Estimation of Coronary Blood Flow by Contrast Propagation Using X-Ray Cineangiographic Images

A C Santos, S S Furuie

Heart Institute (InCor), University of São Paulo Medical School, Brazil

Abstract

In this work, the estimation of coronary blood flow through computational techniques from image sequences of X-ray angiography is presented. This method is based on contrast propagation and involves artery segmentation and motion compensation. The segmentation of coronary arteries is based on the fuzzy connectedness theory and mathematics morphology. Points of correspondence of vessels is carried out using two successive frames based on minimization of deformation measurements between the open curves. The cost function considers displacement vector of corresponding matched points, and curvature information. Propagation of the contrast material bolus is represented in a parametric image of corrected distance as a function of time. From the parametric image, instantaneous velocity can be calculated. The proposed methodology was assessed through simulations with synthetic images, images obtained from in vitro assays and coronary X-ray angiographic images.

1. Introduction

In clinical practice, the severity of vascular diseases is usually assessed through subjective visual examination of stenosis in angiograms, leading to certain inter and intra-observer variations. On the other hand, computational techniques have been developed for quantitative analysis of vessel size in angiograms in order to increase diagnostic objectivity. However, nor absolute vessel size nor percentage of stenosis reveal directly the functional significance of stenosis. Other measurements based on angiographic parameters like, for example, blood flow estimates are extremely useful in assessing the functionality of the myocardium irrigated by a stenotic vessel.

X-ray angiography images may provide flow measurements, as well as vessel morphology, parameters of fundamental importance in the assessment and accompanying of coronary artery related diseases.

Yet, measuring coronary blood flow is a great challenge as it involves many difficulties in virtue of the very small dimensions of the vessels, the pulsatile nature of the flow and the high motility of the cardiac structure.

The scope of this work is to present a method to estimate the coronary blood flow through computational techniques from image sequences of X-ray angiography. The method is based on contrast propagation and involves artery segmentation and motion compensation.

2. Methodology

In order to investigate estimation of coronary blood flow, this paper comprised three main phases: segmentation of the region of interest through obtainment of the vessel central line; minimization of the motion of the segment of interest in the coronary artery; and a third phase of estimating the flow using contrast propagation.

2.1. Coronary segmentation

Segmentation of real images based on fuzzy connectedness [1] is used, with the aim, in this work, to extract the skeletons or central lines of the vessel. One defines a point belonging to the region that is to be extracted, and the process incorporates points in that region until some stop criterion is satisfied. Each gray level represents the degree of association of that pixel with the seed pixel.

In this work, to extract a region of the coronary artery, an association function for a fuzzy set is proposed, given by: $\mu(x) = 255 - (255/\Delta)|x - m|$, where Δ represents the maximum variation in x, m represents the mean of the vicinity of the seed pixel or initial point of the region. The value 255 corresponds to the value of the pixel's maximum intensity that belongs to the object and zero corresponds to black and represents the background of the image.

Once the region of interest in the artery is extracted, the central line or skeleton of the vessel is obtained next, by using the skeletonizing morphologic operator. Overlap of a region from the original image and of its skeleton can be seen in figure (1).

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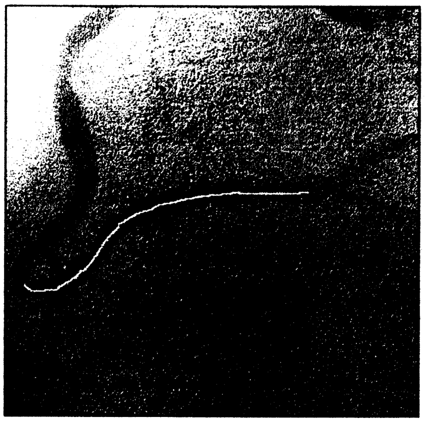


Figure 1. Artery segmentation. The figure shows the skeleton or curve obtained by applying the segmentation process over one image of the sequence.

2.2. Correspondence of artery points

Points of correspondence of vessels is carried out using two successive frames based on minimization of deformation measurements between the open curves. The cost function considers displacement vector of corresponding matched points, and curvature information. The search strategy for optimal matching is carried out using dynamic programming [2].

The figure (2) shows the overlap points of correspondences obtained by applying the proposed methodology (points inside of the black square) over the target curve.

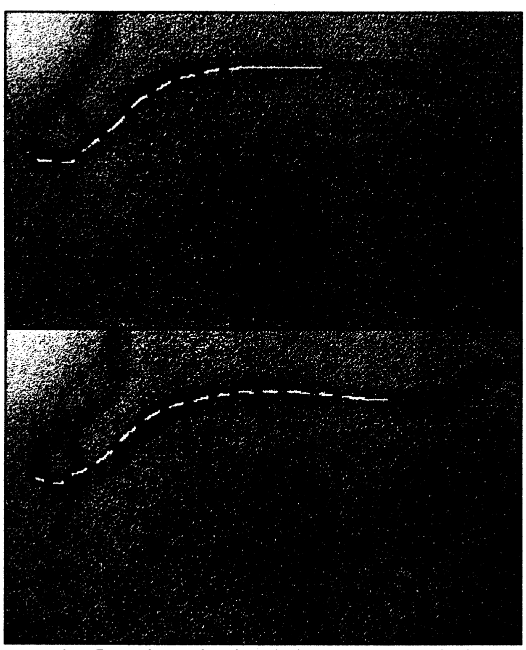


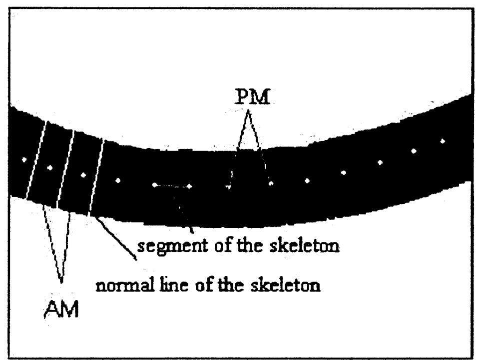
Figure 2. Results obtained in the experiment on real images.

Numerical simulations for the movement removal using several distorted curves showed error (mean square error of matching) below 0.7 pixels. The proposed methodology details and the evaluation of motion estimation on real data were presented in [3].

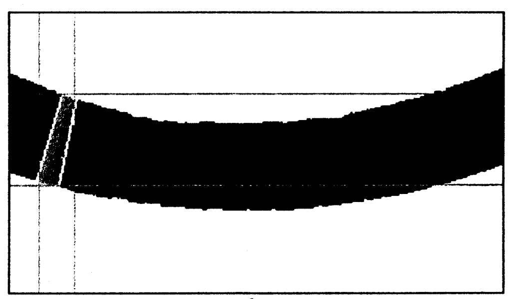
2.3. Flow estimation

The flow estimation is based on contrast propagation of compensated arteries. Propagation of the contrast material bolus is represented in a parametric image of corrected distance as a function of time. From the parametric image, instantaneous velocity can be calculated. The blood flow can be obtained by multiplying the instantaneous velocity by the estimated vessel cross-sectional area.

The parametric image is formed by intensity column vectors at each time instant, where each element of this column vector represents the transverse sum of all intensity values of the pixels in the vessel image, figure (3).



(a)



(b)

Figure 3. Composition of the parametric image. Images of a dye flow passing through an artery used in the algorithm tests. (a) Binary image in which the measuring points (PM) and some measuring areas (AM) were depicted. (b) Example of vector intensity construction for a single sequence image showing an image of a selected area.

Each intensity vector, corresponding to a single image frame, represents contrast concentrations as a function of distance along the vessel and time. In this way, each isointensity boundary on the parametric image follows a part of the contrast material through time and distance, therefore, enabling its use to estimate instantaneous velocity at a given position along the vessel. The procedure carried out to obtain a single vector from an image frame is described next. To build a parametric image, the entire procedure is repeated for all the frame sequences.

The amount of contrast material in the artery is measured through zones. Measurements are performed by means of gray levels in the image; darker zones refer to zones containing higher concentration of contrast material.

In order to obtain each intensity vector the following input are required: an X-ray image, a binary image of the vessel under investigation, a vector containing the measurement points, which are points on the skeleton of the artery obtained during the recording process and which will be used to perform integration.

Finally, building the parametric image is a simple matter of following the same procedure for all the sequence images and storing the intensity vector, in each time period generated by each image and possessing different lengths, due to the displacement of the wave front, forming in this way a parametric curve of contrast intensities or variations as a function of time and displacement.

For a given point of the coronary, assuming that the cross section area can be estimated from the image, the blood flow can be calculated using velocity estimation.

3. Results of blood flow estimation by contrast propagation

Assessments were performed with synthetic images, images obtained from *in vitro* assays, for continuous and pulsatile flow, and coronary X-ray angiographic images.

The evaluation of flow estimation on synthetic data were presented in [4]. For the case of studies in human coronaries, the quantitative comparison could not be attained since we did not have a gold standard. However, the qualitative results were very encouraging.

3.1. *In vitro* experiment

The experimental apparatus for simulation of continuous flow was constituted basically by a centrifugal pump, rubber hose of 60 cm of length and 2.54 cm diameter, and an electrogmagnetic flowmeter. We set the pump to a rate of 1.0 l/min. The sample rate was 30 frames/second and one pixel size was 0.07 cm, and it acquired an image of size 640 x 171 pixels, figure (4).

The experimental apparatus for simulation of pulsatile flow was constituted by a hydraulic simulator of circulation system with 40 beats/min of heartbeat frequency, a rubber hose of 60 cm of length and 2.54 cm diameter, and an ultrasonic flowmeter. The pump was set to a mean rate of 2.0 l/min. The sample rate for those flow condition was 30 frames/second and one pixel size was 0.07 cm, acquiring an image of size 592 x 171 pixels, figure (5).

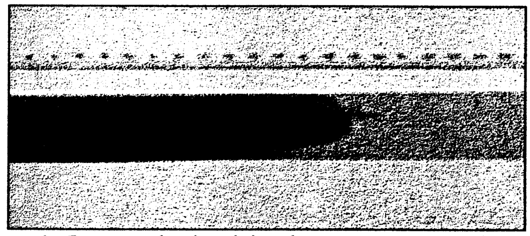


Figure 4. Image obtained in the *in vitro* experiment on continuous flow

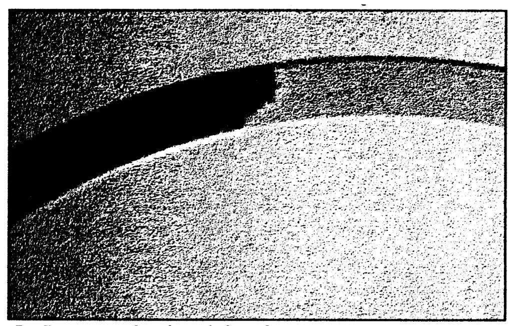


Figure 5. Image obtained in the *in vitro* experiment on pulsatile flow.

In the figures (6) and (7) we show the resulting parametric image yielding the positions of the contrast material along the vessel and time.

Figure 6. Results obtained in the *in vitro* experiment on continuous flow.

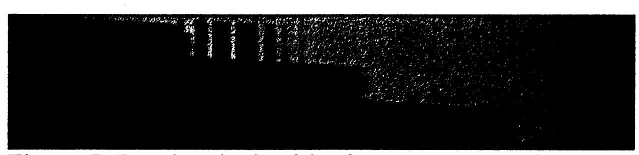


Figure 7. Results obtained in the *in vitro* experiment on pulsatile flow.

Measures of instantaneous velocity can be obtained considering derivatives of the curve that represents the contrast front propagation on the parametric image. Figures (8) and (9) represent the curve on parametric image for continuous and pulsatile flow.

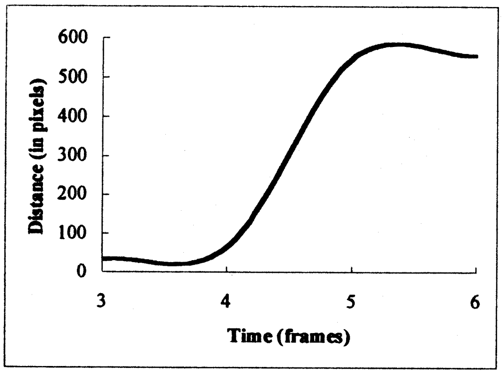


Figure 8. Curve on parametric image obtained in the *in vitro* experiment on continuous flow.

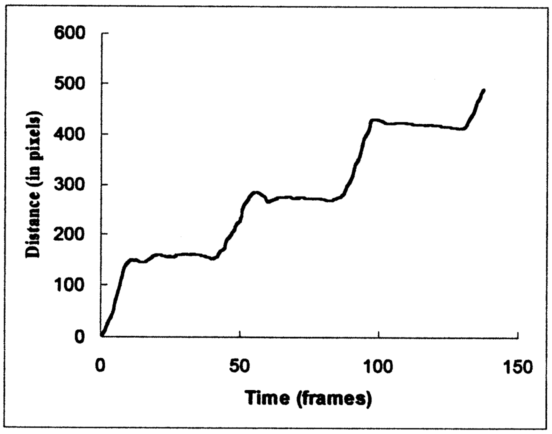


Figure 9. Curve on the parametric image obtained in the *in vitro* experiment on pulsatile flow.

In vitro experiments for the flow estimation, table (1), using continuous (1.0 l/min) and pulsatile flow (4 to 15 l/min) yielded results within 12% of the flow obtained by an ultrasonic equipment, figure (10).

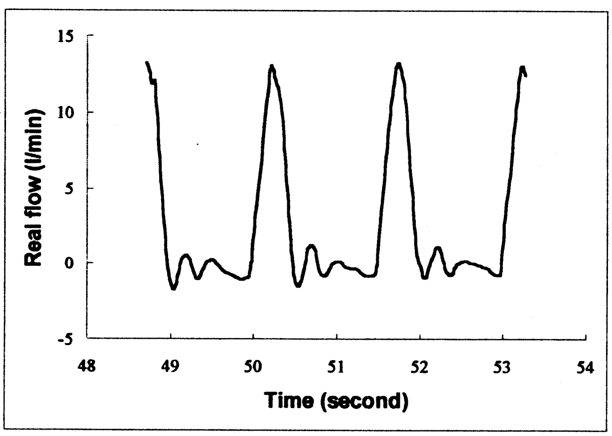


Figure 10. Real flow obtained in the *in vitro* experiment on pulsatile flow.

Table 1. Results of evaluation of *in vitro* experiments on continuous and pulsatile flow.

Flow	Continuous	Pulsatile
Mean flow of the equipment (l/min)	1.0	2.00
Estimated mean velocity (cm/s)	3.70	7.46
Estimated mean flow (l/min)	1.12	2.20

4. Discussion and Conclusions

This method is based on contrast propagation and involves artery segmentation and motion compensation. Propagation of the contrast material bolus is represented in a parametric image of corrected distance as a function of time. From the parametric image, instantaneous velocity can be calculated. The blood flow can be obtained by multiplying the instantaneous velocity by the estimated vessel cross-sectional area

The proposed approach allows estimation of blood flow even in presence of severe movement of containers. Further quantitative comparison should be done with actual angiographic images of heart.

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Address for correspondence.

Ana Cristina dos Santos
ana.santos@incor.usp.br

Service of Informatics - InCor
Av. Dr. Enéas de Carvalho Aguiar, 44
CEP 05403-000 São Paulo, SP, Brazil