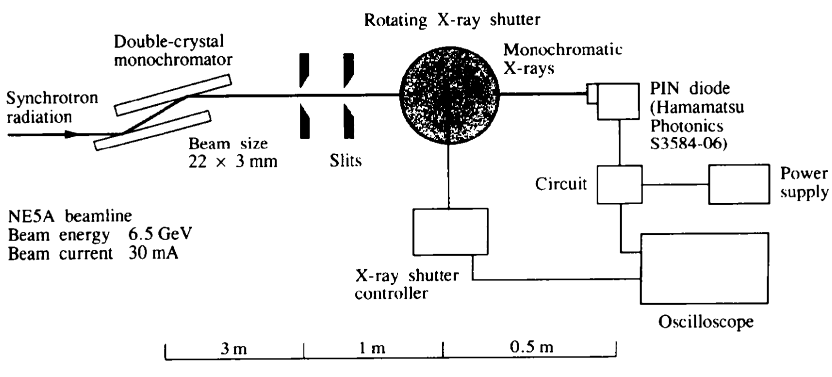

Figure 4
Arrangement of the X-ray shutter experiment.

sidering clinical application at the NE1 beamline of the AR of KEK, the total power of the synchrotron radiation was assumed to be 2.96 kW when the beam energy was 5.0 GeV at a current of 70 mA and a wiggler magnetic field of 0.93 T. As 2.01 kW of thermal power is absorbed when passing through three beryllium filters of 0.3 mm thickness and an aluminium filter of 1 mm thickness of the NE1 beamline, the remaining power of 0.95 kW is absorbed at the X-ray shutter drum. The maximum temperature of the drum in the steady state was estimated at 1570 K if all preceding X-ray shutters fail, and thus the full beam continuously irradiates the stopped X-ray shutter drum. In this calculation, thermal emission and natural conventional heat transfer are considered. As the melting point of SUS304 is ~1683 K, the X-ray shutter drum will not melt.

5. Experiment

The NE5A beamline of the AR of KEK was used to verify the synchronization between the passing of X-rays through the shutter and the sending of the trigger pulses. Synchrotron radiation was monochromated to 33.17 keV X-rays by a silicon (111) double crystal. The X-rays transmitted by the X-ray shutter were detected by a PIN diode (Hamamatsu Photonics, S3584-06), as shown in Fig. 4. Signals from the PIN diode were compared with those of a trigger pulse from the rotating shutter. By adjusting the trigger pulse delay, the X-ray pulse and the trigger pulse could be synchronized completely. In the experiment at the NE5A beamline, t_e was 4.6 ms, because of the difference of beam heights, h_b(3 mm at the NE5A beamline, while the expected period was 4.0 ms for 7 mm at the NE1 beamline).

6. Clinical application

The rotating X-ray shutter was installed in the NE1 beamline (Hyodo *et al.*, 1998; Ohtsuka *et al.*, 1998) for clinical applications (Fig. 5). Synchrotron radiation was monochromated by the silicon crystal, after passing through the rotating X-ray shutter. A photon energy of 35 keV was selected for the clinical examinations because of the relatively lower photon numbers at the third harmonic. A parallel-plate ionization chamber consisting of 3 × 25 μm of Mylar and 100 μm of acetate film was inserted into the beamline to monitor the irradiation just upstream of the patient. The monochromatic X-rays transmitted by the ionization chamber and the patient were detected by the imaging system. The monitoring measures the skin dose of the patient. If the dose exceeds the prescribed value, the 'dose interlock system' interrupts the ring current immediately.

Table 1
Parameters in the clinical application (Hyodo *et al.*, 1998).

Beam energy of the TRISTAN accumulation storage ring	5.0 GeV
NE1 wiggler gap	40 mm
Monochromatic X-ray beam energy	35 keV
X-ray beam size magnification by asymmetric monochromator diffraction	17.4
Al, Be filter thickness and air pass length	1 mm, 0.9 mm, 5000 mm
Average reflection ratio of monochromator	45%
Energy bandwidth of monochromatic X-rays	0.3%
Device type	Multipole wiggler (43-pole)
Device magnetic field	0.79 T
Critical energy of synchrotron radiation	13 keV
Original beam size of synchrotron radiation before the shutter	80 (W) × 7 (H) mm

The exposure of monochromatic photons, X (C kg^{-1}), is

$$X = \Psi_\gamma(\mu_{en}/\rho)_{air} e/W_{air}, \qquad (6)$$

where Ψ_γ is the energy fluence of photons (J m^{-2}), $(\mu_{en}/\rho)_{air}$ is the mass–energy absorption coefficient of air (m^2 kg^{-1}), e is the elementary electric charge, and W_{air} is the W value of air (J).

The energy fluence, Ψ_γ, of monoenergetic photons is

$$\Psi_\gamma = h\nu\varphi t, \qquad (7)$$

where $h\nu$ is the photon energy (J), φ is the photon fluence rate (photons s^{-1} m^{-2}), and t is the irradiation period (s).

The exposure per image and per normalized storage ring current (1 mA) can be calculated by the above equations in units of C kg^{-1} image^{-1} mA^{-1}.

As the calculated photon fluence rate of the X-rays whose energy was 35 keV per 1 mA of ring storage current in front of the ionization chamber was 2.4×10^{14} photons m^{-2} s^{-1}, the calculated value of exposure with 4 ms of irradiation period per image was 1.4×10^{-6} C kg^{-1} image^{-1} mA^{-1}, while the monitored values of the exposure ranged from 1.0×10^{-6} to 1.3×10^{-6} C kg^{-1} image^{-1} mA^{-1}. Parameters in the clinical application are shown in Table 1. As the average value of monitored exposure was about 20% less than the estimated value from photon fluence, we found that the rotating X-ray

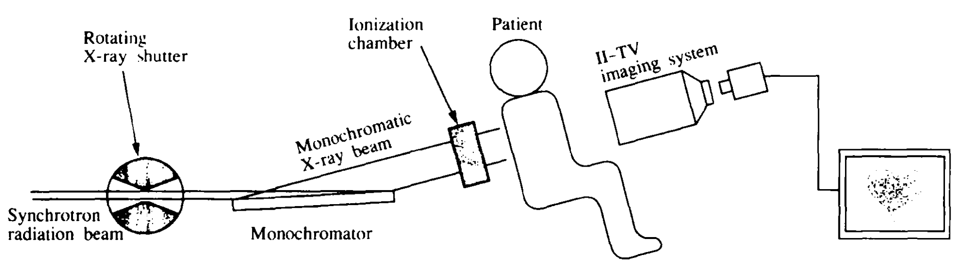

Figure 5
Arrangement for the clinical application of synchrotron radiation coronary angiography (Hyodo *et al.*, 1998).

shutter worked properly and retained the patient dose at the design value.

The images for diagnosis were taken without motional blur by heartbeat and flicker arising from a time lag between the X-ray pulses and the image reading of the TV system in the clinical applications (Hyodo *et al.*, 1998; Ohtsuka *et al.*, 1998).

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