Automatic In-vitro Orifice Area Determination and Fluttering Analysis for Tricuspid Heart Valves

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Abstract. Patients suffering from a tricuspid heart valve deficiency are often treated by replacing the valve with artificial or biological implants. In case of biological implants, the use of porcine heart valves is common. To supply patients with the best such xenograft implants, quality assessment and inspection methods for biological heart valves are necessary. We describe initial approaches to automatically testing tricuspid heart valves in-vitro in an artificial circulation system. We use two criteria to judge the quality of the valve, i.e. the evolution of the orifice area during a heart cycle and the fluttering of the valve leaflets in the stream.

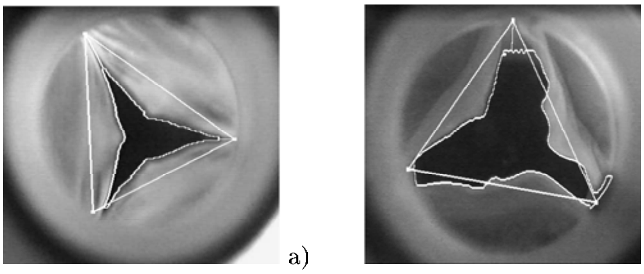
1 Introduction

Replacing a deficient tricuspid heart valve with a xenograft implant is a common procedure in cardiac surgery [1]. Porcine heart valves (see Figure 1) are favoured for this procedure because of their similarity to the human heart valve and the easy access to these valves due to food production. With the high number of available porcine valves quality assessment becomes a vital task to provide the surgeons with the best material only. Major quality criteria of these valves are the orifice area, the opening and closing behaviour and the fluttering of the leaflets in the blood stream. The determination of the orifice area currently is done - if at all - manually by the researcher. An assessment of the fluttering behaviour is provided only by visual observation. In our work we test and compare different algorithms that automatically determine the orifice area. We have implemented three threshold based methods for this task. We first segment the orifice and then compute its area by counting all object pixels. Using the segmented orifice we perform a quantification of the leaflet fluttering. Section 2 of this paper explains the test apparatus and the state of the art. In section 3 we describe our algorithms. Results are shown in section 4, and section 5 closes with conclusions.

2 The test apparatus

Figure 2 a) depicts the test environment as described in [2]. From a reservoir (1) a transparent fluid is transported through a disc valve(4) by a piston pump

Fig. 1. Frames 47 and 124 from heart valve sequences A and B respectively showing boundary outlines, projection lines and anchor points



a) b)

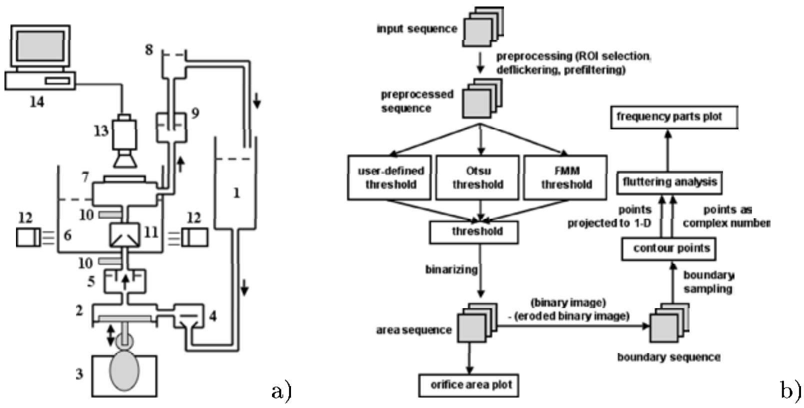
(2), which is driven by a waveform adapted cam plate (3). After passing an input compliance (5) the fluid is pressed through the inspected heart valve (11) into a visualization chamber (7) located in another fluid reservoir (6). Pressure sensors (10) are installed below and above the heart valve. Passing an aortic compliance (9) the fluid reaches a height variable column and flows back to the first reservoir. The heart valve is illuminated by light sources (12) outside the fluid tank (6) made from perspex. A high-speed video camera (13) takes images of the heart valve. The digitized images are stored on a PC (14).

Images of the heart valve are taken with 500 fps and an interlaced resolution of 480x420 gray pixels. An image sequence of one valve cycle has a duration of half a second leading to 250 frames. Figure 1 shows two heart valve images. Determing the orifice area is done manually for each frame so far. The researcher has to select a set of points at the leaflet's tips and the leaflet's connections to define six triangles. Their summed areas give an approximation to the orifice area. An evaluation of the leaflet fluttering is currently done only qualitively by visual inspection. The orifice approximation neglects the rather curved boundary of the leaflets. The methods we propose here are intended to give the researcher a more precise and reproducible way to calculate the area. The fluttering analysis of the leaflets offers a new way to quality inspection and is more reproducible than just human inspection.

3 Methods and algorithms

Algorithm overview In Figure 2 b) an overview of our algorithm is shown. In the preprocessing part we perform Tophat filtering, equalize illumination variations and by user interaction obtain once for the whole sequence three anchor points situated at the intersections between the leaflets and the valve's fixation ring (see Figure 1). The orifice area is determined by one of three threshold methods. These methods include a user-defined threshold, a threshold automatically selected with the method proposed by Otsu in [3] and a threshold derived from the Finite mixture models algorithm proposed by Figueiredo and Jain in [4]. For each image we obtain the orifice area by binarizing it with the threshold. To quantify the fluttering of the heart valve leaflets we first obtain the orifice area

Fig. 2. Scheme of test apparatus (a) and overiew of algorithm (b)



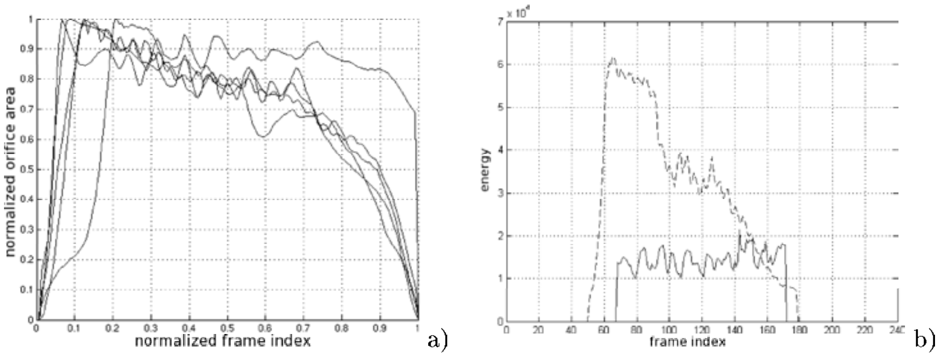
boundary by subtracting the eroded area segmentation from the result itself. As the tricuspid heart valve consists of three leaflets we split up the boundary at those contour points closest to the anchor points. This results in three segments each of which belonging to one leaflet. For each segment we perform a Fourier analysis of the contour points. The contour points coordinates are either treated as complex numbers (2-D data) or are projected to the connection lines between the splitting points leading to 1-D data and also offering better control over the sampling rate. In Figure 1 the orifice boundary outlines, the splitting points and the projection lines are depicted for both valves.

Orifice area determination using thresholds *User-defined threshold:* The threshold used for binarization can be directly specified by the user as a certain percentile of the histogram of the heart valve image. Although we were able to obtain good results, this method has the downside that one has to pick the right threshold by trial and error.

Otsu threshold: The threshold can be automatically selected using the method from Otsu [3]. It is histogram-based and assumes the histogram to be bimodal. It selects the threshold by maximizing the separability between the two resulting classes, i.e. dark 'orifice area' and bright 'leaflet area'.

Finite mixture models threshold: In our case the histogram turned out not to be bimodal, thus a method is needed that can separate multiple classes, i.e. generate multiple thresholds. Knowing that the orifice area is the darkest structure in our images we can select the threshold that separates the histogram peak with the smallest mean from the rest. We use the Finite Mixture Models [4] for this purpose. For a histogram with n samples consisting of multiple distributions the FMM algorithm returns estimates for the number k of distributions in the histogram, the mean values μ_i and the variances σ_i^2. Initialized with a random set of m Gaussian distributions having the probabilities α_i the algorithm fits the estimates iteratively to the histogram data y using an expectation maximization method and a quality criterion for de-

Fig. 3. Orifice areas for five sequences (a) and fluttering energies for sequences A (solid line) and B (dashed line) (b)



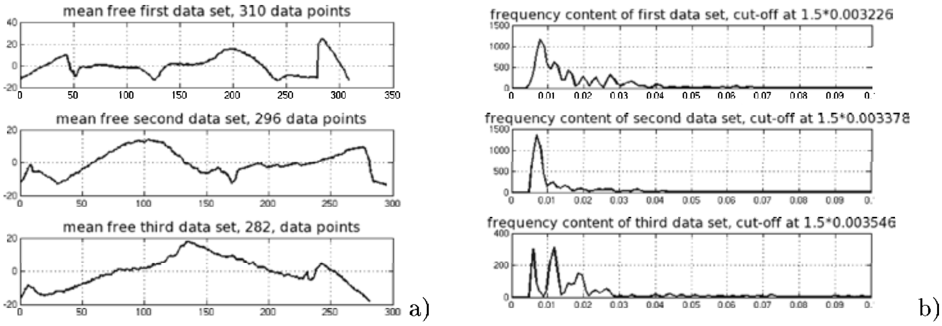
terming the number of distributions. For each distribution p_i and sample y_j we calculate the probability w_i^j that this sample was generated by this distribution as $p_i(y_j) = \alpha_i \frac{1}{\sigma_i\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{y_j-\mu_i}{\sigma_i}\right)^2}$. In each iteration step t the mean values and variances are updated for each distribution according to $\mu_i(t+1) = \left(\sum_{j=1}^{n} w_i^j\right)^{-1} \sum_{j=1}^{n} y_j w_i^j$ and $\sigma_i^2(t+1) = \left(\sum_{j=1}^{n} w_i^j\right)^{-1} \sum_{j=1}^{n}(y_j - \mu_i(t+1))^2 w_i^j$. Furthermore the distribution probabilities α are evaluated and eventually set to 0 if the current distribution does not fit onto the data. To determine the number of distributions hidden in the histogram in each iteration step the criterion $L(\mu, \sigma^2, \alpha, Y) = \frac{N}{2} \sum_{i:\alpha_i>0}(\log(\frac{n\alpha_i}{12})) + \frac{k_{nz}}{2} \log \frac{n}{12} + \frac{k_{nz}(N+1)}{2} - \log(p(Y|\mu, \sigma^2))$ is calculated. With Y being the complete set of samples, N being the number of parameters defining the distributions (2 for 1-dimensional Gauss distributions) and k_{nz} being the number of non-zero (i.e. $\alpha > 0$) distributions this criterion reaches its minimum at that iteration where the number k of distributions fits optimal to the histogram data. Assuming that our histogram consists of at least two classes and that the darkest class, i.e. the distribution with the lowest mean, represents the orifice, we obtain the threshold by calculating the intersection point of the two distributions with the lowest mean values.

Fluttering analysis We apply a Fourier transform to the orifice boundary obtained from thresholding to analyze the fluttering behaviour of the heart valve leaflets. High-pass filtration suppresses the frequencies corresponding to the leaflets' curved shape showing only frequencies characteristic for the leaflet fluttering. Then we compute the energy in the spectrum thus obtained. Only images where the orifice area is above a certain minimum value are considered.

4 Results

Figure 3 a) shows the area over time plot for five of our test sequences. The plot exhibits the typical plateau-like form for heart valve orifice areas. Beginning in the closed state the heart valves open rapidly, remain open for a while and then

Fig. 4. Projected boudary (a) and magnitude spectra (b) for frame 124 of sequence B



close again. The plateau is slightly falling to the right side. It is also exhibits some variations due to the heart valves' leaflets fluttering in the blood stream thus altering the orifice area to some extent. Figure 4 a) shows the contour coordinates projected to 1D and freed from the mean for each of the three heart valve leaflets. This data was taken from our test sequence B, frame 124. Figure 4 b) shows the corresponding energy of the data. We used high-pass filtration to cut off the frequencies belonging to the leaflets' natural curvature. Figure 3 b) shows the fluttering energies for sequences A (solid) and B (dashed). The strong fluttering of B is clearly visible in the plot.

5 Conclusions and outlook

We tested three threshold based approaches to determine the orifice area of heart valves automatically. Although these were only first tests the methods showed good results. We were able to derive typical orifice plots from the given data. This provides the researcher with a tool to perform the so far tedious work automatically. The fluttering analysis we introduced here is a novel approach giving information about the behaviour of the leaflets floating in the blood stream. Further work on this subject may include snakes as an alternative approach to determine the orifice area. The selection of the anchor points may be automated using a Hough transform.

References

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