American College of Cardiology/
European Society of Cardiology International
Study of Angiographic Data Compression Phase I

The Effects of Lossy Data Compression on Recognition of Diagnostic Features in Digital Coronary Angiography

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OBJECTIVES   This study intended to determine the effect of varying degrees of lossy Joint Photographic Experts Group (JPEG) compression on detection of coronary angiographic features.

BACKGROUND   Compression of digital coronary angiograms facilitates playback of images and decreases cost. There are little data on the effect of compression on the accuracy of coronary angiography.

METHODS   At six centers, 71 angiographers each reviewed a set of 100 angiographic sequences. The 100 sequences were divided into four, 25-sequence subsets. Each subset of 25 was displayed either as original images or at one of three compression ratios (CRs) (6:1, 10:1 or 16:1). The effect of lossy compression on the sensitivity and specificity for detection of diagnostic features was determined. The effect of compression on subjective measures of image quality graded by the angiographers was also examined.

RESULTS   Lossy compression at a ratio of 16:1 decreased the sensitivity for the detection of diagnostic features (76% vs. 80% p = 0.004). The largest effect was in the detection of calcification (52% vs. 63% at 16:1 compression vs. original images, p < 0.001). Subjective indicators of image quality indicated a reduction in confidence in interpretation at CRs of 10:1 and 16:1.

CONCLUSIONS   With increased ratios of lossy compression, a degradation of digital coronary angiograms occurs that results in decreased diagnostic accuracy. The sensitivity for detection of common diagnostic features was decreased, and subjective assessment of image quality was impaired. Caution is warranted in the interpretation of coronary angiograms that have been subjected to lossy JPEG compression beyond a ratio of 6:1. (J Am Coll Cardiol 2000;35:1370–9) © 2000 by the American College of Cardiology

Digital angiography is routinely used to guide diagnostic and interventional catheterization procedures, but transmission and long-term archiving of digital cardiac angiograms remains limited because of the relatively large quantities of data that must be dealt with, often exceeding 500 megabytes (MB) for a single angiographic study (1–4). To facilitate the communication and storage functions and reduce the size of digital image files, data compression methods have been employed for medical and non-medical applications. These methods can be divided into two general categories: "lossless" and "lossy" compression (5,6). "Lossless" refers to the use of a compression method that is completely reversible,

resulting in a decompressed, completely restored image that is identical to the original image. "Lossy" compression of a digital data file occurs when a method is used that results in a decompressed image that is not totally identical to the original. Typically, a lossless compression scheme will yield a data reduction of approximately two-fold, whereas lossy compression can yield compression ratios (CRs) of 50:1 or greater.

An international standard for the interchange of digital cardiac angiographic images was released in 1995—the DICOM Standard (Digital Imaging for Communication in Medicine) (7,8). At the time, there were little data to demonstrate clinical equivalence between lossy and lossless compressed coronary angiographic images. Accordingly, the DICOM standards committee specified that only lossless compression methods were acceptable for data reduction in the interchange standard because of the possibility that lossy

Abbreviations and Acronyms

ACC	= American College of Cardiology
ANOVA	= analysis of variance
CASS	= Coronary Artery Surgery Study
CR	= compression ratio
DICOM	= Digital Imaging for Communication in Medicine
ESC	= European Society of Cardiology
fps	= frames per second
JPEG	= Joint Photographic Experts Group
MB	= megabytes

compression could adversely affect interpretation of coronary angiograms.

Concerns about the appropriateness of lossy compression led the American College of Cardiology (ACC) and the European Society of Cardiology (ESC) to initiate a multicenter trial to examine the effects of lossy data compression on coronary angiography. The lossy method studied by the ACC and the ESC is a standard method for image compression originally developed for still photography—the Joint Photographic Experts Group (JPEG) algorithm (5,6,9). The study was performed in three phases. Phase I examined the effects of varying degrees of lossy data compression on detection of common diagnostic features in digital coronary angiography. Phase II examined the effects of varying degrees of lossy data compression on quantitative angiography. Phase III consisted of a side-by-side comparison of compressed and original images. The results of Phase I of the international compression study are presented here.

METHODS

Study design. This compression trial was designed as a multicenter study in which compressed and uncompressed angiograms were displayed for experienced angiographers, who were asked to identify the presence or absence of a pre-designated list of diagnostic features. An angiographic review station containing the study images was transported to six centers (five in the U.S. and one in Europe), and the image evaluation sessions were conducted locally at each site (Appendix 1). At the six centers, a total of 71 experienced angiographer/observers each reviewed a set of 100 digital angiographic sequences (single coronary injection). Angiographic observers were blinded to any information about the

source of the images, and each participant was unaware of how the images had been processed.

A schematic of the study design is shown in Table 1. To avoid observer bias, the study was designed so that no observer viewed any angiographic sequence more than once. To accomplish this randomization, the 100 angiographic sequences were divided into four subsets, each containing 25 angiographic sequences. Each subset of 25 angiographic sequences was displayed either as original images or at one of the three CRs (6:1, 10:1, or 16:1). Each observer was assigned to one of four observer groups. Each observer, therefore, reviewed 100 sequences—25 as original images and 25 at each of three predetermined CRs. Each of the four observer groups reviewed an individual angiographic sequence as an original or at one of the CRs. For example, observer group I reviewed sequences 1 to 25 as original uncompressed images, sequences 26 to 50 at 6:1 compression, sequences 51 to 75 at 10:1 compression and sequences 76 to 100 at 16:1 compression. Similarly, each angiographic sequence was viewed by different observer groups at different CRs. For example, sequence 10 was reviewed by observer group 1 as an original image (uncompressed), group 2 at 6:1 compression, group 3 at 10:1 compression and group 4 at 16:1 compression. Thus, every sequence was reviewed at each of the CRs by one fourth of the observers. Conversely, each observer reviewed all of the sequences, but only as either an original image or at one of the CRs. The compressed and uncompressed images were displayed to each observer in one of two random orders within each observer group.

Image acquisition. The study used a set of 100 digital angiograms specifically collected to determine the suitability of lossy compression for diagnostic coronary angiography. Digital angiographic image sequences were acquired from high-volume cardiac catheterization laboratories, using contemporary equipment supplied by a variety of vendors (Appendix 2). The digital angiograms consisted of single coronary injections acquired at 30 frames per second (fps) in the U.S. and 25 fps in European laboratories at a matrix size of 512×512 pixels with 8-bit gray scale (256 levels). The lengths of sequences varied from approximately 100 to 300 images, corresponding to a duration of 3 to 12 s. The participating centers were requested to submit examples containing the common diagnostic features listed in Table 2. The laboratories were encouraged to perform diagnostic angiography using the radiographic techniques typically

Table 1. Study Design: Digital Sequence Subsets

Observers	1–25	26–50	51–75	76–100
Group 1 n = 18	None	Low (6:1)	Med (10:1)	High (16:1)
Group 2 n = 18	Low (6:1)	Med (10:1)	High (16:1)	None
Group 3 n = 18	Med (10:1)	High (16:1)	None	Low (6:1)
Group 4 n = 17	High (16:1)	None	Low (6:1)	Med (10:1)

Table 2. Diagnostic Feature Types Within the 100
Digital Angiograms

Complex Stenosis/Filling Defect	31
Calcification	36
Stent	17
Dissection	15
Bypass grafts	3
Right coronary injections	48
Left coronary injections	49

employed by the participating center. Specifically, factors such as X-ray dose, use of collimation, source-to-image distance, and choice of angiographic projection were left to the discretion of the operator and laboratory.

Image selection. The acquisition sites submitted a total of 520 image sequences for possible inclusion in the study. These were screened, and 259 sequences were selected that contained suitable examples of the diagnostic features pre-specified in the study design. These sequences were further reviewed by an expert panel of five experienced angiographers (authors C.P., T.B., D.H., J.H. and R.S.) to select the final set of 100 digital angiographic injection sequences used in this study. A panel of three experienced angiographers (R.S., T.B. and J.H.) reviewed the final set of 100 sequences to provide a final consensus on the correct interpretation for each sequence. The consensus panel interpreted the original images using the same review station subsequently used in the trial. The diagnostic features present in the final 100 angiograms are shown in Table 2.

Image processing. After selection of the final set of 100 digital sequences, the images were compressed using standard lossy compression software developed and distributed by the Independent JPEG Group (10). The design of the study specified target JPEG CRs of 6:1, 10:1 and 16:1 to encompass the range likely to be employed in angiographic applications. It should be noted that the JPEG algorithm does not allow a user to specify exact CRs. Instead, a software "quality" factor is selected, which results in variable data reduction that is dependent on image content (i.e., the relative amounts of high-frequency information and noise in the image). Therefore, in practice, the quality factor was adjusted until the average CR for a sequence was as close as possible to the desired value. After the size of the data file was reduced using the selected quality factor, the same software was used to decompress all the images in the sequence, expanding the files back to their original size and resolution. In this manner, for each original image sequence, three additional versions were produced. This process yielded four copies of each injection, an original, which had undergone no processing, and the other three at CRs of approximately 6:1, 10:1 and 16:1.

Workstation preparation. A pair of digital angiographic workstations (Camtronics Medical Systems, Ltd., Hartland,

Wisconsin) were used to display the images reviewed during the observer evaluation sessions. To ensure the highest possible image quality, each angiographic review station was equipped with a high-resolution 21-in. (diagonal measure) gray scale monitor (Siemens Medical Systems, Iselin, New Jersey). Images were digitally zoomed to a display resolution of 1024 × 1024 pixels using a bicubic interpolation algorithm. Each workstation provided the capability for display of images at up to 30 fps, and variable speed control in the forward and reverse directions was available to all observers. To eliminate any display variability, the setup of the review workstation was standardized and subsequently locked to prevent any user from adjusting display controls. This process standardized the major parameters of monitor performance, including brightness, contrast and edge enhancement filtration. Although digital images were enhanced using high-pass spatial filtration, the degree of enhancement was the same, and remained fixed, for each injection.

Angiographic review. As previously described, 71 observers at six centers were randomly assigned to one of four observer groups to review 100 angiographic sequences at varying CRs. The individual angiographic review sessions took from 2 to 5 h to complete. Each observer reviewed the sequences in one of eight fixed orders (two for each of the observer groups). Angiographic observers were asked to identify pre-specified diagnostic features present in each sequence and provide a visual estimate of stenosis severity at a designated Coronary Artery Surgery Study (CASS) location. For each injection sequence, the observers were requested to grade image quality as acceptable or unacceptable. In addition, each observer was asked to provide a confidence score based on his or her ability to confidently interpret the angiogram (0 = low confidence, low quality; 10 = high confidence, excellent quality). An example of the angiographic data form filled out by each observer is shown in Figure 1.

Diagnostic features. The diagnostic features evaluated in this study are listed in Table 2. A complex stenosis/filling defect was defined as a stenosis with irregular borders, haziness, inhomogeneous contrasts, overhanging edges, or intra-luminal filling defects. Observers indicated the presence of a feature by marking a check box corresponding to the diagnostic feature and arterial location (right coronary artery, circumflex, etc.)

Statistical analysis. Random effects logistic regression, as implemented in the Epidemiological Graphics Regression Estimation and Testing epidemiological statistics software package (Version 1.0, CyTel, Cambridge, Massachusetts), was used to estimate and compare sensitivities of, and specificities for, diagnostic features among compression levels while accounting for the additional non-binomial variability introduced by within-image clustering of diagnostic determinations. Interaction between the influence of feature type and compression on sensitivity and specificity

Patient # __1__
Image # __15__

Reviewer____X____

Artery / Graft (includes all branches)

Feature	Left Main Coronary	Left Anterior Descending	Left Circumflex	Right Coronary	Bypass Graft
Filling Defect (Possible Thrombus)					
Dissection					
Calcification		X			
Filled by collaterals					
* Complex Stenosis					
Stent			X		

* (Complex stenosis defined as multiple irregularities, overhanging edges, "haziness" or poorly seen edges).
Lesion Severity: For the location indicated below estimate the severity of the stenosis in % diameter narrowing.

Location	0-49%	50-99%	100%
Prox LAD		70	

Image quality acceptable Yes __X__ No _____

Confidence in interpretation based on image quality
Not confident   Confident   Very Confident
0   1   2   3   4   5   6   7   ⑧   9   10
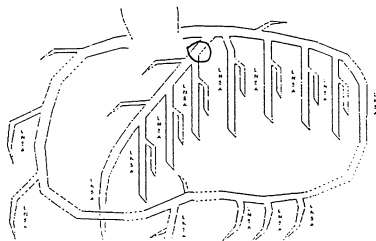
Input # __82__

Figure 1. Representative data form completed for each angiographic sequence. In this example a stent was seen in the circumflex artery and calcification in the left anterior descending (LAD) artery. The Coronary Artery Surgery Study (CASS) location for stenosis estimate was the proximal LAD, which was estimated at 70% diameter stenosis. Image quality was acceptable, and confidence in interpretation was 8 on a 0–10 scale.

was evaluated by testing the significance of appropriately constructed interaction terms within the framework of the logistic model. Random effects logistic regression was also used to compare the proportion of reviewers who found image quality to be acceptable among compression levels. Analysis of variance (ANOVA), with the influence of individual images modeled as a random effect, was used to compare arcsine square root–transformed confidence scores and observer differences in arcsine square root–transformed percentage stenosis estimates relative to the consensus panel among compression levels.

RESULTS

Angiographic observers. Because the 71 observers were randomized into four observer groups, the randomization resulted in there being 18 observers in groups 1 to 3 and 17 observers in group IV. The demographics and angiographic experience of the observers are shown in Table 3.

**Table 3.** Demographics and Experience of Angiographic Raters

Mean age	41
Range	28–69
Mean number of years of training	4
Mean years of experience	7
Interventional Cardiologist	96%
Diagnostic angiographers	4%
Mean number of cases per year (self reported)	
Diagnostic	400
Interventional	200

Detection of diagnostic features. SENSITIVITY. Four common types of diagnostic features were present in the images used for this study: complex stenosis/filling defect, calcification, presence of a stent, and presence of a dissection. Of the 100 analyzed injection sequences, 73 contained at least one of these features according to the consensus panel interpretation. Considering the expert panel as a gold standard, overall observer sensitivity for detection of any of these features was 80.1% using the original uncompressed images. Figure 2 shows the sensitivity for detection of any of these four diagnostic features at the various compression levels. At JPEG CR 6:1 and CR 10:1, there was no significant decrease in the sensitivity of the angiographic observers for detection of these features. However, at CR 16:1 there was a statistically significant decrease in the sensitivity for the diagnostic features compared with the uncompressed images (75.8% vs. 80.1%, p = 0.004).

For the individual features, Figure 3 shows the sensitivities for the uncompressed and lossy JPEG CRs. For uncompressed images, there was wide variability in the sensitivity that was dependent on the feature assessed. Complex stenosis/filling defect had the highest sensitivity (89%) when observers viewed the uncompressed images. For uncompressed images, sensitivity for the detection of calcification was the lowest (62.5%). Also, the reduction in sensitivity with increasing CRs appears to vary with the feature type. There was no apparent decrease in sensitivity
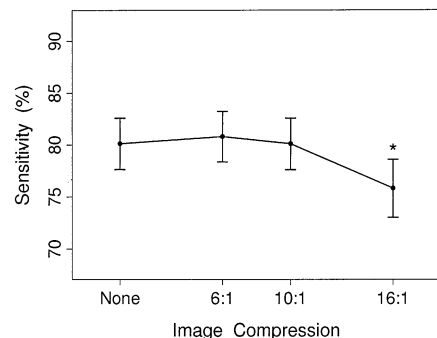
Figure 2. Mean sensitivity and 95% confidence bounds for detection of any of the four diagnostic features at the various CRs. There was no decrease in sensitivity at ratios of 6:1 and 10:1. Sensitivity decreased at a CR of 16:1 compared with no compression (*p = 0.004).
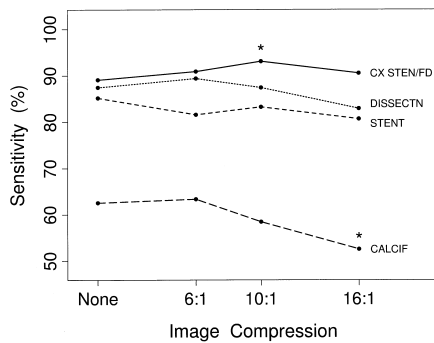
Figure 3. Mean sensitivity for detecting each of the individual diagnostic features at the various CRs. Sensitivity for detecting each of the features varied widely in uncompressed images. The sensitivity for the detection of calcium decreased significantly at a CR of 16:1 compared with uncompressed images. There were trends toward decreased sensitivity with increasing CR for dissection and stent, but these trends did not reach statistical significance.

for complex stenosis or filling defect. However, for calcification, there was a statistically significant decrease in sensitivity compared with the uncompressed images at CR 16:1 (52.5% vs. 62.5%, p < 0.001). Stent and dissection showed trends toward a decreased sensitivity with increasing CRs, but these did not reach statistical significance. Figures 4 a–d show the mean sensitivity and the 95% confidence bounds for each of the features for uncompressed images and for increasing CRs. Calcification showed the only statistically significant decrease at CR 16:1 (Fig. 4d). There was a statistically significant increase in sensitivity for the detec-
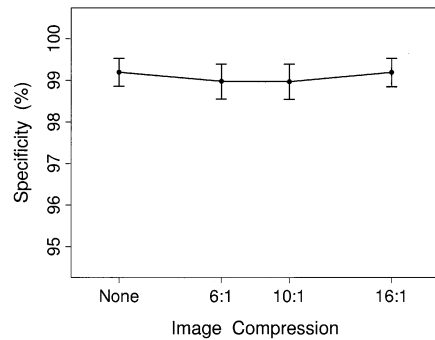

Figure 5. Specificity for detection of dissection in uncompressed images and at each of the CRs. There was no significant decrease in specificity with image compression at these ratios.

tion of complex stenosis/filling defect at CR 10:1 (93.1% vs. 89.1% p = 0.012).

Specificity. The specificities for detecting complex stenosis/filling defect, dissection and stent were greater than 98% at all CRs, while specificities for detecting calcification ranged from 94% to 96%. The specificity for detection of dissection in the uncompressed images and at each of the CRs is shown in Figure 5. There was no decrease in specificity for the detection of any of the features with increasing CRs. Lossy compression did not decrease the specificity for detection of any of the four features assessed in this trial.

Visual stenosis severity estimation. The consensus panel provided an estimate of stenosis severity at a designated
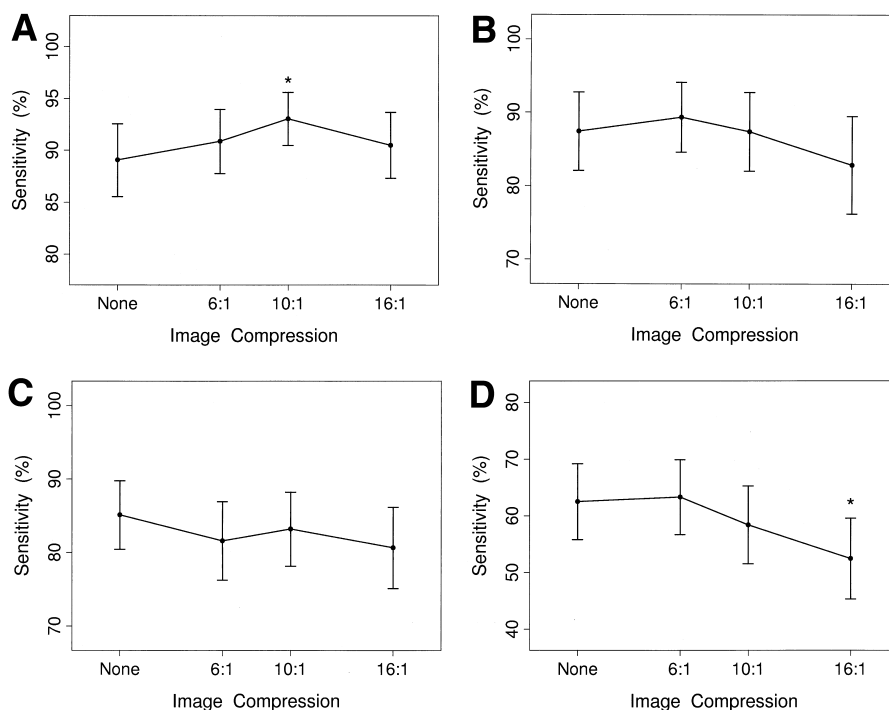
Figure 4. Mean sensitivity and 95% confidence bounds for each of the diagnostic features in uncompressed images and at each of the three CRs. **a)** complex stenosis or filling defect (*p = 0.012); **b)** dissection; **c)** stent; **d)** calcification (*p < 0.001).
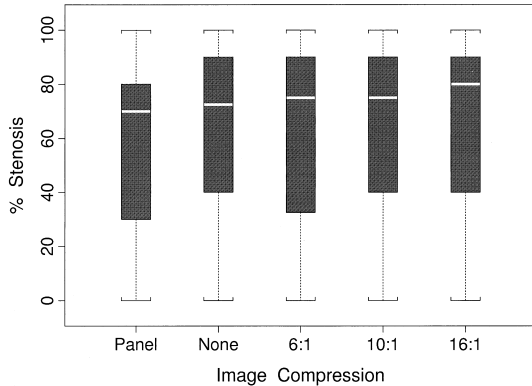
Figure 6. Box plot showing the median stenosis severity for the consensus panel viewing uncompressed images (left), and observers viewing the uncompressed and compressed images. There was no effect of compression on stenosis severity estimation, comparing reviewers with the consensus panel.

CASS segment for each of the 100 cine runs. For the uncompressed images and at each of the CRs, the stenosis severity estimated by each observer was compared with that of the consensus panel. Figure 6 shows the stenosis severity for the uncompressed (CR 1), CR 6:1, CR 10:1 and CR 16:1 compared with the stenosis severity estimated by the consensus panel. There was no significant difference in the estimated percent stenosis compared with that of the consensus panel for any of the CRs. Figure 7 shows the performance of the angiographic observers for each stenosis severity compared with that of the consensus panel. For severe stenoses greater than 80%, including 100% occlusions, there was little variability in the performance of the angiographic observer compared with that of the consensus panel. Variability increased for less severe stenoses. The greatest variability was seen for stenoses of 0% to 30% by the consensus panel. This overall pattern of variability, however, was not different at any of the CRs. Therefore, increasing ratios of data compression did not appear to have an effect on visual estimates of stenosis severity in this study.

Subjective assessment of image quality. Each angiographic observer was asked to determine if the image quality was acceptable. Figure 8 shows the percentage of angiographic raters who reported that image quality was acceptable for the uncompressed images and for each of the CRs. At CRs 10:1 and 16:1 there was a statistically significant decrease, compared with the uncompressed images in the percentage of angiographic observers who found image quality acceptable (no compression, 90.9%; 10:1, 86.8%; 16:1, 74.4%; [p < 0.001]). Angiographic observers also assigned a confidence score on a 0 to 10 scale based on image quality. Figure 9 shows the mean angiographic confidence score for the uncompressed and compressed angiograms. The mean confidence score for the uncompressed images was 7. At CRs 10:1 and 16:1 there was a statistically significant decrease in the confidence score given

by the angiographic raters when compared with the uncompressed images (no compression, 7.0; 10:1, 6.8 [p = 0.017]; 16:1, 6.1 [p < 0.001]).

DISCUSSION

Following its initial introduction to the catheterization laboratory in 1983, digital angiography rapidly achieved acceptance as the optimal imaging method for in-room guidance of diagnostic and therapeutic procedures (3,11,12). Until recently, however, application of digital methods for long-term archiving of angiography has been hampered by the quantity of data that must be stored and retrieved (1,4). For a laboratory performing 2,000 angiograms annually, the data storage burden of digital archiving of angiographic studies can reach 1,000 gigabytes (1 Terrabyte) per year. Similar data capacity issues need to be addressed when considering electronic transmission of digital angiograms within an institution, between clinical centers and over computer networks and telephone services (13). Accordingly, there has been considerable interest in developing methods for reducing the amount of angiographic image data without loss of diagnostic accuracy. Two general approaches to image compression are commonly used, lossless compression, which offers limited data reduction but is completely reversible, and lossy compression, which uses algorithms that result in image degradation but can achieve much higher CRs.

The DICOM standard for X-ray angiography defines the file structure and physical format for interchange of digital angiograms. First released in 1995, the DICOM standard designates the writable compact disk–recordable (CD-R) as the exchange medium and specifies lossless compression for data reduction (14). However, until recently, the data transfer speeds of CD-ROM drives were too slow to allow a full 30 fps review of angiograms. Accordingly, physicians must copy angiograms from the CD-R to a digital review station's hard disk or memory, from which faster display rates are possible. In an effort to improve replay performance directly from the CD-R with minimal delay, a number of vendors offered CD-R digital angiographic systems that incorporated lossy compression. By reducing the amount of stored data, lossy compression, together with adequate decompression methods, enabled full 30 fps replay speeds from the CD-R. However, in the absence of data on the accuracy of clinical interpretation of lossy-compressed angiograms, the DICOM committee refrained from incorporating lossy compression in the standard for the exchange media. With the rapid growth of network communication in the health care environment, similar issues arose with respect to image transmission and display over computer networks. Uncertainty regarding the clinical appropriateness of lossy compression in all potential clinical applications provided the context for the current study.

Several crucial decisions were required in the design of a definitive study of lossy compression in coronary angiogra-

No Compression

6:1 Compression

10:1 Compression
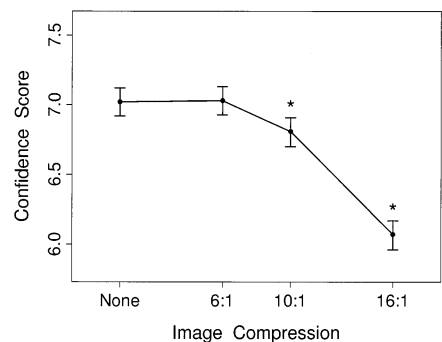
16:1 Compression
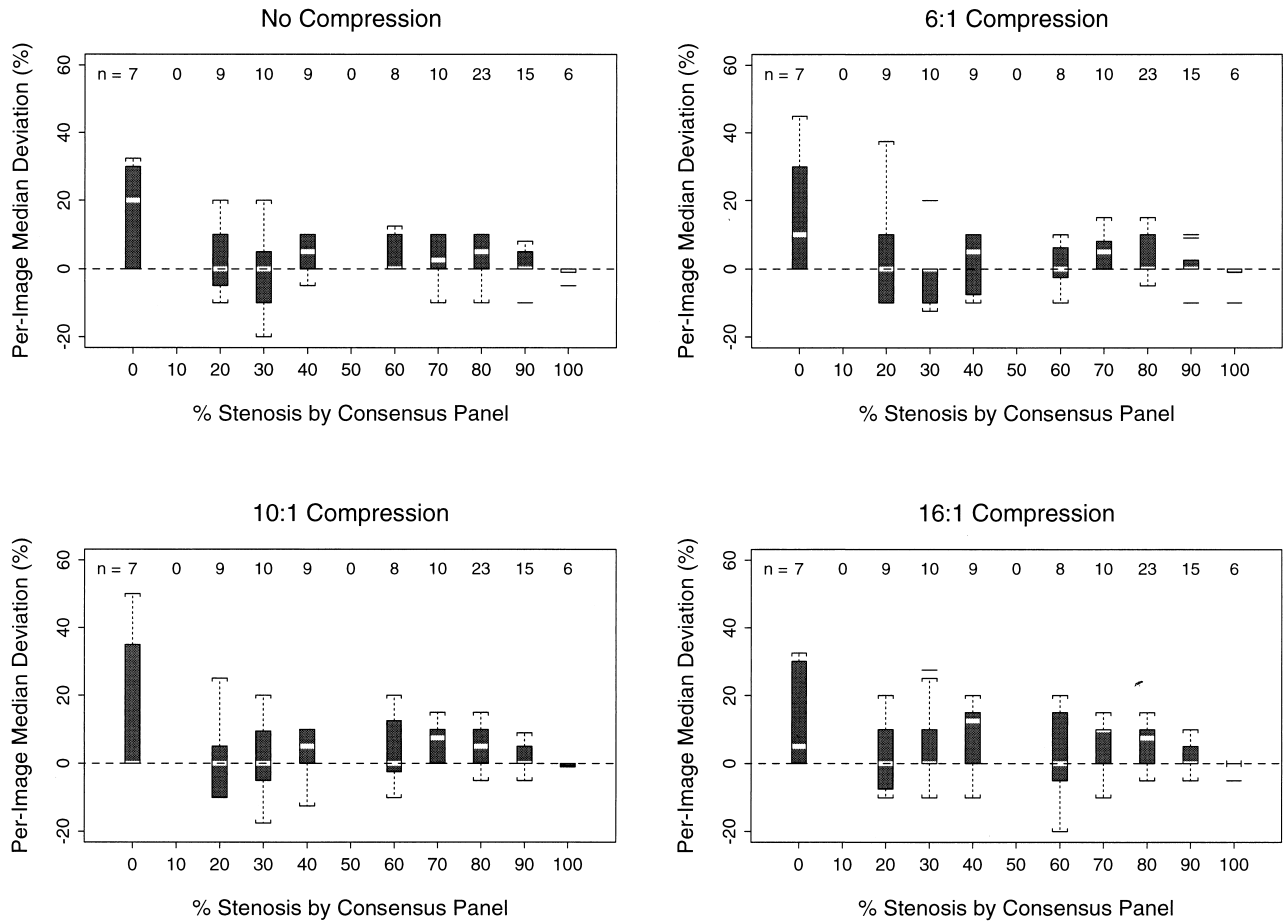
Figure 7. Variability in observer estimates of percentage diameter stenosis depending on the severity of the stenosis as determined by the consensus panel. Greater variability was seen in the less severe stenoses, but increasing CRs had no effect on the pattern or degree of variability.

phy. These included the precise algorithm for compression of the angiograms and target CRs to be studied. Ultimately, JPEG lossy compression was selected as the method for evaluation in our study because of its widespread availability

and acceptance as an international standard. One result of its acceptance in medical and non-medical applications was the availability on multiple computer platforms of compatible software and hardware methods for performing JPEG
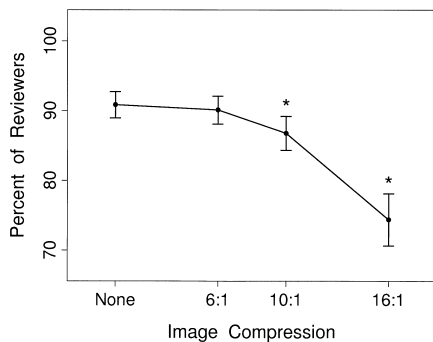
Figure 8. Percent of reviewers finding image quality acceptable with no compression and at each of the compression ratios. At CRs of 10:1 and 16:1, there was a statistically significant decrease in the percent of reviewers who rated images as acceptable (p < 0.001).

Figure 9. Mean confidence score and 95% confidence bounds for no compression and compressed images. Confidence score decreased significantly at CRs of 10:1 and 16:1 relative to no compression (p = 0.017 and p < 0.001, respectively).

decompression at clinically acceptable rates. Although more efficient algorithms may be available, their application is not sufficiently widespread for inclusion in an international standard at this time. Compression ratios of 6:1, 10:1 and 16:1 were selected to cover the likely range of clinical applications. Because of the broad range of potential clinical applications, it was determined that compression would be applied to the original images before application of image processing such as digital zoom, spatial frequency filtering and window and level adjustment. From preliminary studies, it was apparent that, under these circumstances, JPEG compression at ratios greater than 16:1, followed by typical degrees of image processing, resulted in very noticeable visible artifacts. Such a high degree of artifacts would have interfered with blinding of observers and would likely have yielded clearly sub-optimal image quality.

The methods used to determine the acceptability of lossy compression also deserve comment. There is no standard method for determining the clinical quality of a diagnostic image, and there is little agreement on methods for determining the equivalence of two images containing the identical medical features. Representatives of the ACC and the ESC considered these issues carefully and decided to divide the task of evaluating lossy compression into three parts. Phases II and III of the international compression study, conducted in Europe, evaluated the performance of lossy compression in quantitative angiography and the use of side-by-side comparisons, respectively. Phase I of the study, reported here, was designed to compare increasing ratios of lossy-compressed to original images in the detection of subtle diagnostic features within clinical angiograms. Because these features represent the most difficult detection tasks in angiography, the ability of lossy compression to retain diagnostic accuracy was deemed an appropriate, although challenging, requirement. The rationale for a rigorous standard included the relative importance of the detection tasks. For example, the ability to detect the presence or absence of a feature such as calcification can affect the choice of interventional device or approach.

The results of the study indicate that lossy JPEG CRs of 16:1 result in decreased sensitivity in the detection of common diagnostic features. The greatest effect was evident in the detection of calcification, which also showed the lowest sensitivity for detection in the uncompressed images. However, with increasing levels of compression, there was a strong trend toward a decrease in the detection of stents and coronary dissections. The specificity for each of the diagnostic features was high for uncompressed images and showed no decrease with a CR as high as 16:1. There was good agreement between the angiographic observers and the consensus panel for visual estimates of stenosis for all studied CRs. However, qualitative assessment of the images indicated a decrease in the subjective image quality at CR 10:1 and higher. Similarly, confidence in image interpretation based on image quality decreased with CR 10:1 or greater.

Although the study was intended to set a high standard for demonstrating equivalence, certain aspects of the study design served to minimize the ability to detect compression-induced image degradation. The outcome variable was the recognition of an angiographic feature by a human observer. Experienced angiographers, as a result of their extensive training and experience, are adept at decoding degraded images and recognizing features within them. Thus, a highly skilled observer's ability to identify a particular feature in an image does not unequivocally confirm that the image quality is satisfactory. Thus, in our view, even the faintest evidence of impaired observer performance, which may not reach statistical significance, should be considered unacceptable for the purpose of setting standards. The results of our study are consistent with this conclusion because qualitative measures of image quality showed a significant decrease at CR 10:1 but performance in terms of feature detection was not reduced until CR 16:1 was reached. The potential impact of reduced observer confidence on clinical decision making cannot be overlooked, because it seems probable that practitioners will not take decisive action in uncertain clinical circumstances.

Previous studies on the effects of lossy JPEG compression were performed using a relatively small number of angiograms obtained from a single laboratory or using a single type of imaging system (15–18). In the current study, we employed a large group of experienced angiographers to investigate the effects of lossy compression on a broad range of angiographic studies obtained from a variety of laboratories. However, despite the use of very high-quality images, the variability in interpretation, even using uncompressed images, was substantial. This finding emphasizes that the interpretation of coronary angiography is a subtle skill and involves enough uncertainty that experienced observers may not always agree about the presence or absence of a diagnostic feature. Previous studies have indicated wide variability in interpretation of coronary angiograms, but most of these studies have focused on stenosis severity, not identification of subtle features (19–23). This study illustrates the importance of maintaining the highest possible image quality in coronary angiography and further reinforces the principle that no major degradation in image quality is acceptable.

However, in the current environment of wide access to clinical information, there may be situations in which image review does not require the absolute highest image quality. Lossy CRs even higher than those tested in our study may be appropriate in those circumstances. The purpose of this study was to determine the effect of lossy compression on angiograms used in clinical decision making. The requirements of such applications must leave no room for error proceeding from image processing and manipulation.

STUDY LIMITATIONS

The design of this study required the creation of an expert consensus panel to determine the "correct" interpretation of

the coronary angiograms. It remains possible that the expert consensus panel's interpretation of the angiogram was not entirely correct. In addition, the study mandated that no angiographic observer review the same image twice. Therefore, angiographic interpretations by one group of observers in the uncompressed images were compared with those of a different group of observers at each of the compression levels. By randomizing the angiographic observers into four equal groups, we hope to minimize the effect of observer bias. Although each observer evaluated 100 images, the overall data set could be considered relatively small, providing only 17 or 18 observers for each CR. The review of 100 angiograms in one session was a daunting task, and the effect of fatigue on observer performance may have affected the results of this study. We attempted to minimize this effect by providing eight different random sequences (two in each observer group) in which the images were presented to the observers in this study.

The results of this study can be rigorously applied only in the evaluation of lossy JPEG compression using $512 \times 512 \times 8$ bit coronary angiograms. The effects of other lossy compression methods on digital coronary angiograms cannot be concluded from this study, nor can any conclusions necessarily be drawn regarding effects on images at matrix sizes greater than that used in this study. Accordingly, further studies would be required to define the acceptable limits of lossy JPEG compression. It also remains possible that other lossy compression methods such as wavelets will offer better image quality at higher CRs.

CONCLUSIONS

With increased ratios of lossy JPEG compression, a degradation of $512 \times 512 \times 8$ bit digital coronary angiographic images will occur that can result in decreased diagnostic accuracy and confidence. The sensitivity for detection of common diagnostic features was unequivocally decreased at CR 16:1 in our study, and subjective assessment of image quality was impaired at CR 10:1 or higher. Considering the importance of image quality in diagnostic and, particularly, interventional cardiology, the results of this study indicate that caution is warranted in the interpretation of coronary angiograms that have been subjected to lossy JPEG compression beyond a ratio of 6:1.

APPENDICES

APPENDIX 1: ANGIOGRAPHIC REVIEW SITES AND STUDY COORDINATORS

Duke University Medical Center, Durham, North Carolina: Thomas Bashore, MD, Jack Cusma, PhD.

Emory Clinic, Atlanta, Georgia: Jeffrey Marshall, MD.

University of Pittsburgh, Pittsburgh, Pennsylvania: Clarence WU.

University of Pennsylvania, Philadelphia, Pennsylvania: John Hirshfeld, MD.

Mayo Clinic, Rochester, Minnesota: David Holmes, MD, Merrill Wondrow.

University of Mainz, Mainz, Germany: Ruediger Brennecke, PhD.

APPENDIX 2: CENTERS SUBMITTING IMAGES

Cedars Sinai Medical Center, Los Angeles, California; Central Hospital, Gaia, Portugal; Christian-Albrechts University, Kiel, Germany; Duke University Medical Center, Durham, North Carolina; Erasmus University, Rotterdam, The Netherlands; Johannes Gutenberg University, Mainz, Germany; Lille Heart Institute, Lille, France; Martin Luther Hospital, Schleswig, Germany; Mayo Clinic, Rochester, Minnesota; North Shore Hospital, New York, New York; University Clinic, Essen, Germany; University Hospital Eppendorf, Hamburg, Germany; University Hospital, Geneva, Switzerland; University Hospital, Leiden, The Netherlands; University of Pittsburgh, Pittsburgh, Pennsylvania; University of Vienna, Vienna, Austria.

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