Monochromatic energy-subtraction radiography using a rotating anode source and a bent Laue monochromator

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Abstract. A system for area-beam energy-subtraction monochromatic radiography was developed and tested. It utilizes a bent Laue crystal monochromator developed at the National Synchrotron Light Source (NSLS), and a compact rotating anode x-ray source developed at the Science Research Laboratory (SRL). The Kα characteristic lines (both Kα1 and Kα2) of the cerium and barium targets were diffracted by the monochromator and used for the above- and below-K-edge imaging, respectively, of phantoms with iodine contrast agents. Digital subtraction of the images produced an iodine image.

1. Introduction

Today’s angiography systems use polychromatic x-rays and intra-arterial injection of contrast agents. This involves a non-negligible risk of morbidity and mortality, mostly from the arterial catheterization process. Dual-energy subtraction imaging with intravenous injection of the contrast agent can produce useful images with much reduced risk. Early attempts at intravenous angiography with non-synchrotron x-rays included the use of filtered or kVp-modulated polychromatic x-rays and dual-energy subtraction methods (Kelez et al 1977, Brody et al 1981). The broad spectra of the x-rays used by these methods makes it necessary to use three energies (Kelez and Mistretta 1976, Yeh et al 1980) in order to minimize bone artefacts. Recent synchrotron-based patient studies using the dual-energy digital subtraction intravenous coronary angiography technique with monochromatic x-rays have obtained research quality images of the coronary artery anatomy (Thompson et al 1989, Thomlinson et al 1991, Dix et al 1992, Thomlinson et al 1992). However, the cost of a synchrotron prevents its general use for clinical diagnostic imaging. Development of compact sources is necessary for the technology to be widely utilized.

One of the recent developments of compact sources (Rutt et al 1983, Wang et al 1992, Gary et al 1993, Arduini et al 1995, Toyofuku et al 1995) which would have sufficient intensity for digital subtraction coronary angiography is an x-ray generator with a rotating anode coated with barium and cerium proposed by Manning et al (1991). A low-intensity prototype of the proposed source has been developed at the Science Research Laboratory (SRL). In addition to the desired characteristic x-rays, the bremsstrahlung radiation from the source is also present. This continuum in the emitted x-ray spectrum increases the dose
to a patient, creates subtraction artefacts due to beam hardening effects, reduces contrast and adds noise to the subtracted image.

A bent Laue crystal monochromator (Zhong 1996) has been developed at the National Synchrotron Light Source (NSLS). It can diffract an area beam of characteristic x-rays from such an x-ray tube, thereby eliminating the bremsstrahlung problem. An area beam is a beam having an area large enough (e.g. 5 cm × 5 cm) for radiography. The monochromator was initially tested at the X12A beam line at the NSLS using molybdenum, silver and barium fluorescence targets excited by a synchrotron white beam.

This paper reports the use of the NSLS crystal monochromator for digital, dual-energy subtraction imaging at the iodine K edge using the prototype source at SRL. The performance of the monochromator in terms of the spectral purity was studied. Iodine phantom imaging was performed to assess the improvement in contrast with the use of the monochromatic beam.

2. Monochromator for an area beam

The geometry for a cylindrically bent Laue monochromator is shown in figure 1. The x-rays from a point source at S are reflected by the Bragg planes in the bent crystal and focused at the virtual source F. The asymmetry angle χ is defined as the angle between the crystal surface normal and the Bragg planes used for the reflection of x-rays. The Bragg angle θB is the angle between the incident x-rays and the Bragg planes. The distance between the source point and the centre of the crystal (C) is s and the distance between the virtual focal point and C is f (f is negative for a virtual focal point). If there is no variation of the angle of incidence along the crystal surface, then the reflected beam will be a monochromatic beam.

The condition for producing a monochromatic beam is (the Rowland condition)

\[ s = \rho \cos(\chi \pm \theta_B) \]  
\[ f = -\rho \cos(\chi \mp \theta_B) \]  

where \( \rho \) is the bending radius of the bent crystal. \( \rho \) is positive when the source point is on the concave side of the crystal and negative when the source point is on the convex side of the crystal. The upper sign corresponds to the case when the source and the centre of bending are on different sides of the crystal diffraction planes, and the lower sign corresponds to the case when the source is on the same side of the crystal diffraction planes as the centre of bending.

The source caustics is defined as a circle of radius \( \rho \sin(\chi \pm \theta_B) \) centred at the centre of bending and the focal caustics as a circle of radius \( \rho \sin(\chi \mp \theta_B) \) also centred at the centre of bending. (1) requires the source point to be at the intersection of the Rowland circle with the source caustics. In this case the focal point is at the intersection of the Rowland circle with the focal caustics. This point of view will be helpful in understanding the dual-energy monochromator (section 3).

For simplicity, only the lower-sign case will be discussed from now on. For a point source, the virtual source as seen by the patient and detector is not pointlike. To better understand this aberration of the output rays consider figure 2. For a small region of the bent crystal around point A, the corresponding virtual focal point (B) is the intersection of the Rowland circle with the focal caustics, and the direction of the diffracted beam is along the line AB. As point A sweeps to C through the bent crystal characterized by the angle ψ, the corresponding focal point sweeps through an arc on the focal caustics. This aberration of the virtual source point does not degrade the resolution of the resulting image because the diffracted beams originate from an array of sources each with a specific direction of emission tangent to the focal caustics.

A four-bar bender is a device which uses four parallel bars to bend a rectangular crystal by pushing the crystal with two inner bars and pulling with two outer bars (see figure 5 below for the cross section of a four-bar bender). Using a four-bar bender to bend the crystal, for the cylindrically bent crystal achieved by displacing the upper and lower bar by the same amount, the angle the crystal planes make with the incident x-rays is not the same across the crystal surface. This can be solved by unbending the upper bar by an amount \( \Delta \rho \) (differential bending) and bending the lower bar by an equal amount \( \Delta \rho \) in addition to the displacement required to bend the crystal into cylindrical shape. The amount of differential bending is given by

\[ \Delta \rho = \frac{L_1 L_2}{2} + \frac{2}{3} f^2 L_c \left( \frac{1}{\rho^2} \tan(\chi - \theta_B) \right) \]  

where \( 2L_c \) is the distance between the two inner bars, \( L_1 \) is the distance between the outer bar and the inner bar and \( \rho \) is the bending radius.

3. Dual-energy imaging with Ba and Ce K line x-rays

For the present experiment, the \( K_{\alpha_1} \) (low-energy \( E = 32.19 \) keV) line of the Ba is used for the low-energy beam and the \( K_{\alpha_2} \) (high-energy \( E = 34.72 \) keV) line of the Ce is used for the high-energy beam. For the Si{111} reflection the Bragg angles for \( E = 3.522 \) and 3.265°, respectively, with \( \Delta \theta = (\theta_{B_1} - \theta_{B_2}) = 0.257° \). The main operational challenge is to switch between the high and low energies in a time period on the order of 0.01 s (this time is required to minimize motion artefacts of subtraction angiography during the diastolic cycle of the cardiac motion). This can be achieved by coating the anode with layers of Ba and Ce film and switching the focal spot position of the incident electron beam. Using one crystal, there is an angle between the monochromatic high-energy beam and low-energy beam (figure 3). By using two crystals in the proper configuration, the virtual source can be coincident for the two beams (figure 4). In this case, there is no crossing angle between the two beams.
3.1. Using one bent crystal

The $E^+$ and $E^-$ beams can be diffracted by the same bent crystal using the same set of diffraction planes. This can be achieved by moving the source point on the Rowland circle for different energies and shaping the anode so that it intercepts the Rowland circle (figure 3).

For the low- and high-energy beams, the source caustics radii of curvature are

\[ C_L = \rho \sin(\chi - \theta_B^-) \]  
\[ C_H = \rho \sin(\chi - \theta_B^+) \]  

so the motion of the source point is

\[ M \cong \rho \cos(\chi - \theta_B^-) \Delta \theta. \]  

The source point motion is 2.2 mm for a source to monochromator distance of 0.5 m using the Si[111] reflection. The two reflected beams traverse the patient at an angle $\Delta \theta$ to each other. Since we are taking the difference between the high- and low-beam images, the subtracted image will have artefacts due to the misregistration of the two images. The major artefact is from bone edge mismatch in the two images. For the Si[111] reflection, $\Delta \theta$ is 4.5 mrad, which is near the upper limit of an acceptable crossing angle.

3.2. Using two bent crystals

Now consider using two crystals to diffract beams of two different energies assuming that the same crystal reflection is used for both crystals (figure 4).

The radii of the source and focal caustics for $E^-$ and $E^+$ are

\[ C_L = \rho_1 \sin(\chi - \theta_B^-) \]  
\[ D_L = \rho_1 \sin(\chi + \theta_B^-) \]  
\[ C_H = \rho_2 \sin(\chi - \theta_B^+) \]  
\[ D_H = \rho_2 \sin(\chi + \theta_B^+) \]  

where $C_L$ and $C_H$ are the source caustics radii, $D_L$ and $D_H$ are the focal caustics radii, $\rho_1$ is the bending radius of the crystal which reflects the low-energy beam and $\rho_2$ the bending radius of the crystal reflecting the high-energy beam.
The focal caustics define the shape of the virtual object for the diffracted beam. Requiring $D_1 = D_H$ and shaping the anode to intercept the Rowland circles, the virtual sources of the diffracted beams coincide. Thus

$$\rho_1 = \sin\left(\chi + \theta_B^+\right)$$
$$\rho_2 = \sin\left(\chi + \theta_B^+\right)$$  \hspace{1cm} (11)

In this case, the motion of the source point required to switch between the high-energy and low-energy beams:

$$M = C_H - C_L = 2\Delta\theta_B^+ \sin \hat{\theta}_B$$

$$\sin \hat{\theta}_B = \frac{(\rho_H + \rho_L)/2}{\sin(\chi + \theta_B^+)}$$  \hspace{1cm} (12)

where $\hat{\theta}_B = (\theta_B^+ + \theta_B^-)/2$ and $\rho = (\rho_H + \rho_L)/2$.

4. Experimental setup

The setup of the experiment at the SRL compact source is shown in figure 5. An electron beam with maximum energy of 500 keV for the prototype source was produced by an electrostatic accelerator and focused and the beam path bent to hit the anode material. The rotating anode was coated with a section of BaB$_4$ and a section of CeB$_6$. Characteristic lines above or below the iodine K edge were selected by switching between different sections of the coated target. The monochromator crystal was cut from a standard 4 in float zone silicon wafer with the [100] direction perpendicular to the surface normal. The [111] reflection with an asymmetry angle of 35.3° was used. The 0.46 mm thick crystal was cut into a rectangular shape of 5 cm wide by 7.5 cm long and bent into a cylindrical shape with a four-bar bender. The [111] lattice planes were parallel to the short side (5 cm) of the crystal. The usable area of the monochromator crystal between the two centre bending bars was 25 mm high by 50 mm wide. The crystal bender was on a stage which had motor control of the Bragg angle, the height of the crystal relative to the incident beam and the distance to the source. The unreflected beam (white beam) was prevented from reaching the phantom and the detector by lead shielding placed 400 mm behind the crystal. The positioning of the shielding allowed the diffracted beam to reach the detector through a window. The images of the reflected beam were taken with a cooled CCD detector optically coupled to an image intensifier (with CsI phosphor) placed at 600 mm from the crystal. The horizontal and vertical spatial resolution of the detector system was 0.2 mm. The energy spectrum of the beam was measured with a silicon detector (EG&G SLP-16220-P) placed at the image intensifier position.

5. Results

5.1. Spectrum of the diffracted beam

Spectra of the incident beam, the beam filtered with 0.1 g cm$^{-2}$ caesium fluoride and the beam reflected by the crystal bent to a radius of 590 mm were measured at different incident electron beam energies with the silicon detector. Figure 6 shows the measured spectra at an electron energy of 150 keV. The vertical scale was normalized to the intensity of the K characteristic lines so that the intensity at the peak is unity.

For quantitative assessment of the monochromaticity of the beam, the spectral purity is defined as

$$P = \left(\int_{E_0-\Delta E}^{E_0+\Delta E} n(E) dE\right) \left(\int_{E_1}^{E_0} n(E) dE\right)^{-1}$$  \hspace{1cm} (13)

where $E_0$ is the K characteristic line energy of interest, $\Delta E$ is the energy bandwidth chosen as 3 keV to cover the energy resolution of the detector used, $E_1$ and $E_2$ are chosen as 20 and 100 keV respectively to cover the range of useful radiography energies, and $n(E)$ is the energy dependent flux distribution. The spectral purities of the original beam and diffracted beam for different electron energies are listed in table 1. It is apparent that the diffracted beam is almost ideally monochromatic.

![Image of a diffracted beam spectrum](image)

Figure 6. Spectra of the diffracted monochromatic beam, the original beam and the filtered beam at an electron energy of 150 keV.

<table>
<thead>
<tr>
<th>Electron energy (keV)</th>
<th>110</th>
<th>150</th>
<th>190</th>
<th>4.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original beam</td>
<td>0.41</td>
<td>0.43</td>
<td>0.42</td>
<td>0.46</td>
</tr>
<tr>
<td>Diffracted beam</td>
<td>0.94</td>
<td>0.91</td>
<td>0.84</td>
<td>0.83</td>
</tr>
</tbody>
</table>

5.2. Crystal reflectivity and uniformity of the diffracted beam

The intensity of the diffracted beam is calculated by

$$I(\theta) = \int \int \frac{d^2I}{d\omega dE} (\omega, E) R(\theta + \omega + \Delta\theta(E)) d\omega dE$$  \hspace{1cm} (14)

where $\omega$ is the opening angle of a point on the source with respect to the centre of the crystal in the plane of diffraction and $E$ is the energy of the incident beam. $(d^2I/d\omega dE)(\omega, E)$ is the distribution function of the source intensity. $I_0 = \int (d^2I/d\omega dE)(\omega, E) d\omega dE$ gives the total intensity in the incident beam. $R(\omega)$ is the reflectivity of the bent crystal and $\Delta\theta(E) = -\tan\theta_B(E - E_0)/E$ with $E_0$ being the centre energy reflected for $\omega = 0$. 

Figure 7 shows the calculated and measured rocking curves (reflected beam intensity $I(\theta)/I_0$ as a function of the crystal angle) for a cerium source with vertical source size of 1.0 mm. The crystal was bent to a radius of 590 mm. The source geometrical flux distribution function $G(\omega)$ was calculated assuming a circular source (diameter = 1.0 mm) with uniform intensity distribution and assuming that the geometrical flux distribution is independent of the energy distribution in the source, $(d^2I/d\omega dE)(\omega, E) = G(\omega)J(E)$.

The uniformity of the diffracted beam depends on matching the angle of the crystal planes with the divergence of the incoming beam at all points on the crystal. If the angle the crystal planes make with the beam is within the reflection FWHM of the Bragg angle then the beam will be reflected; otherwise the reflectivity is close to zero. With the four-bar bender, the crystal was capable of reflecting the full beam with corresponding image size of 47 mm high by 112 mm wide at the detector position. The variation in intensity of the reflected beam is less than 10%, which can be corrected for by proper calibration images.

5.3. Phantom imaging

Due to the low intensity of the prototype x-ray source used for the testing, preliminary phantom imaging was carried out with phantom thicknesses less than the practical patient thickness in order to achieve a reasonable exposure time. The phantom used consisted of 40 mm thick Lucite block with five vertical channels of different thickness. The channels were filled with iodine solutions with iodine concentrations of 2, 4, 6, 8 and 10 mg cm$^{-2}$. On the lower half of the phantom, a bone block phantom (Nuclear Associates 76-705) was put horizontally to simulate bone density variation. The phantom was placed 100 mm in front of the image intensifier. The phantom was first imaged with the CeB$_6$ target and the monochromator tuned to reflect the cerium K lines. Then the target was switched to the BaB$_6$ section and, with the monochromator tuned to reflect the barium K lines, the image of the same phantom was taken again. For each energy above and below the iodine K edge, a set of four CCD detector images were taken: the flat-field image (image without the phantom in place), the original phantom image and two dark-field images without the x-ray beam at the corresponding imaging conditions. The dark-field images were subtracted from the corresponding images to obtain the calibration image and the phantom image. The phantom images were then divided by the calibration images on a pixel by pixel basis to produce the Ba or Ce K-line energy image used for the subtraction process. The elimination of the beam hardening effect by using the monochromatic beam makes the subtraction algorithm simple. Figure 8 shows the image of the phantom at the Ba and Ce energies and the subtracted images showing the water and iodine concentrations separately. It is seen that the bone structures have been cancelled in the subtracted image.

![Figure 7. Rocking curve.](image)

The surface dose to the phantom was $1.7 \times 10^{-2}$ mGy for both images above and below the iodine K edge. The dose was calculated using the beam intensity measured by the solid state detector. This dose is comparable to typical doses currently used in intravenous coronary angiography with synchrotron radiation when the thickness of the patient is taken into consideration. The signal-to-noise ratio of the subtracted image for the iodine channel with 4 mg cm$^{-2}$ concentration is 1.9, which is comparable to the theoretical value of 2.3 considering Poisson statistics and 100% detector efficiency.

The contrast of the image is higher using a monochromatic beam than using the polychromatic beam if the monochromatic beam energy is just above the K edge of the contrast agent as in the case of cerium K lines. Figure 9 shows the measured contrast of different iodine concentrations at the Ce K-line energy. The error bars are calculated using the standard deviation of the image. The calculated contrast based on the measured monochromatized beam spectrum is plotted with lines.
source is around 23%. In this configuration, the crystal is at 0.58 m from the source and the monochromatic beam is separated from the direct white beam at a distance of 0.7 m from the crystal. If the patient is put at this distance, the beam area is 80 mm high at the patient position. Thus the expected photon flux is $1.5 \times 10^{10}$ cm$^{-2}$ at the patient position using an optimum crystal and the proposed source (using the present crystal and bending configuration would give a flux of $0.6 \times 10^{10}$ cm$^{-2}$ with the same proposed compact source).

![Graph showing contrast of different iodine concentrations at the cerium K-line energy.](image)

**Figure 9.** Contrast of different iodine concentrations at the cerium K-line energy.

To assess the degradation of the image contrast due to the aberration in the vertical direction, a lead square was placed on the phantom. The modulation transfer functions (MTFs) for the horizontal and vertical directions were calculated from the line spread function (LSF) of the lead edge in the Ce K$_\alpha$ energy image (figure 10) measured by the CCD detector. Theoretical calculations of the MTF contributed separately by the source (assuming a uniform disc of 1.0 mm diameter) is also shown in figure 10. It is seen that with a source spot size of 1.0 mm, the source MTF component is insignificant. The beam was not modified by the monochromator in the horizontal direction. The fact that the horizontal MTF is close to the vertical MTF confirms that the image resolution was not affected by the aberration.

6. Discussion

This work was motivated by the desire to apply the synchrotron dual-energy digital subtraction angiography technique to clinical use. The required x-ray fluence for imaging 2 mg cm$^{-2}$ iodine attenuated by 20 cm water with a signal-to-noise ratio of three and pixel size of 0.25 mm x 0.25 mm is approximately $1 \times 10^{10}$ photons/cm$^2$ (Zeman et al 1984). Manning et al (1991) studied the fluence of characteristic x-rays available from their proposed compact source using Monte Carlo simulations and the related target heat loading considerations. The simulation suggests that the compact source would be able to provide a K$_\alpha$ emission line fluence of the order of $10^{15}$ photons/sr in a pulse of 0.01 s duration. The crystal thickness, asymmetry angle and bending radius used in the present experiment were not optimized for the largest reflected beam intensity at the patient position due to limitations of available crystal wafers. Theoretical calculations show that by using a silicon crystal with a thickness of 1.0 mm and an asymmetry angle of 65° bent to a radius of 1.2 m, the absolute reflectivity for the K$_\alpha$ lines of a 1 mm diameter Ba or Ce

![Graph showing MTFs for horizontal and vertical directions.](image)

**Figure 10.** The horizontal and vertical MTFs and the component of MTF (theoretical) contributed separately by the source.

The implementation of the proposed one-crystal or two-crystal schemes in a clinical unit would not be difficult given the fact that the reflection bandwidth of the bent crystal is on the order of 0.1° (a very forgiving angle in terms of alignment of the system and tuning of the crystal). With proper mechanical design, the whole system could have only two adjustments: one for the bending radius and other for the Bragg angle. It was found during the current experiment that, once the crystal is bent and tuned, the system will stay aligned for days without re-aligning even with our prototype bender in a laboratory environment with no special vibration control.

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