Extreme Compression for Extreme Conditions: Pilot Study to Identify Optimal Compression of CT Images Using MPEG-4 Video Compression

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Abstract This study aims to evaluate the utility of compressed computed tomography (CT) studies (to expedite transmission) using Motion Pictures Experts Group, Layer 4 (MPEG-4) movie formatting in combat hospitals when guiding major treatment regimens. This retrospective analysis was approved by Walter Reed Army Medical Center institutional review board with a waiver for the informed consent requirement. Twenty-five CT chest, abdomen, and pelvis exams were converted from Digital Imaging and Communications in Medicine to MPEG-4 movie format at various compression ratios. Three board-certified radiologists reviewed various levels of compression on emergent CT findings on 25 combat casualties and compared with the interpretation of the original series. A Universal Trauma Window was selected at -200 HU level and $1,500$ HU width, then compressed at three lossy levels. Sensitivities and specificities for each reviewer were calculated along with 95 % confidence intervals using the method of general estimating equations. The compression ratios compared were 171:1, 86:1, and 41:1 with combined sensitivities of 90 % (95 % confidence interval, 79–95), 94 % (87–97), and 100 % (93–100), respectively. Combined specificities were

100 % (85–100), 100 % (85–100), and 96 % (78–99), respectively. The introduction of CT in combat hospitals with increasing detectors and image data in recent military operations has increased the need for effective teleradiology; mandating compression technology. Image compression is currently used to transmit images from combat hospital to tertiary care centers with subspecialists and our study demonstrates MPEG-4 technology as a reasonable means of achieving such compression.

Keywords Compression · MPEG4 · Universal trauma window · Combat trauma

Introduction

Cross-sectional imaging data acquired in remote locations present several unique technical and administrative challenges. First, availability (in person or remotely) of around-the-clock staff radiologists is required in combat. Secondly, radiologists in austere locations often consult with other radiologists for difficult cases. Lastly, when patients are evacuated from the combat zone to higher echelons of care, their original scans ideally accompany them. This is usually by CD or scheduled transmission; however, occasionally do not make it to the referral facility. Often, these studies are not consistently available as a result of the complexity of the evacuation process itself. Compressing cross-sectional imaging modalities such as multi-detector computerized tomography and magnetic resonance imaging into Motion Picture Experts Group, Layer 4 (MPEG-4, a type of lossy compression) video may help to address these problems.

The requirement to compress is becoming more relevant as the volume of data and number of detectors increase

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[1]. Due to limited upstream bandwidth availability in remote areas such as deployed military medical facilities or rural emergency medical clinics, data transmission for preliminary interpretation or consultation is sometimes impossible. Bandwidth equivalents have been known to be as low as 28 K modem speeds achieved in the late 1980s. Compression of large image datasets into a more manageable digital movie, of significantly smaller file size, would allow for easier transmission of information and make the process of patient evaluation more efficient.

Teleradiology addresses the need for remote consultation for patients, as well as the archiving and swift transmission of their images and records. Increasing file sizes has increased bandwidth demands that at times are beyond deployed capability.

Previous studies have indicated various acceptable compression ratios (the ratio of compressed dataset size: original), some up to 30:1 [2]. One study found that compressing chest X-rays to 40:1 did not significantly affect diagnostic accuracy [3]. Yet another study used appendicitis as an emergent finding on computed tomography (CT) and found acceptable compression ratios up to 16:1 [4]. Further, there is some evidence that compressing images may actually carry added benefit. For example, one study found improvement of tumor localization with compression in mammography [5]. A review of currently available compression methods is described by Chen et al. [6]. High compression ratios have not been sufficiently evaluated and there may be advantages to higher compression ratios as introduced here.

Our study focuses on dramatically compressing images obtained in the austere, combat environments of today's military medical corps where upstream bandwidth for image transmission is limited. We reviewed the effects of our compression technique and how they affect emergent triage of critically injured soldiers. For uncompressed, small datasets found in plain radiography, the amount of data within a standard trauma CT exam often precludes the possibility of uncompressed transmission for emergent/urgent remote expert consultation. Compressed image sets could be sent easily and quickly to the patient's destination prior to their arrival—even if the sending and receiving facilities have poor bandwidth connections.

With upwards of 170:1 compression ratios, large CT data sets measuring hundreds of megabytes can be reduced to 5 MB or less. This allows for resultant video files to be uploaded to secure Electronic Medical Records (EMR) or health banks such as Microsoft © Health Vault [7, 8]. The Department of Defense is working with the Veterans Affairs in such an EMR called Virtual Longitudinal Health Record.

The Universal Trauma Window (UTW) is a wide window/level selection or algorithm that allows radiologists to quickly review trauma patients in times of mass casualty situations or combat. This is described by one of the authors (LF) based on his experiences in a combat hospital [9]. Since blunt and penetrating trauma is most often regional (occurs in closely related anatomic areas), one window/level preliminary interpretation allows expeditious review of all organ systems in one pass. The reviewing radiologist does not have to go through the body images several times in each lung, bone or soft tissue windows. Preliminary tests of these compressed files combining UTW show the feasibility of this type secure image sharing using approved providers that can access the records centered around the patient [10]. This way, the patient can provide access to military, Veterans Affairs, and civilian providers alike, forever.

We exploited the inherent ability of MPEG-4 compression to compare and correlate among similar voxels on adjacent image slices (saving file size by not duplicating) just as it usually does for adjacent successive movie frames. Our purpose is to evaluate the utility of MPEG-4 compression for guiding emergent treatment regimens.

Materials and Methods

Study Design This retrospective pilot project was approved by our Institutional Review Board and Informed Consent was waived. Patient anonymity was achieved for Health Insurance Portability and Accountability Act compliance during the conversion of Digital Imaging and Communications in Medicine (DICOM) to MPEG-4 video files by removing all identifying patient data prior to video compression.

We sought to establish feasibility of lossy MPEG-4 based video compression scheme of 25 combat trauma casualties. Images were windowed using UTW of −200 HU level and 1,500 HU width then compressed at three lossy compression ratio levels (171:1, 86:1, then 41:1) using VirtualDub compression software (<http://www.virtualdub.org/>; Concord, CA, USA).

Image Study Selection Twenty-five trauma patients evaluated at our institution (Walter Reed Army Medical Center) between January 2002 and March 2007 were selected based on desired findings by an investigator who was not one of the evaluating radiologists. The patients were evacuated from deployed military locations for various reasons such as gunshot wounds and blast injuries as well as non-emergent injuries. The patients were combat casualties including two females and 23 males ranging from 25 to 37 years of age.

The chest, abdomen and pelvis CT exams were 5×5 mm or less (down to 1×1 mm) contiguous (non-overlapping) axial reconstructions from a variety of scanner vendors. Head, neck, and extremity exams were not included in this initial study.

Compression Technique The DICOM images were windowed universally as described earlier, converted to Audio Video Interleave (AVI) files maintaining 10 frames per second (reasonable viewing frame rate, unrelated to compression). The images were compressed using the DIVX V.6 MPEG-4 codec©. The compression rate can be set within the codec settings using kilobits per second rate. Single-pass compression was used rather than multiple pass methods to further conserve time. This method results in more variability in actual compression ratios achieved. The AVI files were converted back to individual frame-by-frame bitmap (BMP) images using a software program called AVI4BMP (Bottomap©. <http://www.bottomap.com/Software/A4B/A4B.html>; Prato, PO, Italy). Once the images were stored as BMP files, they were reconverted to DICOM using a software program called KPACS (Plauen Deutschland)© and resent to Picture Archiving and Communication System (PACS) for review.

The described technique is a compilation of existing technologies into an arrangement that allows application of an existing compression scheme into an open-architecture viewing platform. During trial compressions in the study design, we found that below approximately 180 Kbps, there are minimal changes in file size. For most applications, bitrates somewhere between 250 and 1,000 will give adequate quality despite significant compression (up to 170:1).

Image Analysis The anonymized, MPEG4 compressed CT images were reloaded onto Impax (AGFA, Belgium) by an investigator that was not involved in the image interpretation. In each patient's digital jacket, there were four separate series. The series began with the most compressed images followed by, in decreasing order, the remaining compression ratios. The final series for each patient was the original, axial DICOM images. The studies were reviewed in random order in each of the compression sets; with decreasing compression sets reviewed (random each time) with at least 1 week separation each session. The original reports and final review of non-compressed studies were used as the comparison baseline.

All images were independently reviewed by three board-certified radiologists each with over 5 years of combat trauma interpretation experience. Evaluators noted the presence or absence of the following predetermined emergent findings: (1) free air in the chest or abdomen, (2) major vascular injury, (3) spinal cord injury or impending injury, (4) rupture of solid organs, (5) free fluid/blood in the chest, abdomen or pelvis, and (6) foreign bodies in critical locations.

Sensitivities and specificities for each reviewer were calculated along with 95 % confidence intervals using the method of general estimating equations to adjust for lack of independence in the data structure (all three reviewers evaluated the same 25 studies). These confidence intervals were estimated using the exact binomial method.

Results

The average file size of original DICOM datasets used in our study was 73 MB, see Table 1 for a list of each of the file sizes. The average compressed file sizes were 0.4, 0.8, and 1.7 MB using 250, 500, and 1,000 Kbps MPEG-4 compression, respectively. The average compression ratios were 171:1 for 250 Kbps (ranging from 157 to 180:1), 86:1 for 500 Kbps (from 77 to 94:1), and 41:1 for 1,000 Kbps (from 33 to 49:1). The frame size was 512×512 pixels. The variability of compression resulted from the use of single pass compression. Had additional compression passes been made, the compressed file sizes would be averaged together and would demonstrate less variability. Since efficiency was a primary factor this study aimed to address, we chose to accept this variability because of the time saved during the compression process.

The combined sensitivity of the reviewers' interpretations for the above compression ratios were 90 % (95 % confidence interval of 79–95), 94 % (87–97), and 100 % (93–100), respectively. Combined specificities were 100 % (85–100), 100 % (85–100), and 96 % (78–99), respectively. See Table 2 for comparison of file sizes, compression ratios, and sensitivities. See Table 3 for a breakdown of presence or absence of emergent findings on each trial. In one example, bilateral perinephric fluid collections are demonstrated on the original scan (Fig. 1d) and are readily identified on the highest compression ratio (Fig. 1a) as well as the remaining compression ratios.

Discussion

This study demonstrated greater than 90 % combined sensitivities and specificities for all of the evaluated compression ratios. Such results indicate image compression is a promising technique that would be potentially useful for deployed military medical corps. The authors do not advocate use of this compression system for primary review, rather as a means of obtaining timely consultation and backup transmission when existing systems are not capable.

The proposed compression technique is intended for preliminary rather than diagnostic interpretations, to gain information quickly for damage control surgery and also provides comparison images for subsequent studies. We

Table 1 Compressed file sizes as well as original DICOM files sizes (with and without image header data, 770 KB per image versus 512 KB per image)

Compressed CT scan data (KB)				Original file size (KB)		
Patient	250 Kbps	500 Kbps	1,000 Kbps	# of images	Dicom size (770 KB/image)	DICOM Image size (512 KB/image)
1	406	812	1,625	130	100,100	66,560
2	472	950	2,026	157	120,890	80,384
3	282	594	1,280	94	72,380	48,128
4	436	888	2,078	134	103,180	68,608
5	474	946	2,110	155	119,350	79,360
6	566	1,134	2,346	193	148,610	98,816
7	412	828	1,854	134	103,180	68,608
8	482	966	2,110	162	124,740	82,944
9	482	976	1,989	164	126,280	83,968
10	510	1,022	2,210	169	130,130	86,528
11	374	782	1,370	129	99,330	66,048
12	276	566	1,318	91	70,070	46,592
13	434	832	1,600	153	117,810	78,336
14	820	1,594	3,036	281	216,370	143,872
15	514	1,004	1,962	179	137,830	91,648
16	406	810	1,734	132	101,640	67,584
17	424	834	1,708	135	103,950	69,120
18	216	416	852	71	54,670	36,352
19	378	772	1,642	129	99,330	66,048
20	398	784	1,584	135	103,950	69,120
21	256	502	1,038	88	67,760	45,056
22	456	892	1,864	152	117,040	77,824
23	472	932	1,898	160	123,200	81,920
24	528	1,040	2,248	169	130,130	86,528
25	246	478	948	84	64,680	43,008

believe having a CT exam rapidly available, albeit lower quality, is more advantageous than higher quality CT data that is not available (unfortunately, a common scenario).

Implementation of this technology could also mean that prior studies will be more available for comparison on evacuated wounded soldiers. This may improve the report content of subsequent interpretations as well as decrease the necessity for repeat exams, ultimately decreasing overall radiation doses to wounded soldiers.

Additionally, in 69 out of 75 cases, the findings derived from the compressed images were consistent with the findings

derived from the original noncompressed images. In other words, 92 % of the time, the reviewing radiologist agreed with the presence or absence of emergent findings on all three compression ratios as compared to the original series.

Multiple factors are considered in determining acceptable compression ratios, such as the type of compression, image modality, purpose for compression (archiving or teleradiology), and human perception. Several prior studies looked at some of these parameters, to include diagnostic capability with compression using Receiver Operator Characteristics (ROC) [11]. Human perception in compression is important

Table 2 The three compression ratios demonstrate the overall bitrate trials. The authors believe the 500 kb/s bitrate resulted in the optimal balance of high compression (approximately 86:1) and resultant image quality

Kb/s	File Size start/end (in MB)	Compression ratio (range)	Subjective image quality	Combined sensitivity and 95 % CI	Combined specificity and 95 % CI
250	73/0.4	171:1 (157–180:1)	Average	90 % 79–95	100 % 85–100
500	73/0.8	86:1 (77–94:1)	Good	94 % 87–97	100 % 85–100
1000	73/1.70	41:1 (33–49:1)	Excellent	100 % 93–100	96 % 78–99

Table 3 Compression A= 250 Kbps, B=500 Kbps, and C= 1000 Kbps (for interpretations, 1=yes an emergent finding was identified while 0=no emergent finding was identified)

Patient	Compression Ratios	Radiologist #1	Radiologist #2	Radiologist #3
1	A/B/C/Original	1111	0111	1111
2	A/B/C/Original	1111	1111	1111
3	A/B/C/Original	0011	0000	1111
4	A/B/C/Original	1111	1111	0000
5	A/B/C/Original	1111	1111	1111
6	A/B/C/Original	1111	0111	1111
7	A/B/C/Original	1111	1111	1111
8	A/B/C/Original	1111	1111	1111
9	A/B/C/Original	1111	1111	1111
10	A/B/C/Original	0000	0000	0000
11	A/B/C/Original	1111	1111	1111
12	A/B/C/Original	0000	0000	0000
13	A/B/C/Original	1111	1111	1111
14	A/B/C/Original	0000	0011	0000
15	A/B/C/Original	0011	1111	1111
16	A/B/C/Original	1111	1111	1111
17	A/B/C/Original	0000	0000	0000
18	A/B/C/Original	1111	0000	1111
19	A/B/C/Original	0000	0000	0000
20	A/B/C/Original	1111	1111	1111
21	A/B/C/Original	1111	1111	0000
22	A/B/C/Original	1111	1111	1111
23	A/B/C/Original	1111	1111	1111
24	A/B/C/Original	1111	0000	0000
25	A/B/C/Original	0010	0000	0000

Fig. 1 **a** Demonstrates example compression at 250 bitrate or about 180:1 compression. Although this appears pixilated, one can appreciate the bilateral perinephric fluid; **b** compression of 100:1 (bitrate 500); **c** 40:1 (bitrate 1000); **d** the original image

and has been taken into consideration [12]. One study showed that there was no perceptible difference at compression ratios of 7:1 [13]. Another study determined that a 4:1 ratio is acceptable for primary diagnosis in routine diagnostic practice, and that 8:1 images are very close to being visually lossless [14]. This same recent study looked at 12:1 and 16:1 compression ratios, but determined there to be significant image degradation. Another pilot study compressed images on an aircraft carrier using Microsoft PowerPoint® and Word® to compress the images (before graphic software was readily available) [15]. Results indicated feasibility in novel compression methods in austere conditions; however, there were not enough cases to validate usefulness.

It is not uncommon for radiologists to consult each other through email (select key images) or teleradiology in perplexing cases whether stateside, civilian, or military. This is usually prohibitive in austere combat conditions without interim home-grown solutions such as the compression technique presented here. One of the authors (LF) used this technique to share interesting and perplexing cases, send immediately needed CT data to higher echelons for comparison, and often included a few key images to narrow the attention.

Movie files are now a nearly ubiquitous technology with portable digital cameras and video capabilities on Personal Computers at home and in the workplace. The described technique of compiling large datasets into a simple MPEG-4 movie file will make use of a widely available format, which is easily transmitted to most computers, mobile phones, and personal data assistants on any type and speed of internet connection. Video files can also be viewed one frame at a time using certain video players. The MPEG-4 codecs for video are similar to MP3 compression algorithms for audio, which have become increasingly popular and prevalent in recent years. Several papers have already described MP3 compression of medical audio files [16–19]. Additionally, DICOM header information can be converted to ID3 metadata tags on the MPEG4 file; similar to how music stores album information (text and/or images).

Finding the optimal compression ratio is paramount and must strike the right balance between quality and small file size. In our study, even the most highly compressed images, resulted in subjectively and objectively excellent image quality maintained in a very small file size. In order to maintain maximum compression while preserving image quality, we believe the optimal compression ratio in our study was approximately 86:1 (500 Kbps bitrate).

Benefits and Limitations to DICOM2mp4 Methodology

We believe that MPEG-4 compression of cross-sectional studies obtained in locations with limited internet connectivity will prove to be a rapid and accurate method of

compress for transmitting images. Additionally, one can use AVI4BMP (MPEG4 to BMP) and KPACS (BMP to DICOM; Plauen, Germany) to reconvert the MPEG-4 files into DICOM images at the receiving facility for PACS upload. A benefit of using MPEG4 is improved compression (over still image compressors such as JPEG and JPEG2000) because it makes use of information redundancies between frames. It is intuitive that image quality is preserved at the tested compression ratio/frame rates.

Several limitations are present with this focused study. The studies included in our review were not initial trauma scans but rather follow-up studies performed at our institution following the patient's evacuation. We feel that this should not change the relevance of our conclusions because we chose to focus on the fidelity of compression. In fact, this limitation highlights the need for this compression method, as many of the original trauma scans performed on these patients in the war zone were not available for comparison at our stateside institution. The compression technique presented here is still in prototype development, however, will soon be available (Compressus, Tustin, CA).

We minimized this source of error by having the interpreters review the original DICOM series for each patient after viewing all of the associated compressed series. We realize there are a low number of cases, limiting the power of the study. However, given that this is a pilot study of preliminary data not meant for primary review or for diagnostic interpretation, evaluating 25 subjects was a reasonable number for our pilot study, especially since there was no funding available for this project. Therefore, results should be interpreted accordingly.

Regarding the original CT findings in the included patients, there were a relatively low number of solid organ injuries. During the course of staff review, solid organ injuries were the most difficult findings to resolve on compressed images, likely from inevitable “volume averaging” which is compounded with compression. This limitation warrants further evaluation, especially since solid organ injuries are often present in the setting of trauma and carry significant prognostic value. With re-review times within 1 month, there may have been recollection of findings; however, since reviews started at highest compression; this would not have negatively impacted our results.

From an image manipulation standpoint, the lack of windowing and leveling capability following compression also represents a limitation. Using a single window/level setting allowed us to standardize our results. Standard settings were chosen because they best illustrated the emergent findings we were evaluating. In one of the authors' experience in a combat hospital (LF), UTW was commonly used to prelim multiple casualties during surges (10–40 casualties at a time); with more definitive interpretations done the

following day. Further research is necessary in terms of evaluating UTW for rapid interpretation. Another limitation of our study was the subjectivity of interpretation. We used direct comparison of images rather than using complex ROC evaluation. We feel specific military requirements (major trauma, immediate review, transmission of images); however, lend themselves to the design selected. Lastly, disadvantages of MPEG4 include propagation error. If there is an error occurring in one frame, the error is likely to propagate (and sometimes amplify) in consecutive frames.

The deployed environment makes it difficult to achieve the necessary bandwidth for adequate data transmission. Although low bandwidth may be less relevant to everyday civilian radiology practices, there are similar remote locations such as Alaska where teleradiology started (1987) by a type of digital video photography and fax-like printout at the receiving end [20]. In any event, these techniques are applicable to any rural emergency medicine practice as a means to provide preliminary interpretations after hours. This compression method is also suitable for patients to load CTs into their personal health file for long-term storage. Other considerations are web-based image and reporting systems [16] that could be widely available for deployed patients and providers.

Conclusion

We demonstrated the feasibility of using video compression of DICOM images using MPEG-4 technology at very high compression ratios. Such technology would be useful in combat operations or austere environments where images are acquired in remote locations with limited upstream bandwidth.

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