Proposal of Optimized Intravenous Coronary Angiography System Using Two-Dimensional Monochromatic Synchrotron Radiation

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CONTENTS

1. Introduction

1-1 Availability of coronary angiography with the intravenous injection of a contrast agent using 2D-SR

Heart disease is the largest cause of death in the U.S., while it is the third in Japan, the percentages of which are 60% and 15%, respectively. That number is increasing in Japan due to a westernization of the diet. Furthermore, ischemic heart disease provides poor subjective symptoms in the early stage, even though there exists an important stenosis in the coronary arteries, and 50% of all patients can not be helped after reaching the stage of certain symptoms. Therefore, the early discovery of heart disease is of vital importance for any successful treatment to save the patient's lives. Periodic medical examinations of the heart are desired. Such examinations will give significant benefit to society.

For the diagnosis of ischemic heart disease, coronary angiography is effective. It can directly provide effective information for diagnosis. However, the arterial catheterization procedure, which is commonly used in hospitals as a coronary angiography method, requires skilled technique and the hospitalization of patients. Furthermore, it has some risks due to the injection of a catheter into the coronary artery through a thigh artery. Also heart specialists and technicians who handle emergency equipment must wait for treatment due to occurrence of an accident. Thus, periodic examinations such as for screening seems impossible using this procedure.

If the coronary angiography is carried out by intravenous injection, the examination could be carried out more safely and simply. Thus, it could be applied to a screening examination for heart diseases. However, since the contrast agent is diluted until reaching the coronary arteries, distinct images for a successful diagnosis would not be obtained.

The K-edge subtraction method is useful for resolving this problem. In this method, a subtraction image is generated between two images taken by monochromatic x-rays just above and below of K-edge of the contrast agent (iodine), and gives high-contrast images of the blood vessels without images of soft tissues or bones. The mass-attenuation coefficient of iodine, bone and soft tissue

as a function of the x-ray photon energy is shown in Fig. 1. Although this method is expected to be effective for intravenous coronary angiography, it has not been put in practical use because of insufficient intensity and energy resolution of the usual x-ray sources. Monochromatized synchrotron radiation with such intense x-rays is expected to be applied to clinical use of the intravenous coronary angiography method.

The K-edge subtraction method using synchrotron radiation was proposed first by E. Rubenstein of Stanford University et al. in 1981 (Rubenstein E. et al. 1981). The development of the systems and studies are being carried out not only in the U.S., but throughout the world. A sheet-type beam (one-dimensional imaging) coupled to a linear-position detector has been used in the U.S. (Hughes E. B. et al. 1983, Suortti P. et al. 1988, Thomlinson W. et al. 1988, Thompson A. C. et al. 1989, Rubenstein E. et al. 1990), Germany (Dix W. -R. et al. 1986, Dix W.-R. et al. 1989) and Russia, (Dementyev E. N. et al. 1986, Dementyev E. N. et al. 1989) while in Japan, a two-dimensional dynamic imaging system has been adopted (Akisada A. et al. 1986, Fukagawa H. et al. 1989, Nishimura K. et al. 1989, Hyodo, K. et al. 1991, Hyodo K. et al. 1992) at the High Energy Accelerator Research Organization (KEK).

Recently, only monochromatic x-rays whose energy is just above the energy of the K-edge of iodine are being used without K-edge subtraction in a basic study of SR coronary angiography in Japan, and, finally, in clinical applications in May 1996 (Hyodo K. et al. to be published, Ohtsuka S. et al. to be published). This is because the difference in the mass-attenuation coefficient between iodine and soft tissue or bone is relatively big at this energy, and distinct images were obtained without subtraction in an animal experiment using a goat without K-edge subtraction. (Ohtsuka S. et al. 1997)

1-2 Merits and demerits of 2D-SR coronary angiography

Dynamic imaging using a two-dimensional imaging system is very useful to see the blood flow through coronary arteries on the heart. Furthermore, not only structural diagnosis by using time-sequential images, but also diagnosis of the heart functions are possible. However, it has been pointed out that the exposure

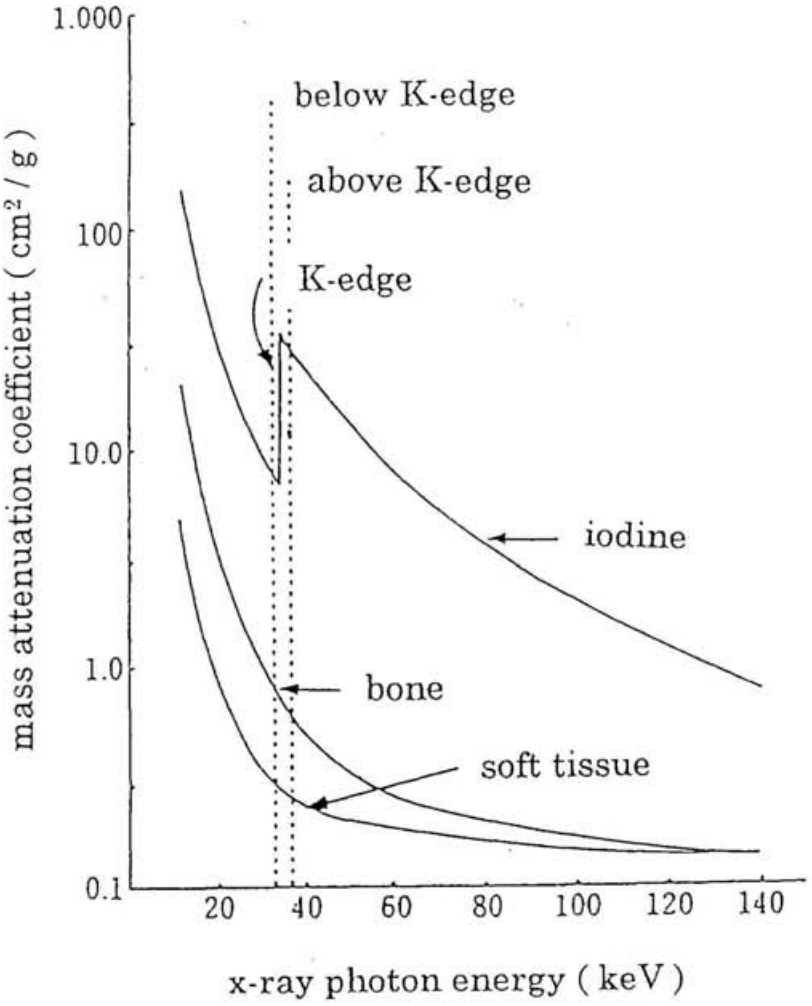


Fig. 1 Mass-attenuation coefficient of x-rays as a function of the photon energy

area covering the whole heart sight is so wide that a scattering of x-rays from a patient's body may cause a deterioration of the image contrast and visibility, as in Fig. 2. X-ray grids are effective for suppressing scattered x-rays. They are commonly used in hospitals when x-ray examinations are performed. The x-ray grid is a plate piled up with thin wood and lead alternately, which stops the scattered x-rays by the lead but allows the primary x-rays to pass through the wood, as in Fig. 3. Thus, it is expected to improve images by suppressing scattered x-rays also in the case of clinical coronary angiography using a monochromatic SR beam.

The image contrast is also deteriorated by the inevitable third higher harmonic diffracted by a monochromator crystal (Konishi K. et al. 1985) as well as scattered x-rays. Since the third higher harmonic and scattered x-rays can not be distinguished on image data, a simulation is very effective for identifying its influence on the deterioration of the image contrast.

In order to see the deterioration of image quality due to scattering and the third higher harmonic, a simulation program for them has been developed (Oku Y. et al. 1995), and their characteristics were investigated.

On the other hand, since a series of images is taken in dynamic imaging, the radiation dose per examination must be relatively larger than that of one-dimensional imaging. Thus, the dose should be suppressed to be as physically small as possible. An Image Intensifier-TV (II-TV) was adopted as an x-ray detector in two-dimensional SR coronary angiography. The TV system reads one image during a period of 1/30 sec; on the other hand, the irradiation period of x-rays per image must be in the range of 2 to 6 msec, because any motional blur of the images due to heart beating must be avoided. Also, continuous and unnecessary irradiation of the x-rays must be avoided. Therefore, SR x-rays should be a pulsed beam with 2～6 msec of beam spill, leading to suppressing any image blurring at a frequency of 30 Hz.

1-3 Studies for improving the image contrast and suppressing of the radiation dose

The merits and demerits of intravenous injection and intra-arterial injection

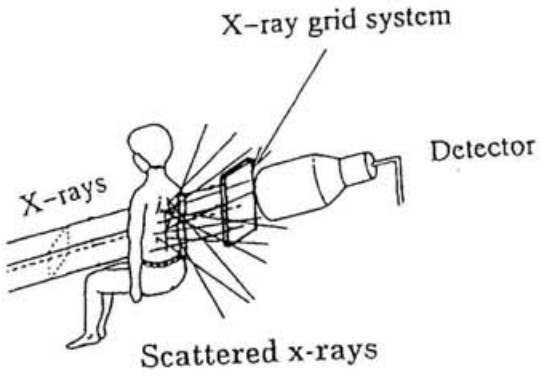


Fig. 2 Scattered x-rays generated when passing through a patient's body. An x-ray grid can suppress them.

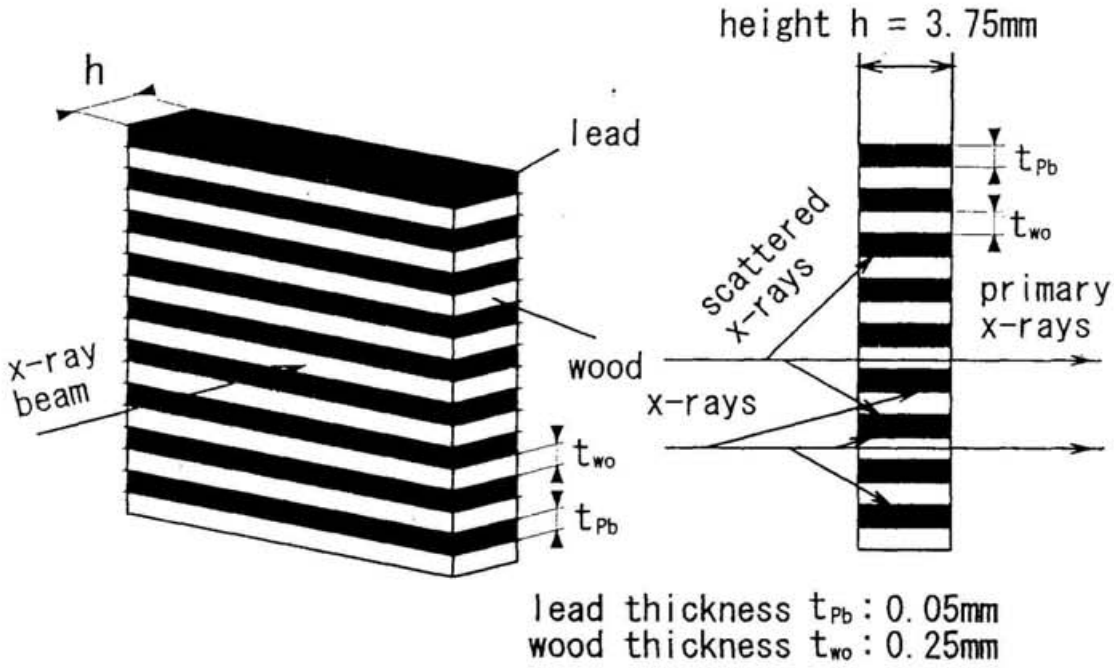


Fig. 3 Structure of the x-ray grid and effect of suppressing scattered x-rays
The x-ray grid is a plate piled up with thin wood and lead alternately, which stops the scattering x-rays, but lets primary x-rays pass through.
The grid ratio $h/t_{wo} = 3.75 / 0.25 = 15$.

of a contrast agent in coronary angiography are given in Table 1, while the merits and demerits of two-dimensional SR coronary angiography and one-dimensional scan method are given in Table 2. In order to make full use of the merits of possible screening examinations as a merit of intravenous injection, constructions of many SR source systems are expected. The arrangement of the SR coronary angiography system is shown in Fig. 4.

From Table 2, it is found that the influence of scattered x-rays must be investigated and an equipment which gives a pulsed SR beam is needed.

1-4 Necessity of a screening coronary angiography system using synchrotron radiation

A realistic intravenous coronary angiography system using SR, which is based on investigations of deterioration of image contrast due to scattered x-rays and the third higher harmonic, its improvement by x-ray grids, in order to avoid of the demerits of two-dimensional coronary imaging, will be needed, if this method is adopted as a screening process. A rotating x-ray shutter for generating a pulsed x-ray beam is also needed in order to suppress image blur and to reduce the skin dose of radiation. A compact radiation source (Wiedemann H. 1985, Wiedemann H. 1988, Oku Y. et al. 1993, Oku Y. et al 1994) will make this method popular. Therefore, the specifications for a practical electron storage ring dedicated to coronary angiography have been fixed on a basis of image-visibility study using the simulation program.

The total photon flux from the source per image is limited by the x-ray shutter. The flux is distributed to the ideal exposure area covering the whole heart sight for coronary angiography. The photon flux per pixel is obtained from the pixel size and photon density in front of the detector. The quantum noise ratio is obtained from the flux per pixel per image, which must be sufficiently small compared to the artery contrast. Thus, the necessary photon flux density at the K-edge of iodine was estimated by quantum noises.

On the other hand, the third higher harmonic at 99.51 keV should be as small as possible in order to avoid any deterioration of the image contrast because of its high transmittance of the contrast agent, and a greater generation of

Table 1 Merits and demerits of intravenous injection and intra-arterial injection of a contrast agent in coronary angiography

	Intravenous injection	Intra-arterial injection
merits	・out patients' examination (screening) possible due to simple method ・small physical load of doctor and patients	・only coronary imaging possible ・clear image
demerits	・dilution of contrast agent ・imaging other blood vessel together	・hospitalization ・high technique ・preparation for emergency

Table 2 Merits and demerits of SR coronary angiography of 2D and 1D imaging

	2D imaging	1D imaging
merits	· dynamic imaging → easy distinction of coronary → heart function diagnosis possible → certain timing of contrast agent flowing in coronary	· small scattering x-rays onto detector · smaller dose for one examination · large dynamic range of detector
demerits	· many scattered x-rays onto detector · more dose for one examination	· fixed imaging by patient's scan → patient's motion necessary → difficulty of timing of contrast agent flowing in coronary

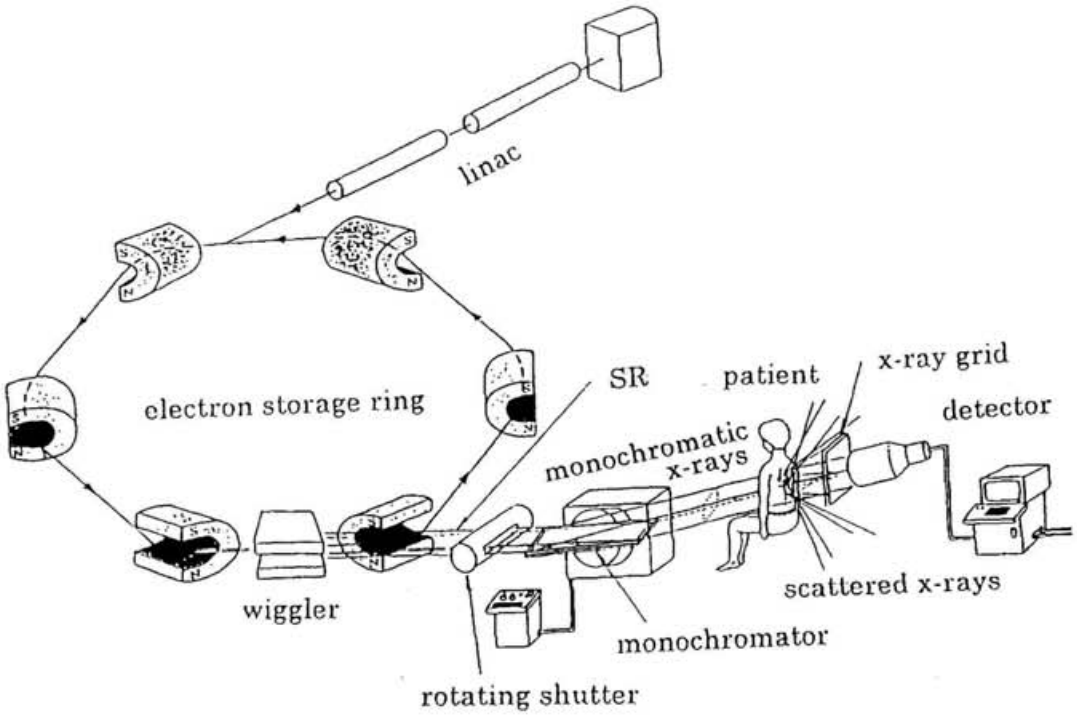


Fig. 4 Constitution of the coronary angiography system using synchrotron radiation

scattered x-rays than that by the x-rays at the iodine K-edge energy of 33.17 keV. Thus, by this study of the simulation program, the limitation of the ratio of the third higher harmonic, 99.17 keV over 33.17 keV, was obtained.

An appropriate beam energy of a storage ring and parameters of an insertion device as a radiation source was determined.

The necessary beam current and the number of poles of the insertion device have been fixed from the necessary photon-flux density of x-rays at the K-edge of iodine. The conceptual design of the dedicated ring was carried out by the program SAD (Oide K. et al. since 1986) . Finally, a consideration of the other system factors, such as optical elements, detectors, contrast agent and the location of a detector was also taken for a complete coronary angiography system. The whole system factors are described in chapter 4.

2. Simulation of image contrast

2-1 Simulation program

A simulation program using the Monte Carlo method has been developed, in order to study influence of the scattered x-rays and the third higher harmonic on images for medical diagnosis and effect of suppressing scattered x-rays by x-ray grid insertion. The simulation concept is shown in Fig. 5. An acrylic block was used as a simple model of a patient's body. In the program, x-ray photons are injected repeatedly into the acrylic phantom. Basic flow chart of the program is shown in Fig. 6. Two-dimensional image simulation model is shown in Fig. 7. The phantom comprises an acrylic block with a hollow tube analogous to a coronary artery filled with iodine diluted by water. The monochromatic incident x-rays are primarily 33.17 keV and 99.51 keV as the third higher harmonic, and uniformly distributed as a two-dimensional beam. The x-ray grid is inserted between the phantom and the detector, if it is used. Coherent scattering, incoherent scattering, photoelectric effect, and fluorescence x-ray generation by photoelectric effect were considered. The photon energy ranges from 10 to 100 keV. Photon free path was calculated as in the next equation: (Nakamori N. et al. 1980)

$$r = -\frac{1}{\mu_0(E_0)} \ln R \,, \qquad (1)$$

where R is (0,1) uniform random number, μ_0 is total x-ray attenuation coefficient of coherent scattering and incoherent scattering, as a function of the photon energy E_0. The attenuation functions due to each interaction of x-rays were calculated by polynomial expression made from data of XCOM (Berger M. J. et al. 1987). Differential cross sections are given by the following equations (Nakamori N. et al. 1981, Namito Y. et al. 1993) which were modified from formula of Thomson scattering and Klein-Nishina formula, where θ is the polar angles (see Fig. 8) of coherent scattering and incoherent scattering :

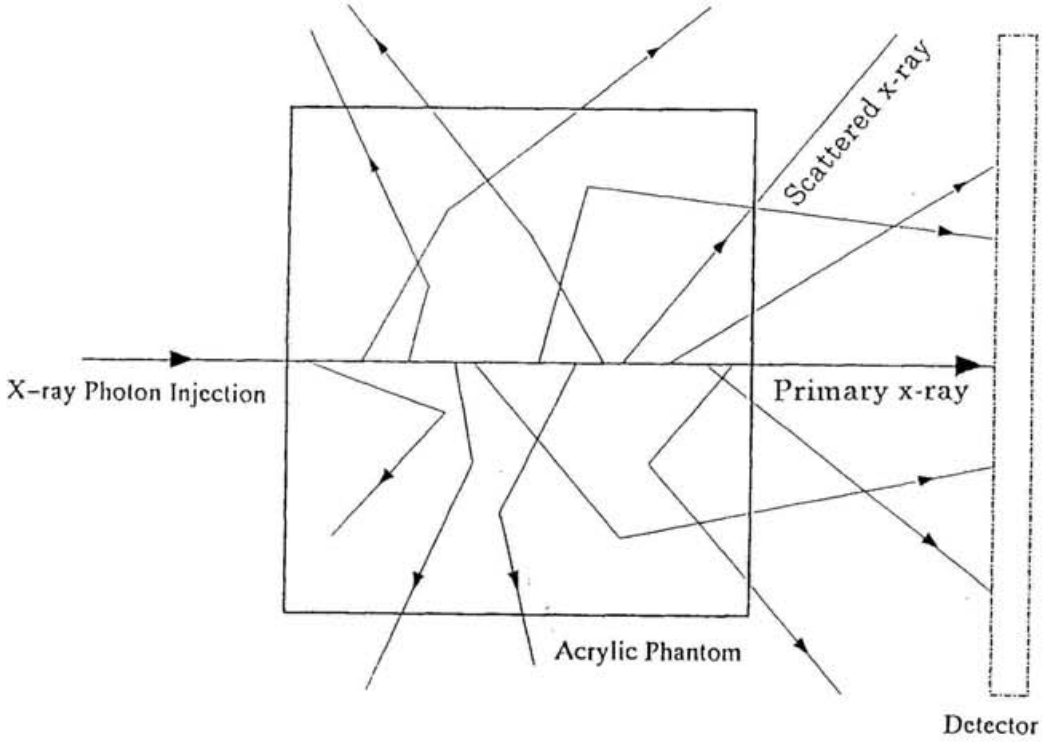


Fig. 5 Monte-Carlo simulation model of scattering x-rays

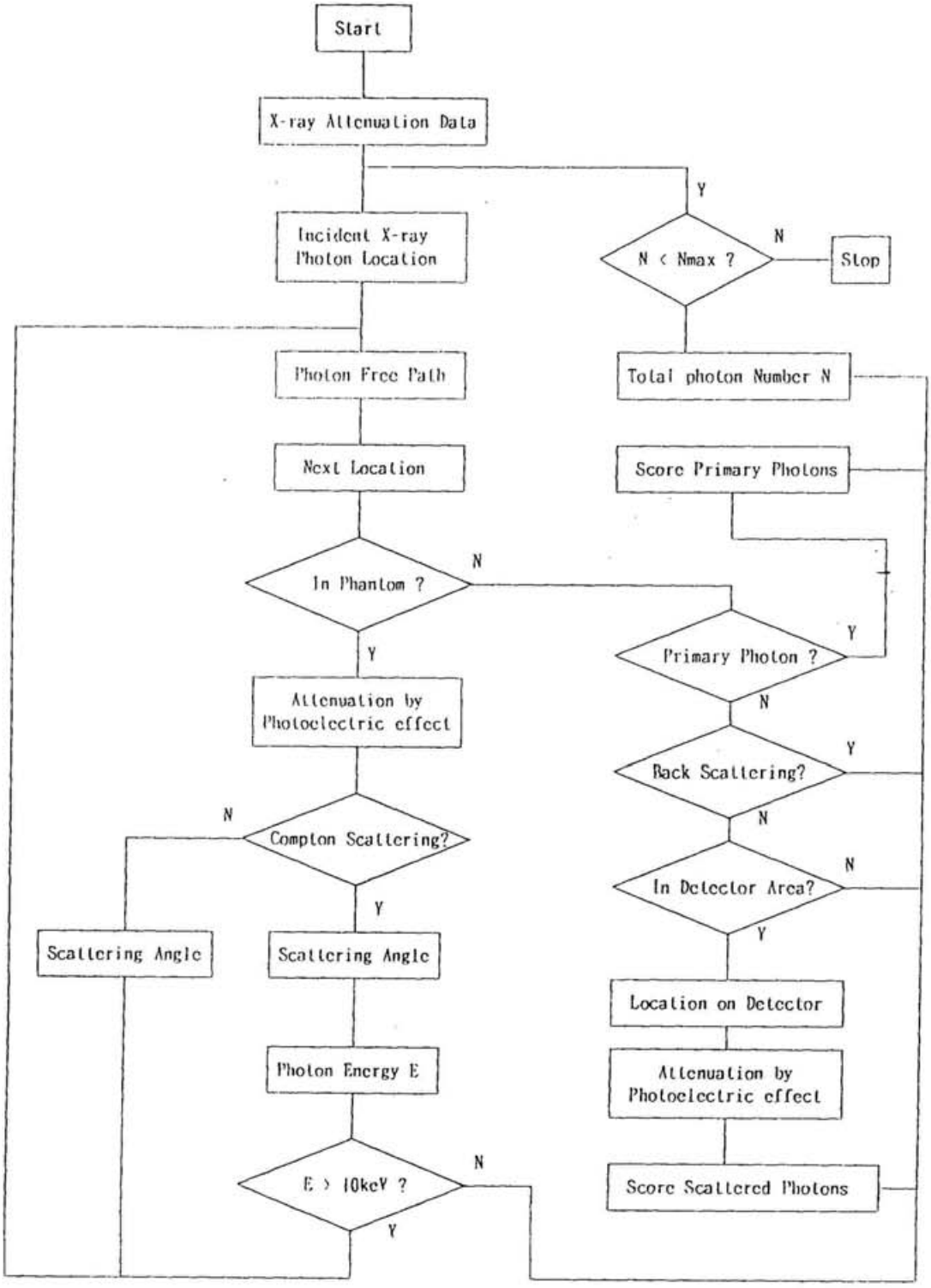


Fig. 6 Flow chart of the scattering x-ray simulation program

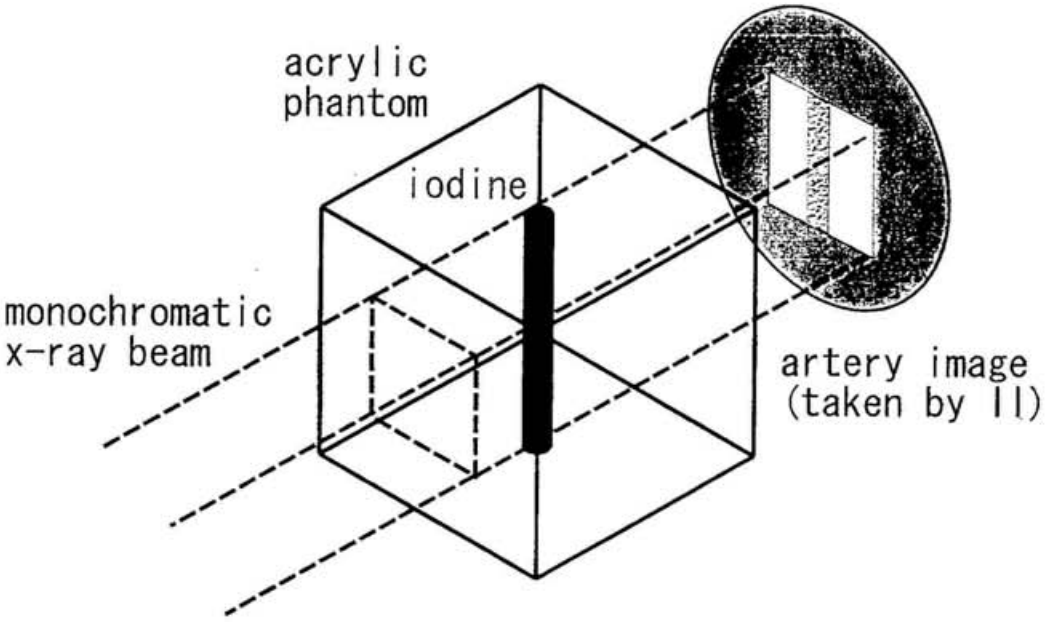


Fig. 7 Model of the two-dimensional image simulation program
The phantom is an acrylic block with a vessel which imitates a coronary artery and contains iodine diluted by water as a simple model of a patient's body and coronaries. In the program, x-ray photons are injected repeatedly into an acrylic phantom as a uniformly distributed two-dimensional beam and photons arriving on the detector plane are integrated as matrix data.

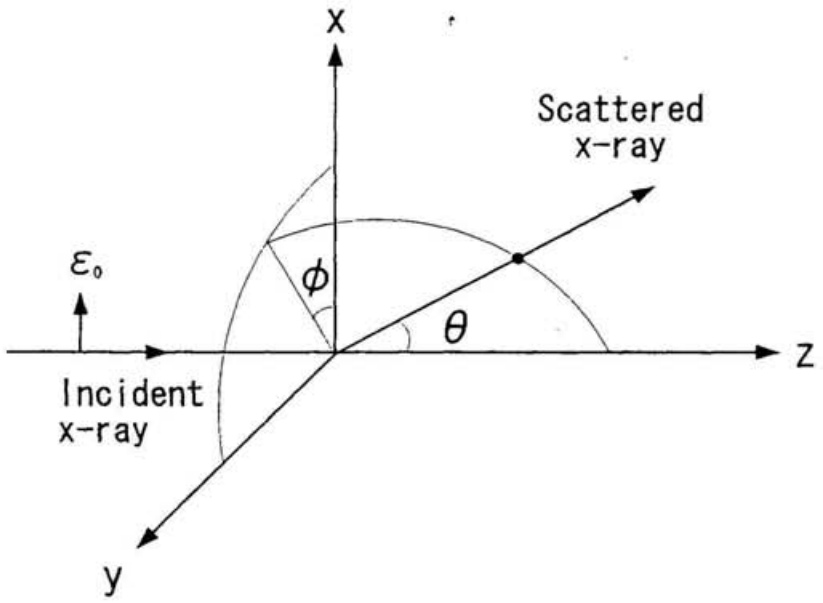


Fig. 8 Scattering polar angle θ and scattering azimuth angle ϕ from the plane of polarization vector ε_0

$$\left(\frac{d\sigma}{d\theta}\right)_{coh} = \frac{r_e^2}{2}(1+\cos^2\theta)\cdot 2\pi\sin\theta\cdot\left[F(x,z)\right]^2 \quad , \tag{2}$$

$$\left(\frac{d\sigma}{d\theta}\right)_{incoh} = \frac{r_e^2}{2}\left(\frac{E}{E_0}\right)^2\left(\frac{E}{E_0}+\frac{E_0}{E}-2\sin^2\theta\right)\cdot 2\pi\sin\theta\cdot S(x,z) \tag{3}$$

where r_e is the classical electron radius and E is the photon energy after incoherent scattering expressed by the next equation;

$$E = \frac{E_0}{1+\gamma\,(1-\cos\theta)} \quad , \tag{4}$$

where

$$\gamma = \frac{E_0}{m_0 c^2}$$

m_0c^2 is the rest mass energy of electrons, F(x,Z) and S(x,Z) are called the atomic form factor and the incoherent scattering function, respectively; they function as a value of x expressed by scattering polar angle θ, photon wavelength λ (Å) and atomic number Z of the subject, as following equation;

$$x = \frac{\sin(\theta/2)}{\lambda} .$$

They are given in the table (Hubbell J. H. et al. 1975). In the simulation program, when these scattering occur after a photon passes the distance given by Eq. (1), the scattering angles are decided by random numbers whose birth probability distribution is in proportion to the above differential cross sections as an angle of photon scattering using Eq.(2)(3).

Scattering azimuth angle from the plane of polarization vector ϕ (see Fig. 8) is determined in the same way by Eq.(5) and (6), they give differential cross sections against solid angle (Ω) of the coherent scattering and the incoherent

scattering with substitution of scattering polar angle θ obtained from Eq.(2) and (3) (Namito Y. et al. 1993),

$$\left(\frac{d\sigma}{d\Omega}\right)_{coh} = r_e^{\,2}(1 - \sin^2\theta \cdot \cos^2\phi) \tag{5}$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{incoh} = \frac{r_e^{\,2}}{2}\left(\frac{E}{E_0}\right)^2\left(\frac{E}{E_0} + \frac{E_0}{E} - 2\sin^2\theta \cdot \cos^2\phi\right) \tag{6}$$

The attenuation by passing through the subject is calculated from the total path length and the value is memorized as each photon reaching the detector. This program gives photon location on the detector, photon energy and attenuation by photoelectric effect. The number of these photons are added to memorize for each pixel located on the detector, and two-dimensional simulation images are generated as digital matrix data.

2-2 Experiments for verification of the simulation program

2-2-1 Scattered x-rays and their injection into the detector

Two experiments have been carried out in order to verify the simulation program. One experiment was held using 33.17 keV monochromatic x-ray from a silicon (111) double crystal monochromator using SR at NE5A beamline of accumulation ring (AR) in KEK. An acrylic block whose thickness was 200 mm as an x-ray scattering matter. An imaging plate (IP) with size of 200 mm wide and 250 mm high was used as an x-ray detector. The arrangement of the acrylic phantom and the IP is shown in Fig. 9. The x-ray beam whose size was 14 mm wide and 2 mm high was injected to the acrylic.

The specifications of the x-ray grid were as follows: The path length of the grid in the direction of passing x-rays is 3.75 mm, the thickness of wood sheet was 0.25 mm and the thickness of lead sheet was 0.05 mm as in Fig. 3. The simulation of x-ray scattering has been carried out under the same conditions as in the experiment. The number of incident photons in the simulation was 10^6 photons, because the ratio of scattered x-rays per 33.17 keV primary photons close

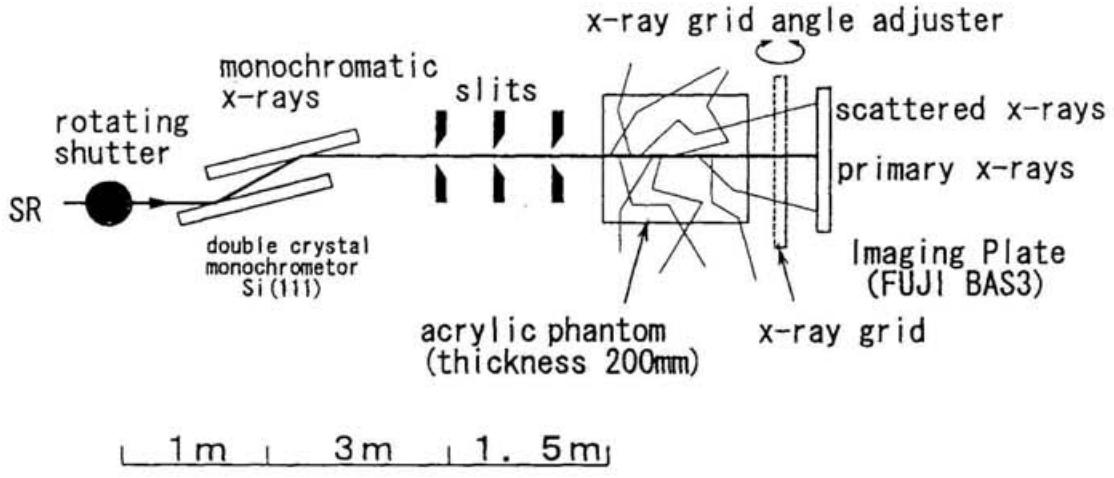


Fig. 9 Arrangement of the experiment to verify the ratio of the scattered x-ray photon flux against the direct x-rays calculated by the simulation program
A silicon (111) double crystal monochromator, an acrylic block whose size was 200 mm long, 250 mm wide, and 250 mm high as x-ray scattering matter and an imaging plate whose size was 200 mm wide and 250 mm high as an x-ray detector were used. The injection x-ray beam to the acrylic was cut by x-ray slits to be a sheet-type beam whose size was 14 mm in width and 2 mm in height.

to the fixed value in the error range due to initial random number, as in Fig. 10. In the experiment, 99.51 keV photons, a third higher harmonic, were also diffracted by silicon monochromator (Konishi K. et al. 1985). Thus, simulation results with 99.51 keV incident photons were added to them of 33.17 keV. Furthermore, the simulation results were corrected using the IP response related to the photon energy of the detected x-rays in order to compare with the experimental result exactly. The IP response was calculated by polynomial expression made from the data of M. Ito et al. (Ito M. et al. 1991).

Figure 11 shows a comparison of a ratio of the number of scattered x-ray photons against the number of primary x-ray photons in the center area of 14 mm $\times$2 mm between the simulation and the experiment. The simulation results are in good agreement with the experiment data. The distributions of scattered x-rays and the profiles of the horizontal center lines on IP are shown in Figs. 12 and 13, each of which corresponds to the simulation by the developed program and simulation by program code EGS4 (Nelson W. R. et al 1985), respectively. The image data made by the EGS4 were calculated by Professor H. Hirayama of KEK. The scattered x-ray distributions and profiles of the developed simulation program as well as the result of EGS4 are almost similar to the experimental ones. These results show that the developed simulation program presents the scattered x-rays' behavior well. Furthermore, it was found that the x-ray grid inserted between acrylic and detector was effective for suppressing the scattered x-rays in the case of 127 mm of the distance between acrylic phantom and detector, equivalent to the case of setting the detector from the phantom with distance of 500 mm without the x-ray grid.

2-2-2 Image contrast

The other experiment was held at X-17 B1 beamline of NSLS in Brookhaven National Lab. (BNL) in order to verify property of the image contrast made by the simulation program. An asymmetric lapped silicon (311) crystal was used as a monochromator. An acrylic block with a hole, which imitates a coronary artery whose diameter was from 1 to 5 mm, containing iodine diluted by water and an image intensifier (II) as an x-ray detector were used. The II was the same type as

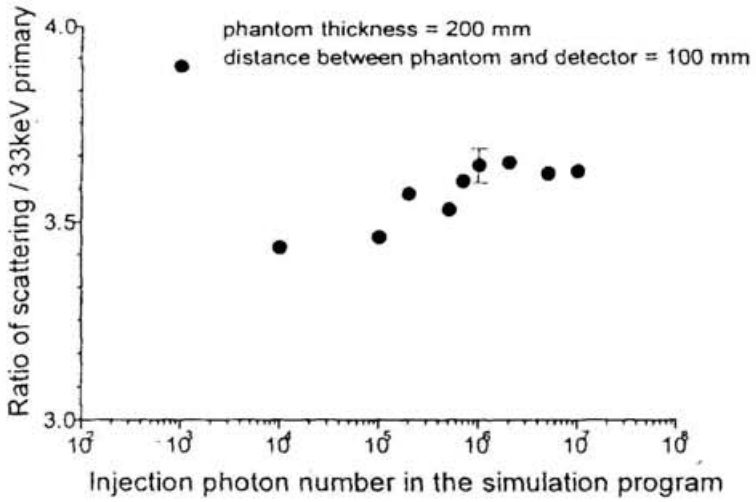


Fig. 10 Ratio of scattered x-rays per 33.17 keV primary photons as a function of injection photon number in the simulation program

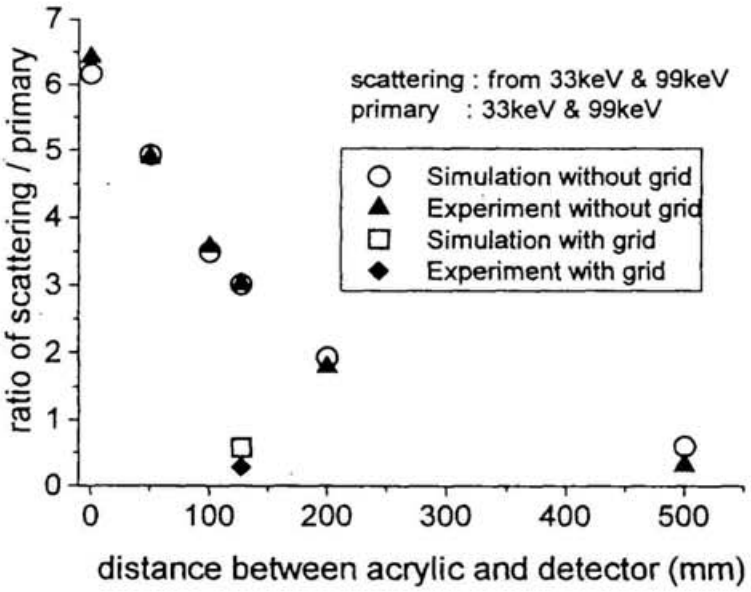
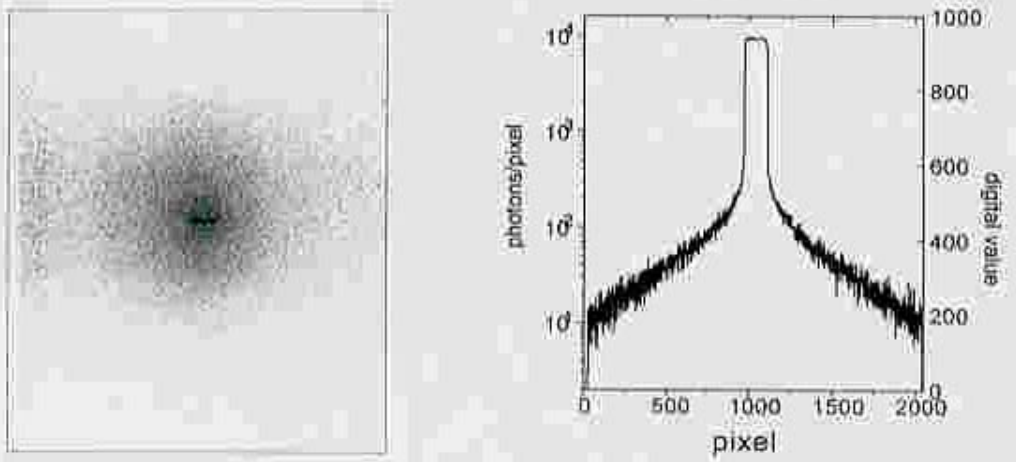
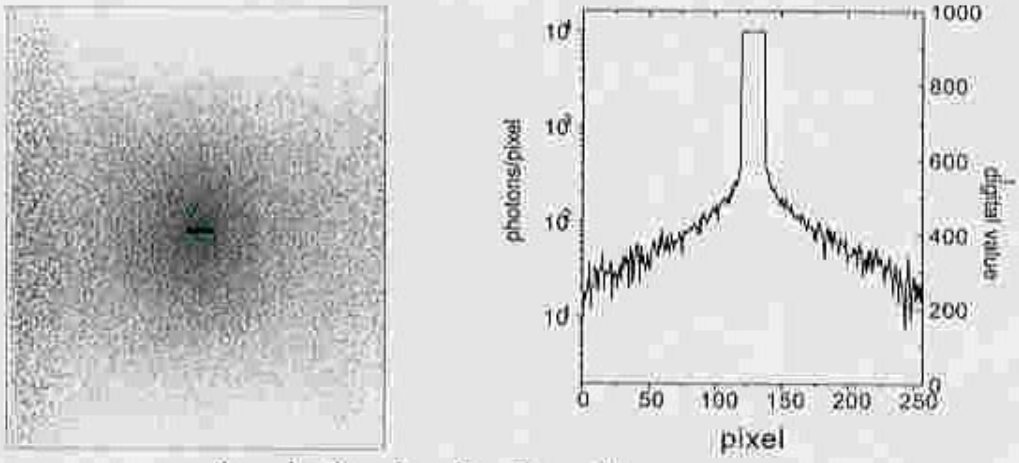


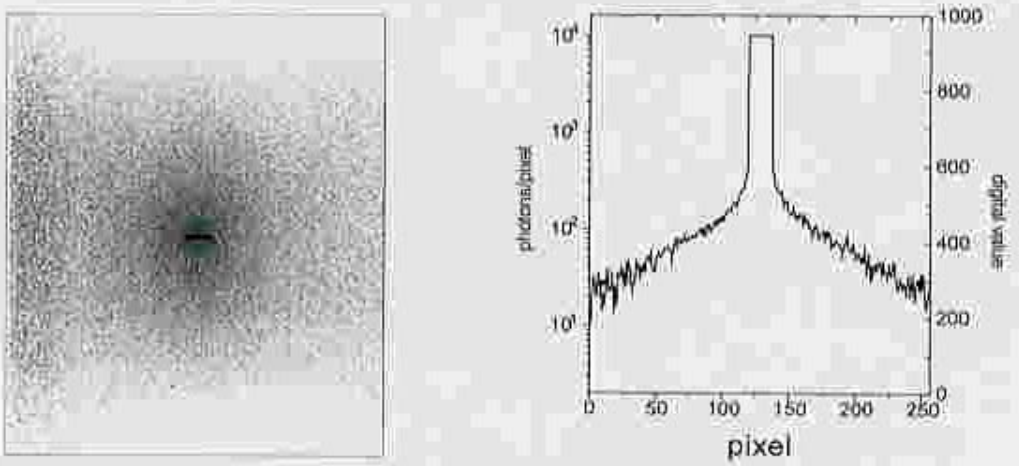
Fig. 11 Comparing result between simulation and experiment of the ratio of the number of scattered x-ray photons per the number of primary x-ray photons as a function of the distance between acrylic phantom and detector (acrylic phantom thickness = 200 mm)



experiment

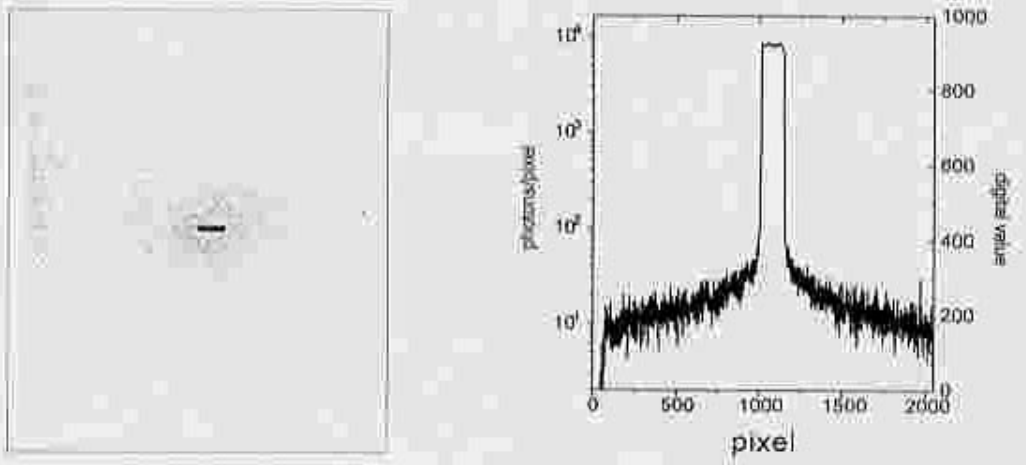


simulation by developed program

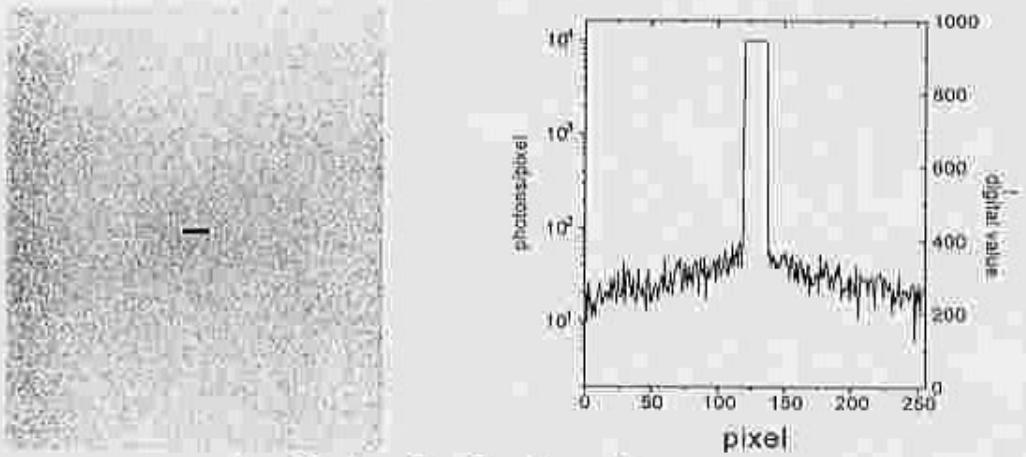


simulation by EGS4

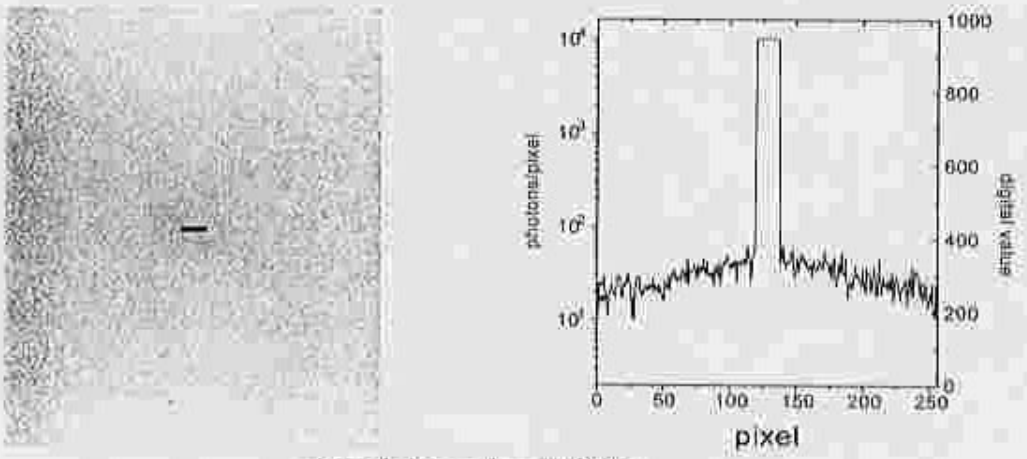
Fig.12 Images of scattered x-ray distributions and their profiles by small beams in the experiment and simulations by the developed program and EGS4. The distance between the phantom and the detector was 0.1 mm.



experiment



simulation by developed program



simulation by EGS4

Fig.13 Images of scattered x-ray distributions and their profiles by small beams in the experiment and simulations by the developed program and EGS4. The distance between the phantom and the detector was 127 mm.

the one used in the clinical application of two-dimensional SR coronary angiography, RTP9211G-G10 made by TOSHIBA (Hyodo K. et al. to be published, Ohtsuka S. et al. to be published). The arrangement of this experiment is shown in Fig. 14. The thickness of the acrylic block was 100 mm, the distance between the acrylic and the detector was 10 mm and the concentration in weight of diluted iodine was 5 %. The experimental images were recorded by a 8 mm video recorder. The analog data of video tapes were transferred to digital data, and analyzed on a personal computer. Fig. 15 shows an example of profile of the image, and contrast against the background is expressed as (a-b)/(a-c). The simulations with the same conditions were carried out considering the II response related to the photon energy, and the contrast were compared between the simulation and the experiment as well as the preceding experiment. Comparing result is shown in Fig. 16 as two-dimensional images, Fig. 17 as image profiles and Fig. 18 as the above contrast value; it was found that the image simulation made images with reasonable contrast .

2-3 Result

2-3-1 Characteristic of x-rays scattered in phantom

As the developed simulation program was verified by comparison with the above two experiments and EGS4 simulation result, it is used for investigations of scattered x-ray characteristics and image contrast with various conditions in this section. The scattered x-rays injected into the exposure area per 33.17 keV and 99.51 keV primary photons of square beam as a function of one side length of beam is shown in Fig. 19. The values were obtained by the developed simulation program. The distance between acrylic and the detector was 100 mm. It was found that scattered x-rays generated from 20% of incident 99.51 keV x-rays against the incident 33.17 keV ones were equivalent to scattered x-rays generated from 33.17 keV x-rays in case where acrylic thickness was 80 mm. In the case of 120 mm, 160 mm and 200 mm of the acrylic thickness, 12%, 7% and 4% of incident 99.51 keV x-rays were equivalent to scattering of 33.17 keV, respectively. The body thickness equivalent to water is 80～120 mm and 160～200 mm, and the length of one side of the exposure area should be 80 mm and 150 mm, in the case

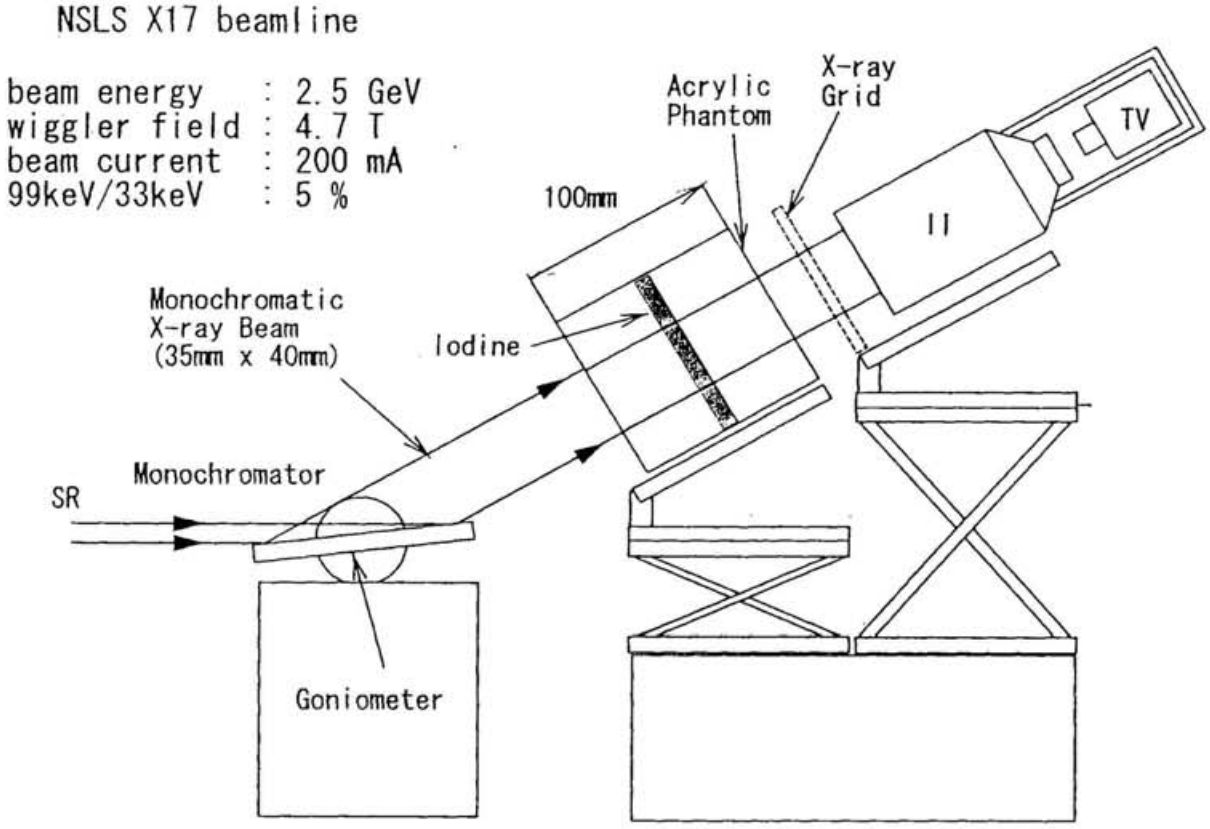


Fig. 14 Arrangement of the experiment to verify the image simulation contrast An asymmetric lapped silicon (311) crystal as a monochromator, an acrylic block with a hole which imitates a coronary artery whose diameter was from 1 to 5 mm and contained iodine diluted by water and an image intensifier as a x-ray detector were used. The thickness of acrylic block was 100 mm, the distance between the acrylic and the detector was 10 mm and the concentration in weight of diluted iodine was 5 %.

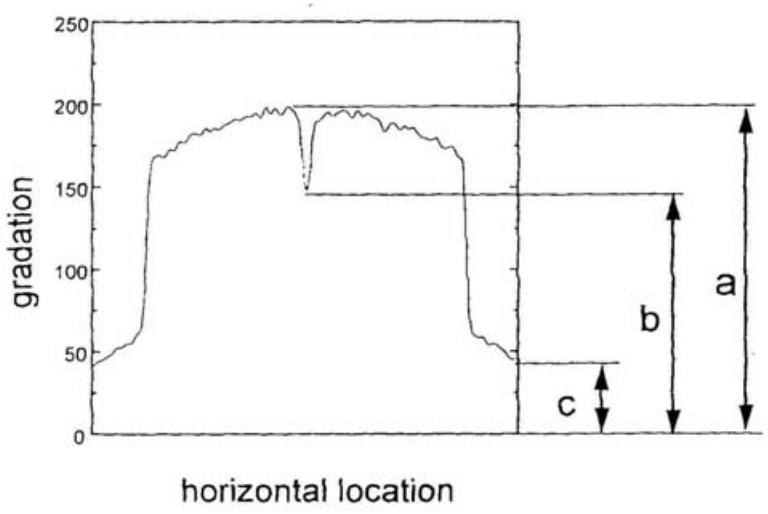


Fig. 15 An example of profile of the image
The contrast of artery against the background is expressed as (a-b)/(a-c).

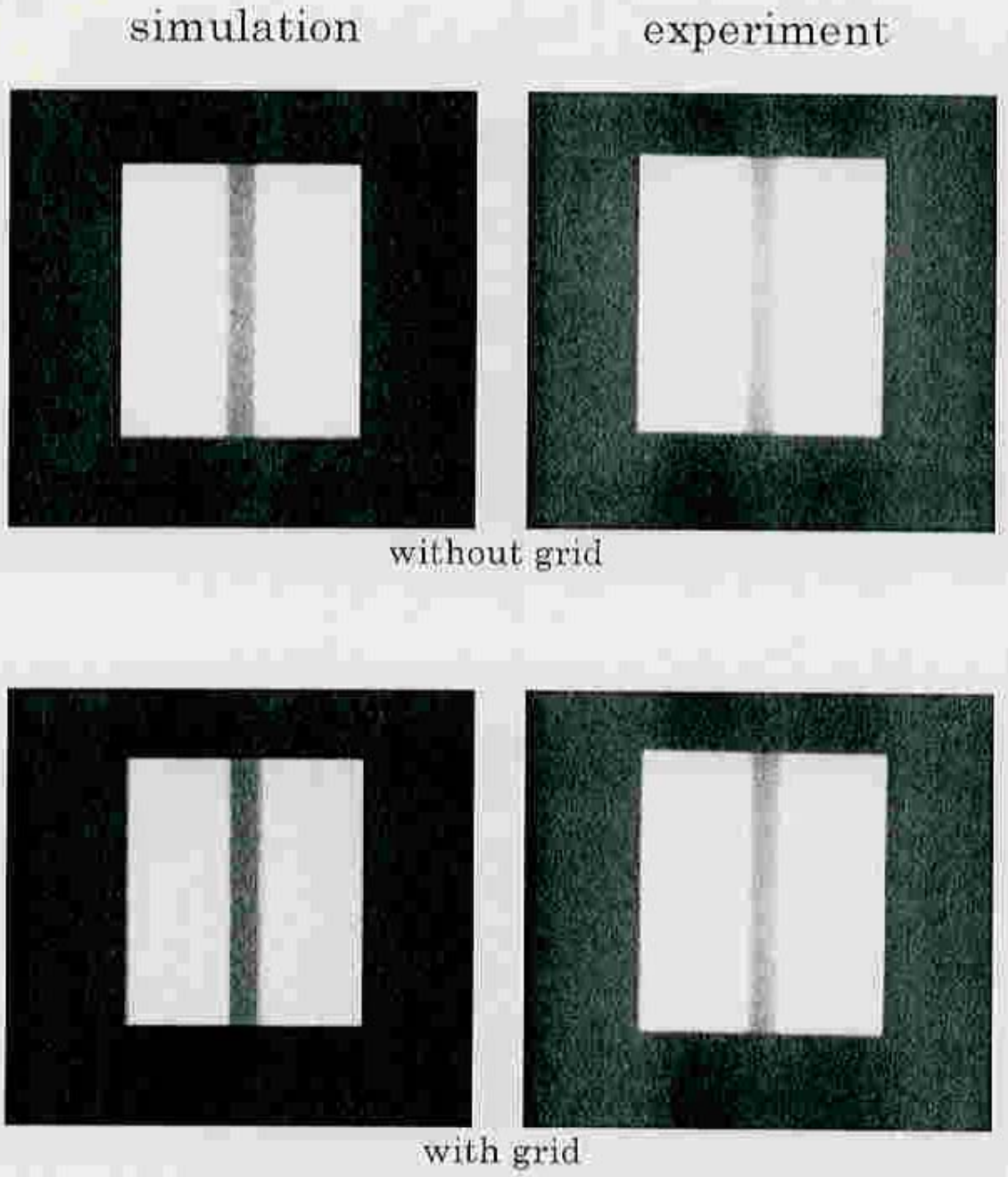


Fig. 16 Two-dimensional coronary images of simulation and experiment in case of no grid and with grid

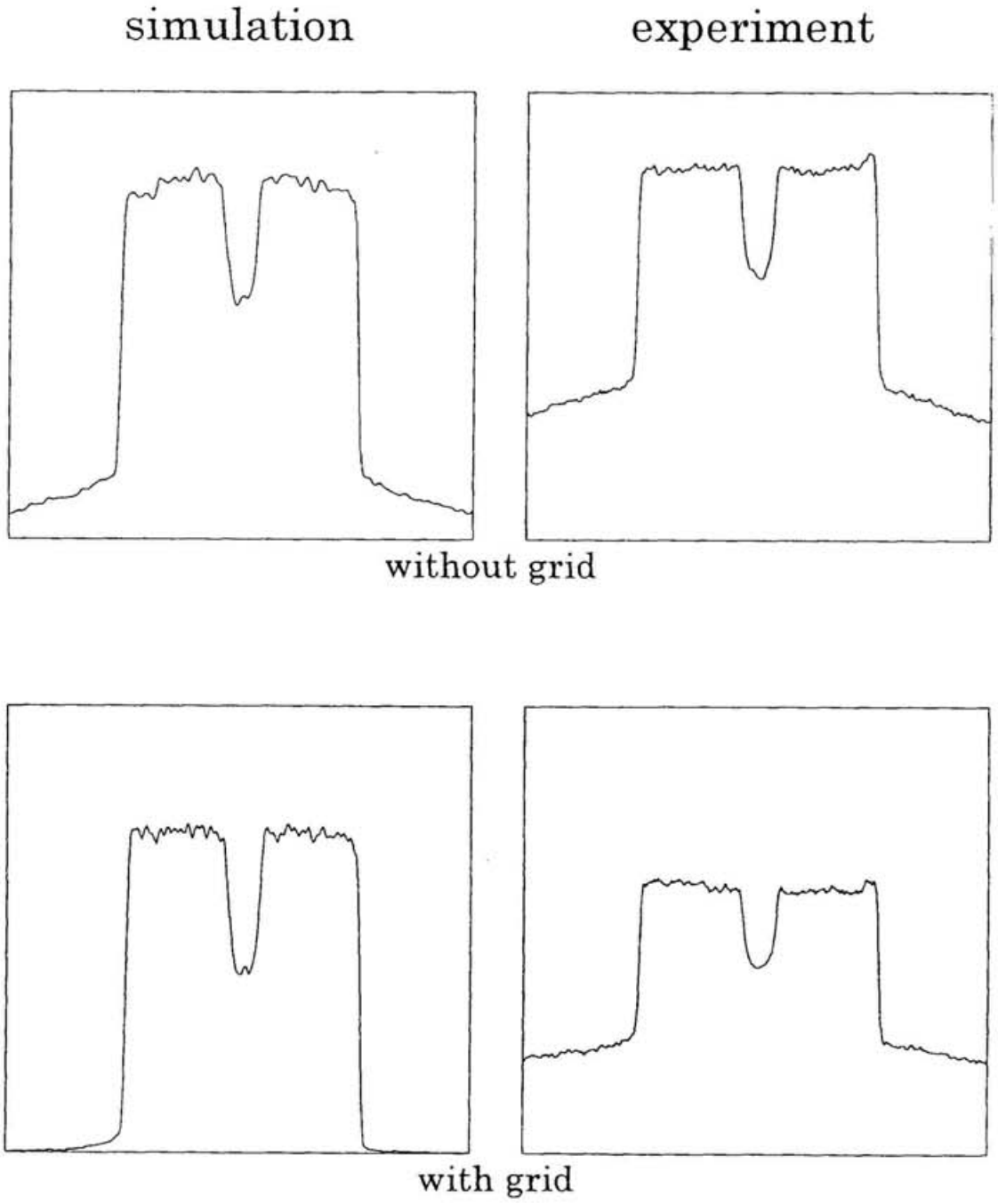


Fig. 17 Profiles of coronary images of simulation and experiment in case of no grid and with grid

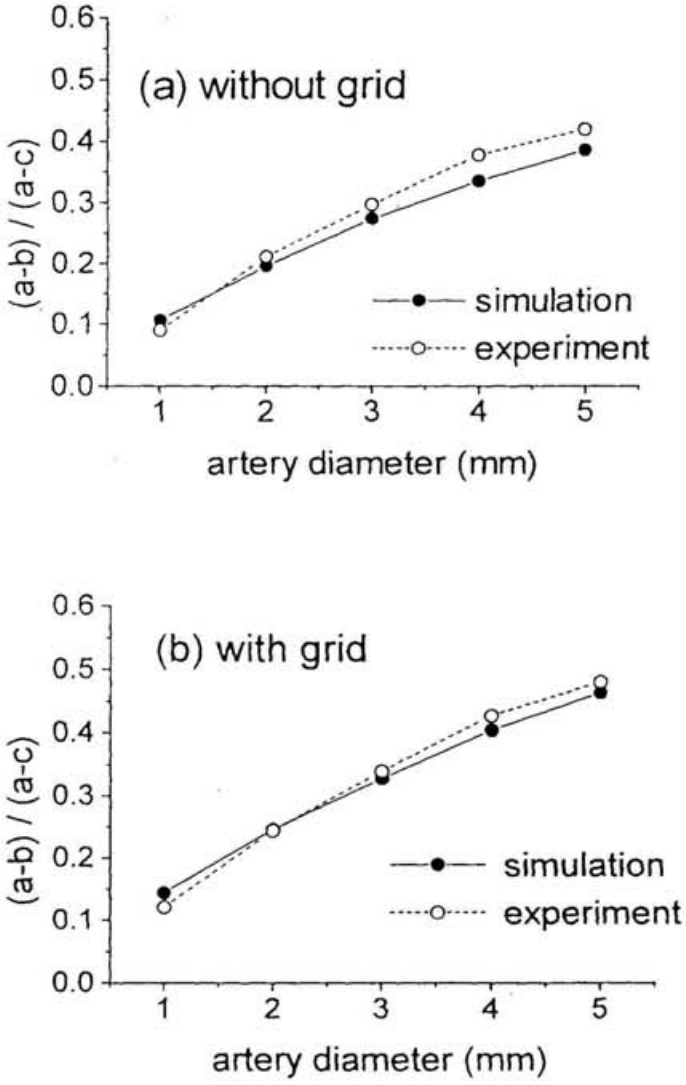


Fig. 18 Comparing result between simulation and experiment of the contrast of artery against the background expressed as (a-b)/(a-c) as a function of the artery diameter. (a) without grid (b) with grid

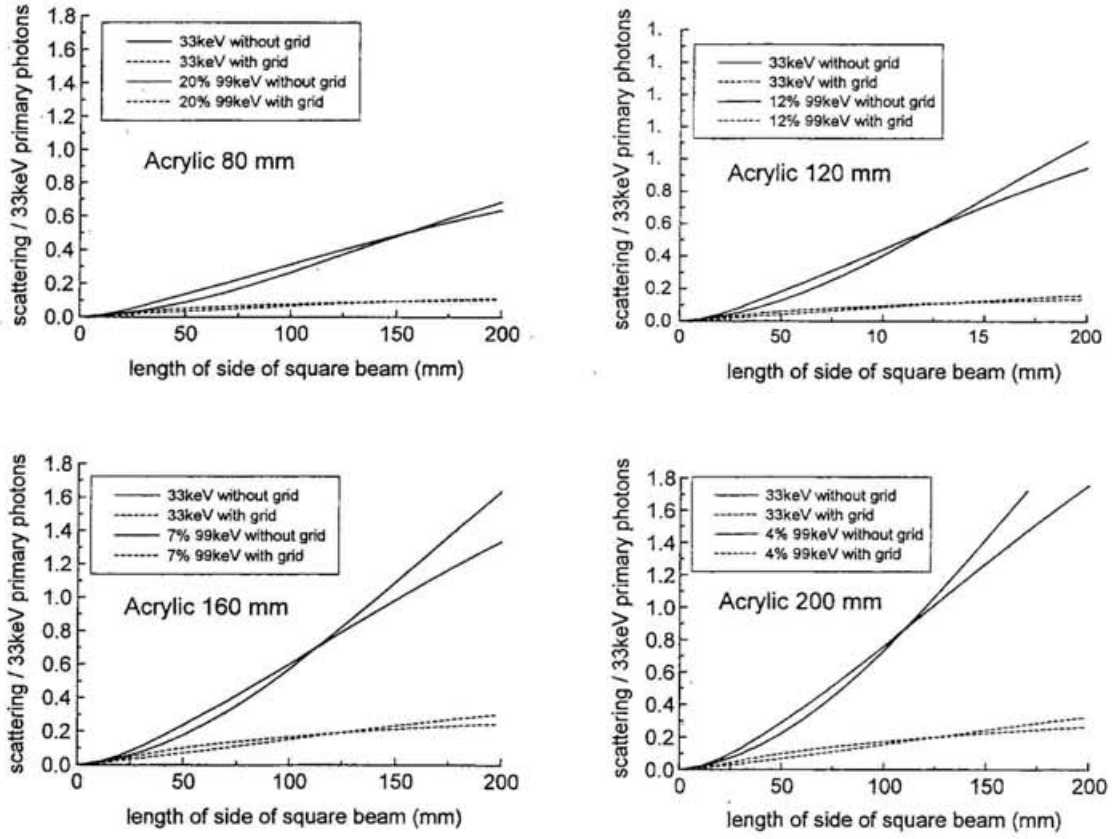


Fig. 19 Scattering x-rays per 33.17 keV direct photons of square beam as a function of one side length of beam

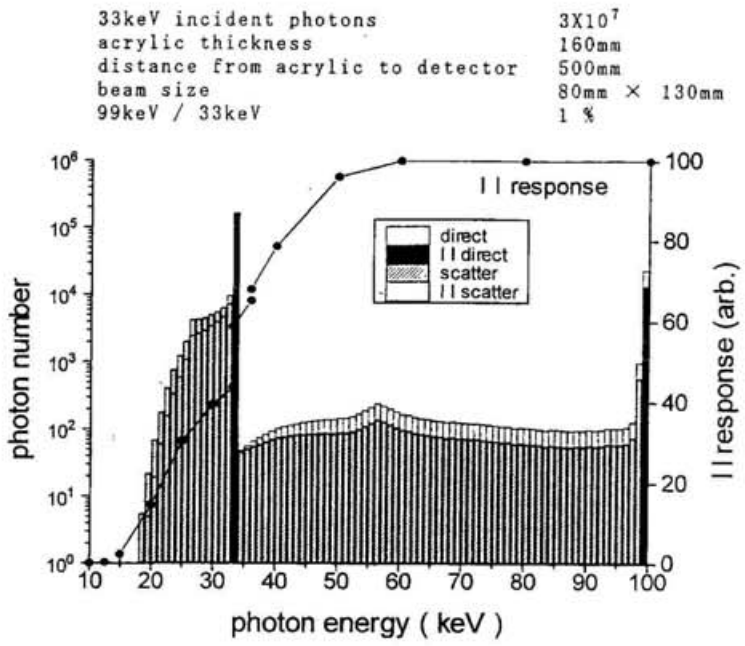
where the experiment use dogs and the clinical applications, respectively. Thus, it was found that the scattered x-rays influence image quality seriously in clinical applications rather than animal experiments, because of the body thickness and the required exposure area size, and especially, the ratio of 99.51 keV contamination is harmful in the case of the higher thickness of body. Energy spectrums of scattered x-rays in the condition of first clinical application at NE1 beamline of KEK are shown in Fig. 20. Real scattered x-ray quantity and one considered energy response of image intensifier are shown. In this case, there were not so many the scattered x-rays due to the distance between the patient's body and the detector of 500 mm. Generally, the distance should be as short as possible in order to make small the penumbra of images. However, the distance was reasonable in the condition of AR NE1, because the penumbra of the artery image was negligible as described in section 4-5.

2-3-2 Characterization and improvement of image contrast

The ratio of 33.17 keV primary x-rays per 99.51 keV primary and scattered x-rays as a function of wood thickness of x-ray grids is shown in Fig. 21. The ratio is almost constant in the region where the wood thickness is thicker than 0.15 mm. The bigger the grid ratio (grid height / wood thickness), the bigger the above ratio, it means more suppression of scattered x-rays by the x-ray grid. However, the grid ratio of 15 is the best available value due to the manufacturing skill. An effective transmittance (I/I_0) is defined here as

$$\frac{I}{I_0} = \frac{t_{wo}}{t_{wo} + t_{Pb}} \cdot e^{-\mu h} ,$$

where, t_{wo} is the wood thickness, t_{Pb} is the lead thickness, h is the grid height and μ is the attenuation coefficient of the wood. In Fig. 22, the effective transmittance of 33.17 keV x-rays is shown as a function of wood thickness under the condition of grid ratio of 15. It was found that the effective transmittance was almost constant in the region above 0.2 mm of wood thickness; especially, it becomes smaller in the region above 0.5 mm. The lead of grid are clearly visible,



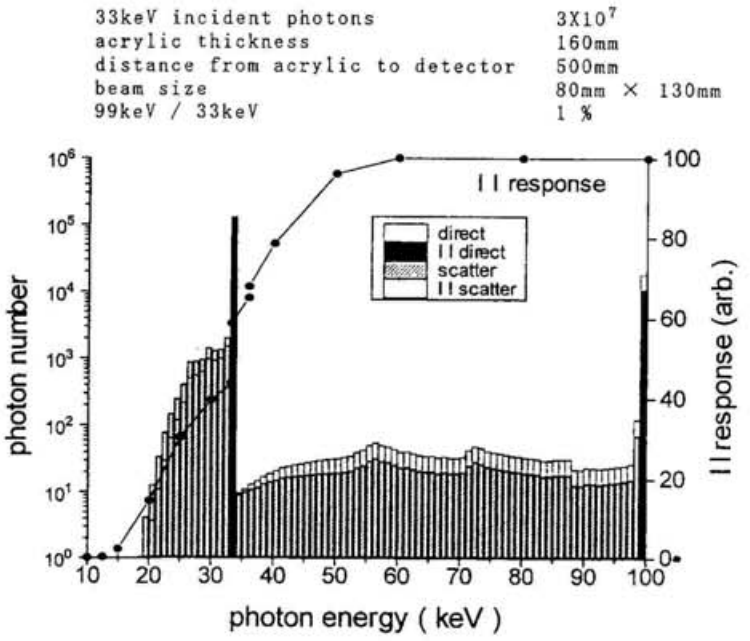


Fig. 20 Energy spectrums of scattering x-rays in the condition of first clinical application at NE1 beamline of KEK. Real scattering x-ray quantity and one considered energy response of image intensifier were shown.

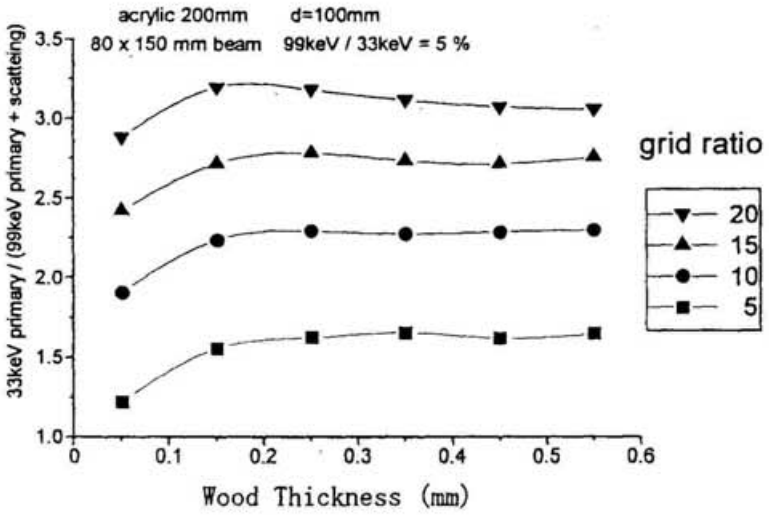


Fig. 21 The ratio of 33.17 keV direct x-rays per 99.51 keV primary and scattered x-rays as a function of wood thickness of x-ray grids

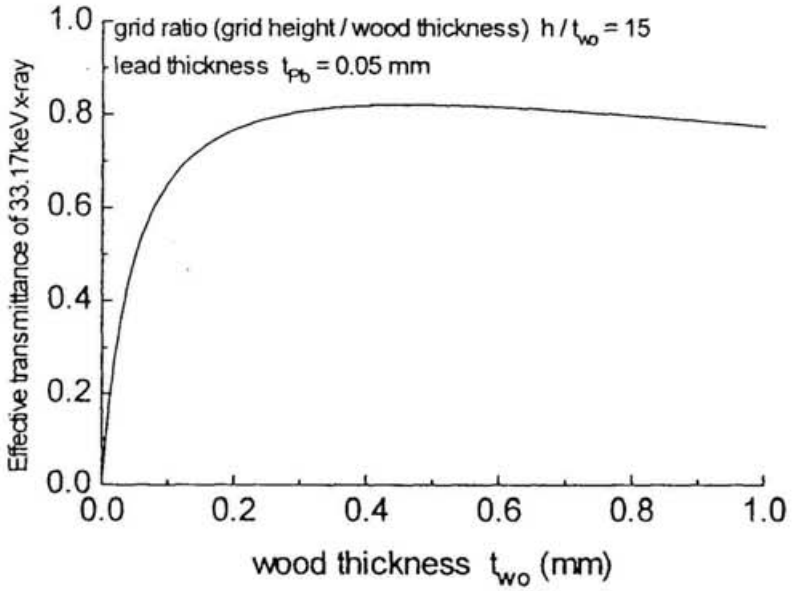


Fig. 22 Effective transmittance of 33.17 keV x-rays as a function of wood thickness of grids under the condition of constant grid ratio of 15. The effective transmittance (I/I_0) is defined here as

$$\frac{I}{I_0} = \frac{t_{wo}}{t_{wo} + t_{Pb}} \cdot e^{-\mu h} ,$$

where, t_{wo} is the the wood thickness, t_{Pb} is the lead thickness, h is the grid height and μ is the attenuation coefficient of the wood.

when its spatial frequency is smaller than that of II-TV system. Thus, 0.25 mm of wood thickness which gave no grid images was adopted as the best x-ray grid for SR coronary angiography. Assuming possibility of manufacturing bigger grid ratio, image contrast ((a-b)/a) is shown in Fig. 23 with the red line, which is as a function of grid height from 1.25 to 80 mm while fixing the wood thickness of 0.25 mm. The contrast saturates around grid height of 10 mm. On the other hand, 33.17 keV primary photons are attenuated as the grid thickness become bigger progressively as shown with the purple line in Fig. 23. Thus, the required maximum grid height should be 10 mm.

I have made simple model images in the case of ideal clinical application with wide exposure area, with the best realizable x-ray grid whose specifications are shown in Fig. 3, and investigated the contrast improvement of images by x-ray grids. The exposure area was assumed to be 150 mm$\times$150 mm covering the whole heart sight, and the distance between acrylic and detector to be 100 mm in order to avoid so much penumbra width due to finite source size as in Fig. 24; the distance was minimal to insertion of the x-ray grid with angle adjustment. The ratio of the third higher harmonic against the iodine K-edge energy was assumed to be 1%. The simulated images and profiles are shown in Fig. 25. The contrast of artery model was improved twice by the x-ray grid insertion. The x-ray grid is very effective in this case.

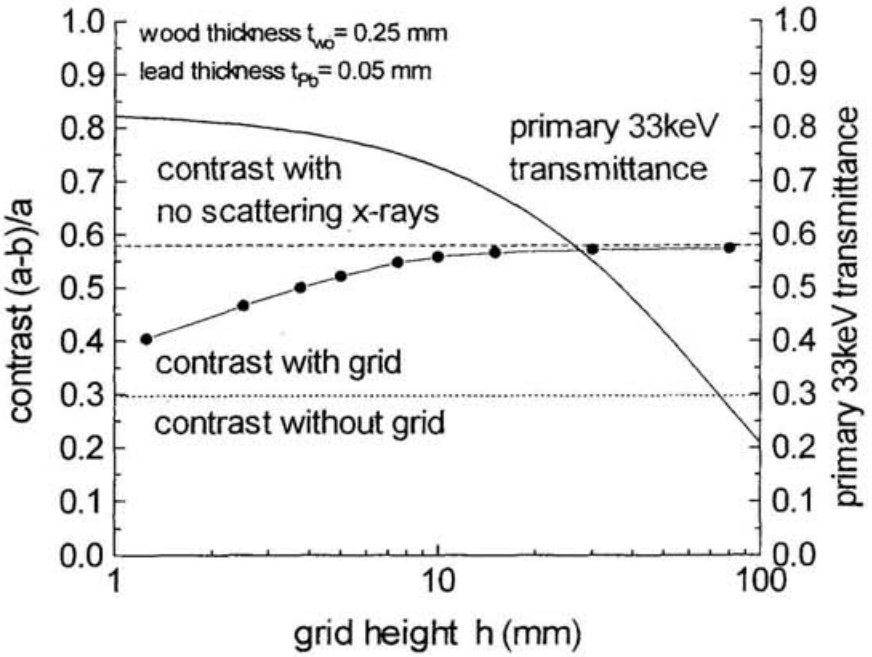


Fig. 23 Image contrast (a-b)/a and transmittance of primary 33.17 keV x-rays as a function of grid height from 1.25 to 80 mm with fixed value of wood thickness of 0.25 mm

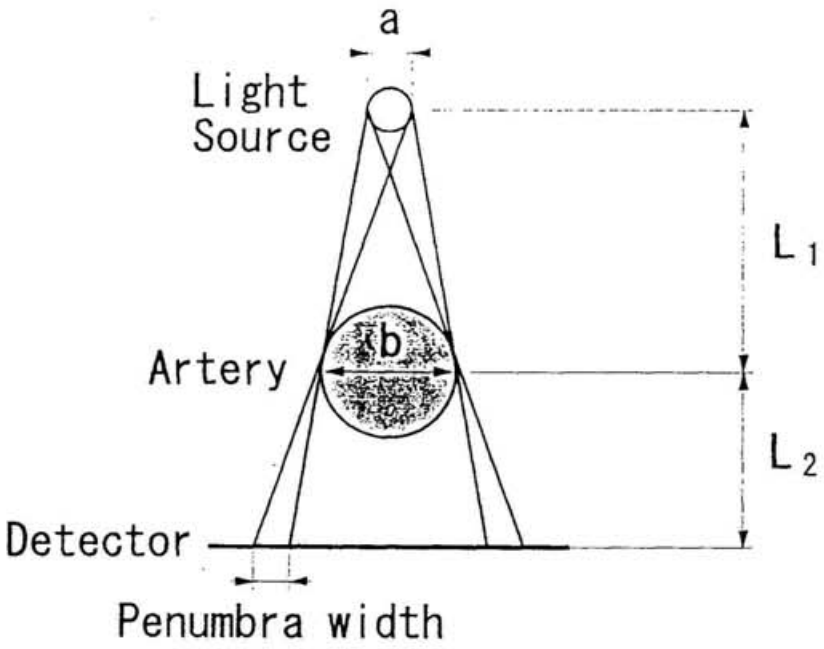
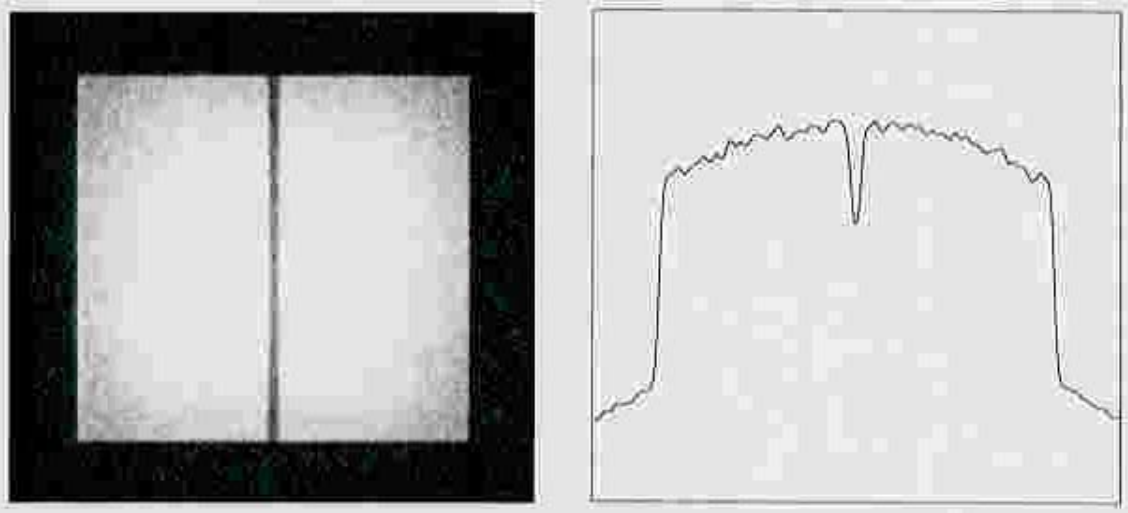
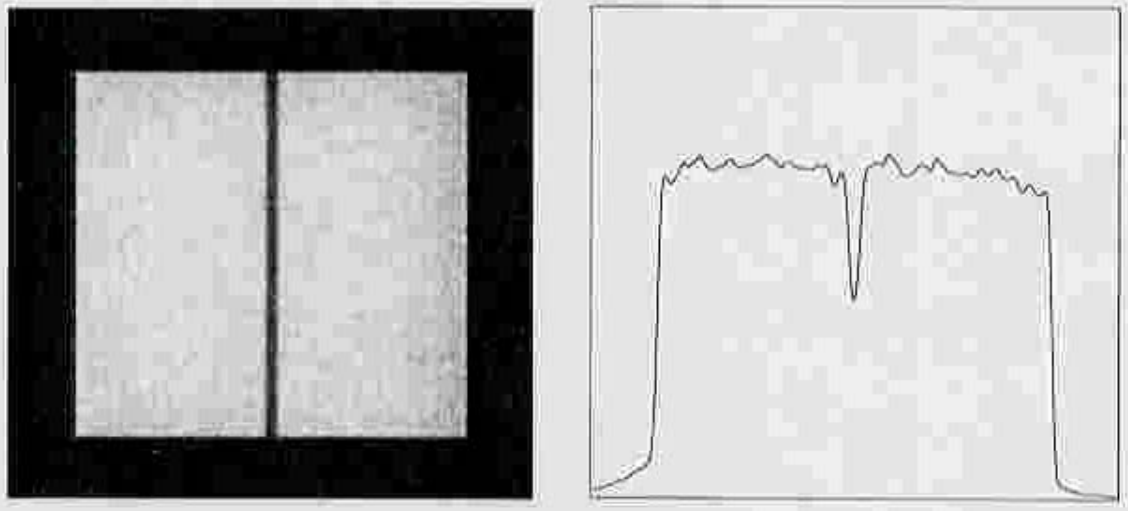


Fig. 24 Penumbra width due to finite light source size
Penumbra width = $a \cdot (L_2 / L_1)$



without grid



with grid

Fig. 25 Simulated images and their profiles in the case of ideal clinical application with wide exposure area of 150 mm×150 mm covering the whole heart sight, and the distance between acrylic and detector to be 100 mm in order to avoid so much penumbra width due to finite source size. The specifications of the x-ray gird are shown in Fig.3.

3. Development of the rotating shutter

3-1 Principle and design

An x-ray shutter which generates pulsed beams is necessary in order first to make blurless artery images and second to suppress the patient's dose as much as possible. Thus, a rotating x-ray shutter was developed in this study. The x-ray shutter consisted of a drum with a hole in the direction of its radius as in Fig. 26 and it rotated at 15 rps. (Zeman H. D. et al. 1983, LeGrand A. D. et al. 1989) X-rays pass through the hole during 2～6 msec, on a frequency of 30 Hz. The x-ray shutter also generated trigger pulses in order to synchronize the read-out starting of the TV system with the x-ray passing. Three different types of sensors for generating trigger pulses were employed; they were a photoelectric sensor, a proximity sensor and a digital encoder. Either one would have survived in an extreme case if radiation damage or other mechanical trouble occurred. In order to make two-dimensional images for coronary angiography, an asymmetric diffraction monochromator (Kohra K. 1962) was employed to magnify vertical x-ray beam size. So, the developed rotating x-ray shutter was arranged in front of the monochromator in order to make a hole of the x-ray shutter as small as possible.

The shape of the hole in the transaxial plane of the drum is shown in Fig. 26. The design of the shape was determined as follows: At the beginning of the irradiation period t_e, phase (a) in Fig. 26, 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. Then, 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. 26 is so determined that the x-ray path length in the attenuation material of the drum should be as long as possible in the transition period between phase (c) and (d) in Fig. 26. The reason for the above is that the energy of x-rays which I used was higher than the x-ray energy used in experiment of physical study, and penetration of the x-rays is high and they should be attenuated. The concrete design of the drum is as follows: As the rotating angle in the transition period t_t, between phase (c) and (d) as in Fig. 26 is twice that of

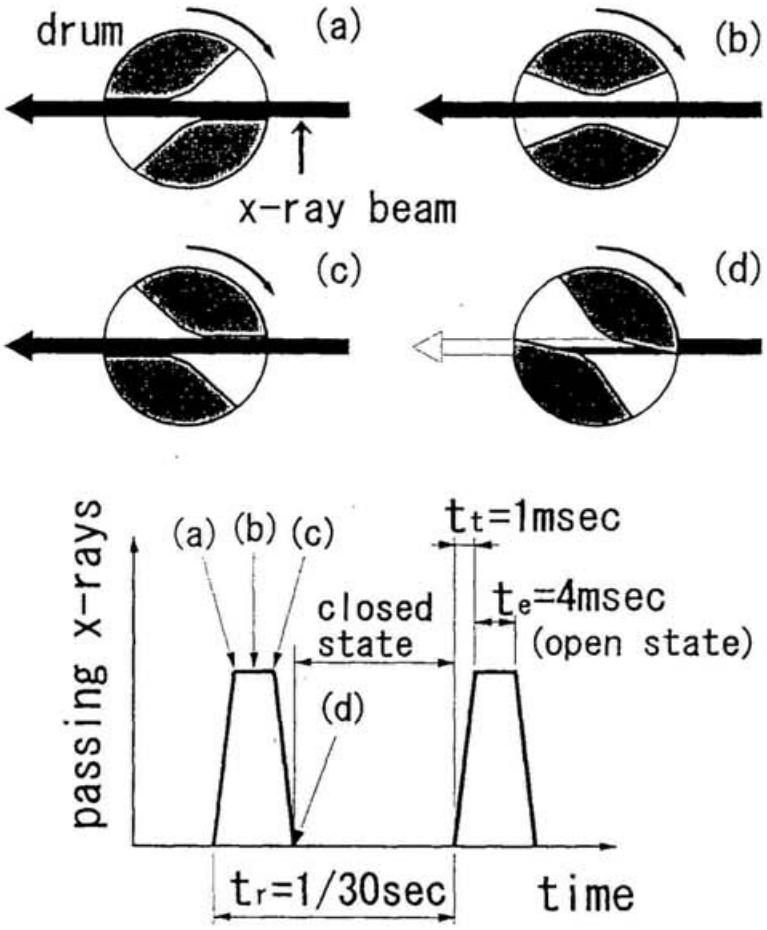


Fig. 26 Time sequential cross section of drum rotating and passing x-ray's quantity as a function of the periodic time

Status (a) is beginning of the irradiation period. Status (b) is center of the irradiation period. Status (c) is end of the irradiation period. Status (d) is end of the transition period and beginning of the drum complete closing period.

t_r : repetitive period of drum half rotation*

t_e : irradiation period of x-rays

t_t : transition period between x-ray passing and stopping

the beam covering angle θ_b in Fig. 27 and the rotating angle in the repetitive period t_r is π, θ_b is represented by t_t and the repetitive period t_r as follows:

$$2\theta_b = \frac{t_t}{t_r}\pi \ . \qquad (7)$$

The radius of the drum, R is represented by θ_b and the synchrotron radiation beam vertical width h_b, as follows:

$$R = \frac{h_b}{2\sin\theta_b} \ . \qquad (8)$$

The opening angle of the drum, θ_o in Fig. 25 is represented by θ_b, the irradiation period t_e and t_r as follows:

$$2\theta_o = \frac{t_e}{t_r}\pi + 2\theta_b \ . \qquad (9)$$

The opening height of the drum is as follows:

$$h_o = 2R \cdot \sin\theta_o \ . \qquad (10)$$

After rotating of $\theta_o - \theta_b$ clockwise from the state as in Fig. 27 as well as in Fig. 26 (b), the edge of the drum is parallel to the beam axis as in Fig. 26 (c). Thus, the cutting angle of the drum, θ_c is as follows:

$$\theta_c = \theta_o - \theta_b \ . \qquad (11)$$

The requirements for the rotating x-ray shutter for medical doctors are as follows: (a) the time structure of the x-ray beam is a pulsed one whose beam spill is either 2, 4 or 6 msec with the frequency of 30 Hz so that the irradiation are synchronized with the timing of the imaging system, (b) in a closing state, the intensity of x-rays of 33.17 keV and 99.51 keV should be attenuated to be less than 10^{-8} of the original photons, (c) transition period t_t between the irradiation period and close state should be less than 1 msec, because x-rays during this period shouldn't contribute to the images, (d) trigger pulse (TTL signal) should be generate as starting 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 sec and the irradiation period t_e is

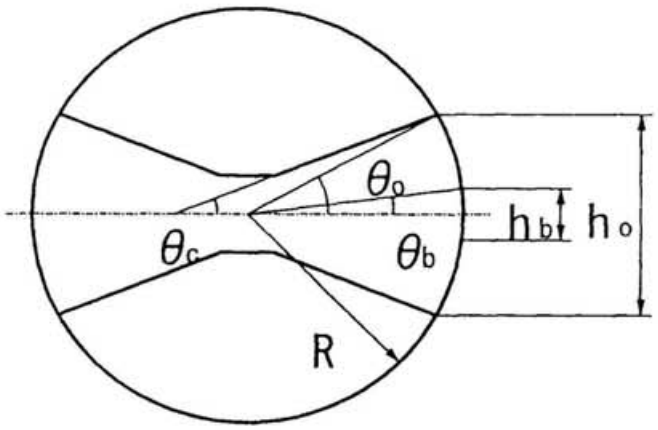


Fig. 27 Design parameters of the x-ray shutter drum
θ_b is the beam covering angle and it is represented by t_t and the repetitive period t_r as $2\theta_b = (t_t / t_r)\pi$. The radius of the drum, R is represented by θ_b and the synchrotron radiation beam height, h_b, as $R = h_b / (2\sin\theta_b)$. The opening angle of the drum, θ_o is represented by θ_b, t_e and t_r as $2\theta_o = (t_t/t_r)\pi + 2\theta_b$. The opening height of the drum is as $h_b = 2R \cdot \sin\theta_b$.
θ_c is given as $\theta_c = \theta_o - \theta_b$.

selected to be 2 msec here. On the other hand, from requirement (c), the transition period, t_t, was assumed to be 1 msec.

With the above parameters and the vertical beam width (h_b = 7 mm) of synchrotron radiation of NE1 beamline at AR of KEK, the design parameters of the drum were obtained from equations (7) to (11) as follows:

$$2\theta_b = \frac{3\pi}{100}\ \text{rad} = 5.4^\circ ,$$

$$R = 75\ \text{mm},$$

$$2\theta_o = 0.282\ \text{rad} = 16.2^\circ ,$$

$$h_o = 21.2\ \text{mm},$$

$$\theta_c = 5.4^\circ .$$

As the horizontal beam width was about 80 mm, opening width of the drum was designed to be 90 mm. The drum was designed as above. The other two types of drums for 4 and 6 msec pulse width were also designed the same as above, and provided. I employed stainless steel SUS304 as the material for the drum. Passing through this drum, the x-rays of 33.17 keV attenuate to less than 10^{-100}, and 99.51 keV, the third higher harmonic, deteriorate to less than 2.2×10^{-18} in the case of the closed state, the latter of which rose from the (311) reflection from silicon crystal monochromator as the third higher harmonic x-rays. (Konishi K. et al. 1985) The arrangement of the system including motors and sensors is shown in Fig. 28. The rotation of the drum is driven by the speed variable 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. Three sensors are used for generating trigger pulses. They are a photoelectric sensor, a proximity sensor and a digital encoder. The photoelectric sensor works for sensing laser beams which pass through a radial hole in the disk. The proximity sensor works for sensing a recess cut on the edge of the disk. These disks are attached to both sides of the drum as in Fig. 28. These disks are set for sensors to work just before the opening position of the x-ray shutter. A pulse motor in Fig. 26 is used for rotating the shutter drum to the closed state when the x-ray shutter

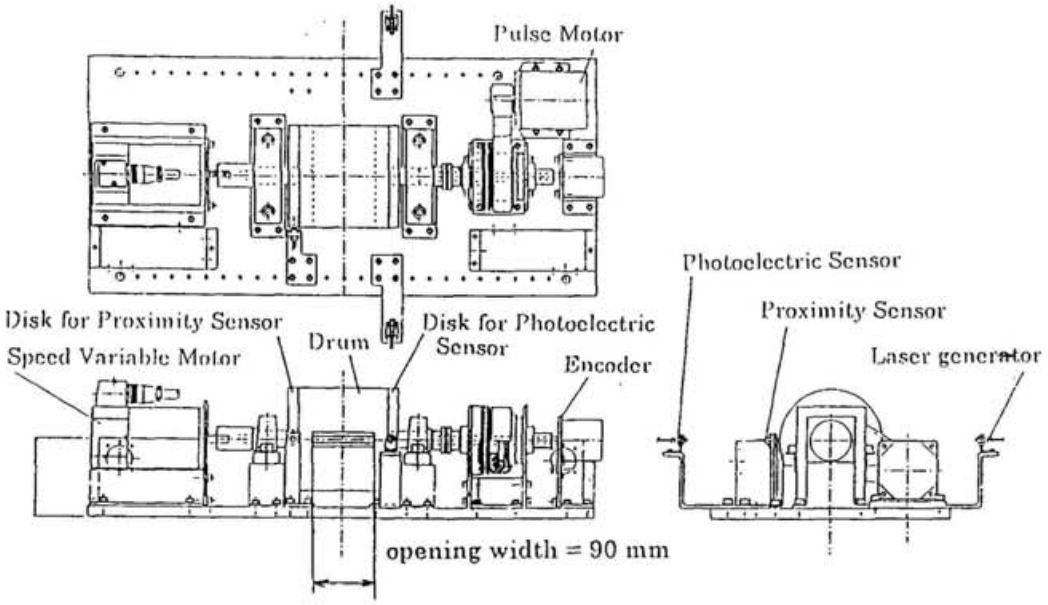


Fig. 28 The rotating x-ray shutter system

The drum is rotated continuously by the speed variable motor. In order to synchronize the timing between the x-rays passing through the x-ray shutter and that of the CCD camera of the II-TV system reading the image signals, the trigger pulses are generated by the three sensors; the photoelectric sensor, the proximity sensor and the digital encoder. A pulse motor is used for deciding shutter drum rotating angle when the x-ray shutter is stopped. After the drum is completely stopped, the drum is controlled to rotate to the closed state.

is stopped. After the drum is completely stopped, the drum is controlled to rotate to the closed state. Even if the x-ray shutter system is stopped by mechanical accidents, the shutter drum shouldn't be kept at the open state, and should be closed promptly in order to avoid useless irradiation to the patients. Input, output, indication and adjustment of the rotating x-ray shutter are shown in Table 3, and specifications of 'open' sensors in use is shown in Table 4.

3-2 Safety analysis against thermal load

Safety analysis of the drum to accidental thermal load had to be carried out in order to confirm the safety of the designed drum. It was necessary to confirm that the drum wouldn't melt by the power of synchrotron radiation even in the case of failure in its rotating mechanism. The thermal investigation was carried out using the program code ANSYS for finite element analysis. Considering clinical application at NE1 beamline of the AR in KEK, the total power of the synchrotron radiation was assumed to be 2.96 kW when the ring parameters were 5.0 GeV as the electron beam energy, 70 mA as the electron beam current and 0.93 T as the wiggler magnetic field. As the thermal power of 2.01 kW was absorbed when passing through three beryllium filters with 0.3 mm thickness and an aluminum filter with 1 mm thickness of NE1 beamline, remaining power of 0.95 kW was absorbed at the x-ray shutter drum. The spatial maximum temperature of the drum in the steady state was estimated to be 1,297℃ when preceding x-ray shutters may fail and thus synchrotron radiation continuously irradiates onto the stopped x-ray shutter drum, according to the result of the numerical analysis. In this calculation, thermal emission and natural conventional heat transfer are considered. As the melting point of SUS304 is about 1410℃, I found that the x-ray shutter drum would never melt even if it received synchrotron radiation at a certain point over a long period due to rotation failure.

Table 3 Input, Output, Indication and Adjustment of the rotating x-ray shutter

Input	Interlock sequencer ready signal
Output	Trigger pulse × 3 routes Signal of required drum rotation number Signal when abnormal drum rotation occurs Emergency stop signal
Indication	Required drum rotation number Drum rotation number (rpm and images/sec) 'Open state' sensor Drum stopping angle (only when drum stopping)
Adjustment	Drum rotation number (accuracy 1 rpm) Delay of trigger pulse (accuracy 0.2 msec) Drum stopping angle (accuracy 1 degree)

Table 4 Specifications of used open state sensors

Digital encoder	Rotation angle resolution less than 0.5 degree Response frequency 10 kHz Type E6F-AB3C made by OMRON
Photoelectric sensor	Response time less than 0.25 msec Type FS-L50 & FS-L70 made by KEYENCE
Proximity sensor	Response time less than 1 msec Type EH-110 & ES-X38 made by KEYENCE

3-3 Experiment for verification of synchronization

An experiment of the x-ray shutter was carried out at the NE5A beamline of the AR in KEK in order to verify the synchronization between passing of x-rays and sending of the trigger pulses. Synchrotron radiation was monochromatized to 33.17 keV x-rays by (111) silicon double crystal. The x-rays that passed through the x-ray shutter were detected by a PIN diode (HAMAMATSU PHOTONICS, S3584-06) as shown in Fig. 29. When the PIN diode received x-rays, electric current flowed in it, when providing 100 volts to the diode. Voltage signals generated from the current by a circuit. The signals from the PIN diode were compared with those of trigger pulse from the rotating shutter on an oscilloscope to analyze their temporal relation. With adjustment of trigger pulse delay, I found that x-ray pulse and the trigger pulse could be adjusted to synchronize completely as in Fig. 30. In the experiment at NE5A beamline, t_e was 4.6 msec, as shown in Fig. 30, because of the difference of beam heights h_b (3 mm at NE5A, while the expecting period was 4.0 msec for 7 mm at NE1) . Synchronization of trigger pulse with x-ray pulse was verified from this result.

3-4 Application for clinical examination

The rotating x-ray shutter was installed in NE1 beamline for clinical application. (Hyodo K. et al. to be published, Ohtsuka S. et al. to be published) The arrangement of equipment is shown in Fig. 31. Synchrotron radiation was monochromatized by the silicon crystal, after passing through the rotating x-ray shutter. Photon energy of 35 keV was selected for the clinical examinations because of relatively lower photon numbers at the third higher harmonic. A parallel plate ionization chamber which consisted of three of 25 μ m of Mylar and 100 μ m of acetate film was inserted in the beamline to monitor the irradiation just upstream of the patient. The ionization chamber was developed by Dr. J. Tada of Spring-8 (Oku Y. et al. submitted). The radiation dose was monitored by the ionization chamber. The monochromatic x-rays that passed the ionization chamber and the patient were detected by the imaging system.

The purpose of the monitoring is to measure the skin dose of the patient to

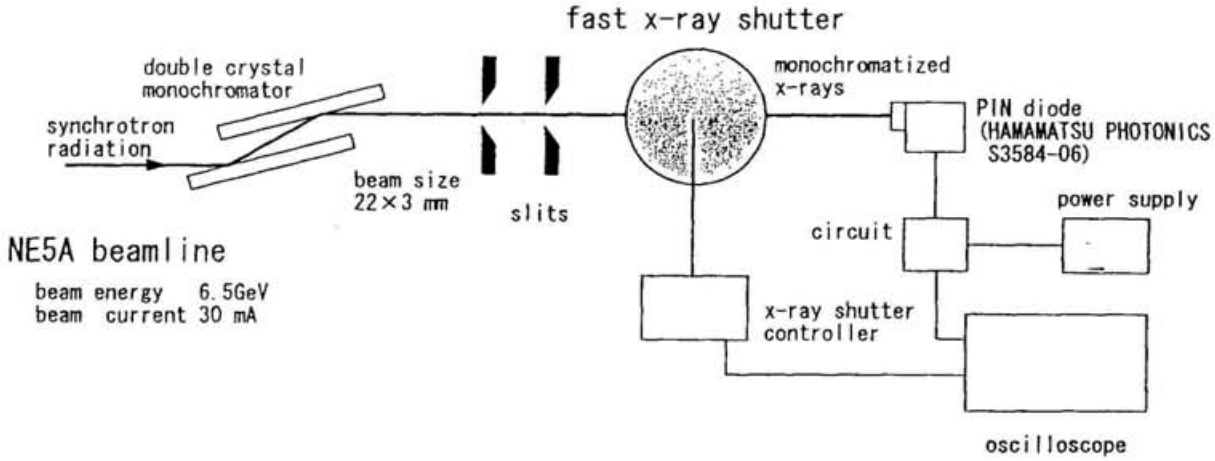


Fig. 29 The arrangement of x-ray shutter experiment
Synchrotron radiation was monochromatized to 33.17 keV x-rays by Si (111) double crystal monochromator. The x-rays passed through the x-ray shutter and reached a PIN diode . When the PIN diode received x-rays, electric current flowed in it, when providing 100 volts to the diode. The current was changed to voltage signals by a circuit. The signals were taken into an oscilloscope as well as the trigger pulse from x-ray shutter controller, and they were compared.

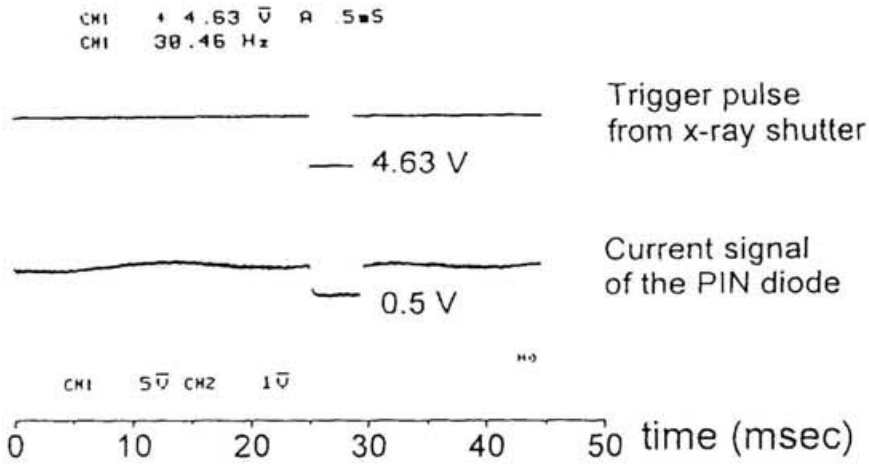


Fig. 30 Synchronizing of the trigger pulse from x-ray shutter controller with current signal of the PIN diode by x-rays passing through the shutter. With adjustment of trigger pulse delay, it is found that x-ray passing and the trigger pulse were completely synchronized.

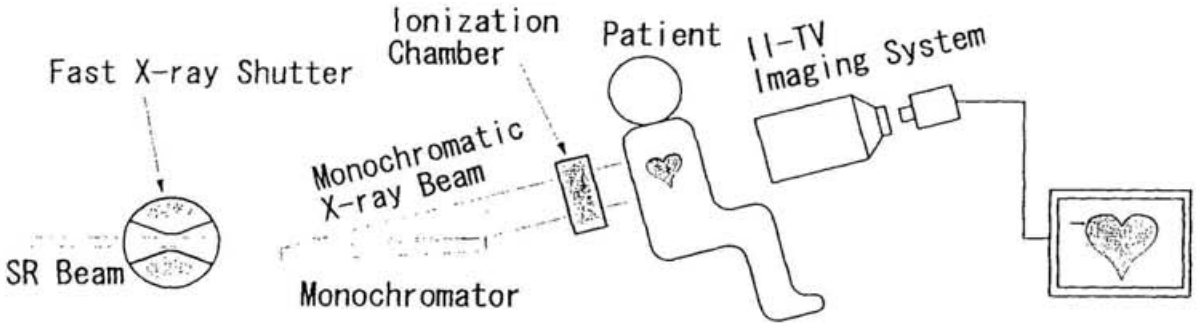


Fig. 31 Arrangement of equipment for clinical application of SR coronary angiography (Hyodo K. et al. to be published)
Synchrotron radiation was monochromatized by the silicon crystal monochromator after passing through the rotating x-ray shutter. The monochromatic x-rays went up to an ionization chamber. The radiation dose was monitored by the ionization chamber. The monochromatic x-rays passed the ionization chamber and the patient, and reached the imaging system.

prevent over exposure. When the dose exceeds the prescribed value, the 'dose interlock system' interrupts the ring current immediately.

The exposure of monochromatic photons is defined as equation (12):

$$X = \Psi_\gamma \cdot (\frac{\mu_{en}}{\rho})_{air} \cdot \frac{e}{W_{air}} \qquad (12)$$

X : exposure (C /kg)

Ψ_γ : energy fluence of photons(J / m^2)

$(\frac{\mu_{en}}{\rho})_{air}$: mass energy absorption coefficient of air (m^2 / kg)

e : elementary electric charge

W_{air} : W value of air (J)

Where energy fluence Ψ_γ of monoenegetic photons is represented as equation (13):

$$\Psi_\gamma = h\nu \cdot \phi \cdot t \qquad (13)$$

$h\nu$: photon energy (J)

ϕ : photon fluence rate (photons $\cdot$ sec^{-1} $\cdot$ m^{-2})

t : irradiation period (sec)

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

As the exposure was monitored for each patient by ionization chamber in the clinical application, the value of exposure per one image and 1 mA of electron storage ring current can be given by dividing monitored exposure by the number of corresponding images and the ring current during the measurement. The image number per each patient could be counted by reading out from a video image later.

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 $\cdot$ m^{-2} $\cdot$ sec^{-1}, the calculated value of exposure with 4 msec of irradiation

period per one image was 1.4×10^{-6} C/kg·image^{-1}·mA^{-1}, while the monitored values of the exposure ranged from 1.0×10^{-6} to 1.3×10^{-6} C/kg · image^{-1} · mA^{-1}. Parameters in the clinical application are shown in Table 5 (Hyodo K. et al. to be published, Ohtsuka S. et al. to be published). As the average value of monitored exposure was abut 20% less than the estimated value from photon fluence, it was found that the rotating x-ray shutter worked properly and could have restrained the patient dose at the design concept value.

The images for diagnosis were taken without motional blur by heart beat and flicker due to a time lag between x-ray pulses and image reading of TV system in the clinical applications (Hyodo K. et al. to be published, Ohtsuka S. et al. to be published).

Table 5 Parameters in the clinical application (Hyodo K. et al. to be published)

Beam energy of storage ring AR	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 band width of monochromatic x-rays	0.3%
Device type	multipole wiggler (43 pole)
Device magnetic field	0.79 T
Critical energy of SR	13 keV
Original beam size of SR before the shutter	$80^{w} \times 7^{h}$ mm

4. Proposal of an optimized system for intravenous angiography using synchrotron radiation source

4-1 Fixing the basic specifications

The S/N ratio of images by quantum noise is given by;

$$S/N = \frac{I}{\sqrt{I}}, \qquad (14)$$

where I is the photon flux injected into one pixel. The quantum noises per signal should be sufficiently smaller than the contrast of the artery images. Simulation images with various S/N ratios were made by the developed image-simulation program, and investigated. The necessary maximum S/N ratio was chosen based on this investigation. The value of the ratio of the artery shadow depth (a-b in Fig. 15) with which 1% concentration of iodine in weight, against the standard deviation of quantum noise, was decided. If the value of the ratio was 1, the artery shadow could not be completely distinguished in the image; thus, the minimum value was chosen to be 2. The S/N ratio was determined based on the ratio of the artery shadow depth against the standard deviation of the quantum noise to be 60 from Fig. 32. Simulation images and their profiles with various value of the S/N ratio are shown in Figs. 33 and 34. From the S/N ratio, necessary photon flux (I) of 3600 into a pixel was obtained by Eq.(14). The necessary total photon flux of 33.17 keV, the iodine K-edge energy, in front of the detector was obtained from the above I and the ideal exposure area of 150 mm × 150 mm for coronary angiography; it was 2.0×10^9 photons/image considering a pixel size of 0.2 mm.

On the other hand, the contrast deterioration of the images due to 99.51 keV photons, the third higher harmonic, was investigated. The analyzed artery contrast, ((a-b)/a in Fig. 15) against the ratio of 99.51 keV per 33.17 keV photons in front of the phantom is shown in Fig. 35. The incident x-ray beam size was 150 mm × 150 mm. The acrylic thickness was 160 mm, the distance between the acrylic and the detector was 100 mm, the artery diameter was 5 mm, and the concentration of iodine in weight was 5%. It was found that the contrast improvement became remarkable if 99.51 keV portion is less than 1 %.

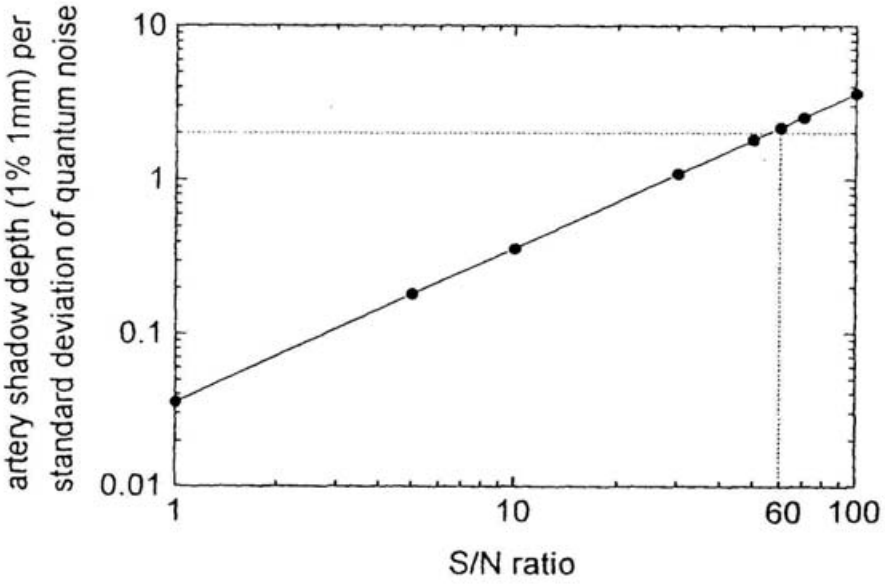


Fig. 32 Artery shadow depth (1% concentration iodine in weight and 1 mm diameter) against the standard deviation of the quantum noise calculated from the photon flux injected into one pixel, as a function of the S/N ratio of the quantum noise.

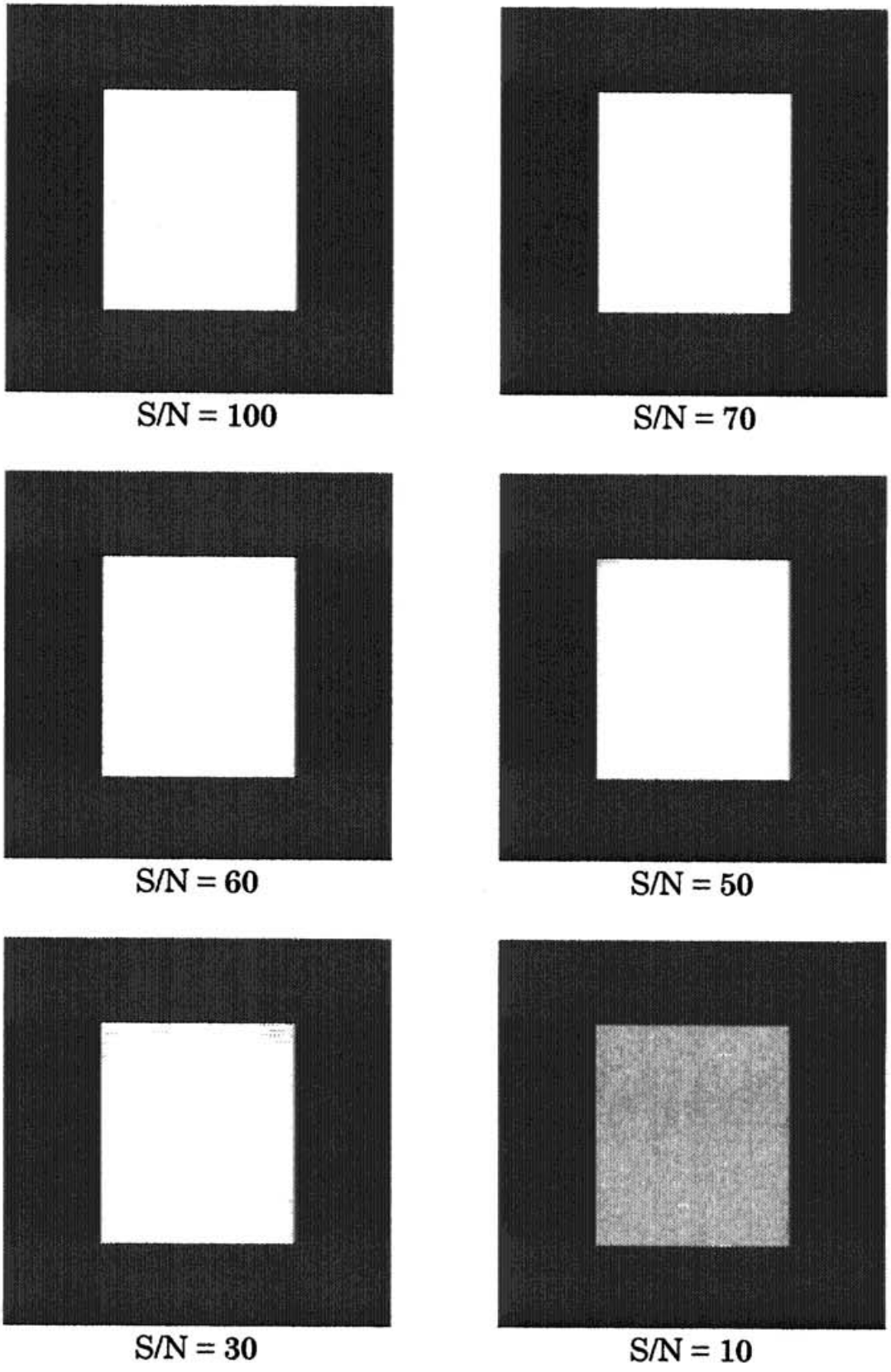


Fig. 32 Simulation images with various values of the S/N ratio

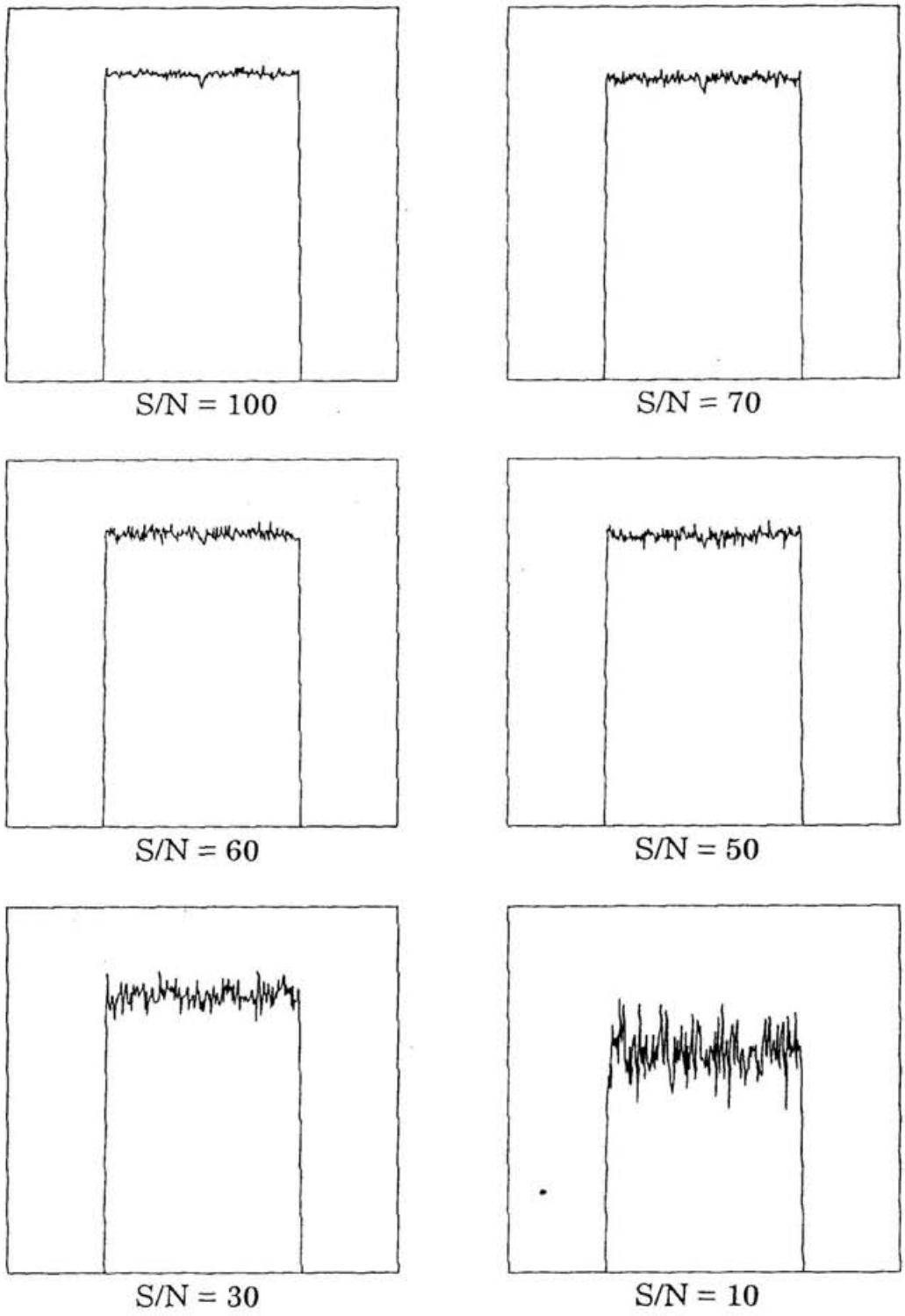


Fig. 34 Simulation image profiles with various values of the S/N ratio

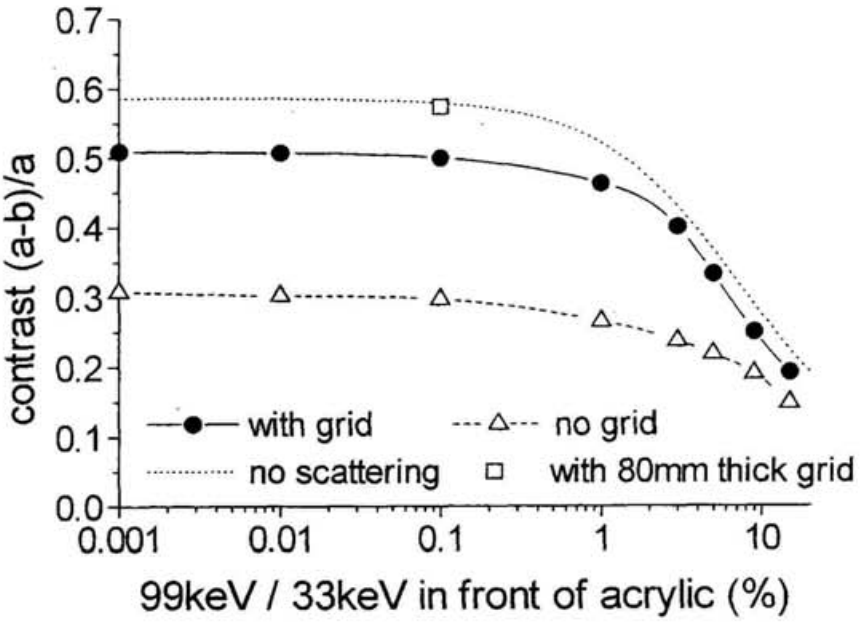


Fig. 35 Artery contrast ((a-b)/a), as a function of the ratio of the third higher harmonics photon flux against 33.17 keV photons in front of the phantom in the case of the 150 mm×150 mm beam required by medical doctors. The acrylic thickness is 160 mm, the distance between acrylic and the detector is 100 mm, the artery diameter is 5 mm, and the concentration of iodine in weight is 5%.

Furthermore, the contamination ratio of the third higher harmonic should be 0.1%, because the contrast when using an x-ray grid was saturated at that point.

At a radiation source, necessary total photon flux of 33.17 keV is 9.7×10^{11} photons/image of the total photons per 4 msec and allowed contamination of the 99.51 keV photons against the 33.17 keV photons is 0.18%, considering photon attenuation process due to passing through three elements such as a beryllium filter with a total 1 mm thickness, an aluminum filter with a 1 mm thickness and across 4 m of air, and the diffraction process at the monochromator. Allowed maximum critical energy of 9.0 keV was obtained from the above allowed contamination of 99.51 keV of 0.18%. While, a stored electron beam current of 500 mA and the number of pole of a superconducting wiggler of 5 were determined as reasonable values with current technologies. From the values of the critical energy, the beam current and the number of the wiggler poles, the electron beam energy to obtain the necessary photon flux of 33.17 keV was determined to be 1.5 GeV. Magnetic field of the wiggler was determined to be 6.0 T by the critical energy and the beam energy. The specifications of the radiation source for SR coronary angiography can be obtained from the necessary photon flux and irradiation period per one image, and the maximum contamination of the third higher harmonic. They are shown in Table 6.

4-2 Design of the storage ring

A conceptual electron storage ring dedicated to coronary angiography to meet the above basic specifications as in Table 6, was designed using the program SAD of KEK (Oide K. et al. since 1986). The Chasman-Green type was adopted as a lattice, because dispersion suppression on the insertion device was easily avoidable of so much emittance growth by exciting the insertion device. The lattice of the designed ring is shown in Fig. 36. Superconducting bending magnets and a wiggler as an insertion device with a field of 4 T and 6 T were adopted. A wiggler with 6 T magnetic field is possible to manufacture (Huke K. et al. 1980, Sugiyama S. et al 1992). The twiss parameters are shown in Fig. 37. The vertical beta functions at the wiggler were set to be small in order to make the wiggler gap as small as possible. The horizontal beta functions at the injector

Table 6 Basic parameters of the radiation source for SR coronary angiography

beam energy	1.5 GeV
magnetic field of insertion device	6.0 T
pole number of insertion device	5 pole
beam current	500 mA

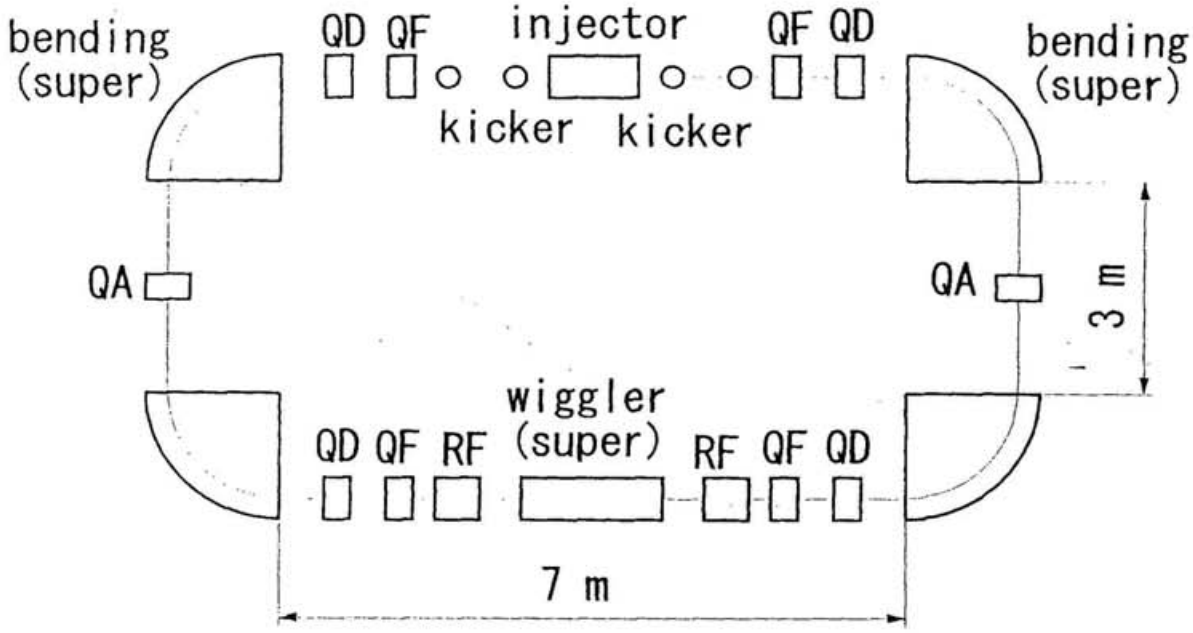


Fig. 36 Lattice of the designed electron storage ring dedicated to SR coronary angiography

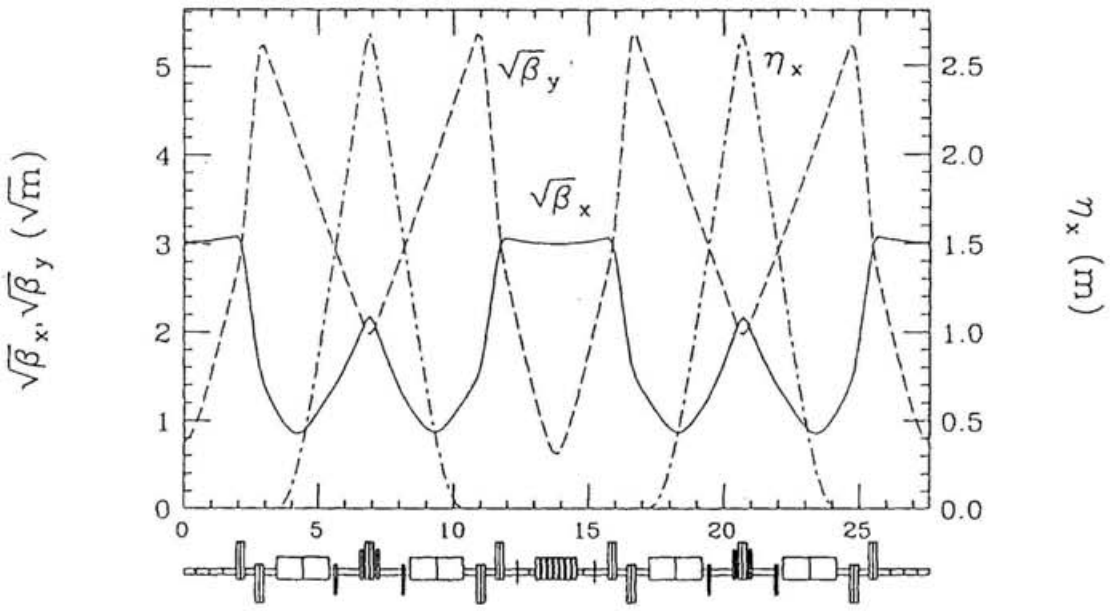


Fig. 37 Twiss parameters of the designed ring

were set to be relatively large in order to make the acceptance at the injection point large. Sextupole magnets were set between the QA magnets and the bending magnets. The dynamic aperture at the injection point is shown in Fig. 38. Based on an assumption that the horizontal and vertical beam size there are 4.22 mm and 0.11 mm, the dynamic aperture is sufficiently wide. The parameters of the ring are given in Table 7. The emittance was set to be relatively large in order to make the storage beam current as large as possible. The synchrotron radiation spectrum of the above-designed medical ring is shown in Fig. 39 with one of AR NE1 under the condition of the first clinical application. They are the total photon number per second when using a lapped single monochromator (integrated intensity of diffracted photons = 0.3% at 33.17 keV) The 33.17 keV photon number of the medical ring was more than that for the AR NE1 clinical application, while 99.51 keV, the harmful third higher harmonic, is opposite.

4-3 Optical Element

A lapped crystal monochromator (Shiwaku H. et al. 1991, Shiwaku et al. 1992, Shiwaku H. 1992) was used for two-dimensional SR coronary angiography in order to obtain a high integrated intensity diffracted from it. Thus, the third higher harmonic was also diffracted and injected into the detector. Since it deteriorates the image contrast, a ratio of its intensity against 33.17 keV should be as small as possible. Thus, a storage ring whose clinical energy of synchrotron radiation is relatively small is suitable for coronary angiography. On the other hand, a multi-layer monochromator is effective for suppressing the third higher harmonic. However, its current technology does not give sufficient image quality for two-dimensional imaging; it is still under development. If the gadolinium is used as a contrast agent, since its K-edge energy is 50.24 keV, the size of a crystal monochromator will be extremely large due to its very small diffraction angle. In this study, a lapped Si (311) crystal which is available was selected as a monochromator.

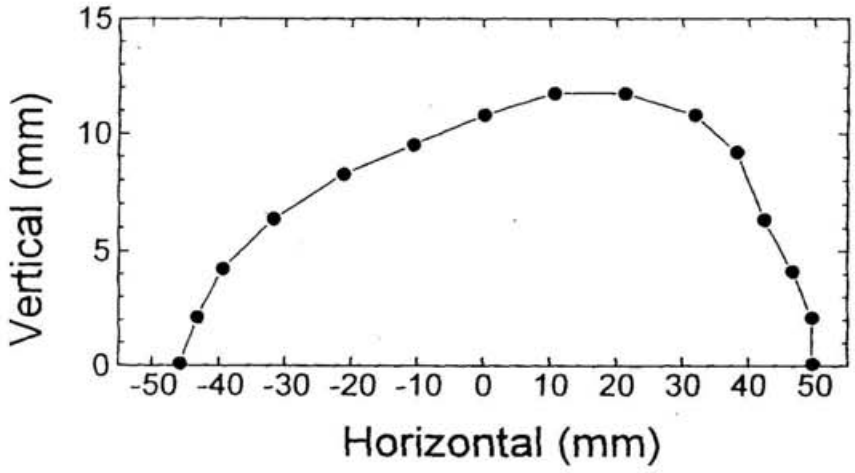


Fig. 38 Dynamic aperture at the injection point

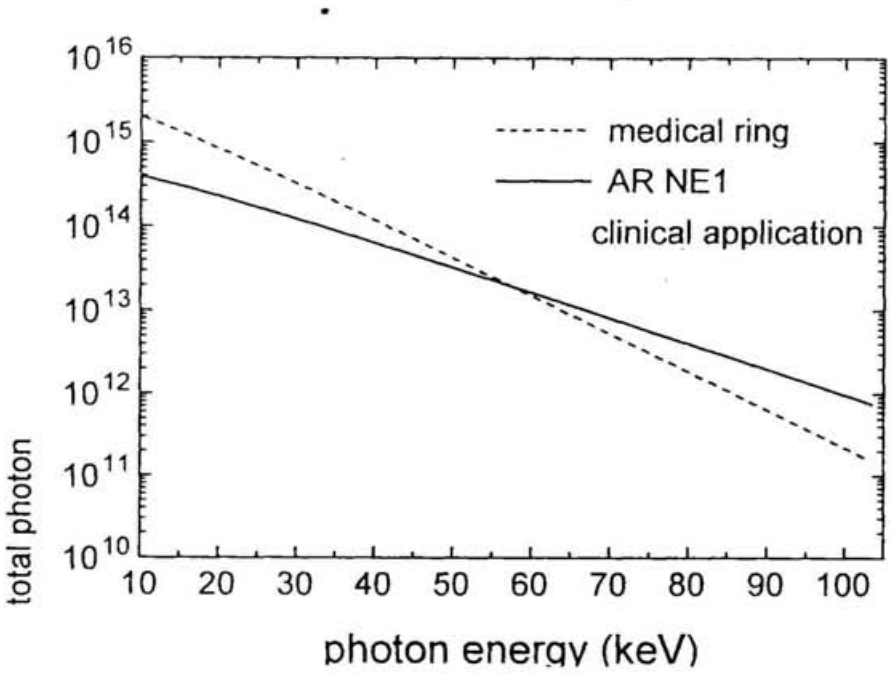


Fig. 39 Synchrotron-radiation spectrum of the above-designed medical ring and of AR NE1 under the condition of the first clinical application of two-dimensional SR coronary angiography

Table 7 Parameters of the storage ring

beam energy	1.5 GeV
beam current	500 mA
magnetic field of insertion device	6.0 T
pole number of insertion device	5 pole
magnetic field of bending magnet	4.0 T
bending radius	1.25 m
bending angle	90°
quadrupole magnet length	30 cm
sextupole magnet length	10 cm
natural emittance	1,970 n m · rad
xy coupling	0.1
beam size σ_x at wiggler & injector	4.2 mm
beam size σ_y at wiggler & injector	0.1 mm
betatron tune ν_x, ν_y	2.150, 1.197
radiation energy loss per turn	428 keV
RF frequency	500 MHz
RF voltage per cavity	700 kV
quadrupole magnet field	
QF	13.1, 12.6 T/m
QD	14.6, 14.5 T/m
QA	12.6 T/m
sextupole magnet field	
SF	75.2 T/m²
SD	154.8 T/m²

4-4 Contrast agent

Iodine is usually used as a contrast agent in x-ray examinations of arteries at hospitals, and was used in the clinical application of coronary angiography using synchrotron radiation (Hyodo K. et al. to be published, Ohtsuka S. et al. to be published). Thus, iodine was adopted as a contrast agent in this image simulation. Recently, the contrast agent of gadolinium has been developed for an NMR examination (Creasy J. L et al. 1990). However, the concentration is very low compared to that of iodine, because of high viscosity of gadolinium. The iodine concentration of the contrast material in clinical coronary angiography using synchrotron radiation was about 5～10% in weight at the coronary arteries (Hyodo K. private communications), and the concentration of gadolinium in the usual NMR examination was less than 1% in weight (Yamasaki K. private communications). Thus, it is difficult to be used in x-ray examinations. If a higher concentration of the gadolinium contrast agent for injection into arteries is developed, it could be effective. Since the K-edge energy of gadolinium is 50.24 keV, a lower exposure to patients is available using monochromatic x-rays of 50.24 keV because of its higher penetration. The differences in the image contrast and exposure between iodine and gadolinium were investigated. The contrast of the artery is obtained by

$$C = 1 - e^{-\mu \cdot \rho \cdot L}, \qquad (14)$$

where C is the contrast, μ is the mass attenuation coefficient (cm^2/g), ρ is the density (g/cm^3), and L is the contrast material path length (cm).

The image contrast when using iodine and gadolinium as contrast materials is given in Table 8. The absorbed energy of attenuated x-rays in the patient's body and the exposure dose per frame are given in Tables 9 and 10. The absorbed energy is given from attenuated x-ray photon number. The exposure is given by equations (12),(13). In the intravenous digital subtraction angiography (DSA) of carotid artery or renal artery at hospitals, 450 frames of images are taken in one imaging of 15 sec, and three imaging from different directions are done in one examination generally. Total exposure with 1,350 frames (450

Table 8 Contrast of an artery filled by a diluted contrast material

Contrast Material	K-edge Energy (keV)	Mass Att. Coefficient (cm^2/g)	Density (g/cm^3)	Att. Coefficient (cm^{-1})	Concentration in Volume (%) *1	Contrast Material Pass Length (cm) *2	Contrast
Iodine	33.17	35.8	4.93	176.5	1.0	1.0×10^{-3}	0.162
Gadolinium	50.24	18.1	7.90	143.0	0.66	6.6×10^{-4}	0.090

*1 Concentration of contrast material in weight in coronary arteries is 5 %.
*2 Diameter of artery is 1 mm.

Table 9 Absorbed energy of attenuated x-rays in the patient's body

Contrast Material	K-edge Energy (keV)	H_2O Mass Att. Coefficient (cm^2/g)	Attenuation *1	Incident Photon No. *2	Absorbed photon No.	Absorbed Energy (J)
Iodine	33.17	0.328	5.26×10^{-3}	3.85×10^{11}	3.83×10^{11}	2.03×10^{-3}
Gadolinium	50.24	0.226	2.69×10^{-2}	4.56×10^{10}	4.44×10^{10}	3.57×10^{-4}

*1 Body thickness (water equivalent) is 160 mm.

*2 Incident photon No. per pixel is 3600, in order to obtain an S/N ratio of 60. Total pixel No. is 5.625×10^5, because the exposure area is 150 mm $\times$ 150 mm and the pixel size of the detector is 0.2 mm $\times$ 0.2 mm. Thus, the total incident photon No. to the detector is 2.025×10^9. The response of the detector (II) at 50.24 keV is 1.65 times as that at 33.17 keV. Thus, the total incident photon No. to the detector is 1.2273×10^9 when gadolinium is used as the contrast agent.

Table 10 Exposure of the patient per frame

Contrast Material	K-edge Energy (keV)	Energy Fluence (J / m^2)	Mass Energy Att. Coefficient (m^2 / kg)	Exposure (C /kg)	Exposure (mR)
Iodine	33.17	0.0908	8.8×10^{-3}	2.37×10^{-5}	91.8
Gadolinium	50.24	0.0163	4.1×10^{-3}	1.98×10^{-6}	7.67

frames × 3 directions) is 3.5×10^{-2} C/kg, because the exposure per frame is about 2.6×10^{-5} C/kg. (Hyodo K. private communication) In case of intravenous coronary angiography using SR from the proposed electron storage ring with iodine as a contrast agent, the exposure per frame is 2.37×10^{-5} C/kg from Table 10. Total exposure in an examination with the same frames as DSA (1,350 frames) is 3.2×10^{-2} C/kg. This exposure is less than usual DSA exposure of 3.5×10^{-2} C/kg.

4-5 Penumbra

When the light-source size is finite, and rays are not parallel, a penumbra is generated in the images, as in Fig. 24. The penumbra size is proportional to the ray beam divergence, and is limited by the projection angle of the beam-source size. In the case of imaging by monochromatic x-rays from synchrotron radiation, the penumbra size is generally negligible, because the beam has a very small divergence. However, the divergence of the diffracted beam is larger in the case of coronary angiography using synchrotron radiation, because a lapped silicon monochromator is used to obtain a high integrated intensity of the x-ray beam. The FWHM of 33.17 keV monochromatic x-rays diffracted by Si(311) with an asymmetric angle of 5 degrees lapped by #1200 abrasives is about 15 arcsec (Shiwaku H. 1992). The angle equals 0.073 mrad. When a white synchrotron radiation beam was monochromatized to 33.17 keV by a Si(311) asymmetric monochromator, the spectral width of diffracted x-rays was 75 eV, as in the experiment at the AR NE5A beamline by Hyodo et al (Hyodo K. private communications). The spectral width is equivalent to 0.27 mrad. The convolution divergence angle (θ_m) of the monochromatic beam's FWMH, and the spectral width of the white beam is 0.35 mrad. The total beam divergence (θ_t) is obtained by the sum of this divergence angle (θ_m) generated at the monochromator and the divergence angle (θ_s) of the original x-ray beam. The horizontal and vertical divergence angles of the irradiated x-ray beam are given in Table 11.

In the case of the first clinical application of SR coronary angiography at the AR NE1 beamline, the horizontal and vertical divergence angles are both less

Table 11 Divergence angles of the x-ray beam

	Beam size $2\sigma_x$ (mm)	Beam size $2\sigma_y$ (mm)	Beamline length (m)	Horizontal θ_s (mrad)	Vertical θ_s (mrad)	Horizontal θ_f (mrad)	Vertical θ_f (mrad)
AR NE1	2.0	0.16	40	0.05	0.004	0.4	0.354
medical ring	8.5	0.22	10	0.85	0.022	1.2	0.372

than 0.4 mrad. In the case of a medical ring dedicated to coronary angiography, the horizontal divergence angle is more than 1 mrad.

Using the developed image simulation program, artery images with an injection beam divergence were generated. They are shown in Figs. 40 and 41. The distance between the acrylic and the detector is 500 mm, and the injecting angle in the horizontal plane is chosen according to the normal distribution. The twice of the standard deviation (2σ) of the normal distribution is from 0 to 1.2 mrad. The differential values of the image profile of Figs. 40 and 41 around the artery are shown in Figs. 42 and 43.

When the standard deviation of the divergence of the incident beam was 0.4 mrad, the penumbra of the artery image was conspicuous. However, when the standard deviation of the injection beam divergence was 1.2 mrad, the edge of the artery image was obviously gradated. Thus, in the case of the clinical application at the AR NE1, although the penumbra was negligible, it deteriorated the image visibility in the case of an examination using the dedicated ring, if the distance from the patient and the detector was set at 500 mm. The images and differential values of the image profile with a distance between the patient and the detector of 100 mm in the case of the standard deviation of the photon-injecting angles of 1.2 mrad (in the case of the medical ring) are shown in Fig. 44. Negligible small penumbra were obtained from the images. Therefore, in the case of using such a dedicated ring, the distance between the patient and the detector should be 100 mm.

4-6 Detector

In this study, an image intensifier TV system was adopted as an x-ray detector for coronary angiography. An image intensifier is suitable for dynamic x-ray imaging, and is used in hospitals as an x-ray examination detector. However, the response of the third higher harmonic (99.51 keV) of the image intensifier is greater than that of 33.17 keV x-rays, as in Fig. 20. Thus, the harmful third higher harmonic is relatively enhanced in the images. When using the imaging plate (IP), its response at 99.51 keV against 33.17 keV is smaller than 1, (Ito M. et al. 1991) and its spatial resolution is higher than that

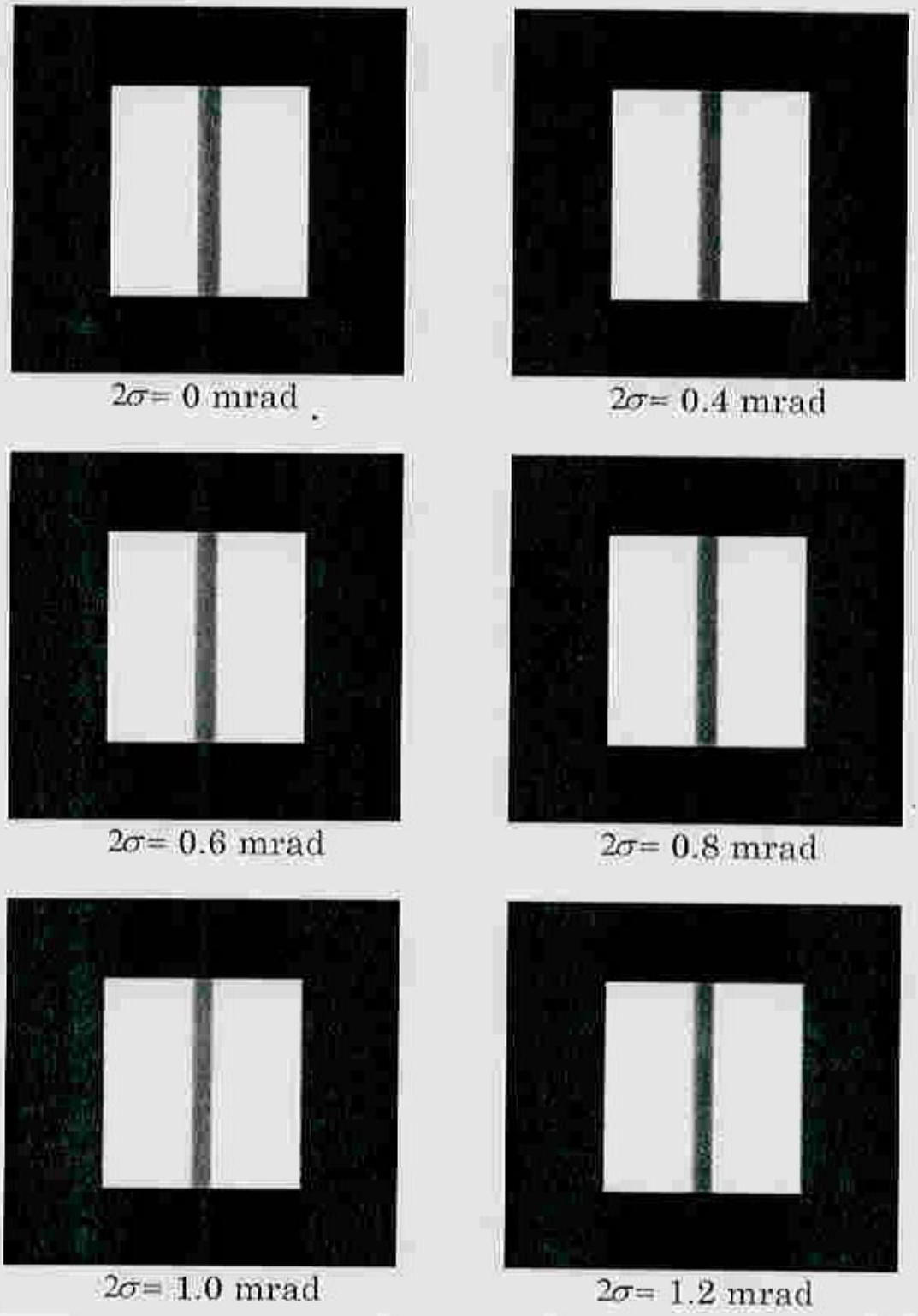


Fig. 40 Simulated images of arteries by 33.17 keV x-ray beams which have various divergences. The distance between the acrylic and the detector is 500 mm, and the injecting angle in the horizontal plane is chosen according to the normal distribution. Twice of the standard deviation (2σ) of the normal distribution is from 0 to 1.2 mrad. The artery diameter is 5 mm.

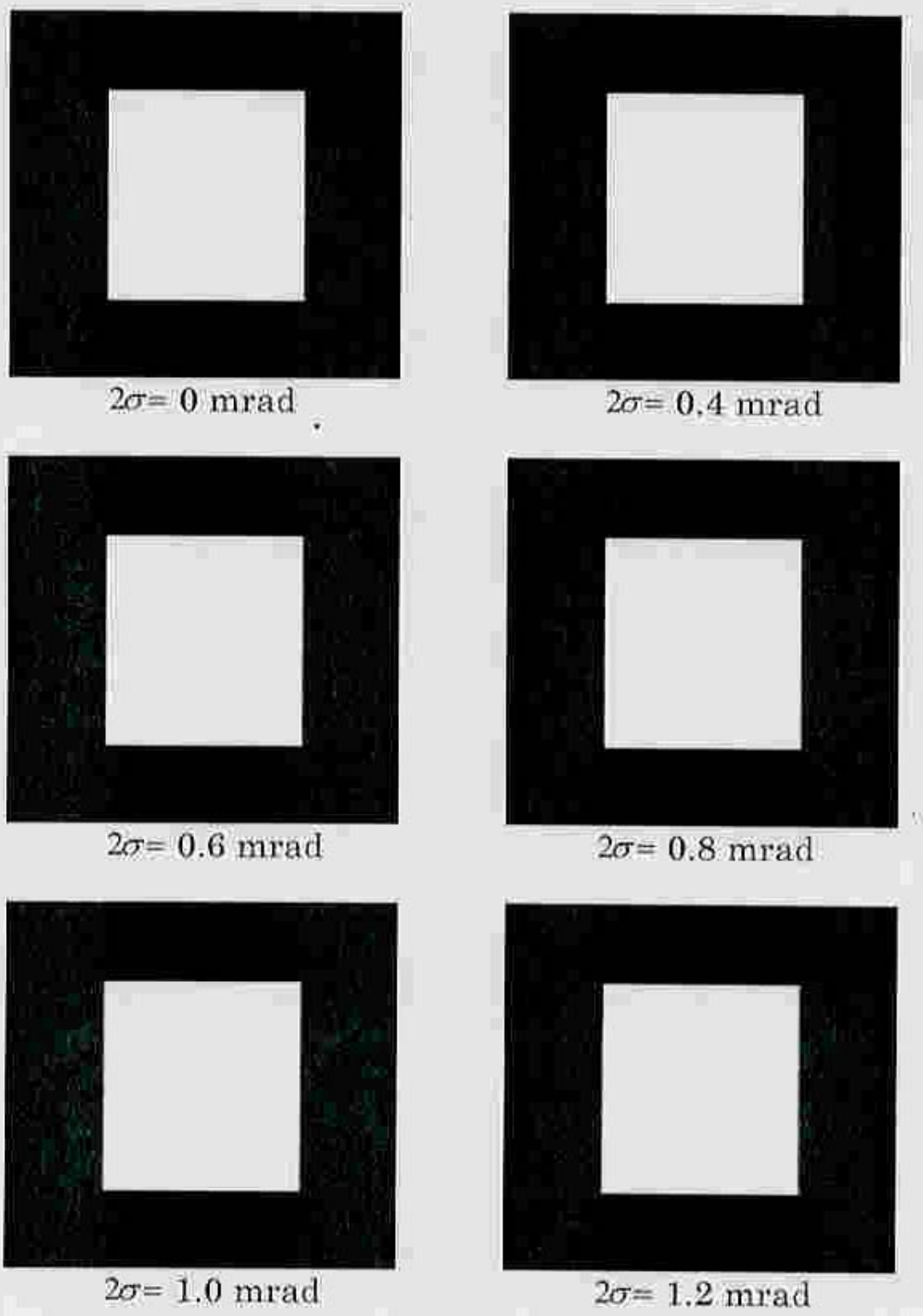


Fig. 41 Simulated images of arteries by 33.17 keV x-ray beams which have various divergences. The distance between the acrylic and the detector is 500 mm, and the injecting angle in the horizontal plane is chosen according to the normal distribution. Twice of the standard deviation (2σ) of the normal distribution is from 0 to 1.2 mrad. The artery diameter is 1 mm.

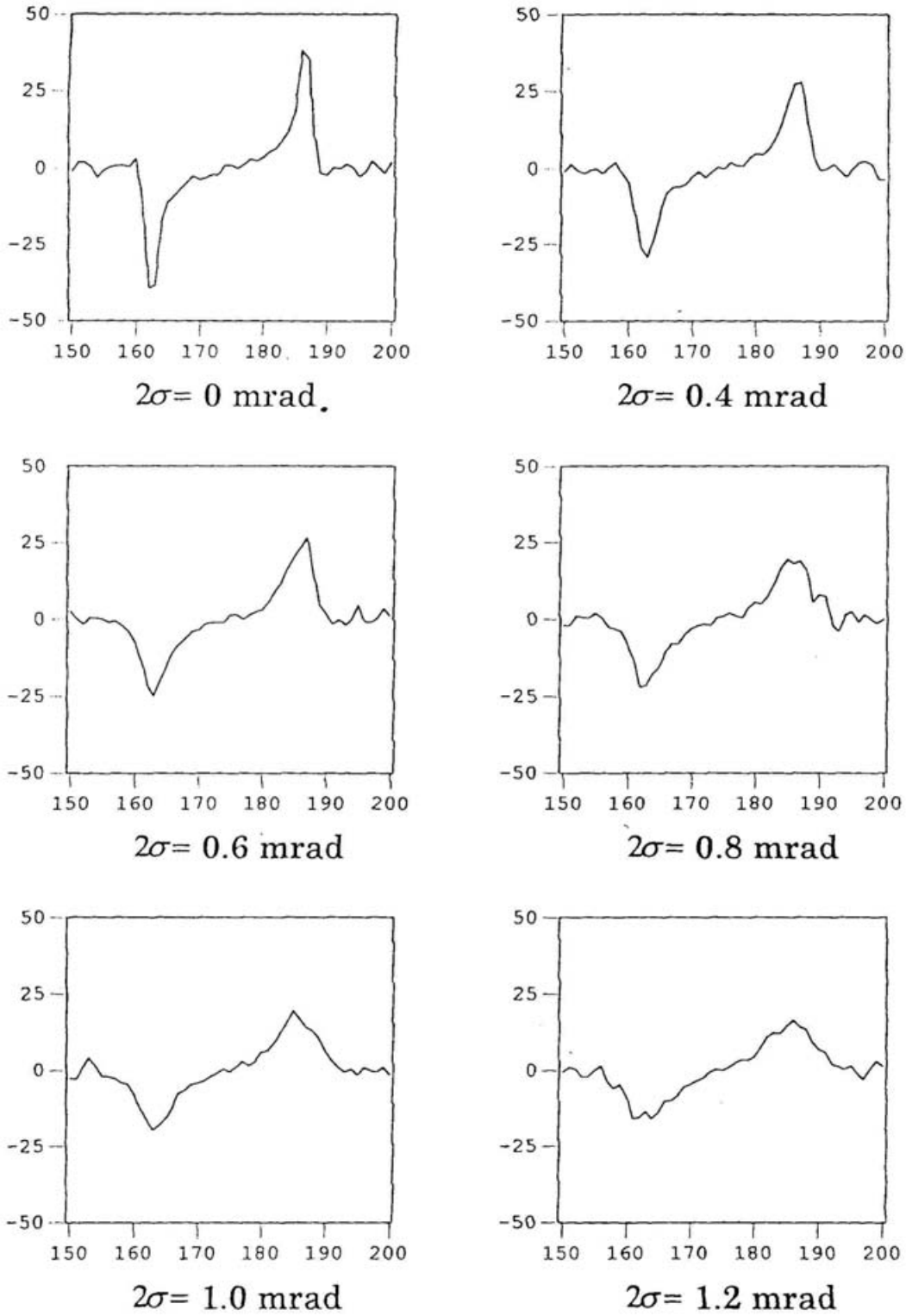


Fig. 42 Profiles of the differential value of images of Fig. 40 around the arteries. The artery diameter is 5 mm.

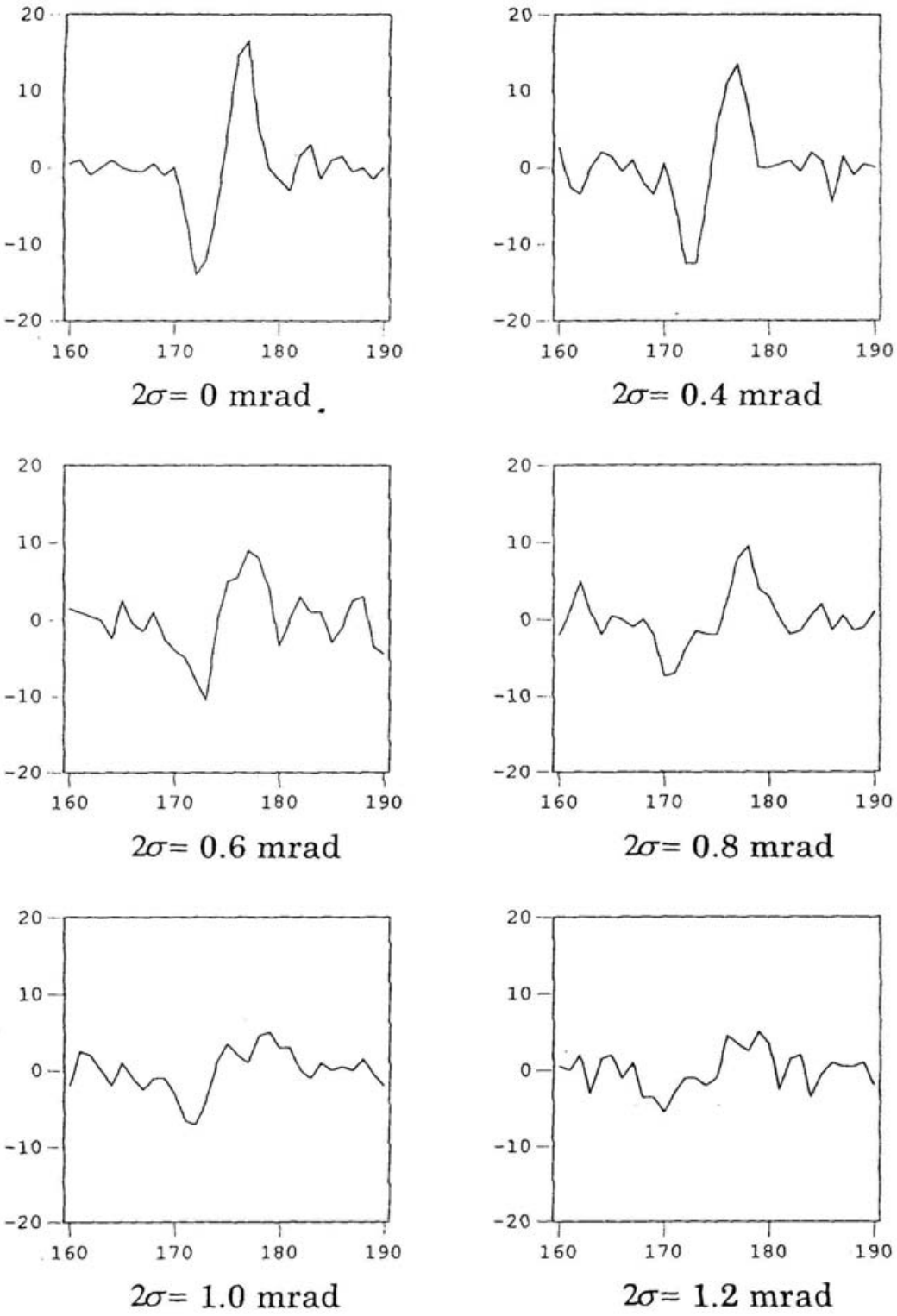


Fig. 43 Profiles of the differential value of images of Fig. 41 around the arteries. The artery diameter is 1 mm.

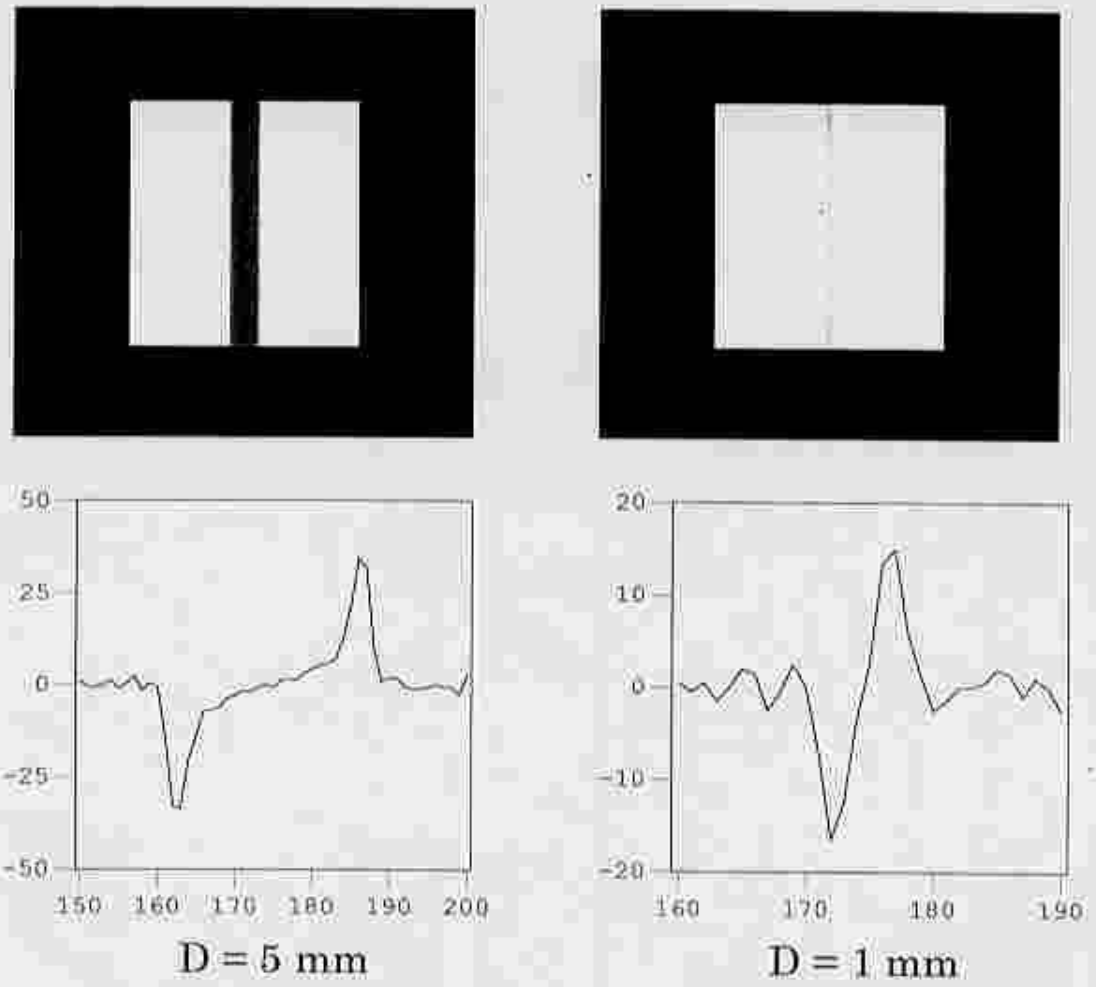


Fig. 44 Simulated images and profiles of their differential value of arteries by 33.17 keV x-ray beams which have various divergences. The distance between the acrylic and the detector is 100 mm, and the injecting angle in the horizontal plane is chosen according to the normal distribution. Twice of the standard deviation (2σ) of the normal distribution is 1.2 mrad. The artery diameters (D) are 5 mm and 1 mm.

of II. Furthermore, since its dynamic range of 10^4 is greater than that of II of 10^3, and its image data are recorded as digital data, it will be a useful detector for the current angiography program, if one can change IP's with fast speed capable of dynamic images.

5. Conclusions

5-1 Summary

Summary regarding image simulation is as follows:

(1) The two-dimensional image simulation program using the Monte Carlo method was developed in order to investigate the influence of harmful scattered x-rays and the third higher harmonic on image contrast.

(2) The simulation program was verified by comparison with results of the experiment and simulation by program code EGS4.

(3) Characteristics of scattered x-rays with various body thickness and exposure area were investigated.

(4) Images in the case without the x-ray grid and with the x-ray grid in ideal clinical conditions were obtained using the simulation program, and the effect of the x-ray grid to improve image contrast was ascertained.

Summary regarding rotating x-ray shutter is as follows: A rotating shutter to produce pulsed x-ray beams was developed for SR coronary angiography, and applied to the clinical application. It was confirmed that dynamic coronary imaging by the pulsed x-ray was possible, and that the irradiation period per one image was reasonable.

Summary regarding coronary angiography system using a dedicated SR source is as follows:

(1) The quantum noise value against the photon flux of iodine K-edge energy from radiation source could be an estimated period, and necessary photon flux was obtained by comparing the standard deviation of quantum noises with artery image contrast.

(2) Characteristics of image contrast and its improvement by x-ray grids against the contamination of the third higher harmonic were investigated by the simulation program, and the allowable contamination limit was determined.

(3) The required specifications of radiation source for SR coronary angiography were obtained from the necessary photon flux, irradiation period per one image

and allowed contamination of the third higher harmonic. They are proposed as a practical radiation source for screening diagnosis of coronary artery by SR angiography.

(4) Conceptual design of the SR source system for coronary angiography with considerations of other system factors such as the beamline element was carried out, and it was proposed as a dedicated system.

5-2 Outcome

Outcome of this study is as follows:

(1) Quantitative characterization of scattered x-rays which were harmful for the two-dimensional coronary imaging method was carried out by investigation of image contrast deterioration by scattered x-rays and the third higher harmonic on image simulation of images made by monochromatic SR x-rays.

(2) A rotating x-ray shutter which generated pulsed x-ray beam and was necessary for two-dimensional SR coronary angiography was developed, and applied to the first clinical examination. The radiation dose whose total per one examination is pointed out as a demerit of the two-dimensional imaging method was suppressed to be minimum physically by the shutter, and the possibility of practical use was shown.

(3) Taking into account the above results and information on the beamline optics, the detectors etc. in the clinical application, the practical synchrotron radiation source system dedicated to medical use was designed using investigations of image characterization.

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Appendix

1. Simulation program list

2. Differential cross section of coherent scattering and incoherent scattering for 33.17 keV and 99.51 keV x-rays

3. Atomic form factor F(x,z)
   and incoherent scattering function S(x,z)
   for 33.17 keV and 99.51 keV x-rays

```
C-------------------------------------------------------------
C      Declarations and Parameters
C-------------------------------------------------------------
      CHARACTER*8 OUTFILEA, OUTFILEG
      CHARACTER*1 NUM1(0:9), CHA(0:10), CALTYPE
      CHARACTER*2 NUM2(0:99)
      CHARACTER*1 DORS, EPHOR
      REAL PI, ME
      REAL XEND, XH2OU, XH2OD, YH2OU, YH2OD, ZH2OU, ZH2OD
      REAL DISTWE
      REAL RFREE, EPHOR33, EPHOR99, LOSEPH
      REAL UNIRAN, TH1
      REAL X0, Y0, XR, YR, Z1, X2, Y2, Z2
      REAL XBAI
      REAL TAU, SIGCOH, SIGINC
      REAL THM(0:1000), PITHOMS(0:99, 0:1000), PIKLNIS(0:99, 0:1000)
      REAL PITHOMSH2O(0:99, 0:1000), PIKLNISH2O(0:99, 0:1000)
      REAL PITHOMSI(0:99, 0:1000), PIKLNISI(0:99, 0:1000)
      REAL PITHOMSWO(0:99, 0:1000), PIKLNISWO(0:99, 0:1000)
      REAL PITHOMSPB(0:99, 0:1000), PIKLNISPB(0:99, 0:1000)
      REAL EPH, LEPH, YEND, ZEND
      REAL FTAU, FSIGCOH, FSIGINC
      REAL LRUN, ETAU, ETAUD
      REAL ENE
      REAL WIB, HIB, YIB, ZIB, WIB2U, WIB2D, HIB2U, HIB2D
      REAL ROUACL, ROUI
      REAL E1X, E1Y, E1Z, E0X, E0Y, E0Z, KX, KY, KZ
      REAL MEWI, MEWH2O, MEWIH2O, MEW, MEWFLOUR
      REAL MEWWO, MEWPB
      REAL LWOI, LWOF, LWOM, LWO, LPBI, LPBF, LPBM, LPB
      REAL LPBEQ, LEQ
      INTEGER NTH, NTRVL, I, J, K
      INTEGER NPHOT
      INTEGER RAN
      INTEGER RANSU(1:10)
      INTEGER LI
      INTEGER CCOH, CINC
      INTEGER DIGIT1, DIGIT2
      INTEGER CD3I, CD3B, CD9I, CD9B, CS3I, CS3B, CS9I, CS9B
      INTEGER CI3I, CI3B, CI9I, CI9B, CF3I, CF3B, CF9I, CF9B
      INTEGER CGD3I, CGD3B, CGD9I, CGD9B, CGS3I, CGS3B, CGS9I, CGS9B
      INTEGER CGI3I, CGI3B, CGI9I, CGI9B, CGF3I, CGF3B, CGF9I, CGF9B
      INTEGER CGG3I, CGG3B, CGG9I, CGG9B
      LOGICAL FELOS, FWOUT, FDOUT, FGOUT, FINCOH, FIBIN, FIARTIN
      LOGICAL F2J, F2JG, FISCAT, FINWO
      LOGICAL FNOPOL
      PARAMETER (PI=3.141592, ME=.511*1E+06)
      PARAMETER (NTH=1000, NTRVL=1000)
      PARAMETER (XH2OD=0.)
      PARAMETER (YH2OU=125., YH2OD=-125., ZH2OU=125., ZH2OD=-125.)
      PARAMETER (YGRIDU=150., YGRIDD=-150., ZGRIDU=150., ZGRIDD=-150.)
      PARAMETER (YDET=70., ZDET=70.)
      PARAMETER (EPHOR33=33.17, EPHOR99=99.51, LOSEPH=10.)
      PARAMETER (EPH12=33.17, EPH23=35.98, EPH34=60.)
      PARAMETER (ROUACL=1.19, ROUI=4.93)
      PARAMETER (ROUWO=0.49, ROUPB=11.34)
      PARAMETER (OMEGAKI=0.882, OMEGAKPB=0.968)
      PARAMETER (RIKA2=53.8, RIKA1=100., RIKB1=29., RIKB2=6.1)
      PARAMETER (RPBKA2=59.3, RPBKA1=100.)
      PARAMETER (RPBKB3=11.6, RPBKB1=22.2, RPBKB2=10.2)
      PARAMETER (EIKA2=28.3172, EIKA1=28.6120, EIKB1=32.3, EIKB2=33.0)
      PARAMETER (EPBKA2=72.804, EPBKA1=74.969)
      PARAMETER (EPBKB3=84.450, EPBKB1=84.936, EPBKB2=87.3)
C-------------------------------------------------------------------
      INTEGER XMAX, YMAX
      INTEGER XSCR, YSCR
      REAL XSCRMAX, YSCRMAX, DENSEMAX
      PARAMETER(XSCRMAX=350., YSCRMAX=350.)
      PARAMETER(XMAX=350, YMAX=350)
      PARAMETER(IMAX=1000000)
      REAL DENSE(XMAX, YMAX), DENSENG(XMAX, YMAX)
      INTEGER JBUFF(XMAX, YMAX, 1)
      PARAMETER (RDAMMY=10.)
      COMMON /GRID/H, DWO, DPB, DBL, XEND, XGRID, XGEND
      COMMON /ANGLE/THM, PITHOMSWO, PIKLNISWO, PITHOMSPB, PIKLNISPB
```

```
      COMMON /RANDAM/RANSU
      COMMON /MEWSIG/MEWWO, SIGCOHWO, SIGINCWO, MEWPB, SIGCOHPB, SIGINCPB
C------------------ Acrylic Attenuation functions ------------------
C       1         2         3         4         5         6         7
      FTAU(X)=3.4777-2.7010*X-.58037*X*X+.44988*X*X*X-.099249*X*X*X*X
     %      -.17341*X*X*X*X*X+.12990*X*X*X*X*X*X-.013523*X*X*X*X*X*X*X
     %      -.014851*X*X*X*X*X*X*X*X+.0053234*X*X*X*X*X*X*X*X*X
     %      -.00050347*X*X*X*X*X*X*X*X*X*X
      FSIGCOH(X)=.54943-1.4373*X+.031150*X*X+.34363*X*X*X-.18688*X*X*X*X
     %      -.083771*X*X*X*X*X+.047459*X*X*X*X*X*X-.0074510*X*X*X*X*X*X*X
     %      +.00053850*X*X*X*X*X*X*X*X+.0037229*X*X*X*X*X*X*X*X*X
     %      -.0013514*X*X*X*X*X*X*X*X*X*X
      FSIGINC(X)=-1.5751+1.2045*X-.29957*X*X-.30516*X*X*X+.14425*X*X*X*X
     %      +.058519*X*X*X*X*X-.068271*X*X*X*X*X*X+.020999*X*X*X*X*X*X*X
     %      +.0051268*X*X*X*X*X*X*X*X-.0063029*X*X*X*X*X*X*X*X*X
     %      +.0013852*X*X*X*X*X*X*X*X*X*X
C------------------ H2O Attenuation functions ------------------
C       1         2         3         4         5         6         7
      FTAUH2O(X)=3.6333-2.6540*X-.47817*X*X+.36500*X*X*X-.26016*X*X*X*X
     %      +.11022*X*X*X*X*X-.025047*X*X*X*X*X*X+.0027131*X*X*X*X*X*X*X
      FSIGCOHH2O(X)=.72275-1.6687*X+.54516*X*X-.12796*X*X*X
     %      -.20230*X*X*X*X+.13069*X*X*X*X*X-.040743*X*X*X*X*X*X
     %      +.0066214*X*X*X*X*X*X*X
      FSIGINCH2O(X)=-1.9590+2.4270*X-1.5951*X*X+.044281*X*X*X
     %      +.46840*X*X*X*X-.22796*X*X*X*X*X+.032741*X*X*X*X*X*X
     %      +.00037069*X*X*X*X*X*X*X
C---------- Iodine Attenuation functions ( TAU ) ----------
C--- over K (150.0keV-33.17keV) ---
C       1         2         3         4         5         6         7
      FTAUIOK(X)=1.4024+4.8165*X-4.7830*X*X+1.2971*X*X*X-.12780*X*X*X*X
C
C--- below K (5.188keV-33.17keV) ---
      FTAUIBK(X)=4.6808-2.2897*X-.18847*X*X
C
C----------  Iodine Attenuation functions ( COH and INC )----------
C       1         2         3         4         5         6         7
      FSIGCOHI(X)=1.1550-.90930*X+.82994*X*X-.75976*X*X*X
     %          +.081096*X*X*X*X+.068894*X*X*X*X*X-.016390*X*X*X*X*X*X
      FSIGINCI(X)=-1.8917+.13499*X+1.2900*X*X-.95821*X*X*X
     %          +.18066*X*X*X*X+.031217*X*X*X*X*X-.011247*X*X*X*X*X*X
C
C--------------------- Wood Attenuation functions ---------------------
C       1         2         3         4         5         6         7
      FTAUWO(X)=3.5236-2.7484*X-.37621*X*X+.27704*X*X*X
     %         -.15634*X*X*X*X-.0094983*X*X*X*X*X+.040787*X*X*X*X*X*X
     %         -.0044162*X*X*X*X*X*X*X-.0048903*X*X*X*X*X*X*X*X
     %         +.000785*X*X*X*X*X*X*X*X+.00014234*X*X*X*X*X*X*X*X*X*X
      FSIGCOHWO(X)=.66777-1.7671*X+.50479*X*X+.10594*X*X*X
     %         -.23882*X*X*X*X-.010028*X*X*X*X*X+.029020*X*X*X*X*X*X
     %         +.0012032*X*X*X*X*X*X*X+.00014212*X*X*X*X*X*X*X*X
     %      -.000059193*X*X*X*X*X*X*X*X*X-.00021609*X*X*X*X*X*X*X*X*X*X
      FSIGINCWO(X)=-1.6426+1.2723*X-.28736*X*X-.31547*X*X*X
     %         +.11111*X*X*X*X+.044465*X*X*X*X*X-.014770*X*X*X*X*X*X
     %         -.0010146*X*X*X*X*X*X*X-.0010616*X*X*X*X*X*X*X*X
     %      -.00064318*X*X*X*X*X*X*X*X*X+.00042586*X*X*X*X*X*X*X*X*X*X
C
C---------- Lead Attenuation functions ( TAU ) ----------
C--- K(130.0keV-88.00keV) ---
C       1         2         3         4         5         6         7
      FTAUPBK(X)=1.6049-6.3643*X+10.364*X*X-5.3968*X*X*X+.84788*X*X*X*X
C
C--- L1(88.00keV-15.86keV) ---
      FTAUPBL1(X)=5.0895-2.2603*X-.13382*X*X
C
C--- L2(15.86keV-15.20keV) ---
      FTAUPBL2(X)=6.5003-4.8770*X+1.0208*X*X
C
C--- L3(15.20keV-13.04keV) ---
      FTAUPBL3(X)=-6.7495+18.147*X-9.0806*X*X
C
C--- M1(13.04keV-5.000keV) ---
      FTAUPBM1(X)=1.0110+5.6711*X-4.4680*X*X
C
C----------  Lead Attenuation functions ( COH and INC )----------
C       1         2         3         4         5         6         7
```

```
      FSIGCOHPB(X)=.84108+.78743*X-1.0856*X*X+.13085*X*X*X
     %          +.040441*X*X*X*X*X-.020131*X*X*X*X*X*X+.0031863*X*X*X*X*X*X*X
      FSIGINCPB(X)=-2.3360+1.0816*X+.061788*X*X-.073134*X*X*X
     %          -.16268*X*X*X*X*X+.10155*X*X*X*X*X*X-.017813*X*X*X*X*X*X*X
C
C------------------- II Response functions ------------------------
      FIIRES1(X)=47.0283-9.45675*X+.559102*X*X-.00836424*X*X*X
      FIIRES2(X)=-15.408+2.237*X
      FIIRES3(X)=-124.362+7.74474*X-.0667544*X*X
      FIIRES4(X)=100.
C-------------------------------------------------------------
C                Read filenames and parameters
C-------------------------------------------------------------
        RIK=RIKA2+RIKA1+RIKB1+RIKB2
        RIKA2KA1=RIKA2/RIK
        RIKA1KB1=(RIKA2+RIKA1)/RIK
        RIKB1KB2=(RIKA2+RIKA1+RIKB1)/RIK
        RPBK=RPBKA2+RPBKA1+RPBKB3+RPBKB1+RPBKB2
        RPBKA2KA1=RPBKA2/RPBK
        RPBKA1KB3=(RPBKA2+RPBKA1)/RPBK
        RPBKB3KB1=(RPBKA2+RPBKA1+RPBKB3)/RPBK
        RPBKB1KB2=(RPBKA2+RPBKA1+RPBKB3+RPBKB1)/RPBK
      OPEN(UNIT=1, FILE='xibvi.inp')
c       WRITE(*,'(A)')' Calculation type charecter?'
       READ(1,'(A1)') CALTYPE
c       WRITE(*,'(A)')' Injection X-ray Photon Number? '
       READ(1,'(I9)') NPHOT
c       WRITE(*,'(A)')' Water thickness (mm)?  Dont forget "."!'
       READ(1,'(F6.2)') XH2OU
c       WRITE(*,'(A)')' Distanse from water to end (mm)? Dont forget "."'
       READ(1,'(F6.2)') DISTWE
        XEND=XH2OU+DISTWE
c       WRITE(*,'(A)')' Injection beam width (mm)? Dont forget "."'
       READ(1,'(F6.2)') WIB
c       WRITE(*,'(A)')' Injection beam height (mm)? Dont forget "."'
       READ(1,'(F6.2)') HIB
c       WRITE(*,'(A)')' 99keV / 33keV ratio in %? Dont forget "."'
       READ(1,'(F6.2)') R99P33P
c       WRITE(*,'(A)')' iodine artery diameter (mm)? Dont forget "."'
       READ(1,'(F6.3)') RI2
c       WRITE(*,'(A)')' iodine weight ratio in %? Dont forget "."'
       READ(1,'(F6.2)') WPER100
c       WRITE(*,'(A)')' Grid thickness (mm)? Dont forget "."'
       READ(1,'(F11.5)') H
c       WRITE(*,'(A)')' Wood pixel size of Grid(mm)? Dont forget "."'
       READ(1,'(F8.3)') DWO
c       WRITE(*,'(A)')' Pb pixel size of Grid(mm)? Dont forget "."'
       READ(1,'(F8.3)') DPB
        DBL=DWO+DPB
c       WRITE(*,'(A)')' Distance form Water to Grid (mm)? Dont forget"."'
       READ(1,'(F8.3)') DISTWG
      CLOSE(1)
       X0=XH2OU/2.
       Y0=0.
       WPER=WPER100*.01
       VPER=WPER/ROU1/((1.-WPER)+WPER/ROU1)
        R99P33=R99P33P/100.
        R33P3399=1./(1.+R99P33)
        RI=RI2/2.
        WIB2U=WIB/2.
        WIB2D=-WIB/2.
        HIB2U=HIB/2.
        HIB2D=-HIB/2.
        WIARTU=Y0+RI
        WIARTD=Y0-RI
        YDETU=YDET/2.
        YDETD=-YDET/2.
        ZDETU=ZDET/2.
        ZDETD=-ZDET/2.
        XGRID=XH2OU+DISTWG
        XGEND=XGRID+H
C+++++++++++++++++++++++++++++++++++++++
         NUM1(0)='0'
         NUM1(1)='1'
         NUM1(2)='2'
```

```
          NUM1(3)='3'
          NUM1(4)='4'
          NUM1(5)='5'
          NUM1(6)='6'
          NUM1(7)='7'
          NUM1(8)='8'
          NUM1(9)='9'
          CHA(1)='x'
          CHA(2)=CALTYPE
          CHA(0)='a'
          CHA(3)='t'
          if(DWO.eq.0.15) CHA(3)='v'
          if(DWO.eq.0.25) CHA(3)='w'
          if(DWO.eq.0.35) CHA(3)='x'
          if(DWO.eq.0.45) CHA(3)='y'
          if(distwe.gt.1000.) then
           cha(4)='z'
          else
           CHA(4)=NUM1(INT(DISTWE/100.))
           if(DISTWE.eq.20.) CHA(4)='9'
          endif
          if(XH2OU.eq.60.) cha(5)='a'
          if(xh2ou.eq.80.) cha(5)='b'
          if(xh2ou.eq.100.) cha(5)='c'
          if(xh2ou.eq.120.) cha(5)='d'
          if(xh2ou.eq.160.) cha(5)='e'
          if(xh2ou.eq.200.) cha(5)='f'
          if(xh2ou.eq.240.) cha(5)='g'
          if(xh2ou.eq.11.) cha(5)='h'
          CHA(8)=NUM1(MOD(INT(R99P33P),10))
          CHA(6)=NUM1(INT(RI2))
          CHA(7)=NUM1(MOD(INT(WPER100),10))
         OUTFILEA=CHA(1)//CHA(2)//CHA(0)//CHA(4)//CHA(5)//CHA(6)//CHA(7)
     %          //CHA(8)
         OUTFILEG=CHA(1)//CHA(2)//CHA(3)//CHA(4)//CHA(5)//CHA(6)//CHA(7)
     %          //CHA(8)
C.............. Read theta kakuritu bunpu integral ..............
        OPEN(UNIT=10, FILE='PIAC3317.DAT')
        OPEN(UNIT=20, FILE='PIHO3317.DAT')
        OPEN(UNIT=30, FILE='PII3317.DAT')
        OPEN(UNIT=40, FILE='PIWO3317.DAT')
        OPEN(UNIT=50, FILE='PIPB3317.DAT')
           READ(10,110) ENE
           READ(20,110) ENE
           READ(30,110) ENE
           READ(40,110) ENE
           READ(50,110) ENE
          J=0
         DO 11 I=1,NTH
           READ(10,100) THM(I),PITHOMS(J,I),PIKLNIS(J,I)
           READ(20,100) THM(I),PITHOMSH2O(J,I),PIKLNISH2O(J,I)
           READ(30,100) THM(I),PITHOMSI(J,I),PIKLNISI(J,I)
           READ(40,100) THM(I),PITHOMSWO(J,I),PIKLNISWO(J,I)
           READ(50,105) THM(I),PITHOMSPB(J,I),PIKLNISPB(J,I)
   11    CONTINUE
         CLOSE(10)
         CLOSE(20)
         CLOSE(30)
         CLOSE(40)
         CLOSE(50)
        OPEN(UNIT=10, FILE='PIAC9951.DAT')
        OPEN(UNIT=20, FILE='PIHO9951.DAT')
        OPEN(UNIT=30, FILE='PII9951.DAT')
        OPEN(UNIT=40, FILE='PIWO9951.DAT')
        OPEN(UNIT=50, FILE='PIPB9951.DAT')
           READ(10,110) ENE
           READ(20,110) ENE
           READ(30,110) ENE
           READ(40,110) ENE
           READ(50,110) ENE
           J=1
         DO 12 I=1,NTH
           READ(10,100) THM(I),PITHOMS(J,I),PIKLNIS(J,I)
           READ(20,100) THM(I),PITHOMSH2O(J,I),PIKLNISH2O(J,I)
           READ(30,100) THM(I),PITHOMSI(J,I),PIKLNISI(J,I)
```

```
          READ(40,100) THM(I),PITHOMSWO(J,I),PIKLNISWO(J,I)
          READ(50,105) THM(I),PITHOMSPB(J,I),PIKLNISPB(J,I)
   12   CONTINUE
        CLOSE(10)
        CLOSE(20)
        CLOSE(30)
        CLOSE(40)
        CLOSE(50)
C---------- Input Number Character ----------------------------
       DO 13 I=10,99
         DIGIT1=MOD(I,10)
         DIGIT2=INT(I/10)
         NUM2(I)=NUM1(DIGIT2)//NUM1(DIGIT1)
   13  CONTINUE
C-------------------------------------------------------------
      DO 15 J=10,99
       OPEN(UNIT=10, FILE='PIAC'//NUM2(J)//'.DAT')
       OPEN(UNIT=20, FILE='PIHO'//NUM2(J)//'.DAT')
       OPEN(UNIT=30, FILE='PII'//NUM2(J)//'.DAT')
       OPEN(UNIT=40, FILE='PIWO'//NUM2(J)//'.DAT')
       OPEN(UNIT=50, FILE='PIPB'//NUM2(J)//'.DAT')
          READ(10,110) ENE
          READ(20,110) ENE
          READ(30,110) ENE
          READ(40,110) ENE
          READ(50,110) ENE
        DO 10 I=1,NTH
          READ(10,100) THM(I),PITHOMS(J,I),PIKLNIS(J,I)
          READ(20,100) THM(I),PITHOMSH2O(J,I),PIKLNISH2O(J,I)
          READ(30,100) THM(I),PITHOMSI(J,I),PIKLNISI(J,I)
          READ(40,100) THM(I),PITHOMSWO(J,I),PIKLNISWO(J,I)
          READ(50,105) THM(I),PITHOMSPB(J,I),PIKLNISPB(J,I)
   10   CONTINUE
        CLOSE(10)
        CLOSE(20)
        CLOSE(30)
        CLOSE(40)
        CLOSE(50)
   15 CONTINUE
  110 FORMAT(F10.5)
  100 FORMAT(F10.7,9X,F10.7,9X,F10.7)
  105 FORMAT(F10.7,9X,F12.7,9X,F12.7)
c      WRITE(*,'(A)') ' Reading file is over'
C-------------------------------------------------------------
C                    Main program
C-------------------------------------------------------------
        CD3I=0
        CD3B=0
        CD9I=0
        CD9B=0
        CS3I=0
        CS3B=0
        CS9I=0
        CS9B=0
        CI3I=0
        CI3B=0
        CI9I=0
        CI9B=0
        CF3I=0
        CF3B=0
        CF9I=0
        CF9B=0
        ETAUTD3I=0.
        ETAUTD3B=0.
        ETAUTD9I=0.
        ETAUTD9B=0.
        ETAUTS3I=0.
        ETAUTS3B=0.
        ETAUTS9I=0.
        ETAUTS9B=0.
        ETAUTI3I=0.
        ETAUTI3B=0.
        ETAUTI9I=0.
        ETAUTI9B=0.
        ETAUTF3I=0.
```

```
ETAUTF3B=0.
ETAUTF9I=0.
ETAUTF9B=0.
ETAUTD3IPSL=0.
ETAUTD3BPSL=0.
ETAUTD9IPSL=0.
ETAUTD9BPSL=0.
ETAUTS3IPSL=0.
ETAUTS3BPSL=0.
ETAUTS9IPSL=0.
ETAUTS9BPSL=0.
ETAUTI3IPSL=0.
ETAUTI3BPSL=0.
ETAUTI9IPSL=0.
ETAUTI9BPSL=0.
ETAUTF3IPSL=0.
ETAUTF3BPSL=0.
ETAUTF9IPSL=0.
ETAUTF9BPSL=0.
CGD3I=0
CGD3B=0
CGD9I=0
CGD9B=0
CGS3I=0
CGS3B=0
CGS9I=0
CGS9B=0
CGI3I=0
CGI3B=0
CGI9I=0
CGI9B=0
CGF3I=0
CGF3B=0
CGF9I=0
CGF9B=0
CGG3I=0
CGG3B=0
CGG9I=0
CGG9B=0
ETAUTGD3I=0.
ETAUTGD3B=0.
ETAUTGD9I=0.
ETAUTGD9B=0.
ETAUTGS3I=0.
ETAUTGS3B=0.
ETAUTGS9I=0.
ETAUTGS9B=0.
ETAUTGI3I=0.
ETAUTGI3B=0.
ETAUTGI9I=0.
ETAUTGI9B=0.
ETAUTGF3I=0.
ETAUTGF3B=0.
ETAUTGF9I=0.
ETAUTGF9B=0.
ETAUTGG3I=0.
ETAUTGG3B=0.
ETAUTGG9I=0.
ETAUTGG9B=0.
ETAUTGD3IPSL=0.
ETAUTGD3BPSL=0.
ETAUTGD9IPSL=0.
ETAUTGD9BPSL=0.
ETAUTGS3IPSL=0.
ETAUTGS3BPSL=0.
ETAUTGS9IPSL=0.
ETAUTGS9BPSL=0.
ETAUTGI3IPSL=0.
ETAUTGI3BPSL=0.
ETAUTGI9IPSL=0.
ETAUTGI9BPSL=0.
ETAUTGF3IPSL=0.
ETAUTGF3BPSL=0.
ETAUTGF9IPSL=0.
ETAUTGF9BPSL=0.
```

```
          ETAUTGG3IPSL=0.
          ETAUTGG3BPSL=0.
          ETAUTGG9IPSL=0.
          ETAUTGG9BPSL=0.
          PSLOR=FIIRES2(EPHOR33)
C--------------- Initial random number ------------------------
        CALL ORRANSU(RANSU)
C------------------ Reperat Injection of X-ray --------------------
        DO 20 I=1,NPHOT
C------------ Initial position of Injected X-ray -------------------
           RAN=RANSU(9)
           CALL NEWRANSU(RAN,UNIRAN)
           RANSU(9)=RAN
          YIB=WIB*(UNIRAN-.5)
           RAN=RANSU(4)
           CALL NEWRANSU(RAN,UNIRAN)
           RANSU(4)=RAN
          ZIB=HIB*(UNIRAN-.5)
          X1=-1.
          Y1=YIB
          Z1=ZIB
          X2=0.
          Y2=YIB
          Z2=ZIB
          TH1=0.
          PHAI1=0.
          ETAU=1.
          CCOH=0
          CINC=0
          FELOS=.FALSE.
          FIBIN=.FALSE.
          F2J=.FALSE.
          F2JG=.FALSE.
          FNOPOL=.FALSE.
           RAN=RANSU(9)
           CALL NEWRANSU(RAN,UNIRAN)
           RANSU(9)=RAN
           IF(UNIRAN.LT.R33P3399) THEN
            EPH=EPHOR33
            EPHOR='3'
           ELSE
            EPH=EPHOR99
            EPHOR='9'
           ENDIF
          DORS='D'
          E0X=0.
          E0Y=1.
          E0Z=0.
           LEPH=LOG10(EPH)
           TAU=FTAU(LEPH)
           TAU=10.**TAU*ROUACL
           ETAUD=EXP(-TAU*(XH2OU-XH2OD)/10.)
C          ( Through rate of direct photons )
C--------------- Repeat of interactions ------------
        DO 30 J=1,NTRVL
C-----------------------------------------------------------
  930     CONTINUE
C-----------------------------------------------------------
          LEPH=LOG10(EPH)
          TAU=FTAU(LEPH)
          SIGCOH=FSIGCOH(LEPH)
          SIGINC=FSIGINC(LEPH)
          TAU=10.**TAU*ROUACL
          SIGCOH=10.**SIGCOH*ROUACL
          SIGINC=10.**SIGINC*ROUACL
          MEW=SIGCOH+SIGINC
C-------------- Decide of free run length -----------------
 7010   CONTINUE
          RAN=RANSU(9)
          CALL NEWRANSU(RAN,UNIRAN)
          RANSU(9)=RAN
        IF(UNIRAN.EQ.0.) GOTO 7010
           RFREE=-10./MEW*ALOG(UNIRAN)
C           ( RFREE UNIT mm )
C---------------- Compute next point ----------------------------
```

```
          OMEGA0D=0.
          CALL NEWCOORD (X1, Y1, Z1, X2, Y2, Z2, E0X, E0Y, E0Z, RFREE, TH1, PHAI1
     %                   ,OMEGA0D)
          IF(OMEGA0D.NE.0.) GOTO 20
C------------------- E-Bector deciding --------------------------------
          KX=X2-X1
          KY=Y2-Y1
          KZ=Z2-Z1
          CALL EDECIDE(E0X, E0Y, E0Z, KX, KY, KZ, E1X, E1Y, E1Z, DELTA0D)
           IF(DELTA0D.EQ.1.) GOTO 20
          E0X=E1X
          E0Y=E1Y
          E0Z=E1Z
c          GOTO 900
C------------ distinction in the iodine or not ----------------------
        AX=X2-X1
        AY=Y2-Y1
        AZ=Z2-Z1
        AXY=SQRT(AX*AX+AY*AY)
      IF(AXY.EQ.0.) GOTO 900
         XR=(AX*AX*X0+AY*AY*X1+AX*AY*(Y0-Y1))/AXY/AXY
         YR=(AY*AY*Y0+AX*AX*Y1+AX*AY*(X0-X1))/AXY/AXY
        CX=XR-X0
        CY=YR-Y0
        CXY=SQRT(CX*CX+CY*CY)
      IF(CXY.GE.RI) GOTO 900
         DXYPAXY=SQRT(RI*RI-CXY*CXY)/AXY
         DX=AX*DXYPAXY
         DY=AY*DXYPAXY
         DZ=AZ*DXYPAXY
         BX=XR-X1
         BY=YR-Y1
      IF((DX*BX+DY*BY).LT.0.) GOTO 900
         BXY=SQRT(BX*BX+BY*BY)
         BZ=AZ/AXY*BXY
         EX=BX-DX
         EY=BY-DY
         EZ=BZ-DZ
         EXYZ=SQRT(EX*EX+EY*EY+EZ*EZ)
      IF(EXYZ.GT.RFREE) GOTO 900
       ETAU=ETAU*EXP(-TAU*EXYZ/10.)
C
C------------------- follow scattering in the iodine --------------------
        DORS='I'
        X2=X1+EX
        Y2=Y1+EY
        Z2=Z1+EZ
      IF(EPH.GE.33.17) THEN
         F2J=.TRUE.
         X1F=X1
         Y1F=Y1
         Z1F=Z1
         X2F=X2
         Y2F=Y2
         Z2F=Z2
         EPHF=EPH
         ETAUF=ETAU
      ENDIF
        TH1=0.
        PHAI1=0.
  910 CONTINUE
         LEPH=LOG10(EPH)
        IF(EPH.GE.33.17) THEN
         TAUI=FTAUIOK(LEPH)
        ELSE
         TAUI=FTAUIBK(LEPH)
        ENDIF
         SIGCOHI=FSIGCOHI(LEPH)
         SIGINCI=FSIGINCI(LEPH)
         TAUH2O=FTAUH2O(LEPH)
         SIGCOHH2O=FSIGCOHH2O(LEPH)
         SIGINCH2O=FSIGINCH2O(LEPH)
         TAUI=10.**TAUI*ROUI
         SIGCOHI=10.**SIGCOHI*ROUI
         SIGINCI=10.**SIGINCI*ROUI
```

```
          TAUH2O=10.**TAUH2O
          SIGCOHH2O=10.**SIGCOHH2O
          SIGINCH2O=10.**SIGINCH2O
          MEWI=SIGCOHI+SIGINCI
          MEWH2O=SIGCOHH2O+SIGINCH2O
          MEWIH2O=MEWI*VPER+MEWH2O*(1.-VPER)
          TAUIH2O=TAUI*VPER+TAUH2O*(1.-VPER)
C------------- Decide of free run length ----------------
 7020   CONTINUE
          RAN=RANSU(9)
          CALL NEWRANSU(RAN,UNIRAN)
          RANSU(9)=RAN
        IF(UNIRAN.EQ.0.) GOTO 7020
           RFREE=-10./MEWIH2O*ALOG(UNIRAN)
C           ( RFREE UNIT mm )
C--------------- Compute next point ----------------------------
          OMEGA0D=0.
          CALL NEWCOORD (X1,Y1,Z1,X2,Y2,Z2,E0X,E0Y,E0Z,RFREE,TH1,PHAI1
     %                  ,OMEGA0D)
          IF(OMEGA0D.NE.0.) GOTO 20
C------------------- E-Bector deciding --------------------------------
          KX=X2-X1
          KY=Y2-Y1
          KZ=Z2-Z1
          CALL EDECIDE(E0X,E0Y,E0Z,KX,KY,KZ,E1X,E1Y,E1Z,DELTA0D)
           IF(DELTA0D.EQ.1.) GOTO 20
          E0X=E1X
          E0Y=E1Y
          E0Z=E1Z
C--------------------------------------------------------------------
            RFRIC=SQRT((X2-X0)*(X2-X0)+(Y2-Y0)*(Y2-Y0))
C----- if P2 is out of artery goto acrylic rootine ------
         IF(RFRIC.GE.RI) THEN
        AX=X2-X1
        AY=Y2-Y1
        AZ=Z2-Z1
        AXY=SQRT(AX*AX+AY*AY)
      IF(AXY.EQ.0.) GOTO 20
         XR=(AX*AX*X0+AY*AY*X1+AX*AY*(Y0-Y1))/AXY/AXY
         YR=(AY*AY*Y0+AX*AX*Y1+AX*AY*(X0-X1))/AXY/AXY
        CX=XR-X0
        CY=YR-Y0
        CXY=SQRT(CX*CX+CY*CY)
      IF(CXY.GE.RI) THEN
         GOTO 20
       ENDIF
         DXYPAXY=SQRT(RI*RI-CXY*CXY)/AXY
         DX=AX*DXYPAXY
         DY=AY*DXYPAXY
           XIOUT=XR+DX
           YIOUT=YR+DY
         IF((X2-X1).EQ.0.) THEN
          IF((Y2-Y1).EQ.0.) GOTO 20
           ZIOUT=(YIOUT-Y1)*(Z2-Z1)/(Y2-Y1)+Z1
         ELSE
           ZIOUT=(XIOUT-X1)*(Z2-Z1)/(X2-X1)+Z1
         ENDIF
           X2=XIOUT
           Y2=YIOUT
           Z2=ZIOUT
           TH1=0.
           PHAI1=0.
           RFREEIL=SQRT((X2-X1)*(X2-X1)+(Y2-Y1)*(Y2-Y1)+(Z2-Z1)*(Z2-Z1))
           ETAU=ETAU*EXP(-TAUIH2O*RFREEIL/10.)
           GOTO 930
         ENDIF
           ETAU=ETAU*EXP(-TAUIH2O*RFREE/10.)
          RAN=RANSU(9)
          CALL NEWRANSU(RAN,UNIRAN)
          RANSU(9)=RAN
           FISCAT=.FALSE.
           IF(UNIRAN.LT.VPER) FISCAT=.TRUE.
           IF(FISCAT) THEN
c the part of disiding scattering angle (SIGINCI,MEWI,PITHOMSI,PIKLNISI)
C------------- Kind of interaction with atom in iodine ---------------
```

```
            FINCOH=.FALSE.
            RAN=RANSU(7)
            CALL NEWRANSU(RAN,UNIRAN)
            RANSU(7)=RAN
C           (Tomson scattering or Compton scattering ?)
            IF (UNIRAN.LT.SIGINCI/MEWI) FINCOH=.TRUE.
            RAN=RANSU(9)
            CALL NEWRANSU(RAN,UNIRAN)
            RANSU(9)=RAN
C           ( Scattering angle )
            TH1=0.
          IF(EPH.EQ.33.17) THEN
            LI=0
            GOTO 1065
          ENDIF
C         ( If photon energy is 33.17keV then use PII9951.DAT data )
          IF(EPH.EQ.99.51) THEN
            LI=1
            GOTO 1065
          ENDIF
C         ( If photon energy is 99.51keV then use PII9951.DAT data )
           LI=INT(EPH)
 1065    CONTINUE
C..............  Compton scattering ..................
         IF (FINCOH) THEN
           CINC=CINC+1
           DO 1072 K2=1,10
             UNIPI=PIKLNISI(LI,K2*100)/PIKLNISI(LI,NTH)
             IF (UNIRAN.LE.UNIPI) THEN
                K100=(K2-1)*100
                GOTO 1092
             ENDIF
 1072      CONTINUE
 1092      CONTINUE
           DO 1071 K1=1,10
             UNIPI=PIKLNISI(LI,K100+K1*10)/PIKLNISI(LI,NTH)
             IF (UNIRAN.LE.UNIPI) THEN
                K10=(K1-1)*10
                GOTO 1091
             ENDIF
 1071      CONTINUE
 1091      CONTINUE
           DO 1070 K=1,10
             UNIPI=PIKLNISI(LI,K100+K10+K)/PIKLNISI(LI,NTH)
             IF (UNIRAN.LE.UNIPI) THEN
                TH1=THM(K100+K10+K)
                GOTO 1090
             ENDIF
 1070      CONTINUE
 1090      CONTINUE
               EPH0=EPH
               EPH=EPH/(1+EPH*1000./ME*(1-COS(TH1)))
                IF (EPH.LE.LOSEPH) THEN
C           ( if energy < min energy , photon is lost )
                  FELOS=.TRUE.
                  GOTO 20
                ENDIF
               EE0E0E=EPH/EPH0+EPH0/EPH
               CALL PHAICOMPT(TH1,PHAI1,RANSU,EE0E0E,FNOPOL)
         ELSE
C..............  Thomson scattering ...................
           CCOH=CCOH+1
           DO 1082 K2=1,10
             UNIPI=PITHOMSI(LI,K2*100)/PITHOMSI(LI,NTH)
             IF (UNIRAN.LE.UNIPI) THEN
                K100=(K2-1)*100
                GOTO 1032
             ENDIF
 1082      CONTINUE
 1032      CONTINUE
           DO 1081 K1=1,10
             UNIPI=PITHOMSI(LI,K100+K1*10)/PITHOMSI(LI,NTH)
             IF (UNIRAN.LE.UNIPI) THEN
                K10=(K1-1)*10
                GOTO 1031
```

```
            ENDIF
 1081     CONTINUE
 1031     CONTINUE
          DO 1080 K=1,10
            UNIPI=PITHOMSI(LI,K100+K10+K)/PITHOMSI(LI,NTH)
            IF (UNIRAN.LE.UNIPI) THEN
               TH1=THM(K100+K10+K)
               GOTO 1033
            ENDIF
 1080     CONTINUE
 1033     CONTINUE
             CALL PHAITHOMS(TH1,PHAI1,RANSU,FNOPOL)
        ENDIF
             ELSE
c the part of disiding scattering angle (SIGINCH2O,MEWH2O,PITHOMSH2O,PIKLNISH2O)
C------------- Kind of interaction with atom in H2O ---------------
          FINCOH=.FALSE.
          RAN=RANSU(7)
          CALL NEWRANSU(RAN,UNIRAN)
          RANSU(7)=RAN
C         (Tomson scattering or Compton scattering ?)
          IF (UNIRAN.LT.SIGINCH2O/MEWH2O) FINCOH=.TRUE.
          RAN=RANSU(9)
          CALL NEWRANSU(RAN,UNIRAN)
          RANSU(9)=RAN
C         ( Scattering angle )
          TH1=0.
        IF(EPH.EQ.33.17) THEN
          LI=0
          GOTO 2065
        ENDIF
C       ( If photon energy is 33.17keV then use PI9951.DAT data )
        IF(EPH.EQ.99.51) THEN
          LI=1
          GOTO 2065
        ENDIF
C       ( If photon energy is 99.51keV then use PI9951.DAT data )
         LI=INT(EPH)
 2065   CONTINUE
C.............. Compton scattering ..................
        IF (FINCOH) THEN
          CINC=CINC+1
          DO 2072 K2=1,10
            UNIPI=PIKLNISH2O(LI,K2*100)/PIKLNISH2O(LI,NTH)
            IF (UNIRAN.LE.UNIPI) THEN
               K100=(K2-1)*100
               GOTO 2092
            ENDIF
 2072     CONTINUE
 2092     CONTINUE
          DO 2071 K1=1,10
            UNIPI=PIKLNISH2O(LI,K100+K1*10)/PIKLNISH2O(LI,NTH)
            IF (UNIRAN.LE.UNIPI) THEN
               K10=(K1-1)*10
               GOTO 2091
            ENDIF
 2071     CONTINUE
 2091     CONTINUE
          DO 2070 K=1,10
            UNIPI=PIKLNISH2O(LI,K100+K10+K)/PIKLNISH2O(LI,NTH)
            IF (UNIRAN.LE.UNIPI) THEN
               TH1=THM(K100+K10+K)
               GOTO 2090
            ENDIF
 2070     CONTINUE
 2090     CONTINUE
             EPH0=EPH
             EPH=EPH/(1+EPH*1000./ME*(1-COS(TH1)))
              IF (EPH.LE.LOSEPH) THEN
C          ( if energy < min energy , photon is lost )
                FELOS=.TRUE.
                GOTO 20
              ENDIF
             EE0E0E=EPH/EPH0+EPH0/EPH
             CALL PHAICOMPT(TH1,PHAI1,RANSU,EE0E0E,FNOPOL)
```

```
      ELSE
C..............  Thomson scattering ...................
         CCOH=CCOH+1
         DO 2082 K2=1,10
           UNIPI=PITHOMSH2O(LI,K2*100)/PITHOMSH2O(LI,NTH)
           IF (UNIRAN.LE.UNIPI) THEN
              K100=(K2-1)*100
              GOTO 2032
           ENDIF
 2082    CONTINUE
 2032    CONTINUE
         DO 2081 K1=1,10
           UNIPI=PITHOMSH2O(LI,K100+K1*10)/PITHOMSH2O(LI,NTH)
           IF (UNIRAN.LE.UNIPI) THEN
              K10=(K1-1)*10
              GOTO 2031
           ENDIF
 2081    CONTINUE
 2031    CONTINUE
         DO 2080 K=1,10
           UNIPI=PITHOMSH2O(LI,K100+K10+K)/PITHOMSH2O(LI,NTH)
           IF (UNIRAN.LE.UNIPI) THEN
              TH1=THM(K100+K10+K)
              GOTO 2033
           ENDIF
 2080    CONTINUE
 2033    CONTINUE
            CALL PHAITHOMS(TH1,PHAI1,RANSU,FNOPOL)
      ENDIF
         ENDIF
        GOTO 910
C---------- flouresent genereting in Iodine ---------------------
  920 CONTINUE
        DORS='F'
        F2J=.FALSE.
        X1=X1F
        Y1=Y1F
        Z1=Z1F
        X2=X2F
        Y2=Y2F
        Z2=Z2F
        EPH=EPHF
        ETAU=ETAUF
        TH1=0.
        PHAI1=0.
         LEPH=LOG10(EPH)
        IF(EPH.GE.33.17) THEN
         TAUI=FTAUIOK(LEPH)
        ELSE
         TAUI=FTAUIBK(LEPH)
        ENDIF
         TAUI=10.**TAUI*ROUI
 7030   CONTINUE
         RAN=RANSU(9)
         CALL NEWRANSU(RAN,UNIRAN)
         RANSU(9)=RAN
       IF(UNIRAN.EQ.0.) GOTO 7030
          RFREE=-10./TAUI/VPER*ALOG(UNIRAN)
C          ( RFREE UNIT mm )
C---------------- Compute next point ----------------------------
        OMEGA0D=0.
        CALL NEWCOORD (X1,Y1,Z1,X2,Y2,Z2,E0X,E0Y,E0Z,RFREE,TH1,PHAI1
     %                ,OMEGA0D)
        IF(OMEGA0D.NE.0.) GOTO 20
C-----------------------------------------------------------------
        RFRIC=SQRT((X2-X0)*(X2-X0)+(Y2-Y0)*(Y2-Y0))
          IF(RFRIC.GE.RI) GOTO 20
        RAN=RANSU(9)
        CALL NEWRANSU(RAN,UNIRAN)
        RANSU(9)=RAN
          IF(UNIRAN.GE.OMEGAKI) GOTO 20
        RAN=RANSU(9)
        CALL NEWRANSU(RAN,UNIRAN)
        RANSU(9)=RAN
          TH1=UNIRAN*PI
```

```
            RAN=RANSU(7)
            CALL NEWRANSU(RAN, UNIRAN)
            RANSU(7)=RAN
              PHAI1=(UNIRAN-.5)*2*PI
            LEPH=LOG10(EPH)
            SIGCOHI=FSIGCOHI(LEPH)
            SIGINCI=FSIGINCI(LEPH)
            TAUH2O=FTAUH2O(LEPH)
            SIGCOHH2O=FSIGCOHH2O(LEPH)
            SIGINCH2O=FSIGINCH2O(LEPH)
            SIGCOHI=10.**SIGCOHI*ROUI
            SIGINCI=10.**SIGINCI*ROUI
            TAUH2O=10.**TAUH2O
            SIGCOHH2O=10.**SIGCOHH2O
            SIGINCH2O=10.**SIGINCH2O
            MEWI=SIGCOHI+SIGINCI
            MEWH2O=TAUH2O+SIGCOHH2O+SIGINCH2O
            MEWFLOUR=MEWI*VPER+MEWH2O*(1.-VPER)
             ETAU=ETAU*EXP(-MEWFLOUR*RFREE)
C---------- deciding flourecent photon energy ----------------------
            RAN=RANSU(9)
            CALL NEWRANSU(RAN, UNIRAN)
            RANSU(9)=RAN
             IF(UNIRAN.LT.RIKA2KA1) THEN
                 EPH=EIKA2
             ELSE
              IF(UNIRAN.LT.RIKA1KB1) THEN
                 EPH=EIKA1
              ELSE
               IF(UNIRAN.LT.RIKB1KB2) THEN
                 EPH=EIKB1
               ELSE
                 EPH=EIKB2
               ENDIF
              ENDIF
             ENDIF
C------------------- No-polarization set ---------------------
            FNOPOL=.TRUE.
C-----------------------------------------------------------------------
            GOTO 910
C------- unless photon pass through iodine artery, come here -------
  900       CONTINUE
C---------------- In the water or not ? -------------------------
              FWOUT=.FALSE.
             IF (X2.GE.XH2OU) FWOUT=.TRUE.
             IF (X2.LE.XH2OD) FWOUT=.TRUE.
             IF (Y2.GE.YH2OU) FWOUT=.TRUE.
             IF (Y2.LE.YH2OD) FWOUT=.TRUE.
             IF (Z2.GE.ZH2OU) FWOUT=.TRUE.
             IF (Z2.LE.ZH2OD) FWOUT=.TRUE.
             IF (FWOUT) GOTO 40
           IF(DORS.EQ.'D') DORS='S'
C------------ Through rate by photo-electron -------------
            ETAU=ETAU*EXP(-TAU*RFREE/10.)
C------------- Kind of interaction with atom ---------------
            FINCOH=.FALSE.
            LEPH=LOG10(EPH)
            TAU=FTAU(LEPH)
            SIGCOH=FSIGCOH(LEPH)
            SIGINC=FSIGINC(LEPH)
            TAU=10.**TAU*ROUACL
            SIGCOH=10.**SIGCOH*ROUACL
            SIGINC=10.**SIGINC*ROUACL
            MEW=SIGCOH+SIGINC
            RAN=RANSU(7)
            CALL NEWRANSU(RAN, UNIRAN)
            RANSU(7)=RAN
C           (Tomson scattering or Compton scattering ?)
            IF (UNIRAN.LT.SIGINC/MEW) FINCOH=.TRUE.
            RAN=RANSU(9)
            CALL NEWRANSU(RAN, UNIRAN)
            RANSU(9)=RAN
C           ( Scattering angle )
            TH1=0.
          IF(EPH.EQ.33.17) THEN
```

```
          LI=0
          GOTO 65
        ENDIF
C       ( If photon energy is 99.51keV then use PIAC9951.DAT data )
        IF(EPH.EQ.99.51) THEN
          LI=1
          GOTO 65
        ENDIF
C       ( If photon energy is 99.51keV then use PIAC9951.DAT data )
         LI=INT(EPH)
   65   CONTINUE
C..............  Compton scattering ..................
       IF (FINCOH) THEN
         CINC=CINC+1
         DO 72 K2=1,10
           UNIPI=PIKLNIS(LI,K2*100)/PIKLNIS(LI,NTH)
           IF (UNIRAN.LE.UNIPI) THEN
              K100=(K2-1)*100
              GOTO 92
           ENDIF
   72    CONTINUE
   92    CONTINUE
         DO 71 K1=1,10
           UNIPI=PIKLNIS(LI,K100+K1*10)/PIKLNIS(LI,NTH)
           IF (UNIRAN.LE.UNIPI) THEN
              K10=(K1-1)*10
              GOTO 91
           ENDIF
   71    CONTINUE
   91    CONTINUE
         DO 70 K=1,10
           UNIPI=PIKLNIS(LI,K100+K10+K)/PIKLNIS(LI,NTH)
           IF (UNIRAN.LE.UNIPI) THEN
              TH1=THM(K100+K10+K)
              GOTO 90
           ENDIF
   70    CONTINUE
   90    CONTINUE
             EPH0=EPH
             EPH=EPH/(1+EPH*1000./ME*(1-COS(TH1)))
              IF (EPH.LE.LOSEPH) THEN
C          ( if energy < min energy , photon is lost )
                FELOS=.TRUE.
                GOTO 20
              ENDIF
             EE0E0E=EPH/EPH0+EPH0/EPH
             CALL PHAICOMPT(TH1,PHAI1,RANSU,EE0E0E,FNOPOL)
       ELSE
C..............  Thomson scattering ..................
         CCOH=CCOH+1
         DO 82 K2=1,10
           UNIPI=PITHOMS(LI,K2*100)/PITHOMS(LI,NTH)
           IF (UNIRAN.LE.UNIPI) THEN
              K100=(K2-1)*100
              GOTO 32
           ENDIF
   82    CONTINUE
   32    CONTINUE
         DO 81 K1=1,10
           UNIPI=PITHOMS(LI,K100+K1*10)/PITHOMS(LI,NTH)
           IF (UNIRAN.LE.UNIPI) THEN
              K10=(K1-1)*10
              GOTO 31
           ENDIF
   81    CONTINUE
   31    CONTINUE
         DO 80 K=1,10
           UNIPI=PITHOMS(LI,K100+K10+K)/PITHOMS(LI,NTH)
           IF (UNIRAN.LE.UNIPI) THEN
              TH1=THM(K100+K10+K)
              GOTO 33
           ENDIF
   80    CONTINUE
   33    CONTINUE
             CALL PHAITHOMS(TH1,PHAI1,RANSU,FNOPOL)
```

```
        ENDIF
   30    CONTINUE
C-------- Count photons which come out yet ------
        GOTO 20
   40    CONTINUE
C--------- Foward scattering or Back scattering ? -----------
         IF (X2.LE.X1) THEN
C        ( Out of water and foward scattering then go next flow )
           GOTO 20
         ENDIF
C--------- Position on the ditecter ---------
           XBAI=(XGRID-X1)/(X2-X1)
           YGRID=Y1+XBAI*(Y2-Y1)
           ZGRID=Z1+XBAI*(Z2-Z1)
C--------- In the ditecter or not ? ---------
           FGOUT=.FALSE.
           IF(YGRID.GE.YGRIDU) FGOUT=.TRUE.
           IF(YGRID.LE.YGRIDD) FGOUT=.TRUE.
           IF(ZGRID.GE.ZGRIDU) FGOUT=.TRUE.
           IF(ZGRID.LE.ZGRIDD) FGOUT=.TRUE.
           IF (FGOUT) THEN
             GOTO 20
           ENDIF
C-------- Calculate the last running distanse in the water ------
           XBAIW=(XH2OU-X1)/(X2-X1)
           XWEND=XH2OU
           YWEND=Y1+XBAIW*(Y2-Y1)
           ZWEND=Z1+XBAIW*(Z2-Z1)
           LRUN=SQRT((XWEND-X1)*(XWEND-X1)+(YWEND-Y1)*(YWEND-Y1)
     %               +(ZWEND-Z1)*(ZWEND-Z1))
C------------ Calculate through rate by last phot-electron ----------
         etaubak=etau
           ETAU=ETAU*EXP(-TAU*LRUN/10.)
c          IF(ETAU.LT..0000001) GOTO 20
C--------- Position on the ditecter ---------
           XBAI=(XEND-X1)/(X2-X1)
           YEND=Y1+XBAI*(Y2-Y1)
           ZEND=Z1+XBAI*(Z2-Z1)
C--------- In the ditecter face or not ? ---------
           FDOUT=.FALSE.
           IF(YEND.GE.YDETU) FDOUT=.TRUE.
           IF(YEND.LE.YDETD) FDOUT=.TRUE.
           IF(ZEND.GE.ZDETU) FDOUT=.TRUE.
           IF(ZEND.LE.ZDETD) FDOUT=.TRUE.
           IF (FDOUT) THEN
             GOTO 7000
           ENDIF
c!!!!!!!!!!!!!!  II response plus  !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
c
           IF(EPH.LT.EPH12) THEN
             PSL=FIIRES1(EPH)
           ELSE
            IF(EPH.LT.EPH23) THEN
              PSL=FIIRES2(EPH)
            ELSE
             IF(EPH.LT.EPH34) THEN
               PSL=FIIRES3(EPH)
             ELSE
               PSL=FIIRES4(EPH)
             ENDIF
            ENDIF
           ENDIF
c
c!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
cYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYY
         XSCR=INT((YEND+YDET/2.)/YDET*XSCRMAX)+1
         YSCR=INT((ZEND+ZDET/2.)/ZDET*YSCRMAX)+1
         IF(XSCR.LT.1) goto 8000
         IF(YSCR.LT.1) goto 8000
         IF(XSCR.GT.INT(XSCRMAX)) goto 8000
         IF(YSCR.GT.INT(YSCRMAX)) goto 8000
         DENSENG(XSCR,YSCR)=DENSENG(XSCR,YSCR)+ETAU*PSL/PSLOR
cYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYY
C@@@@@@@@@@@@@@@  Photon count in front of the Grid  @@@@@@@@@@@@@@@@@@@
         IF(EPHOR.EQ.'3') THEN
```

```
      IF(DORS.EQ.'S') THEN
       FIBIN=.FALSE.
       IF((YGRID.LE.WIB2U).AND.(YGRID.GE.WIB2D).AND.
     %    (ZGRID.LE.HIB2U).AND.(ZGRID.GE.HIB2D)) FIBIN=.TRUE.
        IF (FIBIN) THEN
         FIARTIN=.FALSE.
         IF((YGRID.LE.WIARTU).AND.(YGRID.GE.WIARTD)) FIARTIN=.TRUE.
          IF(FIARTIN) THEN
             CS3I=CS3I+1
             ETAUTS3I=ETAUTS3I+ETAU
             ETAUTS3IPSL=ETAUTS3IPSL+ETAU*PSL/PSLOR
          ELSE
             CS3B=CS3B+1
             ETAUTS3B=ETAUTS3B+ETAU
             ETAUTS3BPSL=ETAUTS3BPSL+ETAU*PSL/PSLOR
          ENDIF
        ENDIF
      ENDIF
      IF(DORS.EQ.'D') THEN
       FIBIN=.FALSE.
       IF((YGRID.LE.WIB2U).AND.(YGRID.GE.WIB2D).AND.
     %    (ZGRID.LE.HIB2U).AND.(ZGRID.GE.HIB2D)) FIBIN=.TRUE.
        IF (FIBIN) THEN
         FIARTIN=.FALSE.
         IF((YGRID.LE.WIARTU).AND.(YGRID.GE.WIARTD)) FIARTIN=.TRUE.
          IF(FIARTIN) THEN
             CD3I=CD3I+1
             ETAUTD3I=ETAUTD3I+ETAU
             ETAUTD3IPSL=ETAUTD3IPSL+ETAU*PSL/PSLOR
          ELSE
             CD3B=CD3B+1
             ETAUTD3B=ETAUTD3B+ETAU
             ETAUTD3BPSL=ETAUTD3BPSL+ETAU*PSL/PSLOR
          ENDIF
        ENDIF
      ENDIF
      IF(DORS.EQ.'I') THEN
       FIBIN=.FALSE.
       IF((YGRID.LE.WIB2U).AND.(YGRID.GE.WIB2D).AND.
     %    (ZGRID.LE.HIB2U).AND.(ZGRID.GE.HIB2D)) FIBIN=.TRUE.
        IF (FIBIN) THEN
         FIARTIN=.FALSE.
         IF((YGRID.LE.WIARTU).AND.(YGRID.GE.WIARTD)) FIARTIN=.TRUE.
          IF(FIARTIN) THEN
             CI3I=CI3I+1
             ETAUTI3I=ETAUTI3I+ETAU
             ETAUTI3IPSL=ETAUTI3IPSL+ETAU*PSL/PSLOR
          ELSE
             CI3B=CI3B+1
             ETAUTI3B=ETAUTI3B+ETAU
             ETAUTI3BPSL=ETAUTI3BPSL+ETAU*PSL/PSLOR
          ENDIF
        ENDIF
      ENDIF
      IF(DORS.EQ.'F') THEN
       FIBIN=.FALSE.
       IF((YGRID.LE.WIB2U).AND.(YGRID.GE.WIB2D).AND.
     %    (ZGRID.LE.HIB2U).AND.(ZGRID.GE.HIB2D)) FIBIN=.TRUE.
        IF (FIBIN) THEN
         FIARTIN=.FALSE.
         IF((YGRID.LE.WIARTU).AND.(YGRID.GE.WIARTD)) FIARTIN=.TRUE.
          IF(FIARTIN) THEN
             CF3I=CF3I+1
             ETAUTF3I=ETAUTF3I+ETAU
             ETAUTF3IPSL=ETAUTF3IPSL+ETAU*PSL/PSLOR
          ELSE
             CF3B=CS3B+1
             ETAUTF3B=ETAUTF3B+ETAU
             ETAUTF3BPSL=ETAUTF3BPSL+ETAU*PSL/PSLOR
          ENDIF
        ENDIF
      ENDIF
     ELSE
      IF(DORS.EQ.'S') THEN
       FIBIN=.FALSE.
```

```
          IF((YGRID.LE.WIB2U).AND.(YGRID.GE.WIB2D).AND.
     %       (ZGRID.LE.HIB2U).AND.(ZGRID.GE.HIB2D)) FIBIN=.TRUE.
           IF (FIBIN) THEN
            FIARTIN=.FALSE.
            IF((YGRID.LE.WIARTU).AND.(YGRID.GE.WIARTD)) FIARTIN=.TRUE.
             IF(FIARTIN) THEN
                CS9I=CS9I+1
                ETAUTS9I=ETAUTS9I+ETAU
                ETAUTS9IPSL=ETAUTS9IPSL+ETAU*PSL/PSLOR
             ELSE
                CS9B=CS9B+1
                ETAUTS9B=ETAUTS9B+ETAU
                ETAUTS9BPSL=ETAUTS9BPSL+ETAU*PSL/PSLOR
             ENDIF
            ENDIF
           ENDIF
           IF(DORS.EQ.'D') THEN
            FIBIN=.FALSE.
            IF((YGRID.LE.WIB2U).AND.(YGRID.GE.WIB2D).AND.
     %       (ZGRID.LE.HIB2U).AND.(ZGRID.GE.HIB2D)) FIBIN=.TRUE.
             IF (FIBIN) THEN
              FIARTIN=.FALSE.
              IF((YGRID.LE.WIARTU).AND.(YGRID.GE.WIARTD)) FIARTIN=.TRUE.
               IF(FIARTIN) THEN
                  CD9I=CD9I+1
                  ETAUTD9I=ETAUTD9I+ETAU
                  ETAUTD9IPSL=ETAUTD9IPSL+ETAU*PSL/PSLOR
               ELSE
                  CD9B=CD9B+1
                  ETAUTD9B=ETAUTD9B+ETAU
                  ETAUTD9BPSL=ETAUTD9BPSL+ETAU*PSL/PSLOR
               ENDIF
             ENDIF
           ENDIF
           IF(DORS.EQ.'I') THEN
            FIBIN=.FALSE.
            IF((YGRID.LE.WIB2U).AND.(YGRID.GE.WIB2D).AND.
     %       (ZGRID.LE.HIB2U).AND.(ZGRID.GE.HIB2D)) FIBIN=.TRUE.
             IF (FIBIN) THEN
              FIARTIN=.FALSE.
              IF((YGRID.LE.WIARTU).AND.(YGRID.GE.WIARTD)) FIARTIN=.TRUE.
               IF(FIARTIN) THEN
                  CI9I=CI9I+1
                  ETAUTI9I=ETAUTI9I+ETAU
                  ETAUTI9IPSL=ETAUTI9IPSL+ETAU*PSL/PSLOR
               ELSE
                  CI9B=CI9B+1
                  ETAUTI9B=ETAUTI9B+ETAU
                  ETAUTI9BPSL=ETAUTI9BPSL+ETAU*PSL/PSLOR
               ENDIF
             ENDIF
           ENDIF
           IF(DORS.EQ.'F') THEN
            FIBIN=.FALSE.
            IF((YGRID.LE.WIB2U).AND.(YGRID.GE.WIB2D).AND.
     %       (ZGRID.LE.HIB2U).AND.(ZGRID.GE.HIB2D)) FIBIN=.TRUE.
             IF (FIBIN) THEN
              FIARTIN=.FALSE.
              IF((YGRID.LE.WIARTU).AND.(YGRID.GE.WIARTD)) FIARTIN=.TRUE.
               IF(FIARTIN) THEN
                  CF9I=CF9I+1
                  ETAUTF9I=ETAUTF9I+ETAU
                  ETAUTF9IPSL=ETAUTF9IPSL+ETAU*PSL/PSLOR
               ELSE
                  CF9B=CS9B+1
                  ETAUTF9B=ETAUTF9B+ETAU
                  ETAUTF9BPSL=ETAUTF9BPSL+ETAU*PSL/PSLOR
               ENDIF
             ENDIF
           ENDIF
 8000 continue
C$$$$$$$$$$$$$$$$$$$  Grid Passing Routine  $$$$$$$$$$$$$$$$$$$$$$$$$$
 7000 CONTINUE
       GOTO 1020
```

```
C---------- flouresent genereting in Pb --------------------
 1010 CONTINUE
        IF(DPB.EQ.0.) GOTO 20
         DORS='G'
         F2JG=.FALSE.
         X1=X1FG
         Y1=Y1FG
         Z1=Z1FG
         X2=X2FG
         Y2=Y2FG
         Z2=Z2FG
         EPH=EPHFG
         ETAU=ETAUFG
         TH1=0.
         PHAI1=0.
            CALL AHEADPASS(X1,Y1,Z1,X2,Y2,Z2,NBL,
     %                    LWOI,LWOF,LWOM,LWO,LPBI,LPBF,LPBM,LPB)
        IF(LPB.EQ.0.) GOTO 20
          LEPH=LOG10(EPH)
          TAUPB=FTAUPBK(LEPH)
          TAUPB=10.**TAUPB*ROUPB
          TAUWO=FTAUWO(LEPH)
          TAUWO=10.**TAUWO*ROUWO
          LPBEQ=LPB*TAUPB/TAUWO
          LEQ=LWO+LPBEQ
C------------- Decide of free run length ----------------
          RAN=RANSU(9)
          CALL NEWRANSU(RAN,UNIRAN)
          RANSU(9)=RAN
            RFREE=-10./TAUWO*ALOG(UNIRAN)
C           ( RFREE UNIT mm )
C-----------------------------------------------------------------------
            IF(RFREE.GE.LEQ) GOTO 20
            CALL XPOSITION(RFREE,TAUWO,TAUPB,NBL,X1,Y1,Z1,X2,Y2,Z2,
     %                     LWOI,LWOF,LWOM,LWO,LPBI,LPBF,LPBM,LPB)
C-----------------------------------------------------------------------
          NBL1=INT(Y1/DBL)
          POBL1=Y1-DBL*REAL(NBL1)
          FINWO=.FALSE.
          IF(POBL1.LT.DWO) FINWO=.TRUE.
          IF(FINWO) GOTO 20
          RAN=RANSU(9)
          CALL NEWRANSU(RAN,UNIRAN)
          RANSU(9)=RAN
            IF(UNIRAN.GE.OMEGAKPB) GOTO 20
          LEPH=LOG10(EPH)
          SIGCOHPB=FSIGCOHPB(LEPH)
          SIGINCPB=FSIGINCPB(LEPH)
          SIGCOHWO=FSIGCOHWO(LEPH)
          SIGINCWO=FSIGINCWO(LEPH)
          SIGCOHPB=10.**SIGCOHPB*ROUPB
          SIGINCPB=10.**SIGINCPB*ROUPB
          SIGCOHWO=10.**SIGCOHWO*ROUWO
          SIGINCWO=10.**SIGINCWO*ROUWO
          MEWPB=SIGCOHPB+SIGINCPB
          MEWWO=SIGCOHWO+SIGINCWO
          MEWFLOURG=MEWPB*LPB+MEWWO*LWO
           ETAU=ETAU*EXP(-MEWFLOURG*RFREE)
          RAN=RANSU(9)
          CALL NEWRANSU(RAN,UNIRAN)
          RANSU(9)=RAN
            TH1=UNIRAN*PI
          RAN=RANSU(7)
          CALL NEWRANSU(RAN,UNIRAN)
          RANSU(7)=RAN
            PHAI1=(UNIRAN-.5)*2*PI
C---------------- Compute next point -----------------------------
          OMEGA0D=0.
          CALL NEWCOORD (X1,Y1,Z1,X2,Y2,Z2,E0X,E0Y,E0Z,RFREE,TH1,PHAI1
     %                  ,OMEGA0D)
          IF(OMEGA0D.NE.0.) GOTO 20
C---------- deciding flourecent photon energy ----------------------
          RAN=RANSU(9)
          CALL NEWRANSU(RAN,UNIRAN)
          RANSU(9)=RAN
```

```
            IF(UNIRAN.LT.RPBKA2KA1) THEN
                EPH=EPBKA2
            ELSE
             IF(UNIRAN.LT.RPBKA1KB3) THEN
                EPH=EPBKA1
             ELSE
              IF(UNIRAN.LT.RPBKB3KB1) THEN
                EPH=EPBKB3
              ELSE
               IF(UNIRAN.LT.RPBKB1KB2) THEN
                EPH=EPBKB1
               ELSE
                EPH=EPBKB2
               ENDIF
              ENDIF
             ENDIF
            ENDIF
C------------------- No-polarization set ----------------------
            FNOPOL=.TRUE.
C--------------------------------------------------------------------------------
c++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
 1020       CONTINUE
          IF(EPH.GE.88.) THEN
            F2JG=.TRUE.
            X1FG=X1
            Y1FG=Y1
            Z1FG=Z1
            X2FG=X2
            Y2FG=Y2
            Z2FG=Z2
            EPHFG=EPH
            ETAUFG=ETAU
          ENDIF
c..... correct from XWEND to XGRID .........
            X2=XGRID
            Y2=YGRID
            Z2=ZGRID
c.....................................................
 1000       CONTINUE
           IF(X1.EQ.X2) THEN
             GOTO 20
           ENDIF
           IF(X1.LT.X2) THEN
             CALL AHEADPASS(X1,Y1,Z1,X2,Y2,Z2,NBL,
     %                      LWOI,LWOF,LWOM,LWO,LPBI,LPBF,LPBM,LPB)
           ELSE
             CALL BACKPASS(X1,Y1,Z1,X2,Y2,Z2,NBL,
     %                      LWOI,LWOF,LWOM,LWO,LPBI,LPBF,LPBM,LPB)
           ENDIF
C-------------------------------------------------------------
           LEPH=LOG10(EPH)
           TAUWO=FTAUWO(LEPH)
           SIGCOHWO=FSIGCOHWO(LEPH)
           SIGINCWO=FSIGINCWO(LEPH)
           TAUWO=10.**TAUWO*ROUWO
           SIGCOHWO=10.**SIGCOHWO*ROUWO
           SIGINCWO=10.**SIGINCWO*ROUWO
           MEWWO=SIGCOHWO+SIGINCWO
C.....................................................
       IF(EPH.GT.88.00) THEN
           TAUPB=FTAUPBK(LEPH)
       ELSE
        IF(EPH.GT.15.86) THEN
           TAUPB=FTAUPBL1(LEPH)
        ELSE
         IF(EPH.GT.15.20) THEN
           TAUPB=FTAUPBL2(LEPH)
         ELSE
          IF(EPH.GT.13.04) THEN
           TAUPB=FTAUPBL3(LEPH)
          ELSE
           TAUPB=FTAUPBM1(LEPH)
          ENDIF
         ENDIF
        ENDIF
```

```
      ENDIF
C
          SIGCOHPB=FSIGCOHPB(LEPH)
          SIGINCPB=FSIGINCPB(LEPH)
C.....................................................
          TAUPB=10.**TAUPB*ROUPB
          SIGCOHPB=10.**SIGCOHPB*ROUPB
          SIGINCPB=10.**SIGINCPB*ROUPB
          MEWPB=SIGCOHPB+SIGINCPB
C-------------------------------------------------------
          LPBEQ=LPB*MEWPB/MEWWO
          LEQ=LWO+LPBEQ
C------------- Decide of free run length ----------------
          RAN=RANSU(9)
          CALL NEWRANSU(RAN,UNIRAN)
          RANSU(9)=RAN
            RFREE=-10./MEWWO*ALOG(UNIRAN)
C           ( RFREE UNIT mm )
C-----------------------------------------------------------------
        IF (RFREE.LT.LEQ) THEN
            CALL XPOSITION(RFREE, MEWWO, MEWPB, NBL, X1, Y1, Z1, X2, Y2, Z2,
     %                     LWOI, LWOF, LWOM, LWO, LPBI, LPBF, LPBM, LPB)
            ETAU=ETAU*EXP(-TAUWO*LWO/10.-TAUPB*LPB/10.)
            IF (ETAU.LT.1.E-8) THEN
               GOTO 20
            ENDIF
C-----------------------------------------------------------------
            CALL SCANGLE(TH1, PHAI1, EPH, FELOS, Y1, FNOPOL)
             IF(FELOS) THEN
               GOTO 20
             ENDIF
C---------------- Compute ahead point ---------------------------------
          AX=X2-X1
          AY=Y2-Y1
          AZ=Z2-Z1
          DA=SQRT(AX*AX+AY*AY+AZ*AZ)
           IF(DA.LE.0.) THEN
             GOTO 20
           ENDIF
C---------------- Compute next point ----------------------------------
          OMEGA0D=0.
          CALL NEWCOORD (X1, Y1, Z1, X2, Y2, Z2, E0X, E0Y, E0Z, RDAMMY, TH1, PHAI1
     %                  ,OMEGA0D)
          IF(OMEGA0D.NE.0.) GOTO 20
C------------------- E-Bector deciding ------------------------------
          KX=X2-X1
          KY=Y2-Y1
          KZ=Z2-Z1
          CALL EDECIDE(E0X, E0Y, E0Z, KX, KY, KZ, E1X, E1Y, E1Z, DELTA0D)
           IF(DELTA0D.EQ.1.) GOTO 20
          E0X=E1X
          E0Y=E1Y
          E0Z=E1Z
C-----------------------------------------------------------------
            X3=X1-(X2-X1)
            Y3=Y1-(Y2-Y1)
            Z3=Z1-(Z2-Z1)
            X2=X1
            Y2=Y1
            Z2=Z1
            X1=X3
            Y1=Y3
            Z1=Z3
           GOTO 1000
        ENDIF
         IF(X1.GE.X2) THEN
           GOTO 20
         ENDIF
C--------- Position on the ditecter ---------
           XBAI=(XEND-X1)/(X2-X1)
           YEND=Y1+XBAI*(Y2-Y1)
           ZEND=Z1+XBAI*(Z2-Z1)
C--------- In the ditecter face or not ? ---------
            FDOUT=.FALSE.
           IF(YEND.GE.YDETU) FDOUT=.TRUE.
```

```
           IF(YEND.LE.YDETD) FDOUT=.TRUE.
           IF(ZEND.GE.ZDETU) FDOUT=.TRUE.
           IF(ZEND.LE.ZDETD) FDOUT=.TRUE.
            IF (FDOUT) THEN
               GOTO 20
            ENDIF
C.......................................................
           ETAU=ETAU*EXP(-TAUWO*LWO/10.-TAUPB*LPB/10.)
c$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
c!!!!!!!!!!!!!!  II response plus  !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
c
            IF(EPH.LT.EPH12) THEN
                PSL=FIIRES1(EPH)
            ELSE
             IF(EPH.LT.EPH23) THEN
                PSL=FIIRES2(EPH)
             ELSE
              IF(EPH.LT.EPH34) THEN
                PSL=FIIRES3(EPH)
              ELSE
                PSL=FIIRES4(EPH)
              ENDIF
             ENDIF
            ENDIF
c
c!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
cYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYY
         XSCR=INT((YEND+YDET/2.)/YDET*XSCRMAX)+1
         YSCR=INT((ZEND+ZDET/2.)/ZDET*YSCRMAX)+1
         IF(XSCR.LT.1) goto 8100
         IF(YSCR.LT.1) goto 8100
         IF(XSCR.GT.INT(XSCRMAX)) goto 8100
         IF(YSCR.GT.INT(YSCRMAX)) goto 8100
         DENSE(XSCR,YSCR)=DENSE(XSCR,YSCR)+ETAU*PSL/PSLOR
cYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYY
C@@@@@@@@@@@@@@  Photon count after passing the Grid  @@@@@@@@@@@@@@@@@@@
         IF(EPHOR.EQ.'3') THEN
          IF(DORS.EQ.'S') THEN
           FIBIN=.FALSE.
           IF((YEND.LE.WIB2U).AND.(YEND.GE.WIB2D).AND.
     %        (ZEND.LE.HIB2U).AND.(ZEND.GE.HIB2D)) FIBIN=.TRUE.
            IF (FIBIN) THEN
             FIARTIN=.FALSE.
             IF((YEND.LE.WIARTU).AND.(YEND.GE.WIARTD)) FIARTIN=.TRUE.
              IF(FIARTIN) THEN
                 CGS3I=CGS3I+1
                 ETAUTGS3I=ETAUTGS3I+ETAU
                 ETAUTGS3IPSL=ETAUTGS3IPSL+ETAU*PSL/PSLOR
              ELSE
                 CGS3B=CGS3B+1
                 ETAUTGS3B=ETAUTGS3B+ETAU
                 ETAUTGS3BPSL=ETAUTGS3BPSL+ETAU*PSL/PSLOR
              ENDIF
            ENDIF
          ENDIF
          IF(DORS.EQ.'D') THEN
           FIBIN=.FALSE.
           IF((YEND.LE.WIB2U).AND.(YEND.GE.WIB2D).AND.
     %        (ZEND.LE.HIB2U).AND.(ZEND.GE.HIB2D)) FIBIN=.TRUE.
            IF (FIBIN) THEN
             FIARTIN=.FALSE.
             IF((YEND.LE.WIARTU).AND.(YEND.GE.WIARTD)) FIARTIN=.TRUE.
              IF(FIARTIN) THEN
                 CGD3I=CGD3I+1
                 ETAUTGD3I=ETAUTGD3I+ETAU
                 ETAUTGD3IPSL=ETAUTGD3IPSL+ETAU*PSL/PSLOR
              ELSE
                 CGD3B=CGD3B+1
                 ETAUTGD3B=ETAUTGD3B+ETAU
                 ETAUTGD3BPSL=ETAUTGD3BPSL+ETAU*PSL/PSLOR
              ENDIF
            ENDIF
          ENDIF
          IF(DORS.EQ.'I') THEN
           FIBIN=.FALSE.
```

```
      IF((YEND.LE.WIB2U).AND.(YEND.GE.WIB2D).AND.
%        (ZEND.LE.HIB2U).AND.(ZEND.GE.HIB2D)) FIBIN=.TRUE.
       IF (FIBIN) THEN
        FIARTIN=.FALSE.
        IF((YEND.LE.WIARTU).AND.(YEND.GE.WIARTD)) FIARTIN=.TRUE.
         IF(FIARTIN) THEN
            CGI3I=CGI3I+1
            ETAUTGI3I=ETAUTGI3I+ETAU
            ETAUTGI3IPSL=ETAUTGI3IPSL+ETAU*PSL/PSLOR
         ELSE
            CGI3B=CGI3B+1
            ETAUTGI3B=ETAUTGI3B+ETAU
            ETAUTGI3BPSL=ETAUTGI3BPSL+ETAU*PSL/PSLOR
         ENDIF
       ENDIF
      ENDIF
      IF(DORS.EQ.'F') THEN
       FIBIN=.FALSE.
       IF((YEND.LE.WIB2U).AND.(YEND.GE.WIB2D).AND.
%        (ZEND.LE.HIB2U).AND.(ZEND.GE.HIB2D)) FIBIN=.TRUE.
       IF (FIBIN) THEN
        FIARTIN=.FALSE.
        IF((YEND.LE.WIARTU).AND.(YEND.GE.WIARTD)) FIARTIN=.TRUE.
         IF(FIARTIN) THEN
            CGF3I=CGF3I+1
            ETAUTGF3I=ETAUTGF3I+ETAU
            ETAUTGF3IPSL=ETAUTGF3IPSL+ETAU*PSL/PSLOR
         ELSE
            CGF3B=CGF3B+1
            ETAUTGF3B=ETAUTGF3B+ETAU
            ETAUTGF3BPSL=ETAUTGF3BPSL+ETAU*PSL/PSLOR
         ENDIF
       ENDIF
      ENDIF
      IF(DORS.EQ.'G') THEN
       FIBIN=.FALSE.
       IF((YEND.LE.WIB2U).AND.(YEND.GE.WIB2D).AND.
%        (ZEND.LE.HIB2U).AND.(ZEND.GE.HIB2D)) FIBIN=.TRUE.
       IF (FIBIN) THEN
        FIARTIN=.FALSE.
        IF((YEND.LE.WIARTU).AND.(YEND.GE.WIARTD)) FIARTIN=.TRUE.
         IF(FIARTIN) THEN
            CGG3I=CGG3I+1
            ETAUTGG3I=ETAUTGG3I+ETAU
            ETAUTGG3IPSL=ETAUTGG3IPSL+ETAU*PSL/PSLOR
         ELSE
            CGG3B=CGG3B+1
            ETAUTGG3B=ETAUTGG3B+ETAU
            ETAUTGG3BPSL=ETAUTGG3BPSL+ETAU*PSL/PSLOR
         ENDIF
       ENDIF
      ENDIF
     ELSE
      IF(DORS.EQ.'S') THEN
       FIBIN=.FALSE.
       IF((YEND.LE.WIB2U).AND.(YEND.GE.WIB2D).AND.
%        (ZEND.LE.HIB2U).AND.(ZEND.GE.HIB2D)) FIBIN=.TRUE.
       IF (FIBIN) THEN
        FIARTIN=.FALSE.
        IF((YEND.LE.WIARTU).AND.(YEND.GE.WIARTD)) FIARTIN=.TRUE.
         IF(FIARTIN) THEN
            CGS9I=CGS9I+1
            ETAUTGS9I=ETAUTGS9I+ETAU
            ETAUTGS9IPSL=ETAUTGS9IPSL+ETAU*PSL/PSLOR
         ELSE
            CGS9B=CGS9B+1
            ETAUTGS9B=ETAUTGS9B+ETAU
            ETAUTGS9BPSL=ETAUTGS9BPSL+ETAU*PSL/PSLOR
         ENDIF
       ENDIF
      ENDIF
      IF(DORS.EQ.'D') THEN
       FIBIN=.FALSE.
       IF((YEND.LE.WIB2U).AND.(YEND.GE.WIB2D).AND.
%        (ZEND.LE.HIB2U).AND.(ZEND.GE.HIB2D)) FIBIN=.TRUE.
```

```
              IF (FIBIN) THEN
               FIARTIN=.FALSE.
               IF((YEND.LE.WIARTU).AND.(YEND.GE.WIARTD)) FIARTIN=.TRUE.
                IF(FIARTIN) THEN
                   CGD9I=CGD9I+1
                   ETAUTGD9I=ETAUTGD9I+ETAU
                   ETAUTGD9IPSL=ETAUTGD9IPSL+ETAU*PSL/PSLOR
                ELSE
                   CGD9B=CGD9B+1
                   ETAUTGD9B=ETAUTGD9B+ETAU
                   ETAUTGD9BPSL=ETAUTGD9BPSL+ETAU*PSL/PSLOR
                ENDIF
              ENDIF
             ENDIF
             IF(DORS.EQ.'I') THEN
              FIBIN=.FALSE.
              IF((YEND.LE.WIB2U).AND.(YEND.GE.WIB2D).AND.
     %           (ZEND.LE.HIB2U).AND.(ZEND.GE.HIB2D)) FIBIN=.TRUE.
               IF (FIBIN) THEN
                FIARTIN=.FALSE.
                IF((YEND.LE.WIARTU).AND.(YEND.GE.WIARTD)) FIARTIN=.TRUE.
                 IF(FIARTIN) THEN
                    CGI9I=CGI9I+1
                    ETAUTGI9I=ETAUTGI9I+ETAU
                    ETAUTGI9IPSL=ETAUTGI9IPSL+ETAU*PSL/PSLOR
                 ELSE
                    CGI9B=CGI9B+1
                    ETAUTGI9B=ETAUTGI9B+ETAU
                    ETAUTGI9BPSL=ETAUTGI9BPSL+ETAU*PSL/PSLOR
                 ENDIF
               ENDIF
             ENDIF
             IF(DORS.EQ.'F') THEN
              FIBIN=.FALSE.
              IF((YEND.LE.WIB2U).AND.(YEND.GE.WIB2D).AND.
     %           (ZEND.LE.HIB2U).AND.(ZEND.GE.HIB2D)) FIBIN=.TRUE.
               IF (FIBIN) THEN
                FIARTIN=.FALSE.
                IF((YEND.LE.WIARTU).AND.(YEND.GE.WIARTD)) FIARTIN=.TRUE.
                 IF(FIARTIN) THEN
                    CGF9I=CGF9I+1
                    ETAUTGF9I=ETAUTGF9I+ETAU
                    ETAUTGF9IPSL=ETAUTGF9IPSL+ETAU*PSL/PSLOR
                 ELSE
                    CGF9B=CGF9B+1
                    ETAUTGF9B=ETAUTGF9B+ETAU
                    ETAUTGF9BPSL=ETAUTGF9BPSL+ETAU*PSL/PSLOR
                 ENDIF
               ENDIF
             ENDIF
             IF(DORS.EQ.'G') THEN
              FIBIN=.FALSE.
              IF((YEND.LE.WIB2U).AND.(YEND.GE.WIB2D).AND.
     %           (ZEND.LE.HIB2U).AND.(ZEND.GE.HIB2D)) FIBIN=.TRUE.
               IF (FIBIN) THEN
                FIARTIN=.FALSE.
                IF((YEND.LE.WIARTU).AND.(YEND.GE.WIARTD)) FIARTIN=.TRUE.
                 IF(FIARTIN) THEN
                    CGG9I=CGG9I+1
                    ETAUTGG9I=ETAUTGG9I+ETAU
                    ETAUTGG9IPSL=ETAUTGG9IPSL+ETAU*PSL/PSLOR
                 ELSE
                    CGG9B=CGG9B+1
                    ETAUTGG9B=ETAUTGG9B+ETAU
                    ETAUTGG9BPSL=ETAUTGG9BPSL+ETAU*PSL/PSLOR
                 ENDIF
               ENDIF
              ENDIF
             ENDIF
C$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
 8100 continue
      IF(F2J) GOTO 920
      IF(F2JG) GOTO 1010
   20 CONTINUE
C¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥ no grid int data output ¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥
```

```
        DENSEMAX=0.
        DO 51 YSCR=1,YMAX
          DO 56 XSCR=1,XMAX
            IF(DENSENG(XSCR,YSCR).GT.DENSEMAX)
     %          DENSEMAX=DENSENG(XSCR,YSCR)
 56       CONTINUE
 51     CONTINUE
C-----------------------------------------------------------
C       Output data
C-----------------------------------------------------------
        DO 67 YSCR=1,YMAX
          DO 66 XSCR=1,XMAX
            DENSENG(XSCR,YSCR)=DENSENG(XSCR,YSCR)/DENSEMAX*255.99
            JBUFF(XSCR,YSCR,1)=INT(DENSENG(XSCR,YSCR))
 66       CONTINUE
 67     CONTINUE
       OPEN (UNIT=1,FILE=OUTFILEA//'.mat')
        DO YSCR=1,YMAX
            WRITE(1,210) (JBUFF(XSCR,YSCR,1),XSCR=1,XMAX)
        ENDDO
       CLOSE(1)
 210   FORMAT(' ',1000(I3,','),I3)
c¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥ with grid int data output ¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥
        DENSEMAX=0.
        DO 50 YSCR=1,YMAX
          DO 55 XSCR=1,XMAX
            IF(DENSE(XSCR,YSCR).GT.DENSEMAX) DENSEMAX=DENSE(XSCR,YSCR)
 55       CONTINUE
 50     CONTINUE
C-----------------------------------------------------------
C       Output data
C-----------------------------------------------------------
        DO 60 YSCR=1,YMAX
          DO 61 XSCR=1,XMAX
            DENSE(XSCR,YSCR)=DENSE(XSCR,YSCR)/DENSEMAX*255.99
            JBUFF(XSCR,YSCR,1)=INT(DENSE(XSCR,YSCR))
 61       CONTINUE
 60     CONTINUE
       OPEN (UNIT=1,FILE=OUTFILEG//'.mat')
        DO YSCR=1,YMAX
            WRITE(1,210) (JBUFF(XSCR,YSCR,1),XSCR=1,XMAX)
        ENDDO
       CLOSE(1)
c¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥¥
      OPEN (UNIT=1,FILE=OUTFILEG//'.num')
        WRITE(1,301) XH2OU
        WRITE(1,302) DISTWE
        WRITE(1,531) DISTWG
        WRITE(1,303) WIB
        WRITE(1,304) HIB
        WRITE(1,305) YDET
        WRITE(1,306) ZDET
        WRITE(1,307) R99P33P
        WRITE(1,308) RI2
        WRITE(1,309) WPER100
        WRITE(1,300)
        WRITE(1,530) H
        WRITE(1,540) DWO
        WRITE(1,545) DPB
        WRITE(1,300)
        WRITE(1,310) NPHOT
        WRITE(1,300)
        WRITE(1,380)
        WRITE(1,350)
        WRITE(1,351)
        WRITE(1,360) CD3I,CD3B,CD9I,CD9B
        WRITE(1,361) CS3I,CS3B,CS9I,CS9B
        WRITE(1,362) CI3I,CI3B,CI9I,CI9B
        WRITE(1,363) CF3I,CF3B,CF9I,CF9B
        WRITE(1,300)
        WRITE(1,381)
        WRITE(1,350)
        WRITE(1,351)
        WRITE(1,364) ETAUTD3I,ETAUTD3B,ETAUTD9I,ETAUTD9B
        WRITE(1,365) ETAUTS3I,ETAUTS3B,ETAUTS9I,ETAUTS9B
```

```
      WRITE(1,366) ETAUTI3I,ETAUTI3B,ETAUTI9I,ETAUTI9B
      WRITE(1,367) ETAUTF3I,ETAUTF3B,ETAUTF9I,ETAUTF9B
      WRITE(1,300)
      WRITE(1,391)
      WRITE(1,350)
      WRITE(1,351)
      WRITE(1,364) ETAUTD3IPSL,ETAUTD3BPSL,ETAUTD9IPSL,ETAUTD9BPSL
      WRITE(1,365) ETAUTS3IPSL,ETAUTS3BPSL,ETAUTS9IPSL,ETAUTS9BPSL
      WRITE(1,366) ETAUTI3IPSL,ETAUTI3BPSL,ETAUTI9IPSL,ETAUTI9BPSL
      WRITE(1,367) ETAUTF3IPSL,ETAUTF3BPSL,ETAUTF9IPSL,ETAUTF9BPSL
      WRITE(1,300)
      WRITE(1,382)
      WRITE(1,350)
      WRITE(1,351)
      WRITE(1,360) CGD3I,CGD3B,CGD9I,CGD9B
      WRITE(1,361) CGS3I,CGS3B,CGS9I,CGS9B
      WRITE(1,362) CGI3I,CGI3B,CGI9I,CGI9B
      WRITE(1,363) CGF3I,CGF3B,CGF9I,CGF9B
      WRITE(1,369) CGG3I,CGG3B,CGG9I,CGG9B
      WRITE(1,300)
      WRITE(1,383)
      WRITE(1,350)
      WRITE(1,351)
      WRITE(1,364) ETAUTGD3I,ETAUTGD3B,ETAUTGD9I,ETAUTGD9B
      WRITE(1,365) ETAUTGS3I,ETAUTGS3B,ETAUTGS9I,ETAUTGS9B
      WRITE(1,366) ETAUTGI3I,ETAUTGI3B,ETAUTGI9I,ETAUTGI9B
      WRITE(1,367) ETAUTGF3I,ETAUTGF3B,ETAUTGF9I,ETAUTGF9B
      WRITE(1,368) ETAUTGG3I,ETAUTGG3B,ETAUTGG9I,ETAUTGG9B
      WRITE(1,300)
      WRITE(1,393)
      WRITE(1,350)
      WRITE(1,351)
      WRITE(1,364) ETAUTGD3IPSL,ETAUTGD3BPSL,ETAUTGD9IPSL,ETAUTGD9BPSL
      WRITE(1,365) ETAUTGS3IPSL,ETAUTGS3BPSL,ETAUTGS9IPSL,ETAUTGS9BPSL
      WRITE(1,366) ETAUTGI3IPSL,ETAUTGI3BPSL,ETAUTGI9IPSL,ETAUTGI9BPSL
      WRITE(1,367) ETAUTGF3IPSL,ETAUTGF3BPSL,ETAUTGF9IPSL,ETAUTGF9BPSL
      WRITE(1,368) ETAUTGG3IPSL,ETAUTGG3BPSL,ETAUTGG9IPSL,ETAUTGG9BPSL
      WRITE(1,300)
      WRITE(1,389)
      WRITE(1,384)
      WRITE(1,385)
      WRITE(1,386)
      WRITE(1,387)
      WRITE(1,388)
      WRITE(1,389)
      CLOSE(1)
300   FORMAT(' ')
310   FORMAT(' ','Total Photons     =',I10)
301   FORMAT(' ','Water Thickness                =',F7.1)
302   FORMAT(' ','Distanse from Water to Detector =',F7.1)
531   FORMAT(' ','Distanse from Water to Grid face=',F7.1)
303   FORMAT(' ','Injection beam width (mm)      =',F7.2)
304   FORMAT(' ','Injection beam height (mm)     =',F7.2)
305   FORMAT(' ','Detector width (mm)            =',F7.2)
306   FORMAT(' ','Detector height (mm)           =',F7.2)
307   FORMAT(' ','99keV / 33keV ratio in %       =',F7.2)
308   FORMAT(' ','iodine artery diameter (mm)    =',F7.2)
309   FORMAT(' ','iodine weight ratio in %       =',F7.2)
530   FORMAT(' ','Grid thickness (mm)            =',F7.3)
540   FORMAT(' ','Wood pixel size of Grid (mm)   =',F7.3)
545   FORMAT(' ','Pb pixel size of Grid (mm)     =',F7.3)
380   FORMAT(' ','*** Photon count in front of Grid ***')
381   FORMAT(' ','*** Total photons in front of Grid (Real)   ***')
391   FORMAT(' ','*** Total photons in front of Grid (II res) ***')
382   FORMAT(' ','*** Photon count after passing Grid ***')
383   FORMAT(' ','*** Total photons after passing Grid (Real)   ***')
393   FORMAT(' ','*** Total photons after passing Grid (II res) ***')
384   FORMAT(' ',' D : Direct photons in the beam area')
385   FORMAT(' ',' S : Scattering photons in the beam area')
386   FORMAT(' ',' I : Photons passing Iodine in the beam area')
387   FORMAT(' ',' F : Iodine flouresence photons in the beam area')
388   FORMAT(' ',' G : Grid flouresence photons in the beam area')
389   FORMAT(' ','-------------------------------------------------')
350   FORMAT(' ','DorS',8X,'33.17 keV ',16X,'99.51 keV')
351   FORMAT(5X,' in Artery   out Artery    in Artery   out Artery')
```

```
  360   FORMAT(' ',' D  ',I10,3X,I10,3X,I10,3X,I10)
  361   FORMAT(' ',' S  ',I10,3X,I10,3X,I10,3X,I10)
  362   FORMAT(' ',' I  ',I10,3X,I10,3X,I10,3X,I10)
  363   FORMAT(' ',' F  ',I10,3X,I10,3X,I10,3X,I10)
  369   FORMAT(' ',' G  ',I10,3X,I10,3X,I10,3X,I10)
  364   FORMAT(' ',' D  ',F11.3,2X,F11.3,2X,F11.3,2X,F11.3)
  365   FORMAT(' ',' S  ',F11.3,2X,F11.3,2X,F11.3,2X,F11.3)
  366   FORMAT(' ',' I  ',F11.3,2X,F11.3,2X,F11.3,2X,F11.3)
  367   FORMAT(' ',' F  ',F11.3,2X,F11.3,2X,F11.3,2X,F11.3)
  368   FORMAT(' ',' G  ',F11.3,2X,F11.3,2X,F11.3,2X,F11.3)
      STOP
      END
C
C*************************************************************************
C               Culculate initial random number
C-------------------------------------------------------
      SUBROUTINE ORRANSU(RANSU)
       INTEGER RANSU(1:10),AMARI
       REAL UNIRAN,MU
       PARAMETER (MU=2.0**31)
        DO 10 I=1,10
          UNIRAN=REAL(I)*0.1
          RANSU(I)=INT(UNIRAN*MU)
          AMARI=MOD(RANSU(I),2)
          IF (AMARI.EQ.0) RANSU(I)=RANSU(I)+1
   10   CONTINUE
      RETURN
      END
CC************************************************************************
C             Calculation next random number
C-------------------------------------------------------
      SUBROUTINE NEWRANSU(RAN,UNIRAN)
        REAL UNIRAN,MU
        INTEGER RAN,LAM,C,T30
        PARAMETER (LAM=843314861,C=453816693,T30=2**30,MU=2.0**31)
        RAN=LAM*RAN+C
        IF (RAN.LT.0) RAN=(RAN+T30)+T30
        UNIRAN=REAL(RAN)/MU
      RETURN
      END
CC************************************************************************
C               E-Bector deciding
C-----------------------------------------------------------------
      SUBROUTINE EDECIDE(E0X,E0Y,E0Z,KX,KY,KZ,E1X,E1Y,E1Z,DELTA0D)
        REAL E1X,E1Y,E1Z,E0X,E0Y,E0Z,KX,KY,KZ
        DELTA0D=0.
        E0K=E0X*KX+E0Y*KY+E0Z*KZ
      IF(E0K.LT.0.0001) THEN
        E1X=E0X
        E1Y=E0Y
        E1Z=E0Z
      ELSE
        ETA=(KX*KX+KY*KY+KZ*KZ)/(E0X*KX+E0Y*KY+E0Z*KZ)
        ALPHA=ETA*E0X-KX
        BETA=ETA*E0Y-KY
        GAMMA=ETA*E0Z-KZ
        DELTA=SQRT(ALPHA*ALPHA+BETA*BETA+GAMMA*GAMMA)
       IF(DELTA.EQ.0.) THEN
          DELTA0D=1.
          GOTO 200
       ENDIF
        E1X=ALPHA/DELTA
        E1Y=BETA/DELTA
        E1Z=GAMMA/DELTA
      ENDIF
  200  CONTINUE
       RETURN
       END
C*************************************************************************
C               PHAI1(Compton) decideing
C-------------------------------------------------------
      SUBROUTINE PHAICOMPT(TH1,PHAI1,RANSU,EE0E0E,FNOPOL)
        INTEGER RAN,RANSU(1:10)
        LOGICAL FNOPOL
        PARAMETER (PI=3.141592,ME=.511*1E+06)
```

```
        IF(FNOPOL) GOTO 200
 100  CONTINUE
        RAN=RANSU(4)
        CALL NEWRANSU(RAN, UNIRAN)
        RANSU(4)=RAN
      PHAI1P4=PI/2. *UNIRAN
      Y=(EE0E0E-2. *SIN(TH1)*SIN(TH1)*COS(PHAI1P4)*COS(PHAI1P4))/EE0E0E
        RAN=RANSU(9)
        CALL NEWRANSU(RAN, UNIRAN)
        RANSU(9)=RAN
      IF(UNIRAN. GT. Y) GOTO 100
 200  CONTINUE
        RAN=RANSU(4)
        CALL NEWRANSU(RAN, UNIRAN)
        RANSU(4)=RAN
      IF(UNIRAN. LT. 0. 5) THEN
       IF(UNIRAN. LT. 0. 25) THEN
         PHAI1=PHAI1P4
       ELSE
         PHAI1=PI-PHAI1P4
       ENDIF
      ELSE
       IF(UNIRAN. GT. 0. 75) THEN
         PHAI1=-PHAI1P4
       ELSE
         PHAI1=-(PI-PHAI1P4)
       ENDIF
      ENDIF
      RETURN
      END
C*************************************************************************
C             PHAI1(Thomson) decideing
C-------------------------------------------------------
      SUBROUTINE PHAITHOMS(TH1, PHAI1, RANSU, FNOPOL)
        INTEGER RAN, RANSU(1:10)
        LOGICAL FNOPOL
        PARAMETER (PI=3. 141592, ME=. 511*1E+06)
         IF(FNOPOL) GOTO 200
 100  CONTINUE
        RAN=RANSU(4)
        CALL NEWRANSU(RAN, UNIRAN)
        RANSU(4)=RAN
      PHAI1P4=PI/2. *UNIRAN
      Y=1. -SIN(TH1)*SIN(TH1)*COS(PHAI1P4)*COS(PHAI1P4)
        RAN=RANSU(9)
        CALL NEWRANSU(RAN, UNIRAN)
        RANSU(9)=RAN
      IF(UNIRAN. GT. Y) GOTO 100
 200  CONTINUE
        RAN=RANSU(4)
        CALL NEWRANSU(RAN, UNIRAN)
        RANSU(4)=RAN
      IF(UNIRAN. LT. 0. 5) THEN
       IF(UNIRAN. LT. 0. 25) THEN
         PHAI1=PHAI1P4
       ELSE
         PHAI1=PI-PHAI1P4
       ENDIF
      ELSE
       IF(UNIRAN. GT. 0. 75) THEN
         PHAI1=-PHAI1P4
       ELSE
         PHAI1=-(PI-PHAI1P4)
       ENDIF
      ENDIF
      RETURN
      END
C*************************************************************************
C           Calcuration next point
C-------------------------------------------------------------------
      SUBROUTINE NEWCOORD(X1, Y1, Z1, X2, Y2, Z2, EX, EY, EZ, RFREE, TH, PHAI
     %                    , OMEGA0D)
        REAL LAMDA
        PARAMETER(PI=3. 141592)
c        common /icommon/i
```

```
C.....................................................
      IF (RFREE.LT.0.001) GOTO 40
C-------------------------------------------------------------------
       AX=X2-X1
       AY=Y2-Y1
       AZ=Z2-Z1
       DA=SQRT(AX*AX+AY*AY+AZ*AZ)
        IF(DA.EQ.0.) THEN
          OMEGA0D=1.
          GOTO 40
        ENDIF
       BX=RFREE*COS(TH)*AX/DA
       BY=RFREE*COS(TH)*AY/DA
       BZ=RFREE*COS(TH)*AZ/DA
       IF((AY.EQ.0.).OR.(AZ.EQ.0.)) THEN
        IF(AY.NE.0.) THEN
           THT=ACOS(AX/DA)
           IF(AY.GT.0.) THT=-THT
        ENDIF
        IF(AZ.NE.0.) THEN
           THT=ACOS(AX/DA)
           IF(AZ.GT.0.) THT=-THT
        ENDIF
        IF(EZ.NE.0.) THEN
           PHAIE=ACOS(EY/(SQRT(EY*EY+EZ*EZ)))
           IF(EZ.LT.0.) THEN PHAIE=-PHAIE
           PHAI=PHAI+PHAIE
        ENDIF
          CX=0.
          CY=RFREE*SIN(TH)*COS(PHAI)
          CZ=RFREE*SIN(TH)*SIN(PHAI)
        IF(AY.NE.0.) THEN
          CX=CY*SIN(THT)
          CY=CY*COS(THT)
        ENDIF
        IF(AZ.NE.0.) THEN
          CX=CZ*SIN(THT)
          CZ=CZ*COS(THT)
        ENDIF
       ELSE
C-------------------------------------------------------------------
         OMEGAXY=AX*EY-AY*EX
         OMEGAXZ=AX*EZ-AZ*EX
         OMEGAZY=AZ*EY-AY*EZ
         OMEGAYZ=AY*EZ-AZ*EY
        IF((OMEGAZY.EQ.0.).OR.(OMEGAYZ.EQ.0.)) THEN
          OMEGA0D=1.
          GOTO 40
        ENDIF
         OMEGAXYZY=OMEGAXY/OMEGAZY
         OMEGAXZYZ=OMEGAXZ/OMEGAYZ
         LAMDA=RFREE*SIN(TH)*COS(PHAI)
         AAA=1+OMEGAXYZY*OMEGAXYZY+OMEGAXZYZ*OMEGAXZYZ
         BBB=LAMDA*(AY*OMEGAXYZY/OMEGAZY+AZ*OMEGAXZYZ/OMEGAYZ)
         CCC=(AY*AY/OMEGAZY/OMEGAZY+AZ*AZ/OMEGAYZ/OMEGAYZ)
     %       *LAMDA*LAMDA-RFREE*RFREE*SIN(TH)*SIN(TH)
        IF(ABS(CCC).LT.0.00001) THEN
          CCC=-1.
          CCC=CCC+1.
        ENDIF
        IF((ABS(AAA).GT.100000000.).OR.(ABS(BBB).GT.100000000.).OR.
     %     (ABS(CCC).GT.100000000.)) THEN
            OMEGA0D=1.
            GOTO 40
        ENDIF
        XXX=BBB*BBB-AAA*CCC
        IF(XXX.LT.0.) XXX=0.
        IF(PHAI.GE.0.) THEN
         CX=(-BBB+SQRT(XXX))/AAA
        ELSE
         CX=(-BBB-SQRT(XXX))/AAA
        ENDIF
         CY=-OMEGAXZYZ*CX-AZ*LAMDA/OMEGAYZ
         CZ=-OMEGAXYZY*CX-AY*LAMDA/OMEGAZY
       ENDIF
```

```
C-------------------------------------------------------------
        X3=X2+BX
        Y3=Y2+BY
        Z3=Z2+BZ
        X4=X3+CX
        Y4=Y3+CY
        Z4=Z3+CZ
        X1=X2
        Y1=Y2
        Z1=Z2
        X2=X4
        Y2=Y4
        Z2=Z4
C-------------------------------------------------------------
  40    CONTINUE
        RETURN
        END
CC*****************************************************************************
C       Length of x-ray passing through the Grid ( Ahead )
C-------------------------------------------------------
        SUBROUTINE AHEADPASS(X0, Y0, Z0, X1, Y1, Z1, NBL,
     %                       LWOI, LWOF, LWOM, LWO, LPBI, LPBF, LPBM, LPB)
        REAL LWOI, LWOF, LWOM, LWO, LPBI, LPBF, LPBM, LPB
        REAL LYWOI, LYWOF, LYWOM, LYWO, LYPBI, LYPBF, LYPBM, LYPB
        REAL LGRID, XGRID, XGEND
        COMMON /GRID/H, DWO, DPB, DBL, XEND, XGRID, XGEND
C--------- Position on the entrance of the Grid -----------
            X2=XGEND
            XGBAI=(X2-X0)/(X1-X0)
            Y2=Y0+XGBAI*(Y1-Y0)
            Z2=Z0+XGBAI*(Z1-Z0)
C-------------------------------------------------------------------------
          LGRID=SQRT((X2-X1)*(X2-X1)+(Y2-Y1)*(Y2-Y1)+(Z2-Z1)*(Z2-Z1))
C-------------------------------------------------------------------------
           IF(Y1.GE.0.)THEN
            NBL1=INT(Y1/DBL)
           ELSE
            NBL1=INT(Y1/DBL)-1
           ENDIF
           IF(Y2.GE.0.)THEN
            NBL2=INT(Y2/DBL)
           ELSE
            NBL2=INT(Y2/DBL)-1
           ENDIF
            NBL=NBL2-NBL1
            POBL1=Y1-DBL*REAL(NBL1)
            POBL2=Y2-DBL*REAL(NBL2)
C***********************************************
C   LYWOI, LYPBI, LYWOF, LYPBF, LYWOM, LYPBM
C***********************************************
C  NBL = 0
        IF (NBL.EQ.0) THEN
          IF (POBL1.LT.DWO) THEN
            IF (POBL2.LT.DWO) THEN
                LYWOI=POBL2-POBL1
                LYPBI=0.
            ELSE
                LYWOI=DWO-POBL1
                LYPBI=POBL2-DWO
            ENDIF
          ELSE
            IF (POBL2.LT.DWO) THEN
                LYWOI=DWO-POBL1
                LYPBI=POBL2-DWO
            ELSE
                LYWOI=0.
                LYPBI=POBL2-POBL1
            ENDIF
          ENDIF
                LYWOF=0.
                LYPBF=0.
                LYWOM=0.
                LYPBM=0.
C+++++++++++++++++++++++++++++++++++++++++++++++
C-----------------------------------------------
```

```
        ELSE
C  NBL > 0
          IF (NBL.GT.0) THEN
            IF (POBL1.LT.DWO) THEN
                LYWOI=DWO-POBL1
                LYPBI=DWO
            ELSE
                LYWOI=0.
                LYPBI=DBL-POBL1
            ENDIF
            IF (POBL2.LT.DWO) THEN
                LYWOF=POBL2
                LYPBF=0.
            ELSE
                LYWOF=DWO
                LYPBF=POBL2-DWO
            ENDIF
            IF (NBL.EQ.1) THEN
                LYWOM=0.
                LYPBM=0.
            ELSE
                LYWOM=DWO
                LYPBM=DPB
            ENDIF
C.....................................................
C  NBL < 0
          ELSE
            IF (POBL1.LT.DWO) THEN
                LYWOI=POBL1
                LYPBI=0.
            ELSE
                LYWOI=DWO
                LYPBI=POBL1-DWO
            ENDIF
            IF (POBL2.LT.DWO) THEN
                LYWOF=POBL2
                LYPBF=0.
            ELSE
                LYWOF=DWO
                LYPBF=POBL2-DWO
            ENDIF
          ENDIF
C-----------------------------------------------------
C  ABS(NBL) = 1
          IF (ABS(NBL).EQ.1) THEN
                LYWOM=0.
                LYPBM=0.
C.....................................................
C  ABS(NBL) > 1
          ELSE
                LYWOM=DWO
                LYPBM=DPB
          ENDIF
C-----------------------------------------------------
        ENDIF
C*****************************************************
C     LYWO, LYPB
C*****************************************************
        IF (NBL.EQ.0) THEN
          LYWO=LYWOI+LYWOF
          LYPB=LYPBI+LYPBF
        ELSE
          LYWO=LYWOI+LYWOF+LYWOM*(NBL-1)
          LYPB=LYPBI+LYPBF+LYPBM*(NBL-1)
        ENDIF
C*****************************************************
C     LWOI, LWOF, LWOM, LWO, LPBI, LPBF, LPBM, LPB,
C*****************************************************
        IF ((LYWO.EQ.0.).AND.(LYPB.EQ.0.)) THEN
          IF (POBL1.LT.DWO) THEN
             LWO=LGRID
             LPB=0.
          ELSE
             LWO=0.
             LPB=LGRID
```

```
          ENDIF
             LWOI=LWO
             LPBI=LPB
             LWOF=0.
             LPBF=0.
             LWOM=0.
             LPBM=0.
C-----------------------------------------------
        ELSE
             RWO=LYWO/(LYWO+LYPB)
             RPB=LYPB/(LYWO+LYPB)
             LWO=LGRID*RWO
             LPB=LGRID*RPB
           IF(LYWO.EQ.0.) THEN
             LWOI=0.
             LWOM=0.
             LWOF=0.
           ELSE
             LWOI=LWO*LYWOI/LYWO
             LWOF=LWO*LYWOF/LYWO
             LWOM=LWO*LYWOM/LYWO
           ENDIF
           IF(LYPB.EQ.0.) THEN
             LPBI=0.
             LPBM=0.
             LPBF=0.
           ELSE
             LPBI=LPB*LYPBI/LYPB
             LPBF=LPB*LYPBF/LYPB
             LPBM=LPB*LYPBM/LYPB
           ENDIF
        ENDIF
C***********************************************
             LWOI=ABS(LWOI)
             LWOM=ABS(LWOM)
             LWOF=ABS(LWOF)
             LWO=ABS(LWO)
             LPBI=ABS(LPBI)
             LPBM=ABS(LPBM)
             LPBF=ABS(LPBF)
             LPB=ABS(LPB)
C------------------------------
             X0=X1
             Y0=Y1
             Z0=Z1
             X1=X2
             Y1=Y2
             Z1=Z2
        RETURN
        END
CC*****************************************************************************
C        Length of x-ray passing through the Grid ( Back )
C-------------------------------------------------------
        SUBROUTINE BACKPASS(X0,Y0,Z0,X1,Y1,Z1,NBL,
     %                      LWOI,LWOF,LWOM,LWO,LPBI,LPBF,LPBM,LPB)
        REAL LWOI,LWOF,LWOM,LWO,LPBI,LPBF,LPBM,LPB
        REAL LYWOI,LYWOF,LYWOM,LYWO,LYPBI,LYPBF,LYPBM,LYPB
        REAL LGRID,XGRID,XGEND
        REAL LSAV
        COMMON /GRID/H,DWO,DPB,DBL,XEND,XGRID,XGEND
C--------- Position on the entrance of the Grid -----------
             XS=XGRID
             XGBAI=(XS-X0)/(X1-X0)
             YS=Y0+XGBAI*(Y1-Y0)
             ZS=Z0+XGBAI*(Z1-Z0)
             X2=X1
             Y2=Y1
             Z2=Z1
             X1=XS
             Y1=YS
             Z1=ZS
C-------------------------------------------------------------------
           LGRID=SQRT((X2-X1)*(X2-X1)+(Y2-Y1)*(Y2-Y1)+(Z2-Z1)*(Z2-Z1))
C-------------------------------------------------------------------
             IF(Y1.GE.0.)THEN
```

```
            NBL1=INT(Y1/DBL)
           ELSE
            NBL1=INT(Y1/DBL)-1
           ENDIF
           IF(Y2.GE.0.)THEN
            NBL2=INT(Y2/DBL)
           ELSE
            NBL2=INT(Y2/DBL)-1
           ENDIF
            NBL=NBL2-NBL1
            POBL1=Y1-DBL*REAL(NBL1)
            POBL2=Y2-DBL*REAL(NBL2)
C***********************************************
C   LYWOI, LYPBI, LYWOF, LYPBF, LYWOM, LYPBM
C***********************************************
C  NBL = 0
       IF (NBL.EQ.0) THEN
         IF (POBL1.LT.DWO) THEN
           IF (POBL2.LT.DWO) THEN
               LYWOI=POBL2-POBL1
               LYPBI=0.
           ELSE
               LYWOI=DWO-POBL1
               LYPBI=POBL2-DWO
           ENDIF
         ELSE
           IF (POBL2.LT.DWO) THEN
               LYWOI=DWO-POBL1
               LYPBI=POBL2-DWO
           ELSE
               LYWOI=0.
               LYPBI=POBL2-POBL1
           ENDIF
         ENDIF
               LYWOF=0.
               LYPBF=0.
               LYWOM=0.
               LYPBM=0.
C++++++++++++++++++++++++++++++++++++++++++++++++
C------------------------------------------------
       ELSE
C  NBL > 0
         IF (NBL.GT.0) THEN
           IF (POBL1.LT.DWO) THEN
               LYWOI=DWO-POBL1
               LYPBI=DWO
           ELSE
               LYWOI=0.
               LYPBI=DBL-POBL1
           ENDIF
           IF (POBL2.LT.DWO) THEN
               LYWOF=POBL2
               LYPBF=0.
           ELSE
               LYWOF=DWO
               LYPBF=POBL2-DWO
           ENDIF
           IF (NBL.EQ.1) THEN
               LYWOM=0.
               LYPBM=0.
           ELSE
               LYWOM=DWO
               LYPBM=DPB
           ENDIF
C.................................................
C  NBL < 0
         ELSE
           IF (POBL1.LT.DWO) THEN
               LYWOI=POBL1
               LYPBI=0.
           ELSE
               LYWOI=DWO
               LYPBI=POBL1-DWO
           ENDIF
           IF (POBL2.LT.DWO) THEN
```

```
                LYWOF=POBL2
                LYPBF=0.
            ELSE
                LYWOF=DWO
                LYPBF=POBL2-DWO
            ENDIF
          ENDIF
C-----------------------------------------------
C  ABS(NBL) = 1
          IF (ABS(NBL).EQ.1) THEN
                LYWOM=0.
                LYPBM=0.
C.............................................
C  ABS(NBL) > 1
          ELSE
                LYWOM=DWO
                LYPBM=DPB
          ENDIF
C-----------------------------------------------
        ENDIF
C************************************************
C      LYWO, LYPB
C************************************************
        IF (NBL.EQ.0) THEN
          LYWO=LYWOI+LYWOF
          LYPB=LYPBI+LYPBF
        ELSE
          LYWO=LYWOI+LYWOF+LYWOM*(NBL-1)
          LYPB=LYPBI+LYPBF+LYPBM*(NBL-1)
        ENDIF
C************************************************
C     LWOI, LWOF, LWOM, LWO, LPBI, LPBF, LPBM, LPB,
C************************************************
        IF ((LYWO.EQ.0.).AND.(LYPB.EQ.0.)) THEN
          IF (POBL1.LT.DWO) THEN
             LWO=LGRID
             LPB=0.
          ELSE
             LWO=0.
             LPB=LGRID
          ENDIF
             LWOI=LWO
             LPBI=LPB
             LWOF=0.
             LPBF=0.
             LWOM=0.
             LPBM=0.
C-----------------------------------------------
        ELSE
             RWO=LYWO/(LYWO+LYPB)
             RPB=LYPB/(LYWO+LYPB)
             LWO=LGRID*RWO
             LPB=LGRID*RPB
           IF(LYWO.EQ.0.) THEN
             LWOI=0.
             LWOM=0.
             LWOF=0.
           ELSE
             LWOI=LWO*LYWOI/LYWO
             LWOF=LWO*LYWOF/LYWO
             LWOM=LWO*LYWOM/LYWO
           ENDIF
           IF(LYPB.EQ.0.) THEN
             LPBI=0.
             LPBM=0.
             LPBF=0.
           ELSE
             LPBI=LPB*LYPBI/LYPB
             LPBF=LPB*LYPBF/LYPB
             LPBM=LPB*LYPBM/LYPB
           ENDIF
        ENDIF
C************************************************
             LWOI=ABS(LWOI)
             LWOM=ABS(LWOM)
```

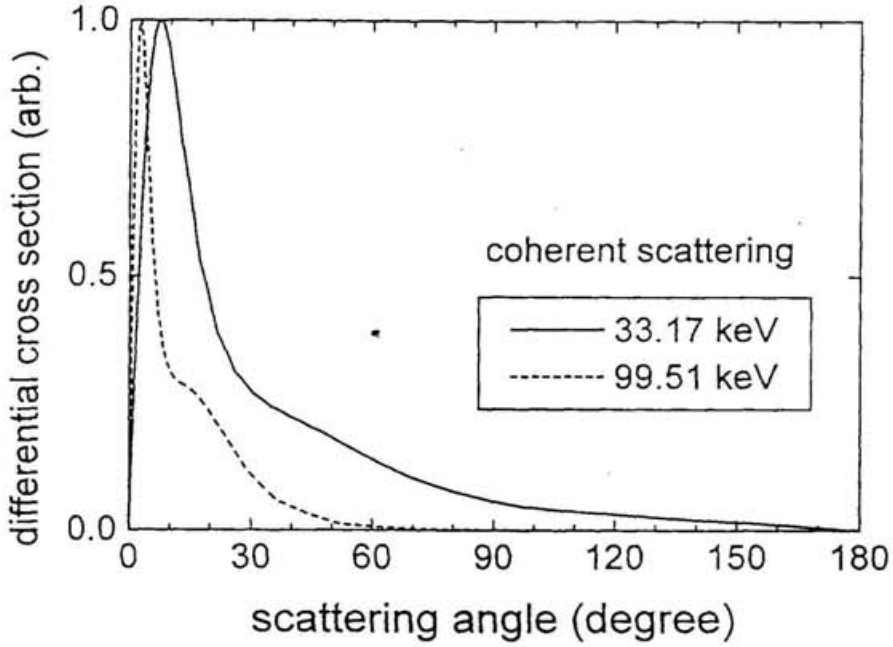
```
            LWOF=ABS(LWOF)
            LWO=ABS(LWO)
            LPBI=ABS(LPBI)
            LPBM=ABS(LPBM)
            LPBF=ABS(LPBF)
            LPB=ABS(LPB)
C-------------------------------
          IF(LWOF.NE.0.) THEN
            LSAV=LWOI
            LWOI=LWOF
            LWOF=LSAV
          ENDIF
          IF(LPBF.NE.0.) THEN
            LSAV=LPBI
            LPBI=LPBF
            LPBF=LSAV
          ENDIF
            X0=X2
            Y0=Y2
            Z0=Z2
        RETURN
        END
CC*****************************************************************************
C        Position of x-ray scattering in the Grid
C-----------------------------------------------------------------------------
        SUBROUTINE XPOSITION(RFREE,MEWWO,MEWPB,NBL,X0,Y0,Z0,X1,Y1,Z1,
     %                       LWOI,LWOF,LWOM,LWO,LPBI,LPBF,LPBM,LPB)
        REAL RFREE
        REAL MEWWO,MEWPB
        REAL LWOI,LWOF,LWOM,LWO,LPBI,LPBF,LPBM,LPB
        REAL LWOI2,LWOM2,LWOF2,LWO2,LPBI2,LPBM2,LPBF2,LPB2
        REAL LPBEQI
        REAL LREALY,LREAL,LEQI,LEQM,LEQF2,LEQF2Y
        COMMON /GRID/H,DWO,DPB,DBL,XEND,XGRID,XGEND
C-----------------------------------------------------------------------------
              NBLS=0
              LWOI2=0.
              LWOM2=0.
              LWOF2=0.
              LWO2=0.
              LPBI2=0.
              LPBM2=0.
              LPBF2=0.
              LPB2=0.
              LPBEQI=LPBI/MEWWO*MEWPB
C-------------------------------------------------------------
        IF (NBL.EQ.0) THEN
          IF ((LWOI.EQ.0.).OR.(LPBI.EQ.0.)) THEN
            IF (LWOI.EQ.0.) THEN
               LPBI2=RFREE/MEWPB*MEWWO
               X2=LPBI2/LPBI*(X1-X0)+X0
               Y2=LPBI2/LPBI*(Y1-Y0)+Y0
               Z2=LPBI2/LPBI*(Z1-Z0)+Z0
            ENDIF
            IF (LPBI.EQ.0.) THEN
               LWOI2=RFREE
               X2=LWOI2/LWOI*(X1-X0)+X0
               Y2=LWOI2/LWOI*(Y1-Y0)+Y0
               Z2=LWOI2/LWOI*(Z1-Z0)+Z0
            ENDIF
          ELSE
            IF (Y1.GT.Y0) THEN
             IF (RFREE.LT.LWOI) THEN
               LWOI2=RFREE
               X2=LWOI2/(LWOI+LPBI)*(X1-X0)+X0
               Y2=LWOI2/(LWOI+LPBI)*(Y1-Y0)+Y0
               Z2=LWOI2/(LWOI+LPBI)*(Z1-Z0)+Z0
             ELSE
               LWOI2=LWOI
               LPBI2=(RFREE-LWOI)/MEWPB*MEWWO
               X2=(LWOI2+LPBI2)/(LWOI+LPBI)*(X1-X0)+X0
               Y2=(LWOI2+LPBI2)/(LWOI+LPBI)*(Y1-Y0)+Y0
               Z2=(LWOI2+LPBI2)/(LWOI+LPBI)*(Z1-Z0)+Z0
             ENDIF
            ELSE
```

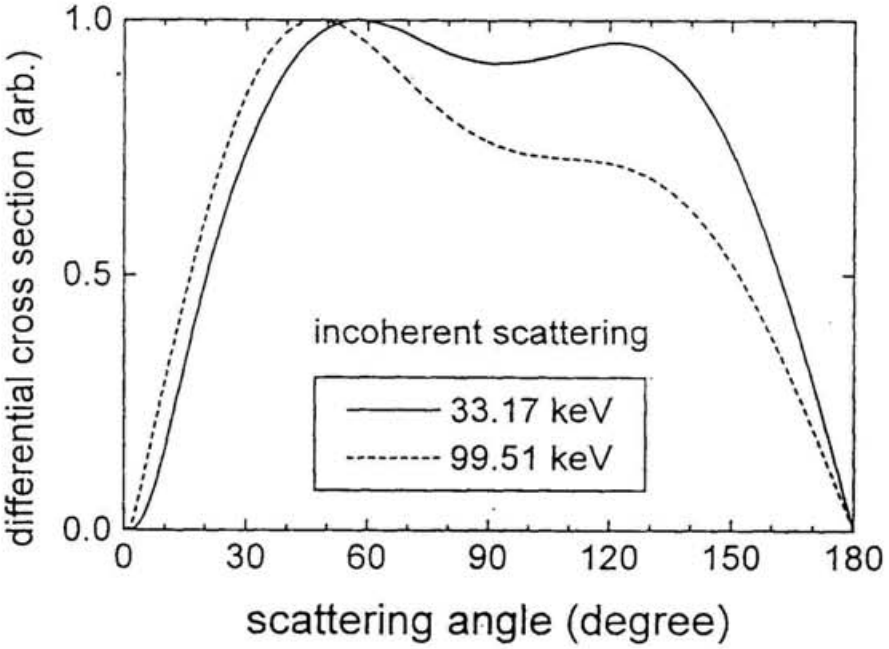
```
            IF (RFREE.LT.LPBEQI) THEN
              LPBI2=RFREE/MEWPB*MEWWO
              X2=LPBI2/(LWOI+LPBI)*(X1-X0)+X0
              Y2=LPBI2/(LWOI+LPBI)*(Y1-Y0)+Y0
              Z2=LPBI2/(LWOI+LPBI)*(Z1-Z0)+Z0
            ELSE
              LPBI2=LPBI
              LWOI2=(RFREE-LPBEQI)
              X2=(LWOI2+LPBI2)/(LWOI+LPBI)*(X1-X0)+X0
              Y2=(LWOI2+LPBI2)/(LWOI+LPBI)*(Y1-Y0)+Y0
              Z2=(LWOI2+LPBI2)/(LWOI+LPBI)*(Z1-Z0)+Z0
            ENDIF
          ENDIF
        ENDIF
            LWO2=LWOI2
            LPB2=LPBI2
      ELSE
C-------------------------------------------------------------
            LEQI=LWOI+LPBI*MEWPB/MEWWO
            LEQM=LWOM+LPBM*MEWPB/MEWWO
          IF(RFREE.LT.LEQI) THEN
            NBLS=0
          ELSE
           IF(LEQM.EQ.0.) THEN
            NBLS=1
           ELSE
            NBLS=INT((RFREE-LEQI)/LEQM)+1
           ENDIF
          ENDIF
        IF (NBLS.EQ.0) THEN
         IF ((LWOI.EQ.0.).OR.(LPBI.EQ.0.)) THEN
          IF (LWOI.EQ.0.) THEN
            LPBI2=RFREE/MEWPB*MEWWO
            X2=LPBI2/LPBI*(X1-X0)+X0
            Y2=LPBI2/LPBI*(Y1-Y0)+Y0
            Z2=LPBI2/LPBI*(Z1-Z0)+Z0
          ENDIF
          IF (LPBI.EQ.0.) THEN
            LWOI2=RFREE
            X2=LWOI2/LWOI*(X1-X0)+X0
            Y2=LWOI2/LWOI*(Y1-Y0)+Y0
            Z2=LWOI2/LWOI*(Z1-Z0)+Z0
          ENDIF
         ELSE
          IF (Y1.GT.Y0) THEN
           IF (RFREE.LT.LWOI) THEN
            LWOI2=RFREE
            X2=LWOI2/(LWOI+LPBI)*(X1-X0)+X0
            Y2=LWOI2/(LWOI+LPBI)*(Y1-Y0)+Y0
            Z2=LWOI2/(LWOI+LPBI)*(Z1-Z0)+Z0
           ELSE
            LWOI2=LWOI
            LPBI2=(RFREE-LWOI)/MEWPB*MEWWO
            X2=(LWOI2+LPBI2)/(LWOI+LPBI)*(X1-X0)+X0
            Y2=(LWOI2+LPBI2)/(LWOI+LPBI)*(Y1-Y0)+Y0
            Z2=(LWOI2+LPBI2)/(LWOI+LPBI)*(Z1-Z0)+Z0
           ENDIF
          ELSE
           IF (RFREE.LT.LPBEQI) THEN
            LPBI2=RFREE/MEWPB*MEWWO
            X2=LPBI2/(LWOI+LPBI)*(X1-X0)+X0
            Y2=LPBI2/(LWOI+LPBI)*(Y1-Y0)+Y0
            Z2=LPBI2/(LWOI+LPBI)*(Z1-Z0)+Z0
           ELSE
            LPBI2=LPBI
            LWOI2=(RFREE-LPBEQI)
            X2=(LWOI2+LPBI2)/(LWOI+LPBI)*(X1-X0)+X0
            Y2=(LWOI2+LPBI2)/(LWOI+LPBI)*(Y1-Y0)+Y0
            Z2=(LWOI2+LPBI2)/(LWOI+LPBI)*(Z1-Z0)+Z0
           ENDIF
          ENDIF
         ENDIF
            LWO2=LWOI2
            LPB2=LPBI2
        ELSE
```

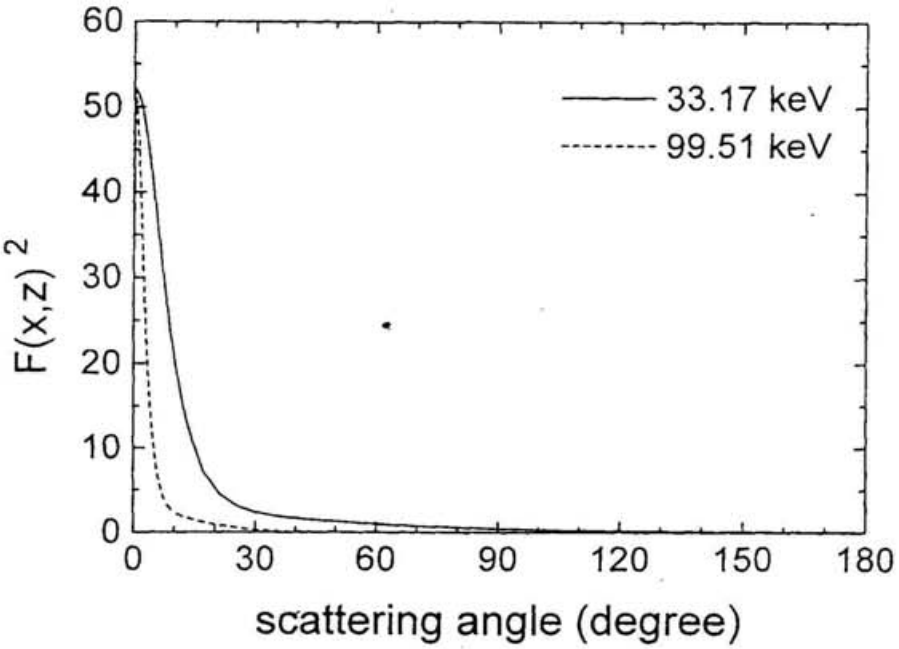
```
C-----------------------------------------------------------------------
              LEQF2=RFREE-LEQI-LEQM*REAL(NBLS-1)
              LREALY=(Y1-Y0)
              LREAL=SQRT((X1-X0)*(X1-X0)+(Y1-Y0)*(Y1-Y0)
     %                   +(Z1-Z0)*(Z1-Z0))
              LEQF2Y=LEQF2*LREALY/LREAL
            IF (Y1.GT.Y0) THEN
             IF (LEQF2Y.LE.DWO) THEN
               LWOF2=LEQF2
               LPBF2=0.
             ELSE
               LWOF2=DWO*LREAL/LREALY
               LPBF2=(LEQF2Y-DWO)/MEWPB*MEWWO*LREAL/LREALY
             ENDIF
            ELSE
             IF (LEQF2Y.LE.DPB*MEWPB/MEWWO) THEN
               LWOF2=0.
               LPBF2=LEQF2/MEWPB*MEWWO
             ELSE
               LWOF2=(LEQF2Y-DPB*MEWPB/MEWWO)*LREAL/LREALY
               LPBF2=DPB*LREAL/LREALY
             ENDIF
            ENDIF
               LWO2=LWOI2+LWOM2*REAL(NBLS-1)+LWOF2
               LPB2=LPBI2+LPBM2*REAL(NBLS-1)+LPBF2
               X2=(LWO2+LPB2)/(LWO+LPB)*(X1-X0)+X0
               Y2=(LWO2+LPB2)/(LWO+LPB)*(Y1-Y0)+Y0
               Z2=(LWO2+LPB2)/(LWO+LPB)*(Z1-Z0)+Z0
          ENDIF
        ENDIF
              NBL=NBLS
              LWOI=LWOI2
              LWOM=LWOM2
              LWOF=LWOF2
              LWO=LWO2
              LPBI=LPBI2
              LPBM=LPBM2
              LPBF=LPBF2
              LPB=LPB2
              X0=X1
              Y0=Y1
              Z0=Z1
              X1=X2
              Y1=Y2
              Z1=Z2
C-----------------------------------------------------------------------
       RETURN
       END
CC*************************************************************************
C           Deciding scattering angle
C-----------------------------------------------------------------------
      SUBROUTINE SCANGLE(TH1, PHAI1, EPH, FELOS, Y1, FNOPOL)
      REAL MEWWO, SIGINCWO, MEWPB, SIGINCPB
      REAL MEW, SIGINC
      REAL THM(0:1000)
      REAL LR
      REAL PITHOMSWO(0:99, 0:1000), PIKLNISWO(0:99, 0:1000)
      REAL PITHOMSPB(0:99, 0:1000), PIKLNISPB(0:99, 0:1000)
      INTEGER RAN
      INTEGER RANSU(1:10)
      LOGICAL FELOS, FINCOH, FINWO, FNOPOL
      PARAMETER (PI=3.141592, ME=.511*1E+06)
      PARAMETER (RE=2.81794092E-15, C=2.99792458E+08)
      PARAMETER (NTH=1000)
      PARAMETER (LOSEPH=10.)
      PARAMETER (ROUWO=0.49, ROUPB=11.34)
      COMMON /ANGLE/THM, PITHOMSWO, PIKLNISWO, PITHOMSPB, PIKLNISPB
      COMMON /RANDAM/RANSU
      COMMON /MEWSIG/MEWWO, SIGCOHWO, SIGINCWO, MEWPB, SIGCOHPB, SIGINCPB
      COMMON /GRID/H, DWO, DPB, DBL, XEND, XGRID, XGEND
C-----------------------------------------------------------------------
          NBL1=INT(Y1/DBL)
          POBL1=Y1-DBL*REAL(NBL1)
          FINWO=.FALSE.
          IF(POBL1.LT.DWO) FINWO=.TRUE.
```

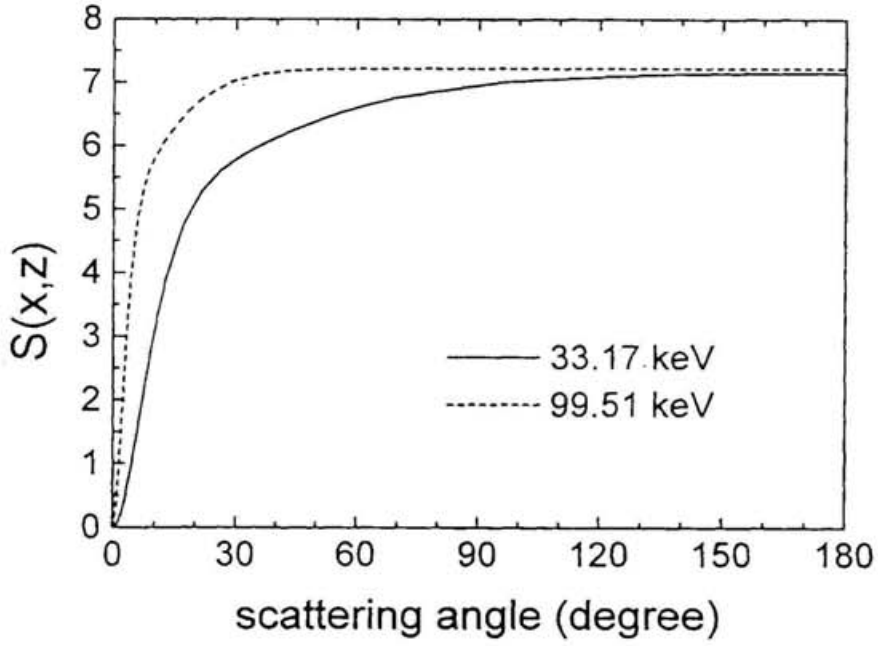
```
            IF(FINWO) THEN
               MEW=MEWWO
               SIGINC=SIGINCWO
            ELSE
               MEW=MEWPB
               SIGINC=SIGINCPB
            ENDIF
C------------- Kind of interaction with atom ---------------
            RAN=RANSU(9)
            CALL NEWRANSU(RAN, UNIRAN)
            RANSU(9)=RAN
C           (Tomson scattering or Compton scattering ?)
            FINCOH=.FALSE.
            IF (UNIRAN.LT.SIGINC/MEW) FINCOH=.TRUE.
            RAN=RANSU(4)
            CALL NEWRANSU(RAN, UNIRAN)
            RANSU(4)=RAN
C           ( Scattering angle )
            TH1=0.
          IF(EPH.EQ.99.51) THEN
            LR=0.
            GOTO 65
          ENDIF
C         ( If photon energy is 99.51keV then use PIA9951.DAT data )
            LR=EPH
   65     CONTINUE
          LI=INT(LR)
C.............. Compton scattering ..................
         IF (FINCOH) THEN
           DO 72 K2=1, 10
            IF(FINWO) THEN
             UNIPI=PIKLNISWO(LI, K2*100)/PIKLNISWO(LI, NTH)
            ELSE
             UNIPI=PIKLNISPB(LI, K2*100)/PIKLNISPB(LI, NTH)
            ENDIF
             IF (UNIRAN.LE.UNIPI) THEN
                K100=(K2-1)*100
                GOTO 92
             ENDIF
   72      CONTINUE
   92      CONTINUE
           DO 71 K1=1, 10
            IF(FINWO) THEN
             UNIPI=PIKLNISWO(LI, K100+K1*10)/PIKLNISWO(LI, NTH)
            ELSE
             UNIPI=PIKLNISPB(LI, K100+K1*10)/PIKLNISPB(LI, NTH)
            ENDIF
             IF (UNIRAN.LE.UNIPI) THEN
                K10=(K1-1)*10
                GOTO 91
             ENDIF
   71      CONTINUE
   91      CONTINUE
           DO 70 K=1, 10
            IF(FINWO) THEN
             UNIPI=PIKLNISWO(LI, K100+K10+K)/PIKLNISWO(LI, NTH)
            ELSE
             UNIPI=PIKLNISPB(LI, K100+K10+K)/PIKLNISPB(LI, NTH)
            ENDIF
             IF (UNIRAN.LE.UNIPI) THEN
                TH1=THM(K100+K10+K)
                GOTO 90
             ENDIF
   70      CONTINUE
   90      CONTINUE
               EPH0=EPH
               EPH=EPH/(1+EPH*1000./ME*(1-COS(TH1)))
                IF (EPH.LE.LOSEPH) THEN
C           ( if energy < min energy , photon is lost )
                  FELOS=.TRUE.
                  GOTO 30
                ENDIF
               EE0E0E=EPH/EPH0+EPH0/EPH
               CALL PHAICOMPT(TH1, PHAI1, RANSU, EE0E0E, FNOPOL)
         ELSE
```

```
C.............. Thomson scattering ...................
        DO 82 K2=1,10
         IF(FINWO) THEN
          UNIPI=PITHOMSWO(LI,K2*100)/PITHOMSWO(LI,NTH)
         ELSE
          UNIPI=PITHOMSPB(LI,K2*100)/PITHOMSPB(LI,NTH)
         ENDIF
          IF (UNIRAN.LE.UNIPI) THEN
             K100=(K2-1)*100
             GOTO 32
          ENDIF
   82    CONTINUE
   32    CONTINUE
        DO 81 K1=1,10
         IF(FINWO) THEN
          UNIPI=PITHOMSWO(LI,K100+K1*10)/PITHOMSWO(LI,NTH)
         ELSE
          UNIPI=PITHOMSPB(LI,K100+K1*10)/PITHOMSPB(LI,NTH)
         ENDIF
          IF (UNIRAN.LE.UNIPI) THEN
             K10=(K1-1)*10
             GOTO 31
          ENDIF
   81    CONTINUE
   31    CONTINUE
        DO 80 K=1,10
         IF(FINWO) THEN
          UNIPI=PITHOMSWO(LI,K100+K10+K)/PITHOMSWO(LI,NTH)
         ELSE
          UNIPI=PITHOMSPB(LI,K100+K10+K)/PITHOMSPB(LI,NTH)
         ENDIF
          IF (UNIRAN.LE.UNIPI) THEN
             TH1=THM(K100+K10+K)
             GOTO 33
          ENDIF
   80    CONTINUE
   33    CONTINUE
            CALL PHAITHOMS(TH1,PHAI1,RANSU,FNOPOL)
      ENDIF
   30   CONTINUE
C-------------------------------------------------------------
      RETURN
      END
C*********************************************************************
```


1.0
0.5
0.0
differential cross section (arb.)
coherent scattering
33.17 keV
99.51 keV
0
30
60
90
120
150
180
scattering angle (degree)


1.0
0.5
0.0
differential cross section (arb.)
incoherent scattering
33.17 keV
99.51 keV
0
30
60
90
120
150
180
scattering angle (degree)


60
50
40
30
20
10
0
F(X,Z) 2
33.17 keV
99.51 keV
0
30
60
90
120
150
180
scattering angle (degree)


8
7
6
5
4
3
2
1
0
S(X,Z)
33.17 keV
99.51 keV
0
30
60
90
120
150
180
scattering angle (degree)