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Developing an automatic brachial artery segmentation and bloodstream analysis tool using possibilistic C-means clustering from color Doppler ultrasound images

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ABSTRACT

Automatic segmentation of brachial artery and blood-flow dynamics are important for early detection of cardiovascular disease and other vascular endothelial malfunctions. In this paper, we propose a software program that is noise tolerant and fully automatic in segmentation of brachial artery from color Doppler ultrasound images. Possibilistic C-Means clustering algorithm is applied to make the automatic segmentation. We use HSV color model to enhance the contrast of bloodstream area in the input image. Our software also provides index of hemoglobin distribution with respect to the blood flow velocity for pathologists to proceed further analysis. In experiment, the proposed method successfully extracts the target area in 59 out of 60 cases (98.3%) with field expert's verification.

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1. INTRODUCTION

The vascular endothelium is a delicate monolayer of cells lining all blood vessels and endothelial dysfunction is associated with numerous cardiovascular diseases [1]. The existing methods for assessing endothelial dysfunction and atherosclerosis in humans are based on functional tests in the brachial artery. Brachial artery is a medium-sized main arterial supply of the upper limb providing the blood supply to most of its structures [2].

Flow-mediated dilation (FMD) is commonly used non-invasive assessment of vascular endothelial function [3]. The brachial artery dilation following a transient period of forearm ischemia is measured to determine the FMD [4]. FMD can measure vascular endothelial function and vasodilation following an acute increase in blood flow (reactive hyperemia), typically induced by a period of circulatory occlusion [5] and it can also be used to measure the blood flow and its velocity [6]. Impaired brachial artery FMD has been reported in several recent studies as a parameter of endothelial dysfunction [1]. Thus, it is regarded as a good blood vessel health predictor of cardiovascular disease [6-9]. Not only for cardiovascular disease patients, is FMD-related blood flow dynamics in brachial artery related with the effect of sports activities in health [10-12]. A recent report also confirmed that the brachial artery diameter and FMD were significantly correlated with age, body mass index, systolic blood pressure, diastolic blood pressure, triglycerides, high-density lipoprotein cholesterol, and glucose as well as Framingham risk score [13].

In examining FMD, color-flow Doppler ultrasonography is frequently used noninvasive method that can provide sufficient diagnostic information to plan the surgical procedure. 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 [14, 15].

However, results of brachial FMD vary across institutions [16] and it might be partly explained by operator dependency, technical factors, and methodological varieties of FMD measurement [1]. There are many practical difficulties to obtain reliable non-subjective information such as lack of well-trained operators [17], inter-operator disagreement [18], and lack of equipment standardizations [8]. Thus, we need a software program that can perform automatic segmentation of brachial artery and bloodstream velocity analysis to provide most useful information to the pathologists with minimal, hopefully no human intervention. There have been several edge-detection and filtering based approaches to make automatic segmentation of brachial artery and compute associated performance indices [19, 20] but the limitation of such methods is well discussed already [21, 22].

Pixel clustering approaches are also attempted to make such automatic segmentation of brachial artery and bloodstream area detection with different controls of fuzzy C-means (FCM) clustering algorithm [15, 21, 23]. However, even dynamically controlled FCM is not sufficiently immune to the noisy input images. Possible reason of such sensitivity over noisy data is that for each object, the sum of the membership degrees in the clusters must be equal to one in FCM and such a constraint may cause meaningless results, especially when noise is present [24].

In this paper, we apply possibilistic C-means (PCM) unsupervised clustering algorithm in automatic segmentation of brachial artery and blood flowing area extraction. PCM, first proposed by Krishnapuram and Keller [25], is designed to overcome that noise sensitivity of FCM by relaxing constraint in clustering process. PCM has been applied to numerous medical imaging problems and obtained decent results [26-29]. However, usually the color Doppler ultrasound images give low contrast in intensity among hyper and hypotension areas and region where blood flow regurgitates. Thus, we transform the RGB scale of the image to the HSV channels. Then, the index of the hemoglobin (IHb), a mode of endoscopic observation that visualizes levels of mucosal circulation [30] is analyzed to monitor the velocity of bloodstream in brachial artery of the interest region. IHb has been studied and reported to obtain useful images for the early detection of gastric cancer, colorectal cancer, and *Helicobacter pylori* infection by differentiating the circulation condition of mucosa [31, 32]. All procedures explained in this paper is done without any human intervention thus the system’s output will be verified by human pathologists on its feasibility after the experiment.

2. METHOD

2.1. Possibilistic C-means (PCM) clustering

In a standard FCM technique, a noisy pixel can be wrongly classified because of its abnormal feature data [33]. Possibilistic C-means (PCM) clustering is another unsupervised clustering method where the component generated by PCM corresponds to a dense region in the dataset. PCM is known to be more robust in the case of noisy data. The PCM membership degree refers to the degree of ‘typicality’ between data and clusters [25]. The PCM is based on the relaxation of the probabilistic constraint in order to interpret in a possibilistic sense the membership function or degree of typicality.

Then we call $Up = (u_{ij})$ a *possibilistic cluster partition* of X if;

$$\sum_{j=1}^{n} u_{ij} > 0, \forall i \in \{1, \ldots, c\} \tag{1}$$

The $u_{ij} \in [0, 1]$ are interpreted as degree of typicality of the datum $\boldsymbol{x}_j$ to cluster i and u_{ij} for $\boldsymbol{x}_j$ resembles the possibility of being a member of corresponding cluster. The objective function in PCM clustering can be calculated as:

$$J_m(L, U) = \sum_{i=1}^{C} \sum_{j=1}^{N} {u_{ij}}^m {d_{ij}}^2 + \sum_{i=1}^{C} n_i \sum_{j=1}^{N} \left(1 - {u_{ij}}^m\right) \tag{2}$$

where n_i denotes the average distance between points in the same group in this paper. The first term of (2) tries to minimize the distance between the data point and the cluster center and the second term is a penalty term to avoid having a trivial solution and there are C number of clusters over N data and d_{ij} denotes the distance between the center of cluster C_i and data x_j.

The update formula for membership degree is defined as (3).

$$u_{ij} = \frac{1}{1 + \left(d_{ij}/n_i\right)^{\frac{1}{m-1}}} \tag{3}$$

The value n_i, the center of gravity, decides the distance that the membership degree becomes 0.5 in the cluster. Thus, it represents the relative importance of the second term with respect to the first term in the objective function (2) and typically estimated as (4).

$$n_i = \frac{K\sum_{i=1}^{N} u_{ij}{}^m d_{ij}{}^2}{\sum_{i=1}^{N} u_{ij}{}^m} \tag{4}$$

where K=1 and m=2 in this paper.

The learning procedure continues until the typicality u_{ij} is stable.

2.2. HSV color model and index of hemoglobin (IHb) for bloodstream velocity analysis

In color image processing, RGB model is the most popular one but in this domain, we found that there exists several cases that RGB intensity is not sufficient to discriminate the hypertension area (red) and hypotension (red) blood flow regurgitating area (blue) due to low intensity contrast as shown in Figure 1.

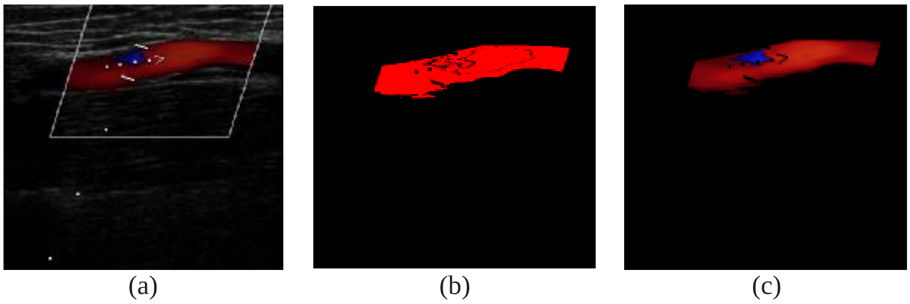

(a) (b) (c)

Figure 1. Brachial artery hypertension vs. hypotension area clustering; (a) input image, (b) RGB modeled [16], (c) enhanced hypertension area by HSV

When viewing a color object, human visual system characterizes it by its brightness and chromaticity. The latter is defined by hue (H) and saturation (S). Brightness (V) is a subjective measure of luminous intensity. It embodies the achromatic notion of intensity. Hue is a color attribute and represents a dominant color. Saturation is an expression of the relative purity or the degree to which a pure color is diluted by white light [34]. Inspired by such human visual system, HSV color model has shown better performance than RGB model in several domains. We adopt RGB to HSV transformation as in [34] and we further emphasize the brightness (V) as (5).

$$\begin{aligned} &if \quad V_r \times \left(1 + (1.0 - V_r)\right) > 1.0\ then\ V_{new} = 1.0 \\ &else\ V_{new} = V_r \times \left(1 + (1.0 - V_r)\right) \end{aligned} \tag{5}$$

where V_r denotes the V value of the pixel r in the region of interest (ROI) marked as a trapezoid as shown in Figure 1(a) and V_{new} is the enhanced new V value by the above equation.

In HSV color model, V value is in [0, 1] interval and the brighter the V value is closer to 1. With this enhancement, we obtain better brachial artery representation as shown in Figure 1(c). After detecting the bloodstream area in brachial artery, we need to analyze the velocity of the blood flow. It is known that the degree of hemoglobin in the mucosa and the distribution of the amount of blood flow in the mucosa are consistent with the distribution of the IHb [30].

$$IHb = 32 \times \log_2(V_r/V_g) \tag{6}$$

where V_r and V_g denote the R value and G value of the intensity in RGB color model, respectively.

IHb values computed by (6) are grouped and represented as shown in Figure 2 which gives a good deal of information for pathologists in analyzing blood flow analysis.

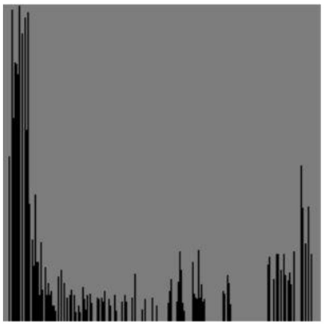


Figure 2. Histogram by IHb grouping: Example

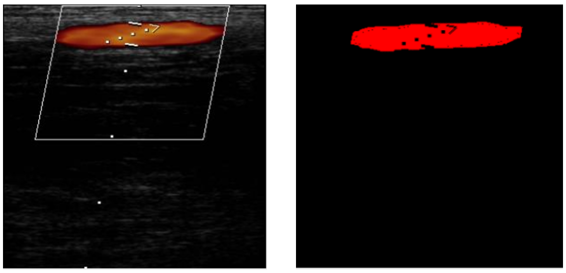
3. RESULTS

The implementation of the proposed method is written by C# under Visual Studio 2017 environment on IBM compatible PC with Intel(R) Core(TM) i7 CPU @ 1.80 GHz and 8 GB RAM. Sixty (60) color Doppler images of 800x600 size from 60 hypertension suspicious patients were provided by Kyunghee University Hospital, Korea. Some examples of successful segmentation by the proposed method are demonstrated in Figure 3. In this experiment, the proposed PCM-based clustering method fails in only one case out of 60 color Doppler ultrasound images by pathologists' evaluation and that is much better result than previous dynamically controlled FCM-based method explained in [15] as shown in Table 1.

In retrospective analysis, the average number of clusters created by the proposed method is similar to that of FCM (average 3.12). FCM is known to have some disadvantage in underestimating the cluster creation meaning that it tends to have fewer number of clusters than desired. But, in this experiment, there is no such improper clustering case in comparison with FCM. For the bloodstream velocity analysis, the system also provides IHb_percent with respect to the blood flow velocity based on normalized grouping of IHb distribution as shown in Figure 4 for pathologists to proceed further analysis.

Table 1. Experiment result

Method	Success	Failure	Rate
FCM [15]	53	7	88.3%
PCM-Proposed	59	1	98.3%



(a) (b)

Figure 3. Examples of successful extractions, (a) input, (b) successful extraction

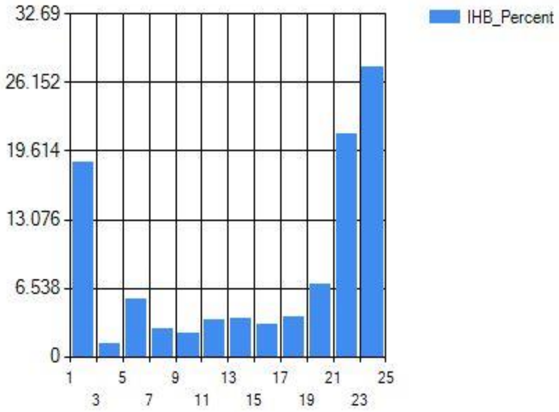


Figure 4. Normalized IHb-percent w.r.t. the flow velocity

4. CONCLUSION

In this paper, we propose a method to extract brachial artery from ultrasound images based on intelligent PCM clustering algorithm from color Doppler ultrasound images. The implemented software also provide associated statistics like the thickness of the artery as well as Ihb-percent distribution with respect to the blood flow velocity that is a useful performance statistics for pathologists that is a good source of measurement for hypertension diagnosis. To provide such measurements, we transform usual RGB color model to HSV model to enhance the contrast of bloodstream area.

In experiment, the proposed method is almost perfect in automatic segmentation of target brachial artery with red/blue area clustering. Only 1 out of 60 cases is not meet the criteria of field expert. This result is far better than our previous attempt that used dynamically controlled FCM-based method thus again, PCM is proved to be better classifier with noisy input.

However, PCM has its own disadvantages such that it needs good initialization to obtain good result. To classify a data point, cluster centroid has to be closest to the data point (by membership) and for estimating the centroids, the typicality needs to alleviate the undesirable effect of outliers. There exists a possibility that PCM stops with a smaller number of clusters than the actual number of clusters but in this experiment, such case does not occur.

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