Computed Tomography Diagnosis Utilizing Compressed Image Data: An ROC Analysis Using Acute Appendicitis as a Model

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Using receiver-operating characteristic (ROC) methodology, the ability to diagnose acute appendicitis with computed tomography (CT) images displayed at varying levels of lossy compression was evaluated. Nine sequential images over the ileocecal region were obtained from 53 consecutive patients with right lower quadrant pain who were clinically suspected to have acute appendicitis. Thirty were proven surgically to have acute appendicitis, alternative diagnoses confirmed in 23. The image sets were subjected to a lossy wavelet-based compression algorithm "Embedded Predictive Wavelet Image Coder" (EPWIC). Compression levels were: none, 8:1, 16:1, and 24:1, resulting in 4 sets of images per patient. Image sets were randomized and evaluated separately by 4 body radiologists on a 1,024 × 768-pixel SVGA color PC monitor in 512 × 512 format. The readers were aware of the clinical suspicion of appendicitis but were unaware of the positive fraction of cases. Individual and combined reader ROC and χ^2 analyses of sensitivity, specificity, and accuracy were determined. For all readers, sensitivity decreases at 16:1 and 24:1 levels ($P < 0.01$, $P < 0.001$, respectively). Accuracy decreased at 24:1 levels ($P < 0.01$). Specificity was unaffected. By ROC analysis there was statistically significantly decreased area under the curve at 24:1 levels ($P < 0.02$) as compared with uncompressed images. Finite levels of lossy wavelet compression may be applied to CT images without compromising diagnostic performance.

KEY WORDS: Image compression, computed tomography, image processing, appendix CT

IMAGE COMPRESSION TECHNIQUES find their use primarily in facilitating radiologic image transmission across teleradiology and picture archive communication systems (PACS). To date, the majority of clinically accepted applications of image compression has been with reversible (lossless) techniques. These techniques provide compression of up to 3:1. These modest compression levels provide image data that can be restored to identically match its

original form for diagnostic purposes. The rapidly increasing use of multislice computed tomography (CT) and increasingly complex magnetic resonance (MR) protocols generate larger and larger data sets, placing increased stress on network bandwidth and new challenges to efficient workflow. Compression algorithms that preserve diagnostic information at higher levels could alleviate this data stress, potentially improving radiologists' efficiency as well. To achieve sufficient compression levels, irreversible (lossy) algorithms are necessary. Recently developed lossy compression, based on wavelet transform, has emerged as a particularly powerful technique for medical image compression. By using a pair of high and low pass filter functions, contrast and texture characteristics of the original image may be preserved at compression levels much larger than 3:1.

Several published studies have examined the feasibility of applying lossy wavelet compression algorithms to medical imaging data acquired from a variety of techniques.^{9,10,22} This study was undertaken to evaluate the effect of varying compression levels on the ability of radiologists to make a CT diagnosis of acute appendicitis, the presence of which is detected

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by the perception of subtle differences in contrast. Appendicitis is common, the CT accuracy is well known from multiple published studies,^{6,14} and rapid surgical verification is possible.

METHODS

CT studies collected prospectively from 58 consecutive patients with clinically suspected acute appendicitis seen at our hospital between February 1, 2000 through August 31, 2000 were included. From this group, 32 had acute appendicitis at surgery, and 26 had alternative causes for the clinical presentation. All scans were performed on a single-slice helical CT scanner (CT/I Performix or HiSpeed RP, GE Medical Systems, Milwaukee, WI). Patients consumed a total of 700 to 900 mL of oral positive contrast over a 60- to 90-minute time interval before the scanning procedure. A single preintravenous (IV) contrast-enhanced image over the upper margin of the sacroiliac joint (SI joint) was obtained to insure sufficient oral contrast opacification of the distal ileum and the proximal colon. If bowel opacification was judged to be satisfactory, the diagnostic study was performed with IV contrast enhancement. All studies were performed in association with 150 mL of IV iodinated contrast, delivered via power injector at rates between 2 and 3 mL/sec. Scanning began immediately after completion of the infusion (50- to 75-second delay). Images were obtained with 7-mm sections, reconstructed every 6 mm (1 mm overlap) from the diaphragm through the upper margin of the SI joint, and 5 mm sections, reconstructed every 4 mm (1-mm overlap) from this point through the symphysis. The pitch was set at 1.5:1. Five patients were excluded from the study because they did not satisfy protocol requirements (2 unenhanced studies, 2 incomplete coverage of the abnormal appendix, and 1 not acquired with 5-mm sections). The radiologic research data sets presented to the readers consisted of 30 positive cases (acute appendicitis determined at surgery) and 23 negative cases (alternative causes for the clinical presentation). If the patients were not operated on, clinical follow-up was used as proof of an alternative diagnosis.

Nine sequential images from the portion of the clinical examination over the right lower quadrant (including the appendix) and scanned with 5 mm collimation were chosen by the senior author. These 9 images (referred to as study sets) were presented to the readers for interpretation. Neither the precontrast image, nor images acquired at 7 mm were included in the study set. The range of anatomy displayed on each study set was similar extending from the top of SI joint through portion of upper pelvis.

Each of the 53 study sets (comprising 9 images each) was subjected to a lossy wavelet compression algorithm "Embedded Predictive Wavelet Image Coder" (EPWIC) for which the source code is available.⁸ The EPWIC algorithm exploits the highly non-Gaussian nature of wavelet coefficients that has been observed in natural and medical images.¹⁹ The intuitive characterization of this distribution of wavelet coefficients reflects the presence of large smooth areas interspersed with occasional abrupt edges. We have modified EPWIC by adding DICOM file input and output

capability and by extending the file format to the 12 bits/pixel used in CT images. Compression levels applied to the study sets were none, 8:1, 16:1, 24:1. The levels of reduction are not exact; however, the discrepancy was less than 1%. Therefore, each radiologist evaluated 4 sets (the compression levels), 9 images per patient for a total of 1,908 ($53 \times 9 \times 4$) images seen per radiologist.

The 53 study sets were randomized and evaluated independently by 4 body radiologists whose experience ranged between 1 and 7 years posttraining. The images were viewed at a full 512×512 resolution using DICOM viewing software (CT Image Viewer, version 5.8.1, copyright Richard Beier) on a $1,024 \times 768$ -pixel SVGA display color monitor and 8-mb video controller. No interpolation algorithm was utilized. Window and level were fixed at 450 HU and 20 HU. No other demographic or technical data were available to the reader from the images being evaluated. The study sets were reviewed in the same order by each of the 4 radiologists. The data sets were NOT presented at sequentially increasing compression levels for any case. Cases were repeated at random over the entire mix for the group. To minimize bias, the uncompressed set was never displayed first for any given case. Readers looked at the entire study set of cases at one or 2 sessions with minimal separation of time. The actual time spent reading the studies was not recorded. The randomization was constrained so that the uncompressed images were never presented before any of the other 3 compression levels. Readers scored cases on a 0 to 4 confidence scale, where 0 = absolutely no appendicitis, 1 = probably no appendicitis, 2 = indeterminate, 3 = probably appendicitis, and 4 = absolutely appendicitis.

The readers were aware of the clinical history (right lower quadrant pain, rule out appendicitis) and that all of the image data were derived from patients being evaluated for that diagnosis. Readers were unaware of the percentages of negative and positive cases mixed in the 53 cases being evaluated. None of the readings from this study were used for clinical purposes, and all cases were accessed after either surgical or clinical confirmation of the diagnosis.

Individual, as well as combined readers' areas under ROC curves, were computed using ROCFIT (Metz, CE and colleagues; <http://www.radiology.uchicago.edu/krl/toppage11.htm>) software. Combined ROC curves represent the average for each false-positive fraction ($FPF = 1 - \text{specificity}$) of the fitted true-positive fraction ($TPF = \text{sensitivity}$) of each of the 4 readers. Partial areas under the ROC ($T_{0.03-0.07}$) curves in the range of 0.03 to 0.07 of specificity were calculated. This allowed a more precise analysis in the clinically relevant portion of the ROC curve. A 1-tailed χ^2 test was used to analyze sensitivity, specificity, and accuracy. The value of P less than .05 was taken as a threshold of statistical significance. No correction for multiple comparisons was applied. For purposes of the analysis, scores of 3 and 4 were interpreted as "True, positive for appendicitis," and scores 0, 1, or 2 were interpreted as "False, no evidence of appendicitis."

RESULTS

As an example, one slice level from a patient with proven acute appendicitis is presented

Fig 1. Focused views of the right lower quadrant of a patient with proven acute appendicitis. Frame (A) is uncompressed, frame (B) is compressed at 8:1, frame (C) at 16:1, frame (D) at 24:1. On all 4 levels of compression, one can recognize the presence of a retrocecal inflammatory process. On A and B, one can discern the minimally enhanced rim of the inflamed appendix (arrows). This is less apparent on C and indistinguishable on D.

uncompressed (Fig 1A) and at the 3 tested compression levels (Fig 1B-C). The combined reader ROC curves (Fig 2) showed relatively high performance at each level of compression. The areas (A_z) under the ROC curve (Fig 3A, Table 1) showed no statistically significant drop off at 8:1 when compared with baseline. There is a 1% decrease in areas A_z comparing 16:1 compression level against no compression; however, the difference does not achieve statistical significance. There is a further 1% decrease in the area under the curve at 24:1 compression level. This achieves significance level when compared against no compression ($P = 0.02$). Similarly, analysis of the partial areas under the ROC curve ($T_{0.03-0.07}$, Fig 3B, Table 3), shows the decrease in the reader's performance at increasing levels of compression. Within this range of specificity the degradation in performance achieves statistical significance at both 16:1 as well as 24:1 compression levels.

ROC at different compression ratios

Fig 2. Combined ROC curves at each level of compression. The curves were obtained by averaging the corresponding ROC curves of the 4 readers. The combined reader performances decrease with increasing compression levels.

The ROC results parallel the results of conventional sensitivity and specificity findings as reported in Table 3. Using a 3 to 4 rating as a positive interpretation, the overall accuracy of diagnosis of appendicitis based on the uncompressed CT images was 95.3% (96.7% sensitivity, 93.5% specificity). Analysis of these combined data for the 4 readers showed a statistically significant decrease in sensitivity at 16:1 ($P < .01$) and 24:1 ($P < .001$) levels of compression as compared with no compression. There were no statistically significant differences in specificity at either of the 3 levels of compression compared with uncompressed data. In terms of overall accuracy, each reader had a slight decrease in performance at increasing compression levels; however, the differences were not statistically different from uncompressed data. The combined accuracy at 24:1 was significantly decreased ($P < .01$).

DISCUSSION

The accelerating use and reliance on teleradiology-based imaging networks has driven the evaluation of image compression.^{15,26} Wavelet transformation techniques have been recognized as particularly powerful for compressing

Fig 3. (A). The distribution of areas under the ROC curves A_z . The bars indicate mean values and standard deviations. The decrease in performance at 24:1 compression achieves significance ($P = .02$) as compared with uncompressed images. (B). The distribution $T_{0.03-0.07}$. The values $T_{0.03-0.07}$ represent the true-positive fraction estimated from the ROC curves at false-positive fraction in the 0.03 to 0.07 range. The bars indicate mean values and standard deviations. Decrease in performance achieves statistical significance at 16:1 ($P = .008$) and 24:1 ($P = .047$) as compared with uncompressed images. Notice a large standard deviation at 24:1 compression level.

medical images.^{21,23} The power of this method is exemplified by the fact that the emerging Joint Photographic Experts Group (JPEG) 2000, the standard compression algorithm for medical images, is based on wavelet compression techniques.

Published studies have shown that plain chest images suffer virtually no degradation at compression rates in the 5–10:1 range.²⁵ The changes induced by this magnitude of wavelet compression tend to eliminate only very high frequency noise and otherwise are visually imperceptible. As the compression ratio is in-

Table 1. Values of the Areas Under ROC Curves (A_z) Shown in Figure 2 at Each Level of Compression

Compression Level	1:1	8:1	16:1	24:1
Mean	0.985	0.979	0.973	0.965
SD	0.008	0.010	0.004	0.007
$p(T \leq t)$		0.132	0.070	0.020

creased, the observer begins to appreciate changes in the form of increased blurring and the appearance of artifacts.

The effects of lossy image compression have been studied in a wide range of radiologic imaging techniques. Goldberg et al¹² found that diagnostic ability is not impaired in evaluating a variety of plain radiographs subjected to wavelet-based compression algorithms at levels below 30:1, although skeletal radiographs seemed more sensitive to compression than chest or abdominal radiographs. Several investigators have found that diagnostic information may be preserved on digitized chest radiographs at levels as high as 20 to 25:1 allowing diagnosis of interstitial fibrosis, pneumothorax, and detection of lung nodules.^{1,5,18} Others have evaluated image compression in digital mammography^{13,20} and coronary angiography.^{3,17}

To date, an optimal compression rate has neither been established nor are the criteria that might be used to determine such optimum defined. Several studies have suggested that levels between 10:1 and 20:1 are the lower and upper bounds of “compression tolerance” for CT and MR images.²⁵ The results of our study are concordant with speculation that these compression levels may not affect diagnostic performance negatively.

There are few studies that evaluate the effect of image compression on diagnostic ability in body CT. Cosman et al⁹ found that compression levels of 9:1 did not impair diagnosis of mediastinal adenopathy or pulmonary nodules on CT images. Goldberg et al¹¹ looked at the

Table 2. Performance of Observers Measured at High Specificity (0.03 to 0.07) expressed as Partial Areas Under ROC Curves in Figure 2

Compression Level	1:1	8:1	16:1	24:1
Mean	0.935	0.917	0.904	0.868
SD	0.029	0.037	0.019	0.054
$p(T \leq t)$		0.056	0.008	0.047

Table 3. Sensitivity, Specificity, and Accuracy of Diagnosis of Appendicitis for Each Reader and Each Compression Level

	Sensitivity(%)	Specificity(%)	Accuracy(%)
Reader 1			
No compression	93.3	95.7	94.3
8:1 compression	90.0	95.7	92.5
16:1 compression	86.7	95.7	90.6
24:1 compression	86.7	95.7	90.6
Reader 2			
No compression	100.0	95.7	98.1
8:1 compression	100.0	95.7	98.1
16:1 compression	83.3	100.0	90.6
24:1 compression	76.7	100.0	86.8
Reader 3			
No compression	100.0	91.3	96.2
8:1 compression	100.0	87.0	94.3
16:1 compression	96.7	91.3	94.3
24:1 compression	90.0	91.3	90.6
Reader 4			
No compression	93.3	91.3	92.5
8:1 compression	90.0	95.7	92.5
16:1 compression	83.3	95.7	88.7
24:1 compression	80.0	91.3	84.9
All readers			
No compression	96.7	93.5	95.3
8:1 compression	95.0	93.5	94.3
16:1 compression	87.5*	95.7	91.0
24:1 compression	83.3 [†]	94.6	88.2*

[†]Statistically significant difference ($P < .001$) as compared with no compression.

*Statistically significant difference ($P < .01$) as compared with no compression.

effect of varying compression levels on the ability to detect hepatic space occupying lesions. This study failed to show statistically significant differences between 10:1,15:1, and 20:1 data sets, but offered a conservative conclusion that 10:1 levels of compression may be satisfactory. Zheng et al²⁸ found no loss in the ability to detect coronary artery calcification by CT at compression levels of 20:1. Kalyanpur et al¹⁶ evaluated varying wavelet-based compression algorithms and found image quality could be preserved sufficiently at 10:1 lossy compression to preserve diagnostic ability for diagnosing renal calculi in electronically transmitted images. Lossy compression levels of 20:1 did not affect the ability to recognize polyps from virtual colonographic images.²⁷

The CT diagnosis of appendicitis requires the detection of both high-contrast features (the enhanced appendix, the contrast filled bowel) and low contrast features (minimal changes in the periappendiceal fat, Fig 1). Although the trained radiologist seamlessly integrates these features, preservation of contrast, detail, and texture are required to render an accurate diag-

nosis.¹⁴ Therefore, we felt this disease entity to be a unique test of the application of image compression. Figure 1 shows the decreasing ability to resolve the appendiceal wall at 16:1 and especially 24:1 levels of compression. At these higher levels of compression, the reader should be able to identify the presence of pericecal inflammation; however, the specific diagnosis of appendicitis rests on visual data, which are less apparent at these higher compression levels.

We did not feel that the small sample size of 30 positive and 23 true-negative cases would provide sufficient statistical power to stratify the results by disease severity. Therefore, we could not look at the effects of compression across the spectrum of radiologic presentation. The overall accuracy among the readers in this study is comparable with that reported in the literature using similar scanning techniques and in a similar case mix.^{4,6,7} The use of ROC analysis method allowed us to look at the combined reader performance and to correct for reader thresholds that may vary individually. Furthermore, the readers were presented with a volume of data in which the abnormality could

be “buried” in any one of the 9 images presented. This simulates the clinical setting in which images are evaluated and diagnoses are rendered. This allows for a more clinically relevant evaluation of image compression on the diagnostic process compared with methods used in other studies in which single images at the same anatomic location were compared. Bias is introduced in that the readers were aware that all patients were suspected of acute appendicitis; however, in clinical practice, this pretest diagnosis usually is available to the interpreting physician. We used ‘2’, as a score to indicate “indeterminate.” There were 71 responses at level ‘2’, as opposed to 336 at ‘4’ or 212 at ‘0’. The readers, therefore, were relatively sure of their diagnoses. We defined a positive interpretation to include ‘3’ and ‘4’. True-positive rate was established at surgery.

We chose to refine our analysis by focusing between 0.03 and 0.07 as a clinically relevant area. This range approximates the false-positive fraction (FPF, i.e., 93% to 97% specificity), which characterizes the CT diagnosis of appendicitis as reported in the literature.^{4,6,7,14} The findings do not change radically within other ranges. However, because CT performs at this level, we thought that all levels of compression should be able to perform similarly (null hypothesis).

Our results are concordant with an emerging volume of data that diagnostic performance on cross-sectional imaging is unimpaired at compression levels less than 10:1. We found virtually no performance differences for the combined reader scores between no compression and compression at levels of 8:1, with a drop off in performance at 16:1 and 24:1. These levels might begin to define an optimal range for routine application of image compression. Published studies have shown that lossy compression does not effect evaluation of renal calculi¹⁶ or hepatic metastases;¹¹ we speculate that other common forms of abdominal pathology could be evaluated using lossy compression, including assessment of lymphadenopathy and CT angiography. Although all of the readers in the study were “body imagers,” their levels of training were 1 year, 3 years, 5 years, and 7 years after residency, respectively. Sensitivity was reduced by approximately 10% at 16:1 and by further 3% (total 13%) at 24:1 levels. Of note

is the preservation of specificity among all readers independent of compression levels.

Our data do not support the hypothesis that 8:1 compression improves the accuracy at the doses and collimation utilized in this study. We see a trend of reduced sensitivity for 8:1 versus 1:1 (Fig 3, Table 2), with the difference not being statistically significant probably because of insufficient number of cases. Regardless of whether the difference in diagnostic accuracy is real, the magnitude is small (1% to 2%), and therefore using 8:1 as a baseline is unlikely to yield drastically different conclusions.

We made no attempt to evaluate different wavelet compression algorithms. The EPWIC algorithm used here is a proven method in image compression and has characteristics that make it relevant to diagnostic imaging.^{8,24}

Although the readings were performed on a PC monitor, its light output is less than a PACS monitor; therefore, some bias against image quality may be introduced. We did not have the ability to reproduce the study on a PACS quality monitor. Because readers were interpreting these images in a dark room with no ambient light, we felt it unlikely that a brighter monitor could selectively improve diagnosis at high compression rates.

Finally, all readers admitted to a degree of “case memory.” If a reader diagnosed appendicitis on the uncompressed image, he or she could retain that mental image favorably influencing the reading of the less detailed (compressed) images. Possible strategies to reduce the bias resulting from case memory would be to increase the number of cases within the study; however, in its current form, each of the 4 readers evaluated 1,908 images. Alternatively, a longer delay between readings might have decreased this potential bias. However, the logistics of asking 4 individual radiologists to separately read the studies over 4-month period was not feasible. The approach used to overcome this bias was to present the study sets in such a way that *no* reader was ever presented the images from an uncompressed study set before seeing any of the 3 compressed study sets. The consistent decrease in performance over the 4 compression levels supports the validity of this approach.

The ultimate use of lossy compression in imaging networks remains to be determined.

One potential use of lossy compression may be in the postreading archival of diagnostic examinations. In this scheme, lossy compressed images are stored remotely on a network. This would lead to shorter recovery times to fetch the "old films" for comparison purposes. Bae and Whiting² describe a method by which a lossy compression algorithm might be applied to projection (raw) data generated from CT studies. Storage of raw data frees the radiologist to apply new filters, rendering techniques and reconstruction algorithms at any time. The resultant image data would be presented at an effective compression level of 12:1. The authors showed that the resultant images preserved contrast and spatial detail.² Even though there is decreasing storage cost and rapidly increasing bandwidth capacity, efficiencies gained in 3-dimensional data transfer and teleradiology are compelling enough to continue investigating wavelet transform compression techniques.

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