Validation of a Digital Mammography Image Simulation Chain with Automated Scoring of CDMAM Images

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Abstract. A wide variety of digital mammography systems are available for breast cancer imaging, each varying in physical performance. However, the relationship between physical performance assessment and clinical outcome is not clear. Thus, a means of simulating technically and clinically realistic images from different systems would represent a first step towards elucidating the impact of physical performance on clinical outcome. To this end, a framework for simulating technically realistic images has been developed. A range of simulated test objects, including CDMAM have been used to determine whether the simulation chain correctly reproduces these objects thus validating the simulation framework. Results evaluated for two digital mammography systems have been promising, with simulated images proving similar to experimental images for Modulation Transfer Function and Normalised Noise Power Spectrum measurements differing by approximately 3%.

Keywords: Digital mammography, simulation, CDMAM phantom, validation.

1 Introduction

With the growing availability of commercial digital mammography technology, it is becoming increasingly important to be able to assess the physical performance of these systems in terms relevant to impact on clinical outcome, i.e. cancer detection. Since extensive clinical trials to examine any one particular technology are prohibitively expensive, a method of synthesising technically and clinically realistic images would be highly relevant. This could be used to assess the performance of radiologists and CAD systems in detecting cancers when different systems, beam qualities, radiation doses and image processing is employed. Therefore, a simulation framework has been developed to generate images typical

of specific digital mammography systems. This framework uses measurements of physical performance parameters such as Modulation Transfer Function (MTF) and Normalised Noise Power Spectrum (NNPS). However, before simulating clinically realistic mammographic images, we have attempted to simulate a range of common test objects, including the CDMAM to examine whether our simulated images correctly represent the experimental data, and thereby validate the simulation framework. The CDMAM phantom is a contrast-detail test object widely used to evaluate the performance of mammography systems in terms of their ability to demonstrate very fine and low contrast details. The test object is made up of cells with two identical gold discs: one at the centre, and a second disc located in one of the four corner quadrants within the cell. The task of an observer is to attempt to locate the corner disc in each cell. As this is a time consuming and subjective task, automated scoring software has been developed [1],[2],[3],[4] and used as part of the validation process. Results for two digital mammography systems are presented here, one with a selenium detector and the other with a CsI phosphor detector system.

2 Methodology

Images of three types of test phantom were simulated.

- Uniform images of a 45mm thick block of PMMA (to compare the NNPS of real and simulated images)
- Images of a straight edge for MTF measurement (to compare the MTF of real and simulated images)
- Images of the CDMAM phantom (to assess the contrast degradation of small discs and contrast detail detection curves for real and simulated images)

The image simulation chain to simulate the CDMAM test object is described below. Similar steps were used albeit simplified to generate synthetic images for assessing the MTF and NNPS. This simulation chain comprised of two parts: the first part creates a noise free image blurred according to the particular MTF or impulse response and the second creates a noise image associated with a particular dose level for a specific imaging technology. This is illustrated in Fig. 1. The noise free blurred image was created from a binary template representing the background structures in the CDMAM test object (cell mesh, manufacturer icons and numerical labelling). The binary template was created by thresholding an actual high-dose X-ray image of the CDMAM phantom. The pixel values of the background and mesh were assigned as measured experimentally for a specific dose. A heel effect mask was applied at this point to account for residual artefacts left after the manufacturer’s flat-field algorithm had been applied to the detector images. This was derived through median filtering of an X-ray image of the CDMAM phantom, acquired on the system to be simulated, and normalised. This idealised template is upsampled to $10\mu\text{m}$ per pixel so that the image simulation chain may be applied to any digital mammography detector currently available. Discs are added with contrasts based initially on the

Fig. 1. Flow chart of image simulation chain

theoretical contrast-thickness relationship for the beam quality and phantom geometry used, and adjusted to match empirically measured disc contrasts on real images.

The presampled MTF of the detector is measured experimentally and modelled in 2D to produce a Fourier filter [5]. This is multiplied by the Fourier transform of the idealised image to produce the noise free blurred image, I_B , representing an idealised (noise free) image of the particular imaging system under examination. In addition to the presampled MTF, the geometric MTF, due to the finite size of the focal spot, was also modelled based on Sandborg's work [6]. It is assumed that the focal spot intensity distribution follows a box function, where there is uniform emission distribution within the box with sides f_0 and no emission outside of the box. Therefore, the MTF_{geo} can be modelled as:

$$MTF_{geo} = |\sin(\pi f_0 v (m - 1)) / \pi f_0 v (m - 1)| \quad (1)$$

where v is the spatial frequency and m is the magnification of the system for the images of the gold discs in the CDMAM. The geometric MTF is also applied to the Fourier transformed I_B and inverse Fourier transformed before it is downsampled to the detector pixel size of the particular system to be simulated, using neighbourhood averaging methods, leaving the blurred resampled image, I_{BR} .

To create a noise image, a Fourier noise filter is derived based on the NNPS of the system. Each dose was simulated with the use of NNPS measured from a uniform image taken at a dose similar to the experimental CDMAM image. This is measured in 2D with a Hann window [5] and used to filter a Gaussian noise

field in Fourier space. This is inverse Fourier transformed to create the noise image, I_N . Flat field correction algorithms are used in digital mammography sets to correct pixel intensity values due to device defects and the heel effect. However, this does not correct for the non-uniform variance across the image due to structural and geometric variations photon statistics across the detector face. Therefore, a variance map [7] was incorporated to model this effect as shown in equation 2:

$$I_{NV}(x, y) = \sqrt{I_V(x, y)} \cdot I_N(x, y) \quad (2)$$

The noise image, I_{NV} , is scaled on a pixel by pixel basis in relation to the resampled blurred image, I_{BR} . This is denoted in equation 3 by $\sigma^2(I_{BR}(x, y))$, an empirically measured mean-variance relationship for a particular detector[8]:

$$I_{NS}(x, y) = I_{NV}(x, y) \cdot \sqrt{\sigma^2(I_{BR}(x, y))} \quad (3)$$

As dose increases, the noise (measured as variance) also increases. Finally the simulated image is created by adding this scaled noise image to the blurred resampled image as illustrated in Fig 1.

2.1 Validation

Validation of this simulation chain was achieved by comparing the simulated images with the real images based on image quality metrics such as MTF and NNPS as shown in Fig 2(a) and 2(b).

The contrast degradation factor (CDF) [6] was calculated for different disc diameters. As the discs were added on a contrast-thickness relationship, the contrast for each disc is known, therefore the effects of MTF modelling could be assessed. The peak contrasts were measured for each disc using equation 4

$$C_{peak} = \frac{(P_b - \phi) - (P_{disc} - \phi)}{(P_b - \phi)} \quad (4)$$

where P_b is the mean background pixel value within the cell, P_{disc} is the peak pixel value in the disc and ϕ is the pixel value offset for the detector. The pixel values are linear with the absorbed radiation dose to the detector.

The peak contrast of each disc was measured in the disc input iamge, C_{input} , (before the MTF blurring) and blurred resampled image, C_{BR} , after the MTF blurring and resampling stage, (but before noise is added) in order to remove any discrepancies due to noise, using the following CDF equation:

$$CDF_{MTF} = \frac{C_{BR}}{C_{input}} \quad (5)$$

It is expected that the CDF will be 1.0 for the larger discs and fall below 1.0 for the smaller discs due to contrast losses due to MTF-induced blurring.

The simulated images of the CDMAM were automatically analysed using a CDMAM scoring software tool, CDCOM, to predict the threshold gold thickness for a typical observer as outlined in previous papers[1],[3],[9],[4] and compared

with results of a similar analysis of experimental CDMAM images. Sets of eight images of the CDMAM test object were simulated at three doses (1.56mGy, 3.21mGy, 6.46mGy) for a selenium detector and contrast-detail curves plotted. Results were also obtained for a system with a CsI/amorphous silicon detector at one dose (6.46mGy).

3 Results

Experimental and simulated straight edge and uniform images for the system were used to derive the MTF and NNPS curves, and these are compared in Figures 2 and 3, respectively. The experimental and simulated MTF profiles for the selenium system differed by 4.5% compared with 3.2% for the CsI system. Both systems differed by approximately 3% for the radial NNPS profile. The CDFs for different detail diameters are shown in Fig. 4, demonstrating the effect

Fig. 2. Comparison of real and simulated images using (a) MTF and (b) radial NNPS for the selenium detector

Fig. 3. Comparison of real and simulated images using (a) MTF and (b) radial NNPS for the CsI phosphor detector

Fig. 4. Contrast degradation factor for various disc diameters. Error bars indicate 2 standard errors of mean.

Fig. 5. Contrast detail curves for (a) experimental and (b) simulated CDMAM images at three doses for the selenium system. Error bars indicate 2 standard errors of mean.

Fig. 6. Contrast detail curve for experimental and simulated CDMAM images at one dose for the CsI system. Error bars indicate 2 standard errors of mean.

of the presampled MTF on disc contrast in simulated images. The CDF for the CsI system degraded smaller discs earlier than for the selenium system. Contrast detail curves were fitted to predicted human results[1][3][9] of the experimental and simulated CDMAM image sets are plotted in Fig. 5 and Fig. 6. As a result of on-going work, we have found that NNPS is critically dependent on dose. Therefore, only one dose level has been successfully simulated for the system with a CsI detector.

4 Discussion

MTF and NNPS curves for the real and simulated images provided good matches for all spatial frequencies. The average difference between experimental and simulated data for MTF and radial NNPS profiles was approximately 3% illustrating the effectiveness of the simulation framework.

The CDF curve (Fig. 4) showed the effect of the MTF curve applied in our framework on the contrasts of the smaller discs. Both systems exhibited a CDF close to one for large details and was much smaller for details with diameters below 0.4mm. The lower MTF of the system with a CsI detector caused a lower CDF for the smaller discs when compared to the system with the selenium detector as expected.

The contrast detail curves for simulated images of the CDMAM test object were successfully obtained as shown in Fig. 5 and 6. Results for the simulated data for the selenium system are comparable to that obtained experimentally. As mentioned in the results, we have found that NNPS is critically dependent on dose, and as such only one dose was successfully simulated for the CsI detector. This is currently under development. This validation has shown that our simulation framework largely addresses our initial aims, but some further refinement is needed to improve the match to real images from this system.

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