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PIV System for the Flow Pattern Anaysis of Artificial Organs ; Applied to the In Vitro Test of Artificial Heart Valves

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=Abstract=

The most serious problems related to the cardiovascular prothesis are thrombosis and hemolysis. It is known that the flow pattern of cardiovascular prostheses is highly correlated with thrombosis and hemolysis. Laser Doppler Anemometry (LDA) is a usual method to get flow pattern, which is difficult to operate and has narrow measure region. Particle Image Velocimetry (PIV) can solve these problems. Because the flow speed of valve is too high to catch particles by CCD camera, high-speed camera (Hyspeed; Holland-Photonics) was used. The estimated maximum flow speed was 5m/sec and maximum trackable length is 0.5 cm, so the shutter speed was determined as 1000 frames per sec. Several image processing techniques (blurring, segmentation, morphology, etc) were used for the preprocessing. Particle tracking algorithm and 2-D interpolation technique which were necessary in making gridrized velocity profile, were applied to this PIV program. By using Single-Pulse Multi-Frame particle tracking algorithm, some problems of PIV can be solved. To eliminate particles which penetrate the sheeted plane and to determine the direction of particle paths are these solving methods. 1-D relaxation fomula is modified to interpolate 2-D field. Parachute artificial heart valve which was developed by Seoul National University and Bjork-Shiely valve was testified. For each valve, different flow pattern, velocity profile, wall shear stress and mean velocity were obtained.

Key words : Cardiovascular prostheses, Artificial heart valve, In vitro test, Flow pattern, PIV (Particle Image Velocimetry), High-speed camera, Image processing technique, Single-pulse multi-frame tracking.

INTRODUCTION

The body fluid of most artificial organs, in particular, circulation organ, have rheological characteristics. The most serious problem in developing cardiovascular prostheses is thrombosis and hemolysis, which is closely related to the rheological characteristics of the passing fluid. Thromboembolic and hemolytic characteristics of cardiovascular prostheses can be tested by *in vivo* experiment. But, in vivo test is difficult to perform, is hard to make same testing enviroment and cannot satisfy the need for the frequent modification of model in developing stage. There are several ways to test the performance of artificial heart valve in vitro. Hydraulic dynamics test informs us of regurgitation, pressure drop, energy loss and effect valve orifice area (EVOA)[1]. Flow pattern analysis is another way which can give us velocity profile, shear stress, Reynolds number, flow separation and turbulence intensity. Cavi-

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tation and leaflet motion analysis are also valuable test. The flow pattern analysis has been used to develop artificial heart and ventricular assist device[2]. This flow is not so easy to be modeled, since the flow is unstationary, follows a complex law of pressure and velocity variation, is three-dimensional, asymmetric and has a changing geometry. Because the flow is so complex, there is a need for method to visualize it for a better understanding. There are many different methods of flow visualization, most of them do not permit the quantification of the flow. For quantification, the laser doppler anemometry method is most widely used, but it has the great disadvantage that velocity can only be measured at one paticular location at a time. If a velocity profile or field is to be measure, then many point measurements must be made; if these measurements are not performed simultaneously, any stochastic elements of the flow, which are closely related with turbulence and laminar-turbulent transition, will be lost. Another disadvantage of this method is that the ensamble averaging smooths out the higher frequency velocity variations that occur, thereby masking many important detail of the flow and resulting in a loss of information. The method of PIV (particle image velocimetry) can solve these problems. So in this experiment PIV technique was used as a testing method of artificial heart valve.

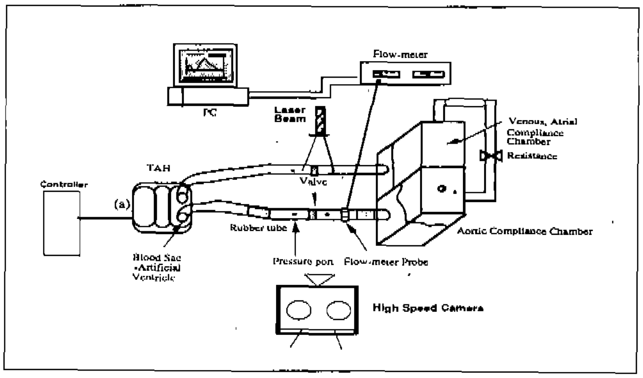

Fig. 1. Experimental Setupp for *In Vitro* Testing of Artificial Heart Valves.

METHODS

1. PIV

An important achievement of modern experimental fluid mechanics is the invention and the development of techniques for the measurement of whole instantaneous field of scalars and vectors. One of the most popular method of these technique is PIV (particle image velocimetry) or PTV (particle tracking velocimetry). It is a member of LSV (laser speckle velocimetry), which uses plane laser beam to make a object plane. Object planes are visualized by sheeting laser. Movement of particles informs velocity direction and magnitude. PIV is discriminated into high density PIV and low density PIV depending on the density of particle. In high density PIV, auto-correlation, cross-correlation and Young's Fringe are used to find out the velocity profile. In this experiment, low density PIV is adopted. There are several methods in low density PIV depending on the number of frames and pulses; single frame/single pulse, single frame/double pulse, single frame/multi-pulse, multi-frame/single pulse, multi-frame/double pulse and multi-frame/multi-pulse. Single frame/single pulse method is the most simple one to get pictures. But it is difficult to find out the direction of moving particles in complex flow and to differenciate the penetrating particles from the normal particles by using this method. Multi-frame or multi-pulse method can solve these problems. Multi-frame/single pulse method is used in this experiment.

2. Recording method

There are usually two method to capture images; using video camera and using cine camera. For quantification, CCD video camera is better useful to process data[3]. But, this method has the fundamental capturing speed limit; maximum recording speed is 30 frames/sec. If the maximum trackable length 1 cm, than the upper bound of measurable velocity is 30 cm/sec.

$$v = l \cdot f \tag{1}$$

where v is maximium measurable velocity, l is maximum trackable length and f is frame speed.

However, in this testing usual speed is above 2~3 m/s and maximum trackable length is smaller than 1 cm. This problem can be solved by using high speed cine camera. In this experiment object frames are filmed by high speed camera. Then the developed film is projected on the white board by film projector. Projected image are captured frame by frame by CCD camera and image capturing board installed on a personal computer. On this computer this digitized image data is processed to get a velocity profile.

3. Experimental Setup

To test valves, a mock circulation system was devised, which simulate the human physiological circulation. Schemetics of this system are showed in Fig. 1. 33% glycerin and destined water used as a blood analogue solution. Light source is He-Ne laser (30 Watt, 6.5A, 2.45~3.20 KV DC) and optical slit was used to make a plane beam. Amberite partilcle (diameter about 0.4 mm) was used for its similarity of specific gravity with blood analogue solution. Pulse-type flow was generated by TAH (Total Artificial Heart) actuator which has been developed in Department of Biomedical Engineering, Seoul National University. High speed camera made by Holland-Photonics was used (shutter speed: 100-10000 frames/sec). Kodak EXR 7296 film was used (ASA: 500T, length: 125ft). The distance between the camera and object was about 40 cm. Image processing board which had multi-frame memory was necessary. MATROX image processing board which has four independent 1M byte memory frames was used. In this processing frame size was 640 pixels*480 pixels. Each pixel has 8 bits resolution; 256 gray level.

PROCESSING ALGORITHM

1. Pre-processing

Digitized 256 gray image has too much information to be processed at once and has considerable noise and warping made in the course of digitizing. So a series of pre-processing is needed to eliminate noise and to extract simple valuable data. Becuase most of digitizing noise has high frequency, lowpass filtering is effective to eliminate this noise. Most popular 2-D lowpass flitering (3×3 kernel convolution; 121; 242; 121) is used. To extract valuable information, image segmentation and finding center of mass were performed.

1) Lowpass filtering

Lowpass filtering is one of the image enhancement techniques based on spatial operation performed on local neighborhoods of input pixels. Often, the image is convolved with a finite impulse response filter called spartial mask or kernel. Here each pixel is replaced by a weighted average of its neighborhood pixels, that is,

$$v(m, n) = \sum\sum_{(k,l)\in W} a(k,l) \cdot y(m-k, n-1) \qquad (2)$$

where $y(m, n)$ and $v(m, n)$ are the input and output images, respectively, W is suitably chosen window, and $a(k, l)$ is the filter weight. Here the lowpass filter weights are as follows.

$$a = \begin{bmatrix} 1 & 2 & 1 \\ 2 & 4 & 2 \\ 1 & 2 & 1 \end{bmatrix}$$

2) Image segmentation

The idea of using simply the pixel intensity of gray-level to produce either an ON or OFF intensity in the output image is both conceptually obvious and simple to be implemented. Especially in this thesis, it is most important to identify the visual tracer from other images. There are two kinds of thresholding: Global image thresholding and locally adaptive image thresholding.

An obvious approach to converting a gray-level image to a binary image is to form an input/output relationship of the form

$$v(m, n) = \begin{cases} A \text{ if } y(m, n) \leq T \\ B \text{ if } y(m, n) > T \end{cases} \qquad (3)$$

where $y(m, n)$ and $v(m, n)$ are the respective input and output image function. The value of the threshold, T, and the bilevel output image intensity values, A and B, are chosen a prioi.

The autonomous determination of the suitable threshold for a wide class of images is a nontrivial task. A typical algorithm is based on the formation of a global histogram of image intensity values and consequent selection of a threshold that yields a desired fraction (typically 10~50%) of ON output pixels. In this processing, each parameter deter-

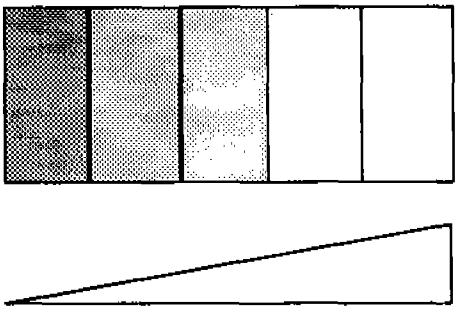

Fig. 2. Base slope of digitized image

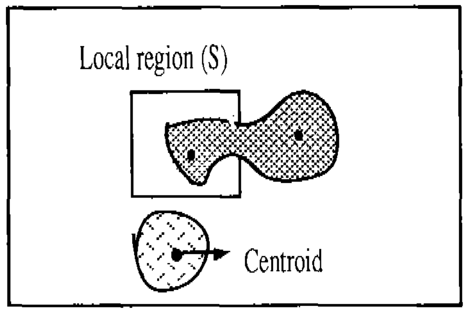

Fig. 3. Find center of mass & local region limit

mined as follows. A = 0, B = 255. T was determined so that only particle tracers can appear. In this experiment, only the speckle points of each frame are needed. These are the only points which are on the object plane which is sliced by laser. Most of image captured by CCD camera have a base slope which human eye can hardly recognize. Fig. 2 is illustrating this base slope. To eliminate base slope, local image thresholding is performed. Whole image are segmented horizontaly as Fig. 2. For each segment, a mean pixel value is calculated. Local thresholding levels are determined with the following formular.

$$Ti = Mi + OFFSET \tag{4}$$

where, Ti is the threshold level of i th segment, Mi is the mean pixel value of ith segment and $OFFSET$ is user defined offset which is determined so that only the particles can appear.

3) Finding center of mass

Each particles on a thresholded image are represented as a group of pixels which are clustered. As tracking should be performed from point to point, each particle must be represented as a point. Most reasonable method to reduce a cluster to a point is to find out its center of mass. First of all, all pixels in a cluster are recognized as a group which is distinguished from other cluster pixels. Computer program begins to search from the first pixel to the last on a frame. When it account a pixel of a particle, it begin to search consecutive neighbor pixels of a particle and register these pixels as a group. Then it continue to search for new pixels which are not registered. When it meet new pixel, above processing is repeated. In this way, all pixels are registered as a member of a certain group. For each group, each center of mass point is found. The following equations are used for this purpose[3].

$$Xc = \frac{1}{N} \sum_{(Xi, Yi) \in W} Xi, \quad Yc = \frac{1}{N} \sum_{(Xi, Yi) \in W} Yi \tag{5}$$

where, Xc, Yc are respectively the x coordiante and the y coordinate of a centroid, N is the number of pixels in this group, Xi, Yi are each coordinates of pixels in this group and W is area of pixels that represent a particle.

Particles have regular size and form, so a particle can be differentiated from a erroneous large lump island. Local searching regions which have some limit should be defined by user. Fig. 3 shows how to determine searching region and how to separate large lump island to target points. Above centroid finding procedure is repeated to resume good finding and to sum up erroneously partitioned points to a point.

2. Tracking

To get a velocity profile particle, tracking is performed. Traking regions are determined under the assumption that a particle cannot move too far at this short period and cannot chage its direction abruptly. Tracking is performed based on the minimum variance of length and angle. Above coordinates of center of masses are stored in a computer memory. At the first tracking, a particle of the next frame is searched in a determined circular tracking region of which center is a particle position of the first frame. The closest

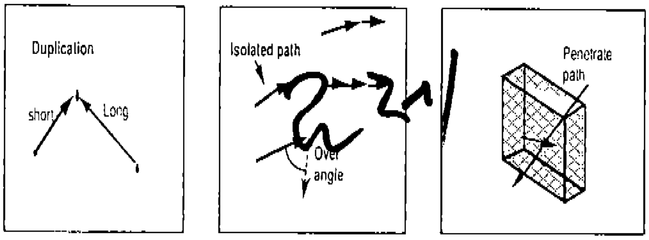

Fig. 4. False particle trackings; dulicate, over angle & penetrating pathes

particle is selected to made a path line. After all path lines from first to second frame had been searched, there may be two or three to one mapping, which is impossible in real situation. So only the shortest path was selected, and other paths were eliminated. From second tracking, another modification is needed. A particle path cannot change its direction much in the next plane. In this reason, the searching area is modified from circle to fan shape. The direction of fan-shape searching region is determined by the direction of the previous connected path. The angle of fan shape must be selected reasonably. After the fitst searching is performed, some false traces should be eliminated.

1) Duplication

A particle tracking should be one-to-one mapping not one-to-two or one-to-multi point mapping. So one of the duplicate paths is false trace. To select the shorter and reect the longer may be reasonable choice.

2) Over angle

Particles cannot change its direction much in this short period. So over angle path as Fig. 4 is not right trace. The path whose angle is over the predefined angle limit should be rejected. Used formulars for this choice are as follows.

$$\begin{aligned} \theta_1 &= \arg((X_{1e} - X_{1s}) + j(Y_{1e} - Y_{1s})) \\ \theta_2 &= \arg((X_{2e} - X_{2s}) + j(Y_{2e} - Y_{2s})) \\ \theta diff &= |\theta_1 - \theta_2| \\ \text{if} \quad & \theta diff \geq \theta threshold \quad \text{wipe off} \end{aligned} \tag{6}$$

where, (X_{1s}, Y_{1s}), (X_{1e}, Y_{1e}), (X_{2s}, Y_{2s}), (X_{2e}, Y_{2e}) are the start points and the end points of the first path and second path respectively.

3) Isolated path

Object flow has 3-D structure but observed flow is only on 2-D plane. There is a problem for this reason. Is short path really short? Short path can be the path which is penetrating the objective plane. To discriminate really short path from penetrating path, multi-frame traces(above three frames) should be examined. As illustrated in Fig. 4, a penetrating path cannot endure through several frames. So it is represented as a isolated path(not connected to previous or next frame)which should be removed.

3. Interpolation

The velocity vector on a grid point is predicted from the spatial average of three neighbouring values in the searching area. If searching area is too small, three vectors do not exist in the area and in order to obtain a full distribution further extrapolation becomes necessary. Hence, the uniform and adquate distribution of trace particles improves the accuracy of the prediction process. Another method of interpolating velocity vectors is relaxation procedure. 1-D relaxation formula is as follows[4].

$$\begin{aligned} a_i &= c_i b_i + (1-c_i)(a_{i+1} + a_{i-1})/2 \\ a_i^0 &= c_i b_i + (1-c_i)(b_{i+1} + b_{i-1})/2 \\ a_i^1 &= c_i b_i + (1-c_i)(a_{i+1}^0 + a_{i-1}^0)/2 \\ a_n &= c_i b_i + (1-c_i)(a_{i+1}^{n-1} + a_{i-1}^{n-1})/2 \end{aligned} \tag{7}$$

where, a_i is ith measured weighted value. b_i is the average of the neighbors' value. c_i is the confidence factor as the weight.

By using these formular as following procedure reasonable 1-D interpolation can be done.

1. Call the input array the current array.
2. Until all values are changing sufficient slowly:
   2. 1 For each element in the current array, calculate an element for a new array using the relaxation formula.
   2. 2 Call the new array the current array.

For the 2-D interpolation above formular should be modified.

2-D vector has two component; length and angle. To evaluate the 2-D interpolation, two 1-D interpolations should be performed respectively.

1) Grid

To gridrize the raw velocity vectors, the following fom-

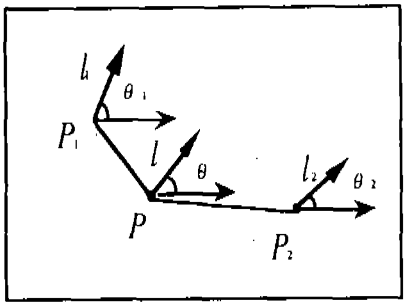

Fig. 5. Simple interpolation

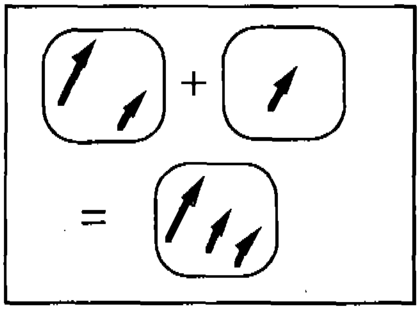

Fig. 6. Summing up frames

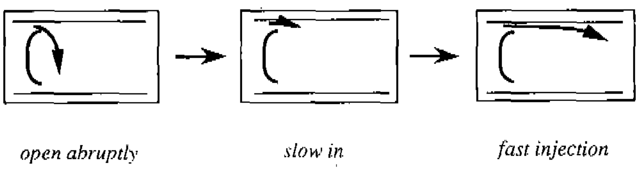

Fig. 7. Flow sequence of Parachute heart valve

ular is used.

$$Xg = \frac{X}{G} \cdot G,\ Yg = \frac{Y}{G} \cdot G \qquad (8)$$

where (X, Y) is the start point of a raw velocity vector, (Xg, Yg) is the start point of a gridized vector, G is the grid size & [·] is the Gauss function.

A raw velocity vector is transported parallely as (X-Xg, Y-Yg) to a gridrized vector.

2) Simple interpolation

Fig. 5 is illustrating a simple interpolation. To get a interpoted result a point P, at first we find the two nearest raw data point P1 and P2. The distances between P1 and P and between P2 and P are used as interpolating weights.

3) Summing up interpolation

If raw vectors are too few to interpolate reasonable vector field, the summed data of several consecutive frames are used under the assumption that the field does not change in this short period. The mean of summing up is illustrated on Fig. 6.

RESULTS & DISCUSSION

1. Flow pattern analysis of artificial valves

With a result of this experiment, A velocity profile of a Parachute valve and A velocity profile of a Bjork-Shiely valve can be obtained. This velocity profile are examined at the begining of the systolic period. Bjork-Shiely valve flow has fast direct stream lines on the upper region slow and direct stream at the lower region. No back flow can be observed on this flow. Parachute valve has fast stream lines near the bounds of glass (upper region and lower region) and central fast back-flow can be observed.

The mean speed of these velocity profile is 130 cm/s. Calculated wall shear stress is 0.5525 N/m^2. This vlaue is too small to make hemolysis which is observed in vivo experiment. We can conclude that wall shear stress does not generate hemolysis.

The flow injection patterns of a Parachute valve at the systolic period is also observed. At the chaging stage from diastole to systole, flow injection occur abruptly, after then major flow injection begins slowly resulting in fast injection. This stages are illustrated in Fig. 7.

2. Comparison with other researches.

In[5], they magnified heavily the experimental system to reduce the velicity of flow. Polymer valves one of which is parachute, are hard to be magnified heavily. Frequent modification is hard to be performed using this method. Simple image acquisition by using CCD camera which is adopted in[2, 3, 6], has fundamental limit of measurable maximum speed. PIV using high energy pulsed laser, which is used in [7], is complex and expensive to set up experimental settings. One of disadvantages of low density PIV is fewer valuable data. Because image aquisition speed is high, several con-

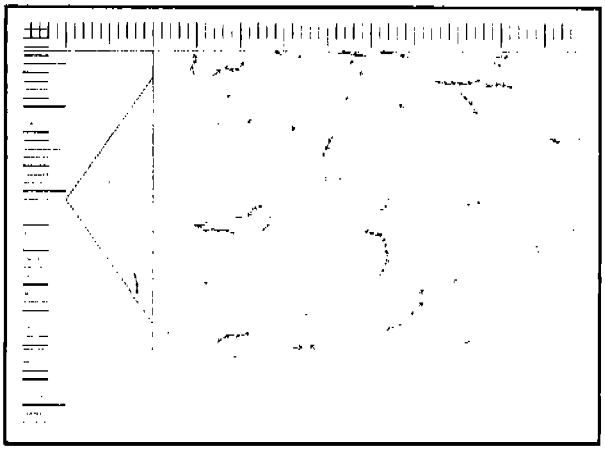

Fig. 8. Parachute valve velocity sum up

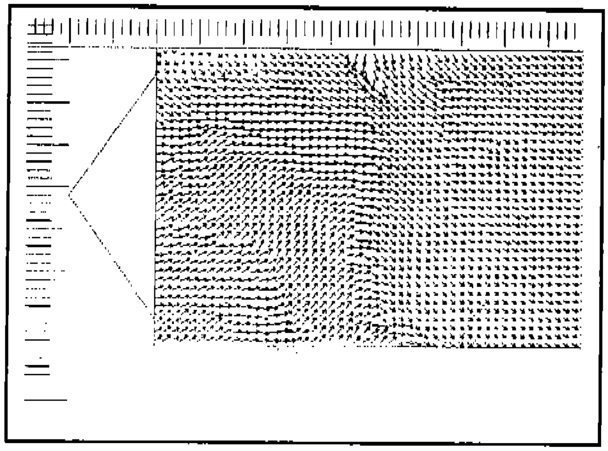

Fig. 9. B-J Valve velocity profile interpolated

sequtive frames can be summed under the assumption that velocity field does not change in this short period.

3. Advantages of used algorithm.

Base slope of image can be removed by modeling this slope as a 3-D polinomial surface. Base surface can be fitted by using second order polinomial and LSE (least square estimation) formular as follows.

$$f(x, y) = a_1x^2 + a_2xy + a_3y^2 + a_4x + a_5y + a_6$$

$$P = \begin{bmatrix} x_1^2 & x_1y_1 & y_1^2 & x_1 & y_1 & 1 \\ x_2^2 & x_2y_2 & y_2^2 & x_2 & y_2 & 1 \\ x_3^2 & x_3y_3 & y_3^2 & x_3 & y_3 & 1 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ x_n^2 & x_ny_n & y_n^2 & x_n & y_n & 1 \end{bmatrix} A = \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \\ a_6 \end{bmatrix} Q = \begin{bmatrix} f(x_1, y_1) \\ f(x_2, y_2) \\ f(x_3, y_3) \\ \cdot \\ \cdot \\ f(x_n, y_n) \end{bmatrix} \quad (10)$$

$$A = (P^TP)^{-1}P^TQ$$

Where, (xi, yi)is a sampled point, f(xi, yi)is a pixel value at(xi, yi) and A is a parameter matrix of a polynomial surface.

But, this method is time consuming becuase of large matrix calculations and may generate false surface depending on sampled points. One of the characteristics of PIV image is sharp peak profile as Fig. 12. If data is sampled at sharp peaks, erroneous surface may be fitted. For this sharp peak, rough removal of base slope using local histogram segmentation which was used in this development, is very effective in a sense of time saving and no erroneous fitting.

Usual method to register pixels to a cluster is to trace from a pixel to all consecutive pixels which are connected to a resistered pixel. This algorithm is summarized as follows.

1. Scan from origin to last pixel.
2. If the scanning point meet a particle pixel, trace begins.
3. Search for connected pixels in four direction sequently as Fig. 13. Found pixels are registered.
4. If the tracing point meet a no−particle point or a registered point at a direction, Trace back to a prevoius registered point.
5. Search next direction as step 3. 4.
6. If the tracing point back to the first registered point and remains no direction to search in, a cluster registeration is complete and scan again until it meets a particle point which is not registered.
7. Repeat 1-6 until scan all pixels of a frame.

This method is useful in particular when cluster have a hole or convex form. But PIV images do not have these forms and particle size is in a certain range. So the following algorithm used in this development, can save time.

1. Scan from origin to last pixel.
2. If the scanning point meet a particle pixel, register all paticle pixels in a rectangular of which center is the first partilcle point.

Most of tracking particle methods search points in a range once. In this algorithm, searching is performed roughly,

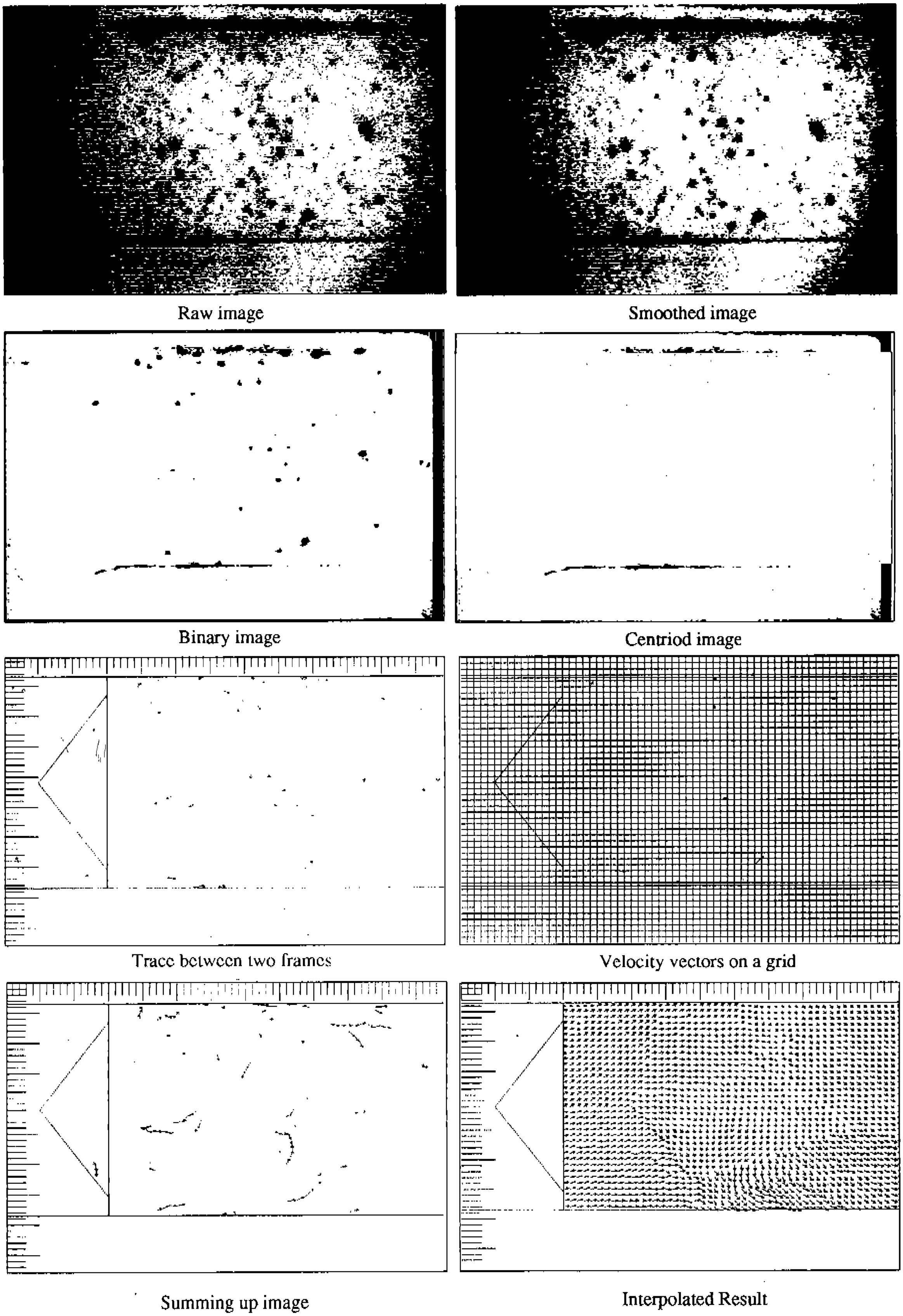

Fig. 10. Processing stages of a image

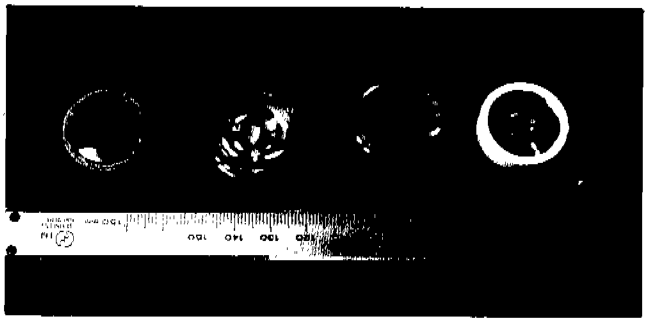

Fig. 11. Testified Valves;from right to left Bjork-Shiely, Saint-Jude and Parachute Heart Valve

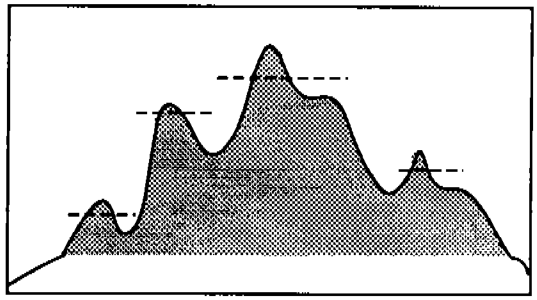

Fig. 12. Horizontal Profile of a PIV image and sharp peaks.

but false tracked pathes are removed in three steps; duplicate, over−angle, short path. In this way, processing procedures are simplified and only correct pathes can be obtained.

4. Further application

Flow visualization method which are developed in this experiment can be used various field of medical and biomedical field. Flow pattern of TAH (Total Artificial heart), VAD (Ventricular Assist Device) and ECMO is very important information to develop these artificial organs. Turbulence in blood flow is strongly implicated in atherogenesis. This tubulence can be analysed by this flow visualization technique.

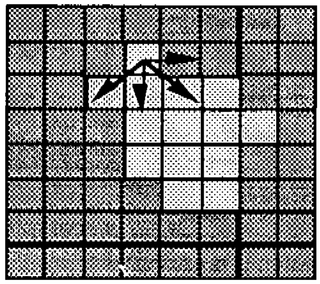

Fig. 13. Cluster registration

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