Digital Compression in Medical Images

Compresión Digital en Imágenes Médicas

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Abstract: Imaging technology has long played a principal role in the medical domain, and as such, its use is widespread in the diagnosis and treatment of numerous health conditions. Concurrently, new developments in imaging techniques and sensor technology make possible the acquisition of increasingly detailed images of several organs of the human body. This improvement is indeed advantageous for medical practitioners. However, it comes to a cost in the form of storage and telecommunication infrastructures needed to handle high-resolution images reliably. Ordinarily, digital compression is a mainstay in the efficient management of digital media, including still images and video. From a technical point of view, medical imaging could take full advantage of digital compression technology. However, nuances unique to medical data impose constraints to the application of digital compression in medical images. This article provides an overview of digital image compression applied to medical imaging, along with a brief discussion on the regulatory implications associated with its use.

Keywords: digital, compression, medical, imaging, JPEG, DICOM.

Resumen: La Imagenología desempeña un papel protagónico en el campo médico, siendo su uso ampliamente generalizado en el diagnóstico y tratamiento de numerosos trastornos de la salud. Nuevos desarrollos en la adquisición de imágenes y en la tecnología de sensores hacen posible obtener imágenes más detalladas de varios órganos del cuerpo humano. Tal mejora es ciertamente ventajosa para la práctica médica, pero supone un encarecimiento de los recursos tecnológicos necesarios para manejar imágenes de alta resolución de manera confiable. Comúnmente, el manejo eficiente de medios digitales se apoya principalmente en la compresión digital. Desde un punto de vista técnico, las imágenes médicas podrían aprovechar las ventajas de la compresión digital. Sin embargo, peculiaridades de los datos médicos imponen restricciones a su uso. Este artículo presenta un vistazo a la compresión digital en el contexto de las imágenes médicas, y una breve discusión de los aspectos regulatorios y legales asociados a su uso.

Palabras clave: digital, compresión, imagenología, JPEG, DICOM.

I. Introduction

Medical imaging has a critical role in contemporary clinical diagnosis. Among the many advantages of the technology, the possibility of avoiding patients from going through hazardous ordeals, such as exploratory surgery and other invasive procedures, stands out. Previous research has linked imaging technology to longer life expectancy, declines in mortality and hospital admissions, as well as shorter hospital stays [1]. Furthermore, the ever-increasing volume of digitized medical data allows the collection of large datasets, which, in conjunction with novel machine-learning algorithms, are paving the way for the emergence of computer-aided diagnosis (CAD) systems [2-7].

Ordinarily, medical images produce large data volumes and thus require large storage spaces. The data size depends on the resolution, digitization method, or scanning approach, but as a rule of thumb, the data volume increases with the resolution of the images. Consequently, archiving, processing, distributing, and consuming high-resolution images require specialized information systems. Such systems, known as Picture Archiving and Communication Systems (PACS), are at the core of imaging management in modern hospitals.

Medical imaging technology is in constant evolution and refinement. While novel image modalities emerge, existing modalities frequently improve resolution and detail. For instance, current computer tomography (CT) technology can imagine at a sub-millimeter spatial resolution. Whereas twenty years ago, a CT scanner would top at a resolution of an order of magnitude lower [8]. Given the increasing detail of medical images, efficiency becomes critical for storage and transmission. Thus, image compression becomes instrumental in the effective management of medical data in PACS.

The application of digital compression to medical imaging has motivated a great deal of research. On the one hand, a significant portion of the works has focused on developing suitable methods to compress medical images and biological signals [9-12]. On the other hand, extensive research has concentrated on technological infrastructure such as information management systems [13], storage technology [14], and communication protocols [15]. All these works provide in-depth discussions of the technical aspects concerning digital compression. However, they left out relevant issues related to applying digital compression to medical data. This paper does not discount previous work but builds upon it to present a broader picture of digital compression in the context of medical images and its associated regulatory and legal implications.

The remaining part of the paper proceeds as follows, Section II introduces common imaging modalities and related technological requirements. Section III presents an overview of current standards for compression of medical images. Section IV discusses regulatory and legal implications concerning compression and medical data. Lastly, section V presents the conclusions and recommendations for future work.

II. Background

A. Characteristics of medical images

Medical imaging encompasses a wide range of techniques that generate visual representations of the human body. These visual representations are typically still images generated through the acquisition and processing of biomedical signals. Depending on the imaging technology, clinicians have access to structural, morphological, and physiological information at different anatomical levels such as cellular, tissue, or organ. This information plays a prominent role in diagnosing, monitoring, and treating illnesses and injuries.

The acquisition method and the anatomical part under study determine the features of medical images. The chemical and physical characteristics of the examined tissue determine the data encoded in every pixel or voxel. In general, imaging mechanisms corresponding to physiological phenomena, such as spontaneous contrast, fluid motion, or metabolic exchanges. These mechanisms lead to a wide variety of features that differ from one type of image to another.

Compared to natural images, medical images have more intensity levels and thus, use more bits to encode each pixel or voxel. For instance, a CT image (Fig. 1) utilizes 16 bits to store up to 3000 unique intensity values, whereas a photograph uses 8 bits to encode up to 256. The spatial resolution depends on the acquisition method and ranges from micrometers in ultrasound to centimeters in nuclear imaging. Table I summarizes typical spatial resolution, temporal resolution, file size, and depth of a representative sample of imaging modalities.

B. The DICOM Standard

Given that images are produced by diverse imaging equipment, with most having trademarked communication protocols and file formats, interoperability is only possible by integrating imaging equipment and PACS through a non-proprietary standard.

Nowadays, the dominant standard in medical image communications is the Digital Imaging and Communications in Medicine (DICOM) standard [16]. DICOM aims to provide platform-independent methods for interconnecting medical imaging devices over standard computer networks. The standard defines a file format and a network protocol based on the TCP/IP protocol that enables interchanging medical data between PACS and imaging devices, such as scanners, servers, workstations, and printers.

In addition, DICOM defines a comprehensive set of algorithms for compressing medical images. The standard refers to these algorithms as "Transfer syntaxes" and in its current version it specifies compressed transfer syntaxes for a wide variety of compressing algorithms which includes: JPEG, Run Length Encoding, Lossless/near-lossless JPEG, and JPEG-2000 [17]

III. Algorithms for Medical Image Compression

A. Run Length Encoding (RLE)

Run-length encoding defines a very straightforward approach to lossless compression. The RLE algorithm encodes a sequence (or run) of identical pixels as the symbol in the run and the length of the run. RLE can provide high compression ratios in medical images showing large uniform areas, such as ultrasound images (Fig. 2). However, it might result in larger data streams than the uncompressed data when it is applied in images exhibiting complex structures, and/or noise.

Compared to other compressing algorithms, RLE is relatively easy to implement and has a low time complexity but is rarely used on its own. In the context of DICOM, RLE is used as compressing algorithm mainly for ultrasound images, and as a data transformation with other image modalities.

FIG. 1
CT scan in the coronal (C), axial (A) and sagittal (S) planes.
[18]

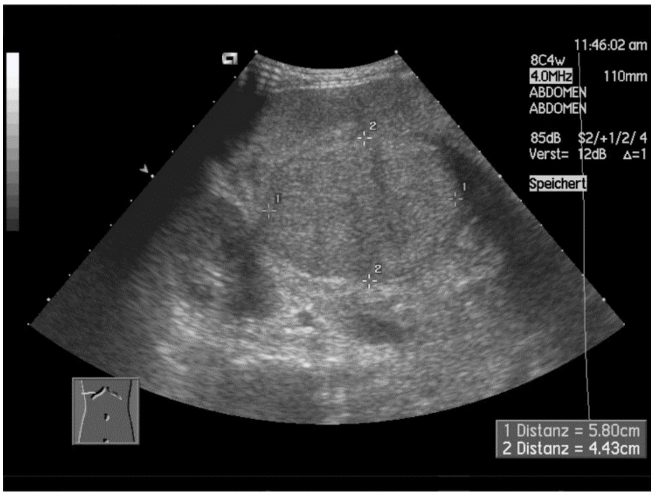

FIG. 2
Ultrasound single frame image showing large areas of constant value around the region of interest.
[19]

TABLE I
Summary of typical features of common image modalities

Modality	Organ	Image size	Bits per pixel	Slices/frames	File size
Radiography	Thorax	2060x2060	10-16	-	8 MB
Computerized tomography	Brain	512x512	12-16	≈ 300	150 MB
	Abdomen	512x512	12-16	≈ 500	250 MB
	Heart	512x512	12-16	126x16 frames	1 GB
Magnetic resonance imaging	Brain	512x512	12-16	≈ 20x6 sets	10 to 60 MB
	Abdomen	512x512	12-16	≈ 30	15 MB
	Heart	256x256	12-16	20x20 frames	50 MB
Positron emission tomography	Whole body	128x128	16	350	10 MB
	Heart	128x128	16	47x16 frames	24 MB
	Brain	256x256	16	47	6 MB
Ultrasound	Standard	512x512	8	50 images/sec	12.5 MB/sec
	Doppler	512x512	(RGB) 3x8	50 images/sec	37.5 MB/sec

[8]

B. Joint Photographic Experts Group (JPEG)

JPEG is the primary compression method in DICOM. This standard was jointly developed by the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) through the working group ISO/IEC JTC 1/SC 29/WG 1, informally known as the "Joint Photographic Experts Group" —hence the standard acronym.

The standard provides lossy and lossless compression techniques which are suitable for different imaging modalities. One of the DICOM standard lossy medical image storage formats uses JPEG compression at file size reductions (compression ratios) of 6:1 or lower [20]. Despite its popularity JPEG has significant limitations such as low efficiency in lossless compression and blocking artifacts at high compression ratios in lossy compression. In addition, the lossy mode is limited to inputs of up to 12 bits which renders it unsuitable for some imaging modalities.

C. Lossless JPEG

JPEG lossless compression specifies a compressing method based on differential pulse-code modulation to reduce redundancy. The algorithm reduces repetition by predicting the value of one pixel with the values of neighboring pixels. Later, the difference between the actual value and the prediction is encoded using variable-length codes such as Huffman or arithmetic coding.

Lossless-JPEG compression supports images with bit-depths between 2 and 16 bits and performs reasonably well despite its simplicity. Regardless of its modest performance, lossless JPEG mode is widespread in medical imaging.

D. Lossless/near-lossless JPEG-LS

JPEG-LS comprises a set of lossless and near-lossless compression methods designed for coding continuous-tone, greyscale, or color still images. This single-pass coding technique uses predictive coding and context-based adaptive Rice-Golomb coding scheme.

The near-lossless mode of JPEG-LS guarantees that any sample value in the reconstructed image is within a predefined amount β of its original value. This specification is achieved by quantizing the prediction error in slots with size 2β + 1 and using reconstruction level at the center of the interval.

With a moderate increase in computational complexity, JPEG-LS performance is considerably better than the performance of lossless JPEG with Huffman coding with fixed tables (TABLE II). Compared to JPEG with arithmetic coding, JPEG-LS matches its performance but with less computational complexity.

TABLE II .
AVERAGE COMPRESSION RATIO ON MEDICAL IMAGES

Image modality	Lossless JPEG	JPEG-LS
Computerized radiology	2.24	2.74
Computerized tomography	2.14	2.79
Magnetic resonance	2.37	2.75
Nuclear medicine	2.55	3.68
Ultrasound	2.02	2.90

[21]

E. JPEG-2000

The JPEG2000 algorithm leverages a discrete wavelet transform (DWT) to decompose an image on either scale or resolution components. The general principle of DWT is that it handles the image as a succession of waves, organizing the image information into peaks and dips, where each color channel (red, green, and blue) is represented by an individual wave.

The image can also be broken into tiles for facilitating the processing. Provided that the wave is centered at zero, the algorithm computes coefficients representing the distance from the points of the wave to the zero line; and then averages adjacent coefficient to obtain a simplified version of the wave. As a result, the image resolution gets halved. The procedure (decomposition) is repeated over and over for producing simpler waves. As coefficients are averaged and differences are recorded, smaller differences (slight variations in the sequence) are selected for smoothing and simplification.

On the other hand, larger differences signal more significant variations that should be preserved. As the decomposition progress, it generates increasingly lower-resolution versions of the original wave that approximate the general shape and color of the image. Fig. 3 shows a DWT decomposition of a brain image acquire through MRI.

JPEG2000 uses a multilevel DWT with octave-scaled decomposition in baseline that achieve a better image quality than JPEG. Wavelet transformation improves compression performance of JPEG allowing compression ratios of up to 40:1 without perceptible loss in radiology images [22]. This makes wavelet-based coding a suitable compression approach for telemedicine and picture archiving. DICOM added support for the use of JPEG2000 in 2009 defining several transfer syntaxes to allow lossless (bit preserving) and lossy compression schemes [23]. Relevant features of JPEG2000 for medical imaging include:

- Supports bit depths of up to 38 bits per channel and up to 16384 channels.
- Lossless and lossy compression.
- Region of Interest (ROI) encoding. Allows compressing of irrelevant data with higher ratios while keeps relevant features for diagnosis.
- Support for metadata embedding within the compressed files.
- Interactive transmission and decoding. Allows to change coding parameters during transmission at convenience.
- Support for three-dimensional data compression. Suitable for spatially correlated modalities such as CT and MRI.
- Error resilience for more reliable transmission of images through wireless networks.
- Security features including authentication, access control, and IPR protection both for storage and transmission.

IV. Regulatory and Legal Implications

Worldwide, image compression in medical imaging is subject to regulation by government bodies and professional organizations. The Food and Drug Administration (FDA) in the United States, the Royal College of Radiologists (RCR) in the United Kingdom, the Deutsche Röntgengesells (DRG) in Germany, and the Royal Australian and New Zealand College of Radiologists all have released guidelines for image compression of diagnostic imaging [24-27]. Although regulators coincide with the definition of limits for lossy compression, there is no consensus on the compression ratios. For example, while the FDA does not permit compressing digital mammography, the RCR and the DRG recommend compression ratios of 15 to 1 and 20 to 1 (Table III).

While advances in lossy compression methods allow more efficient storage and transmission of large medical image datasets, clinical practice refrains from taking full advantage of these techniques, particularly lossy compression methods. The rationale behind the hesitation, is that irreversible loss of information may be instrumental in disputing medical diagnosis in a court of law. To illustrate this, suppose a physician detects a small abnormality immediately after acquisition and reaches a diagnosis based on that finding. Then, the image undergoes lossy compression before it gets stored in the PACS. In this circumstance, it is plausible that small details were not visible in the compressed image. This would place the physician in a bad predicament in case of legal dispute, because the clinician will be unable to recover the finding upon which them determined their diagnosis [28].

The discussion about lossy compression has also echoed in academia, where there is a considerable amount of studies stressing that a conservative selection of compression ratios lead to inefficient compression [29-33]. Alternatively, other studies propose coding algorithms based on subjective performance metrics, e.g. perceptual quality [34, 35]. These methods are inspired on properties of the human vision and focus on visual quality rather than image content.

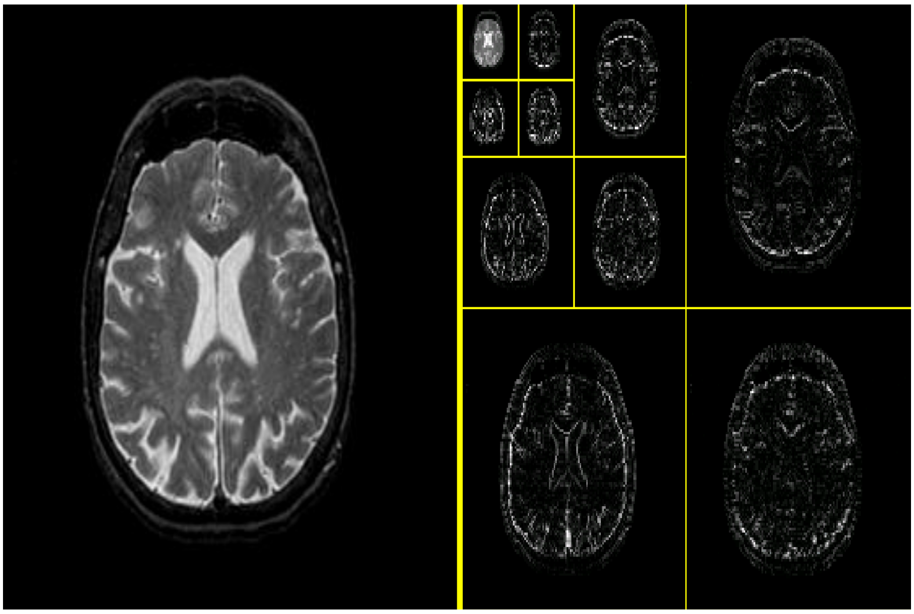

FIG. 3
DWT decomposition of a brain MRI.
[36]

V. Conclusions

The widespread use of medical imaging has been instrumental in improving the quality of clinical diagnosis but at the same puts pressure on technological infrastructure.

Digital compression is a valuable tool for efficient archiving and transmission of medical images in modern healthcare information systems.

International standards for medical imaging such as DICOM recognize the need for efficient compression of medical images by incorporating in their specifications a variety of lossless and lossy compression techniques.

Even though lossy compression techniques allow higher ratios of compression than those of lossless techniques, clinical practice refrains to use lossy compression because of the legal ramifications that might involve the loss of critical information.

Aiming to assure the safe use of digital compression in sensible medical images, several government bodies and professional organizations recommend limiting the amount of lossy compression on medical imaging.

On the other hand, considerable amount of research has devoted to making a case for the use of lossy compression by studying the impact of information loss in the perceived visual quality of compressed medical images.

The issue of lossy compression in medical image remains an open problem pointing to further research on methods that balance compression efficiency and the preservation of critical information for accurate diagnosis in clinical practice.

TABLE III
Comparison of acceptable lossy compression ratios issued by the Royal College of Radiologists (RCR) and the German Society of Radiology (DRG)

Imaging Modality	RCR	DRG
Mammography	20:1	15:1
Radiography	10:1	10:1
Ultrasound	10:1	-
Angiography	10:1	6:1
Computerized tomography	5:1	8:1
Magnetic Resonance	5:1	7:1
Radio Fluoroscopy	-	6:1

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