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Automatic Extraction of Blood Flow Area in Brachial Artery for Suspicious Hypertension Patients from Color Doppler Sonography with Fuzzy C-Means Clustering

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Abstract

Color Doppler sonography is a useful tool for examining blood flow and related indices. However, it should be done by well-trained operator, that is, operator subjectivity exists. In this paper, we propose an automatic blood flow area extraction method from brachial artery that would be an essential building block of computer aided color Doppler analyzer. Specifically, our concern is to examine hypertension suspicious (prehypertension) patients who might develop their symptoms to established hypertension in the future. The proposed method uses fuzzy C-means clustering as quantization engine with careful seeding of the number of clusters from histogram analysis. The experiment verifies that the proposed method is feasible in that the successful extraction rates are 96% (successful in 48 out of 50 test cases) and demonstrated better performance than K-means based method in specificity and sensitivity analysis but the proposed method should be further refined as the retrospective analysis pointed out.

Index Terms: Blood flow area, Brachial artery, Color Doppler sonography, Fuzzy C-means, K-means, Pixel clustering

I. INTRODUCTION

Doppler ultrasound becomes a popular tool to estimate the blood flow through blood vessels with its noninvasive nature. While a regular ultrasound uses sound waves to produce images which can't show the blood flow [1], the Doppler test uses bouncing high-frequency sound waves off circulating red blood cells. Any flow moving towards the ultrasound probe is conventionally depicted as red and flow away from the probe is displayed as blue. A mixture of red and blue together can be the result of circular flow, turbulence, aliasing, or insufficiently resolved coherent flow.

Flow-mediated dilation (FMD) [2] is the most commonly used non-invasive assessment of vascular endothelial function [3]. It is regarded as a good blood vessel health predictor of cardiovascular disease as traditional risk factors [4]. Using ultrasound, the brachial artery dilation following a transient period of forearm ischemia is measured to determine the FMD [5]. FMD can measure vascular endothelial function directly, and it can also be used to measure the blood flow and its velocity [6].

While the color Doppler sonography and FMD measure are used in wide range of medical areas [7, 8], we are especially interested in hypertension related issues.

Hypertension is known as the major cause of congestive cardiac failure and if diagnosed, the optimal therapy is diffi-

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cult to obtain and costly [9]. Thus, we need to detect the disease as soon as possible to provide better treatment. Prehypertension is a new blood pressure category (systolic blood pressure 120–139 mmHg and/or diastolic blood pressure 80–89 mmHg) that represents a state between normal and established hypertension [10]. It is not considered to be a disease state, per se, as it was created to draw attention to possible risks for future development of established hypertension. FMD through color Doppler sonography is believed to be an effective measure for detecting prehypertension. It is reported that there exists a significant increase in the relative risk of hypertension with each unit decrease of FMD even independent of age and baseline systolic and diastolic pressure value [11].

However, as other ultrasonography usage, color Doppler sonography investigation should be done by sufficiently well trained operator [12]. The display of the spectral and Doppler directional information is under operator control [13]. Lack of standardization among different equipment is also a problem. Because FMD value can be compromised when it is improperly applied, there is a growing need to standardize the methodology for measuring FMD but actual attempts have been made only very recently [4]. Furthermore, commercial products measure arterial diameter automatically but such methods are based upon edge detection techniques [12] which is well debated that the measurement quality is below satisfaction [14, 15].

In this paper, we propose an automatic extraction method to detect the blood flow area in brachial artery without human intervention from color Doppler sonography. This procedure is an essential preprocessor in developing computer aided tool for diagnosis of hypertension related symptoms using FMD or intima-media thickness (IMT) of the vessel. Rather than edge detection based methods, we apply pixel clustering approach that has shown better performance against edge detection algorithms in automatic segmentation of organs [15, 16] due to its noisy tolerant or adaptive soft-constraint characteristics. Specifically, we adopt fuzzy C-means (FCM) clustering with semi-adaptive initialization in this paper. The accuracy of the proposed method is evaluated by human field expert in the experiment.

II. PROPOSED METHOD

Our goal is to extract the blood flow area in the brachial artery from color Doppler sonography automatically. The red and blue color in the sonography means the direction of the flow that is toward (red) or away (blue) of the probe. And the speed of the flow is represented as the brightness of the color. The naked eye investigation by human may have difficulty to determine the relative speed or to be confused when the color is mixed in the area if the operator does not have enough experience.

A. Preprocessing

An example of typical input sonography is shown as Fig. 1(a). A trapezoid window represents the region of interest (ROI) where the brachial artery with blood flow would exist. Then, we apply a thresholding binarization algorithm to remove the noise without ROI. The binarization formula is as following:

$$X_{max}^{G} = \mathrm{MAX}(\textstyle\sum_{i=0}^{MN} X_i^G), \quad (1)$$

where M, N denote the width and the height of the ROI and let X_i^G be the intensity of the current pixel in grey scale. Formula (1) determines the maximum brightness in the ROI and use it as the threshold as formula (2).

$$\begin{array}{l} \mathrm{if}(\sum_{i=0}^{MN} X_i^G = X_{max}^G)\ then\ X_i^G = 255 \\ \mathrm{else}\ X_i^G = 0 \end{array} \quad (2)$$

The trapezoid ROI is extracted by 2×2 mask and 4-directional contour tracing [17] with ease thus we can obtain the data as shown in Fig. 1(c) and then we can only focus on the red/blue area where the blood flows as shown in Fig. 1(d).

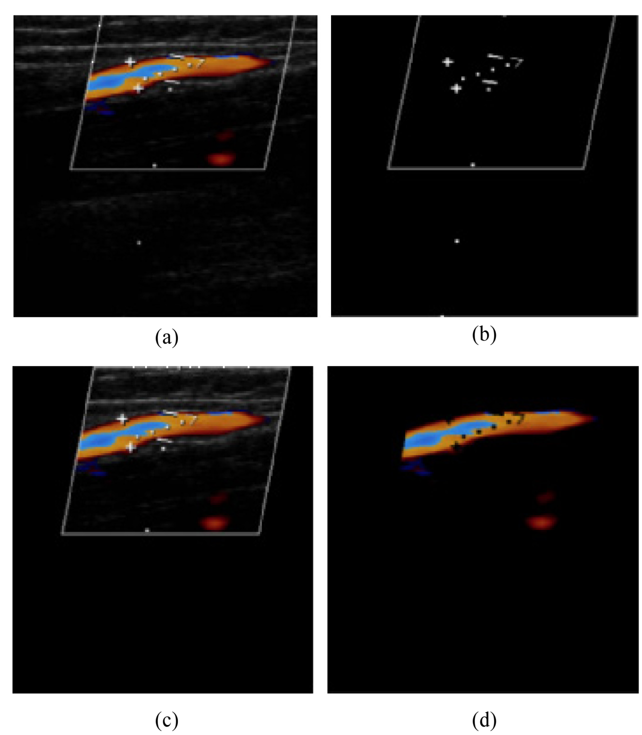
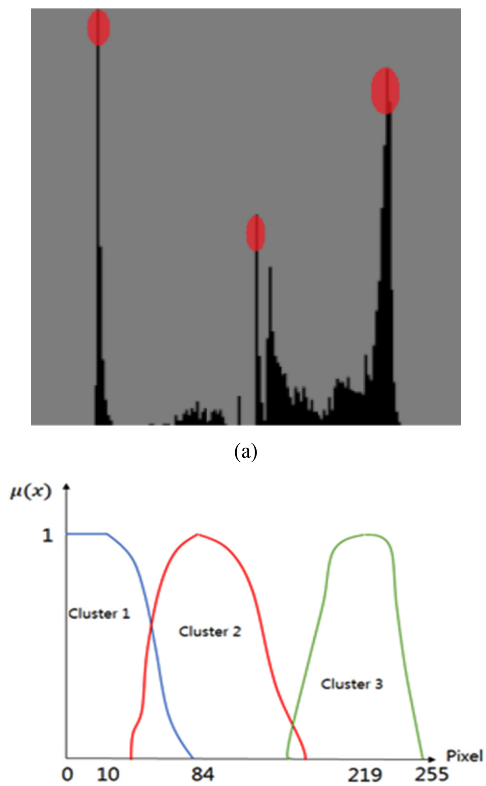


Fig. 1. Preprocessing steps: (a) input sonography, (b) binarized, (c) focused on ROI, and (d) after noise removal.



(b)

Fig. 2. Preparation for FCM based quantization. (a) Picks from histogram analysis and (b) Typical membership function for FCM quantization.

B. Fuzzy C-Means Quantization

FCM is an unsupervised learning method where data with similar features is grouped into the same cluster. FCM has been widely used for ultrasound image analysis [15]. It measures the distance between the pixel and cluster centers in the spectral domain to compute the membership degree that the pixel would be grouped into. The cost function is decreased when pixels close to the centroid of their clusters are assigned relatively higher membership values, and thus low membership values are assigned to pixels far from the centroid of the cluster. The value of the membership function represents the fuzzy probability that a pixel belongs to a specific cluster.

However, FCM is sensitive to the good initialization because it has to set the number of clusters before processing. Thus, we take the histogram analysis before FCM application and take the number of picks as the static initialization of the number of clusters for FCM as shown in Fig. 2(a) where a graph representing the number of pixels in an image at each different intensity value found in that image.

Then the FCM quantization is done as following:

Step 1: Initialize c ($2 \le c < n$) as the number of picks from the histogram analysis, and exponential weight m ($1 \le m < \infty$). Also initialize the error threshold (ε) for terminating condition and the membership degree $U(0)$.

Step 2: Compute the value of central vector V_{ij} as shown in Eq. (3) for $\{v_i \mid i=1, 2, \ldots, c\}$.

$$V_{ij} = \frac{\sum_{k=1}^{n}(U_{ik})^m X_{kj}}{\sum_{k=1}^{n}(U_{ik})^m} \tag{3}$$

where X is the input pattern, i is the cluster index, j is the pattern node index. k is the pattern index, n is the number of patterns, and U is the membership function.

Step 3: Define the FCM cost function J as Eq. (4)

$$J(u_{ik}, v_i) = \sum_{i=1}^{c}\sum_{k=1}^{n}(u_{ik})^m (d_{ik})^2 \tag{4}$$

where the distance d_{ik} is defined as between the k-th pattern x_k and the central vector of the i-th cluster, and u_{ik} is the membership degree of x_k among patterns in the i-th cluster.

In order to minimize J, d_{ik} and membership function U are defined as Eqs. (5) and (6), respectively.

$$d_{ik} = \sqrt{\sum_{i=1}^{l}\left(x_{kj} - v_{ij}\right)^2} \tag{5}$$

$$U_{ik} = \frac{1}{\sum_{i=1}^{c}\left(\frac{d_{ik}}{d_{jk}}\right)^{\frac{2}{m-1}}} \tag{6}$$

where l denotes the number of pattern nodes and c denotes the number of clusters.

Step 4: Compute the difference ($U_{ik}(r+1)$-$U_{ik}(r)$) between the new membership and the previous membership degree. If the difference is less than the error threshold (ε), then the algorithm terminates otherwise go to Step 2.

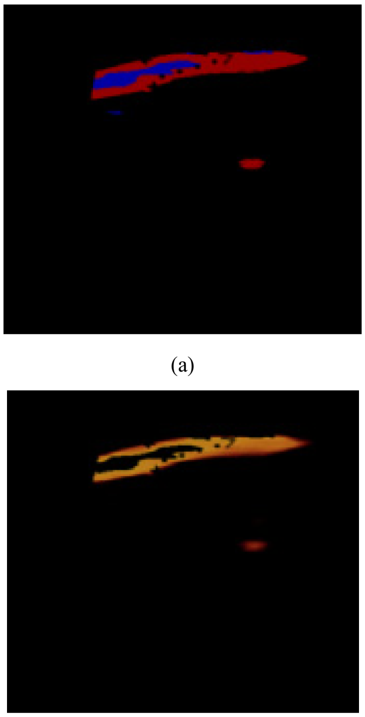
A typical fuzzy membership function used in this paper is as shown in Fig. 2(b).

In this quantization, we use the difference of R(ed) value from B(lue) value of the pixel as the magnitude of the membership to the red/blue clusters. Thus, the boundary pixels are more clearly classified to the red/blue object.

Fig. 3 demonstrates the effect of FCM quantization compared with the red area extraction by human expert.

III. RESULTS AND DISCUSSION

The implementation of the proposed method is written by C# under Visual Studio2015 environment on IBM compatible PC with Intel Core i5-7200U CPU@2.50 GHz and 8 GB RAM. Fifty color Doppler images from 50 hypertension suspicious patients were provided by Kyung Hee University Hospital, Korea.



(a)

(b)

Fig. 3. Effect of FCM quantization. (a) Quantized by FCM and (b) Extracted by human (red).

Among 50 images, the proposed method was successful in 48 cases (96%) by human expert's verification. Some of the successful extraction results are shown in Fig. 4.

The performance of the proposed system can also be viewed as the agreement rate compared with human expert's own extractions. For each pixel, we evaluate on what color the pixel is classified into such that how much the blood flow area extracted by the proposed system agrees to that of the human expert.

True Positives (TP): human and the system agreed as red (blue);

False positives (FP): human does not but the system classify it as red (blue);

False negatives (FN): human does but the system does not classify it as red (blue);

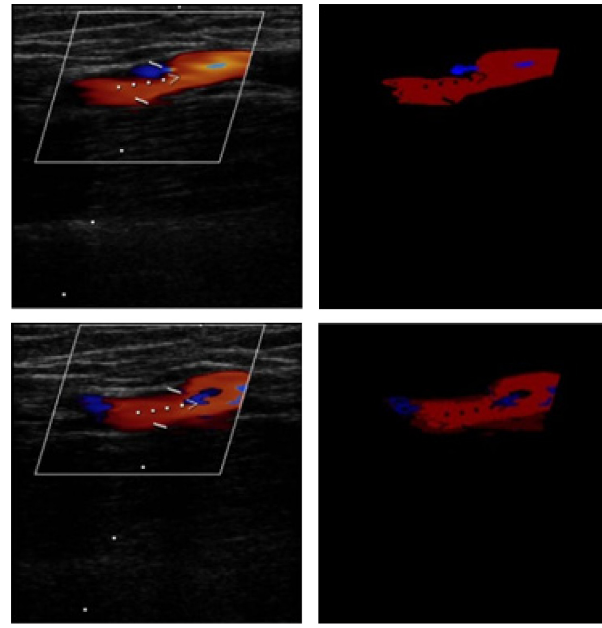
True Negatives (TN): human and the system agreed as not red (blue).

The sensitivity and specificity were calculated using the formula (7) and (8).

$$Sensitivity = TP/(TP + FN) \quad (7)$$

$$Specificity = \frac{TN}{TN+FP} \quad (8)$$

Among 48 successfully extracted cases the sensitivity in this experiment was 92.8% and the specificity was 85.2% in average.



(a) (b)

Fig. 4. Examples of successful extractions. (a) Input and (b) Successful extraction.

In order to evaluate the relative performance of the proposed method in this domain, we compare this FCM-based approach with K-means based method. K-means [18] is another well-known unsupervised clustering algorithm to form *k* homogeneous clusters with iterative updates of arbitrarily given *k* centers thus the within-cluster sum of squares would be minimized when the algorithm terminates. Typically, K-means clustering begins with *k* centers, chosen at random with uniformity from the data points. Then, each point is assigned to one of the clusters under nearest neighbor principle. After that assignment, each center is revised as the center of all points assigned to it. These assignment and revision steps are repeated until terminating condition holds (the set of clusters are sufficiently stabilized).

While its advantage is the speed and the simplicity as opposed to the accuracy, it can be used in medical imaging domain with careful treatment [19-21]. We apply the same strategy that uses histogram analysis to determine the number of clusters that should be preset as shown in Fig. 2 to K-means as well. Thus, any difference in this comparative experiment exhibits the different effect between FCM and K-means as clustering engine.

With the same set of 50 images, K-means based method was successful in 43 cases or simply 86% accurate in extraction rate as opposed to 96% by FCM. Among those successful extractions, with the same metric shown as Eqs. (7) and (8), K-means based method shows 90.3% in sensitiv-

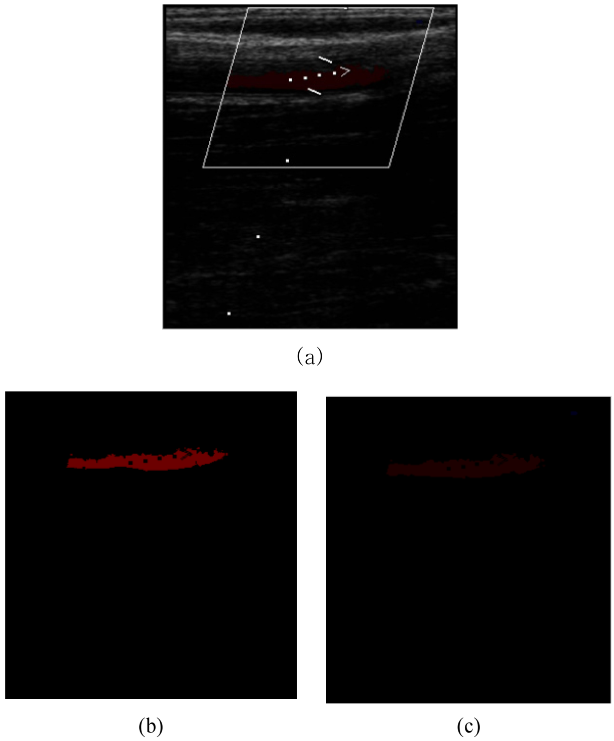


Fig. 5. Different blood flow area extractions by FCM and K-means: (a) Original input, (b) Extraction by FCM, and (c) Extraction by K-means.

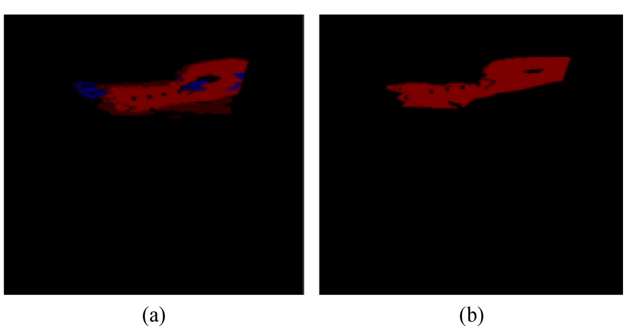


Fig. 6. Failed extractions. (a) Case 1 and (b) Case 2.

ity and 82.9% in specificity in average. Thus, it is safe to say that FCM-based automatic extraction is better than K-means based one under the environment as this experiment. Fig. 5 demonstrates the typical case of failed or unsatisfactory result from K-means as compared with the acceptable result by FCM. Even with the same initialization, two clustering algorithms form different clusters with different objective functions and the mere Euclidean distance used in K-means as the classifying tool may not be appropriate to classify red (toward flow) area correctly as shown in Fig. 5(c). For the case shown in Fig. 5, the number of clusters was initialized as 2 for both methods.

Unfortunately, FCM was not ideal in extraction task either. There were two failed cases in extraction process as shown in Fig. 6. In retrospective analysis, we found that case 1 of Fig. 6(a) happened due to wrong FCM cluster initializations by confused histogram analysis and case 2 (Fig. 6(b)) showed some loss of information (existence of a hole) during the preprocessing phase.

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