GEORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION

# PROJECT ADMINISTRATION DATA SHEET

[XX] ORIGINAL [ ] REVISION NO. ______

Project No. E-19-674 R6134-0A0 GTRC/GIT DATE 6 /13 / 86

Project Director: Dr. A.P. Yoganathan School/Lab Chemical Engineering

Sponsor: American Heart Association, Georgia Affiliate, Inc.

Type Agreement: Grant-in-Aid Agreement, dated May 5, 1986

Award Period: From 7/1/86 To 6/30/87 (Performance) 8/30/87 (Reports)

Sponsor Amount:

| | This Change | Total to Date |
|---|---|---|
| Estimated: | $ | $ 14,850 |
| Funded: | $ 14,850 | $ 14,850 |

Cost Sharing Amount: $ ______ Cost Sharing No: ______

Title: Doppler Ultrasound Assessment of Prosthetic Heart Valves

## ADMINISTRATIVE DATA

OCA Contact E. Faith Gleason X4820

1) Sponsor Technical Contact:

2) Sponsor Admin/Contractual Matters:

Charles Taylor
American Heart Association
Georgia Affiliate, Inc.
2581 Piedmont Road, N.E.
P.O. Box 13589
Atlanta, Georgia 30324 (404) 261-2260

Defense Priority Rating: N/A

Military Security Classification: N/A

(or) Company/Industrial Proprietary: N/A

## RESTRICTIONS

See Attached N/A Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval – Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with GIT

## COMMENTS:

Continuation of E-19-636

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SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date 8/18/87

Project No. E-19-674 School/~~Lab~~ Che

Includes Subproject No.(s) N/A

Project Director(s) Dr. A.P. Yoganathan GTRC / ~~GIT~~ X

Sponsor American Heart Association, Georgia Affiliate, Inc.

Title Doppler Ultrasound Assessment of Prosthetic Heart Valves

Effective Completion Date: 6/30/87 (Performance) 8/30/87 (Reports)

Grant/Contract Closeout Actions Remaining:

- [ ] None
- [X] Final Invoice or Final Fiscal Report
- [ ] Closing Documents
- [X] Final Report of Inventions - Questionnaire to P.I.
- [ ] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other

Continues Project No. E-19-636 Continued by Project No.

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DESIGNING TOMORROW TODAY

August 4, 1987

Ms. Linda LaChanse
American Heart Association - Georgia Affiliate
1685 Terrell Mill Road
P.O. Box 6997
Marietta, GA 30065

Dear Ms. LaChanse:

Enclosed are three copies of my terminal report on my grant "Doppler Ultrasound Assessment of Prosthetic Heart Valves," for the period 7/1/86 through 6/30/87. If you need any further information please contact me.

Sincerely,

Ajit P. Yoganathan
Associate Professor
Chairman, Bioengineering Committee

cc: Ms. Ina Lashley - OCA

AMERICAN HEART ASSOCIATION - GEORGIA AFFILIATE

# DOPPLER ULTRASOUND ASSESSMENT OF PROSTHETIC HEART VALVES

(GRANT-IN-AID)

FINAL REPORT (7/1/86-6/30/87)

## I. Principal Investigator

## II. Project Report

### (a) General

In vitro laser Doppler studies have demonstrated that individual prosthetic devices exhibit specific hydraulic performance characteristics, and that the resultant flow patterns may be associated with valve malfunction. However, the clinical evaluation of prosthetic heart valves has been limited to measurement of pressure and flow data by cardiac catheterization, a procedure which does not provide information regarding velocity or turbulence, and is not suitable for widespread or repetivive studies. Recently, ultrasound Doppler (UD) technique have become available which provide the potential to obtain quantitative data comparable to in vitro techniques and cardiac catheterization. This study was based upon the hypothesis that UD recordings can be utilized to assess the hydraulic performance characteristics and detect malfunction of prosthetic heart valves. Our specific objectives include, comparing UD with laser Doppler anemometry as regards to its ability to identify the spatial distribution of flow jets, identify regions of flow separation and stagnation, and provide accurate estimate of transvalvular pressure gradients in a physiologically realistic left heart simulator. To define the spatial distribtion of flow patterns, studies will be performed in the pulsed Doppler mode with the sample volume positioned at various locations within the flow field distal to the valve. To obtain accurate measurements of maximal velocity, from which transvalvular pressure gradient ~~can be calcul~~ated by a modified Bernoulli equation, continuous wave techniques was used.

(b) **Pressure Gradient Study**

Simultaneous continuous wave ultrasound Doppler velocity and pressure drop measurements were conducted with the following size 21 and 27 mm mechanical aortic valve prostheses: Bjork-Shiley, Medtronic-Hall, Starr-Edwards, and St. Jude. Linear correlations of the velocity and pressure drop data were compared to a simplified version of the Bernoulli equation of ascertain the validity of using non-invasive velocity data to predict the pressure drops across mechanical aortic heart valve prostheses. An ultrasound Doppler system operated in the continuous wave mode was used to obtain maximum flow field velocities. Pressure drop measurements were conducted using a differential pressure transducer with downstream pressure drops detected at the flow channel wall via a needle tap, and in the flow stream via a side hole catheter. Experiments were conduted under steady and pulsatile flow conditions. Steady flow rates of 10, 15, 20, 25, and 30 l/min were used. The pulsatile flow experiments were conducted under physiological conditions: a heart rate of 70 beats/min; systolic time period of about 300 ms; mean aortic pressure of 90 and 100 mm Hg; and peak systolic flow rates of 15, 20, 25, 30, and 35 l/min. The velocity, volumetric flow, and pressure drop signals were integrated over the systolic time period to obtain mean systolic values. Correlations based on the mean data were also compared to the Bernoulli equation.

The results showed that obtaining pressure drops and velocities which correlate with the theoretical Bernoulli equation id dependent on where in the flow field the pressure and velocity measurements are made.

(i) Bjork-Shiley Tilting Disc Valve:

Generally good agreement between the empirical correlations and theory was obtained for the 21 and 27 mm valves under all experimental conditions. The main discrepancy between the experimental correlations and theory was in the pulsatile flow experiments with the 21 mm valve. In this case, the peak pressure drop data was measured with the catheter did not correlate with the theoretical predictions. The better agreement between the theoretical predictions and the pressure drops measured with the needle tap suggests that streamline flow occurs from the point of impingement of the major orifice jet on the flow channel wall to the downstream needle tap. The discrepancy between the 21 mm valve's data correlations and theory was removed as a result of integration. This suggests that the pressure recovery (i.e., the flow relaminarization) occurs more rapidly for the peak systolic flow field than for the mean systolic flow field.

(ii) **Medtronic-Hall Tilting Disc Valve:**

Less than satisfactory agreement between theory and the empirical correlations occurred for both the size 21 and 27 mm valves. For the steady flow experiments, both the needle and catheter data correlated poorly with the theory for the 27 mm valve. However, for the 21 mm valve, the catheter data did correlate with theory while the needle tap data did not. Similarly under pulsatile flow conditions, poor correlation with theory was obtained for the 27 mm valve; however in the 21 mm valve case, the needle tap data correlated with theory while the catheter did not. The relative positions of the needle and catheter in the flow stream suggests that the high pressure drop region occurs less than 20 mm downstream from the 27 mm valve. Due to larger effective orifice area of the 27 mm valve, it is possible that the flow field recovers more rapidly than for the 21 mm valve. This data is substantiated by the fact that for the

21 mm valve, the catheter data resulted in correlations that agree with theory; suggesting that the high pressure drop region extends at least 20 mm downstream for the smaller valve.

The similar phenomena was noted for the Bjork-Shiley disc valve. In this case the 21 mm size valve yielded correlations agreeing with theory for the needle tap data only. Suggesting that the smaller opening angle of the Bjork-Shiley valve results in the velocity jet being located nearer the flow channel wall than for the 21 mm Medtronic-Hall valve. However, for both valves the maximum flow field pressure drops were detected at the 20 to 40 mm downstream position.

(iii) Starr-Edwards Ball Valve:

Very good agreement between theory and empirical correlations was obtained for the 27 mm valve under all experimental conditions. However, generally less than ideal agreement was obtained between theory and the empirical correlations for the 21 mm valve. These results show the dramatic effect of valve size on the pressure drop estimation. An explanation for the discrepancy between theory and the 21 mm valve's correlations was provided by the pressure mapping studies. In these experiments, the high pressure drops that correlated with the Bernoulli equation predictions were located in the annular region around the valve poppet. This area is nto accessible for invasive (i.e., clinical) pressure drop measurements since interference of the catheter with the valve operation is likely. For in vitro experiments, the effect of interference with normal valve operation is to invalidate the experimental results. Therefore no pressure measurements were taken in this annular region for the velocity/pressure drop correlation studies. The findings from the ball valve experiments are opposite to those for the tilting disc valves, namely that the flow field tends to recover more quickly for the 21 mm ball valve than for the 27 mm valve. This may be explained by the fact that for the tilting disc valves, the only difference between the 21 and 27 mm valves is a reduction of the orifice diameter (from a diameter of 22 mm to a diameter of 16 mm). For the ball valve the orifice diameter decreases from 17 mm to 13 mm (with a decrease in ball diameter of approximately 12%); however, the length of the cage is also reduced from 20 mm to 17 mm. This results in an overall increase in the annular region surrounding the ball and cage, and hence an overall decrease in the obstruction to flow for the 21 mm ball valve. These combined effects may result in a quicker recovery of the pressure and velocity fields.

(iv) St. Jude Bileaflet Valve:

Generally poor correlation of the data with theory was obtained for both the size 21 and 27 mm valves under both steady and pulsatile flow conditions. As with the Starr-Edwards 21 mm valve, some insight to the discrepancies between the theoretical and empirical correlations was provided by the pressure mapping studies. In these experiments, high pressure drops which correlated with the Bernoulli equation were obtained only when the catheter tip was placed between the valve leaflets. Once again placement of the catheter in this region was not done in the pressure drop/velocity correlation studies, so that interference of the catheter with normal valve function would not occur. For the 21 mm size valve, in only two cases did the empirical correlations agree with theory - the mean systolic catheter pressure drop/root mean square velocity correlations. Similarly for the 27 mm size valve, there was agreement between theory and the needle and catheter mean data correlations. As was noted in the discussion for the Bjork-Shiley valve, the agreement of the mean pressure drop data correlations with theory may be the result of the generally slower recovery of the mean pressure field.

(v) **Conclusions:**

The results from the prosthetic valve studies clearly indicate that the use of the simplified and modified Bernoulli equations for the estimation of pressure drop based on the CW Doppler ultrasound velocity is <u>valid</u>. The accuracy with which the Bernoulli equation predicts the pressure drop is a function of the valve type and flow conditions. Valves like the Starr-Edwards 27 mm which produce clearly defined and symmetric jet flow regions yield measurable pressure drops and velocities that correlate with the Bernoulli equation. Low profile valves, such as the St. Jude, produce flow fields which recover rapidly downstream of the valve, and hence the maximum flow field velocities correlate with pressure drops that only occur in the inaccessible near region of the valve superstructure.

A final result of this study was the measurement of ultrasound Doppler velocities that compare well to laser Doppler anemetry results. The flow apparatus and experimental methodology of this study were modeled on earlier LDA work in the hopes of discerning the accuracy of the ultrasound Doppler method. Comparison of the peak systolic velocities obtained with ultrasound Doppler instrumentation with those measured in LDA experiments (Woo, 1984; Woo and Yoganathan, 1985) show differences of less than 10%. These results give a good indication that the ultrasound Doppler technique provides accurate and reproducible measurement of the velocities downstream of prosthetic heart valves.

### (b) Quantitative (Ultrasound Doppler and Laser Doppler) Flow Mapping Study

#### (i). Ball-and-Cage Mechanical Valves:

With the laser Doppler anemometry in vitro studies, high velocities were detected in the annular region between the surface of the ball and the flow channel wall. The maximum velocity measured was 100 cm/sec. Reverse velocities occurred in the central part of the flow channel as a result of flow separation from the surface of the ball. The maximum reverse velocity measured -10 cm/sec. The velocity profile shows that the flow field is not axis-symmetric. The lowest velocity did not occur at the center of the flow channel, but was shifted to one side. High root mean square velocities (i.e., turbulence levels) were located on either side of the annular jet, while relatively low values were observed in the center of the left ventricular model (i.e., the mitral outlfow chamber). The maximum root mean square velocity measured was in the order of 35 to 40 cm/sec.

Ultrasound color Doppler flow mapping studies showed that all three types of ball-and-cage values had similar very turbulent, high velocity (100 to 150 cm/sec) peripheral circumferential jets. The areas of the jets adjacent to the left ventricular outflow tract appeared larger than the areas adjacent to the left ventricular free wall. There were wake regions of flow reversal just distal to the cages during mid- and late diastole, measuring -20 to -30 cm/sec. Turbulence displayed as mosaic green/yellow was detected along the edges of the forward flow jets.

**(ii) Disc-and-Cage Mechanical Valves:**

With the _in vitro_ laser Doppler studies, this type of valve design produced a narrow circumferential jetlike flow field. A large wake was observed distal to the valve, which was a result of flow separation from the edge of the occluder. The center line profile 11 mm downstream of the valve showed a high velocity jetlike flow occurring along the wall of the left ventricular model chamber. This jet was narrow and had a peak velocity of 69 cm/sec. The maximum reverse velocity measured in tie wake region was -10 cm/sec. The center line profile taken 17 mm downstream of the valve was relatively symmetric with respect to the center line of the left ventricular model. High velocities (114 cm/sec) were measured close to the walls. Again, a region of reverse flow, with a velocity of -20 cm/sec and a diameter of 40 mm, nce located at the edges of the jetlike flow field. The maximum root mean square velocities measured on the centerline plane, 11 mm downstream of the valve, were 66 cm/sec. Root mean square axial velocities measured in the central part of the flow model were very low.

The disc-and-cage valves studied with the ultrasound color Doppler system also revealed high velocity, turbulent jets adjacent to the cage and occluder similar to the ball-and-cage-valves. However, the disc-and-cage valves had more narrow and more turbulent jets. These jets decayed approximately 2 cm distal to the valve housing, thereby achieving velocities of no more than 60 cm/sec during mid-and late diastole. The portions of the peripheral, circumferential jet adjacent to the left ventricular free wall were exceptionally small, demonstrating flow areas of no more than 5 mm in diameter. A large region of flow reversal with velocities ranging up to -50 cm/sec and diameters approaching 2 cm occurred distal to the occluder, extending as far as 2 cm towards the left ventricular apex. Additionally, there were small areas of stagnation (no detectable velocities) immediately distal to the occluder.

(iii) **Tilting Disc Mechanical Valves:**

The laser Doppler velocity profile taken across the major and minor orifices, 15 mm downstream of the valve sewing ring, showed two jets; one from the major orifice and the other from the minor orifice. The maximum velocities measured in both orifices were the same, approximately 100 cm/sec. The region between the two jets was found to be relatively stagnant. Regions of flow separation were observed adjacent to the walls of both orifices with velocities of -7 cm/sec. The region of flow separation in the minor orifice extended 12 mm from the wall, and the region in the major orifice extended 6 mm from the chamber wall. For this valve design, maximum root mean square axial velocities (i.e., turbulence levels) on the borders of the two jets at locations where the highest velocity gradients were observed. The minor orifice flow field was more disturbed and turbulent than the major orifice flow field.

Color (ultrasound) Doppler flow mapping of the tilting disc valves showed no major differences between the five types of valves. The valves characteristically had two high velocity jets (maximal velocities 100 to 150 cm/sec in both the major and minor orifices). However, these jets decayed during the late diastole such that the entire flow field became laminar with velocities of 60 cm/sec or less. Eddies of velocity reversal measured -20 to-30 cm/sec just distal to the disc. However, these areas of velocity reversal were much smaller than those occurring with the ball-and-cage and the disc-and-cage valves. Comparisons were made of valve orientation in the mitral position, i.e., with the major orifice towards the septum (left ventricular outflow tract) or with the major orifice towards the left ventricular free wall. Greater intraventricular turbulence occurred with septal orientation than free wall orientation. Large areas of velocity reversal, ranging from -25 to -50 cm/sec, directed against the minor orifices' inflows occurred along the left ventricular free wall in mid- and late diastole with the major orifice oriented towards the septum. In contrast, valves with the major orifice oriented towards the left ventricular free wall and velocity profiles that became laminar and directed to the left ventricular apex 1 to 2 cm distal to the disc, measuring 50 to 80 cm/sec in mid and late diastole. These studies indicate that tilting disc valves in the mitral position have better (more normally physiologic) velocity profiles with the major orifice oriented to the left ventricular free wall than to the septum.

(iv) Bileaflet Mechanical Valves:

The laser Doppler velocity profiles for this valve design showed three jets, corresponding to the locations of the three outflow orifices. Most of the forward flow emerged from the two lateral orifices. The maximum velocity measured 19 mm downstream in the lateral orifices was 105 cm/sec; the maximum velocity in the central orifice was 95 cm/sec. The forward flow occupied the central part of the flow chamber with regions of flow separation on either side of the jetlike forward flow. The maximum reverse velocity measured was in the range of -8 cm/sec. The root mean square axial velocity profiles (i.e., turbulence profiles measured 19 mm downstream from the valves showed that maximum turbulence occured along the outer edges of the side orifice jets. The maximum root mean square axial velocity measured was in the range of 23 cm/sec. As with the previously described valve designs, the maximum root mean square axial velocity occurred in a region where high velocity gradients were observed. However, compared to the other mechanical valve designs, the bileaflet design appeared to create lower levels of turbulence, at least during mitral inflow.

With the color Doppler studies, three jets were observed with the bileaflet valves. The jets from the lateral two orifices appeared larger and had velocities measuring from 80 to 120 cm/sec. The two jets from the lateral orifices were directed towards the left ventricular septum and free wall. The jet from the central orifice was delayed by 20 to 30 sec. These jets decayed, producing laminar velocity flow fields between 1.0 and 0.5 cm downstream. No areas of velocity reversal were observed with these valves. Color spectrum variance, indicating turbulence, was present only in the region of in-orifice flow.

(v). Trileaflet Porcine Aortic Bioprosthetic Valves:

The centerline laser Doppler velocity profile showed a jetlike flow field in the center of the flow chamber. The jet was, however, not axisymmetric. High velocity gradients were observed at the edges of the jet. Maximum velocity measured was 215 cm/sec. The region adjacent to and extending 18 mm from the wall appeared to be relatively stagnant. The root mean square axial velocity (i.e., turbulence) profile showed that elevated levels of turbulence were confined to a narrow region at the edges of the jet. The maximum root mean square velocity measured was on the order of 50 cm/sec indicating very high levels of turbulence for this type of valve design.

The ultrasound color Doppler studies showed that porcine aortic bioprosthetic valves had high velocity (maximal 150-200 cm/sec), turbulent, eccentric jets, usually directed towards the septum during ventricular diastole. These jets persisted 2 to 3 more cm downstream often without the flow profiles becoming laminar before reaching the left ventricular septum or apex. The valve flow areas, as determined from the valves' suprastructures occupied approximately 50 percent of the cross-sectional orifice inflow areas. Areas of flow separation and stagnation appeared beneath the leaflets during ventricular systole.

### (vi). Trileaflet Bovine Pericardial Bioprosthetic Valves:

The broad jet was observed with the in vitro laser Doppler 21 mm downstream of this type of valve. The maximum velocity measured was 190 cm/sec. A large region of low velocity recirculaitng flow was observed adjacent to and extending 20 mm from the wall of the chamber. Regions of high root mean square axial velocities were confined to a narrow region at the edges of the outflow jet. The maximum root mean square velocity measured was 45 cm/sec, again revealing elevated levels of turbulence.

The color Doppler studies of the bovine pericardial valves showed broad centralflow fields; however, the velocity profiles usually were eccentric because of asynchronous opening of the three leaflets. Valve flow areas, as determined by color Doppler velocity profiles distal to the valve, occupied no more than 75 percent of the cross-sectional, orifice inflow areas. These valves demonstrated maximal velocities in the range of 150 cm/sec, with in-orifice turbulence that decayed 1 to 2 cm downstream. Like the porcine aortic valves, the bovine pericardial valves had areas of flow separation and stagnation beneath the leaflets during ventricular systole.

(vii) Conclusions:

Doppler flow imaging techniques demonstrate that all prosthetic valves have abnormal velocity and flow fields compared to normally functioning native valves. Ball-and-cage and disc-and-cage valves have peripheral flow patterns. Tilting disc valve designs have two eccentric jets. Disc orientation affects their flow characteristics. Bileaflet hemidisc valves have three jets. These valves more nearly approach a central orifice type of flow and generate lower velocities than other types of mechanical valves. Both generic types of bioprosthetic valves (porcine aortic and bovine pericardial) have central flow fields; however, these flow fields are not axisymmetric but tend to be directed eccentrically. Doppler flow imaging does permit evaluation of normally functioning prosthetic valves and should prove useful for detecting and understanding the clinical problems associated with prosthetic heart valves.

**(o) Lay Research Summary**

This research work was mainly directed towards understanding the flow of blood through various designs for heart valve prostheses. State of the art ultrasound Doppler (UD) instruments were used to map the velocity and turbulence patterns created by different artificial heart valve designs, in a realistic left heart simulator. Ultrasound Doppler is a relatively new non-invasive technique for measuring blood flow in human subjects. UD techniques have the potential for providing quantitative hemodynamic information about the performance of prosthetic heart valves in valve patients. The in vitro ultrasound Doppler data were compared to the more accurate laser Doppler results. Such a detailed and quantitative comparison is essential, in order to validate the accuracy of ultrasound Doppler techniques in measuring blood flow patterns in human subjects.

## III. Collaborators

(a)

1. Dr. M. Jones - Cardiac Surgeon at NIH assisted with the color Doppler studies.

2. Dr. D.J. Sahn - Pediatric Cardiologists, University of California-San Diego.

3. Dr. N.C. Nanda - Cardiologist, University of Alabama -Birmingham.

   Both Drs. Sahn and Nanda participated in the ultrasound Doppler studies conducted at the Cardiovascular Fluid Mechanics Laboratory at Georgia Tech.

(b) The following students worked on the project:

1. A.J. Ridgway
2. A. Jimoh
3. E. Mumpower
4. S.T. McMillan

## V. Research Continuation

(a) This research work is being continued. Both animal and non -invasive human studies are to be conducted during the coming year.

(b) Funding from two major valve manufacturers has been obtained for the continuation of this work for the coming year.

## IV. Publications

### (a). Abstracts and Presentations

1. Yoganathan, A.P. Ridgway, A.J., Jones, M., and Sahn, D.J., "Bernoulli gradient calculations for mechanical prosthetic heart valves," 59th Scientific Sessions - American Heart Association, Dallas, TX, November 1986.

2. Jones, M., Eidbo, E., McMillan, S.T., and Yoganathan, A.P., "Tilting disc orientation for prosthetic mitral valves," 59th Scientific Sessions - American Heart Association, Dallas, TX, November 1986.

3. Krabill, K.A., Tamura, T., Sahn, D.J., and Yoganathan, A.P., "The shape of regurgitant jets: in vitro flow visualization and color flow Doppler studies," 36th Scientific Sessions-American College of Cardiology, New Orleans, LA, March 1987.

4. McMillan, S.T., Woo, Y-R., Jones, M., and Yoganathan, A.P., "Velocity and turbulence measurements in the vicinity of mitral prosthetic valves using ultrasound Doppler," Joint ASME/ASCE Biomechanics Conference, Cincinnati, OH, June 1987.

5. Yoganathan, A.P., McMillan, S.T., Mumpower, E., Jones, M., and Eidbo, E., "Doppler flow characterization of prosthetic mitral valves," 22nd Congress-European Society of Surgical Research, Aarhus, Denmark, May 1987.

6. Yoganathan, A.P., McMillan, S.T., Sung, H-W., Woo, Y-R., and Jones, M., "Laser Doppler and color Doppler flow mapping of mitral heart valve prostheses," International Conference on Fluid Mechanics, Beijing, China, July 1987.

### (b) Manuscripts

1. Yoganathan, A.P., Valdes-Cruz, L.M., Schmidt-Dohna, J., Jimoh, A., and Sahn, D.J., "Continuous wave Doppler velocities and gradients across fixed tunnel obstructions," - to be published in Circulation, September 1987.

2. Yoganathan, A.P., Ridgway, A.J., Jones, M., and Sahn, D.J., "Continuous wave Doppler estimates of gradients across prosthetic arotic valves," to be submitted to Circulation, October 1987.

3. Yoganthan, A.P., and Jones, M., "Experimental Doppler flow mapping of prosthetic heart valves," Invited Book Chapter for Echocardiography and Doppler in Cardiac Surgery.