OPEN ACCESS

ISSN: 2676-7473

RBMS.2022;27(1):e13

ORIGINAL RESEARCH

Automatic colorization of non-enhanced brain CT images for clinical diagnosis

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Date Received: December, 2020 *Date Accepted: January, 2021* *Online Publication: July 15, 2022*

Abstract

Background: The frequent use of brain computed tomography (CT) scans in emergency settings necessitates accurate reporting of CT results as quickly as possible. Conventional CT scans produce grayscale images, requiring window width and center level changes, resulting in a need for time-consuming interpretation by experienced radiologists. This study aimed to design a novel software application for automatic smart colorization of conventional brain CT images and to evaluate the diagnostic accuracy, visual quality, ease of diagnosis, and reporting time for color CT images compared to conventional grayscale CT images.
Materials and Methods: First, we designed an application that converted non-enhanced grayscale brain CT images into color images according to the Hounsfield unit value of different tissues (e.g., brain, fat, bone, fluid, air) with minimal noise so that all brain tissues could be evaluated using one window level. This process took less than one second, without the need for high-end systems. Next, 75 printed images (25 unprocessed grayscale CT, 25 processed color CT, and 25 magnetic resonance imaging [MRI]) from 25 patients with hemorrhagic or ischemic stroke were read by two experienced radiologists. The radiologists scored the CT images from each patient (unprocessed grayscale and processed color) on a ten-point scale for visual quality and ease of diagnosis compared to the MRI image.
Results: The mean visual quality score was 18% higher and the mean ease of diagnosis score was 23% higher for colorized images than for grayscale images (both $P < 0.001$). Statistically, there were no significant differences in the diagnostic accuracy or reporting time between color and grayscale images.
Conclusion: This is the first study to report automatic smart colorization of non-enhanced brain CT images, producing high-quality colorized images with better visual quality and ease of diagnosis compared to grayscale CT. This low-cost solution can be widely applied in clinical settings, regardless of minimal facility or resource availability.

Keywords: Acute stroke, Automatic data processing, Image enhancement, Software design

Introduction

Brain computed tomography (CT) scanning is currently one of the important and useful imaging modalities, particularly in emergency settings. Expeditious diagnosis and treatment of acute stroke is crucial for reducing rates of comorbidities and mortality [1]. The high demand for brain CT scans in hospitals combined with the limited number of radiologists in each center makes necessitates finding new ways to facilitate accurate and efficient reporting of findings from CT images.

The sensitivity and specificity of non-enhanced CT (NECT) for diagnosis of acute stroke are estimated to be 40% and 90%, respectively [2]. Window width and center level settings for CT images play an important role in diagnostic accuracy of pathology in various tissues; studies have shown that reviewing brain NECT images in multiple window width and center levels can improve sensitivity for acute stroke diagnosis [3]. However, due to the large volume of patients in emergency departments and the resultant need to evaluate numerous CT scans in a limited time, pathologies can be overlooked during reporting due to using limited window widths and center levels for the sake of efficiency. In addition, when patients are given printed grayscale brain NECT images, physicians have to identify pathologic lesions using only one or two window widths and center levels (e.g., bone and brain window), which can reduce diagnostic accuracy [4, 5]

Conventional CT scans produce grayscale images with values between 0 and 255 for each pixel (i.e., 8-bit grayscale), where pixels with a value of 0 appear black and those with a value of 255 appear white. In comparison, 24-bit RGB color images have 8 bits for red, 8 bits for green, 8 bits for blue, creating over 16.7 million possible values. Some studies have shown that colorization of CT images can improve image quality and diagnostic accuracy [6-9]. In addition, it has been suggested that image processing, such as increasing the contrast of brain CT images, can increase the diagnostic sensitivity of CT for pathologies [10]. Although some research in CT image colorization has been done in clinical settings, such as in pig brain CT images for finding the wooden foreign bodies [11] and in lung CT scans for emphysema diagnosis [9], the image colorization in both studies was limited and neither automatic nor smart.

Evidently there is a need to develop a more practical method for the colorization of CT images in clinical settings to facilitate efficient and accurate diagnosis. In this study, we designed a novel software application for automatic colorization of brain NECT images capable of differentiating bone, brain tissue, edema, hemorrhage, fat, fluid, and air for easier evaluation. The software also incorporated denoising and contrast enhancement to produce high-quality color images. We then evaluated the diagnostic accuracy, visual quality, ease of diagnosis, and reporting time of color CT images compared to conventional grayscale CT images with magnetic resonance imaging (MRI) scans as a baseline. To the best of our knowledge, this is the first study to apply automatic smart colorization to brain NECT images in a clinical setting.

Materials and Methods

Software Application Development:

The first objective of this research was to design a novel software application using JDK 8 (Java™, Oracle Corporation) to process and colorize brain CT images. With help from the PixelMed™ Java DICOM Toolkit (PixelMed Publishing, LLC), our application was designed to extract the Hounsfield unit (HU) values of every pixel in a DICOM file and save them as an integer matrix. Next, using the Haar wavelet transform with JWave (http://code.google.com/p/jwave/), noise was decreased and contrast was enhanced to improve the smoothness and quality of the final images. The wavelet algorithm decomposes a signal into multiple wavelet coefficients [12]. Typically, small amplitude wavelet coefficients indicate noise while larger amplitude coefficients indicate the main image information in the signal. In this study, we reduced noise by lowering the small coefficients to 0 [hard thresholding [13, 14]] and then increased the contrast of the image by slightly amplifying the larger coefficients. After processing, each image was automatically colorized such that each pixel was assigned an RGB value according to its HU value: bone in the green spectrum; fluid in the blue spectrum; fat in the yellow spectrum; air in the black spectrum; and edema, brain tissue, and hemorrhage in the dim gray, dark gray, and light gray spectrums, respectively. Finally, the colored CT images were saved as high-quality JPG images with lossless compression (Fig. 1). This entire process took less than one second for each brain CT image and did not require the use of high-end computer systems.

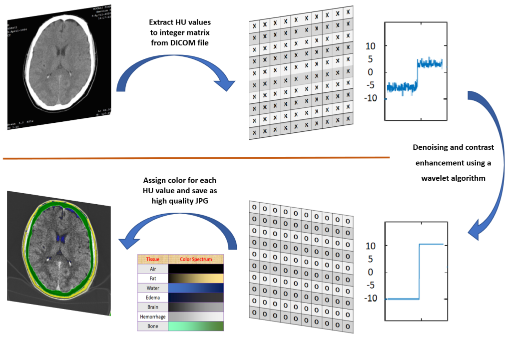

Fig. 1. Software application development process

Patient selection:

In order to evaluate our CT image colorization application in a clinical setting, we performed a retrospective review of brain scan images (NECT and MRI) from patients with hemorrhagic or ischemic brain stroke who had been diagnosed at Abu Ali Sina Hospital, Sari, Iran between January and April 2020. Images from patients for whom stroke had been diagnostically confirmed using MRI, and showed subtle changes on NECT, were selected for inclusion in this study. Patients with obvious lesions in brain CT scans image were excluded. All CT scans were performed with a Somatom Emotion 6 slice CT (Siemens Healthineers AG, Erlangen, Germany) and all MRI were performed with a 1.5T MAGNETOM Avanto^{fit} (Siemens Healthineers AG, Erlangen, Germany). The ethics committee at the Shahid Beheshti University of Medical Sciences approved the research protocol (IR.SBMU.MSP.REC.1397.254) and informed consent was obtained from all participants.

CT image evaluation:

Three high-quality images from equivalent brain slices were printed on separate sheets of glossy paper for each patient: one conventional grayscale CT image, one processed color CT image, and one corresponding MRI scan. Two experienced radiologists who were blinded to diagnosis and MRI reports independently read and reported on all unprocessed grayscale and processed colored CT images over two weeks. The grayscale and color CT images were randomly assigned to each radiologist such that they evaluated both images for every patient in two separate weeks. Reporting time for each image was measured in seconds, from the time that the radiologist received the image to the time that the report was finished. To assess diagnostic accuracy, each patient's CT image reports were compared to the corresponding MRI report and classified as false positive, false negative, true negative, or true positive for edema or hemorrhage diagnosis. After all CT images had been evaluated, both radiologists were asked to score each patient's CT images (unprocessed grayscale or processed color) on a ten-point scale for visual quality and perceived ease of diagnosis compared to the MRI scan (10: very good; 1: very bad).

Data analysis:

Statistical analyses were performed using SPSS Statistics 20 (IBM). Due to the non-normal distribution of the data, the Wilcoxon signed-rank test was performed to compare visual quality and ease of diagnosis scores between unprocessed grayscale and processed color images. McNemar's test was used to compare correct diagnosis (true positive and true negative) between the two types of CT images. Paired t-tests were performed to comparing reporting times for each image between the two types of CT images. The P-value threshold for statistical significance was set to 0.05 for all parameters.

Results

Patient demographics:

Images from 25 patients (mean: 65.9 years; 12 males, 13 females) were included in the study; based on the MRI scans, there were a total of 22 edematous lesions and 6 hemorrhagic lesions present. Several other brain pathologies were also noted in the 25 patients: intraventricular lipoma (n = 1), falx calcifications (n = 2), and pineal and choroid plexus calcifications (n = 6). Three examples of lesions seen in the study patients' images are shown in Fig. 2–4.

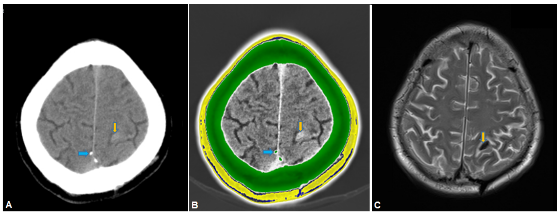

Fig. 2. A small hemorrhagic lesion in left parietal lobe (yellow arrow) with tiny falx calcifications (blue arrow). (A) unprocessed grayscale CT image; (B) processed color CT image; (C) corresponding T2-weighted MRI scan.

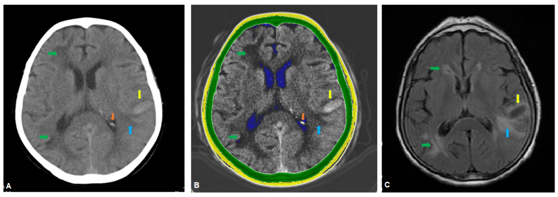

Fig. 3. A hemorrhagic lesion in left temporal lobe (yellow arrow) associated with adjacent edema (blue arrow) and periventricular edema (green arrows) due to microvascular changes and choroid plexus calcification in the left side (orange arrow). (A) unprocessed grayscale CT image; (B) processed color CT image; (C) corresponding T2-FLAIR MRI scan.

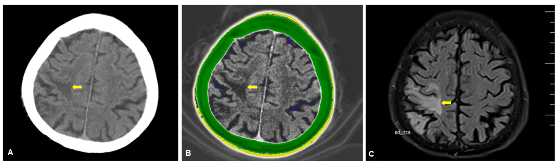

Fig. 4. An edematous lesion in right parietal lobe (yellow arrow). (A) unprocessed grayscale CT image; (B) processed color CT image; (C) corresponding T2-FLAIR MRI scan.

CT image evaluation:

The mean visual quality scores for unprocessed grayscale and processed color CT images were 5.96 ± 1.19 and 7.02 ± 1.50, respectively (mean ± standard deviation). The mean visual quality score was 18% higher for color images compared to grayscale images, and the difference was statistically significant ($P < 0.001$). The mean ease of diagnosis scores were 6.10 ± 2.54 and 7.50 ± 2.46 for unprocessed grayscale and processed color CT images, respectively; the mean ease of diagnosis score was 23% higher in colorized vs grayscale images ($P < 0.001$).

Between the two radiologists, there were 11 incorrect diagnoses (false negative or false positive) of edematous lesions in unprocessed grayscale images (22%) compared to 12 incorrect diagnoses in processed color images (24%) ($P = 1$). Misdiagnoses for hemorrhage occurred in 2 images (4%) and 1 image (2%) for grayscale and color CT images, respectively ($P = 1$). Likewise, there was 1 misdiagnosis (2%) in unprocessed grayscale images and 2 misdiagnoses (4%) in processed color images ($P = 1$). The mean reporting time for each grayscale CT image was 20.4 ± 5.6 s and for color CT images was 21.6 ± 4.8 s ($P = 0.418$).

Discussion

In the present study, we designed a new software application to colorize and process conventional grayscale brain CT images with high quality and low noise. The process takes less than one second per image without the need for high-end computer systems, so it can be applied in most radiological settings regardless of financial or equipment constraints. We used an HU integer matrix for processing and colorization that improved enhancement and denoising, unlike most previous studies that only colorized derived grayscale CT images.

There have been several studies that have tried to improve the quality of radiologic images. Some studies focused on enhancing the visibility of pathologies on brain NECT scans by processing the images without colorization. For example, Bier et al. [10] processed brain NECT images to improve the visualization of edema in stroke patients. They used non-linear scaling to separate pixels in the range of 25–35 HU with a center of 30 HU and demonstrated that this method increased the sensitivity of NECT for diagnosing edema. This method is limited to edema and other functions must be defined to expand its application for other pathologies. Moreover, the specificity of edema diagnosis decreased significantly (i.e., from 100% to 64%) following the application of Bier and colleagues' image post-processing method.

Other studies have tried to improve radiologic image quality by adding color; the majority of these studies used derived grayscale radiologic images. Lagodzinski and Smolka [7] and Shah et al. [8] colorized medical images using color 'scribbles' within regions of interest to guide a colorization algorithm and showed that this process can be performed in real-time. However, these methods cannot be applied to printing medical images. Nida et al. [15] and Khan et al. [16] colorized medical images by adding chromatic colors, reporting that their methods increased the contrast and clarity of information within the images. Neither study colorized the images according to its tissue components (e.g., fat, bone) and instead relied on the grayscale intensity of each pixel. In comparison, Selvapriya and Raghu [17] focused on colorization of previously-identified pathologic regions, leaving other parts of the medical images monochromatic. They suggested that their method might be applicable in a teaching setting for medical practitioners since a diagnosis and localization of the pathologic region is necessary prior to colorization. Accordingly, this method cannot be used to improve diagnostic accuracy or efficiency in clinical settings. None of these studies assessed the application of their methods in a clinical setting; parameters, such as overall reporting time, must be evaluated for these methods in future studies.

Several more recent studies colorized CT images using HU values, similarly to the current study, but they have primarily focused on colorizing specific pathologies within the image, ignored other surrounding tissues. Muehlematter et al. [9] showed that colorization of lung CT images with a density mask technique facilitated more accurate and less observer-dependent quantitation and localization of pulmonary emphysema, compared to conventional and multiplanar reconstruction CT images. However, Muehlematter and colleagues only colorized the image in the range of -1000 to -760 HU, and all other values were hidden on the CT images. Similarly, Matsuda et al. [11] conducted a study using 3D-rendered CT images colorized with OsiriX software for identifying wooden foreign bodies in pig heads. They showed that dry foreign bodies that typically cannot be identified in abdomen or bone window settings can be seen in colorized CT images. They used a 16-bit colorization, in comparison to the 24-bit RGB colorization used in the current study, and although the processed images showed wooden bodies well, the quality was decreased for other tissues.

The visual quality and ease of diagnosis for our automatically colorized CT images were higher than those of conventional grayscale CT, as scored by experienced radiologists. Statistically, there were no significant differences in the accuracy and reporting time between grayscale and color CT images in our study; however, there are several limitations that must be considered. One important limitation was the minimal familiarity of the radiologists with colorized images, compared to more than 10 years of experience reading grayscale CT images. We can minimize this discrepancy in future studies by evaluating individuals with less extensive experience with grayscale CT images, such as radiology residents or physicians with expertise other than radiology. Additionally, we could train radiologists to read color CT images prior to beginning the study. Another limitation was the use of only one brain NECT slice from each patient, which can lower the diagnostic accuracy with both unprocessed and processed images. We made this decision in order to specifically choose CT images with faint indications of stroke; however, we anticipate that providing access to all slices would improve the ease of diagnosis overall—a factor that we were concerned might obscure any differences between reading unprocessed and processed CT images in our study.

Although we tried to decrease noise using a wavelet algorithm, some artifacts (such as beam hardening that can erroneously resemble hemorrhage HU values) would require a more sophisticated algorithm for removal. In addition, partial volume effects can contribute to the reduction of colored image quality, although using thinner slices from brain CT scans can minimize their influence. Another challenge was the small sample size in this study due to limited available of CT scans with faint stroke findings and corresponding MRI scans at our center. We anticipate that future studies with larger sample sizes will corroborate our findings with higher levels of significance than were possible in this study. The colorization technique presented in this study is novel, but there is plenty of opportunity to expand upon this work. More studies are needed to evaluate the cost benefit and efficacy of using color CT images in clinical settings.

To the best of our knowledge, this is the first study in which automatic smart colorization and processing of high-quality CT images—simultaneously differentiating between brain tissue, fat, bone, edema, hemorrhage, fluid, and air—has been applied to clinical diagnosis in the brain. We believe that this method can improve the efficiency and accuracy of diagnosis of brain pathology from CT images without significant additional cost. As a result, this application could be applied in any radiology center, even with minimal facilities or resources.

Acknowledgements: We would like to thank Editage (www.editage.com) for English language editing.

Conflict of interest

Author declares no conflict of interest.

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