Quantitative Visually Lossless Compression Ratio Determination of JPEG2000 in Digitized Mammograms

Verislav T. Georgiev · Anna N. Karahaliou ·
Spyros G. Skiadopoulos · Nikos S. Arikidis ·
Alexandra D. Kazantzi · George S. Panayiotakis ·
Lena I. Costaridou

Published online: 13 October 2012
© Society for Imaging Informatics in Medicine 2012

Abstract The current study presents a quantitative approach towards visually lossless compression ratio (CR) threshold determination of JPEG2000 in digitized mammograms. This is achieved by identifying quantitative image quality metrics that reflect radiologists' visual perception in distinguishing between original and wavelet-compressed mammographic regions of interest containing microcalcification clusters (MCs) and normal parenchyma, originating from 68 images from the Digital Database for Screening Mammography. Specifically, image quality of wavelet-compressed mammograms (CRs, 10:1, 25:1, 40:1, 70:1, 100:1) is evaluated quantitatively by means of eight image quality metrics of different computational principles and qualitatively by three radiologists employing a five-point rating scale. The accuracy of the objective metrics is investigated in terms of (1) their correlation (r) with qualitative assessment and (2) ROC analysis (A_z index), employing pooled radiologists' rating scores as ground truth. The quantitative metrics mean square error, mean absolute error, peak signal-to-noise ratio, and structural similarity demonstrated strong correlation with pooled radiologists' ratings (r , 0.825, 0.823, -0.825 , and -0.826 , respectively) and the highest area under ROC curve (A_z , 0.922, 0.920, 0.922, and 0.922, respectively). For each quantitative metric, the highest accuracy values of corresponding ROC curves were used to define metric cut-off values. The metrics cut-off values were

subsequently used to suggest a visually lossless CR threshold, estimated to be between 25:1 and 40:1 for the dataset analyzed. Results indicate the potential of the quantitative metrics approach in predicting visually lossless CRs in case of MCs in mammography.

Keywords Image compression · Visually lossless · Compression ratio threshold · Image quality metrics · JPEG2000 · Mammography · Microcalcification cluster

Introduction

Breast cancer ranks first with respect to cancer incidence rate and second as a cause of cancer death among women [1]. Mammography is widely recognized as the most sensitive technique for early breast cancer detection [2]. Potential operational efficiencies of mammography, including soft-copy display and interpretation, computer-aided detection and diagnosis [3], image transmission and storage, require a digital format of mammograms. A digital mammogram is obtained by computed radiography or full-field digital mammography (FFDM) systems, while screen-film mammograms can be digitized with dedicated high spatial and contrast resolution scanners. The use of digital mammography is expected to rise in the near future due to the FFDM superiority to the existing screen-film mammography (SFM) with respect to overall image quality [4]. Furthermore, the wider accessibility and effectiveness of picture archiving and communication system (PACS) pushes the transition from film-based analog systems to filmless radiology, as well as towards digitization of existing SFM archives. A typical digitized/digital mammographic image results in electronic image files of up to 90 MB, thus, a complete study of four mammographic views can produce about 360 MB of data. This increases considerably the demands

V. T. Georgiev · A. N. Karahaliou · S. G. Skiadopoulos ·
N. S. Arikidis · G. S. Panayiotakis · L. I. Costaridou (✉)
Department of Medical Physics, Faculty of Medicine,
University of Patras,
26504 Patras, Greece
e-mail: costarid@upatras.gr

A. D. Kazantzi
Department of Radiology, Faculty of Medicine,
University of Patras,
26504 Patras, Greece

of the existing hospital infrastructure required for image storage, management, transmission, and display. Current PACS implementations offer image compression as a means of reducing image volume and speeding up communication [5], further allowing for faster telemammography and access to expert radiologists.

Image compression algorithms may be divided in two main categories: reversible and irreversible ones. Reversible (lossless) techniques used in medical imaging result in compression ratio (CR) ranging from 2:1 to 3:1 [6]. To effectively solve image data management problems in PACS or teleradiology systems, larger CRs are required. These CRs are provided by the second category, irreversible compression, also known as “lossy” compression [6]. However, greater compression is obtained at the expense of image quality. In case of image compression in mammography, more conservative requirements are dictated by the need to preserve image quality of microcalcification clusters (MCs) which correspond to high spatial frequency and low contrast information in case of dense parenchyma.

There are two major approaches in determining the optimal CR threshold up to which image quality is preserved: the diagnostically lossless and the visually lossless approach [7]. The diagnostically lossless approach investigates whether diagnostic accuracy is preserved in images compressed at various compression levels. The visually lossless approach investigates whether a compressed image is visually indistinguishable from its original version at various compression levels. The latter approach is based on the idea that, if compression artifacts are imperceptible, they should not affect the diagnosis. The visually lossless approach has been shown to be more robust and conservative than the diagnostically lossless in determining compression for medical images [7]. It is also suggested that the visually lossless approach has to precede the diagnostically lossless one [7, 8].

In case of mammographic image compression, most studies have focused on the determination of diagnostically lossless CR thresholds [9–14], employing mainly observer performance analyses. These studies have aimed at evaluating the quality of digitized and digital compressed mammograms with respect to lesion detection [9–13] or a lesion diagnosis [14] task. Specifically, Good et al. [9] evaluated observers’ ability in detecting breast masses and MCs on lossy Joint Photographic Experts Group (JPEG) compressed mammograms. Results demonstrated that lossy compression with CR up to 101:1 did not degrade the detection of masses but affected the detection of MCs for CRs greater than 34:1. Kocsis et al. [10] investigated the effect of JPEG2000 on the detection of MCs in digitized mammograms. A diagnostically lossless threshold of 40:1 for MCs detection was reported. Suryanarayanan et al. [11] evaluated the effect of JPEG2000 compression method on the detection of

simulated masses and MCs on digital mammograms compressed at 15:1 and 30:1 CR. The detection of simulated masses was not affected by compression, while the detection of MCs was significantly reduced for CR greater than 15:1. Penedo et al. [12] assessed the effect of two irreversible wavelet-based compression algorithms (a standard JPEG2000 and an object-based set partitioning in hierarchical trees) on the detection of MCs and masses on digitized mammograms. Results suggested that lossy compression of digitized mammograms at 80:1 with both methods considered can be performed without decreasing the rate of detection for either type of lesions. Kallergi et al. [13] evaluated the effect of an adaptive wavelet compression method on the detection of masses and MCs. The original and compressed images were evaluated in an observer study involving three radiologists. It was demonstrated that CRs of 14:1 to 205:1 could be achieved depending on the degree of parenchymal density. Liang et al. [14] investigated whether lossless and lossy (CRs, 20:1 and 40:1) image compression techniques affect the diagnostic accuracy of breast masses on digitized mammograms, suggesting a CR of 40:1.

Fewer studies have focused on the determination of visually lossless CR thresholds in mammography [8, 15, 16]. Kang et al. [8] investigated the acceptable CRs of digital mammograms (40 depicting masses and 40 depicting MCs) using JPEG2000. According to observer evaluation of compressed image quality preservation, CRs up to 60:1 render compressed images visually identical to original images and potentially acceptable for interpretation. Sung et al. [15] employed observer studies to determine visually and diagnostically lossless CR thresholds of JPEG2000 for 20 digitized mammograms (eight normal and 12 depicting masses and MCs). Results suggested a visually lossless compression ratio of 15:1, while 80:1 compression ratio can be achieved without affecting lesion detectability. Koff et al. [16] investigated both visually and diagnostically lossless CR thresholds for JPEG and JPEG2000 compression algorithms for medical images corresponding to seven anatomical areas and five imaging modalities including computed radiography and FFDM images. Results suggested that CRs of 15:1 to 25:1 affected neither the readers’ subjective assessment of mammographic image quality nor the detection of breast lesions.

Observer performance analysis and especially receiver operating characteristic (ROC) analysis [17] represent the current widely accepted method for visually or diagnostically lossless compression threshold determination in medical imaging. However, such evaluation approach requires an adequate number of radiologists, for considering inter- and intra-observer variability, while special training for the radiologist to familiarize with the rating system is required. Furthermore, such evaluation approach is time-consuming and cannot be incorporated into automatic compression systems that adjust

themselves in real-time, based on the feedback of a compressed output image. These limitations have motivated the investigation of mathematical descriptors of image quality degradation of compressed mammograms.

Quantitative image quality approaches of compressed mammograms have been considered in the framework of evaluating image compression schemes [18–21] but have not been exploited toward the determination of visually or diagnostically lossless CR thresholds. Sung et al. [15] considered a quantitative approach toward image quality evaluation by means of the peak signal-to-noise ratio (PSNR) metric in addition to observer studies performed for lossy CR threshold determination. Perlmutter et al. [18] employed the signal-to-noise ratio (SNR) metric and observer ratings reflecting mammographic interpretation criteria (related to screening and diagnosis) to assess image quality of lossy compressed mammograms as compared with analog or digital originals. Results demonstrated that digital mammograms compressed in a lossy fashion to 0.015 bits per pixel (bpp), about 80:1 CR, using an embedded wavelet coding scheme result in no significant differences from the analog or digital originals. Zyout et al. [19] employed mean square error (MSE) and PSNR metrics for evaluating a wavelet-based progressive lossy to lossless image compression scheme applied on regions of interest (ROIs) of digitized mammograms containing MCs. Kim et al. [20] exploited objective metrics such as SNR, PSNR, root mean square error, and mean average error (MAE) for evaluating image quality of digital mammograms compressed by JPEG2000 and JPEG, in case of direct and indirect detectors in FFDM. Przelakowski et al. [21] proposed a hybrid image quality measure reflecting diagnostic accuracy, based on a linear combination of image quality metrics. The feasibility of the proposed metric in approximating diagnostic accuracy was tested in a pilot dataset of mammograms compressed with JPEG2000 at four different bpp.

The current study is aimed at a quantitative approach toward visually lossless CR threshold determination of JPEG2000 for digitized mammograms. This is achieved by identifying quantitative image quality metrics that reflect radiologists' ability (visual perception) in distinguishing between original and wavelet-compressed mammographic ROIs. Specifically, image quality of wavelet-compressed mammograms is evaluated by means of image quality metrics of different computational principles. Image quality preservation between the original and compressed versions of mammographic ROIs is also qualitatively assessed by three radiologists employing a five-point rating scale. The accuracy of the objective metrics is investigated in terms of (1) their correlation with qualitative assessment and (2) ROC analysis, employing pooled radiologists' rating scores as ground truth. The most accurate metrics are further exploited to define cut-off values, used to suggest a visually lossless CR range.

Materials and Methods

Dataset

Sixty-eight digitized mammograms (digitization at 12-bit pixel depth, spatial resolution of 50 μm) originating from the Digital Database for Screening Mammography (DDSM) [22, 23] were selected. Thirty-eight images contained MCs (22 malignant and 16 benign), and 30 images were normal. A single view was selected from each case. Mammograms spanned the four types of breast composition, as described in the American College of Radiology BI-RADS lexicon [24]: 14 almost entirely fat; 20 with scattered fibroglandular densities; 20 heterogeneously dense; and 14 extremely dense. The 38 MCs spanned five subtlety levels where level 1 corresponds to "subtle" and level 5 corresponds to "obvious" (level 1=3 MCs, level 2=8 MCs, level 3=14 MCs, level 4=10 MCs, and level 5=3 MCs), as described in DDSM for each case analyzed. The distribution of MCs with respect to morphology was—seven punctate, 12 amorphous, 16 pleomorphic—granular, and three casting-fine linear branching.

From each mammogram, a 256×256 -pixel ROI was manually centered at the MC. The size of the ROI was accommodating the size of the MCs encountered in our dataset. In case of normal mammograms, the 256×256 -pixel ROI was positioned at the central breast region, immediately behind the nipple [25].

Compression Algorithm

The JPEG2000 wavelet-based compression algorithm used in this study is included in the public domain evaluation version of the View-Med application (Pegasus Imaging Corporation, Tampa, Florida). The default irreversible transform for image decomposition is implemented by means of the Daubechies nine-tap/seven-tap filter, proposed also by the JPEG2000 standard [26]. The transform coefficients are quantized and entropy coded by means of entropy-logarithmic scale arithmetic coder, which operates in a similar way to embedded zerotree wavelet [27] coder. To avoid artifacts associated with small tile sizes, no tiling was used. Each mammogram of the dataset was compressed to five CRs—10:1, 25:1, 40:1, 70:1, and 100:1, resulting in a total of 340 compressed mammograms. ROIs on compressed mammograms were generated using ROI center coordinates identical to the ones employed for generating ROIs on original mammograms.

Observer Performance Study

Three experienced radiologists participated in this study (two radiologists with 10 years and one radiologist with 5 years of mammographic image interpretation). Each of the 340 compressed ROIs was paired with its original version. The

340 image pairs were randomly presented to each radiologist, who was blinded to the ROIs CR, in a different order for each radiologist. The original version always presented in the same position on the screen monitor. The radiologists were asked to independently evaluate the quality of each compressed ROI with respect to the corresponding original one, employing a five-point rating scale (very good quality: no difference from original one; good quality: no significant difference from original one; intermediate quality: there is perceivable difference but is marginally accepted; poor quality: significant difference from original one—image not acceptable; very poor quality: obvious difference—not accepted). One single rating score was assigned to each compressed ROI considering the number and morphology (contrast and shape) of MCs within the cluster, as well as the mammographic parenchyma texture.

During reading, the room illumination was diminished (ambient light, <10 lux) and kept constant, whereas observer–monitor distance was not restricted. Mammographic ROIs were reviewed on a DICOM Part 14 GSDF calibrated EIZO ColorEdge CG210 display monitor using a mammographic image visualization software tool [28]. The observers were allowed to use only gray-scale window-level functions and magnification to compensate for display monitor spatial and contrast resolution limitations.

Each radiologist evaluated the 340 mammographic ROIs pairs in four sessions, interpreting 85 mammographic ROIs pairs in each session. To investigate inter-observer and intra-observer agreement in the task of image quality evaluation of compressed ROIs with respect to corresponding original ones, each reading session (observation) was repeated after a time interval of 4 weeks.

Quantitative Image Quality Evaluation

In the framework of image quality evaluation of general-purpose compressed images, several categories of metrics including pixel difference, correlation-based, edge-based, spectral distance-based, context-based, and metrics simulating the human visual system have been proposed [29]. In case of mammographic image compression, metrics such as: SNR, PSNR, MAE, and MSE have been previously exploited [15, 18–20], while a linear combination of metrics has been proposed and correlated to diagnostically related image quality [21].

In this study, the following metric categories are considered:

- I. Pixel difference metrics [20, 30, 31] for calculating the distortion between the compressed and the original image in a pixel-wise basis: MSE, MAE, normalized absolute error (NAE), SNR, and PSNR.
- II. Correlation-based metrics for quantifying the similarity between two digital images in terms of the correlation function [30]: structural content (SC) and normalized cross-correlation (NK).

III. The recently proposed structural similarity (SSIM) index [32] for quantifying structural changes, i.e., strong dependencies of spatially proximate pixels, caused by various types of distortions.

In the current analysis, a digital image (i.e., the mammographic ROI) is denoted as an $M \times N$ matrix, where M denotes number of columns and N number of rows; $f(i, j)$ and $f'(i, j)$ denote pixel values of the original image before the compression and of the degraded image after the compression, respectively.

The metrics considered in the current study are given by the following equations:

1. MSE

MSE [31] represents the power of noise. Increasing values of the MSE reflects degradation of image quality.

$$\text{MSE} = \frac{1}{MN} \sum_{i=1}^M \sum_{j=1}^N [f(i, j) - f'(i, j)]^2 \quad (1)$$

2. MAE

The higher the value of MAE [20], the higher the degradation of image quality is.

$$\text{MAE} = \frac{1}{MN} \sum_{i=1}^M \sum_{j=1}^N |f(i, j) - f'(i, j)| \quad (2)$$

3. NAE

NAE [30] is a measure of the difference of the compressed image from original one. A zero value of NAE indicates no difference from original one, while a large value of NAE reflects poor compressed image quality.

$$\text{NAE} = \frac{\sum_{i=1}^M \sum_{j=1}^N |f(i, j) - f'(i, j)|}{\sum_{i=1}^M \sum_{j=1}^N |f(i, j)|} \quad (3)$$

4. SNR

SNR [18, 20] is defined as the power ratio between a signal (meaningful information) and background noise (unwanted signal). Because many signals have a very wide dynamic range, it is often expressed using the logarithmic decibel scale.

$$\text{SNR} = 10 \log_{10} \frac{\sum_{i=1}^M \sum_{j=1}^N [f(i, j)]^2}{\sum_{i=1}^M \sum_{j=1}^N [f(i, j) - f'(i, j)]^2} \quad (4)$$

5. PSNR

PSNR [31] has been the most widely used index of image distortion due to its computational simplicity.

PSNR is useful in comparing images of different dynamic range, without providing additional information as compared to MSE. Large PSNR values indicate small difference between the original and compressed image.

$$\text{PSNR} = 10\log_{10}\left(\frac{4095^2}{\text{MSE}}\right) \quad (5)$$

6. SC

Correlation is a familiar concept in image processing, estimating the similarity of the structure of two signals. The SC measure [30] effectively compares the total weight of an original signal to a compressed one.

$$\text{SC} = \frac{\sum_{i=1}^M \sum_{j=1}^N (f(i,j))^2}{\sum_{i=1}^M \sum_{j=1}^N (f'(i,j))^2} \quad (6)$$

7. NK

The closeness between two digital images can also be quantified in terms of correlation function. NK [30] tends to 1, as the difference between two images tends to zero.

$$\text{NK} = \frac{\sum_{i=1}^M \sum_{j=1}^N [f(i,j)f'(i,j)]}{\sum_{i=1}^M \sum_{j=1}^N [f(i,j)]^2} \quad (7)$$

8. SSIM

SSIM [32] is an implementation of the idea of structural image similarity, which takes into account image contrast (expressed by standard deviation), image luminance (expressed by mean image intensity), and image structure to determine the similarity between two images. SSIM is defined as follows:

$$\text{SSIM}(x, y) = \frac{(2\mu_x\mu_y + C_1)(2\sigma_{xy} + C_2)}{(\mu_x^2 + \mu_y^2 + C_1)(\sigma_x^2 + \sigma_y^2 + C_2)} \quad (8)$$

$$\sigma_{xy} = \frac{1}{N-1} \sum_{i=1}^N (x_i - \mu_x)(y_i - \mu_y)$$

where x and y are subimages (windows) of the original image X and the compressed image Y , of the same size, which moves pixel by pixel over the entire image. N is the total number of pixels in each window, μ_x is the average of x ; μ_y is the average of y ; σ_x is the standard deviation of x ; σ_y is the standard deviation of y . $C_1 =$

Fig. 1 Mammographic ROI (DDSM, C_0012_1.RIGHT_MLO) depicting a malignant microcalcification cluster (a) along with compressed ROIs at the following compression ratios 10:1 (b), 25:1 (c), 40:1 (d), 70:1 (e), and 100:1 (f)

$(K_1L)^2$ and $C_2 = (K_2L)^2$; L is equal to the dynamic range of the pixel values of the image (4,095 in case of 12-bit grayscale image), and K_1 and K_2 are set to 0.01 and 0.03 default values. Finally, the mean SSIM is computed for the entire image by the average value of SSIM for all local windows. A value of mean SSIM of 1 indicates perfect similarity [32].

Statistical Analysis

For the 340 compressed mammographic ROIs, the Spearman rank-order correlation coefficient (r) was calculated between each radiologist rating scores and each one of the quantitative metrics considered, as well as between the pooled radiologists' rating scores (estimated by the median of the three radiologists' ratings for each mammographic ROI), considered as ground truth and each one of the quantitative metrics considered. Correlation was characterized as very strong [0.9, 1.0] or [−1.0, −0.9], strong [0.7, 0.9] or (−0.9, −0.7], moderate [0.4, 0.7] or (−0.7, −0.4], weak [0.2, 0.4] or (−0.4, −0.2], and very weak to negligible [0.0, 0.2] or (−0.2, 0.0]. A p value of less than 0.01 was accepted to indicate statistical significance.

The accuracy of the quantitative metrics (i.e., ability to reflect radiologists' visual perception) was also assessed by

means of ROC analysis considering the pooled radiologists' rating scores as ground truth. A high area under ROC curve (A_z index) suggests a highly accurate metric, thus a metric that could reflect radiologists' ability (visual perception) in distinguishing between original and compressed mammographic ROIs. A statistical software package (NCSS Statistical Software 2007, Kaysville, Utah) was employed for generation of ROC curves and comparison of A_z values of the quantitative metrics. Specifically, a z -score test was employed to test statistically significant differences among A_z values of the compared metrics. A Bonferroni correction for multiple comparisons (i.e., all possible pairwise comparisons of eight metrics result in 28 comparisons in total) was considered to adjust the level of significance ($\alpha = 0.05/28 = 0.0018$).

The most accurate metrics were then employed to define a visually lossless CR threshold, i.e., a CR threshold above which the quality of compressed mammograms is significantly degraded as compared with the corresponding original ones. ROC curves of the most accurate metrics were used to identify metrics cut-off values corresponding to the highest accuracy value. The metrics cut-off values were then employed to suggest a visually lossless CR range, assuming each metric as a monotonically increasing or decreasing function of CR.

Fig. 2 Mammographic ROI (DDSM, C_0320_1.LEFT_MLO) depicting a benign microcalcification cluster (a) along with compressed ROIs at the following compression ratios 10:1 (b), 25:1 (c), 40:1 (d), 70:1 (e), and 100:1 (f)

Inter- and intra-observer agreement in the task of image quality evaluation of compressed ROIs with respect to corresponding original ones was evaluated by means of Kappa statistics [33] which determines the agreement beyond that which would be expected due to chance. In order to estimate the inter-observer agreement, the comparison was performed among the three radiologists' ratings scores derived by the first reading. In order to estimate the intra-observer agreement, the kappa statistic was determined for each radiologist by comparing the rating scores derived by the first reading with corresponding ones derived by the second reading. The interpretation of the kappa values was performed as follows: a value greater than 0.8 to be considered "almost perfect," 0.6–0.8 as "substantial," 0.4–0.6 as "moderate," 0.2–0.4 as "fair," and 0–0.2 as "slight."

The IBM SPSS Statistics software package (SPSS Release 20.0, SPSS Inc., Chicago, IL, USA) was employed to estimate Spearman rank-order correlation and Kappa statistic values.

Results

Figures 1, 2, and 3 illustrate mammographic ROIs depicting a malignant MC cluster (Fig. 1a), a benign MC cluster

(Fig. 2a), and normal mammographic parenchyma (Fig. 3a), along with compressed ROIs at the following CRs—10:1 (b), 25:1 (c); 40:1 (d); 70:1 (e); and 100:1 (f). As observed, image quality is decreased with CR increase and is significantly degraded for CRs 70:1 and 100:1.

Table 1 provides average $\pm$ standard deviation (SD) values of radiologists' rating scores reflecting image quality of compressed mammographic ROIs (at CRs of 10:1, 25:1, 40:1, 70:1, and 100:1) with respect to the corresponding original ones, derived by the first reading. The distribution of the pooled radiologists' rating scores with respect to CR values is illustrated in Fig. 4.

Results of the intra- and inter-observer agreement analyses are provided in terms of kappa statistic values in Table 2. Specifically, the intra-observer agreement for evaluating image quality of compressed mammographic ROIs with respect to original versions was substantial, while inter-observer agreement ranged from moderate to substantial, reflecting the reliability of the observer performance study.

Table 3 summarizes average $\pm$ SD values, as well as range of values [minimum, maximum] of each quantitative metric employed for evaluating quality of the compressed mammographic ROIs at the five CRs. As expected, the average values of SNR, PSNR, NK, and SSIM metrics

Fig. 3 Mammographic ROI (DDSM, B_3038_1.RIGHT_MLO) depicting normal parenchyma (a) along with compressed ROIs at the following compression ratios 10:1 (b), 25:1 (c), 40:1 (d), 70:1 (e), and 100:1 (f)

Table 1 Average $\pm$ standard deviation values of radiologists' image quality rating scores considered independently and as pooled data (ground truth)

	Compression ratio				
	10:1	25:1	40:1	70:1	100:1
Radiologist 1	1.06 $\pm$ 0.24	2.09 $\pm$ 0.48	3.09 $\pm$ 0.71	4.34 $\pm$ 0.73	4.76 $\pm$ 0.46
Radiologist 2	1.59 $\pm$ 0.58	2.28 $\pm$ 0.62	2.93 $\pm$ 0.68	4.26 $\pm$ 0.64	4.68 $\pm$ 0.50
Radiologist 3	1.00 $\pm$ 0.00	1.35 $\pm$ 0.62	2.56 $\pm$ 0.90	3.69 $\pm$ 0.76	4.19 $\pm$ 0.65
Ground truth	1.03 $\pm$ 0.17	1.99 $\pm$ 0.40	2.93 $\pm$ 0.55	4.16 $\pm$ 0.59	4.59 $\pm$ 0.55

decrease as CR increases, while the MSE, MAE, NAE, and SC metrics demonstrate the highest average values for CR 100:1.

Table 4 provides results of the correlation analysis between the radiologists' rating scores derived by the first reading and each quantitative image quality metric studied. Spearman rank-order correlation coefficient values and corresponding p values are provided independently for each radiologist, as well as for the pooled radiologists' rating scores referred as ground truth.

The MSE and MAE metrics demonstrate strong positive correlation ($r > 0.7$, $p < 0.0001$) with each radiologist image quality assessment of compressed ROIs, as well as with the pooled radiologists' rating scores (ground truth). The PSNR and SSIM metrics demonstrate strong negative correlation ($r < -0.7$, $p < 0.0001$) both for each radiologist ratings independently, as well as for the pooled radiologists' rating scores. The NK metric demonstrates moderate to strong negative correlation ($r < -0.6$, $p < 0.0001$) for each radiologists' ratings independently and strong negative correlation ($r = -0.734$, $p < 0.0001$) for the pooled radiologists' rating scores. The remaining metrics demonstrate moderate correlation with radiologists' qualitative assessment.

Results of ROC analysis are summarized in Table 5, in terms $A_z \pm$ standard error (SE) values and corresponding lower and upper 95 % asymmetric confidence interval values, for each quantitative image quality metric studied. The

MSE, MAE, PSNR, and SSIM metrics demonstrated the highest A_z values among the quantitative metrics studied, without presenting statistically significant differences in performance among them ($p > 0.0018$). Furthermore, the performance of the aforementioned metrics is, statistically, significantly higher ($p < 0.0018$) as compared with the performance of the remaining metrics considered.

The metrics demonstrating the highest A_z index (i.e., MSE, MAE, PSNR, and SSIM) were subsequently used for CR threshold determination. Table 6 summarizes the cut-off values of these metrics along with corresponding accuracy, sensitivity, and specificity values as derived by each metric ROC curve. Each metric's cut-off value is indicated by a solid line on the graphs illustrating the correlation between the most accurate metrics and pooled radiologists' rating scores (Fig. 5).

Employing these cut-off values and considering the differentiation of each metric range values with respect to CR (Table 3), a visually lossless CR threshold range of 25:1 up to 40:1 is suggested, with 25:1 being a safe (a more conservative) CR threshold above which the quality of compressed mammograms is significantly degraded. Specifically, we observe that the cut-off value 407.8 of the MSE metric is greater than MSE range values for CR 10:1 and 25:1, while it belongs to the corresponding MSE range values of the 40:1, 70:1, and 100:1 CRs. Consequently, the suggested visually lossless CR ranges between 25:1 and 40:1. Likewise, the cut-

Fig. 4 Distribution of pooled radiologists' image quality rating scores (1: very good, 2: good, 3: intermediate, 4: poor, and 5: very poor image quality, with respect to the original ROI) for mammographic ROIs compressed at five compression ratios

Table 2 Kappa statistic values for assessing intra-observer and inter-observer agreement among the three radiologists (R1, R2, and R3) participating in the performance evaluation study

Comparison	Intra-observer	Comparison	Inter-observer
R1 vs. R1	0.79	R1 vs. R2	0.66
R2 vs. R2	0.66	R1 vs. R3	0.63
R3 vs. R3	0.71	R2 vs. R3	0.53

off value 46.14 of the PSNR metric is lower than PSNR range values of CR 10:1 and 25:1, while it belongs to the corresponding PSNR range values of the 40:1, 70:1, and 100:1 CRs. Consequently, the suggested visually lossless CR ranges between 25:1 and 40:1. The CR range values suggested by the MAE and the SSIM metrics are derived in a similar fashion to MSE and PSNR metrics, respectively.

Discussion

Previously reported literature on image quality evaluation of compressed mammograms has focused on the determination of diagnostically lossless CR thresholds [9–14] and less on the visually lossless approach [8, 15, 16], with both approaches employing observer performance analysis methods. The quantitative image quality approach of compressed mammograms has been considered as an additional option to observer performance analysis [15, 18], as well as in the framework of evaluating image compression schemes utilizing mammographic images [19–21], phantom images [34], and computer-generated test objects images [10]. However, the quantitative image quality approach has not been exploited towards the determination of visually or diagnostically lossless CR thresholds in mammography.

The current study attempts to identify quantitative metrics that could reflect radiologists' ability (visual perception) in distinguishing between original and wavelet-compressed mammographic ROIs. This is a quantitative approach towards visually lossless threshold estimation of a JPEG2000 compression algorithm, a task that should precede the analysis for a diagnostically lossless threshold determination [7, 8]. For the purpose of this study, eight quantitative metrics of different computational principles have been investigated in an image quality preservation task of JPEG2000 compressed mammograms depicting MCs or normal parenchyma. An observer study was performed to qualitatively assess image quality of compressed mammographic ROIs as compared with originals ones, by means of five-point ratings assigned by three independent radiologists. The accuracy of the objective metrics was evaluated by investigating their correlation with qualitative image quality assessment and by means of ROC analysis, considering pooled radiologists'

Table 3 Average $\pm$ standard deviation and range [minimum, maximum] values of the quantitative metrics for the mammographic ROIs of the dataset compressed at five compression ratios

Metric	Compression ratio				
	10:1	25:1	40:1	70:1	100:1
MSE	113.5 $\pm$ 16.2 [76.4, 164.3]	282.9 $\pm$ 47.7 [129.4, 383.9]	374.3 $\pm$ 68.0 [153.7, 502.9]	482.0 $\pm$ 94.2 [175.6, 690.9]	557.3 $\pm$ 114.4 [190.2, 829.7]
MAE	8.44 $\pm$ 0.60 [6.94, 10.22]	13.37 $\pm$ 1.17 [9.01, 15.67]	15.37 $\pm$ 1.47 [9.82, 17.95]	17.42 $\pm$ 1.80 [10.48, 20.98]	18.72 $\pm$ 2.04 [10.88, 23.00]
NAE	(3.2 $\pm$ 0.6) $\cdot 10^{-3}$ [1.9 $\cdot 10^{-3}$, 4.6 $\cdot 10^{-3}$]	(5.1 $\pm$ 1.0) $\cdot 10^{-3}$ [2.5 $\cdot 10^{-3}$, 7.4 $\cdot 10^{-3}$]	(5.9 $\pm$ 1.2) $\cdot 10^{-3}$ [2.7 $\cdot 10^{-3}$, 8.6 $\cdot 10^{-3}$]	(6.7 $\pm$ 1.4) $\cdot 10^{-3}$ [2.9 $\cdot 10^{-3}$, 9.7 $\cdot 10^{-3}$]	(7.2 $\pm$ 1.5) $\cdot 10^{-3}$ [3.0 $\cdot 10^{-3}$, 10.0 $\cdot 10^{-3}$]
SNR	48.01 $\pm$ 1.48 [44.79, 52.36]	44.06 $\pm$ 1.74 [41.04, 50.07]	42.86 $\pm$ 1.83 [39.78, 49.32]	41.77 $\pm$ 1.89 [38.64, 48.74]	41.15 $\pm$ 1.93 [37.85, 48.39]
PSNR	51.74 $\pm$ 0.61 [50.09, 53.42]	47.79 $\pm$ 0.78 [46.40, 51.13]	46.59 $\pm$ 0.86 [45.23, 50.38]	45.51 $\pm$ 0.95 [43.85, 49.80]	44.89 $\pm$ 1.00 [43.06, 49.45]
SC	(99,962 $\pm$ 5) $\cdot 10^{-5}$ [99,947 $\cdot 10^{-5}$, 99,974 $\cdot 10^{-5}$]	(99,965 $\pm$ 4) $\cdot 10^{-5}$ [99,955 $\cdot 10^{-5}$, 99,973 $\cdot 10^{-5}$]	(99,966 $\pm$ 4) $\cdot 10^{-5}$ [99,954 $\cdot 10^{-5}$, 99,974 $\cdot 10^{-5}$]	(99,967 $\pm$ 4) $\cdot 10^{-5}$ [99,954 $\cdot 10^{-5}$, 99,976 $\cdot 10^{-5}$]	(99,970 $\pm$ 7) $\cdot 10^{-5}$ [99,959 $\cdot 10^{-5}$, 99,977 $\cdot 10^{-5}$]
NK	(100,018 $\pm$ 2) $\cdot 10^{-5}$ [100,013 $\cdot 10^{-5}$, 100,025 $\cdot 10^{-5}$]	(100,015 $\pm$ 2) $\cdot 10^{-5}$ [100,012 $\cdot 10^{-5}$, 100,019 $\cdot 10^{-5}$]	(100,014 $\pm$ 2) $\cdot 10^{-5}$ [100,011 $\cdot 10^{-5}$, 100,018 $\cdot 10^{-5}$]	(100,013 $\pm$ 2) $\cdot 10^{-5}$ [100,008 $\cdot 10^{-5}$, 100,017 $\cdot 10^{-5}$]	(100,011 $\pm$ 3) $\cdot 10^{-5}$ [100,006 $\cdot 10^{-5}$, 100,018 $\cdot 10^{-5}$]
SSIM	(994 $\pm$ 1) $\cdot 10^{-3}$ [990 $\cdot 10^{-3}$, 995 $\cdot 10^{-3}$]	(984 $\pm$ 3) $\cdot 10^{-3}$ [978 $\cdot 10^{-3}$, 992 $\cdot 10^{-3}$]	(979 $\pm$ 4) $\cdot 10^{-3}$ [972 $\cdot 10^{-3}$, 991 $\cdot 10^{-3}$]	(973 $\pm$ 5) $\cdot 10^{-3}$ [963 $\cdot 10^{-3}$, 990 $\cdot 10^{-3}$]	(969 $\pm$ 6) $\cdot 10^{-3}$ [956 $\cdot 10^{-3}$, 990 $\cdot 10^{-3}$]

Table 4 Spearman rank-order correlation coefficient values between quantitative metrics and radiologists' image quality rating scores, for each radiologist independently and for pooled radiologists' ratings scores (ground truth)

Metric	Correlation coefficient Rho (<i>p</i> value)			
	Radiologist 1	Radiologist 2	Radiologist 3	Ground truth
MSE	0.818 (<0.0001)	0.771 (<0.0001)	0.778 (<0.0001)	0.825 (<0.0001)
MAE	0.816 (<0.0001)	0.769 (<0.0001)	0.777 (<0.0001)	0.823 (<0.0001)
NAE	0.628 (<0.0001)	0.590 (<0.0001)	0.598 (<0.0001)	0.636 (<0.0001)
SNR	−0.634 (<0.0001)	−0.595 (<0.0001)	−0.603 (<0.0001)	−0.642 (<0.0001)
PSNR	−0.818 (<0.0001)	−0.771 (<0.0001)	−0.778 (<0.0001)	−0.825 (<0.0001)
SC	0.519 (<0.0001)	0.490 (<0.0001)	0.420 (<0.0001)	0.516 (<0.0001)
NK	−0.736 (<0.0001)	−0.696 (<0.0001)	−0.647 (<0.0001)	−0.734 (<0.0001)
SSIM	−0.820 (<0.0001)	−0.771 (<0.0001)	−0.782 (<0.0001)	−0.826 (<0.0001)

rating scores as ground truth. The most accurate metrics were further exploited to define cut-off values used to suggest visually lossless CR. To the best of the authors' knowledge, the analysis of identifying quantitative metrics that can reflect radiologists' ability in distinguishing between original and compressed medical images has not been previously investigated in case of CR threshold determination in mammography [35, 36].

Results of the observer study suggested that a CR ranging from 25:1 to 40:1 may be achieved without introducing visually perceived image quality degradation as compared with corresponding original ones. While a direct comparison to previously reported qualitative visually lossless CR threshold determination studies is not feasible, due to heterogeneity of the datasets employed, the CR suggested herein ranges within previously reported CR values (15:1 up to 60:1) [8, 15, 16], depending on image type (digitized or digital) and on lesion type (e.g., masses, MCs). Results of the current study are also in accordance to Kocsis et al. [10], who investigated a diagnostically lossless CR threshold for the same compression algorithm in terms of detection accuracy of MC clusters and suggested a CR threshold of 40:1 for a dataset of 68 mammograms, identical to the one

analyzed in the current study. The visually lossless CR threshold range of 25:1 to 40:1 suggested herein is more conservative as compared with the previously reported diagnostically lossless one for the same compression algorithm tested on the same dataset, as expected [7, 8].

Correlation analysis between quantitative image quality metrics and pooled radiologists' rating scores, as well as results of ROC analysis, demonstrated that MSE, MAE, PSNR, and SSIM outperformed the rest of the image quality metrics tested, implying that they can successfully reflect observer's confidence in evaluating the distinguishability of compressed mammograms from corresponding original ones and have the potential to be incorporated in an automatic adaptive compression system. MSE and PSNR metrics, accounting for two equivalent measures, are the most commonly adopted in quantitative mammographic image quality evaluation studies [15, 19, 20], while their incorporation into medical image compression evaluation has been recently highlighted [7]. The use of the recently proposed SSIM metric [32] as a new measure that quantifies structural changes caused by various types of distortions is also suggested in image compression evaluation schemes further being more consistent with the performance of the human visual system [7].

Cut-off values of the most accurate metrics (i.e., MSE, MAE, PSNR, and SSIM) were selected by means of the highest accuracy values of corresponding ROC curves. These cut-off values were then employed to suggest a visually lossless CR range, taking into account the metrics differentiation as a function of CR. As expected, all four

Table 5 Area under ROC curve (A_z) $\pm$ standard error (SE) values, along with lower and upper asymmetric 95 % confidence interval (CI) values for each quantitative metric studied

Metric	ROC analysis	
	$A_z \pm SE$	Lower, upper asymmetric 95 % CI
MSE	0.922 $\pm$ 0.015	0.887, 0.946
MAE	0.920 $\pm$ 0.015	0.886, 0.945
NAE	0.802 $\pm$ 0.024	0.750, 0.844
SNR	0.806 $\pm$ 0.024	0.754, 0.847
PSNR	0.922 $\pm$ 0.015	0.887, 0.946
SC	0.762 $\pm$ 0.027	0.705, 0.809
NK	0.868 $\pm$ 0.020	0.824, 0.901
SSIM	0.922 $\pm$ 0.015	0.888, 0.946

Table 6 Cut-off values and corresponding accuracy, sensitivity, and specificity values of the most accurate quantitative metrics

	MSE	MAE	PSNR	SSIM
Cut-off value	407.8	16.12	46.14	0.977
Accuracy (%)	86.18	86.18	86.18	86.18
Sensitivity (%)	85.93	85.93	85.93	80.09
Specificity (%)	86.34	86.34	86.34	87.27

Fig. 5 Correlation between the most accurate metrics (MSE, MAE, PSNR, and SSIM) and pooled radiologists' image quality rating scores (ground truth). Each metric cut-off value is indicated by *solid line*

quantitative metrics have suggested a visually lossless CR ranging from 25:1 to 40:1. These metrics cut-off values may be used as an alternative to CR thresholds to indicate acceptable image quality of JPEG2000 compressed mammograms, in case of MCs. In addition, these metrics may be exploited toward image compression algorithms performance inter-comparison studies.

The dataset analyzed in the current study originated from 68 mammographic images compressed at five CRs. An augmented dataset should be considered including additional lesion types (masses of varying margin types, architectural distortions, as well as additional microcalcification morphology types). The effect of image compression on image quality of the entire mammogram is also worthwhile being investigated. The dataset should also be augmented with respect to image type also considering image data originating from different digital mammographic image acquisition systems (both FFDM and computed radiography ones). Furthermore, more refined sampling of CRs should be considered, especially within the suggested visually lossless CR range (25:1 up to 40:1) of the current study.

Additional compression algorithms should be considered in future efforts, especially those focusing on preserving the high-frequency components of the mammographic image [37]. Furthermore, metrics of different computational principles, such as edge-based-measures, spectral distance-based measures, and metrics simulating human visual system [29]

should also be tested. Finally, future efforts will focus on investigating the effect of image compression on the performance of computer-aided detection [38] and diagnosis schemes, accounting for an indirect approach towards quantitative image quality evaluation of compressed mammograms, currently being under-researched.

Conclusions

The current study presents a quantitative approach towards determination of a visually lossless CR threshold for digitized mammograms. This was achieved by identifying quantitative image quality metrics that can adequately reflect observers' visual perception of distinguishability/indistinguishability between original and JPEG2000 compressed mammographic ROIs containing microcalcification clusters. Among the quantitative metrics considered, MSE, MAE, PSNR, and SSIM demonstrated the highest performance, in terms of correlation and ROC analyses, in reflecting radiologists' visual perception. The current study suggested specific cut-off values of these metrics capable of defining a visually lossless CR threshold, estimated to be between 25:1 and 40:1 in case of microcalcification clusters in JPEG2000 compressed digitized mammograms. Results of this study indicate the potential of the quantitative image quality evaluation approach as a method for visually lossless CR threshold determination.

Acknowledgments The authors would like to thank the staff of the Department of Radiology of the University Hospital of Patras for their contribution in this work.

References

- Jemal A, Siegel R, Xu J, Ward E: Cancer statistics, 2010. *CA Cancer J Clin* 60(5):277–300, 2010
- Clark R: Breast cancer screening: is it worthwhile? *Cancer Control* 2(3):189–194, 1995
- Costaridou L, Skiadopoulos S, Karahaliou A, Arikidis N, Panayiotakis G: Computer-aided diagnosis in breast imaging: Trends and challenges, In: Exarchos TP, Papadopoulos A, Fotiadis DI Eds. *Handbook of Research on Advanced Techniques in Diagnostic Imaging and Biomedical Applications*. Hershey, PA: IDEA Group Inc. Global, 2009, p142–159
- Skaane P: Studies comparing screen-film mammography and full-field digital mammography in breast cancer screening: updated review. *Acta Radiol* 50(1):3–14, 2009
- Bankman I: *Handbook of Medical Image Processing and Analysis*, 2nd edition. Academic, Burlington, 2008
- Huang HK: *PACS and Imaging Informatics: Basic Principles and Applications*. WILEY-LISS, Hoboken, 2004
- European Society of Radiology (ESR): Usability of irreversible image compression in radiological imaging. A position paper by European Society of Radiology (ESR). *Insights Imaging* 2(2):103–115, 2011
- Kang BJ, Kim HS, Park CS, Choi JJ, Lee JH, Choi BG: Acceptable compression ratio of full-field digital mammography using JPEG 2000. *Clin Radiol* 66(7):609–613, 2011
- Good WF, Sumkin JH, Ganott M, Hardesty L, Holbert B, Johns CM, Klym AH: Detection of masses and clustered microcalcifications on data compressed mammograms: an observer performance study. *AJR, Am J Roentgenol* 175(6):1573–1576, 2000
- Kocsis O, Costaridou L, Varaki L, Likaki E, Kalogeropoulou C, Skiadopoulos S, Panayiotakis G: Visually lossless threshold determination for microcalcification detection in wavelet compressed mammograms. *Eur Radiol* 13(10):2390–2396, 2003
- Suryanarayanan S, Karellas A, Vedantham S, Waldrop SM, D'Orsi CJ: Detection of simulated lesions on data-compressed digital mammograms. *Radiology* 236(1):31–36, 2005
- Penedo M, Souto M, Tahoces PG, Carreira JM, Villalón J, Porto G, Seoane C, Vidal JJ, Berbaum KS, Chakraborty DP, Fajardo LL: Free-response receiver operating characteristic evaluation of lossy JPEG2000 and object-based set partitioning in hierarchical trees compression of digitized mammograms. *Radiology* 237(2):450–7, 2005
- Kallergi M, Lucier BJ, Berman CG, Hersh MR, Kim JJ, Szabunio MS, Clark RA: High-performance wavelet compression for mammography: localization response operating characteristic evaluation. *Radiology* 238(1):62–73, 2006
- Liang Z, Du X, Liu J, Yang Y, Rong D, Yao X, Li K: Effects of different compression techniques on diagnostic accuracies of breast masses on digitized mammograms. *Acta Radiol* 49(7):747–751, 2008
- Sung MM, Kim HJ, Kim EK, Kwak JY, Yoo JK, Yoo HS: Clinical evaluation of JPEG2000 compression for digital mammography. *IEEE Trans Nucl Sci* 49(3):827–832, 2002
- Koff D, Bak P, Brownrigg P, Hosseinzadeh D, Khademi A, Kiss A, Lepanto L, Michalak T, Shulman H, Volkening A: Pan-Canadian evaluation of irreversible compression ratios (“lossy” compression) for development of national guidelines. *J Digit Imaging* 22(6):569–578, 2009
- Erkel AR, Pattynama PM: Receiver operating characteristic (ROC) analysis: basic principles and applications in radiology. *Eur J Radiol* 27:88–94, 1998
- Perlmutter SM, Cosman PC, Gray RM, Olshen RA, Ikeda D, Adams CN, Betts BJ, Williams MB, Perlmutter KO, Li J, Aiyer A, Fajardo L, Birdwell R, Daniele BL: Image quality in lossy compressed digital mammograms. *Signal Processing* 59(2):189–210, 1997
- Zyout I, Abdel-Qader I, Al-Otun H: Progressive lossy to lossless compression of ROI in mammograms. Effects on microcalcification detection. *Integr Comput-Aided Eng* 15(3):241–251, 2008
- Kim H, Jeong J, Lee J, Kang H, Dong K, Chung W, Kim E: Picture quality according to the type of detector in full-field digital mammography. *J Korean Phys Soc* 58(2):364–371, 2011
- Przelaskowski A: Vector quality measure of lossy compressed medical images. *Comput Biol Med* 34(4):193–207, 2004
- Heath M, Bowyer KW, Kopans D, Kegelmeyer P, Moore R, Chang K, Kumaran SM: Current status of the Digital Database for Screening Mammography. *Proceedings of the Fourth International Workshop on Digital Mammography*. Kluwer, Dordrecht, 1998, pp 457–460
- Heath M, Bowyer KW, Kopans D, Moore R, Kegelmeyer P: The Digital Database for Screening Mammography. *Proceedings of the Fifth International Workshop on Digital Mammography*. Madison, WI: Medical Physics Publishing, 2001, pp 212–218
- D'Orsi CJ, Bassett LW, Berg WA, et al. BI-RADS: Mammography, 4th edition in: D'Orsi CJ, Mendelson EB, Ikeda DM, et al: *Breast Imaging Reporting and Data System: ACR BI-RADS – Breast Imaging Atlas*, Reston, VA, American College of Radiology, 2003
- Li H, Giger ML, Olopade OI, Margolis A, Lan L, Chinander MR: Computerized texture analysis of mammographic parenchymal patterns of digitized mammograms. *Acad Radiol* 12(7):863–73, 2005
- Skodras A, Christopoulos C, Ebrahimi T: The JPEG 2000 still image compression standard. *IEEE Signal Process Mag* 18(5):36–58, 2001
- Kofidis E, Kolokotronis N, Vassilarakou A, Theodoridis S, Cavouras D: Wavelet-based medical image compression. *Future Gener Comp Sy* 15(2):223–243, 1999
- Sakellariopoulos P, Costaridou L, Panayiotakis G: An image visualization tool in mammography. *Med Inform Internet Med* 24(1):53–73, 1999
- Avcibas I, Sankur B, Sayood K: Statistical evaluation of image quality measures. *J Electron Imaging* 11(2):206–223, 2002
- Eskicioglu AM, Fisher PS: Image quality measures and their performance. *IEEE Trans Commun* 43(12):2959–2965, 1995
- Wang Z, Bovik AC: Mean squared error: love it or leave it? A new look at signal fidelity measures. *IEEE Signal Process Mag* 26(1):98–117, 2009
- Wang Z, Bovik AC, Sheikh HR, Simoncelli EP: Image quality assessment: from error visibility to structural similarity. *IEEE Trans Image Process* 13(4):600–612, 2004
- Cohen I: A coefficient of agreement for nominal scales. *Educ Psychol Meas* 20(1):20–37, 1960
- Suryanarayanan S, Karellas A, Vedantham S, Waldrop SM, D'Orsi CJ: A perceptual evaluation of JPEG 2000 image compression for

- digital mammography: contrast-detail characteristics. *J Digit Imaging* 17(1):64–70, 2004
35. Kim KJ, Kim B, Mantiuk R, Richter T, Lee H, Kang HS, Seo J, Lee KH: A comparison of three image fidelity metrics of different computational principles for JPEG2000 compressed abdomen CT images. *IEEE Trans. Med. Imag* 29(8):1496–1503, 2010
36. Kim B, Lee KH, Kim KJ, Mantiuk R, Hahn S, Kim TJ, Kim YH: Prediction of perceptible artifacts in JPEG 2000-compressed chest CT images using mathematical and perceptual quality metrics. *AJR Am J Roentgenol* 190:328–334, 2008
37. Penedo M, Pearlman WA, Tahoces PG, Souto M, Vidal JJ: Region-based wavelet coding methods for digital mammography. *IEEE Trans Med Imaging* 22(10):1288–1296, 2003
38. Zheng B, Sumkin JH, Good WF, Maitz GS, Chang YH, Gur D: Applying computer-assisted detection schemes to digitized mammograms after JPEG data compression: an assessment. *Acad Radiol* 7(8):595–602, 2000