An Effective Ultrasound Video Communication System Using Despeckle Filtering and HEVC

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***Abstract*—The recent emergence of the high-efficiency video coding (HEVC) standard promises to deliver significant bitrate savings over current and prior video compression standards, while also supporting higher resolutions that can meet the clinical acquisition spatiotemporal settings. The effective application of HEVC to medical ultrasound necessitates a careful evaluation of strict clinical criteria that guarantee that clinical quality will not be sacrificed in the compression process. Furthermore, the potential use of despeckle filtering prior to compression provides for the possibility of significant additional bitrate savings that have not been previously considered. This paper provides a thorough comparison of the use of MPEG-2, H.263, MPEG-4, H.264/AVC, and HEVC for compressing atherosclerotic plaque ultrasound videos. For the comparisons, we use both subjective and objective criteria based on plaque structure and motion. For comparable clinical video quality, experimental evaluation on ten videos demonstrates that HEVC reduces bitrate requirements by as much as 33.2% compared to H.264/AVC and up to 71% compared to MPEG-2. The use of despeckle filtering prior to compression is also investigated as a method that can reduce bitrate requirements through the removal of higher frequency components without sacrificing clinical quality. Based on the use of three despeckle filtering methods with both H.264/AVC and HEVC, we find that prior filtering can yield additional significant bitrate savings. The best performing despeckle filter (DsFlsmv) achieves bitrate savings of 43.6% and 39.2% compared to standard nonfiltered HEVC and H.264/AVC encoding, respectively.**

***Index Terms*—Bitrate gains, clinical evaluation, despeckle filtering, encoding, high efficiency video coding (HEVC), H.264/AVC, mHealth, video quality assessment (VQA).**

I. Introduction

THE new high-efficiency video coding (HEVC) standard is expected to revolutionize mobile health (mHealth) medical video communication systems [1]. Specifically designed for beyond high-definition (HD) video coding [2], HEVC supports real-time transmission of medical video at the acquired in-hospital resolution and frame rates. The latter is expected to play a key role in the adoption of HEVC-based mHealth video systems and services in standard clinical practice by eliminating spatiotemporal conversions that could limit clinical capacity.

Ultrasound video exhibits significant levels of speckle that are inherent in the ultrasound imaging process itself. Significant levels of speckle noise can compromise medical video image quality and require the moderate use of despeckle filtering that does not compromise diagnostic quality through overfiltering. Thus, the use of despeckle filtering prior to video compression provides an opportunity to improve quality while also lowering bandwidth requirements by reducing noisy components from higher frequency components.

The need to guarantee the diagnostic capacity of the communicated clinical content motivates the development of diagnostically driven mHealth systems. The use of diagnostic region(s) of interest (d-ROI) allows us to allocate bitrate budgets based on diagnostic capacity. As demonstrated in [3]–[5], the use of d-ROI can provide significant bitrate gains. Furthermore, d-ROI can be protected more strongly during transmission in error-prone wireless networks as discussed in [3], [6], and [7]. Diagnostically resilient encoding and decoding described in [4] and [8] provides support for effective mHealth video communications in noisy channels.

Unfortunately, the quality of the compressed videos requires medical expert verification and cannot be done automatically. The development of new clinical video quality assessment (c-VQA) algorithms is a necessary prerequisite for the wider adoption of modern mHealth video communication systems in standard clinical practice [1]. At the same time, the timely integration of new compression and wireless technologies enhances the capacity of mHealth systems to accommodate diagnostically robust architectures and expedites utilization in standard clinical care.

This is also highlighted in a preliminary study reported by our group in [9], where the HEVC was shown to outperform the d-ROI approach described in [4] that used H.264/AVC. We also published another preliminary study on the use of HEVC for reproducible clinical diagnosis in mHealth systems in a recent conference paper in [10]. Similarly, preliminary results on the use of despeckle filtering were published in conference papers in [11] and [12]. A wide range of despeckle filtering methods have been summarized in [13] and [14].

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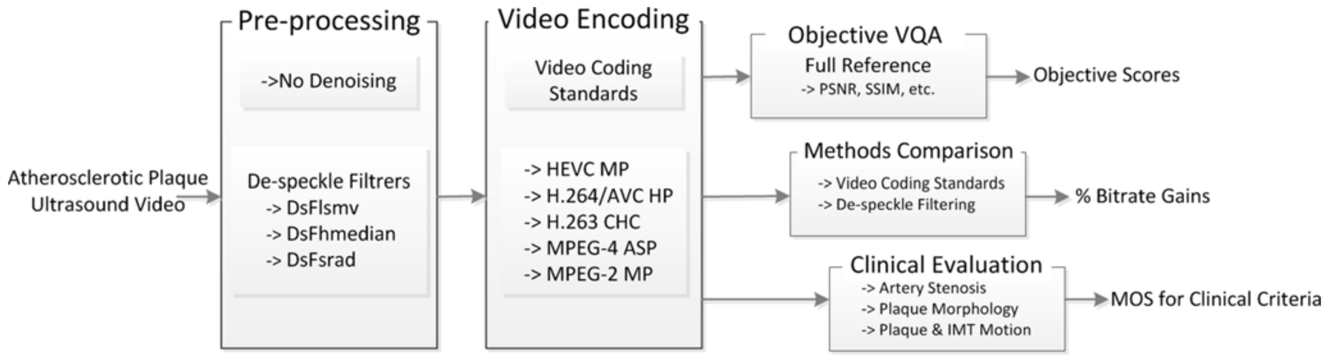

Fig. 1. Ultrasound video encoding and evaluation system diagram. Ultrasound video denoising precedes video encoding. The user can select the appropriate despeckle filtering algorithm and the most efficient video compression standard. VQA includes clinical evaluation by the relevant medical expert as well as objective measurements. Despeckle filtering methods and video coding standards comparison provides the bitrate gains achieved by the best performing methods.

The paper has two objectives as reflected in the system diagram of Fig. 1. The first objective is to examine the effectiveness of the use of despeckle filtering prior to encoding. The second objective is to investigate the efficiency of the HEVC standard for ultrasound video communications, while performing a comprehensive comparison to other video coding standards. Experimental evaluation is based on 1) full reference video quality assessment (VQA) algorithms [e.g., peak signal-to-noise ratio (PSNR) and structure similarity (SSIM)], 2) bitrate requirements and resulting bitrate gains of the assessed methods following comparison using the Bjontegaard metric (BD-rate), and 3) clinical evaluation of ultrasound videos compressed using different methods by a neurovascular specialist.

The contributions of this paper are summarized under three areas.

1) *Despeckle filtering for ultrasound video communication mHealth systems*: Here, we investigate the use of despeckle filtering as a preprocessing step to ultrasound video coding and transmission. The aim is to document significant coding efficiency attributed to the use of despeckle filtering algorithms without compromising clinical capacity of the communicated ultrasound video.
2) *Video coding standards comparison for ultrasound video communications*: The emerging HEVC standard is compared against its predecessor, the H.264/AVC standard, and also MPEG-4, MPEG-2, and H.263. Results are documented using both VQA metrics and a clinical-VQA protocol for ultrasound-based assessment of atherosclerosis.
3) *Clinical evaluation using a clinically established protocol*: Clinical evaluation is based on a clinically established protocol that reflects the assessment of in-hospital atherosclerotic plaque ultrasound examinations. Clinical criteria evaluate a) artery stenosis by assessing atherosclerotic plaque structure, b) atherosclerotic plaque type by assessing atherosclerotic plaque morphology, and c) atherosclerotic plaque motion patterns by assessing clinical motion of within plaque, boundary, and artery motions. Clinical motion criterion is used for the first time in medical video communication mHealth systems evaluation.

The rest of this paper is organized as follows. Section II provides a brief overview of video coding standards evolution, while Section III summarizes the methodology, including the examined ultrasound video despeckle filtering algorithms. Section IV discusses the experimental results analysis. Finally, Section V highlights the potential impact of the depicted results and provides some concluding remarks.

II. Video Coding: From H.261 to HEVC

We provide a brief overview of the capabilities and motivation behind the video coding standards that are considered in the current paper. We then provide a summary of the important new features that were recently introduced in the new HEVC standard.

The standard use of earlier video coding standards suffers from limited options of spatial resolutions. For example, H.261 [15] supports the common intermediate format ($\mathrm{CIF} = 352 \times 288$) that was later extended to 16CIF (1408×1152) in H.262/MPEG-2 [16]. H.262/MPEG-2 is still widely used for satellite TV broadcasting and DVD storage. H.263 introduced in 1995 provided for improved quality at lower bit rates and also allowed lower, sub-QCIF (128×96) video resolution encoding [17]. Significant coding tools improvements over H.262/MPEG-2 include multiple reference pictures, scalability support, and the introduction of error resilience tools that are essential for wireless medical video communications.

Compared to prior standards, H.264/AVC design tackles heterogeneous networks transportation. More specifically, H.264/AVC defines a video coding layer (VCL) and a network abstraction layer (NAL) [18]. The VCL enrichment with new coding tools (such as slice-based bi-predictive coding and context-adaptive binary arithmetic coding (CABAC) for entropy coding) and refinement of intra/intercoding, documents 50% bitrate demands reductions for perceptually equivalent quality compared to its predecessors [19]. CABAC has become standard for HEVC.

H.264/AVC provides error resilience techniques for communications in noisy wireless channels used in m-Health systems. Error resilient methods include the use of multiple reference pictures, flexible macroblock ordering (FMO) (widely used in diagnostic-ROI systems), redundant slices, arbitrary slice ordering (ASO), data partitioning, and switching-predictive/switching-intra pictures.

HEVC was launched in 2013 by the Joint Collaborative Team on Video Coding [20]. In terms of motion estimation, HEVC includes advanced motion vector prediction and merge mode for motion vector signaling and substantially enhanced intraprediction extending directional modes to 33 (from 8 in H.264/AVC).

HEVC defines three parallel encoding schemes, namely *tiles*, *wavefront parallel processing* (WPP), and *dependent slices.* Tiles allow independent parallel decoding of rectangular regions. Despite the fact that tiles appear similar to the H.264/AVC FMO concept, their primary objective is to expedite parallel decoding rather than provide for error resilience. WPP facilitates parallel processing of CTUs rows composing a slice. Dependent slices concept provides for a wavefront entry point or tile to be assigned to different NAL units, thus potentially speeding up the coding process. Parallel processing will significantly contribute to beyond HD real-time video streaming, one of the primary objectives of the HEVC standardization efforts. HEVC supports ultra-HD 8k × 4k (7680×4320) and up to 8192×4320 video resolutions compared to 4k × 2K $(4096 \times 2048$ and 4096×2304 for 16:9 aspect ratio) in H.264/AVC. By supporting much higher resolutions, HEVC allows encoding of clinical video at the original in-hospital resolution.

III. Methodology

The basic system diagram is presented in Fig. 1. Despeckle filtering is applied prior to video compression to improve quality while reducing bandwidth requirements. The filtered image is then encoded using a variety of different standards and then decoded in order to allow for comparisons with the original video. Validation of the system includes objective VQA, clinical evaluation based on mean opinion scores (MOS), and methods comparison to determine bitrate gains. We provide details on each component below.

A. Despeckle Filtering

We briefly introduce the despeckle filters used in this study and discuss how they impact video compression by reducing higher frequency content. For implementation details, we refer to [13]. The three despeckle filters used in this study were selected among ten different despeckle filtering techniques investigated in [12]–[14]. More specifically, the considered filters achieved the best performance in terms of visual (clinical) quality as assessed by medical experts [12]–[14], edge and texture preservation, and image quality evaluation performance [14].

1) Linear Despeckle Filtering (DsFlsmv): The DsFlsmv filter which utilizes first order statistics of the image, such as the variance and the mean of a pixel neighborhood is based on a multiplicative noise model [13], [14]. The despeckled image is estimated using

$$f_{i,j} = \bar{g} + k_{i,j}\left(g_{i,j} - \bar{g}\right) \tag{1}$$

where $f_{i,j}$ denotes the despeckled image, $g_{i,j}$ denotes the input image, $\bar{g}$ is the local mean over a local window, and $k_{i,j}$ is a weighting factor. The weighting factor $k_{i,j} \in [0, 1]$ is estimated based on local image statistics as follows [13], [14]:

$$k_{i,j} = \left(1 - \bar{g}^2\sigma^2\right) / \left(\sigma^2\left(1 + \sigma_n^2\right)\right). \tag{2}$$

The values σ^2 and σ_n^2 represent the variance in the moving window and the variance of noise in the whole image frame, respectively. The noise variance σ_n^2 can be estimated for each video frame based on the average noise variance over a number of windows with dimensions considerable larger than the filtering window. The local averages are applied using a moving window of size 5×5 and the filter is applied twice over the input image. In (1), weighting factor $k_{i,j}$ varies between zero and one. At near zero values, the output will be dominated by the mean value which is highly compressible since it can be effectively represented by the dc component. On the other hand, since the weighting factor remains at or below 1, deviation from the mean value will never be as high as in the original image.

2) Hybrid Median Filtering (DsFhmedian): DsFhmedian [21] computes the average of the outputs generated by median filtering with three different window shapes (cross shape, x-shape, and square windows of 5×5 pixels). As for DsFlsmv, the filtered image is a smoothed average that suppresses higher frequency content from the original input image.

3) Speckle Reducing Anisotropic Diffusion Filtering (DsFsrad): Speckle reducing anisotropic diffusion attempts to smooth image content within uniform regions while avoiding smoothing across edges [22]. The smoothed equation is based on

$$f_{i,j} = g_{i,j} + \frac{1}{n_s}\mathrm{div}\left({}_{\mathrm{srad}}\left(|\nabla_g|\right)\nabla g_{i,j}\right) \tag{3}$$

where the diffusion coefficient for the speckle anisotropic diffusion, ${}_{\mathrm{srad}}\left(|\nabla_g|\right)$, is used to discourage smoothing across edges. Refer to [14] for implementation details. Clearly, DsFsrad attempts to improve over DsFlsmv by preserving edge structures. Yet, as for DsFlsmv, DsFsrad will smooth regions and remove higher frequency content.

B. Video Coding Standards Comparison

The highest efficiency modes are selected for each encoding standard as given in [23]. Indicatively, for HEVC, all new coding tools are enabled—except weighted prediction—as per the single defined profile in the standard termed Main Profile (HEVC MP). For H.264/AVC the High Profile was selected (H.264/AVC HP), also with weighted prediction disabled. For MPEG-4 the Advanced Simple Profile (MPEG-4 ASP) was used, while the Conversational High Compression was selected for H.263 (H.263 CHC), and finally, the Main Profile was used for MPEG-2/H.262 (MPEG-2 MP). For a fair comparison, we vary the quantization parameters to achieve a similar range of rate-distortion performance for all standards. Furthermore, the quantization parameter step size is selected so that a single step results in PSNR increase of approximately 3 dB. More specifically, for MPEG-2, MPEG-4, and H.263, ultrasound videos are encoded using QPs ranging from 2 to 31 using QP = 2, 3, 4, 5, 6, 8, 10, 13, 16, 20, 25, 31, while for H.264/AVC and HEVC QPs range between 20 and 42, with a QP step size of 2. For all cases, 200 frames per video sequence were encoded and an intraencoded frame (I-frame) was inserted every 48 frames.

C. Video Quality Assessment

We consider the PSNR and the SSIM [24] for assessing video quality. Here, we note that the average PSNR and SSIM are computed over each video frame [25] and then averaged over the entire video. Both the PSNR and the SSIM are full reference methods that require access to the original, uncompressed videos. For evaluating image quality, SSIM correlates significantly better to perceived, visual quality than the standard use of PSNR [26]. However, it does not assess the motion of the reconstructed videos as required in our application. The subject of VQA is still an open area of research. For our application, we use extensive clinical VQA methods to properly address these issues.

D. Rate-Distortion Comparisons

To estimate bitrate savings, we compute the percentage savings for equivalent (objective) video quality. This is accomplished using the BD-rate algorithm [27]. The BD-rate algorithm is used to compute the objective differences between two rate-distortion curves and provides the percentage bitrate difference. The rate-distortion curves for the compared methods are constructed as functions of 12 rate points based on the luma PSNR (*Y*-PSNR). The final percentage difference is averaged over the examined dataset.

E. Clinical Video Quality Assessment

c-VQA aims to address the diagnostic quality of the reconstructed videos. There are three d-ROI that are considered here.

1) *Atherosclerotic plaque region*: This is the primary d-ROI (see caption in Fig. 2) and it is used to determine the plaque's type by assessing the plaque's morphology and texture characteristics.
2) *Near and far wall regions*: Visualizing the artery walls and associated motions are needed for the assessment of the degree of stenosis. Moreover, the motion differences between the arteries and atherosclerotic plaque(s) can be associated with plaque instability.
3) *ECG region for visualizing ECG waveform*: The ECG region is needed for measuring how stenosis and motion patterns of different plaque components change during the cardiac cycle.

Based on the aforedescribed clinically sensitive regions, the following c-VQA *criteria* are used for establishing the reproducibility of the diagnosis.

1) *The degree of the artery stenosis:* The percentage of the artery that is blocked by the plaque's presence, obscuring blood flow. Significant stenosis can be associated with stroke events.
2) *The plaque's morphology [28]:* The appearance of the plaque can be used to determine the plaque's type and infer the possible composition of the plaque. The composition

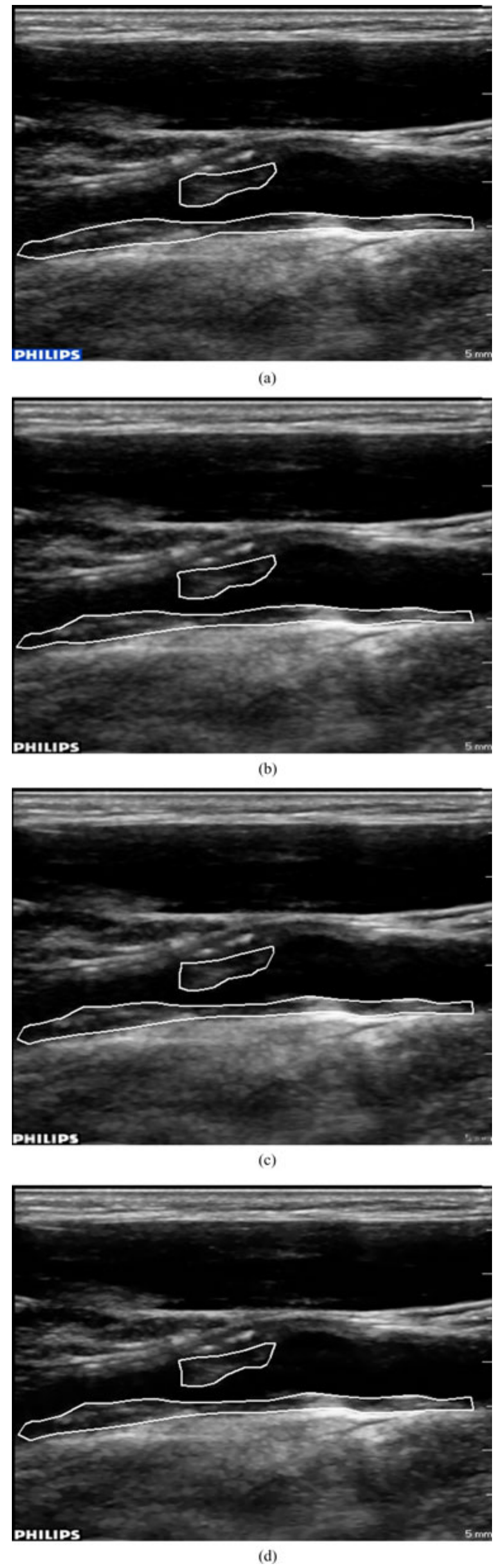

Fig. 2. Original and despeckled ultrasound images examples. Near and far wall atherosclerotic plaque segmentation (outlined by the white lines) using the segmentation algorithm described in [30]. (a) Original, (b) DsFlsmv, (c) DsFhmedian, and (d) DsFsrad. Note that the subtle differences between the despeckled and original image are difficult to detect which indicates that the moderate amount of despeckling used here removes higher frequencies that are not easily detected by the HVS (as desired). They become visible when the clinicians zoom into the regions of interest.

of the plaque provides critical information on the risk factors associated with stroke events.

3) *The plaque's and artery walls motion characteristics:* Plaque motion stability can be classified as concordant or discordant and be used as a potential risk factor as described in [29]. Here, we note that discordant motion is associated with instability. On the other hand, stiff plaques exhibit concordant motion and tend to be safer. Significant differences between plaque and arterial wall motions can also be used as an indicator of instability.

Individual scores are collected for each of the aforedescribed clinical criteria. The rating scale allows scores between one (1) at the lowest end, and five (5) on the opposite, highest end. A rating of 5 is assigned to the processed video that is diagnostically equivalent to the original, uncompressed video. A rating of 4 signals the loss of minor clinical details that is still diagnostically acceptable and provides sufficient information for a confident diagnosis. The clinical information present in the processed video is compromised and cannot be trusted for diagnosis purposes when the rating falls below the diagnostically acceptable margin of 4. As a result, a rating of 3, while it still contains clinical information does not qualify for atherosclerosis disease assessment. The lowest clinical rating of 1 corresponds to clinically useless ultrasound video.

IV. Results and Discussion

We first present the results of the efficiency of despeckle filtering as a preprocessing step to video coding for ultrasound video communications, followed by video coding standards comparison. In addition to the objective measurements, clinical evaluation is used to verify the clinical capacity of the processed ultrasound videos.

A. Clinical Ultrasound Video Dataset

The dataset is composed of ten atherosclerotic plaque ultrasound videos, with a spatial resolution of 560×416 at 50 frames/s. Instead of using the QCIF (176×144) and CIF (352×288) resolutions reported in [4], the collected videos at 560×416 do not include any resolution conversions. VQA is based at this higher resolution exported by the ultrasound equipment. Furthermore, this new set of videos has been specifically collected at 50 versus 15 frames/s of [4] to evaluate motion estimation (not covered in [4]). As in [4], to support the reproducibility of the results, we follow an established clinical protocol given in [30].

B. Video Compression Results After Despeckle Filtering

The use of despeckle filtering prior to video encoding can lead to significant improvements in rate-distortion performance as demonstrated in Fig. 3. As we describe next, these improvements vary significantly depending on the despeckle filtering method.

We present video despeckling examples in Fig. 2. Atherosclerotic plaque(s) formed on the near and far wall are outlined using the segmentation algorithm described in [31]. The segmented images allow visualization of the plaque boundaries and plaque morphology. The despeckled images exhibit very subtle differences that are hard to detect using the human visual system

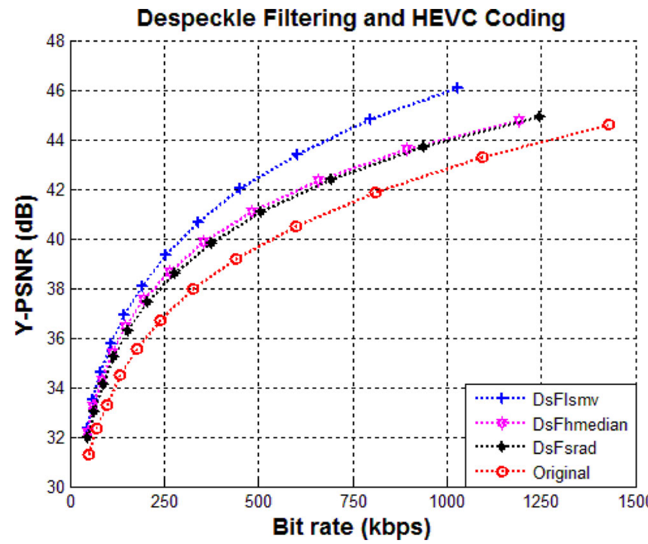

Fig. 3. Despeckle filtering algorithms efficiency. Rate-distortion curves of HEVC encoded videos (mean values of the ten 560×416@50 frames/s ultrasound videos for all investigated rate points). All algorithms outperform the conventional encoding procedure involving no speckle filtering. The best performing algorithm is the DsFlsmv. The DsFhmedian filter marginally outperforms the DsFsrad.

TABLE I
Bitrate Savings When Using Despeckle Filtering Prior to H.264/AVC and HEVC Encoding

	Bitrate Savings Relative to	
Despeckle Filtering Method	H.264/AVC Original	HEVC Original
DsFlsmv	39.2%	43.6%
DsFhmedian	32.5%	34.1%
DsFsrad	23.4%	23.5%

(HVS). Note that this is the desired behavior. Ideally, despeckle filtering removes higher frequencies that allow for better compression without visualizing significant artifacts that can compromise the diagnosis. After zooming into the images, it becomes clear that the despeckled images are smoother, missing some of the finer details that are present in the original image. The differences between the different despeckling methods are more difficult to visualize than their differences from the original image.

The differences among the examined methods are easily visualized in the rate-distortion curves of Fig. 3. As depicted in the graph, we have significant improvements for all methods.

Indicatively, as documented in Table I, DsFlsmv reduces bitrate requirements by as much as 43.6% and 39.2%, compared to standard HEVC and H.264/AVC encodings, respectively. The DsFhmedian filter lowers bitrate requirements by 34.1% for HEVC and 32.5% for H.264/AVC, while the DsFsrad filter achieves bitrate reductions of approximately 23% for both standards. As evident, the trend is the same for both standards. Based on objective evaluation, the DsFlsmv is the best performing filter, as it achieves the best PSNR scores while requiring lower bitrates than alternative methods. The hybrid median marginally outperforms the DsFsrad filter. It is important to note here that

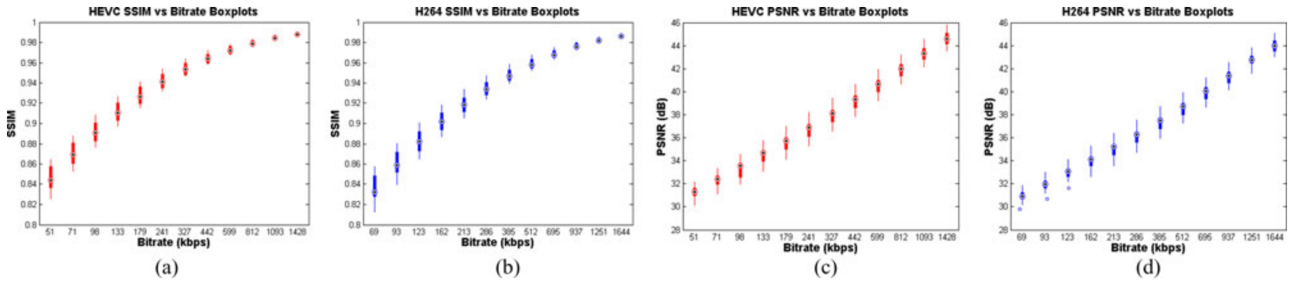

Fig. 4. Boxplots of HEVC (red) versus H.264/AVC (blue) that demonstrate video quality (SSIM and PSNR) as a function of bitrate (rate distortion), for ten ultrasound videos. HEVC requires significantly less bitrate while it achieves higher SSIM and PSNR scores than rival H.264/AVC standard. (a) HEVC SSIM scores versus Bitrate boxplots, (b) H264 SSIM scores versus Bitrate boxplots, (c) HEVC PSNR scores versus Bitrate boxplots, and (d) H264 PSNR scores versus Bitrate boxplots. The bitrate values used here are mean values of the ten ultrasound videos of the examined dataset of the 12 quantization parameters (QP range 20–42) discussed in Section III.

the objective results regarding the efficiency of the speckle filtering algorithms are also verified by the clinical evaluation as discussed below in Section IV-D. To highlight the necessity of efficient video compression methods, we note that for ultrasound video communication purposes, an original uncompressed video would require 93.18 Mbps (560 width resolution $\times$ 416 horizontal resolution $\times$ 50 frames/s $\times$ 8 bits per pixel $=$ 93.18 Mbps). Using the DsFlsmv and HEVC encoding for a QP of 28, which achieves diagnostically lossless ultrasound video quality, the transmission rate is reduced to 340 kbps. In other words, a compression ratio of 274 is achieved. Beside the obvious storage space savings, efficient compression that preserves the ultrasound video's clinical capacity allows transmission over existing 3.5G wireless infrastructure (for the particular video resolution), otherwise not feasible for 4G cellular networks (for the uncompressed video).

C. Video Coding Standards for Ultrasound Video Communications

Fig. 4 shows boxplots of video quality measured in PSNR and SSIM as a function of bitrate for the HEVC MP and H.264/AVC HP video coding standards. From the plots, it is clear that HEVC MP requires less bitrate while achieving higher video quality than H.264/AVC HP. More directly, Fig. 5 presents a comparison of the median rate-distortion performance of HEVC MP against H.264/AVC HP, H.263 CHC, MPEG-4 ASP, and MPEG-2/H.262 MP. From Fig. 5, for the same bitrate, it is clear that HEVC achieves higher levels of video fidelity.

As documented in Table II, HEVC achieves average bitrate gains of 33.2% compared to H.264/AVC. Bitrate savings of 54.6% and 58.3% are observed for earlier H.263 CHC and MPEG-4 ASP standards, respectively, while bitrate gains extend up to 71% when compared to MPEG-2/H.262 MP. Bitrate reductions from using H.264/AVC or other later standards compared to earlier ones are also summarized in Table II.

D. Clinical Evaluation

1) Despeckle Filtering: Two medical experts (a cardiovascular surgeon and a neurovascular specialist) were asked to grade the ultrasound videos based on the clinical criteria that were discussed in Section III-E. To emphasize the effects of despeckling, the original videos were presented side-by-side with the despeckled videos. All evaluations were performed using laptop equipment with a spatial resolution 1920×1080 and maximum screen brightness, in a mildly dark environment. Sufficient time was allocated for the medical expert's eyes to adjust to the current lighting conditions. The viewing distance was approximately 1 m. Overall, the viewing conditions were comparable to a routine clinical exam.

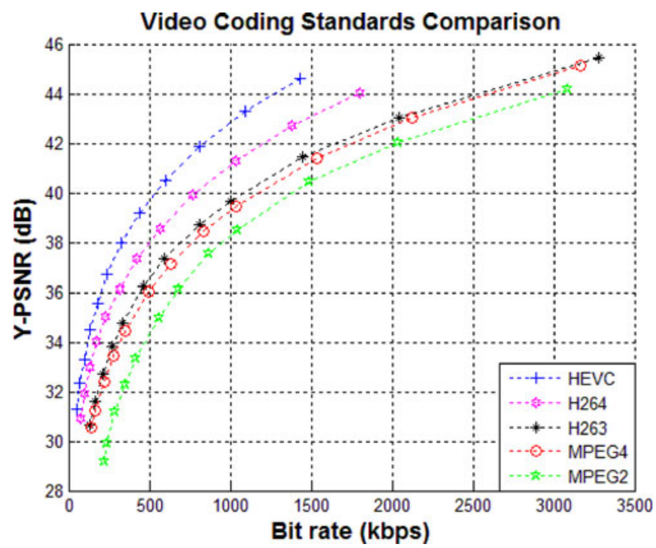

Fig. 5. Video coding standards comparison. Rate-distortion curves (mean values of the ten 560×416@50 frames/s ultrasound videos for all investigated rate points). HEVC lowers bitrate requirements while it provides for higher PSNR values compared to all prior video coding standards.

Table III summarizes the average scores for the three clinical criteria for the ten ultrasound videos of the dataset, prior to compression. As evident in the table, the DsFlsmv and DsFhmedian filters, yield comparable clinical ratings as the original video. Furthermore, the medical experts emphasized that the overall clinical capacity was neither compromised nor improved from the use of the DsFlsmv and DsFhmedian filters. On the other hand, in some cases, the DsFsrad filter did seem to negatively affect the visualization of the morphology of the plaque as presented in Table III.

The clinical capacity of the despeckled and original ultrasound videos following compression was also clinically validated. The results are presented in Table IV for a subset of the

TABLE II
VIDEO BITRATE SAVINGS OF DIFFERENT STANDARDS COMPARED AGAINST PREVIOUS CODING STANDARDS

	Bitrate Savings Relative to			
Encoding	H.264/MPEG-4 AVC HP	H.263 CHC	MPEG-4 ASP	MPEG-2/H.262 MP
HEVC MP	33.2%	54.6%	58.3%	71%
H.264/MPEG-4 AVC HP	-	32.3%	37.7%	56.8%
H.263 CHC	-	-	7.5%	32.4%
MPEG-4 ASP	-	-	-	27.4%

TABLE III
CLINICAL CRITERIA EVALUATION FOR DESPECKLED VIDEOS (UNCOMPRESSED)

Filter	Stenosis	Morphology	Motion
Original Video	5.0	5.0	5.0
Dflsmv	4.9	4.7	4.8
DsFhmedian	5.0	4.7	4.9
DsFsrad	5.0	4.2	4.7

The average values for stenosis, morphology, and motion are graded from 1 (lowest) to 5 (highest).

TABLE IV
DESPECKLE FILTERING ULTRASOUND VIDEOS CLINICAL CAPACITY FOLLOWING HEVC ENCODING

	Stenosis			Morphology			Motion		
Quantization Parameter	36	32	28	36	32	28	36	32	28
Original Video	4.8	4.8	4.8	4.8	4.8	4.8	4.8	5.0	4.8
DsFlsmv	4.4	4.6	4.6	3.8	4.2	4.6	4.6	4.6	4.6
DsFhmedian	4.6	4.6	4.6	3.8	4.2	4.8	4.4	4.8	4.8
DsFsrad	4.6	4.8	4.4	4.2	4.6	4.4	4.8	4.8	4.8

MOS are presented for four videos for three QPs: 36, 32, and 28.

TABLE V
CLINICAL VALIDATION OF A SINGLE VIDEO FOR ALL INVESTIGATED VIDEO CODING STANDARDS

	Stenosis			Morphology			Motion		
Quantization Parameter[a]	42 (31)	32 (10)	28 (6)	42 (31)	32 (10)	28 (6)	42 (31)	32 (10)	28 (6)
HEVC MP	5	5	5	4	5	5	3	5	5
H.264/AVC HP	5	5	5	3	4	5	4	5	5
MPEG-4 ASP	3	5	5	2	5	5	2	4	5
H.263 CHC	3	4	5	3	5	5	3	5	4
MPEG-2/H.262 MP	3	4	4	2	4	4	2	3	3

[a]The quantization parameter outside the parenthesis corrsponds to HEVC and H.264/AVC standards while the QP inside the parenthesis is used for MPEG-4, H.263, and MPEG-2 standards.
A clinical score from 1 to 5 is assigned for the three clinical criteria described in Section III. Here, for three QPs: 42, 32, and 28. This table also appeared in our conference paper in [10].

examined QPs averaged over four videos. Clinical scores verify that despeckled ultrasound videos yield comparable diagnostic capacity to the original, nondespeckled videos. Despite documented outliers (mostly for the DsFsrad filter), clinical capacity of the compressed videos is enhanced as bitrate budget increases (quantization levels decreases). Overall, ultrasound video denoising can be effectively used to minimize bitrate and storage requirements, providing a powerful tool in wireless medical video communications. Artery stenosis and the atherosclerotic plaque's motion assessment received consistently high ratings. Both criteria relate to the ultrasound video's frame rate and support the requirement of communicating medical videos at the acquired frame rate. Morphology assessment requires encoding using QPs lower than 32 for providing diagnostically acceptable clinical scores ($\geq$4). Still, diagnostically acceptable HEVC compression threshold needs to be investigated for a higher number of cases.

2) Video Coding Standards Comparison: Table V records the clinical ratings of a neurovascular specialist for each of the assessed clinical criteria for all investigated video coding standards. Evaluation is performed for a subset of the total encoded instances of a single video. However, the trend is the same for the ultrasound video dataset used in this study. As the clinical scores indicate, the new HEVC standard is the only standard that achieves maximum scores for all evaluated criteria for a QP of 32. On the other hand, H.264/AVC and MPEG-4 require finer quality encoding to achieve the highest clinical capacity possible at a QP of 28. Earlier standards such as H.263 and MPEG-2 do not provide quality comparable to the uncompressed video at these QPs.

In general, for the ultrasound video dataset used in this study, HEVC encoded videos are typically assigned higher clinical scores than the H.264/AVC encoded videos for the same QPs, which in turn outperform MPEG-4 videos. H.263 and MPEG-2 videos attain similar clinical ratings. As documented in [23], HEVC achieves even greater bitrate gains compared to H.264/AVC when the comparison is based on perceptual quality.

V. Concluding Remarks

Both objective evaluations and MOS based on clinical criteria provide evidence that the emerging HEVC standard yields significant improvements in compression efficiency compared to prior video coding standards. For wired communications channels, we recommend that HEVC be adopted for medical video communication systems. For wireless communications channels, there needs to be an exhaustive evaluation of HEVC's error-resilient performance in noisy channels. Despeckle filtering prior to video encoding can lead to significant bitrate savings without compromising diagnostic quality.

Ongoing work involves investigating different medical video modalities and emergency trauma videos for (beyond) HD encoding using HEVC and transmission over LTE, LTE-Advanced, and WirelessMAN-Advanced wireless networks based on both simulations and real-life scenarios [31]. Future work should also focus on the development of automated methods that can be used to predict the MOS on each one of the clinical criteria.

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