Tracking Contrast in Echocardiography by a Combined Snake and Optical Flow Technique

K Althoff, G Hamarneh, M Beckman Suurküla*, T Gustavsson

Department of Signals and Systems, Chalmers University of Technology, Göteborg, Sweden
*Department of Clinical Physiology, Sahlgrenska University Hospital, Göteborg University, Sweden

Abstract

Contrast-echocardiography in conjunction with real-time video-densiometry can be an effective means of studying right ventricular (RV) structural changes, e.g. in patients diagnosed with Arrhythmogenic Right Ventricular Dysplasia (ARVD). In order to characterize RV flow pattern it may be necessary to track the front of the contrast agent as it enters the RV. Active contour models (ACM) is a standard image analysis method, which can be applied to time-dynamic tracking problem. To improve tracking speed we extended the formulation of ACM by including an additional force, derived from the optical flow field, another standard image analysis algorithm. This reduced the number of iterations needed to find the front of the contrast agent significantly.

Also the changes in intensity of the contrast agent over time were studied. Two groups were compared, one with 30 patients diagnosed with ARVD and one with 18 healthy volunteers. Our study shows that that using our suggested method (calculating wash-in and wash-out time indices) it is possible to discriminate between the two groups.

1. Introduction

The assessment of human right ventricular (RV) function is of great importance in many diseases afflicting the heart. Arrhythmogenic Right Ventricular Dysplasia (ARVD) is a rare but clinically important disease, which afflicts young adults and may play a role in the etiology of sudden death among young people [1]. The impairments of the RV function in this group of patients can be described in terms of wall motion abnormalities, or as localized bulgings and sacculations. These abnormalities are mainly located at the inflow, outflow or apical regions. To study these abnormalities we use sequences of contrast echocardiographic images.

In the first part of this article, a method to describe the hemodynamics, by calculating time parameters (wash-in/ wash-out indices) corresponding to the time needed for filling and elimination of the contrast agent in the RV, is described. These indices are calculated for two regions in the RV, one located in the right ventricular inflow tract (RVIT) and one in the apex.

In the second part we suggest a method for tracking the front of the contrast agent during the filling process, using Active contour models (ACM). We extend the formulation of ACM using information about the optical flow to make the contour find the front in less iterations. By tracking the front of the contrast agent we will get more information about the hemodynamics.

1.1 Imaging procedure

Thirty patients with biopsy-verified ARVD and 18 healthy volunteers were investigated by use of contrast echocardiography. The investigations were performed with an Acuson XP 128 computed system or a Sequoia system equipped with multiHertz transducers. As a contrast agent, 2 ml of Haemaccel® (Hoechst) was injected intravenously. Transthoracic apical four-chamber view with focus on the right ventricle was used and continuously recorded during and after the injection.

The video sequence of the filling and elimination of the contrast agent was then digitized using a PC with a frame grabber (Matrox, Meteor II), giving about 600 images for each sequence. Figure 1 shows a schematic illustration of the image sequence, presenting frame #1,

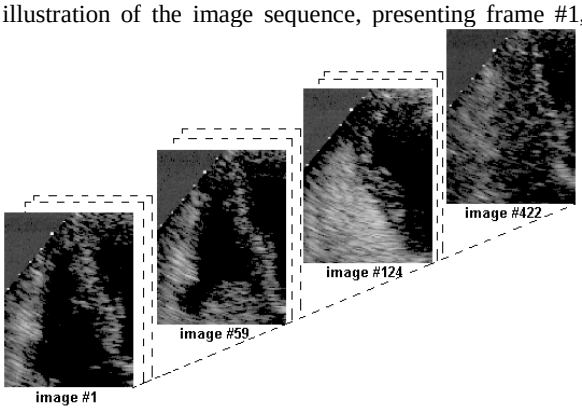

Figure 1. A schematic illustration of the digitized image sequence. In frame #1, #59, #124 and #422 the contrast agent has not arrived, just arrived, totally filled and been almost totally washed out, respectively, in the RV.

#59, #124 and #422. They represent the phases of the sequence when the contrast agent has not yet arrived, just arrived, totally filled and almost been washed out, respectively, in the RV.

2. Wash-in / wash-out indices

2.1. Material and method

A total of 48 frame sequences were analyzed, 30 from patients with ARVD and 18 from healthy subjects.

For each sequence, two regions of interest (ROI) were defined, each with size 5x5 pixels. One ROI was (manually) placed in the right ventricular inflow tract

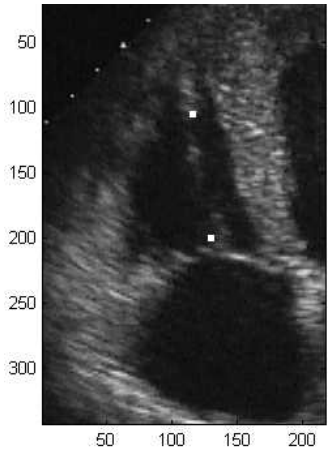

Figure 2. Image from one of the sequences with selected ROI showing as white squares. Note that the in this image the contrast agent has not yet reached the RV.

(RVIT) and one in the apex. Figure 2 shows a single frame with the two ROI showing as white squares.

For each ROI, the mean intensity of that ROI, for all frames in the sequence (i.e. intensity vs. time) was studied. An example of a filtered intensity curve is shown in Figure 3. Also shown in the figure are the three time parameters T_o, T_a and T_e. They are defined as follows:

- T_a : the time when the intensity of the contrast agent is at maximum
- T_o: indicating the time it takes for the contrast agent to reach the ROI (the time when the intensity has reached $0.2*T_a$)
- T_e: time indicating the wash-out time of the contrast agent for that ROI (the time when the intensity has dropped to $0.5*T_a$)

Since the starting point of each sequence depends on when the digitization started, a direct comparison of the values of T_o, T_a and T_e between the different sequences is not meaningful. Instead, the time differences

$$\Delta_{eo} = T_e - T_o, \quad \Delta_{ea} = T_a - T_o, \quad \Delta_{ao} = T_e - T_a$$

are calculated and compared.

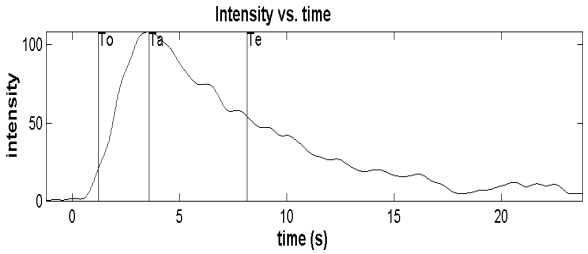

Figure 3. Example of graph showing the filtered intensity for a certain ROI vs. time. Also showing are the locations of the calculated time parameters, T_o, T_a and T_e.

2.2. Results

The mean and standard deviation of the resulting time differences for the different groups and ROI are shown in Table 1.

Table 1. Mean values and standard deviation for the ARVD-group and the control group

Test	ARVD-group	Control-group
Δ_{eo} RVIT	11.1 ± 6.9	5.5 ± 1.7
Δ_{eo} apex	11.0± 5.0	6.3 ± 1.7
Δ_{ea} RVIT	8.6 ± 6.6	3.9 ± 1.6
Δ_{ea} apex	7.1 ± 4.2	4.0 ± 1.5
Δ_{ao} RVIT	2.6 ± 1.4	1.7 ± 0.8
Δ_{ao} apex	3.8 ± 1.9	2.3 ± 0.6

2.3. Separation of groups

As shown in Table 1, the standard deviation for the ARVD-group is very high. This can also be seen in the histograms showing in Figure 4. To test if the groups are statistically well separated a Mann-Whitney U-test was performed, since it doesn't require that the groups have normal distribution. The result is presented in Table 2.

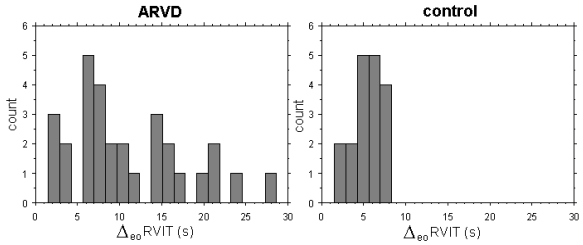

Figure 4. Example of histograms presenting Δ_{eo} RVIT, for the ARVD group and the control group, respectively.

Table 2. Resulting P-values after a Mann-Whitney test

Test	P-value
Δ_{eo} RVIT	0.0019
Δ_{eo} apex	0.0002
Δ_{ea} RVIT	0.0109
Δ_{ea} apex	0.0031
Δ_{ao} RVIT	0.0203
Δ_{ao} apex	0.0019

3. Tracking the front of the contrast agent

Tracking the front of the contrast agent entering the RV, will provide us with valuable information about the dynamics of the RV.

It may seem that classical edge detectors lend themselves to the problem of detecting the front edge of the contrast agent. However, typical echocardiographic images reveal weak ultrasound echoes, echo dropouts and high levels of noise. Thus, the application of simple edge detectors result in detecting erroneous edges or producing gaps in the detected edge. An intelligent approach, referred to as Active contour models (ACM) or snakes, for detecting boundary edges was introduced first in [2] and ever since has been highly appreciated within the machine vision community. This is mainly because of the way boundaries are considered; inherently connected and smooth structures.

Before the images were analyzed, they were filtered using a non-linear diffusion filter [3].

3.1. Active contour models

In ACM, or snakes, a contour is initiated on the image and left to deform in a way that, firstly, moves it toward features of interest in the image and, secondly, maintains a certain degree of smoothness in the contour. In order to favor this type of contour deformation, an energy term is associated with the contour and designed to be inversely proportional to the contour's smoothness and the fit to desired image features. Certain forces can be designed (or derived from energy terms) in a way that the resulting contour deformations will reduce the contour's energy. Using these forces, the equation for updating a single snake node can be written:

$$\mathbf{v}_i(t) = \mathbf{v}_i(t-1) + w_1\mathbf{F}_i^{tensile}(t) + \\ + w_2\mathbf{F}_i^{flexural}(t) + w_3\mathbf{F}_i^{external}(t) \quad (1)$$

where

- w_1,w_2 and w_3 are weighting factors
- $\mathbf{F}_i^{tensile}$ resists stretching of the snake
- $\mathbf{F}_i^{flexural}$ resists bending of the snake
- $\mathbf{F}_i^{external}$ makes the snake node move towards regions of higher intensity gradient.

3.2. Optical flow

In our application of tracking the front of the contrast agent we are presented with a sequence of images, i.e. a dynamic image $I(x,y,t)$. Optical flow [4] is a well-established method for calculating the velocity field ($u(x,y)$, $v(x,y)$) of the apparent 2D motion of pixels in an image, due to the 3D motion of imaged objects, by examining the spatial and temporal changes in intensity values. Classical optical flow is based on two main constraints. The first states that the brightness of any object point is constant over time. This can be written as:

$$I(x+dx, y+dy, t+dt) = I(x, y, t) \quad (2)$$

Using Taylor series expansion and neglecting higher order term gives the optical flow constraint equation:

$$I_x u + I_y v + I_t = 0 \quad (3)$$

where $u = \frac{dx}{dt}$, $v = \frac{dy}{dt}$ are the desired velocity field components, I_x and I_y are the spatial image derivatives and I_t is the temporal image derivative.

Equation (3) alone is not enough to calculate (u,v), and hence a second constraint, the velocity field smoothness constraint, is introduced. The velocity field can now be calculated as that which best satisfies both constraints by minimizing the following square error function:

$$\xi^2 = (I_x u + I_y v + I_t)^2 + \lambda(u_x^2 + u_y^2 + v_x^2 + v_y^2) \quad (4)$$

where λ is a Lagrange multiplier. Using an iterative algorithm described in [4] gives the velocity field (u,v).

3.3 Optical flow snake forces

In order to track the front of the contrast agent in an echocardiographic image sequence we need to accomplish two tasks. The first is to locate the region where the contrast front has moved to from one frame to the next, and the second is to detect this front as a smooth and connected boundary. We use the optical flow to address the first task and snakes to address the second. To combine the two techniques we include an additional force term proportional to the calculated velocity field at the current snake node position in equation (1):

$$\mathbf{v}_i(t) = \mathbf{v}_i(t-1) + w_1\mathbf{F}_i^{tensile}(t) + \\ + w_2\mathbf{F}_i^{flexural}(t) + w_3\mathbf{F}_i^{external}(t) + w_4\mathbf{F}_i^{flow}(t) \quad (5)$$

where w_4 is a weighting factor and

$$\mathrm{F}_\mathrm{i}^{\mathrm{flow}}(t) \propto (u(x_i(t-1), y_i(t-1)), v(x_i(t-1), y_i(t-1))) .$$

3.4 Result

The front of the contrast agent during the filling process was tracked in eight sequences, five from the ARVD-group and three from the control group. In each sequence, the front was tracked, on average, in about eight images. Histograms of the number of iterations needed for the contour to find the edge for all tested frames are shown in Figure 5. The mean number of iterations needed when using / without using information about the optical flow was 6.3 and 12.3, respectively.

This shows that adding the extra optical flow force was beneficial.

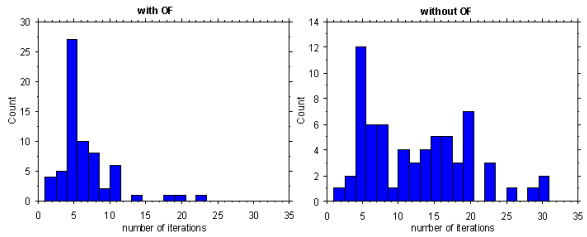

Figure 5. Histogram of the total number of iterations needed for the contour to find the edge.

4. Discussion

As can be seen in Table 2, the ARVD and the control group are well separated for all tests. The best measure seems to be Δ_{eo}, i.e. the time it takes for the contrast agent from the time it entered the RV until it gets washed-out. Looking at all the six time indices for a sequence we found that it was possible to discriminate 21 of the ARVD-patients from the control group. For the remaining 9 ARVD patients, it was not possible from these measurements to separate them from the control group. Tracking the front of the contrast agent could give the extra information needed to separate these cases. In Figure 6 the result of tracking the front in one of the sequences not separable from the control group is shown. The first contour, at t=0, shows the contour of the flow as it first enters the RV and the last contour, at t=2960 ms, shows the contour of the contrast agent when it has totally filled the ventricle. As can be seen, the contrast agent moves quite fast in the first part of the ventricle, but then slows down about half way and then, with the next heart beat, starts moving upwards again, but much slower than before. This indicates that the whole ventricle is not working homogeneously and tracking the contrast front, could be a way to detect the difficult ARVD cases. Therefore, we plan to continue our work with tracking the front of the contrast agent entering the RV, and do further testing.

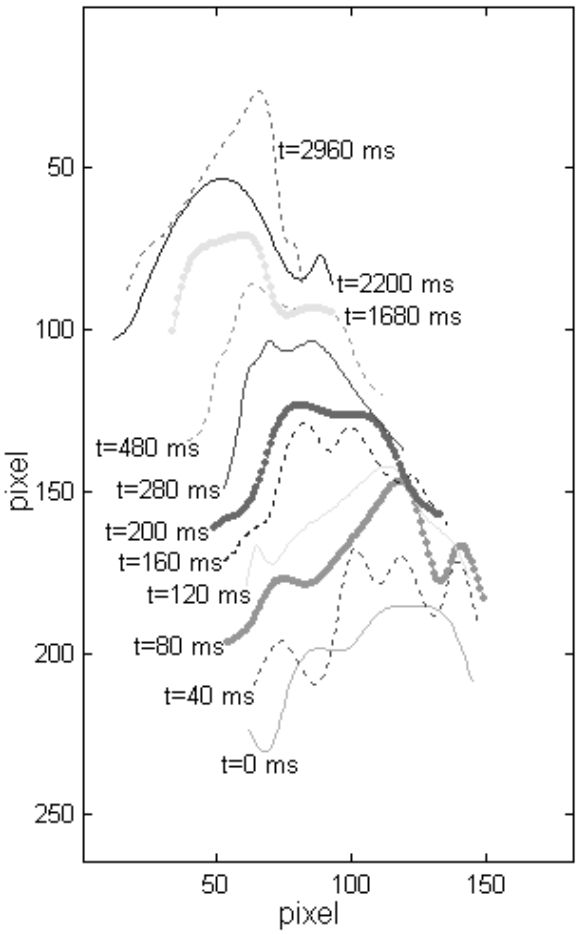

Figure 6. The results of tracking the leading edge in one of the sequences from the ARVD-group. Each contour represents how far the contrast agent has come at the time indicated to the left or the right of the contour.

The contours are drawn without an example of an echocardiographic image from the analyzed sequence as background to make the image clearer.

Acknowledgements

The authors would like to acknowledge the funding for this work by the Swedish VISIT (Visual Information Technology) program and also acknowledge the excellent technical assistance of sonographer Carina Olausson.

References

[1] McKenna WJ, Thiene G, Nava A, Fontaliran F, Blomström-Lundqvist C, Fontaine G, Camerini FDiagnosis of arrhythmogenic right ventricular dysplasia/ cardiomyopathy. Br Heart J 1994; 71:215-218.

[2] Kass M, Witkin A, Terzopoulos D. Snakes: Active Contour Models. International Journal of Computer Vision 1987; 1(4):321-331.

[3] Perona P, Malik J. Scale-space and edge detection using anisotropic diffusion. IEEE Trans. on Patt. Analysis and Machine Intelligence 1990;12(7):629-639.

[4 Horn B, Schunk B. Determining Optical Flow. Artificial Intelligence 1981; 17:185-204.

Address for correspondence.

Karin Althoff
Department of Signals and Systems
Image Analysis Group
SE-412 96 Gothenburg, Sweden
althoff@s2.chalmers.se