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COMPARISON OF VISUALLY LOSSLESS COMPRESSION OF DENTAL IMAGES BY DIFFERENT CODERS BASED ON HAARPSI METRIC

Abstract. The object of the study is the process of visually lossless compression of dental images by means of five coders using HaarPSI metrics and its distortion invisibility threshold. **The subject of the study** is the method for selection of parameters that control compression to provide invisibility of distortions with further comparison of performance characteristics for the considered coders. **The goal of the study** is to analyze compression ratio range for image fragments of different complexity and to give recommendations concerning coders to be used and their parameters setting. **Methods used:** numerical simulation, verification for a set of test images. **Results obtained:** 1) the compression ratios vary in rather wide limits depending on image complexity and noise characteristics; 2) the coders AGU-M and BPG produce the best compression ratios for the same visual quality compared to other considered coders; 3) there is high correlation of compression ratios of the considered coders. **Conclusions:** 1) it is possible to provide rather large compression ratios without losing diagnostically valuable information; 2) adapting the compression to image complexity allows significant increasing of compression ratios for simple structure images.

Keywords: visually lossy compression; five different coders; performance comparison.

Introduction

Imaging systems are extremely useful in numerous applications including medical diagnostics [1], social networking [2], ecology [3], etc. Due to better resolution of novel imagers, the use of more components in acquired images and other factors the average image size rapidly increases.

Although memory facilities and communication network characteristics also improve, this takes place not so quickly. This leads to necessity to design new methods for image compression where lossless techniques [4, 5] are often unable to satisfy requirements to compression ratio (CR). This has led to special attention to lossy compression techniques and methods for image quality control [5–7].

Lossy compression of medical images in general and dental images (considered in this paper) in particular has specific features [8–10]. About 20 years ago, it was intensive discussion in medical image processing community is it possible to apply lossy compression or only lossless compression can be used [11, 12]. The agreed solution was that lossy compression could be employed under condition that it could be treated as near-lossless or visually lossless where the introduced distortions are invisible and do not have a negative impact on diagnostically valuable information [13, 14]. After getting such understanding, the corresponding techniques started to be developed [15–17]. Additional necessity in design of visually lossless compression techniques stems from the fact that modern medical images often have the size larger than 1 MB [18].

Three main requirements to visually lossless compression are the following [17]. First, the provided CR should be as large as possible. Second, a developed algorithm has to guarantee that the compression is really visually lossless. Third, such a compression should be realized quickly enough and in automatic way (without participation of a human). Thus, design and testing of visually lossless compression techniques and algorithms is a complex and non-trivial task.

Concerning the first requirement, it is clear that the theory and practice of lossy image compression continuously develops and new approaches appear. In particular, AVIF [19] and HEIF [20] coders are relatively new ones. However, their ability to carry out visually lossless compression has not been intensively studied yet. BPG coder [21] has been already tested for lossy [8] and visually lossless [17] compression of medical images; it has been demonstrated that, on the average, it outperforms JPEG and other coders but the main benefits are mainly observed for simple structure images [17, 22]. Neural network based coders are quickly developing with providing very good results [23] but, to the best of our knowledge, the task of providing visually lossless compression for them is paid very little attention at the moment. So, the task of considering visually lossless compression for new compression techniques remains actual.

Concerning guaranteeing really visually lossless compression – the concept of just noticeable differences (JND) has been introduced recently and intensively studied by several researchers [22, 24–26]. Other approaches based on applying special modifications of coders intended on providing improved visual quality (for example, the coder AGU-M considered in [17]) with fixed setting of a parameter that controls compression (PCC) have been put forward. It has been demonstrated that the first JND point (JND#1) considerably depends on image complexity that cannot be uniquely described [22]. Besides, JND#1 depends on noise properties (if noise is visible) and noise visibility in medical (including dental) images is quite typical [27]. In such cases, noise presence introduces additional peculiarities into image lossy compression [28].

Then, techniques of visually lossless compression have to be intensively tested with attraction of professionals of medical image analysis [17].

Metrics used in visually lossless compression is a special aspect. The theory of image quality assessment develops rapidly and designers produce tens of new visual quality metrics each year that need to be intensively tested and compared to already existing ones. Since analysis of medical images by professionals presumes special attention to image parts dealing with possible diagnostically valuable features, in this paper, we prefer using one of metrics, HaarPSI [29], that incorporates visual saliency maps, i.e., employs mechanisms similar to image analysis by medical specialists.

Analysis using HaarPSI in visually lossless compression states one more novelty aspect of this paper.

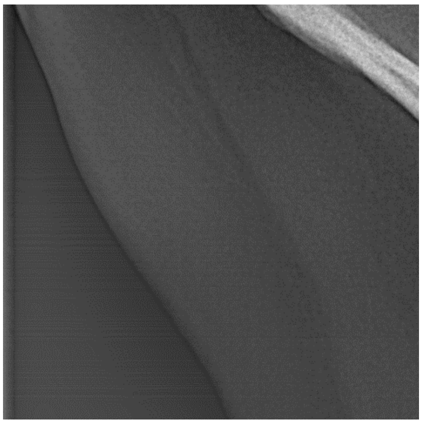
Concerning automatic realization of visually lossless compression, we pay basic attention to PCC values for which JND#1 happens (or is supposed to happen according to HaarPSI). Such preliminary analysis is important for the so-called two-step methods of providing a desired visual quality [17, 30] which rely on the starting point to be set based on preliminary experiments with a set of test images.

Thus, the **object of our study** is the process of HaarPSI-based visually lossy compression of dental images by several coders including HEVC-based ones. Our **basic idea** is that HaarPSI is able to provide preconditions for one- or two-step compression for different coders. **The goal** of this paper is twofold: 1) to compare performance of the considered coders and give the corresponding practical recommendations; 2) to show how HaarPSI metrics can be exploited in design and realization of fast procedures for compressing dental images without loss of diagnostically important information.

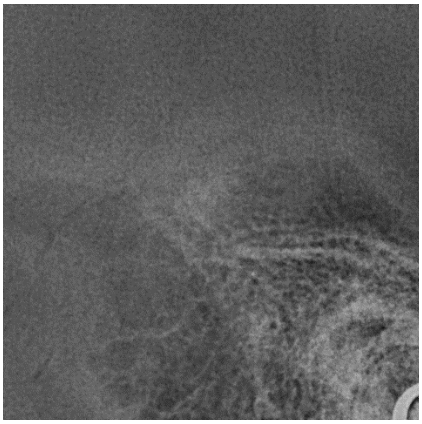
Background of image lossy compression and quality assessment

The main approach to analysis of image lossy compression is to obtain and investigate the so-called rate-distortion curves (RDCs), e.g., dependences of a used quality metric on PCC for a given coder. Here, we consider five coders for which three coders, namely, JPEG, AVIF, and HEIF, use the same PCC called quality factor (although the essence of this PCC is slightly different for these coders) and the BPG coder uses the parameter Q whilst AGU-M employs scaling factor (SF). Without losing generality, we well denote PCCs as Q for all coders with brief preliminary analysis of RDC specific features for each coder.

Since RDC in any case depends on properties of an image to be compressed [7, 17, 26], for each coder, we present RDCs for simple and complex structure images. Examples of such images (in fact, 512×512 pixel fragments taken from large size dental images) are given in Fig. 1 where the simple structure image is shown in Fig. 1, a and the complex structure one – in Fig. 1, b. The reason for further analysis for two images of considerably different complexity is that usually just for them the difference in behavior of the corresponding RDCs is the most essential.



a



b

Fig. 1. Fragments of dental images with simple (part 20) (a) and complex (part 11) (b) structures

Fig. 2, a presents dependences of peak signal-to-noise ratio (PSNR) on QF for JPEG. As seen, for the same QF (e.g., equal to 40), the difference in PSNR can be almost 5 dB. An advantage is that, in the region of the main interest (RMI, PSNR from 35 to 40 dB), both dependences behave almost linearly and are “almost parallel”.

The dependences of PSNR on SF for AGU-M coder are given in Fig. 2, b. As seen, difference of PSNRs for simple and complex structure images in RMI is rather large again (3-4 dB). RDCs for the BPG encoder are represented in Fig. 2, c. As one can see, in the RMI (Q about 27), PSNR can differ by 3 dB depending on image complexity. Finally, Fig. 2, d shows dependences for AVIF and HEIF coders. For AVIF, the difference in PSNR in the RMI (QF about 65) reaches approximately 3 dB. The difference is even larger for HEIF in the RMI (QF about 42).

After getting imagination about typical RDCs (they are usually monotonically increasing or decreasing functions, at least, for rather small CR), it is worth giving brief information concerning the considered coders. JPEG is well known; AGU-M uses 32×32 pixels blocks, non-equal quantization of coefficients of discrete cosine transform (DCT) in these blocks, bit-plane coding of quantized DCT coefficients, and embedded deblocking after decompression. SF used as PCC can be, in general, any positive value where SF≈8 provides compression near JND#1.

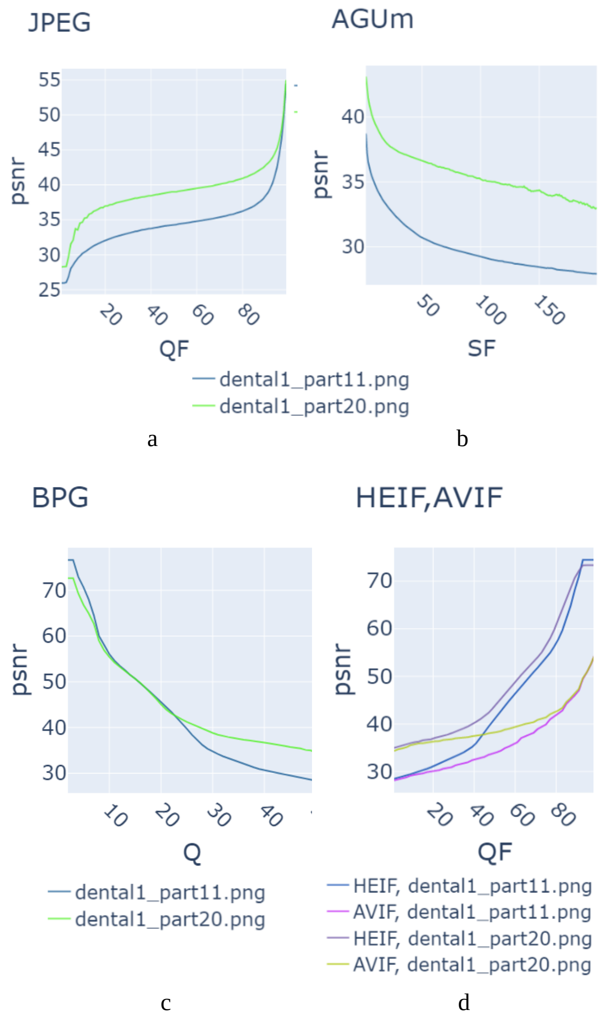


Fig. 2. RDCs PSNR on Q for JPEG (a), AGU-M (b), BPG (c), and AVIF and HEIF (d)

A larger SF produces a larger CR by the expense of worse quality. BPG, AVIF, and HEIF are all used in HEVC-based video compression. Due to adaptation to image content, they, on the average, significantly outperform JPEG. However, there is difference in the used PCC. The BPG coder exploits Q that can be integer and its maximal value is 51. A larger Q results in a larger CR and worse quality (Fig. 2, c). Q≈28 corresponds to distortion invisibility threshold (JND#1). AVIF and HEIF, similarly to JPEG, are controlled by QF. However, there are two specific features. First, for two neighbor QF values (e.g., 39 and 40), the compression results are identical. Because of this, we further consider only odd values of QF for these coders. Second, the behavior of RDCs for these coders is not like for JPEG. It is more similar to behavior for the BPG coder in the sense that QF changing by 2 leads to PSNR changing by ≈1 dB (for the BPG coder, Q changing by 1 results in PSNR decrease of about 1 dB). Recall here that PSNR changing by 1 dB for a given image subject to lossy compression can be usually hardly noticed.

For PSNR, JND#1 varies in wide limits from 23 dB to 42 dB [31] that, for JPEG, corresponds to QF from ≈30 to ≈80. Just these facts make problematic visually lossless compression of images using PSNR in general and using JPEG in particular. In turn, an important and positive moment is that RDCs for all coders are quite smooth and behave almost linearly for the RMI, i.e. for PSNR in the limits from 35 to 40 dB.

Visual quality metrics provide a more reliable assessment of visual quality. For example, JND#1 is observed if PSNR-HVS-M is within the narrower limits from 37 to 48 dB [31] that corresponds to HaarPSI in the limits from approximately 0.92 to 0.97. Recall here that HaarPSI, similarly to many other visual quality metrics, varies from 0 (terrible quality) to 1 (perfect quality). Then, it is possible to state that HaarPSI=0.95 approximately corresponds to JND#1 and use this value in our further experiments with dental image fragments as we previously [17] used PSNR-HVS-M=42 dB as distortion invisibility threshold.

Then, let us briefly analyze RDCs HaarPSI vs PCC for the considered coders. The obtained RDCs for the image fragments in Fig. 1 are presented in Fig. 3.

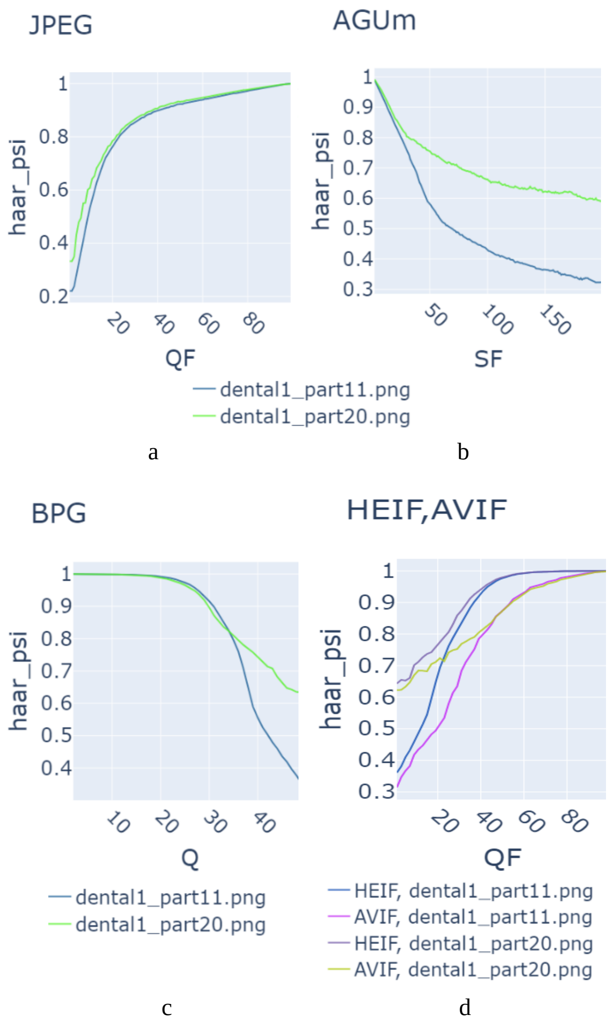


Fig. 3. RDCs HaarPSI on Q for JPEG (a), AGU-M (b), BPG (c), and AVIF and HEIF (d)

Again, we have quasi-monotonous functions demonstrating quality degradation (HaarPSI reduces) if QF decreases or Q and SF increase. Again, there are significant differences in visual quality of compressed images of different structure, especially for small QF or large Q and SF. Meanwhile, the results also show that HaarPSI=0.95 is observed for QF≈65 for JPEG, SF≈8 for AGU-M, Q≈28 for BPG, QF≈67 for AVIF, and QF≈43 for HEIF coders.

This allows setting HaarPSI=0.95 as JND#1 and to compare the coder performance in the sense of provided CR and other performance characteristics.

Analysis of the results for two sets of dental image fragments

One way to compare different coders is to set identical quality of compressed images according to a given metric and to compare the provided CR assuming that a better coder produces a larger CR. So, let us fix HaarPSI=0.95 supposing that it corresponds to invisibility of introduced distortions and analyze CR. Two images of simple and complex structure are not enough for analysis. Because of this, we have created a set of dental image fragments. It consists of twelve fragments of different complexity from a large dental image produced by Morita system [32] in the first operation mode and eight fragments of different complexity produced by the same system in the second operation mode (fragments in Fig. 1 are taken from Morita produced image in the first mode). There are two reasons for using image fragments from two different dental imagers.

First, we would like to show that the proposed approach to visually lossless compression is applicable to different dental data. Second, noise properties for images produced in different modes are not the same and this has impact on the obtained results [17].

Let us first analyze CRs obtained for five considered coders for two groups of test image fragments. For the first group (12 fragments), the obtained data are presented in Fig. 4, a, whilst the calculated CR are given in Fig. 4, b for the second group. The following conclusions can be preliminarily drawn from analysis of data in Fig. 1. For the first group of test image fragments:

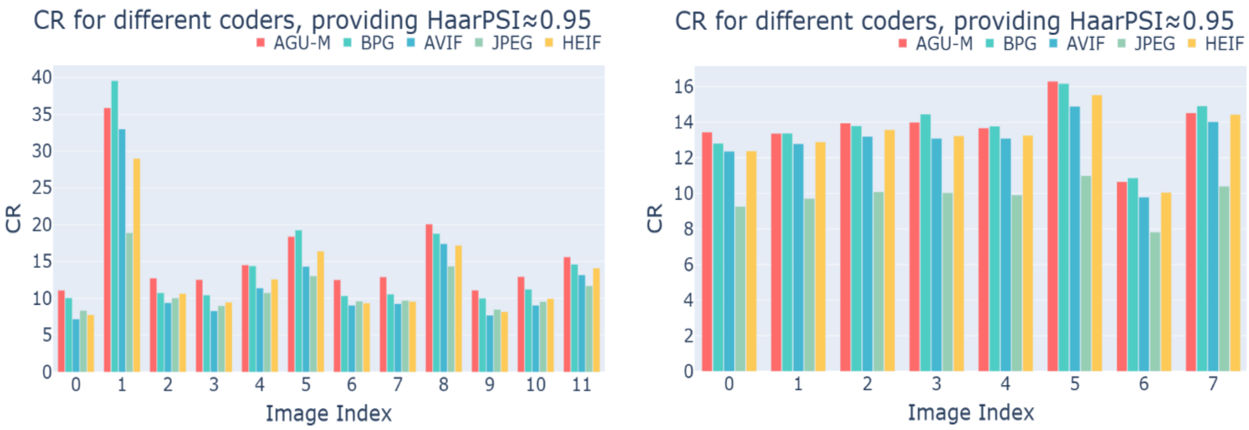
1) The worst results, as expected, are in general provided by JPEG although CR for JPEG is not the smallest for all fragments; CR values are about 10 with exception of three fragments having simple structure for which CR is from 13 to 19;

2) The best results for most fragments are provided by the BPG coder for which most CR values are about 12 whilst for three simple structure fragments CR is from 18 to 40;

3) The results for AGU-M are close to the results for the BPG-coder, most CR values are about 12, for simple structure fragments CR values are equal to 18.4, 20.1, and 35.7;

4) The CR values for AVIF and HEIF coders are of the same level as for JPEG for 8 out of 12 image fragments and they are significantly larger than for JPEG only for 4 out of 12 image fragments; meanwhile, the results for AVIF and HEIF are worse than for the AGU-M and BPG coders;

5) Attentive analysis allows predicting high correlation between CR values for different coders. To check this hypothesis, we have calculated Spearman rank order correlation coefficient between CRs for different coders. The obtained data are presented in Table 1.



a b

Fig. 4. Values of CR for the first (a) and second (b) groups of test image fragments for five considered coders providing HaarPSI≈0.95

Table 1 – **SROCCs between CR values for different coders**

Coder	AGUm	AVIF	BPG	HEIF	JPEG
AGUm	**1**	0,937063	0,979021	0,979021	0,937063
AVIF	0,937063	**1**	0,93007	0,965035	1
BPG	0,979021	0,93007	**1**	0,979021	0,93007
HEIF	0,979021	0,965035	0,979021	**1**	0,965035
JPEG	0,937063	1	0,93007	0,965035	**1**

Analysis of data in Table 1 shows that there exists very high correlation between CR for coders. In the worst case, it is equal to 0.93 (between CRs for BPG and AVIF or JPEG) whilst SROCC occurred to be equal to 1 for AVIF and JPEG. Certainly, the results are obtained for a limited number of image fragments of certain type. However, these data clearly show that image complexity is very important for any coder.

Data for the second group of test image fragments (Fig. 4,b) demonstrate that CRs in this case for modern coders are better than for JPEG. The CR values for the BPG and AGU-M coders are again slightly better than for the AVIF and HEIF coders. For JPEG, CR is again about 10. These results for JPEG are in good agreement with the recommendations in [13].

The results obtained for JPEG, AGU-M, and BPG are also in good agreement with data in [17]. To partly prove this, let us give the intervals of PSNR-HVS-M observed for the provided HaarPSI=0.95 for the considered test fragments (Table 2).

Analysis for the first set shows the following:

1) The intervals of CR for all coders partly coincide, but the largest CR is observed either for the BPG or AGU-M coder;

2) The intervals of PSNR-HVS-M partly coincide as well but the best results are provided by JPEG;

3) The intervals for MS-SSIM [34] (the larger the better, variation range is from 0 to 1) partly coincide as well; the best results are provided by HEIF.

Thus, according to different metrics, the best results are provided by different coders. The main reason is that different metrics of visual quality take into account different aspects of human vision system (HVS). Then, in aggregate, the BPG coder can be recommended with Q=27 used as fixed or starting value (the details will be given below).

Analysis for the second set results in almost the same conclusions:

1) The intervals of CR again partly coincide and the largest CR is again provided by the BPG or AGU-M coder;

2) According to PSNR-HVS-M, the best results are produced by JPEG;

3) According to MS-SSIM, the best results are produced by HEIF.

In such a situation, it is possible to propose using the BPG coder with Q=30 used as fixed or starting value.

Let us explain the approaches with the fixed setting and two-step procedure more in detail. There are two reasons why the provided quality in visually lossless compression can be, in some degree, inacceptable. First, the visual quality metric and the distortion invisibility threshold set for it are not perfect. For example, setting a larger threshold for HaarPSI or PSNR-HVS-M leads to higher probability that introduced distortions cannot be noticed. Second, the visually lossless compression procedure does not produce the desired metric value perfectly. In particular, this might happen if one uses setting a fixed PCC. Then, for different images one, in fact, obtains different values of visual quality metrics. Besides, errors in providing a desired value of visual quality metrics can be due to discrete nature of PCC as this happens for JPEG, BPG, AVIF, and HEIF coders. Then, one has to be sure that the results of visually lossless compression are acceptable for a given application.

Table 2 – **Intervals of CRs and metric values for the considered coders and test fragment sets**

Performance characteristic	Coders				
	JPEG	AGU-M	BPG	AVIF	HEIF
Set 1					
PCC	62-67	7-9	26-28	63-71	41-43
CR	8.3-14.4	11.1-35.9	10.0-39.5	7.2-33.0	7.8-29.0
PSNR-HVS-M	42.5-46.9	41.9-44.1	40.9-43.1	41.4-43.0	42.5-43.3
MS-SSIM	0.983-0.987	0.985-0.989	0.984-0.988	0.987-0.989	0.988-0.989
Set 2					
PCC	47-57	9-12	29-31	57-63	41
CR	7.8-10.1	10.7-14.5	12.8-16.2	12.3-14.9	12.3-15.5
PSNR-HVS-M	42.3-43.5	41.3-42.9	40.9-42.1	41.2-42.4	41.5-42.2
MS-SSIM	0.988-0.992	0.990-0.993	0.990-0.992	0.991-0.993	0.991-0.994

The two-step procedure [17, 30] allows avoiding the second aforementioned factor. A part of work is done in advance. Suppose one deals with compression of images acquired by a given imaging system for a given mode and a coder for visually lossless compression as well as a visual quality metric S to be employed are chosen. Then, using a set of K images or their large fragments, it is possible to obtain a set of RDCs $S_k(PCC)$, k=1,…,K. After this, one obtains the averaged curve $S_{aver}(PCC)$ and determines its derivative S`(PCC). Both $S_{aver}(PCC)$ and S`(PCC) are saved for the further use. Assume now that one has an image to be compressed with providing a desired S_{des}. The first step is to determine PCC_1 for which $S_{aver}(PCC_1)$ is equal or approximately equal to S_{des}. Then, the considered image has to be compressed using PCC_1 and decompressed. After this, $S(PCC_1)$ should be determined. If the calculated difference $|S(PCC_1) - S_{des}|$ is satisfactory (e.g., less than 1 dB for PSNR-HVS-M), the second step is not needed. If the difference is too large, linear approximation using $S_{aver}(PCC)$ and $S`(PCC)$ is performed and $PCC_2$ is determined as $PCC_2=PCC_1+(S_{des}-S(PCC_1))/S`(PCC_1)$. After this, the final compression using PCC_2 is carried out.

The two-step procedure might have several peculiarities depending on used metrics or PCC [30] intended on achieving better accuracy. Meanwhile, usually it produces quite good results.

Practical aspects and discussion

First of all, any designed method of visually lossless compression has to be tested. For dental images, the corresponding experiments carried out with attraction of dentistry specialists similarly to [17] have to be conducted. Since for the coders JPEG, AGU-M, and BPG the experiments have been already carried out [17] and here we have practically the same intervals of PSNR-HVS-M values as in [17], we have concentrated more on the coders AVIF and HEIF. Examples of original (uncompressed) and compressed (by both coders with providing HaarPSI≈0.95 by the two-step procedure) image fragments are shown in Fig. 5. It is very difficult to find differences between image fragments in Fig. 5 but here the fragments are presented not in full size.

a	b	c

Fig. 5. Original (a) and compressed by HEIF (b, QF=43) and AVIF (c, QF=63) image fragments

Thus, special experiments have been carried out using full size representation of pairs of the original and compressed image fragments for these two coders (see [17] for more details).

The fragments were put at monitors in random order. Convenient distances from the monitors were taken. Four specialists from University Dental Center, at the Department of Pediatric Dentistry and Implantology of Kharkiv National Medical University, Kharkiv, Ukraine, after obtaining informed consent from all patients took part in experiments. Only in 16% of cases for AVIF and 13% cases for HEIF the differences have been noticed but in no case they have been treated as such that lead to degradation unacceptable from the correct diagnostics viewpoint. Thus, we can state that HEIF performs slightly better than AVIF but anyway the results for HEIF are worse than for the BPG and AGU-M coders studied earlier.

Some difference in the results for images acquired by different modes of Morita imaging systems has been observed (see data in Table 2). In the latter case (for the second set of image fragments), the intervals of CRs are more narrow, the values of MS-SSIM are larger. We associate this with two factors. First, it is worth testing more image fragments for images acquired by Morita imager. Second, we believe that the properties of the noise have specific impact on compression results. In this sense, special studies are needed for the cases of compressing images contaminated by spatially correlated and signal-dependent noise.

Finally, it has been demonstrated that CR for simple structure images can be significantly larger than for most other images. In this sense, pre-detection of such simple structure images might be useful.

Conclusions

In this paper, we have demonstrated that HaarPSI metric can be successfully used for providing visually lossless compression of dental images or their fragments. The applicability is shown for 5 coders including both conventional JPEG and modern coders such as BPG, AVIF, and HEIF. The high correlation between CR values for the considered coders is established. This, probably, this phenomenon can be used in prediction of CR for modern coders using JPEG data.

All modern coders, on the average, produce better results than JPEG. Meanwhile, it is demonstrated that AVIF and HEIF produce worse results than the BPG coder. The presented results also show that the performance characteristics for images acquired in different modes of imaging systems can be slightly different.

Noise present in dental images might have essential impact on compression results. Then, special studies for spatially correlated and signal-depended noise are needed.

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Порівняння візуального непомітного стиснення зображень стоматології різними кодерами на основі метрики HaarPSI

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Анотація. Об'єктом дослідження є процес візуально безвтратного стиснення стоматологічних зображень за допомогою п'яти кодерів із використанням метрики HaarPSI та її порогового значення непомітності спотворень. **Предметом** дослідження є метод вибору параметрів, що керують стисненням, з метою забезпечення непомітності спотворень, а також подальше порівняння ефективності розглянутих кодерів. **Метою** дослідження — проаналізувати діапазон коефіцієнтів стиснення для фрагментів зображень різної складності та надати рекомендації щодо вибору кодерів і налаштувань їх параметрів. **Методи дослідження:** чисельне моделювання, верифікація на наборі тестових зображень. **Отримані результати:** 1) коефіцієнти стиснення змінюються в досить широких межах залежно від складності зображення та характеристик шуму; 2) кодери AGU-M та BPG забезпечують найкращі коефіцієнти стиснення за однакової візуальної якості порівняно з іншими розглянутими кодерами; 3) спостерігається висока кореляція між коефіцієнтами стиснення для всіх розглянутих кодерів. **Висновки: 1)** можливо досягти досить високих коефіцієнтів стиснення без втрати діагностично важливої інформації; 2) адаптація параметрів стиснення до складності зображення дозволяє суттєво підвищити ступінь стиснення для зображень із простою структурою.

Ключові слова: візуально непомітне стиснення; п'ять різних кодерів; порівняння ефективності.