Wavelet Compression on Detection of Brain Lesions With Magnetic Resonance Imaging

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The purpose of this report is to assess clinically acceptable compression ratios on the detection of brain lesions at magnetic resonance imaging (MRI). Four consecutive T₂-weighted and the corresponding T₁-weighted images obtained in 20 patients were studied for 109 anatomic sites including 50 with lesions and 59 without lesions. The images were obtained on a 1.5-T MR unit with a pixel size of 0.9 to 1.2 × 0.47 mm and a section thickness of 5 mm. The image data were compressed by wavelet-based algorithm at ratios of 20:1, 40:1, and 60:1. Three radiologists reviewed these images on an interactive workstation and rated the presence or absence of a lesion with a 50 point scale for each anatomic site. The authors also evaluated the influence of pixel size on the quality of image compression. At receiver operating characteristic (ROC) analysis, no statistically significant difference was detected at a compression ratio of 20:1. A significant difference was observed with 40:1 compressed images for one reader ($P = .023$), and with 60:1 for all readers ($P = .001$ to $.012$). A root mean squared error (RMSE) was higher in 0.94- × 0.94-mm pixel size images than in 0.94- × 0.47-mm pixel size images at any compression ratio, indicating compression tolerance is lower for the larger pixel size images. The RMSE, subjective image quality, and error images of 10:1 compressed 0.94- × 0.94-mm pixel size images were comparable with those of 20:1 compressed 0.94- × 0.47-mm pixel size images. Wavelet compression can be acceptable clinically at ratios as high as 20:1 for brain MR images when a pixel size at image acquisition is around 1.0 × 0.5 mm, and as high as 10:1 for those with a pixel size around 1.0 × 1.0 mm.

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KEY WORDS: wavelet, image compression, magnetic resonance imaging, brain, receiver operating characteristic analysis, picture archiving and communication system (PACS).

RECENT ADVANCES in technology and lowering the price of archival storage media have made it possible to put a large-scale picture archiving and communication system (PACS) into

practice. However, storage and transmission of a large number of digital images still pose a computational challenge. Image production within a large all-digital radiology department could produce several terabytes (10^{12} byte) of information per year.¹ In this situation, it is difficult to archive all original image data on-line for more than a couple of years. Furthermore, the volume of digitally acquired medical image data still is increasing because of the diffusion of computed radiography and the development of faster acquisition techniques in magnetic resonance imaging (MRI) and computed tomography (CT). Thus, to reduce the cost for image storage and the time for image transmission, there is a substantial need for effective data compression in PACS as well as in teleradiology.

Image data compression can be divided into 2 general categories: reversible (lossless) and irreversible (lossy). Although reversible techniques allow perfect reconstruction of the original image after compression, they achieve only 1.5:1 to 3:1 reduction for medical images.² However, irreversible techniques can provide higher compression ratios at the cost of irreversible data loss. Among the irreversible techniques, the Joint Photographic Experts Group (JPEG) method has been used most widely.³ Although the JPEG method maintains good image quality at low compression ratios, it degrades ungracefully at high compression ratios and producing prominent artifacts at block boundaries.⁴ Wavelet-based compression schemes generally outperform JPEG compression in terms of image quality at higher compression ratios.⁵⁻⁸ Most studies, however, were based on numerical analysis of pixel values before and after compression. Because there is little correlation between the numeric measures of pixel error and the degradation of diagnostic quality,⁴ it is valuable to conduct subjective evaluation on image quality, especially a receiver operating characteristic (ROC) analysis. By using subjective evaluation methods, clinically acceptable compression ratios using wavelet-based method has been evaluated for digitized radiographs; however, they have not been elucidated for most digital images except CT of the liver tumor

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and coronary artery calcification.⁹⁻¹³ Because it will be digital image, not digitized image, that will mainly be stored and transmitted in PACS, and because MR imaging has come to play a central part in neuroimaging studies, we conducted an ROC analysis on the detection of brain lesions at MRI to assess clinically acceptable compression ratios by wavelet-based method.

MATERIALS AND METHODS

Case Selection

A verification panel of 3 neuroradiologists who did not participate as readers selected eligible cases from an image database of Hokkaido University Hospital. Selection was based on difficulty of lesion detection owing to small size, location, or subtle lesion-to-brain contrast. The selected cases were those of 16 patients with brain lesions, 3 patients with distinct perivascular spaces, and 1 patient without perceivable lesions. From each case, 4 consecutive transverse T₂-weighted images and the corresponding T₁-weighted images were selected to be evaluated by readers. The panel determined whether each anatomic site in these images had lesions, based on a combination of clinical findings and all MRIs including FLAIR (fluid-attenuated inversion recovery) or proton-density-weighted images. In some of the cases the panel also referred to coronal MRIs, postcontrast T₁-weighted images, CT images, and previous or follow-up MR studies. A total of 109 anatomic sites finally were included in the study; 50 with brain lesions and 59 without lesion. The anatomic sites were defined as follows: frontal lobes, temporal lobes, parietal lobes, occipital lobes, basal ganglia including internal and external capsules, thalami, cerebellar hemispheres, midbrain, pons (including superior and middle cerebellar peduncles), and medulla oblongata.

The 50 anatomic sites involved the following pathologic conditions: infarction (n = 15), chronic hemorrhage or hemorrhagic infarction (n = 6), leukodystrophy (n = 8), encephalitis or chemotherapy-induced encephalopathy (n = 7), wallerian degeneration (n = 3), metastatic or disseminated tumors (n = 2), heterotopias (n = 2), postoperative encephalomalacia (n = 1), lesions related to liver dysfunction (n = 4), and nonspecific white matter lesions (n = 2).

Image Acquisition and Compression

All MR images were acquired on a 1.5-T MR system (Magnetom Vision; Siemens, Erlangen, Germany). T₁-weighted images were acquired with a conventional spin-echo sequence (TR/TE/Acquisition = 600 ms/14 ms/2) and T₂-weighted images with a fast spin-echo sequence (TR/effective TE/Acquisition = 4,000 to 5,000 ms/96-115 ms/2, echo train length = 5 or 7). The images had a matrix size of 192 to 200 × 512 with a 180- to 240- × 240-mm field of view (FOV), which resulted in a pixel size of 0.9 to 1.2 × 0.47 mm. The section thickness was 5 mm with a 1- to 2-mm intersection gap. These images were stored on magneto-optical disc archives as ACR-NEMA files that had 512- × 512- × 12-bit data with a 240- × 240-mm FOV. The image data were retrieved and converted to DICOM file format (512- × 512- × 16-bit data, 532 Kbytes) and

transferred to a workstation (SparcStation 5; Sun Microsystems, Palo Alto, CA).

Image compression was performed with a wavelet algorithm. Image quality is influenced by the wavelet filter and decomposition level.¹⁴ Therefore, we had evaluated performance of 16 wavelet filters (Adelson, Antonini, 2 subtypes of Brinslaw, 3 subtypes of Daubechies, Haar, Odegard, and 7 subtypes of Villasenor) on compression of CT and MR images of several anatomic locations by using a root mean squared error (RMSE) and a subjective measure. Among the 16 filters, the biorthogonal filter of Antonini et al.¹⁵ had constantly shown an excellent performance for all images tested, and was available widely. Thus, the filter of Antonini et al was adopted in this study. We also had evaluated the influence of decomposition levels on image quality for the filter of Antonini et al.¹⁵ It showed that decomposition at 4 levels is much better than decompression at 3 levels, whereas there was little visible difference between decomposition at 4 levels and that at 5 or higher levels. Thus, decomposition of 4 levels was adopted. Each image was compressed at a ratio of 20:1, 40:1, and 60:1. Consequently, 4 folders were created for each patient; 1 folder included 8 original images (4 consecutive T₂-weighted images and the corresponding 4 T₁-weighted images) and each of the other folders included corresponding compressed images at 1 of the ratios tested.

Image Review

Image folders were assigned to 4 queues consisting of 20 folders. Each queue contained 5 folders of original images and 15 folders of compressed images (5 folders at a ratio of 20:1, 5 folders at 40:1, and 5 folders at 60:1). A given patient appeared only once per queue. Individual images were displayed on the interactive diagnostic workstation (SparcStation 5) that was equipped with 2 high-resolution (1,280 × 1,024) color monitors.

Three radiologists interpreted the images independently. The readers had been dedicated to diagnostic radiology for 5 to 13 years (reader 1, 13 years; reader 2, 11 years; reader 3, 5 years). In the last 2 years, the percentage of interpreting neuroimaging studies in their daily work was more than 80% for reader 3, and less than 30% for the rest of the readers. To minimize learning bias, the name, age, and identification number were masked. The image review was conducted on an anatomic location-by-anatomic location basis at 4 separate sessions. The readers interpreted the images of 1 queue per session. The order of the queue was selected randomly for each reader. Any of the 2 consecutive sessions were separated 2 to 7 weeks. The 2 monitors were set side by side, and each monitor displayed 4 MR images. Readers could adjust image contrast (window and center) and rated the presence or absence of a lesion with a continuous 50-point scale for each anatomic site.

Data Analysis

ROC curves were fitted for each reader with use of maximum likelihood method as implemented in the ROCKIT program.¹⁶ ROCKIT is designed to fit binormal ROC curves to both continuously distributed and ordinal category (eg, "confidence-rating") diagnostic test results. For each reader, paired analysis was performed between the original images and the compressed images obtained with each of the ratios tested. The area under

Table 1. Image File Size

MR Scanner		PACS (DICOM File)	
Data Acquisition	Matrix Size for Display	Matrix Size for Storage	Image File Size
192 × 256 × 12 bit	256 × 256 × 12 bit	256 × 256 × 16 bit	139 Kbytes
192 × 512 × 12 bit	512 × 512 × 12 bit	512 × 512 × 16 bit	532 Kbytes

the ROC curves (A_z) was calculated, and the differences were compared with "the Area Test," which is a univariate z-score test of the difference between the areas under the 2 ROC curves. Statistical significance was defined as a P value less than .05 for the Area Test with a 1-tailed analysis.

Error Measurement

Quantitative data analysis was performed on MR images of a normal volunteer. Transverse T_1 -weighted and T_2 -weighted image at the level of lentiform nuclei were used to calculate a RMSE of compressed images by the wavelet algorithm. To compare the influence of the matrix size of the MR image on the compression error, the original images were obtained with 2 different matrix sizes; 192 × 256 for one study and 192 × 512 for the other with the same FOV (180 × 240 mm), resulting in a pixel size of 0.94 × 0.94 mm and 0.94 × 0.47 mm, respectively. T_1 -weighted images were acquired with a conventional spin-echo sequence (TR/TE = 600 ms/14 ms) and T_2 -weighted images with a fast spin-echo sequence (TR/effective TE = 4500 ms/96 ms, echo train length = 7). To keep the same signal-to-noise ratio (SNR), the sampling bandwidth was fixed for each sequence, and 4-fold image acquisition was used for 192 × 512 matrix-size data, one acquisition for 192 × 256 matrix-size data and 4 acquisitions for 192 × 512 matrix-size data. These image data were converted to DICOM file format (256- × 256- × 16-bit, or 512- × 512- × 16-bit data). The image file size is shown in Table 1.

The RMSE was calculated as follows:

$$\text{RMSE} = [(\sum_{x,y} |I_{x,y} - C_{x,y}|^2)/P]^{1/2}$$

where P is the number pixels in a given image, I denotes the original value of the pixel, and C denotes the value of the pixel after compression and decompression.

Error images were calculated by subtracting the compressed image from the original image.

RESULTS

The actual compression ratio by the wavelet method varied somewhat from the requested ratio, but the difference was within 5%.

The A_z values and the corresponding P values are given in the Table 2. No statistically significant difference was identified with compressed images at 20:1 for all readers. However, there was a statistically significant difference for all readers at a ratio of 60:1. At a compression ratio of 40:1, a significant difference was observed for 1 reader (reader 1).

Figure 1 shows the ROC curves. From these graphs, it can be seen that there was some difference in the performance among the 3 readers. The performance roughly paralleled the percentage of neuroimaging studies in the reader's daily work.

The images in Fig 2 and 3 show the subjective effects of the wavelet compression. On both T_1 -weighted and T_2 -weighted images, blurring was seen with compressed image at a ratio of 20:1, and it became more prominent with the increase of the compression ratio. In Fig 2, blurring of a small lesion on T_2 -weighted images also was discernible with increasing degree as the compression ratio became higher. The lesion was hardly discernible on any of the T_1 -weighted images including the original. The lesion was detected by the readers even at the highest compression ratio with varying degree of confidence. In Fig 3, constellating perivascular spaces on T_2 -weighted images tended to coalesce each other with the increase of the compression ratio, and the area mimicked a white matter lesion on the 60:1 compressed image. Two of the readers misinterpreted the area as abnormal on 40:1 and 60:1 compressed images.

The effects of the wavelet compression on different matrix sizes are shown in Fig 4. There was no difference in SNR that was calculated for the frontal white matter between the 256- × 256-

Table 2. Detection of Focal Brain Lesions at MRI With Wavelet Compression

Reader	Original A_z	Compressed Images					
		20:1		40:1		60:1	
		A_z	P	A_z	P	A_z	P
1	0.846	0.79	.084	0.749	.023*	0.714	.002*
2	0.855	0.819	.146	0.829	.188	0.695	.001*
3	0.978	0.965	.266	0.961	.189	0.912	.012*

* Statistically significant difference.

Fig 1. ROC curves for readers (a) 1, (b) 2, and (c) 3. For all readers, diagnostic performance with images compressed at 60:1 was significantly worse than performance with original image. For reader 1, the diagnostic performance at 40:1 also was significantly worse (a). Original image, ●; compressed image, ■ (20:1); ▲ (40:1); ×, (60:1).

matrix and 512×512 -matrix DICOM file images (the SNR was around 37 for the T_1 -weighted images, and 23 for the T_2 -weighted images). For the 256×256 -matrix size DICOM file images, the structures were already identifiable in the error images at 5:1 compression on both T_1 -weighted and T_2 -weighted images. Blurring could be detected at a compression ratio of 5:1 on T_1 -weighted image and at 10:1 on T_2 -weighted image. The T_1 -weighted image became objectionable at 15:1, and the T_2 -weighted image became objectionable at 20:1. For the 512×512 -matrix size DICOM file images, the error and image degradation was less severe than the corresponding 256×256 -matrix size images at the same compression ratio. The subjective image degradation and the error image at 20:1, 40:1, and 60:1 compression for 512×512 -matrix size images were comparable roughly with those at 10:1, 15:1, and 20:1, respectively for 256×256 -matrix size images.

The RMSE are depicted graphically in Fig 5. The images used for the calculation were the ones used in Fig 4. The RMSE increased with increasing degree of compression. Both the RMSE itself and the degree of increase was higher in 256×256 -matrix size images than in 512×512 -matrix size images and higher in T_2 -weighted images than in T_1 -weighted images. For both T_1 -weighted and T_2 -weighted images, the RMSE at 20:1, 40:1, and 60:1 compression for 512×512 -matrix size images was almost equal to that at 10:1, 15:1, and 20:1, respectively for 256×256 -matrix size images.

DISCUSSION

In this study, there was no statistically significant difference in the detection of brain lesions at MR images compressed at a ratio of 20:1 as long as both T_1 -weighted and T_2 -weighted images were used for interpretation. A significant difference was observed at a ratio of 40:1 for one reader, and at 60:1 for all readers. Because this study included a variety of pathologic processes encompassing hypo-, iso-, and hyperintense lesions, wavelet compression at a ratio of 20:1 can be used for MR images for a wide variety of brain lesions when a pixel size at data acquisition is around 1.0×0.5 mm.

Subjective image degradation already was perceived as image blurring at a compression ratio of 20:1. However, the blurring did not affect the

Fig 2. T₂-weighted image (a) and T₁-weighted image (b) with a small infarction in the medulla oblongata and region of interest. (c-f) Magnified region of interest. T₂-weighted fast spin-echo images are presented in the upper row, T₁-weighted images in the lower row. (c) Original; (d) compressed 20:1; (e) compressed 40:1; (f) compressed 60:1. A small lesion (arrow) is seen on the original T₂-weighted image (c). Blurring of the image is already seen on 20:1 compressed image. The lesion can be detected on the compressed T₂-weighted images, but it becomes more blurred as the compression ratio becomes higher. On T₁-weighted images, the lesion is hard to detect even on the original image because of the subtle lesion-to-brain contrast.

lesion detectability at this compression ratio. Several investigators have noted that subjective losses in image quality begin to occur before diagnostic quality is lost,¹⁷⁻¹⁹ which implies that human visual perception may be flexible to a certain range

of image degradation. This necessitates ROC studies in the evaluation of diagnostic quality of compressed images rather than a simple comparison of image details between the original and compressed images. With the wavelet algorithm, blurring oc-

Fig 3. T_2 -weighted image (a) and T_1 -weighted image (b) with perivascular spaces in the cerebral white matter and region of interest. (c-f) Magnified region of interest. T_2 -weighted fast spin-echo images are presented in the upper row, T_1 -weighted images in the lower row. (c) Original; (d) compressed 20:1; (e) compressed 40:1; (f) compressed 60:1. Five small high-intensity areas constellate in the white matter representing perivascular spaces (arrow) are seen on the original T_2 -weighted image (c). These high-intensity areas become more blurred and tend to coalesce with the increase of the compression ratio. The area mimics a white matter lesion on the 60:1 compressed T_2 -weighted image (f). On T_1 -weighted images, the perivascular spaces can be seen as slightly low intensity areas on the original image (c) and they become more blurred with the increase of the compression ratio.

Fig 4. Region of interest from brain MR images compressed with wavelet method at 5:1, 10:1, 15:1, 20:1, 30:1, 40:1, and 60:1 with their error images directly below. T_1 -weighted (A) and T_2 -weighted images (B) displayed with a matrix size of 256×256 , and T_1 -weighted (C) and T_2 -weighted images (D) displayed with a matrix size of 512×512 . For the 256×256 -matrix size images, the structures are already identifiable in the error images at 5:1 compression on both T_1 -weighted and T_2 -weighted images (A, B). Blurring is discernible at a compression ratio of 5:1 on T_1 -weighted image (A), and at 10:1 on T_2 -weighted image (B). The image quality becomes objectionable at 15:1 for T_1 -weighted image (A), and at 20:1 for T_2 -weighted image (B). For the 512×512 -matrix size images, the image degradation is less severe than 256×256 -matrix size images at the same compression ratio. Note that the image degradation at 20:1, 40:1, and 60:1 for 512×512 -matrix size images is comparable with that at 10:1, 15:1, and 20:1 for 256×256 -matrix size images, respectively.

4A**Fig 4**

4B**Fig 4 (Cont'd).**

4C**Fig 4 (Cont'd).**

Fig 4. (Cont'd).

Fig 5. Root mean squared error (RMSE) of wavelet-compressed MR images of the brain with 256×256 and 512×512 matrix (DICOM file). The original images used for the calculation are the ones used in Fig 4. The RMSE increases with increasing degree of compression. Note that RMSE is higher in images with 256×256 matrix than with 512×512 matrix, and higher in T_2 -weighted images than in T_1 -weighted images. The RMSE of 20:1, 40:1, and 60:1 compressed images with 512×512 matrix is almost equal to that of 10:1, 15:1, and 20:1 compressed images with 256×256 matrix, respectively. T_2 -weighted image with 256×256 matrix, ●; T_1 -weighted image with 256×256 matrix, ■; T_2 -weighted image with 512×512 matrix, ▲; T_1 -weighted image with 512×512 matrix, ×.

curs at moderate to high levels of compression. Unlike the JPEG algorithm, blocking artifact does not occur on wavelet-compressed images.²⁰ Mild blurring does not affect diagnostic accuracy; however, moderate to severe blurring may affect the diagnostic accuracy. In this study, 40:1 or higher compression affected the normal structures such as perivascular space. When the perivascular spaces constellate, the blurring will make these spaces coalescent to mimic a white matter lesion. So it is mandatory to include constellating perivascular spaces as small normal structures in the evaluation of diagnostic accuracy for compression of brain MR images.

The clinically acceptable compression ratios, or compression tolerance, varies according to the content and the type of the image.^{4,20} It differs between modalities or even between images of a single modality. It has been reported that using wavelet compression, digitized chest radiographs are tolerant to high compression ratios (at least 40:1, or even 80:1^{10,21}), and digitized bone radiographs are moderately tolerant (between 20:1 and 40:1^{4,9}). Because of the difficulty and cost of rigorous design and evaluation, reports on the wavelet compression of CT and MR images using

ROC studies are sparse. It has been reported, however, that CT and MR images are much harder to compress than digitized radiographs.^{4,12,20} Chan et al²¹ stated that the factors related to the compression difficulty of CT and MR images are smaller size, lower SNR, and, in the case of CT, a larger dynamic range in contrast to digitized radiographs. Persons et al²⁰ reported that the relative amount of energy present in low-frequency subbands could be a good predictor of compression tolerance based on their finding that digitized chest radiographs averaged 99.69% of their energy in the lowest frequency subband versus 92.12% for direct-digital CT and 78.03% for direct-digital MR images. Considering these previous reports, the factors that will affect the compression tolerance in MR images are the SNR, the type of the contrast of image such as T_1 -weighting or T_2 -weighting, the pixel size, and the organ aimed to be evaluated. When applying our results to clinical practice, these factors should be comparable. One should also be aware that our results do not apply to digitized MR images because the percentage of energy in each frequency subband should be different between direct-digital and digitized image data.

The wavelet filter influences the quality of the compressed image.¹⁴ To find the best wavelet filter for gray-scale medical images or, more specifically, for MR images, is a big issue. Wavelet filters available to date are so numerous that evaluation of all wavelet filters is beyond the scope of this report. In the report by Abu-Rezq et al,¹⁴ the numerical analysis showed that the best wavelet filter (Coiflet 5) outperformed the worst wavelet filter (Haar wavelets) significantly in wavelet-packet-based compression of MR images. In their report, however, they stated also that there was almost no visible difference between the 2 images compressed with the 2 different filters on subjective evaluation. We could not compare the Antonini filter with Coiflet 5. However, the Antonini filter outperformed Haar wavelets in our evaluation and is considered an excellent filter for MR and CT images even if it might not outperform Coiflet 5. We believe that the influence on the image degradation is almost the same between these 2 filters (Antonini and Coiflet 5) on subjective evaluation, and the difference, if any, would be negligible.

In the current study, we also evaluated the influence of pixel size on the quality of image com-

pression. At any given compression ratio, the degradation of the images of 0.94×0.94 -mm pixel size (256×256 -matrix size on DICOM file) was severer than that of the images of 0.94×0.47 -mm pixel size (512×512 -matrix size on DICOM file) both subjectively and objectively. Particularly, the degradation became much severer for the larger pixel size images as the compression ratio became higher. The RMSE, subjective quality, and error images of 10:1, 15:1, and 20:1 compressed images with 256×256 -matrix size were comparable with those of 20:1, 40:1, and 60:1 compressed images with 512×512 -matrix size, respectively. Any numeric measure to date has not proved correlation with observer performance nor a consistent threshold value that predicts the point at which image degradation becomes either perceivable or aesthetically unacceptable.⁴ However, there is a general correlation between a numeric measure and image degradation when a given compression technique is used for a given image. Therefore, when a clinically acceptable compression ratio is determined for a given image, the RMSE value at the acceptable compression ratio can be used as an indicator of another acceptable compression ratio for the image with different pixel size if the imaging plane, image contrast, SNR, and a compression technique are identical. Although we did not perform an ROC study for the 256×256 -matrix size images, the clinically acceptable compression ratio with the wavelet method should be 10:1 for the 256×256 -matrix size images, because the RMSE of 10:1 compressed 256×256 -matrix size images were almost equal to those of 20:1 compressed 512×512 -matrix size images.

In this study, we evaluated the lesion detectability on the compressed images using both T_1 -weighted and T_2 -weighted images to represent daily routine work because usually both types of images are obtained to characterize the lesion in the brain MR examinations. Compared with T_2 -weighted images, T_1 -weighted images showed image degradation at lower compression ratios subjectively, whereas the RMSE was lower in T_1 -weighted images than in T_2 -weighted images at any compression ratio. This confirms that an RMSE cannot predict compression tolerance for MR images with different contrast weighting. One of the most distinguishing features of MR imaging, when compared with other x-ray-based modalities

including CT, is the extraordinarily large innate contrast that can be on the order of several hundred percent for 2 soft tissues.²² In general, adequately planned brain MR examination obtains distinct contrast between lesions and normal structures on at least either of T_1 -weighted, T_2 -weighted, proton density-weighted, or FLAIR images. T_1 -weighted images also can be obtained with intravenous injection of contrast material such as gadolinium (Gd)-DTPA to make lesions hyperintense and more conspicuous. In other words, lesions that show subtle contrast on all imaging sequences are encountered only rarely. We selected difficult cases considering the level of difficulty in lesion detection in daily interpretation of brain MR images; however, there were few lesions that showed subtle contrast on both T_1 -weighted and T_2 -weighted images. Most of the lesions showed subtle contrast on T_1 -weighted images, but they showed moderate to large contrast on T_2 -weighted images. Nevertheless, we thought that it was appropriate to include these relatively difficult lesions in this study considering the rarity of the subtle contrast lesions on all imaging sequences. Furthermore, subtle abnormalities, that may be difficult for the human eye to discern because of low contrast, may remain visible at high levels of compression if they have a substantial spatial extent, because they are characterized by low frequencies in the spectral domain, which are well preserved by wavelet compression as well as the JPEG quantization table.²⁰

Wavelet compression can be acceptable clinically at ratios as high as 20:1 for brain MR images with a pixel size around 1.0×0.5 mm at data acquisition, such as 256×512 matrix with 240 mm FOV, as long as both T_1 -weighted and T_2 -weighted images were used for interpretation, and the images have sufficient SNR. For brain images with a pixel size around 1.0×1.0 mm (such as 256×256 matrix size with 240 mm FOV), compression ratios as high as 10:1 may be acceptable. The result encourages us to use wavelet technology for transfer MR images in direct digital form to reduce the time and cost of image transmission and the requirements for image storage.

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