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Improving Diagnostic Viewing of Coronary Cine-Angiogrphy through Frequency Filtering based Frame Enhancement Method

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Abstract— **Coronary angiography is an invasive medical image modality which is widely used in Interventional Cardiology to detect luminal obstructions in Coronary Arteries (CA). It has been reported that these recorded Coronary Cine-angiograms (CCA) are suffered from various visual artifacts such as noise, non-uniform illumination, low contrast and epicardial motion. As a consequence of these problems, the diagnostic visualization of the CCA degrades. In this study, it has been proposed a frequency filtering based frame enhancement method for CCA to improve its diagnostic visualization. The proposed method is based on homomorphic butter worth high pass filter and empirically validated contrast stretching technique. In order to correct the epicardial deformations optical flow based frame stabilization method has been applied in later stage of the proposed method. Study results clearly emphasized the visual improvement obtained through this novel method. The resulting enhanced CCA frames produced in this study can be further used to improve the angiography image modality for quantitative stenosis assessment.**

Keywords— **Homomorphic filtering, optical flow, angiogram enhancement.**

I. Introduction

Coronary angiography is a gold standard invasive medical image modality which is widely used in Interventional Cardiology to detect luminal obstructions in Coronary Arteries (CA). During the angiography procedure, a contrast dye will be injected into the CA through a catheter and blood flow through CA is recorded using an X-ray system called fluoroscopy. Angiogram can be produced either as still images or video and the video based coronary angiogram is known as Coronary Cine-angiogram (CCA).

Even though the angiography is used as one of the mandatory diagnosis modalities in Percutaneous Coronary Intervention (PCI), it has been reported that noise, non-uniform illumination, low contrast and motion as the factors which make visual degradations of the recorded CCAs [1][2][3]. Moreover, these factors formulate some visual disturbances in subjective stenosis analysis. In addition to that, the recent research attempts have reported that these visual degradation factors cause some hindrances when formulating objective stenosis diagnosis approaches based on coronary angiography [4].

Even though angiography has effected of visual degradations, it is still the most common modality for clinicians to assess the severity of stenosis during the PCI [5]. One of the main reasons for that is, it provides excellent visualizations of arterial lumen, which can be used for stenosis diagnosis and treatment planning. Moreover, it is a low cost invasive image modality compared to IVUS, FFR and OCT techniques and the equipment is readily available in most hospitals, even in less-developed countries. In addition to that, all cardiologists are familiar with the equipment, and have experienced in interpreting the resulting images. Further, the angiography is a relatively short imaging procedure, which facilitates effective clinical planning [6]. Hence, it has a great potential to improve the CCA to obtain an advanced visual quality. Moreover, it can be assisted to increase the level of accuracy of the medical judgments done using the CCAs.

In order to overcome the reported visual hindrances in CCAs, frequency filtering based a novel frame enhancement method has been implemented in this study. The proposed frame enhancement method is based on homomorphic filtering and empirically validated contrast stretching technique. Moreover, the motion reduction of CCA is achieved through an optical flow based motion stabilization technique. The results of this study have proven the ability to obtaining the uniformly illuminated noise reduced CCA frames. Moreover, the Left Main CA (LMA), Circumflex artery (CX) and Right CA (RCA) are considered as the main CAs to be analyzed under the selected angiography views.

The rest of the article is organized as follows: Next section explains the research problem and literature review of the study. Afterwards, the proposed frame enhancement method has been explained in detail. The experiment setup and the results are reported in the subsequent section. Discussion on the study results and the future work that can be extended based on the results of this study have been elaborated in final sections of this article comprehensively.

II. Background and Related Work

This section emphasizes the background of the research problem and related research work done in recent past.

A. Background

The non-uniform illumination, poor contrast, noise and motion are the reported factors which degrade the visual quality of CCAs. Non-uniform illumination in CCAs visualizes an individual vessel breaking into several segments.

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Moreover, it makes some hindrances to clearly recognize which branch segment belongs to which Coronary Artery in the frame to be processed [1]. The poor contrast opacification of the vessel may lead to a false impression of an angiographically significant lesion or lucency, which could be considered a clot. Further, inadequate mixing of contrast material and blood could be seen as a luminal irregularity. It occurs when there is a strong presence of blood and contrast agents in the vessels, the thick vessels have more contrast to noise ratios than the small narrow ones [1]. Fig. 1(a) depicts the effect of non-uniform illumination and within the circular area, it is hard to identify which vessel branch belongs to which CA apparently. Moreover, Fig. 1(b) depicts the effect of poor opacification. Contrast of the vessel depicted in the circular area is extremely poor when compared to the main blood vessel. In addition to the non-uniform illumination and poor opacification, CCA suffers from noise. The electrical system in cath-lab system adds Gaussian and impulse noise to the CCAs [7][8].

In general, CCAs are recorded with motion, which is another factor that affects to the CCAs. Mainly, there are three types of motions in CCAs namely, global, radial and the local motions. Global and radial motions occur due to the systolic and diastolic movements of the heart [9]. Global motion produces rapid displacements of vessel structures from its' initial recorded point, and radial motion makes tiny movements in distal parts of the main CA. Local motion occurs due to the flow of the contrast agent within the CA. CA are adhering to the epicardium of the heart and follow dynamic performances of the related myocardium during heart beat. Hence cardiac motion can be directly determined by arterial motion.

These visual hindrances create some obstructions when formulating an angiography based quantitative coronary analysis procedures. Nonetheless, the methodology suggested in this research study can be able to evade the aforementioned visual degradations in CCAs significantly.

B. Related Work

There are some reported standards in the area of angiographic image enhancement, which have been widely accepted by cardiologists [10]. Those are; (i) the image enhancement is used for visualization purposes only, and not for quantitative analysis, (ii) detailed image structures should not be lost during the enhancing procedure and (iii) the original dimensions of vascular structures should be preserved in the enhanced image.

It has been reported that the multi-scale Hessian based techniques with image morphology, image filtering and Contrast Limited Adaptive Histogram Equalization (CLAHE) based methods have been widely employed on resent past studies for coronary angiography enhancement [11],[12],[13],[14].

An improved multi-scale Hessian matrix combined with morphological top-hat operation has been implemented in resent research study to enhance angiography [11]. The main objective of this study was to suppress non-vascular structure and improve the profile of small tiny blood vessels recorded in angiography. In CLAHE, the histogram is cut at some threshold levels and then equalization is applied to enhance. It is an adaptive technique because an image is enhanced by applying CLAHE on small data regions called tiles rather than the entire image [12][13]. It is apparent that various filtering techniques are being used for enhancing angiography images by reducing noise and non-uniform illumination. Angiogram enhancement technique mentioned in [14] is based on directional filter banks and those directional filters were implemented using high pass filters.

Motion is another negative effect in CCAs and motion stabilization becomes extra pre-processing activity in CCA based processing. However, it has been reported that the motion of anatomy is quiet complex and cannot be accurately corrected by estimating models with low degree of freedom such as rigid or affine transformation [2]. The literature survey of this study reveals that the feature descriptor based method, image registration and optical flow based methods are among the major techniques for motion stabilization in CCAs and provided acceptable results for determining the cardiac dynamics[4][8][15][16].

A Scale Invariant Feature Transform (SIFT) based motion estimation and video stabilization technique was described in a recent research study [8]. In this study, SIFT was used to obtain the key points between two consecutive frames. The shortest distance between SIFT feature in two consecutive frames were calculated during the SIFT feature matching step of this study to determine the Global Motion Vector (GMV). Optical flow based method is proposed by Meunier and team to compute the regional epicardial deformation from coronary cine angiograms [16]. The motion of the CA is tracked using the proposed algorithms as a whole and quantify the two dimensional deformation of the epicardial surface locally. Arterial dynamics is also analyzed by the Zheng and Weirong using an optical flow based technique and elastic registration [15]. Improved template matching technique has been implemented in [4] to obtain the visual alignment of the CCAs frames.

III. METHOD

The proposed method for frame enhancement in CCA is explained in this section. The direct CCA frames denoted as $f_0(x,y)$ are input to the proposed method and (x,y) denotes the coordinates of the image function f_0. This proposed method iteratively processes the frames of input direct CCA sequentially and uniformly illuminated noise reduced enhanced frames are produced as output.

The proposed method consists of five major implementation phases namely; noise removal, application of homomorphic filter, contrast stretching, calculating motion vector, creating stabilized frame. The following sections briefly describe the important steps of each and every implementation phase of the proposed method.

C. Noise Removal

In order to eliminate noise, a median filter with kernel size 3×3 was applied to the input direct CCA frame to be processed [8]. The frame obtained after the noise reduction is denoted as $f_1(x,y)$ and it can be characterized by two components namely illumination (i) and reflectance (r) as shown in (1);

$$f_1(x,y) = i(x,y) \times r(x,y) \quad (1)$$

D. Application of Homomorphic Filter

Subsequently, this noise-reduced frame is further processed to remove the effect of non-uniform illumination. In order to achieve that, homomorphic butterworth high pass filter was applied to attenuate the illumination component (i) from the CCA frame [14]. Homomorphic filtering is a method in which the illumination and reflectance components can be filtered individually. It consists of several steps and those steps have been elaborated subsequently.

Initially, the CCA frame $f_1(x,y)$ is mapped into the natural logarithm domain to transform the frame as sum of its illumination and reflectance components. After that, the Discrete Fourier Transform (DFT) is applied to the frame to transform it into the frequency domain. Equation (2) represents the transformation of $f_1(x,y)$ in to DFT;

$$p(u,v) = i(u,v) + r(u,v) \quad (2)$$

Where, $i(u,v)$ and $r(u,v)$ are the Fourier transforms of $ln\{i(x,y)\}$ and $ln\{r(x,y)\}$. Moreover, (u,v) represents coordinates of the frequency spectrum obtained by the DFT.

It has been reported that the illumination components of the CCA frame can be easily identified through the low frequency content in the frequency domain because the illumination is considered as a slowly varying pattern in a particular image [14]. Hence, the butter worth high pass filter was applied to emphasize the high frequency components of the frame to be processed. These high frequency components are responsible in saving the ridge structures in the frame and for attenuating the low frequency bands, which are responsible for illumination. In order to filter out the high frequency bands, convolution was done between the DFT frame (p(u,v)) and the butter worth high pass filter ($b(u,v)$) as shown in (3);

$$h(u,v) = p(u,v) * b(u,v) \quad (3)$$

Where $h(u,v)$ denotes the resulting filtered frame obtained finally.

Moreover $b(u,v)$ is obtained multiplying the log transformed frame ($f_1(x,y)$) by the butter worth high pass filter function (hpf) given in (4);

$$hpf = \frac{1}{1 + \{D_0 + D(u,v)\}^{2n}} \quad (4)$$

Where, D_0 is the distance from origin to cutoff frequency in the DFT frequency spectrum, $D(u,v)$ is the radial distance from the origin and n is the order. According to the empirical results, values of both D_0 and n have been set as 10 and 2 respectively. After the filtering, inverse DFT has been applied to transform the image into natural logarithm domain. Then, to get back the homomorphic filtered CCA frame to the spatial domain, the transformation of natural logarithm has been inversed, which is exponential. Equation (5) represents this operation.

$$f_2(x,y) = i_0(x,y) \times r_0(x,y) \quad (5)$$

Where, $f_2(x,y)$ denotes the homomorphic filtered image. $i_0(x,y)$ and $r_0(x,y)$ are the illumination and reflectance components of the homomorphic filtered image where $i_0(x,y) \neq i(x,y)$ and $r_0(x,y) \neq r(x,y)$.

E. Contrast Stretching

Moreover, this uniformly illuminated frame has been normalized by using (6) to obtain the better contrast among the vessel structures[4] [14].

$$f_3(x,y) = \begin{cases} M_d + \sqrt{\frac{V_d (f_2(x,y) - M)^2}{V}} & if (f_2(x,y) > M \\ M_d - \sqrt{\frac{V_d (f_2(x,y) - M)^2}{V}} & otherwise \end{cases} \quad (6)$$

Where M and V denote the estimated mean and variance of input frame ($f_2(x,y)$) and M_d and V_d are desired mean and variance values respectively. $f_3(x,y)$ is the output frame. As mentioned in [14], M_d was set as $M/2$ and V_d was set as $(V\times4)$ to obtain better results. It is important to note that the radial distance and order parameters of butter worth high pass filter and M_d, V_d parameters of normalization are adjustable according to CCA obtained under different machines. Fig. 2

clearly depicts a visual illustration of this proposed frame enhancement method.

F. Calculating Motion Vector

Motion vectors among the two consecutive frames of the CCA are processed iteratively to correct the epicardial deformations within the frames. Initially, it calculates the motion vectors between first and second frame of the CCA to be processed and motion stabilized frame is produced as the output. From the second iteration onwards, it takes the motion stabilized frame produced in the previous step and the next frame in the input CCA as inputs to calculate the motion vectors. Hence, it produces the subsequent motion stabilized frames as output. Moreover, this phase has been implemented based on the technique called optical flow because it can compute the motion among the two consecutive frames of the CCA to be processed. Additionally, optical flow is 2D vector field where each vector is a displacement vector showing the movement of points from first frame to second [17]. Noise reduced, uniformly illuminated contrast stretched frames are input to this phase to obtain the matrix of calculated motion vectors as the output.

Initially the Harris corner detector was applied to the current frame to detect the good features to track in the next frame [18]. Moreover, the corners were detected in sub pixel level to improve the accuracy. In the later stage of this phase, Lucas-Kanade optical flow is applied to iteratively track those points in the next consecutive frame [17]. Image (a) and (b) of Fig. 3 depict two consecutive frames of a selected CCA and image (c) of same figure depicts the computed motion vectors (marked using lines) based on the tracked feature points in those two frames.

G. Creating Stabilized Frames

Objective of this phase is to correct the epicardial deformations in the frame and obtain the stabilized CCA frames. It begins after tracking the corners in current frame which are identical to the corners in the previous frame. Within the phase, it calculates the 3×3 homography matrix based on the correspondence of marked points in two consecutive frames. In order to obtain the stabilized frame, it is required to change the perspective of the frame using the transformation matrix obtained during the application of homography. Hence, the perspective warping has been applied to the current frame to obtain the stabilized frame by evading epicardial deformations. Image (d) of Fig. 3 clearly depicts the stabilized frame for further clarifications. The proposed algorithm is as follows;

```
ALGORITHM: FrameEnhancer BEGIN
  current frame := Extract frame
  IF currentFrame == Null THEN
    EXIT
  ELSE
    Remove noise
    Apply homomorphic filter
    Contrast stretching
    If currentFrame == firstFrame THEN
      previousFrame := currentFrame
      continue with step 1
    ELSE
      calculate motion vector
      create stabilized frame
      previousFrame := currentFrame
      continue step 1
    END IF
    Save currentFrame
  END IF
END
```

IV. Results

This section elaborates the validation methods and results of the proposed study. The direct CCAs produced by Philips Medical System were used for the experiments and those were recorded in frame rate of 15fps with 512×512 resolution. In order to create a data set for validation the proposed methods, thirty direct CCAs were extracted under Left Anterior Oblique Cranial (LAO-CRA) view, Anterior Posterior Caudal (AP-CODL) view and Anterior Posterior Cranial (AP-CRA) view because those views provide excellent visualizations for the main CA namely RCA, CX and LAD respectively. Hence, it was tested 400 total CCA frames in the selected dataset using the implemented algorithm and Fig. 4 depicts the visual illustration of the resulting frames obtained from the proposed frame enhancement method.

Moreover, the proposed enhancement method is compared with some of the selected latest enhancement methods proposed in resent past publications which are based on adaptive histogram equalization and CLAHE method (Lara et.al) [13] [12]. Visual illustrations of the frames obtained from those published methods and respective intensity histogram are clearly depicted in Fig. 5 for benchmarking the proposed enhancement method. In order to evaluate the visual quality among the proposed method and the CLAHE method the frame entropy was calculated for 50 randomly selected frames and Fig. 6 depicts the distribution of the calculated entropy of those frames.

Four consecutive frames of an original CCA in the data set and the identical stabilized frames of the same CCA are depicted in Fig. 7 to visually analyze the robustness of proposed motion stabilization method.

V. Discussion

The objective of this section is to critically discuss the results of this proposed frame enhancement method. Fig. 5 visually illustrates the consequences of various image enhancement methods after applying them for a direct CCA frame. Fig. 5 (a) and (e) depicts the original CCA frame and its intensity histogram whereas Fig. 5(b) and (f) depict the adaptive histogram equalization result of direct CCA frame shown in image (a) and its intensity histogram respectively. Determining the uniform threshold values for implementing the adaptive histogram equalization is the major difficulty of this method. Moreover, the non-uniform threshold values cause failures or loss of spatial connectivity of the vessel structures and it leads to incorrect vessel segmentation when this enhancement frames have been used in quantitative coronary analysis. Lara and team have used CLAHE method as the contrast enhancement technique in their proposed angiography segmentation study [13]. Fig. 5(c) and (g) depicts the CLAHE result and the intensity histogram respectively. Even though CLAHE stretches the contrast of the image to obtain the visual quality, it cannot remove illumination frequencies recorded in the angiogram images, which cause the degradation of visual quality in the CCA frames. Moreover, it amplifies the noise signals in the CCA frames. Fig. 5 (d) and (h) depict the enhancement results provided by our proposed method. This image has deemphasized the illumination in the original image and preserved the whole vessel structure as it can be visualized in a clear manner. Moreover, it produced the balance intensity distribution among the all intensity histograms produced by other methods.

Non-uniform illumination is a definite visual degradation effect recorded in the CCA frames and in this proposed enhancement method, the homomorphic high pass filter has been applied to cut off the frequencies, which are responsible for the illumination. As a result of that, it would be possible to save the frequencies, which are reflected from the desired objects significantly. Hence, this frame enhancement method has provided excellent visualizations of the CCAs. The applied contrast stretching technique also improves the contrast of the frame and it further improves the visualization of CA so that it can be supportive for the diagnosis. Additionally, this homomorphic filter based enhancement does not amplify the noise components in the frames to be processed because it performs the frame enhancement by subtracting unnecessary frequency bands from the original frame. Fig. 4 depicts the sample frame enhancement results for visually analyzing the results.

The entropy provides the amount of information in the image. Both the number of unique spatial samples and unique spectral values contribute to the entropy in different weights [19][20]. Any typical contrast enhancement technique would reduce the entropy because some information can vanish due to intensity saturation (at 255 or at 0). If the contrast enhancement technique simultaneously reduces the illumination variation also, then the entropy will be extremely small. The reasons are the illumination variation also contributes to the entropy and the number of unique intensities becomes lower as the illumination is being normalized. This feature clearly emphasized in the graph shown in Fig. 6. According to Fig. 6, the calculated frame entropy of the proposed method is lower than the entropy of CLAHE. Hence, this proves how well the illumination is normalized and how well the unnecessary details such as noise were suppressed in the processed frames.

D_0 is the distance from origin to cutoff frequency in the DFT frequency spectrum and is used by the homomorphic filter mentioned in (4). Logically D_0 can vary from *0-256* interval. A prior experiment was carried out to determine the best value for this parameter. During the experiment, the intensity histograms of the three CCA frames of three selected angiography views were tested by setting the integer values for D_0 and Fig. 8 depicts the selected results for proving the effect. According to the results, it could be able to visually analyzed the contrast of the tested frames were gradually increased when D_0 is changing from 1 to 10 and reduced after that. Moreover, the dynamic range of the intensity histogram was also stretched maximally at D_0=10. These facts are clearly depicted in Fig. 8 and therefore 10 is set as the best value for D_0 parameter.

Chen and his team have implemented a CCA enhancement method based on improved multi-scale Hessian matrix combined with morphological top-hat operation [11]. In order to calculate Hessian matrix, it is required to obtain the derivative images of the angiography images to be processed. These derivative images can be calculated by applying convolution of a second order partial derivatives of a Gaussian filter. Application of Gausian filter leads to loss of image data and it violates image enhancement standards mentioned in the related work section in this section.

Research work in [8] has been reported a motion stabilization method in CCAs using the SIFT feature descriptor. According to this study, the global motion vector has been determined based on SIFT feature matching between the two consecutive frames. It has been empirically observed that SIFT provides many miss-corresponding key point pairs in angiography and feature matching as depicted in Fig 9. This illustration clearly emphasizes that most of the detected feature points are located in the background of the frame. Moreover, the detected feature points in vessel structures have not perform correct feature matching with the corresponding frame for all detected feature points. As a result of that, it provides erroneous motion vectors for motion compensation.

By analyzing aforementioned factors, it can be concluded that this proposed frame enhancement method provides better visualization of the CA vasculature without any loss to the quality of the image. Further, the original dimensions of the vascular structures are also being preserved within this enhancement technique and it is a mandatory requirement for implementing a quantitative coronary analysis based on angiography.

VI. Conclusion

In this study, we proposed a frequency filtering based frame enhancement method for CCA to improve its diagnostic visualization. The proposed method is based on homomorphic butter worth high pass filter and empirically validated contrast stretching technique. In order to correct the epicardial deformations, optical flow based frame stabilization method has been applied in later stage of the proposed method. Study results clearly emphasized the visual improvement obtained through this novel method. Moreover, the proposed method is compared with the other recently published CCA enhancement techniques to benchmark the results. Finally, the enhanced CCA produced in this study can be further used to do some experiments on developing angiography based quantitative coronary analysis techniques.

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