

Contrast to Noise Ratio and Contrast Detail Analysis in Mammography: A Monte Carlo Study

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Abstract. The mammographic spectrum is one of the major factors affecting image quality in mammography. In this study, a Monte Carlo (MC) simulation model was used to evaluate image quality characteristics of various mammographic spectra. The anode/filter combinations evaluated, were those traditionally used in mammography, for tube voltages between 26 and 30 kVp. The imaging performance was investigated in terms of Contrast to Noise Ratio (CNR) and Contrast Detail (CD) analysis, by involving human observers, utilizing a mathematical CD phantom. Soft spectra provided the best characteristics in terms of both CNR and CD scores, while tube voltage had a limited effect. W-anode spectra filtered with k-edge filters demonstrated an improved performance, that sometimes was better compared to softer x-ray spectra, produced by Mo or Rh anode. Regarding the filter material, k-edge filters showed superior performance compared to Al filters.

1. Introduction

The carcinogenic risk associated with the exposure of the breast tissue, in addition to the requirements for high image quality have made optimization of mammography an issue of high importance [1-4]. Technological developments have led to Digital Mammography (DM). DM can be combined with post-processing algorithms, to compensate a possibly suboptimal image contrast and improve lesion detectability. This is mainly due to the separation of image acquisition and display processes, that enables independent optimization of each one. However, any contrast amplification is limited by the subject contrast, because as the displayed contrast is increased, so is the visibility of noise.

A critical factor determining image quality is the mammographic spectrum, characterized by anode/filter material combination and tube voltage. The detectability of low-contrast breast masses is most limited by low-contrast resolution [5]. An objective image quality metric should incorporate the measurement of the CNR in selected Regions of Interest (ROIs). Image quality may also be characterized by subjective methods, utilizing CD phantoms [6]. These phantoms provide a tool for conducting CD experiments by individuating the boundary between visible and invisible objects [7].

Several experimental and simulation studies have been carried out, in order to investigate the effect of mammographic spectrum on image quality. In Screen-Film (SF) mammography, Mo/Mo combination has been considered the optimal choice, especially for thinner breasts, but other choices have also been introduced [8-10]. For DM, W-anode spectra, combined with proper k-edge filtration, provide improvement of image quality, especially for thicker breasts [1-5, 10-15].

In this study, a validated MC simulation model dedicated for mammography [16-18] was used with a mathematical CD phantom, to perform quantitative and qualitative evaluation of the imaging performance of several mammographic spectra, in terms of CNR and CD analysis.

2. Materials and methods

2.1. Simulation of mammographic procedure

The MC model is described in detail in previous works [16-18]. The exposure of the photons exiting the phantom towards the detector plane was recorded and the two dimensional exposure map (with



pixel size of 25 μm) was transformed to an 8-bit greyscale image, to illustrate the results in a pictorial form (subject contrast). In this study, the effect of detector was not considered. In order the results to be comparable, the number of the MC photons was selected to produce the same exposure just above the detector plane. This exposure was selected to be 200 mR, in order to balance between acceptable statistical fluctuation and reasonable simulation computational time. MC experiments were performed for 396 different cases combining various sizes of inhomogeneities, anode/filter combinations and tube voltages (Table 1). The mean execution time was 2h.

2.2. Geometrical model

The main geometrical model adopted, was the one presented by Spyrou et al. [16-18]. The focal spot dimensions were considered to be 0.01 x 0.01 cm^2 , while the x-ray intensity distribution was selected to be uniform. The collimators were placed 15 cm from the focus, corresponding to a Field of View (FOV) of 0.42 x 0.42 cm^2 on the detector plane. This specific FOV was selected in order to irradiate only the appropriate part of the phantom and therefore to reduce the executional time. The antiscatter grid was removed, since the selected FOV offers, to some extent, limitation of inherent scatter.

The breast phantom was specifically designed, to allow CD analysis. The compressed breast was represented by a semi-cylinder with 4 cm radius, positioned to an x-ray focus-to-detector distance of 60 cm. The background material was selected to be PMMA with a thickness of 1 cm. The phantom included two identical spherical air inhomogeneities of logarithmically varied diameters (90-250 μm) (Table 1), in order to simulate low-contrast details. The first inhomogeneity was placed at the centre of the phantom and the second was randomly placed at one of the four corners of the phantom.

2.3. Mammographic spectra

The mammographic spectra utilized were computed using a previously developed and validated analytical method [2]. Twelve anode/filter combinations, with 1mm Beryllium (Be) inherent filtration, were considered for tube voltages between 26 and 30 kVp. The anode/filter combinations (Table 1), were based on combinations proposed, either for DM [1-5, 10-15], or for SF technique [8-9].

Table 1. Anode/filter material, tube voltage and inhomogeneity sizes studied. The thickness of each filter is indicated in parenthesis.

Anode	Filter	Tube Voltage (kVp)	Inhomogeneity Size (μm)
Mo	Mo (30 μm), Nb (30 μm), Rh (29 μm), Al (510 μm)	26, 28, 30	90-250
Rh	Rh (29 μm), Al (510 μm)		
W	Mo (30 μm), Nb (50 μm), Rh (30 μm), Pd (50 μm)+2mm Al, Zr (50 μm), Al (500 μm)		

2.4. Quantitative evaluation of image quality

On the generated Monte Carlo images, CNR was derived according to the formula [4]:

$$\text{CNR} = \frac{|C_{\text{INH}} - C_{\text{BG}}|}{\sqrt{N_{\text{INH}}^2 + N_{\text{BG}}^2}}$$

where C_{INH} and N_{INH} is the mean grey level value and its standard deviation in the selected ROI under the inhomogeneity, and C_{BG} and N_{BG} is the mean grey level value and its standard deviation at the same point with the absence of the inhomogeneity. CNR values were normalized to the case of Mo/Mo anode/filter material combination at 28 kVp. The generated images were analysed using ImageJ [19].

2.5. Observer study

A four-alternative experiment was conducted, as a result of the randomly positioned inhomogeneity. For verifying the detection of each inhomogeneity, the observers were asked to indicate the corner where the inhomogeneity was located. Images were evaluated on a dedicated high resolution monitor.

The images were presented in a random order, with the room light off, while the observers were free to adjust magnification factor, brightness (window and level settings) and contrast, in order to get the best visibility. Two experienced observers independently reviewed all the images in one session. 396 images were evaluated plus an additional sample of 100 random copies, for the evaluation of the intraobserver variability. Observer's performance was based on a CD index, related to the visibility of the randomly positioned inhomogeneity. A 0-3 scale of visibility was used [20]. The individual visibility scores were averaged to obtain the mean CD score. The CD index was defined as the product of the CNR of each inhomogeneity with the corresponding mean CD score. Statistical analysis was performed using the SPSS statistical package. A p-value of less than 0.05 was considered to indicate the threshold of statistical significance.

3. Results and Discussion

3.1. Contrast to Noise Ratio

The CNR of small low-contrast details strongly depends on mammographic spectrum. Beam hardening results in a decrease of signal differences between the inhomogeneity and the background and thus the subject contrast is degraded. Grey level values, for the case of Mo/Mo spectrum, are presented in Figure 1a. The corresponding values of CNR are presented in figure 1b, for all inhomogeneity sizes. The CNR decreases with the inhomogeneity size, while an increase of tube voltage leads to CNR decrease. The reduction of CNR is due to the fact that beam hardening decreases noise, but at the same time significantly decreases signal differences between inhomogeneity and background (figure 1a), since Compton scattering is the most dominant effect at these energies. The same trend appeared for all spectra, as observed in figure 2a, which presents the CNR values obtained with a 110 μm inhomogeneity. Increasing tube voltage from 26 to 30 kVp, the CNR decreases up to 22% for the 110 μm and 13% for the 250 μm detail.

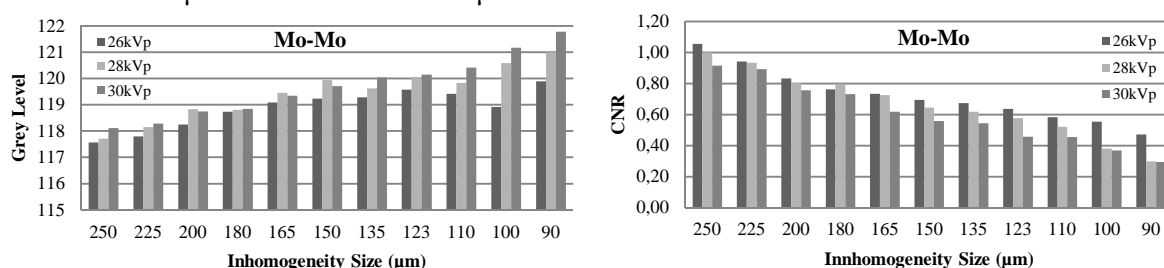


Figure 1. a) Signal strength, and b) CNR for all inhomogeneity sizes and tube voltages studied, for the case of Mo/Mo anode/filter combination.

The influence of anode/filter material combination on the CNR is presented in figure 2a. Concerning filter material, k-edge filters demonstrated improved performance compared to Al filter, especially for smaller inhomogeneities. In the case of Rh-anode spectra, if an Al-filter is used instead of Rh-filter, the CNR is reduced up to 23% for the 110 μm inhomogeneity. In general, as the size of inhomogeneity decreases, softer beams are required to achieve better CNR. The performance of k-edge filters is reversely proportional to the energy of their absorption edge. These filters cut off the photons with energy above their absorption edge, which causes subject contrast degradation due to the increased penetration through the breast. Regarding anode material, W- anode spectra demonstrated similar performance, which sometimes was better compared to softer x- ray spectra, produced by Mo or Rh anodes. Furthermore, W/0.050mmPd+2.00mmAl combination demonstrated the worst CNR.

3.2. Contrast-Detail Analysis

The main objective of CD experiments was to investigate the detection of inhomogeneities. No significant differences were found between and within the two observers. Figure 2b presents the influence of mammographic spectrum on the observers' performance. For most anode/filter material combinations, the highest CD scores occurred at the lowest tube voltage and tend to decrease as the

tube voltage increases. Indicatively, the relative CD score differences are approximately 18% for the case of Mo/Mo between 26 and 30 kVp. It is interesting to notice that CD scores tend to increase as a function of kVp only for W/Mo anode/filter combination, possibly due to noise reduction [14]. Regarding filter material, k-edge filters demonstrated a superior performance compared to Al filters, with their performance being reversely proportional to the energy of their absorption edge. The latter is more obvious in the case of Mo-anode spectra. This relationship is not monotonous for W-anode spectra as noise reduction associated to harder spectra results to the enhancement of the CNR and consequently to improved detectability of inhomogeneities (figures 2a, 2b) [14]. W-anode spectra showed an improved performance, which sometimes was better or comparable to softer x-ray spectra produced by Mo- or Rh-anodes, especially when combined with k-edge filters of lower k-absorption edge. It should be noted, that low-contrast detection was investigated over a uniform CD phantom. These conditions do not simulate the clinical practice, since apart from the quantum noise, additional structure noise limits the detection of details.

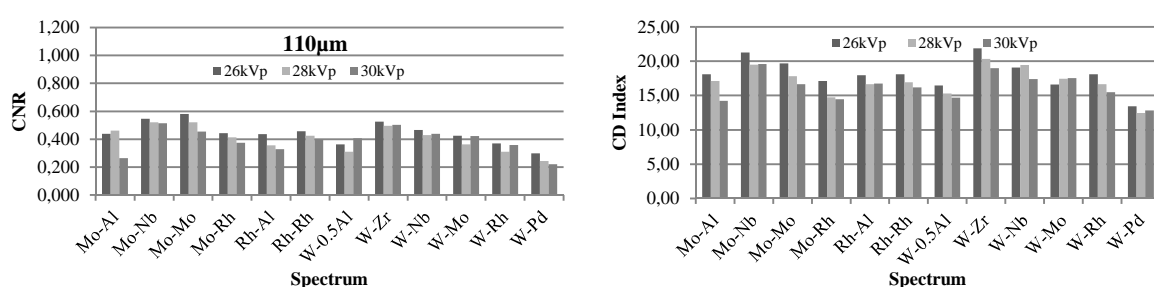


Figure 2. a) CNR for the various spectra studied, for a 110 μm detail, b) CD scores for the various spectra studied.

4. Conclusion

The detection of small low-contrast details was enhanced by using a softer x-ray beam, when the exposure and thickness of the breast tissue remain constant. Optimum performance, in terms of CNR and CD scores, was achieved by selecting the lowest tube voltage value in combination with filters of low energy k-edge.

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