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PII: S0168-9002(10)02125-X
DOI: doi:10.1016/j.nima.2010.09.092
Reference: NIMA 52410

To appear in: *Nuclear Instruments and Methods
in Physics Research A*

Received date: 15 June 2010
Revised date: 26 August 2010
Accepted date: 21 September 2010

Cite this article as: J. Loveland, O. Gundogdu, E. Morton, K. Wells and D.A. Bradley, Phase contrast imaging: Effect of increased object-detector distances at X-ray diagnostic and megavoltage energies, *Nuclear Instruments and Methods in Physics Research A*, doi:10.1016/j.nima.2010.09.092

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Phase contrast imaging: effect of increased object-detector distances at x-ray diagnostic and megavoltage energies

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ABSTRACT

The effect of varying object to detector separation at constant and varying magnification has been investigated at an accelerating potential of 30 kVp. Edge-contrast enhancement provided by phase effects was investigated for a drinking straw and found to provide up to $2.52 \pm 0.02 \times$ the contrast for a PVC Heaviside step function. An optimum magnification of $1.5 \times$ was found to apply for the microfocus x-ray tube setup used. Imaging at nominal megavoltage energies was investigated using a Rapiscan Systems Eagle M4500 series scanner. For a fixed source-detector separation, increased magnification improved edge contrast and spatial resolution.

Keywords: Phase contrast, keV photons, megavoltages, Rayleigh and Delbruck scattering

1. Introduction

Considerable interest has been shown in recent years in a number of imaging techniques that make use of the wave properties of x-rays, each offering enhancement of edge contrast of low atomic number media. These phase contrast imaging techniques depend on the method applied in obtaining the phase information, categorized by the method by which the phase information is utilised. The predominant techniques are known as 'diffraction enhanced imaging', 'x-ray interferometry', and 'propagation based imaging' [1]

Present interest is in propagation based imaging, avoiding a number of stringent requirements placed on the temporal coherence of the x-ray source. We investigate: (i) low photon energies (using a microfocus x-ray tube and accelerating potentials of some tens of kV), and; (ii) high energy photons (using a linac operating in the nominal energy range 4.5-10 MV). Interests include potential biomedical imaging and security applications. For both regimes, test objects were imaged at a number of distances and magnifications, investigation being made of the effects of increasing object to detector distance.

1.1 Theory

In its passage through a medium, a photon beam is reduced in intensity and altered in its phase. This can be described in terms of the complex refractive index of the object,

$$n = 1 - \delta + i\beta, \quad (1)$$

where δ is an absorption term proportional to the linear attenuation coefficient and β is a phase term proportional to the electron density of the object. Variations in the imaginary part of the refractive index across the object create variations in intensity of the beam; changes in the real part of the refractive index lead to variations in the phase of the beam. The wave optics can be explained in terms of spherical wave fronts, provided the object is sufficiently far from the source that the source approximates a point. At large distances the spherical

waves approximate plane waves. Use of spherical waves simply scales the distance at which a given intensity distribution occurs [2], shown herein for just one spatial direction:

$$I_s(u, b, \lambda) = I_p(Mu, z_{eff}, \lambda), \quad (2)$$

where $I_s(u, b, \lambda)$ is the intensity pattern for spherical waves incident on a detector at position b along the propagation direction z (in Cartesian coordinates) and $I_p(Mu, z_{eff}, \lambda)$ is the intensity pattern for plane waves incident on the detector, at location $z_{effective} = b/M$, with M the magnification factor, u the spatial frequency and λ the mean wavelength of the source.

The magnification factor M arises from the geometry of the setup (Fig. 1), independent of any phase effects and can be easily derived for a point source using ray optics. The geometrical term for M remains valid for a finite source of size s provided that $s \ll a$. The magnification provides an improvement in the images, the system no longer being limited by the spatial resolution of the detector. One factor degrading image quality and countering the benefits of phase effects is the penumbra effect, the extent of which increases with detector-object distance and decreasing source-object distance. Thus said, although blurring from the penumbra reduces the contrast of the edge enhancements it may aid their detection [3], smearing of the edge across a larger area possibly aiding detail to be more easily resolved.

Fig. 1: Geometric magnification

It has been shown theoretically and experimentally that the propagation technique does not require a monochromatic source [4]. For polychromatic sources the intensity distribution can be described as a weighted sum of the intensity distributions from monochromatic sources [5]. If there is sufficient lateral coherence, the phase effects remain visible. To produce phase contrast with polychromatic sources is one of the main advantages of the propagation based phase contrast method. While this allows use of x-rays without temporal coherence, it does require quite a high degree of spatial coherence. This is because there must be good correlation between the amplitude of the beam from different points on the source [4]. The coherence length of a setup can be calculated through the relation:

$$d_l = \lambda a / s, \quad (3)$$

with d_l the lateral coherence length. For incident energies of a few tens of keV and propagation direction length scales of ~ 1 m, this must be $\geq 1 \mu\text{m}$ [6]. Obtaining a sufficiently large coherence length suggests a low energy beam or a large source to detector distance.

The change in phase can be expressed in terms of the real part of the atomic scattering factor. Since this can be derived from the coherent scattering of electromagnetic waves [7] it follows that the phase shift is a result of coherent scattering. Although elastic scattering is not necessarily coherent scattering [8] there are three main types of elastic collision which can be considered coherent – Rayleigh, nuclear Thomson and Delbruck scattering. In the former, the incident photon excites an electron and is absorbed. The electron rapidly de-excites to its original configuration via emission of a photon with the same wavelength as the original photon. This is the dominant form of elastic scattering at low energies [9]. Nuclear Thomson scattering is essentially the nuclear analogue (scattering off nucleons) of Rayleigh scattering. In Delbruck scattering the incident photon creates a pair in the external field of the nucleus which then annihilates [10]. This results in the emission of a photon with the same energy as the incident photon [10]. Nuclear Thomson and Delbruck scattering become significant contributors to the total elastic scattering cross-sections at higher energies.

2. Materials and Methods

Fig. 2: Oxford Instruments XTF5011 x-ray tube set up

2.1 Microfocus x-ray tube investigations

Use was made of an Oxford Instruments XTF5011 x-ray tube with a Ag target. The maximum current was 500 μA . The spot size for the particular tube, measured by Oxford Instruments, is 309 μm width by 51 μm height. The detector was an xDI Photonics Science CCD camera with a resolution of 1330 $\times$ 1030 pixels, each 6.7 μm square, the system offering 12-bit depth. The set up was arranged to provide for phase propagation (Fig. 2).

2.2 Megavoltage photon investigations

Rapiscan Systems offers a number of security solutions many of which involve the use of x-rays. The system of interest herein was an Eagle M4500 series scanner, a mobile unit capable of imaging whole trucks in a single scan. It has an unfiltered Varian Linatron 4.5 MV linac as the x-ray source, mounted on the back of a truck chassis (Fig.3). The detector bank is on a retractable boom which during scanning is positioned opposite the linac such that a 4.9 m high arch is formed which can pass over the truck to be scanned. The source size of the linac is less than 2 mm and the beam is emitted at an angle to the horizontal of 28° with a 3 mm slit lead collimator fitted to form a fan beam. The detector consisted of a linear array of photodiodes with 20-bit pixel depth and a pixel size of 5 mm arranged into blocks, each coupled to a CdWO_4 scintillator crystal. These were all angled to point at the centre of the source. When acquiring an image the Eagle M4500 is driven forward at a fixed rate such that the boom passes over the top of objects of interest. The distance of the objects from the detector was varied as widely as possible. Due to the structure of the truck, the closest position to the source attainable was 2.5 ± 0.1 m while the furthest distance investigated for an initial series of investigations was 6.0 ± 0.1 m. The linac was operated at 90 Hz and during acquisition the truck speed was 0.25 ms^{-1} resulting in a horizontal resolution of 2.8 mm. The test objects were mounted on Al stands 1.509 ± 0.005 m high with wooden platforms to support a range of objects under study. These consisted of a series of cylinders of differing thicknesses, radii and compositions; glass beads of various radii; a bottle of water; and a PIPSPRO QC3 phantom (Standard Imaging, Inc., Middleton, WI) were also imaged (manuscript length limitations allowing only results for the cylinders to be discussed herein). Images of one of the Al stands were also collected at much larger distances (> 10 m) by retracting the detector boom and using a set of identical detectors set in a portable light tight box.

Fig. 3: The Eagle M4500 with the boom deployed for scanning.

3. Example Results

3.1 Microfocus x-ray tube investigations

Profiles across a drinking straw at constant magnification and varying object-detector distance have demonstrated considerable edge enhancement (Fig. 4). A contrast improvement of 2.52 ± 0.02 was found using a PVC Heaviside step function at 1.5 magnification.

Fig. 4: Profiles averaged over 300 lines for a straw imaged at constant magnification 1.5 $\times$. Exposure factors were 30 kVp and 100 μA . The error bars indicate 95% confidence levels.

In addition to phase effects enhancing edge contrast, simple geometric magnification was also seen to increase contrast in the images, up to a peak value at 1.5 $\times$ for a source to detector distance of 1.5 m (Fig. 5), reducing with further magnification to a minimum at $\sim 4.5 \times$. This compares favourably with findings by Gundogdu et al. [1], in which for investigations of magnifications from 1 to about 1.65 $\times$ the contrast reached a plateau at around 1.5 $\times$.

Fig. 5: Variation of contrast as a function of magnification for a 30 kVp, 100 μ A beam incident on a drinking straw; 3 min exposure for each data point. With a source to detector distance of 1.5 m, the sample position was varied to alter magnification. Error bars as before.

Fig. 6: Simulation of experiment in Fig. 5. The error bars indicate 95% confidence levels.

Apparent from simulation (Fig. 6) is the similarity of peak shape at a magnification of 1.5 $\times$. The simulation models the effects of absorption only, neglecting phase; the peak is therefore a result of magnification alone. The contrast in the simulation is consistently higher than the contrast in the experiment and can be explained in part by the fact that the model does not take into account air attenuation ($\sim 6\%$), inexact account of the composition of the straw and the assumption of a monochromatic beam. The 95% confidence levels of the simulation are much larger than those from the experiment, use of an available 2 GHz single core processor restricting the number of rays to a maximum of some 10^6 per image. The decrease in contrast following the peak value is believed to be a consequence of penumbra effect, blurring from the penumbra dominating image quality at higher magnifications.

The improvement in contrast gained from phase can be obtained by examining data from the Heaviside step function [11]. For an incident energy of 30 kVp at a detector to object distance of 0.5 m and magnification 1.5 $\times$ (corresponding to the maximum contrast), the contrast between the peak and trough of the profile across the Heaviside function (Fig. 6)) is 0.037 ± 0.001 . Conversely, the contrast between the average transmitted beam grayscale level and the average attenuated beam gray-scale value (i.e. contrast between far left and far right of the 30 kVp profile in Fig. 5) is 0.016 ± 0.001 . This suggests the phase effects provided an increase in contrast above that provided by absorption of a factor of 2.52 ± 0.02 .

3.2 Megavoltage nominal energy investigations

For profiles obtained through images of scanned cylinders (Figs. 7 and 8), a trend towards increasing contrast is obtained with increasing object-detector distance. However this was also observed in an absorption-only simulation of the experiment and is therefore believed to have been a geometric rather than a phase effect.

Fig. 7: The cylinders in the photograph appear in the same orders in the x-ray profiles of Fig. 8 below (cylinder 1 (Cu), cylinders 2 and 3 (brass), cylinders 4 and 5 (PVC); cylinder 6 (polymethylmethacrylate)).

Fig. 8: Mean of seven profiles taken through the cylinder images for the two extreme object-detector separation. A progressive change in edge contrast with separation was obtained (to aid image clarity the intervening separations have been omitted).

The final Rapiscan experiment involved much larger distances, providing for increased lateral coherence length. For this, the detector bank on the truck was retracted, the source was kept static and a small bank of detectors in a light-tight box were deployed at several distances to provide for object to detector separations from 7.5 m up to 53 m. An Al stand placed at a distance of 2.50 ± 0.05 m from the source was made to act as the test object. A dark field image was obtained for the remote detector, averaged over 100 readings and this was subtracted from all subsequent data. For each data set the results were averaged over 100 lines of data. Results indicate progressive reduction in overall contrast with distance to the detector, the S/B ratio decreasing to just in excess of dark field conditions. Apparent was an absence of enhanced edge contrast (Fig. 9), almost certainly due to the limited lateral coherence length at the megavoltage energies and source size investigated.

Fig. 9: Image contrast for Al stand (source-object dist. 2.5 m, object-detector dist. 53 m).

4. Conclusions

We have studied edge contrast as a function of separation of imaging detector and object. At kVp potentials, phase contrast enhances edge contrast above that due to absorption alone. At 30 kVp, we find an improvement of 2.52 ± 0.02 over that using a PVC Heaviside step function. In addition to phase contrast effects, simple geometric magnification increases the contrast, peaking for a magnification of $1.5 \times$ for a source-detector distance of 1.5 m, degrading with further magnification. The effect of object-detector separation on image quality was also studied at megavoltage energies. Profiles taken through scanned cylinder images show a trend towards increasing contrast with increasing object-detector separations, from a fraction of 1 m up to several m. However this was also observed in a simulation of photon absorption and is therefore believed to be a geometric rather than phase effect. At these elevated photon energies significant and untenable increase in separation distance would be required in order to establish sufficient lateral coherence (for the focal spot used, a separation of > 1 km would be indicated). While for such photon energies, propagation based phase contrast imaging is only indicated for a focal spot of submicron dimensions, increasing object-detector distances have nevertheless revealed improvement in edge contrast. This is interesting, particularly given that in electronic radiotherapy portal imaging the detector is typically placed as close as possible to the patient.

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Fig. 1: Geometric magnification

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Fig. 3: The Eagle M4500 with the boom deployed for scanning.

Figure 4

Fig. 5: Variation of contrast as a function of magnification for a 30 kVp, 100 μ A beam incident on a drinking straw for an exposure time of 3 min for each data point. The source to detector distance was kept constant at 1.5 m and the sample position varied to alter the magnification. The error bars indicate 95% confidence intervals.

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Figure 9