IRREVERSIBLE MEDICAL IMAGE COMPRESSION: CONDITIONS OF ACCEPTABILITY

ARTUR PRZELASKOWSKI

Nuclear and Medical Electronics Division,
Warsaw University of Technology,
Nowowiejska 15/19, 00-665 Warsaw, Poland
arturp@ire.pw.edu.pl

Abstract: Acceptance of irreversible image compression applicable to medical imagery is controversial in the medical community. The influence of this irreversible process on degradation of diagnostic image features is considered and how to preserve diagnostic accuracy. Fears, doubts, the disadvantages of the data distortion process and the advantages of safe and efficient irreversible compression for image information storage and interchange are discussed. The effects of compression on various image exams are analysed. The conclusion is that irreversible compression is not to be afraid of, but its characteristics should be well understood before implementing it in current practice.

Keywords: irreversible compression, medical image compression, diagnostic accuracy, diagnostic image quality

1. Introduction

The application of irreversible compression in medical image archiving or interchange is problematic because of the possible damage to diagnostically important information in the distorted original image. It is said that an irreversible process loses something every time it is applied and therefore conditions of diagnosis must necessarily be worse after 'lossy' compression. The doubts are intensified by the concern that correct interpretation of image information protects the health and even the life of a patient. Popular opinion also has it that the application of irreversible, implied to be lossy, compression in medical imagery is limited by legal restrictions, because of the loss of diagnostic accuracy. The scientific community has not yet reached a consensus on irreversible compression and medical image data alteration (*i.e.* the reduced diagnostic accuracy of reconstructed images).

However, the need for significantly increased efficacy of image compression in medical applications is great and unquestionable. Fully lossless image compression reconstruction offers only a modest reduction in data size. The limited efficiency of reversible compression technologies (mostly up to 3 : 1) does not satisfy the

current needs concerning image storage and transmission. The volume of data from medical imaging systems, growing at exponential rates, and the development of newer radiology diagnostic procedures and conditions (in Picture Archiving and Communications (PAC) and teleradiology systems) require much more effective tools for compression of image data files and streams. The only way to significantly improve performance is to apply irreversible methods which are safe in the context of image-based diagnosis. Substantially higher compression ratios are achievable with irreversible techniques even with no perceptible or diagnostic degradation in image quality. Various image exams can be irreversibly compressed without losing diagnostic accuracy in the opinion of experts participating in reliable evaluation tests [1–7] (and many others). Furthermore, image quality enhancement is possible [4, 8–10] in an irreversible process, where compressed high quality information may be superior to the initial lower quality image.

Moreover, Digital Imaging and Communications in Medicine (DICOM) has incorporated lossy JPEG and JPEG2000 procedures but have not addressed the amount of compression acceptable to users (responsibility is directed with radiologists and medical centres applying medical imaging technologies). The Food and Drug Administration (FDA), in spite of previous restrictions, have found the use of irreversible compression acceptable [11]. Their final ruling has removed the restriction relating to irreversible compression and extended the exemption from premarket notification to all medical image storage and communications devices (the technique and ratio are left to the radiologist's discretion, although the use of irreversible compression must be noted). Labelling and promotional materials of devices that utilize irreversible compression should clearly state the compression ratios provided. Such devices should be supplied with instructions that explain the effects of compression and include examples of the effects of information loss on image quality. A message stating that irreversible compression has been applied and the approximate compression ratio (CR) should accompany images that have been subjected to irreversible compression. Many vendors of medical software support irreversible compression (compressed image transfer syntax as specified in the DICOM standard, making it possible to both store and distribute irreversibly compressed clinical images) in medical imaging systems (GE RadWorks, Centricity PACS, PERS, PICTools Medical Compression Toolkit, MedXpress, LEADTOOLS Medical, Aware JPEG2000, FUJIFILM Medical Systems and others).

Nevertheless, the final decision to safely apply irreversible compression strongly depends on the preferences, experience and knowledge of the responsible radiologist. Practicing radiologists need to understand the visual effects of irreversibility and nature of the degradation that occurs in order to optimise their image-based diagnosis procedure.

This paper includes considerations, discussion and presents experiments related to irreversible processing of the acquired image data in a compression procedure prior to primary diagnosis. It summarises our long-term experiences with compression of medical images to clearly and objectively explain the influence of this process on images' diagnostic accuracy so that more reliable, sensitive and useful medical applications of irreversible compression could be developed.

2. Performance of irreversible compression

The main concern of medical image data compression is to maintain images' diagnostic quality. Ultimately, the physician interpreting an image has to be confident that image quality and conditions of interpretation have not been sacrificed in a way that would compromise diagnostically important content. Many researchers have conducted studies to determine what levels of compression their facility would tolerate. Recent enhancements of information systems designed for storage, exchange and retrieval of digital medical images have significantly increased the system's flexibility and performance by application of effective and multifunctional compression tools. This enables administrators to design compression strategies to optimise image usage while also supporting the fundamental requirements of image accuracy. These provide means of managing image information access for medical institutions that wish to make their radiology departments all-digital.

2.1. Examples of verification studies

Irreversible message extraction techniques were introduced to medical applications in the early 1980s [12]. These techniques attempted to extract diagnostically important semantic content as structural features that were selectively retained (*e.g.* by reversible coding). Image information clinically designated as unimportant was subsequently discarded. The obtained irreversible compression acceptance was close to the 5 : 1 ratio, but compression ratios of up to 15 : 1 might be achieved without significant degradation of diagnostic quality. However, the acceptable compression ratio varied with the modality (computed tomography (CT), magnetic resonance imaging (MRI), nuclear medicine, ultrasound (US)), acquisition conditions, pathology cases *etc.*

More sophisticated coders based on the discrete cosine transform (DCT) or the wavelet transform have been used in more recent studies. The Mayo Clinic tested JPEG compression prior to interpretation on all of their ultrasound images for two years before including it in the imaging chain of its ultrasound practice [6]. They have found that color and gray-scale images compressed at approximately 9 : 1 are indistinguishable from the originals (no evidence of degradation has been found in their study). The use of irreversible compression enables Mayo to maintain all of its ultrasound data online, contributing to the efficiency of the practice and improving patient care. It has reduced infrastructure costs by approximately $250 000 per year. Other practices should perform their own studies to determine the best algorithms and acceptable conservative compression ratios for image exams, since each facility (modality) is different, and one size may not fit all. Similar studies from other radiological research centres demonstrate that the accuracy of reconstructed images is preserved in the calculated range of compression ratios.

Perlmutter *et al.* have evaluated fifty-seven digital mammograms compressed with a wavelet-based algorithm [2]. They have found no significant differences between analog and compressed images even at the lowest bit rate tested, 0.15 bpp (bits per pixel, CR = 80 : 1). Good *et al.* have assessed by means of a Receiver Operating Characteristics (ROC) study the detection of masses and clustered microcalcifications in sixty digital mammograms compressed using the standard JPEG [1]. Their results

have shown that detection of masses is not affected by compression, while observer performance is degraded in detecting clusters of microcalcifications at ratios of $101:1$. A similar study reported by Zheng *et al.* has compared the performance of a Computer Aided Detection (CAD) system for the detection of primary signs of breast cancer using original images and images reconstructed after JPEG compression [5]. They have concluded that JPEG does not affect the CAD scheme for detecting masses, but that detection of clusters of microcalcifications is affected by compression. In all these research studies, optimisation of the compression process was achieved by identifying the least rectangular area containing the breast region and compressing it at a different factor than the rest of the image.

According to [13], digitized chest radiographs are very tolerant to compression (at least $40:1$ for wavelet compression). In other research the JPEG2000 coder was used [14]. They evaluated the diagnostic quality of JPEG2000-compressed computed radiography chest images with compression ratios from $5:1$ to $200:1$. ROC and t-tests were performed to ascertain clinical performance using reconstructed images. The authors found that compression ratios as high as $20:1$ can be utilized without affecting lesion detectability. No significant differences between original and compressed images were recognized up to the compression ratio of $50:1$, within a confidence level of 99%.

Nevertheless, while applying JPEG compression to a large number of head CTs and head MRIs, there have been images considered acceptable by all observers at ratios $22:1$. At the same time, other images were considered unacceptable by the same viewers at a ratio of $5.3:1$ [15].

2.2. *Effects of irreversibility*

One cannot assign a single compression ratio to a modality, even for a given organ system. The degree of irreversibility acceptable for medical images depends on many important factors and cannot be fitted automatically without checking. First, the modality of imaging (acquisition and digitization of an image, quality of the apparatus) has to be considered; second, the characteristics of the depicted object (structures to diagnose); third, the purpose of information (kind of exam, diagnosis technology, diagnosis procedure, way of interpretation). However, preferences of the responsible radiologist seem to be the most important.

Generally, image compression dedicated to medical applications should be lossless, or without loss of diagnostically important information. Hence, the possible compression without loss may be divided into four categories:

(a) **numerically lossless**, which means reconstruction of data bit-to-bit equal to the original (after acquisition, digitization); $CR = 2:1$–$3:1$;

(b) **visually lossless**, *i.e.* of quality reduced to much the information content to the limits of human perception; $CR = 10:1$;

(c) **functionally lossless**, which stands for image reconstruction designed to match the data to the purpose for which the image will be used (diagnosis, consultation, reference example in database, exam documentation, including conditions of visualisation and the way of interpretation); $CR = 15:1$–$40:1$;

(d) **approximately lossless**, *i.e.* with no fine detail needed for just recognising the objects (structures) if browsed (reviewed) at speed; $CR = 200:1$.

Local image features which influence the human perception of image information and, consequently, lesion detection and classification ability (*i.e.* image interpretation for the purpose of diagnosis) are as follows: edge gradient, smoothness, blurring, contrast, shape, outline and sharpness of certain particulars, texture clearness, relation of the inside and outside textures of the selected structures, *etc.* Irreversible compression affects these image features with gradually increased performance, and the feature distortions should be considered separately for each case. Nevertheless, taking into account a particular compression method and a hypothetical medical image of typical characteristics, general observations can be made.

Numerically lossless compression is realised with limited efficacy by reversible algorithms (with data modelling and binary encoding). But, increased performance means irreversibility of the original reconstruction. When high bit rates (low CRs) are used, the (threshold-like) step of quantization with modest power done in the frequency (DCT-based algorithms) or wavelet domain mostly discards (*e.g.* only by rounding-off to integers) high frequency noise (widespread, large number of very low magnitude coefficients). Image feature distortion is imperceptible (visually lossless compression). The first noticeable changes for decreased bit rates is removal of more noise (speckle, 'salt-and-pepper') without degradation of signal structures (typically represented by higher-magnitude coefficients). Radiologists often prefer these enhanced (de-noised) images [14]. The structures important for diagnosis may be more visible and therefore images' diagnostic accuracy is even improved.

In the range of moderate bit rates, quantization error may cause a distortion of useful signal features, *e.g.* low magnitude, high frequency coefficients representing low-gradient edges, small distinct structures or textures with wide-spread coefficients over the scale-frequency domain. Hence blurring of diagnostically important information may be observed. For example, speckle noise in US images with widespread spectra, trabecular bones in radiograms, or brain tissues in MRIs or CTs are highly susceptible to blur caused by wavelet compression. In these case, recognizable features could be noticed in subtraction images (original – reconstruction). Compression to these bit rates should be carefully tested in order to reliably evaluate the diagnostic accuracy of the reconstructed images, as first doubts concerning image accuracy may occur. The border of functionally lossless compression often lies in this range of bit rates.

At still lower bit rates, the blurring phenomenon increases and additionally artefacts characteristic for a particular algorithm appear: blocking effects, artificial lines at block borders, deformation of structures processed independently in several neighbour blocks in JPEG compression and, for the wavelet-based JPEG2000, the Gibbs effect, close large jumps in the spatial domain or rice-shaped effects with orientation and spatial extension corresponding to the applied wavelet family and the subband of significantly distorted coefficients. In most cases, these bit rates are unacceptable for medical applications because of the accompanying meaningful degradation of diagnostic information and loss of accuracy. Artificial or changed structures may cause an over-interpreted diagnosis (false positives) or hidden local features may be omitted (false negatives).

The great concern is preserving the fine structures and subtle findings that are very important for diagnosis (*e.g.* microcalcifications in mammograms or a faint

nodule in a chest radiogram). Artefacts introduced during processing often mask fine structures. Subtle findings may be difficult for the human eye to discern because of low local contrast, but if they have a significant spatial extent in the low frequency range of the spectral domain, they are generally well preserved in the compression process. Such subtle findings may remain visible even at low ratios of compression and become even more extracted from noise-free surroundings with higher local contrast.

Examples of differential susceptibility to irreversible compression of medical images are presented in Figure 1. Generally considering irreversible wavelet compression, the following compression ratios could be estimated as acceptable: close to $40:1$ for a majority of chest and bone radiograms and mammograms, and approximately $10-20:1$ for US, MR and CT exams.

Furthermore, when digital images are compressed to facilitate rapid transfer and most of them are not of original diagnostic quality on the receiving end, they can still be useful for confirming diagnoses, consulting or reporting to the referring physician. The trade-off in quality is usually worth reducing the large stream size and making teleradiology applications possible.

2.3. Implementation of compression in imaging systems

There are forms of data alteration to worry about other than compression, for example, those resulting from malice or machine malfunction [14]. Compression is not substantially different from any other step in the image creation and presentation chain of a medical imaging system. The quality of each of these steps influences the final image accuracy. Useful signal formation with the associated generation of noise and artefacts, next signal processing with noise reduction and information enhancement procedures distributed across the whole imaging chain have to be permanently optimised, controlled and verified in clinical practice. An additional step of irreversible compression should be treated in the same way.

Radiologists routinely use their own profiles of imaging, accepting the trade-offs of using different parameters of the system:

- to reduce imaging time (fewer excitations in MR acquisition or interpolation of higher resolution by symmetry of FFT),
- to enhance image perception by routine irreversible processing (*e.g.* applying data approximation procedures in nuclear medicine),
- to reduce an X-ray dose (higher voltage with reduced contrast in screening mammography).

They often do not optimise the processing of X-ray films, *etc.* Therefore, they should be able to accept irreversible compression when it is demonstrated that no degradation of diagnostic accuracy is involved.

A requirement that all diagnostically important (*i.e.* semantic) information must be preserved does not mean that information in its stochastic meaning cannot be reduced. Nor does it mean numerical identity with the original.

In sum, many years of experiments have demonstrated that irreversible compression can be used for medical applications. Clinical reports and serious studies reported in hundreds of papers have proven that diagnostic accuracy is preserved in an acceptable range of compression ratios.
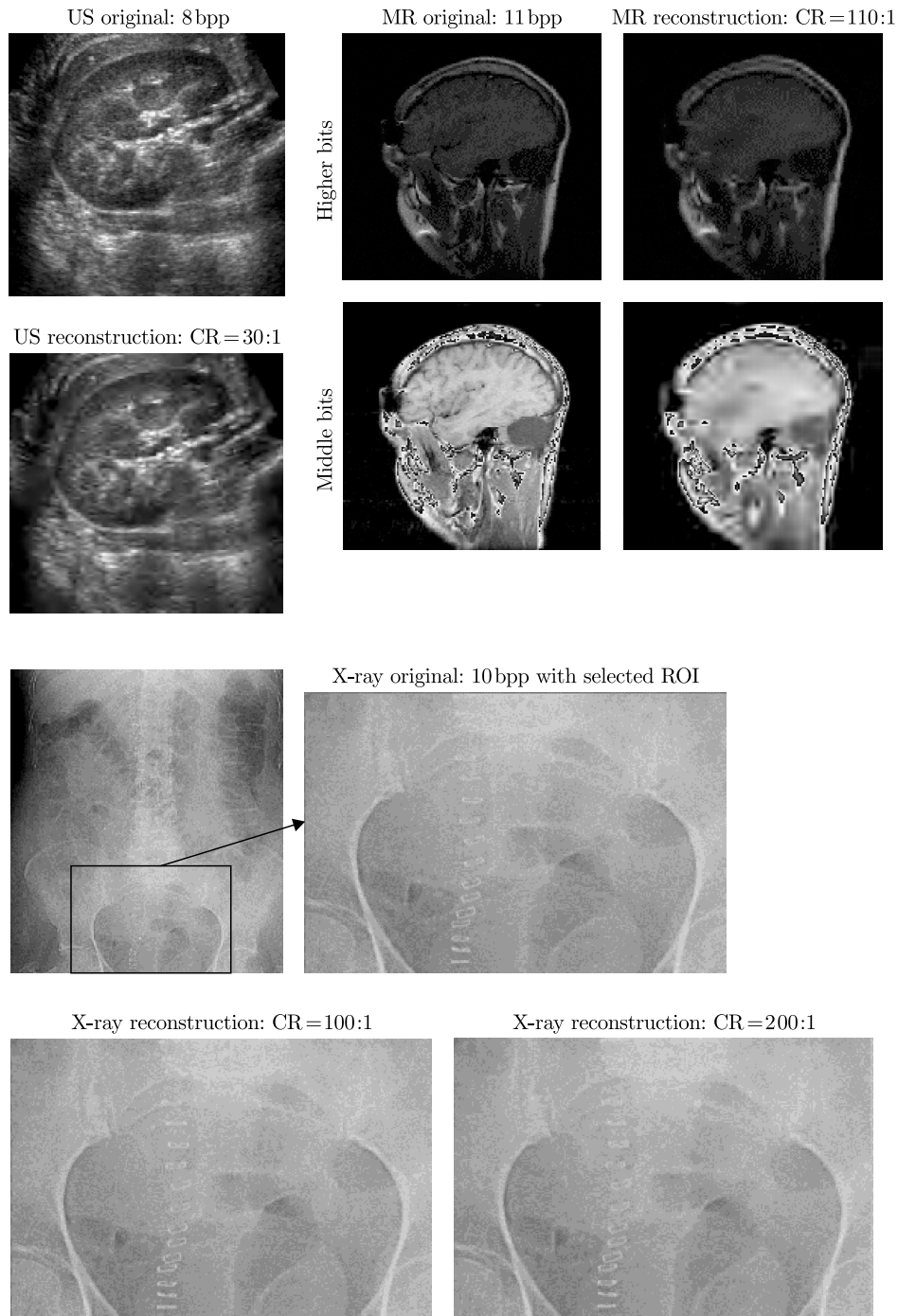
US original: 8 bpp

MR original: 11 bpp   MR reconstruction: CR = 110:1

Higher bits

US reconstruction: CR = 30:1

Middle bits

X-ray original: 10 bpp with selected ROI

X-ray reconstruction: CR = 100:1   X-ray reconstruction: CR = 200:1

Figure 1. Examples of irreversibly compressed medical images: US (slightly distorted, functionally or approximately lossless depending on the purpose), MR (significantly distorted, unacceptable for most purposes) and X-ray (the image reconstructed from ratio 100 : 1 is visibly lossless, the reconstruction from ratio 200 : 1 is functionally lossless)

Additionally, we have such arguments as the FDA's acceptance of routine usage irreversible compression in medical information systems, DICOM improvements of irreversible tools and procedures (JPEG and the just developed JPEG2000 tools, currently considered are additional image attributes, including accepted compression ratios), many vendors and products of this kind of compression, usefulness of images in spite of reduced quality, and factors other than compression that influence the ultimate image quality in the successive steps of image formation and presentation (conditions of acquisition, digitalization or visualization, fixed parameters of imaging devices, internal preprocessing, interpolation or approximation and reconstruction procedures applied in the apparatus, *etc.*).

3. Conditions of acceptability

All the above-mentioned diagnostic, legal or procedural uncertainties impede widespread use of irreversible compression in medical imaging systems. Nevertheless, some important, general remarks can be formulated for their use in clinical practice:

- an acceptable compression level should be established carefully, depending on many factors important for diagnosis and conditions of a particular exam;
- practicing radiologists need to understand the visual effects of irreversibility and the nature of the occuring degradation in order to optimise their compressed image-based diagnostic procedures;
- an image version that was used in diagnosis should be archived and made accessible at request;
- if any further image processing is expected (enhancement, fitting to new presentation conditions, *etc.*) numerically lossless algorithms should be used for image compression;
- the irreversible compression process should be permanently controlled, *i.e.* its options cannot be fitted automatically for all images without adjustment;
- any imperfect, uncertain algorithms of compression should be avoided;
- current parameters of the acquisition process and quality of the imaging systems and created original images should be taken into account in evaluating irreversible compression with respect to its acceptability for clinical applications.

4. Experiments

Subjective ratings and ROC-based analysis were used in experimental estimation of the acceptable bit rate. Rates given for the reconstructions equal the original image rates; no statistical difference (hypothesis verification) between decisions concerning lesion detection in originals and reconstructions can be used as proof of diagnostic accuracy preservation. We have conducted a few experiments to verify acceptability of irreversible compression for medical applications.

4.1. Methodology

4.1.1. Simple subjective rating – a single MR case

The following subjective test was organised to evaluate the impact of irreversible compression on MR image quality: each observer rated the compressed images in

comparison to the original independently, in similar comfortable conditions, all images compressed by *i*-technique were grouped and displayed together, then classified and evaluated. The following rating scale with descriptions related to diagnostic quality was established (a compressed image compared with the original image):

7 – better than original,
6 – unnoticeably changed,
5 – slightly changed (no accuracy degradation),
4 – noticeably changed (slight quality degradation),
3 – annoying quality degradation,
2 – glaring, significant quality degradation,
1 – unacceptable quality degradation.

4.1.2. Optimised subjective rating (with increased reliability of evaluation) of a group of mammograms

Observers were asked to describe breast lesions in more objective terms, *i.e.* quality of local image features that influence detection efficiency in mammography. The test procedure was optimised to estimate the diagnostic accuracy score of each image quickly and unequivocally, with reduced complexity and costs. Four features were rated: contrast (related to density), interpretation clarity (visibility, noticeability of abnormalities, related to detection ability), shape (possibility of detection) and margin (outline, contour distinction) of the chosen structures including lesions and other abnormalities. Seven experienced radiologists evaluated the perceptibility of these image diagnostic features on a scale of 1 (weak, indistinct, scarcely perceptible, distorted) to 3 (distinct, clearly perceptible, regular, beyond doubt). A sum of four feature scores (which are averages of all observer rates for a test image) is a general score of diagnostic image quality for a given image. The time of evaluation, carried out under the conditions of clinical practice, was unlimited.

4.1.3. ROC-based analysis of mammograms

The original mammograms and their reconstructions were presented in long-term sessions. The applied 'gold standard' was consensus and separate, *i.e.* determined by the consensus of two judges (experts in radiology) on the original, reconstructions, other projections and all the available exams and results. Independent observations and decisions of each of the seven experienced radiologists from three medical centres made in similar, comfortable conditions of clinical practice were provided. A statistical test with *t*-statistics (a *t*-Student test) was applied to analyse the sensitivity, specificity and PVP of the detection decisions in selected Regions of Interests (ROIs) to verify a hypothesis about statistically significant differences between the originals and the reconstructions.

4.2. Results

The results of simple and optimised subjective rating are presented in Tables 1 and 2, respectively. ROC curves estimated for the original mammograms and the compressed at the ratio of 120 : 1 are presented in Figure 2. Representative MR image compressed at the ratio of 10 : 1 was rated as very similar to the original. Several test mammograms were visually indistinguishable from their originals after compression

Table 1. The results of the simple subjective rating test; only one selected MR image
was irreversibly compressed with 3 different coders: wavelet-based SPIHT [15]
and MBWT [16], and a DCT-based JPEG-like coder; the table contains average
values of scores in terms of the rating scale; seventeen persons took part in this
evaluation: 2 radiologists, 8 medical engineers and 7 students experienced
in image processing and analysis

Observers	Compression method	Mean subjective rates for different CRs						
		10:1	15:1	20:1	25:1	30:1	35:1	40:1
Physicians	SPIHT	5.5	4.5	3.5	3	2.5	1.5	1.5
	MBWT	5.5	4.5	4.5	3	2.5	1.5	1.5
	DCT	5.5	3.5	2.5	1	1	1	1
Medical engineers	SPIHT	5.88	5.38	4.63	4.38	3.25	2.75	2.5
	MBWT	5.75	5.5	4.75	4.25	3.75	3.38	2.88
	DCT	6.12	5.5	3.08	2.0	1.42	1.08	1.08
Students	SPIHT	6	5.15	4.29	3.57	2.86	2	1.57
	MBWT	5.86	4.71	4.43	3.71	3	2.43	1.71
	DCT	5.86	5	4.57	3.43	2.43	1	1

Table 2. The results of the optimized subjective rating test; mean subjective scores given for
mammograms, 15 originals (12bpp) and their reconstructions (1bpp) after JPEG2000
and MBWT compression; the results of image ordering according to diagnostic quality
are also presented; 7 observers (experienced radiologists) pointed out the image
of better quality or decided about equal accuracy of the original
and reconstructed images

Images	Subjective rating: mean scores					Quality ordering (number of 1st positions/number of classifications)			
	contrast (1–3)	inter-pretation (1–3)	margin (1–3)	shape (1–3)	cumulated score (4–12)	contrast	inter-pretation clarity	margin	shape
Originals	2.38	2.48	2.47	2.50	9.83	24/105	33/105	21/105	22/105
Recon-structions CR = 12:1	2.45	2.43	2.46	2.49	9.83	30/105	29/105	17/105	17/105

to ratio 12:1 and, generally, the group of mammograms compressed at the ratio of
120:1 was not statistically different from the originals in their diagnostic accuracy,
according to the opinion of experienced radiologists from three medical centres (see
Figure 3).

4.3. Discussion

According to the assumed rating scale of the simple test with a representative
MR image (Figure 2a) mean scores under 5 are a sign of reduced diagnostic quality.
Subjective rating of reconstructed MR images have clearly shown a degradation of
diagnostic quality after compression at CR = 20:1 and more in the opinion of all
observers. Engineers (for 3 compression techniques) and students (for 2 techniques)
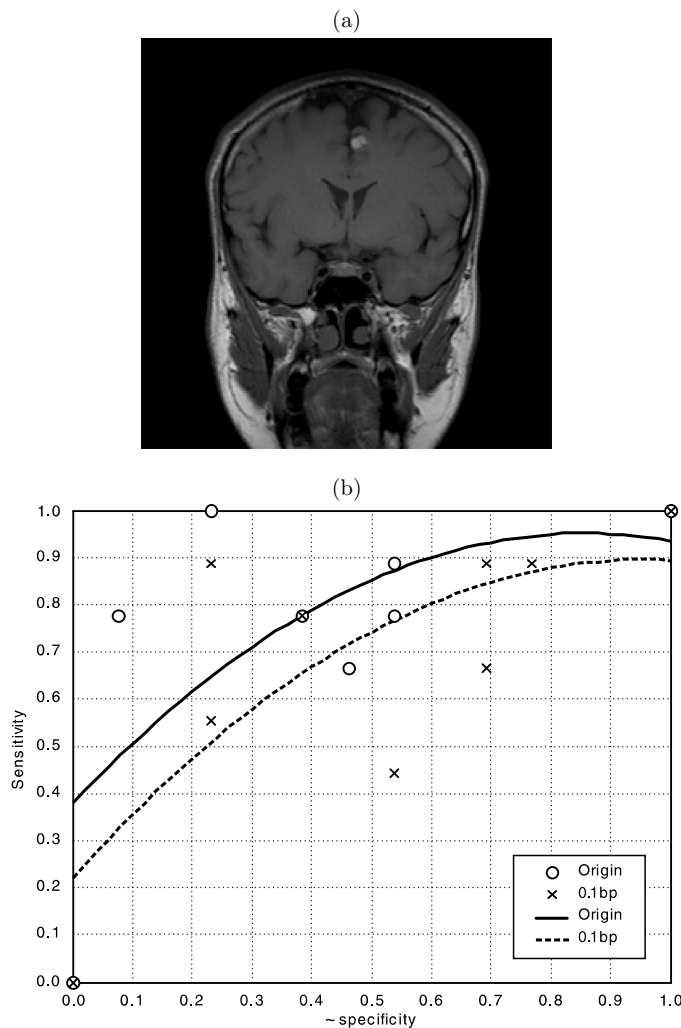have accepted the reconstruction of CR = 15:1, but radiologists have marked small

(a)

(b)

Figure 2. (a) Representative MR image from the simple test of subjective rating; (b) ROC curves for a group of original mammograms and those compressed to 0.1 bpp (CR = 120 : 1), rated in terms of lesion detection by 7 observers

and even annoying quality degradation for this image. 2 radiologists have accepted the accuracy of an image compressed at the ratio of 10 : 1, similarly engineers and students. Generally, DCT-based compression gave the worst efficiency of reconstruction, but engineers noticed even improved quality of DCT-based reconstruction at the ratio of 10 : 1 in comparison to the original image. This experiment has no statistical reliability. Therefore, another subjective test with an extended set of test images and a group of seven professional observers was organized.

Similar, almost the same rates given for the original and reconstructed images (Table 2) prove the preserved accuracy in irreversible compression of mammograms up to 12 : 1. Moreover, 54% of ordering decisions voted for equal diagnostic quality of the rated images, 23.8% of cases were indications of higher quality of the original, and the remaining 22.2% rates pointed out higher quality of the reconstructed image.
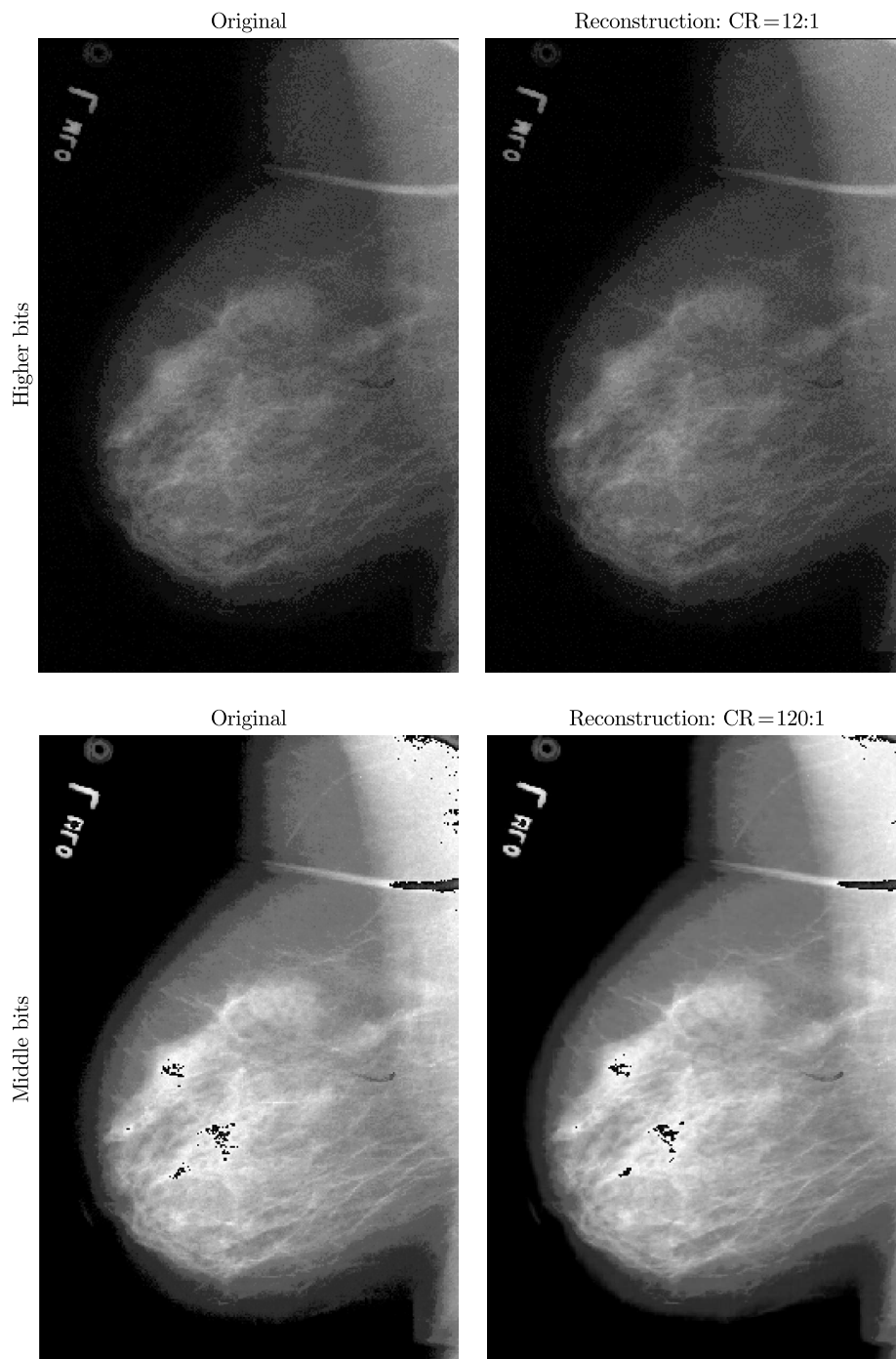
Original Reconstruction: CR = 12:1

Higher bits

Original Reconstruction: CR = 120:1

Middle bits

Figure 3. Original and reconstructed mammograms; reconstruction after wavelet compression to CR = 12 : 1 is perceptually indistinguishable from the original (visually lossless), and compression to CR = 120 : 1 (differences between the reconstruction and original are more noticeable in the range of middle bits) is functionally lossless according to ROC-based tests

This means indistinguishable diagnostic quality of the original and the irreversibly compressed mammograms.

The area under the approximated ROC curve is slightly smaller for reconstructed images; the variation in sensitivity and PVP values among observers is small with insignificant distinctions in the opinions given for the originals and the compressed mammograms. The assumed two-sided significance level $p = 0.05$ means that null hypothesis that the reconstructed information performs as well as the original (*i.e.* mean values of the populations are equal) is true for sensitivity test 0.1 bpp reconstructions (the value of t-statistics is 0.9321). Moreover, the specificity and PVP test are also positive for the compressed images (t-statistics for $\sim$specificity test is -0.9321, and for the PVP test is 1.1035). Hence, the general conclusion suggests an acceptance for diagnosis of mammograms compressed to 0.1 bpp (confirmed by recorded test remarks of radiologists). Several 0.1 bpp mammograms have obtained better accuracy rates (*i.e.* these mammograms have received more true diagnostic decisions and less false positives than the originals, which means improved lesion detection) and, generally, no significant differences were found between the originals and the 0.1 bpp images.

5. Conclusions

Generally, radiologists have agreed in their optimised subjective ratings that wavelet compression up to 1 bpp is safe in each case and does not reduce diagnostic accuracy of compressed mammograms. Sometimes enhanced diagnostic quality of mammograms has been observed after irreversible compression. The traditional ROC-based analysis was less demanding and mammograms compressed up to $120:1$ were statistically not different from the originals. Furthermore, different groups of observers have agreed that, in a particular case of MR high quality image, compression at the ratio of $10:1$ preserves quality (diagnostic quality in the opinion of radiologists). All these examples are additional proofs of possible, useful and advantageous irreversible compression of medical images.

The following may be concluded from the presented considerations and experimental results:

- Costs efficiency, improved system functionality and new diagnostic capabilities drive the development of irreversible compression methods in medical applications. Diagnostic accuracy of reconstructed images is necessary and worthy of investigating as well.
- Diagnostic accuracy of images can be preserved in a process of irreversible compression if bit rates from an acceptable range are applied.
- A practising radiologist is finally responsible for the application of irreversible image storage or exchange and an estimation of the acceptable level of compression.
- It is increasingly necessary for radiologists to become conversant in compression techniques and their effects on images. Increased radiologist knowledge, experience and awareness concerning the nature of diagnostic image information and the process of image formation is important for further developments. They are more fluent in application of compression tools when the nature of effects is clearer and efficiency of practice may thus be improved.

• Increasing evidence that some forms of irreversible compression may be applied without compromising the diagnostic accuracy of images requires more objective and reliable methods of diagnostic accuracy evaluation and verification of images. The search for these continues.

References

[1] Good W F, Sumkin J H, Ganott M, Hardesty L, Holbert B, Johns C M and Klym A H 2000 *American J. Roentgenology* **175** 1573

[2] Perlmutter S M, Cosman P C, Gray R M, Olshen R A, Ikeda D, Adams C N, Betts B J, Williams M B, Perlmutter K O, Li J, Aiyer A, Fajardo L, Birdwell R and Daniel B L 1997 *Signal Processing* **59** 189

[3] MacMahon H, Doi K, Sanada S, Montner S M, Giger M L, Metz C E, Nakamori N, Yin F-F, Xu X-W, Yonekawa H and Takeuchi H 1991 *Radiology* **178** 175

[4] Savcenko V, Erickson B J, Palisson P M, Person K R, Manduca A, Hartman T E, Harms G F and Brown L R 1998 *Radiology* **206** 609

[5] Zheng B, Sumkin J H, Good W F, Maitz G S, Chan Y-H and Gur D 2000 *Academic Radiology* **7** 595

[6] Persons K R, Hangiandreou N J, Charboneau N T, Charboneau J W, James E M, Douglas B R, Salmon A P, Knudsen J M and Erickson B J 2002 *J. Digital Imaging* **15** (1) 15

[7] Cosman P C, Gray R M and Olshen R A 1994 *Proc. IEEE* **82** (6) 919

[8] Chang S G, Yu B and Vetterli M 2000 *IEEE Trans. Image Proces.* **9** (9) 1532

[9] Sarty G E and Atkins M S 1997 *Proc. 5th Annual Meeting of the Int. Society for Magnetic Resonance in Medicine*, Vancouver, Canada, p. 2046

[10] Sarty G E, Atkins M S and Pierson R A 1998 *20*th *Annual Canadian Western Society for Reproductive Biology Workshop*, Saskatoon, Canada, Abstract 35

[11] 2000 Food and Drug Administration, Center for Devices and Radiological Health, Guidance for the Submission of Premarket Notifications for Medical Image Management Devices, http://www.fda.gov/cdrh/ode/guidance/416.pdf

[12] Bramble J M, Huang H K and Murphy M D 1988 *Investigative Radiology* **23** 707

[13] Erickson B J, Manduca A, Persons K R *et al.* 1997 *J. Digital Imaging* **10** 97

[14] Erickson B J 2002 *J. Digital Imaging* **15** (1) 5

[15] Said A and Pearlman W A 1996 *IEEE Trans. Circ. & Syst. Video. Tech.* **6** (3) 243

[16] Przelaskowski A 1998 *Fundamenta Informaticae* **34** (4) 369