A GEOMETRIC METHOD FOR NEAR-FIELD ARTIFACT REDUCTION IN PLANAR CODED APERTURE NUCLEAR MEDICINE IMAGING

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Abstract: Coded apertures have a number of theoretical advantages over collimators in diagnostic nuclear medicine. The near-field conditions of nuclear medicine, however, cause the image to be corrupted by near-field artifacts. An examination of the origin of near-field artifacts makes the problem clear. Gamma-rays originating from the same point source have significantly different intensities when arriving at different locations on the detector. For a perfect reconstruction, the intensities must be identical. A novel geometric solution for artifact reduction is to limit the field of view, which in turn limits the change in intensities. Placing multiple identical limited field of view coded apertures side by side, in the form of a matrix, allows the overall field of view of the system to remain unaltered. Such a change can readily be made. Computer simulation results for a planar digital phantom are presented. The geometric technique enhances the image not only visually, but also in terms of a root-mean-square error measurement, which decreases from 32 to 8. Both the near-field artifacts and the ghosting are reduced.

Introduction

Coded apertures are used as an alternative to pinhole cameras and collimators in gamma-ray imaging. The apertures have the potential to increase the signal-to-noise ratio (SNR) of the system [1], and can theoretically be applied advantageously to diagnostic imaging in nuclear medicine. The increased SNR can be manipulated to improve image resolution, to shorten imaging time, or to reduce the patient's dose of radioactivity.

Coded apertures were originally developed for use in astrophysics, where far-field imaging conditions hold. Such conditions allow for the acquisition of images that are close to perfect for two-dimensional (2D) noise-free data [2]. The near-field conditions of nuclear medicine, however, cause the image to be corrupted by near-field artifacts.

Past research has indicated apertures that are optimal for the purposes of nuclear medicine [3]. Although a reduction of near-field artifacts can be achieved by taking a second image with a rotated aperture, and by then summing the two sets of data [4], ghosting of the object becomes prominent.

This paper outlines a novel methodology for limiting near-field artifacts by means of the imaging geometry.

Method

Background: Coded aperture imaging requires that for each point of the source, the aperture pattern must be projected onto the detector. This results in overlapping aperture patterns, each shifted and weighted according to the location and the intensity of the specific point source that projected the pattern [5].

Theoretically, this acquisition process is modelled by convolving the source with the aperture pattern. The image is reconstructed by correlating the encoded data with the original coded aperture pattern [5]. This pattern is designed such that a unique reconstruction exists.

Convolution implies that a point source must be imaged equally by each pinhole of the coded aperture, without change in intensity, and with the image of the point source falling directly below the pinhole. The decoding procedure performs correctly under these conditions. An examination of the origin of near-field artifacts makes the problem clear.

The general case: The intensity I_q at a distance r_q away from a point source S with intensity I_S is given by:

$$I_q = \frac{I_S}{4\pi r_q^2} \quad (1)$$

Consider the general imaging geometry shown in Figure 1. For a point source S, at a height h above a square detector of dimension w, the shortest distance between the source and the detector is represented by r_x, which is perpendicular to the plane of the detector. The longest possible distance then, is represented by r_y. From Figure 1:

$$r_x = h \quad (2)$$

$$r_y = \sqrt{h^2 + 2w^2} \quad (3)$$

The greatest possible change in I_q on the detector, expressed as a fraction of the maximum I_q, is given by:

$$\Delta I = \frac{I_x - I_y}{I_x} \quad (4)$$

Substituting equation (1) into equation (4) gives:

$$\Delta I = \frac{r_y^2 - r_x^2}{r_y^2} \quad (5)$$

ISSN: 1727-1983

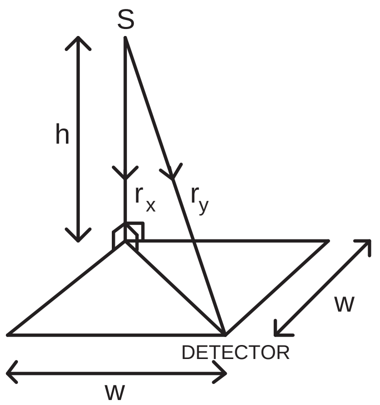

Figure 1: General imaging geometry

It becomes useful to work with the ratio h/w, which is the height h of the source above the detector relative to the detector dimension w. Substituting equation (2) and equation (3) into equation (5), and writing as a percentage, gives $\triangle I$ in its final form:

$$\Delta I = \frac{2}{\left(\frac{h}{w}\right)^2 + 2} \times 100\,\% \qquad (6)$$

With this tool in place, the general case can be applied to particular imaging geometries. Figure 2 provides a graphical interpretation of equation (6). It shows how the detector intensities change from the near-field case on the left, to the far-field case on the right, where $h \gg w$.

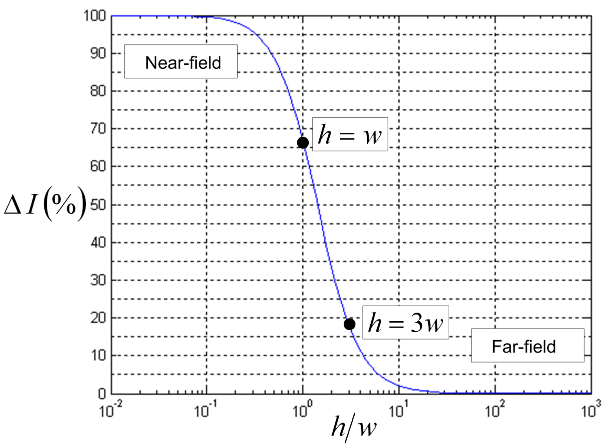

Figure 2: Relationship between geometry and detector intensities

For a perfect reconstruction, the intensities must be identical. This is a requirement of the decoding procedure. Under near-field conditions, gamma-rays originating from the same point source have significantly different intensities when arriving at different locations on the detector – one cause of near-field artifacts.

A geometric solution: If coded apertures are to be compared directly with parallel-hole collimators in nuclear medicine, it becomes necessary to image at a 1:1 ratio. The field of view (FOV) of the system is then of the same dimensions as the detector.

Figure 2 makes it clear that, for a given height h above the detector, the change in intensities can be manipulated by decreasing the detector dimension w. Limiting the FOV in turn limits the change in intensities. Near-field artifacts, then, can be traded for a narrower FOV.

This is implemented physically by positioning a tube of screening material around the coded aperture, between the source and the detector, resulting in a quasi-collimator. Placing multiple identical limited-FOV coded apertures side by side, in the form of a matrix, allows the overall FOV of the system to remain unaltered.

Accorsi's technique for the reduction of second order near-field artifacts, which requires rotating the aperture by 90° [4], can still be carried out with ease. Rotating each aperture or element of the matrix individually is the same as rotating the whole matrix of coded apertures.

Testing: In order to test the geometric solution, a computer simulator based on ray tracing techniques, and capable of predicting image acquisition in the field of nuclear medicine, was developed.

Simplifying assumptions were made while modelling the imaging process. Background radiation was omitted, as it is typically small. More importantly, ideal coded apertures were used. This means that the apertures were modelled as being infinitely thin, with opaque elements that completely attenuate gamma-rays, and with transparent elements that act as perfect pinholes, without loss of resolution.

The purpose was to cut to the root cause of near-field artifacts, such that any artifacts that arise can only be the result of a near-field imaging geometry. A comparison of the existing and novel near-field artifact reduction techniques follows.

Results

Computer simulation results for a planar digital Shepp-Logan phantom [6] are presented. The results incorporate both far-field and near-field imaging conditions. For the latter, the existing technique is applied and contrasted to the results obtained with the novel methodology.

Ideal conditions: The convolution model must hold, and $\Delta I \longrightarrow 0$ as $h \longrightarrow \infty$, resulting in a perfect image of the digital Shepp-Logan phantom (Figure 3). Computing the root-mean-square error (RMSE) relative to the phantom gives 0. The results are summarised in Table 1.

Far-field: The convolution model must still work under relatively far-field conditions, and putting $h = 5000w$ gives a negligible change in intensities. The simulated image is presented without correction (Figure 4). Following a far-field correction [5], the RMSE would be close to 0.

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Figure 3: Digital Shepp-Logan phantom

Figure 4: Far-field image, RMSE of 10

Near-field: h will be at least equal to w, if not smaller, and ΔI rises substantially. Accorsi's method for the reduction of second order near-field artifacts [4] was applied (Figure 5).

Limited-FOV: Under the same near-field conditions, the coded aperture was replaced with a 3×3 array of limited-FOV coded apertures, such that the overall FOV of the system remained unaltered. Reducing w by $\frac{1}{3}$ gives $h = 3w$, and pushes ΔI towards the lower region of the curve. Again, Accorsi's method was applied [4] (Figure 6).

Table 1: Summary of changes in % intensity as a function of the ratio h/w

Situation	Geometry	ΔI (%)	RMSE
Ideal	$h \longrightarrow \infty$	0	0
Far-field	$h = 5000w$	8×10^{-8}	10
Near-field	$h = w$	67	32
Limited-FOV	$h = 3w$	18	8

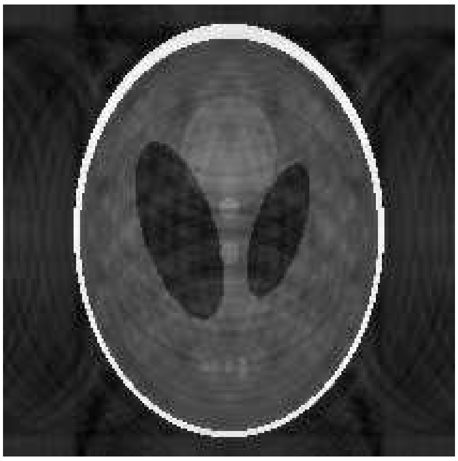

Figure 5: Near-field image, RMSE of 32

Figure 6: Limited-FOV image, RMSE of 8

Discussion

The simulation results show that both the ideal and the far-field imaging geometries adhere to the theory of coded aperture imaging. In accordance with the analysis of the general geometry, there is little or no RMSE with respect to the digital phantom – refer to Table 1.

At the chosen near-field geometry, the change in intensities rises substantially. This is mirrored by an increased RMSE, and by prominent ghosting of the object, which occurs even after the application of the existing technique for the reduction of second-order near-field artifacts.

Based on an understanding of the origin of near-field artifacts, a limited-FOV coded aperture was proposed and simulated. For a given height h above the detector, the curve shown in Figure 2 can be used to judge the appropriate detector dimension w for the limited-FOV system.

The analysis suggests that the change in intensities will be reduced to less than $\frac{1}{3}$. The enhancement is evident both visually and in terms of the RMSE measurement.

ISSN: 1727-1983

These results show that the geometric technique successfully limits near-field artifacts. Furthermore, ghosting of the object is considerably reduced.

The only change between these two near-field test scenarios was that an ideal coded aperture was replaced with a matrix of ideal limited-FOV coded apertures. From a practical perspective, such a change can readily be made.

The next stage, therefore, is to examine the artifacts that will be introduced by the use of realistic coded apertures under near-field conditions. It is anticipated that limited-FOV apertures will remain advantageous.

Conclusion

A novel methodology for limiting near-field artifacts by means of imaging geometry has been outlined. While the technique is based on narrowing the field of view, a matrix of coded apertures ensures that there is no loss with respect to the overall field of view of the system.

This paper has presented simulation results that compare the existing and novel methodologies, a critical analysis of which shows that the geometric method successfully reduces both near-field artifacts and ghosting. It is anticipated that this will enhance the practicality of coded aperture imaging in the field of nuclear medicine.

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ISSN: 1727-1983