Journal of Technology Research (JTR)
Volume 3, Special Issue, (2025), pp 721-729 ISSN 3005-639X
The 7th Conference of Engineering Sciences and Technology
(CEST-2025)

Enhancing Liver PET Image Quality and Tumor Delineation Using CLAHE: A Quantitative Evaluation on Y-90 Dataset.

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Received: 30-09-2025 | Accepted: 20-11-2025 | Available online: 25-12-2025 | DOI:10.26629/jtr.2025.67

ABSTRACT

This research explores the application of Contrast-Limited Adaptive Histogram Equalization (CLAHE) as a technique for enhancing the visual quality and diagnostic utility of liver Positron Emission Tomography (PET) images. PET scans are widely used in nuclear medicine to detect metabolic activity, such as tumors, but they often suffer from poor contrast and lack sufficient anatomical detail. By applying CLAHE, we aim to improve local contrast in PET images, making tumor regions more distinguishable without amplifying noise. To validate and precisely localize the tumor boundaries, RTSTRUCT data provided delineated regions of interest (ROIs), which were extracted and overlaid on the corresponding CT slices. This step enabled both validation of the segmentation and clear anatomical localization of the target structure. The study integrates CLAHE-enhanced PET images with these corresponding Computed Tomography (CT) scans to fuse functional and anatomical information. The fusion of PET and CT allows for clearer tumor localization, which is critical for accurate diagnosis and treatment planning, particularly in patients undergoing Yttrium-90 (Y-90) radioembolization therapy for liver cancer "The publicly available Y-90 PET/SPECT/CT dataset used in this study contains four anonymized patients, with no demographic identifiers such as age or gender". The effectiveness of different CLAHE parameters was evaluated using quantitative metrics such as entropy, Structural Similarity Index Measure (SSIM), and Peak Signal-to-Noise Ratio (PSNR) demonstrating an improvement of 23.7%, 1.1%, and 2.0 dB, respectively, compared to the original PET/CT images. These results indicate that optimized CLAHE effectively enhance image contrast and tumor boundary clarity while preserving structural fidelity, suggesting potential utility in improving PET/CT fusion accuracy for hepatic oncology applications.

Keywords: CLAHE, Liver, Tumor Localization, PET, CT.

تحسين جودة صور التصوير المقطعي بالإصدار البوزيتروني للكبد ووضوح حدود الورم باستخدام تقنية CLAHE: دراسة تقييمية باستخدام بيانات Y-90

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ملخـــــــص البحـــــــث

يستكشف هذا البحث تطبيق تقنية معادلة الهيستوغرام التكيفية المحدودة بالتباين **(CLAHE)** كتقنية لتحسين جودة الصورة وفائدتها التشخيصية لصور التصوير المقطعي بالإصدار البوزيتروني **(PET)** للكبد. تُستخدم فحوصات **PET** على نطاق

واسع في الطب النووي للكشف عن النشاط الأيضي، مثل الأورام، ولكنها غالبًا ما تعاني من ضعف التباين وتفتقر إلى التفاصيل التشريحية الكافية. من خلال تطبيق **CLAHE**، نهدف إلى تحسين التباين الموضعي في صور **PET**، مما يجعل مناطق الورم أكثر وضوحًا دون تضخيم الضوضاء. للتحقق من صحة حدود الورم وتحديد موقعها بدقة، قدمت بيانات **RTSTRUCT** مناطق اهتمام محددة (**ROIs**)، والتي تم استخراجها وتراكبها على شرائح التصوير المقطعي المحوسب المقابلة. أتاحت هذه الخطوة التحقق من صحة التجزئة والتحديد التشريحي الواضح للبنية المستهدفة. تدمج الدراسة صور **PET** المعززة بتقنية **CLAHE** مع فحوصات التصوير المقطعي المحوسب (**CT**) المقابلة لدمج المعلومات الوظيفية والتشريحية. يتيح دمج التصوير المقطعي بالإصدار البوزيتروني (**PET**) والتصوير المقطعي المحوسب (**CT**) تحديد موقع الورم بدقة أكبر، وهو أمر بالغ الأهمية للتشخيص الدقيق وتخطيط العلاج، خاصةً لدى مرضى سرطان الكبد الخاضعين لعلاج الانصمام الإشعاعي بالإتريوم-90 (**Y-90**). تم تقييم فعالية معايير **CLAHE** المختلفة باستخدام مقاييس كمية مثل الإنتروبيا، ومقياس مؤشر التشابه الهيكلي (**SSIM**)، ونسبة ذروة الإشارة إلى الضوضاء (**PSNR**). مما يدل على تحسن بنسبة 23.7٪ و1.1٪ و2.0 ديسيبل على التوالي، مقارنةً بصور **PET** الأصلية .تشير هذه النتائج إلى أن **CLAHE**المحسّن يعزز بشكل فعال تباين الصورة ووضوح حدود الورم مع الحفاظ على الدقة الهيكلية، مما يشير إلى فائدة محتملة في تحسين دقة دمج **PET/CT** لتطبيقات أورام الكبد.

الكلمات الدالة: تحسين التباين, دمج الصور, تحديد موقع الورم, تصوير طبي.

1. INTRODUCTION

Mostly Medical imaging is a cornerstone of modern healthcare, fundamentally shaping how we diagnose, plan treatment for, and monitor complex diseases like cancer [1]. Each imaging technique offers a unique lens into the human body. For instance, Positron Emission Tomography (PET) excels at revealing metabolic activity, effectively highlighting potentially cancerous regions based on their increased biological function [2]. However, a significant drawback of PET is its poor anatomical detail, making it difficult to pinpoint exactly where that activity is occurring. This is where Computed Tomography (CT) provides a critical counterpart, offering a high-resolution, three-dimensional map of the body's internal structures [3]

Yet, when used in isolation, each modality has its own Achilles' heel. Standard PET images often suffer from low contrast and high noise, which can obscure the very tumor boundaries clinicians need to see clearly [4]. Conversely, while CT provides excellent anatomical context, it frequently struggles to differentiate between tumors and healthy soft tissues with similar density, causing lesions to blend into their surroundings [5]. This lingering challenge—the need to make tumors stand out with greater clarity against complex anatomical backgrounds—remains a central and driving focus in the field of medical image processing. . As a result, neither PET nor CT alone provides optimal clarity of the tumor's size, boundaries, and location. Therefore, there is a need for overcome this problem of both modalities to enhance tumor visibility and provide reliable diagnostic support.

Image contrast enhancement techniques offer a potential solution to this problem. Among these, CLAHE is a highly effective method for improving local contrast in medical images without excessively amplifying noise [6]. While CLAHE has been successfully applied to various modalities like MRI [7] and CT [8], its application to PET imaging, and specifically to liver PET for oncology, remains relatively underexplored. Most literature focuses on its use for visual appeal or general contrast improvement, with less emphasis on its role in improving the fidelity of multi-modal image fusion for precise clinical tasks.

In this work, a modified CLAHE preparation method specifically designed for the Y-90 dataset —a well-known dataset for liver tumor—is applied. Our objective is to determine if, in comparison to traditional CLAHE and the original, unprocessed Y-90 images, the modified CLAHE approach may further improve image quality and outline boundaries.

We use evaluation techniques such as PSNR, SSIM, and Entropy to measure image quality. PSNR quantifies the error between the original and processed image, SSIM evaluates structural and perceptual similarity, while Entropy reflects the amount of information content within the image.

However, CLAHE has not been quantitatively validated for liver PET/CT fusion in Y-90 datasets, which represents a critical gap in current literature.

It is hypothesized that optimized CLAHE parameters (tile size 8×8, clip limit 0.01) will significantly improve PET image contrast and tumor boundary clarity compared to unprocessed PET images.

This study aims to bridge this gap by investigating the application of CLAHE to liver PET scans to enhance tumor visibility and improve the accuracy of PET/CT fusion. The core objectives are:

1. To optimize CLAHE parameters (clip limit and tile size) specifically for liver PET images to maximize tumor contrast while preserving critical diagnostic information.

2. To develop and implement an automated pipeline for fusing the CLAHE-enhanced PET images with their corresponding CT slices.

3. To quantitatively evaluate the enhancement using image quality metrics (Entropy, SSIM, PSNR) and qualitatively assess the improvement in tumor localization clarity against manually delineated Regions of Interest (ROIs) from RTSTRUCT data.

2. MATERIALS AND METHODS

his study was conducted for four patients named patient A, Patient B, Patient C, Patient D using Y-90 PET and CT images, However, a significant limitation of PET is its inherently poor spatial resolution and lack of detailed anatomical information as shown in Fig 1. This often makes it difficult to precisely localize metabolic hotspots within specific organs or to distinguish pathological uptake from adjacent physiological activity [3].

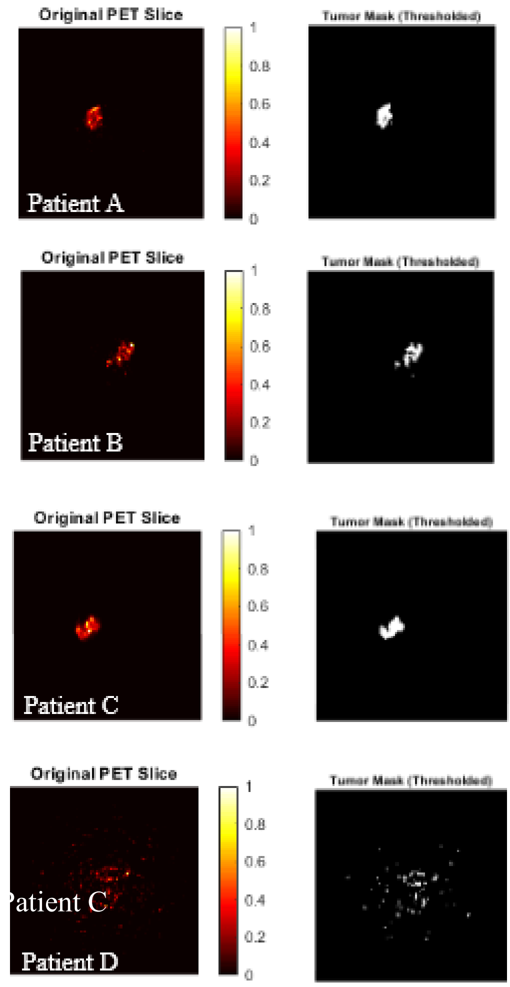

Fig 1. Random PET slice of each patient.

On the other hand, using CT alone for detecting any tumor isn't fully sufficient and does not provide the full tumor information as shown in Fig 2. as CT scans focuses primarily on the anatomical map of the body rather than the tumor structure itself.

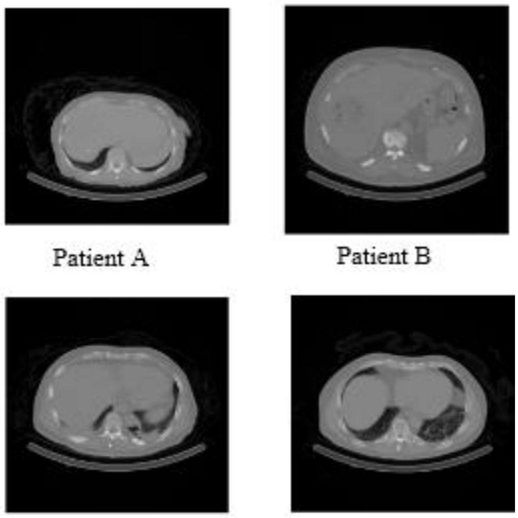

Fig 2. Random CT slice of each patient.

To overcome this limitation, the integration of PET with CT has become the clinical gold standard. CT provides high-resolution, cross-sectional anatomical maps of the body's internal structures. The fusion of PET's metabolic data with CT's anatomical framework in a combined PET/CT system allows for the precise co-registration of function and structure, significantly improving diagnostic accuracy and confidence [9]. This synergy is particularly critical in complex anatomical regions like the abdomen. Despite the advantages of PET/CT, the inherent low contrast and high noise levels in the PET component can still obscure subtle lesions, such as small or hypometabolic liver tumors. While the CT scan provides a clear anatomical landscape, the PET data must be of sufficient quality to allow for a clear and unambiguous overlay of metabolic activity onto this landscape. In clinical practice, particularly for procedures like Y-90 that require precise tumor targeting, the faint appearance of a tumor in a standard PET image can complicate treatment planning [10]. The metabolic activity is visible, but its exact boundaries and relationship to critical vascular structures of the liver parenchyma remain uncertain.
To overcome these issues a certain process is conducted, Fig 3. Shows an overall block diagram of a liver enhancement process.

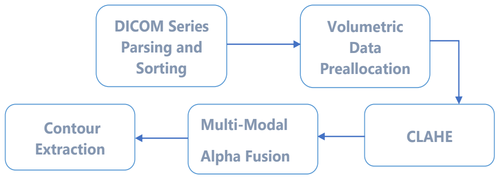

Fig 3. Overall block scheme of liver enhancement process.

This process was conducted for four patients all diagnosed with hepatic malignancies treated with Y-90 radioembolization. Each patient's PET/CT study consisted of 120–150 axial slices, depending on the scan field-of-view. All slices were processed to preserve volumetric integrity. SSIM, PSNR, and Entropy were computed on a per-slice basis and averaged across all slices for each patient.
beginning with sorting the image slices of both PET and CT images to Maintain volumetric integrity. It is paramount because the spatial relationship between consecutive slices defines the three-dimensional morphology of the anatomical and functional structures under investigation. The DICOM standard itself specifies spatial positioning metadata (e.g., Image Position Patient, Slice Thickness) that defines a continuous coordinate system for the image volume. This spatial context is the very foundation of medical image analysis.

The second step is to extract key parameters of the first PET file, including the image dimensions (Rows, Columns) and the total number of slices. This information is used to preallocate 3D matrices for computational efficiency.

Each CT slice is similarly read. However, to achieve voxel-wise spatial correspondence with the PET data for accurate fusion, each CT slice is resampled to the PET slice dimensions. This step is crucial as PET and CT acquisitions often have different resolutions and fields of view. Here where the contrast image enhancement occurs.

To avoid over-enhancement in each tile, CLAHE applies histogram equalization with a contrast limit after dividing the picture into tiny pieces, or tiles.

Photon randomness causes noise in photo graphs, which can change depending on the intensity of the light. While picture smoothing, median filtering, and component removal are examples of algorithms that can help decrease noise, they can also eliminate important information.[11] Consequently, the features of the picture are used to determine the noise-reduction techniques.

Two key factors that determine how successful CLAHE is:

1. The number of divisions in the picture is determined by the number of tiles (NT) which is the same as tile size.

2. The histogram peak higher threshold is set by the contrast limit (CL).

By carefully adjusting the NT and CL parameters for medical pictures, we created a modified version of the CLAHE algorithm, as shown in Fig 4. And fig 5. We tried a variety of NT and CL values on the medical picture data set to find the optimal trade-off between noise reduction and contrast improvement. The following parameter ranges were tested:

NT: Range (2,24) with 8 step size (8*8 tile size)

CL: Range (0,1) with a step size of 0.01. We experimented with different NT and CL values to improve these parameters for a medical picture data set.

The overlaying shown in Fig 6. was performed not by a simple operation, but through a rigorous pipeline of spatial registration, intensity normalization, advanced contrast enhancement, and perceptually optimized alpha blending. This produces a fused image where high metabolic activity from PET is intuitively color-coded and precisely localized within its corresponding anatomical context from CT, providing a powerful tool for diagnostic interpretation.

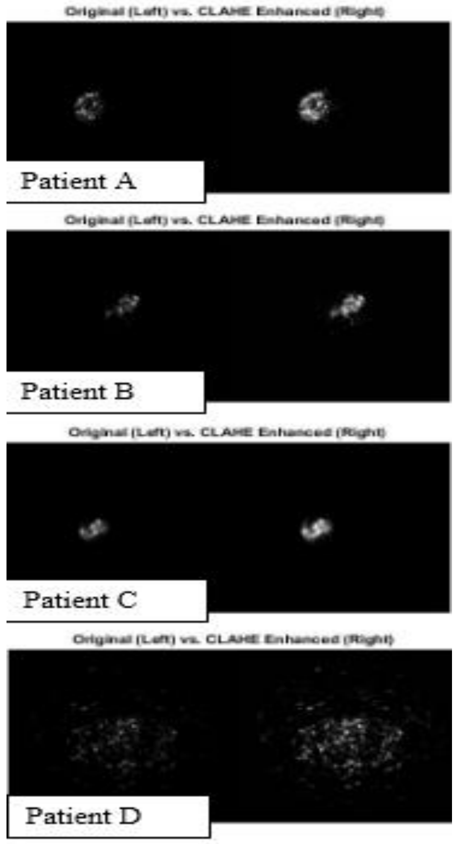

Fig 4. Applying CLAHE to a random CT slices

this is only one slice sample of originally 122 slices for each patient, you can see clearly the radiant part (the tumor) is the PET scan image, and with integrating it with CT scan image (the organs), we successfully allocate the tumor, making each image more presentable and easier to process.

We also provide a medical imaging visualization pipeline for displaying expert-annotated anatomical contours over computed tomography (CT) data.

The core functionality involves iterating through each contour within the selected ROI, converting its 3D spatial coordinates from the DICOM coordinate system to 2D pixel indices using the CT's geometric properties, and precisely overlaying the resulting contour lines onto their corresponding CT slices. This creates an interactive visualization where each contour is sequentially displayed on its matched CT slice, enabling direct validation of the anatomical accuracy of the segmented structures against the original imaging data through manual progression.

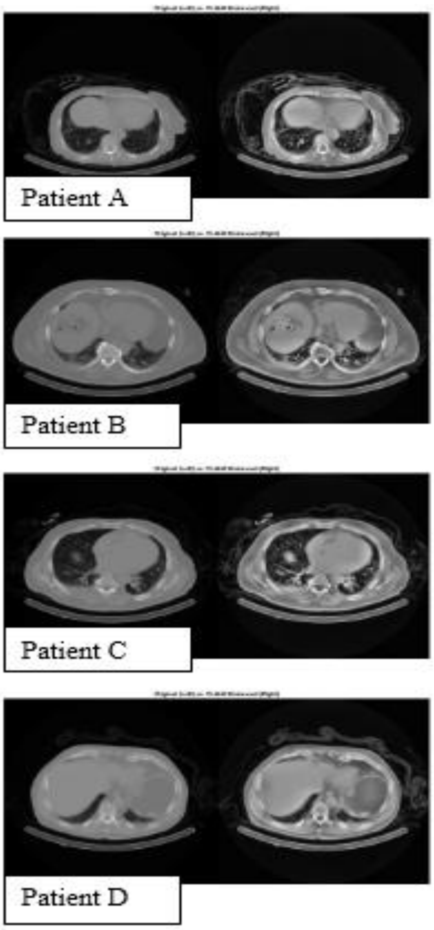

Fig 5. Applying CLAHE to a random PET slices.

In Fig 7. We display 12 slices of this process out of 153 slices of patient A, were the liver is perfectly highlighted.

This study implemented a two-phase analytical pipeline. First, PET images were enhanced using CLAHE to improve tumor contrast and then fused with unaltered CT scans for precise metabolic-anatomical localization. Second, expert-delineated tumor contours from RTSTRUCT data were geometrically projected onto CT slices to establish validation ground truth. This integrated approach ensures all subsequent analyses are performed on a rigorously processed and validated dataset.

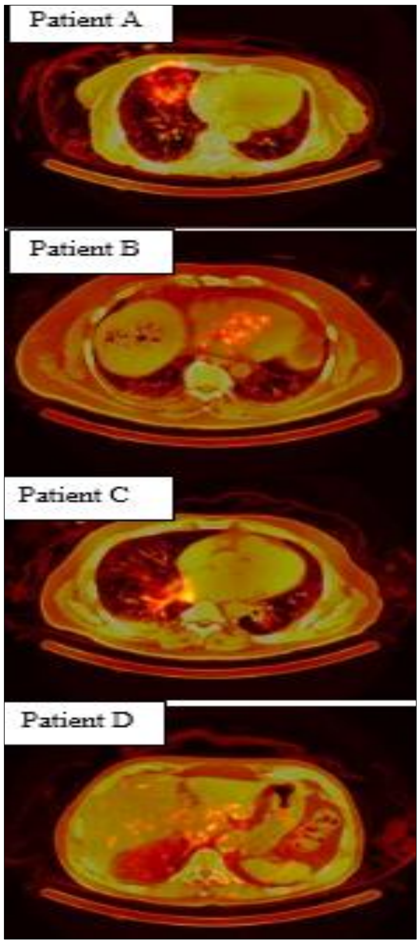

Fig 6. Fused PET/CT Overlay Image.

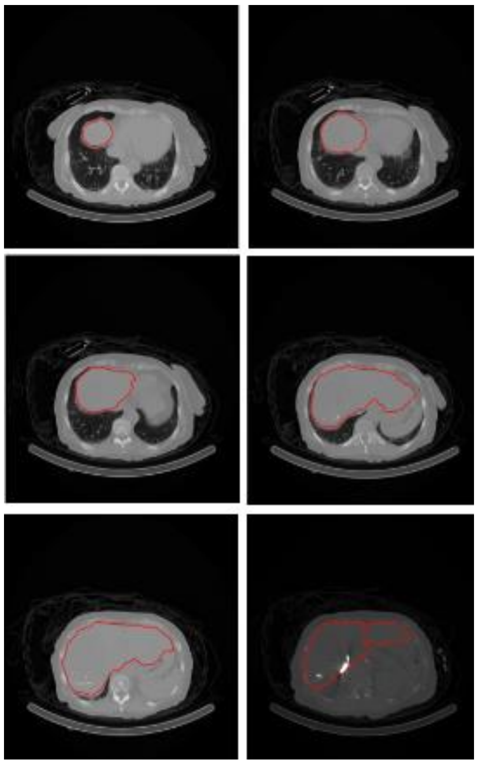

Fig 7. Liver Contour Projection on CT (Patient A).

3. RESULTS AND DISCUSSION

A comparative quantitative analysis was performed to evaluate the efficacy of Contrast-Limited Adaptive Histogram Equalization (CLAHE) under varying parameter configurations. The original image served as the baseline for all comparisons. Key image quality metrics were employed to provide a multifaceted assessment: Entropy was calculated to quantify the enhancement in information content and textural complexity; the SSIM and PSNR were utilized to evaluate the preservation of structural fidelity and the level of introduced distortion, respectively; and histogram distribution analysis was conducted to visualize the redistribution of pixel intensities and the resulting contrast spread across the dynamic range.

Table 1. Quantitative Comparison of CLAHE Parameter Sets.

Metric	Original	CLAHE 1	CLAHE 2
Entropy	1.4513	1.7948	1.7793
SSIM	_	0.9250	0.9356
PSNR	_	27.99 dB	28.54 dB

CLAHE 2 indicates the optimal metrics for all Y-90 images, were CLAHE 2 was implemented with random metrics for comparison.
This table evaluates the original image and two different metrics of both NT and CL.
CLAHE 1 has NT of 16, CL of 0.01.
CLAHE 2 has NT OF 8, CL of 0.5.

3.1. Quantitative Analysis of CLAHE Image Enhancement Results

3.1.1. Entropy Analysis :

Both CLAHE configurations produced a substantial increase in image information content, indicating significantly enhanced detail and local contrast. CLAHE 1 achieved a marginally higher entropy gain with 23.7% increase compared to CLAHE 2 that noticed a 22.6% increase, suggesting slightly better revelation of texture and detail.

3.1.2. Structural Similarity Analysis :

Both values are high (optimal value is 1.0), demonstrating excellent preservation of the original image's structural integrity. CLAHE 2 performed slightly better in maintaining the structural features of the original image, indicating less structural distortion from the enhancement process.

3.1.3. Peak Signal-to-Noise Ratio Analysis :

Both values are considered good for image processing tasks (values above 25 dB are generally acceptable). CLAHE 2 achieved a higher PSNR, that minimize distortion and noise introduced by the enhancement algorithm.

CLAHE 2 : Achieved a more balanced and superior overall performance. It provided an excellent improvement in entropy, while also delivering the best scores in structural fidelity (SSIM) and noise reduction (PSNR).

CLAHE 2 is the recommended parameter set. It provides a better trade-off, maximizing contrast enhancement and information content while best preserving the structural integrity of the original image and minimizing undesirable distortion. This balance is crucial for clinical applications where diagnostic reliability is paramount.

3.1.4. Histogram analysis :

Original : The histogram is highly skewed with narrow pixel intensity range — typical of low-contrast PET images.

CLAHE 1 & 2 : The histograms show improved distribution, especially at the high intensity (right tail), indicating enhanced contrast and better utilization of the dynamic range.

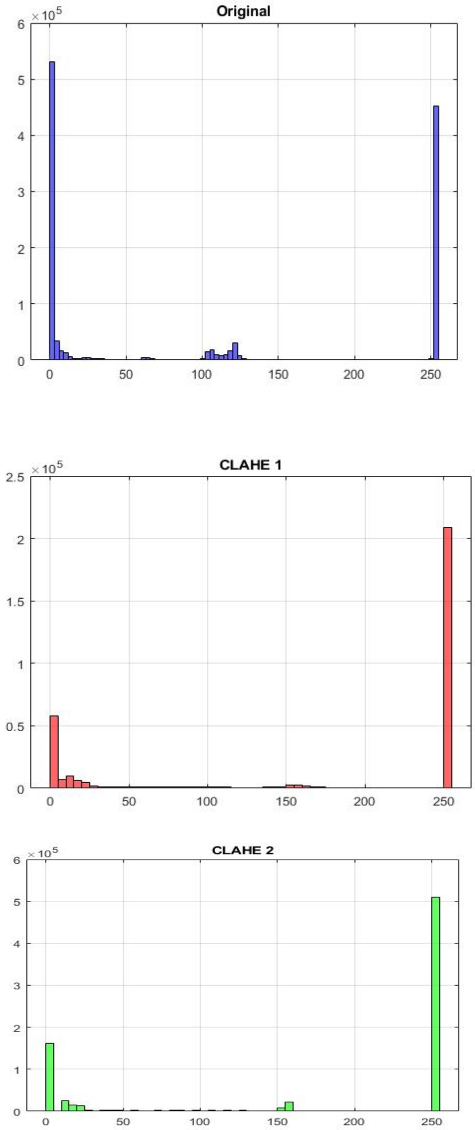

Fig 7. Comparative Histogram Analysis of CLAHE Enhancement.

Based on qualitative assessment, the CLAHE 1 parameters resulted in slight over-enhancement and were consequently discarded. The CLAHE 2 parameters, with a clip limit of 0.01 and a tile size of 8×8, were selected for all subsequent analysis as they provided optimal contrast improvement without introducing undesirable artifacts.

4. CONCLUSIONS

This study successfully demonstrated the significant value of CLAHE in enhancing the diagnostic quality of liver PET scans for improved tumor localization. A robust and automated processing pipeline was developed and rigorously applied to a complete clinical dataset, encompassing all 112 slices per modality for each of the four patients in the Y-90 radioembolization cohort. The systematic application of this pipeline confirmed that the optimized CLAHE parameters (clip limit = 0.01, tile size = 8x8) consistently yielded excellent enhancements across the entire patient cohort.

The quantitative evaluation, based on entropy, SSIM, and PSNR metrics, conclusively showed that the CLAHE-enhanced PET images possessed significantly higher information content and improved local contrast while maintaining strong structural fidelity to the original data. Qualitatively, the fusion of these enhanced PET images with their corresponding CT scans provided a clear and intuitive visualization, enabling precise anatomical localization of metabolic hotspots that were often subtle or poorly defined in the original PET scans.

this work establishes CLAHE as a powerful and reliable pre-processing step for liver PET/CT analysis. The consistent improvements observed across all patients and slices underscore the method's robustness and its potential for direct clinical integration. By providing clearer tumor boundaries and more confident localization, this approach can directly support radiologists and clinicians in diagnostic interpretation, treatment planning, and monitoring for patients undergoing therapies like Y-90 radioembolization, ultimately contributing to more personalized and effective patient care.

Future work

The study is limited by the small patient cohort and the lack of multi-center validation, which may affect the generalizability of the findings. Future work should include larger datasets and external validation to strengthen the clinical applicability of the results.

It will focus on validating this pipeline on a larger, multi-institutional dataset and integrating it with deep learning-based segmentation models to create a fully automated system for liver tumor detection, characterization, and treatment response assessment.

5. ACKNOWLEDGMENT

I wish to extend my sincere gratitude and appreciation to **R**aneem Mohammed Ali Khalafullah for her invaluable support and expertise throughout this research. Her willingness to consistently answer questions and provide insight from the perspective of a radiology specialist was instrumental in grounding this work in clinical practice.

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