REVIEW OF BLOOD VESSELS VELOCITY ESTIMATIONS

IRINA – ANDRA TACHE [1]

Rezumat. *Bolile vasculare se reflectă prin tulburări ale curgelui sângelui cât și modificări morfologice. Imagistica medicală digitală a revoluționat elaborarea diagnosticul și tratamentul acestor boli. Extragerea maximului de informație despre fluxul sanguin din achizițiile medicale imagistice are o mare importanță pentru medicii din zilele noastre. Lucrarea prezintă o trecere în revistă a celor mai semnificative metode de extragere a vitezei sângelui din imaginile medicale. Angiografia cu raze X este standardul în diagnosticarea bolilor vasculare și poate fi utilizată cu succes împreună cu metodele de estimare a vitezei sângelui prezentate în această lucrare.*

Abstract. The vascular diseases are reflected by impairments in both morphology and hemodynamics. Digital medical imaging has revolutionized the diagnosis and treatment of these diseases. The extraction of the blood flow information from the daily clinical medical imaging acquisitions is one of the greatest importance for the physicians nowadays. The paper presents a review of the most noticeable methods of extracting blood velocity from medical images. X-ray angiography is the gold standard of the vascular diseases' diagnosis, and it can be used successfully along with blood velocity estimation methods presented in this paper.

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1. Introduction

The cardiovascular diseases are the leading cause of death worldwide, followed by cancer as stated by World Health Organization. Medical imaging is intensively used in the diagnostics of vascular diseases in the past tens of years. The gold standard for the diagnosis of the coronary artery diseases remains the X-ray angiography.

The main goal is the extraction of the maximum knowledge from a medical images. There are efforts in extracting the velocity from fluoroscopic angiography which offers important information about the propagation of the contrast agent into blood stream.

2. Blood Velocity Methods

[1] Assis. Prof., PhD, Eng., Junior Researcher, affiliation: Faculty of Automatic Control and Computers, University Politehnica of Bucharest, Bucharest, Romania, (e-mail: irina.tache@upb.ro).

2.1 Bolus tracking methods

The transit time method is used to compute the time density curve between two regions of interest (ROIs) along the same vessel, proximal and distal, and estimate the transport time.
The approximated distance between the proximal and distal locations can be determined as Euclidian distance between the centerline pixels. Based on the assumption that the contrast agent perfectly mixes with the blood and it travels with the same speed into the vessels, the mean blood velocity can be estimated as the ratio between vessel length and transit time between the ROIs. This method was successfully applied for non-pulsatile flows of the cerebral and coronary vessels [1].

2.2 Velocity determination from distance density curves

The method is based on obtaining, shifting, and matching the distance density curves at certain moments of time. Seifalian et al. in [2] defined the spatial shift L_0 as the best match of the curves. Finally, the fluid velocity is equaled with the ratio between the best shift d_0 and time interval between the two profiles:

$$v(t) = \frac{L_0}{\Delta t} \tag{1}$$

Hawkes et al. in [3] concluded that if the contrast agent bolus moves completely from the tagged vessel area between two consecutive frames, the method would fail.
To reduce the noise sensitivity, Rhode et al. in [4] developed a blood flow waveform shape model using the principal component analysis for fitting the concentration distance curves. An improvement of this method is found in [5]. After this step the optimal shift between successive fitted distance density curves is computed. They concluded that the concentration-distance curve matching algorithm is the most successful from all the distance density curve techniques.

2.3 Velocity determination from flow map

Colchester et al in [6] built the iso-concentration flow map or the parametric image to overcome the limitations of the bolus tracking methods. The parametric image contains information about the variations of the vessel densities in time along its length. Therefore, its columns contain the series of density distance curves and its rows the time density curves. The velocity is computed as the slope of the iso-concentration contours in the parametric image [7]:

$$v = \frac{dL}{dt} = \tan\theta \tag{2}$$

Where L is the distance along the vessel, t - time and θ - inclination of the iso-contours.
Brunt et al in [8] has applied this method to Digital Subtraction Angiography (DSA) for determining the carotid blood velocity and Bateman et al in [9] combined them with the parametric imaging for quantifying the blood flow rates from the volume flow and total cardiac output.

2.4 Indicator-dilution method

Cunningham et al. in [10] adapted the Stewart–Hamilton dye dilution method for stenosis assessment by computing the axial velocity - v(x) as:

$$v(x) = \frac{V}{A(x) \cdot \int_0^T c(x,t)\,dt} \tag{3}$$

Where A(x) is the surface area of the stenosis vessel.

2.5 Inverted continuity equation method

This method uses the continuity equation of the local mass conservation law which is written for moving fluids as:

$$\frac{\partial D}{\partial t} + \nabla(D \cdot v) = F \cdot \nabla^2 D \tag{4}$$

Where D is the contrast agent density, v is the blood velocity, F is the diffusion coefficient.
Assuming a negligible diffusion, the coefficient F is set to zero, and the above equation is written for the single dimensional case [11]:

$$\frac{\partial D(x,t)}{\partial t} + v(x,t) \cdot \frac{\partial D(x,t)}{\partial x} = 0 \tag{5}$$

Where the velocity v(x,t) is determined as the ratio between the partial differentials of density in function of time and distance:

$$v(x,t) = -\frac{\partial D/\partial t}{\partial D/\partial x} \tag{6}$$

An additional prerequisite must be taken for the term $\partial D/\partial x$. It was observed [12] that for small values it can introduce noises. Therefore, it must be high enough in order not to increase the velocity errors. Also, the applicability of this method for overall velocity measures is not recommendable [1]. Nevertheless, the assumption of zero-diffusion condition is valid only for the contrast agent which travels near the tip of the bolus leading edge.

2.6 Optical flow methods

They are intensively used in computer vision and it is dedicated to compute the velocity of rigid objects in every pixel from temporal image series.
Imbert et al. in [13] developed an optical flow method for symmetric axis and parabolic flow patterns:

$$v_{max} \cdot \frac{\partial D}{\partial x} \cdot \left(1 - \frac{(x - x_c)^2}{r^2}\right) + \frac{\partial D}{\partial t} = 0 \quad (7)$$

Where v_{max} is the maximum axial velocity for parabolic flows, x_c is the axial position of the vessel's centerline and r is the vessel radius with symmetric axis. It was successfully applied for human femoral artery quantification.
A weighted optical flow algorithm is proposed by Rhode et al. in [4] by averaging the estimated velocity along a vessel with the magnitude weightings of the spatial derivative. Another approach of the optical flow algorithm was adapted to DSA images by Bonnefous et al in [14].

2.7 Fluid continuity method

The one-dimensional equation of the mass conservation law to volume of fluids computed from two axial locations x_{v_1} and x_{v_2} which delimitate the vessel segment can be expressed as in [1]:

$$\int_{x_{v_1}}^{x_{v_2}} [D(x, t_{v_2}) - D(x, t_{v_1})]\, dx + Q \cdot \int_{t_{v_1}}^{t_{v_2}} \left[\frac{D(x_{v_2}, t)}{A(x_{v_2})} - \frac{D(x_{v_1}, t)}{A(x_{v_1})}\right] dt = 0 \quad (8)$$

Where A is the cross-sectional area and Q is the flow rate. This mathematical expression considers a negligible diffusion and a uniform contrast mixing. The flow rates are fitted using least squares algorithm for overlapping or variable sizes of vessels' segments and computation of the global flow rate Q between the times t_{v_1} and t_{v_2}.

2.8 Model based approach

The computational flow dynamics was a recently adapted to medical imaging. It models sufficiently accurate the blood vessels flow, for normal or abnormal geometries. This makes it desirable for clinical practice, but its drawback is the high computational power. A solution could be the parallelization on graphical parallel units or cloud computing.
Wächter in [15] proposed an overall model for predicting the iodine concentration after the injection into a vessel. The main hemodynamic components taken into consideration are the shape of the waveform model, the contrast agent injection model, the mixing of blood and contrast agent model at the injection site and the contrast agent propagation model.

2.9 Velocity estimation after 3D reconstruction

This is a research topic which appeared in scientific papers shortly after the rotational angiography [16]. In these scientific papers a rotational C-arm angiograph is used for generating a more accurate 3D reconstruction of the vessels and the 2D fluoroscopic angiography projections for extracting the vessels' contrast agent irrigation patterns. Different methods for mapping the 3D and 2D information [17] are proposed for these image sequences.
The spatial velocity is determined based on the bolus transportation time estimated from fluoroscopic angiography and the absolute length and radius of the vessel segment of the re-projected centerline obtained after 3D reconstruction of the rotational angiography [16]. This information can be further used as the boundary conditions in the computational fluid dynamics models [17].
The rotational transit time [15] is estimated directly from the 3D image acquisition to extract the flow parameters from the flow map. Both are further used as parameters in the identification of the physical model of the blood flow and the contrast agent transportation [18].

Conclusions

The physiological and structural information of the vascular system are evaluated by the physicians in dedicated clinics using medical imaging for diagnosis and even treatment of the coronary artery diseases.
The paper presents a brief review of the velocity estimation methods varying from analyzing the propagation of the contrast agent into the blood stream, until modeling the blood flow dynamics. Most of these methods can be applied for medical imaging techniques, such as X-ray monoplane or rotational angiography, magnetic resonance angiography, etc.

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