Diagnostic Accuracy of Film-Based, TIFF, and Wavelet Compressed Digital Temporomandibular Joint Images

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The purpose of this research was to determine if digitization and the application of various compression routines to digital images of temporomandibular joint (TMJ) radiographs would diminish observer accuracy in the detection of specific osseous characteristics associated with TMJ degenerative joint disease (DJD). Nine observers viewed 6 cropped hard-copy radiographic films each of 34 TMJs (17 radiographic series). Regions of interest measuring 2 in × 2 in were digitized using an 8-bit scanner with transparency adapter at 300 dpi. The images were placed into a montage of 6 images and stored as tagged image file format (TIFF), compressed at 4 levels (25:1, 50:1, 75:1, and 100:1) using a wavelet algorithm, and displayed to the observers on a computer monitor. Their observations regarding condylar faceting, sclerosis, osteophyte formation, erosion, and abnormal shape were analyzed using ROC. Kappa values were determined for relative condylar size and condylar position within the glenoid fossa. Indices were compared using ANOVA at a significance level of $P < .05$. Although significant and substantial observer variability was demonstrated, there were no statistically significant differences between image modalities, except for condylar position, in which TIFF and wavelet (at all compression ratios) performed better than the original image. For faceting, wavelet 100:1 performed better than radiographic film images. Little actual image file reduction was achieved at compression ratios above 25:1.

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KEY WORDS: temporomandibular joint, radiography, images, compression, diagnostic accuracy, wavelet.

IN THE FIELD of orthodontics and dentofacial orthopedics, imaging is an integral part of the diagnostic process. The American Association of Orthodontics¹ recommends that the appropriate radiographic examination for all patients commencing orthodontic treatment consist of a minimum of a lateral cephalogram, a panoramic radiograph, and a complete-mouth set of intraoral periapicals and

bitewings. Lateral,² and sometimes frontal, cephalometric radiographs are essential in the detection and diagnosis of skeletal and dental jaw discrepancies. Orthodontists also may be called on to diagnose and treat temporomandibular joint (TMJ) disorders. These conditions, which may affect up to 28% of the population,³ include internal derangement and myofascial dysfunction syndrome. For patients presenting with suspected osteoarthritis, also called degenerative joint disease (DJD), either with or without internal derangement, tomography is considered an inexpensive and appropriate initial imaging procedure.⁴⁻¹⁰ It provides a representation of the morphology, surface features, and shape of the osseous structures of the TMJ articulation and an accurate view of the relationship between the temporal (glenoid fossa) and mandibular (condyle) components. Subtle deviations from normal, including faceting, sclerosis, erosion, and osteophyte formation are more readily detectable using TMJ tomography and provide better accuracy than panoramic radiology.⁹ On the basis of the tomographic findings, further imaging studies, such as MRI and scintigraphy, may be considered necessary.

A typical TMJ tomographic examination involves 15 images: a submentovertex (SMV) and a series of tomograms of the left and right sides; "scout" sagittally corrected lateral tomograms at 3 section depths; tomograms in the closed, rest, and open jaw positions; and frontal tomograms. Because tomographic imaging is used only in selected orthodontic cases and requires dedicated and expensive equipment, the procedure usually is provided by a radiology specialist at a separate location. Typically the radiographic series, either with or without written report, are then returned to the referring orthodontist through the mail. To expedite this information transfer, tomographic images can be digitized and sent inexpensively via either the Internet or a modem¹¹ rather than by a dedicated picture archive and communication system (PACS). Additional benefits of digitization include the potential for electronic claims submission and facilitation of consultation among other health care professionals. The DICOM standard has now been extended (supplement 32) to include all imaging

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modalities used in dentistry such as intraoral cameras and intraoral and extraoral radiography including tomography. Because of the potential number and size of the files generated from TMJ tomographic imaging, transmission (at least via nondedicated media such as the Internet) will require adoption of image compression algorithms.

While the DICOM 3.0 standard supports joint photographic experts group (JPEG) lossy compression, there has been some effort to extend it to support wavelet compression.¹² The effect of wavelet compression on image quality depends on image content, spatial and spectral distribution, and the compression level that determines the degree of quantization. At low levels of compression quantization mostly discards high-frequency noise without any noticeable loss of diagnostic information and, in fact, makes the transformed image more pleasing to the human eye.¹³ The major disadvantage of wavelet transforms is that at moderate to high levels of compression, similar to JPEG, resolution at sharp edges is poor.^{14,15} However, the wavelet algorithm tends to create smeared edges rather than "blocking" artifacts, as occur with JPEG.

A number of investigators have reported the effects of wavelet compression on image quality and diagnostic accuracy of various medical images.^{12,16-22} Some researchers have used custom wavelet algorithms¹⁹; others have used Accupress (Aware Inc, Bedford, MA), a purposely designed commercial product for radiographic images.^{16,18} Despite the task, the results of these authors indicate that wavelet transforms can be used on medical images at low to moderate data rates without loss in diagnostic accuracy (range, 10:1 to 40:1) or appreciable image quality (10:1 to 30:1).

In the dental literature, 3 studies have compared the effect of compression on dental radiographs. For dental caries detection on intraoral images, Wenzel et al²³ found that a JPEG compression ratio of 1:12 can be justified before accuracy and image quality are affected significantly. Investigating the perceived quality of JPEG compressed digital panoramic images, Sanderink et al²⁴ concluded that file sizes could be reduced considerably and subjective diagnostic quality maintained with compression ratios of up to 28:1. Using a personal computer, Eraso et al¹¹ digitized tomograms of the TMJ at various resolutions and formats, compressed the Tagged Image File format (TIFF)

images using Lempel-Ziv-Welch (LZW) compression, and transmitted them via the "plain old" telephone system (POTS) using a point-to-point proprietary software package incorporating a database, image manipulation, and a compression algorithm. They found no difference in image quality between digitized and transmitted images. However, they noted that transmitted and transmitted-and-printed images were of significantly lower quality than the original radiographs or the digitized images viewed on a computer monitor.

Hence, we report a study designed to evaluate the effect of wavelet compression on the diagnostic accuracy of specific osseous characteristics observable in a series of digitized TMJ radiographs.

MATERIALS AND METHODS

Image Sample

A database of fifty (50) patients who had a corrected-angle tomographic radiographic examination taken within a 4-year period (1994-1998), referred from a local practicing orthodontist specializing in the diagnosis and treatment of TMJ disorders, was initially screened. Of the 50 patients identified, only 24 had a complete and original set of TMJ radiographs. From these, 4 film sets were identified which best represented a spectrum of radiographic image quality. These were then used by 3 dentists trained in TMJ radiological diagnosis (2 board certified oral and maxillofacial radiologists and an orthodontist with more than 16 years' experience) as reference radiographs to rate the radiographic image quality of the remaining 20 sets. Three examinations were eliminated because of poor quality or ambiguity, providing 17 sets and therefore a sample size of 34 TMJ images.

All radiographs were acquired with a Quint Sectograph Model 2000 (Denar Corp, Anaheim, CA) using a Lanex T-Mat G (Eastman Kodak Co, Rochester, NY) screen film system with a 10:1 parallel grid and a 153.6-cm source-to-midsagittal distance. The SMV exposures were taken at 200 mA, 0.25 seconds, with kilovoltage at approximately 90 kVp. Corrected angle sagittal tomograms were narrow-cut (approximately 2 mm to 3 mm) and taken at 50 mA, 3 seconds, with kVp ranging from 67 to 82 kVp according to stature. The exposure area was collimated to a rectangular region of approximately 6 cm × 20 cm. Finally, frontal anterior-posterior (AP) collimated wide-cut tomograms were taken at 1.25 seconds and approximately 66 kVp. In all cases the patients were imaged with a 8- × 10-inch horizontally oriented cassette with films developed in an automatic processor (X-OMAT, Model M7B; Eastman Kodak, Rochester, NY) with a processing time of 90 seconds at 32°C.

While each radiographic examination consists of a series of 15 images, only 6 images were selected for presentation and digitization: the central cut lateral TMJ tomographic image in rest position as representative of lateral tomographic images, the bilateral SMV condyle images, and bilateral frontal tomograms. For each image, 2- × 2-in regions of interest, centered on the condyle, were demarcated for digitization and film-based viewing.

The radiographs were digitized at 8-bit monochrome (gray-

scale) using a flatbed scanner (Expression 636; Epson, Torrance, CA) with a transparency adapter with proprietary driver software (Scanner Utility Program 2.10E; Epson, Torrance, CA) operated by a PC (300 MHz, 64 MB Ram, Packard Bell, Los Angeles, CA). Two-inch square regions of interest were identified and scanned at a resolution of 300 dpi to provide an image matrix size of 600×600 , equivalent to 5.9 lp/mm, which is the maximum perceptible by the tomographic configuration and screen/film combination. Halftoning, dropout, and auto adjustment options that were available in the scanning utility program were not used.

The 6 images were individually imported into a 1,200- $\times$ 1,800-pixel template montage within PhotoShop 4.0 (Adobe Systems Inc, San Jose, CA). The montage was stored in TIFF format (Fig 1) and also in wavelet format using a plug-in for PhotoShop (Accupress, Version 1.0; Aware Inc, Bedford, MA) at ratios of 25:1, 50:1, 75:1, and 100:1 (Fig 2).

Each montage was pasted into PowerPoint 97 (Microsoft Corp, Redmond, WA) and randomly displayed to 9 graduate orthodontic residents who served as observers with interpretative skills considered representative of general orthodontic practitioners. The observers viewed a single montage of 6 images for each case on multiple SVGA monitors (Optquest Q51-15i, ViewSonic Corp, San Diego, CA) with a resolution of $1,024 \times 768$ pixels (display area, 262 mm [H] $\times$ 196 mm [V]) at 65 MHz and a 0.28-mm dot pitch. These monitors were previously calibrated for brightness and contrast using a CRT

grayscale test pattern.²⁵ This resulted in displayed images having a 1.7 $\times$ magnification. Overhead fluorescent room lighting was turned off for viewing, and extraneous light from adjacent monitors minimized by seating observers at least 2 monitors apart. Twenty sets of images were randomly selected and presented to the observers in this session to assess intra-rater reliability. Before observer participation, a PowerPoint orientation presentation was viewed to familiarize and standardize the observer's decisions on the normal and abnormal appearances of the TMJ articulation with respect to the characteristics to be described. On a separate day, each observer completed his evaluation of the film-based images. This was accomplished by one of us (C.J.T.) accompanying each observer into a small separate reading room with minimal ambient light. Case-by-case, the following selected film images were presented on a 4-section table illuminator (FVS, Picker International, Inc, Cleveland, OH): the SMV, central-cut corrected lateral tomograms in rest position and frontal tomograms. For both left and right condyles, 2-inch-square regions of interest on each film were identified by masking the remaining image with black cardboard.

Visual Rating

Observers independently assessed each of the 34 TMJs under optimal viewing conditions to determine several specific characteristics associated with DJD. The viewers were asked to record

Fig 1. Uncompressed reference digital image file (TIFF) comprising a montage of 2-in $\times$ 2-in selected regions of 3 left (top) and 3 right (bottom) TMJ images. From left to right: SMV condylar image, central narrow-cut corrected sagittal TMJ tomogram in the mandibular rest position, and wide-cut corrected coronal TMJ tomogram.

Fig 2. Effect of various levels of wavelet compression on cropped central narrow-cut corrected sagittal TMJ tomograms from the case presented in Fig 1. (A) TIFF, (B) wavelet 25:1, (C) wavelet 50:1, (D) wavelet 75:1, and (E) wavelet 100:1. Note the progressive degradation in anatomic detail owing to "smearing" effects.

their certainty as to the presence or absence of the following 5 characteristics: sclerosis, osteophyte formation, facet formation, erosion, and the presence of abnormal shape. The observers also were asked to categorize TMJ size as either large, normal, or small, and condylar position relative to the glenoid fossa as concentric, posterior, superior, inferior, or anterior. Consensus radiographic truth was determined using the radiographic film images by 2 board-certified oral and maxillofacial radiologists and an orthodontist with 16 years' experience in interpreting TMJ tomograms. Decisions of disagreement were viewed together and a consensus determined for each of the seven criteria for each set. The number of abnormalities present within the 34 TMJs is shown in Table 1.

For the characteristics producing ordinal categorical data, ROC analysis was performed by generating the area under the ROC curves (A_z) for individual observers using ROCFIT software (Meltz CE, University of Chicago, IL) and calculating the average ROC curve. This method was used because it is considered preferable when a variable observer population is used.^{26,27} For the nominal categorical data (condylar position relative to the fossa and relative size of the condyle) Cohen's kappa (κ) was generated.²⁸ Values greater than 0.61 indicate

Table 1. Characteristics of Abnormal TMJs (n = 34) for ROC Analysis

Characteristic	No. of Cases		Total
	Left Side	Right Side	
Facet	7	6	13
Osteophyte	3	2	5
Sclerosis	10	5	15
Erosion	2	1	3
Shape	2	0	2
Size*			
Small	3	1	4
Normal	0	0	0
Large	0	0	0
Condylar position†			
Superior	1	1	2
Anterior	4	3	7
Inferior	5	4	9
Posterior	0	3	3

*All remaining cases were normal.

†All remaining cases were concentric (left [7] and right [6]), which is considered normal.

substantial agreement and values over 0.81 indicate near-perfect agreement.²⁸

Intrarater kappa values were compared using one-way repeated-measures analysis of variance (ANOVA) with a two-tailed a priori level of significance set at $\alpha = 0.05$. Modality and inter-observer performance indices (kappa values and A_z values) for each TMJ characteristic also were compared using ANOVA. Following a significant F-test in the ANOVA, post-hoc pairwise comparisons were performed using the Scheffe procedure for multiple comparisons.

RESULTS

Modality mean A_z and kappa values together with ANOVA for each characteristic and modality are shown in Table 2. Unfortunately, the ROC analysis for TMJ erosion, condylar osteophyte formation, and shape abnormalities resulted in degenerate data for each observer and therefore kappa values were calculated. This can result when observers fail to use all 5 points on the decision scale and consider that disease is either present or absent, or if the number of actual disease states in the sample is low. A statistically significant difference between wavelet 100:1 and film was demonstrated for faceting ($P = .046$); while for condylar position, TIFF, and wavelet (at all compression ratios) performed better than film ($P = .0001$). One observer for TMJ faceting was deleted owing to poor intra-rater performance; another was deleted because of degenerate values for TMJ sclerosis.

The inter-observer ANOVA for each characteristic (Table 2) demonstrated a significant difference between observers for all characteristics except faceting. Comparing the contribution of the observers to the total variability (as evidenced by the relative values between the sums of squares), it is

Fig 3. Effect of wavelet compression on absolute image file size and percentage of compression. The TIFF (LZW) format was not presented for observation, but is included to provide a comparison of lossless to lossy (wavelet) compression.

apparent that the observers, for all characteristics except faceting, contributed substantially and significantly to the total variability, ranging from 40% (condylar position) to 84% (condylar shape).

The mean kappa values for 8 observers after re-reading for each characteristic varied from .535 to .653. While there was no significant difference ($P < .05$) in the intra-observer reliability of the viewers, one observer (as previously indicated) demonstrated consistently poor performance in recharacterizing TMJ features ($\kappa = .315$).

The absolute mean file size versus percentage of compression for each modality and level of wavelet compression is shown in Fig 3. TIFF with LZW compression is included to compare the effect on file size of lossless and lossy (wavelet) compression.

Table 2. Mean Diagnostic Index Values (Receiver Operator Characteristic A_z or Kappa) and ANOVA for Various TMJ Characteristics Using Various Modalities

Observer	Film	TIFF	Wavelet				ANOVA					
							Observers (Inter-rater)			Modality		
			25:1	50:1	75:1	100:1	Sum of Squares	F-test	P Value	Sum of Squares	F-test	P Value
ROC Az												
Faceting*	.662	.713	.696	.731	.787	.804	.156	2.006	.0783	.118	2.536	.0464
Sclerosis†	.534	.645	.589	.605	.655	.627	.344	4.669	.0007	.079	1.614	.1821
Kappa												
Erosion	.052	.11	.073	.085	.052	.056	5.98	27.936	.0001	.024	.162	.9749
Osteophyte	-.038	-.069	-.058	-.058	-.054	-.021	2.262	17.043	.0001	.013	.147	.9799
Condylar shape	.02	-.004	.024	.052	.01	-.017	3.86	31.4	.0001	.026	.316	.9005
Condylar size	.61	.683	.659	.683	.639	.634	.856	10.844	.0001	.038	.749	.5918
Condylar position	.248	.387	.355	.317	.359	.387	.184	3.88	.0015	.123	6.78	.0001

*Eight observers (without observer G).

†Eight observers (without observer E).

DISCUSSION

Intuitively, one would expect that the observers' diagnostic accuracy of TMJ characteristics would be reduced with digitization and with increasing compression. However, the results suggest that diagnostic accuracy of specific TMJ characteristics is not influenced by the type or level of wavelet compression. In fact, the only statistically significant difference between modalities was opposite to the expected trend, in that TIFF and wavelet compressed images provided increased diagnostic accuracy over film for the condylar position. This may be attributable to the relative ease of this task. Observers may be more familiar in analyzing gross positional changes than subtle low-contrast differences inherent to the other characteristics. In addition, all 6 cropped images were displayed on the monitor simultaneously, using PowerPoint, and presented at approximately $1.7\times$ magnification. The positive effect of image magnification in dental radiology has been reported in low-contrast detection tasks like the determination of instruments²⁹ or lateral canals³⁰ in endodontics and in dental caries detection.^{31,32} Most recently, Versteeg et al showed that a reduction in the size of digital images, at least in file length determination in endodontics, may reduce diagnostic accuracy.³³ The effect of magnification in the discernment of high-contrast details, as performed in this study (ie, condylar shape and surface morphology), should intuitively make structures more clearly visible and assist the observers in favor of the digital images; however, this has not been investigated in the dental literature. The wavelet algorithm also may have contributed by decreasing noise within the image.

In this study there are inherent differences in the presentation of film-based images on a viewbox to digitally acquired images displayed on a CRT, which could result in sources of variability. We selected the particular viewbox and CRT for display to represent normal viewing conditions available in general dental practice. Currently all commercial systems for acquisition and display of digital dental images are PC-based and use either 14- or 15-in SVGA monitors ($1,024 \times 768$ pixel matrix) or notebook 12.1-in thin film transistor (TFT) liquid crystal displays. Although these monitors have inferior spatial resolution (range, 6 to 10 line pairs per millimeter)³⁴ and luminance (range, 86 to 250 cd/m³)³⁵ compared with viewboxes, observer performance for dental diagnostic tasks

does not, thus far, appear to be dependent on the visual characteristics of the monitor.³⁵⁻³⁹

The diagnosis of temporomandibular joint DJD is based on recognition of multiple characteristics as seen on the tomograms that we asked observers to rate independently. Almost all observers were reliable when compared with themselves, but their ability to accurately recognize subtle characteristics depended on their individual training and experience. The observers themselves were significant and substantial sources of variability. This may be attributable to their lack of familiarity and inexperience in interpreting the tomographic series, difficulty of the task in assessing osseous characteristics, and likely fatigue owing to the length of time for observation and numbers of images viewed in one session.

The results suggest that wavelet compression up to the ratio of 100:1 does not affect the observers' ability to recognize TMJ characteristics. Initial compression from the original file size (2.06 MB) to wavelet 25 (82 Kb) results in a 96% reduction in file size. Further compression to wavelets 50, 75, and 100 results in 98%, 98.7%, and 99% reduction in file size (41 Kb, 27 Kb, and 21 Kb, respectively). Because this means that only an additional 2%, 2.7%, and 3% of the original file is saved, the value of using these levels of compression must be weighed against their potential image degradation effects. Although our results indicate that there is no appreciable difference, we did not investigate the perceived quality of the images, which may influence confidence.

For our study we detected differences between modalities for condylar position, and at the significance level of $P < .05$, the sample size of 34 was determined to provide power of 78%.

The significant and substantial sources of variability between observers suggest that only experienced and qualified clinicians should interpret tomograms. For the majority of orthodontists, it would be prudent to refer patients requiring TMJ tomographic imaging to qualified radiologists for interpretation. With regard to compression techniques and systems that are marketed to orthodontists, the Food and Drug Administration⁴⁰ requires that devices using lossy compression be provided with instructions explaining their effects and including examples of the type and nature of diagnostic information loss with decreasing subjective image

quality. Numerous imaging programs are available to orthodontists that use some type of image compression; however, few software manufacturers have complied with the FDA guidelines.

Based on our data, we believe that TMJ images may be compressed using the wavelet algorithm without loss in diagnostic accuracy; however, at compression levels beyond 25:1, little absolute file size reduction is achieved. However, to justify implementation of expensive wavelet algorithms

and recommend the incorporation of proprietary elements into the DICOM standard, significant differences in quality and compressibility compared with JPEG must be established.⁴¹ Currently we are investigating this question by replicating this study using the JPEG algorithm. Ultimately, the orthodontist or oral and maxillofacial radiologist has responsibility for interpreting images that have been subjected to compression, and must be aware of its potential undesirable effects.

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