Turbulent Stresses in the Region of a Hancock Porcine Bioprosthetic Aortic Valve[1]

F. J. Walburn
Research Division,
Miami Heart Institute,
Miami Beach, Fla. 33140

H. N. Sabbah

P. D. Stein
Department of Medicine
(Division of Cardiovascular Medicine),
and Department of Surgery,
Henry Ford Hospital,
Detroit, Mich. 48202

The purpose of this study was to measure stresses associated with turbulence (Reynolds stresses), in the region of a 29-mm-dia porcine bioprosthetic valve (Hancock, Model 242). Studies were performed in an in vitro pulse duplicating system with the valve mounted in the aortic position. The Reynolds stresses were calculated from velocities obtained with a two channel laser Doppler anemometer. The largest Reynolds shear stress and normal stress occurred at the highest stroke volume used (80 mL). Averaged over ejection they were 38 dynes/cm^2 and 380 dynes/cm^2, respectively. The maximal instantaneous Reynolds shear stress was 2500 dynes/cm^2 and the maximal instantaneous Reynolds normal stress was 6800 dynes/cm^2. Stresses of these magnitudes are in the range reported to damage platelets.

Introduction

Turbulent flow has been observed near various types of prosthetic valves in vitro [1-4] and with one type of prosthetic aortic valve in vivo [5]. Associated with turbulence are stresses known as Reynolds stresses [6]. These stresses consist of both normal and shear components [6]. In general, the Reynolds stresses are higher than the viscous shear stresses [6]. The Reynolds shear stress is of interest because high shear stresses in the cardiovascular system may have detrimental effects upon blood constituents, particulary the platelets [7]. While a number of investigators have estimated the Reynolds stress on the basis of meaurements of axial velocity alone [4, 8], a few have actually measured Reynolds stresses [3, 9, 10]. There have been no studies, which actually measured the Reynolds stresses in the region of a porcine bioprosthetic valve. It is the intent of this study, therefore, to measure such stresses in the region of a porcine bioprosthetic aortic valve.

Methods

Velocity was measured with a two-channel laser Doppler anemometer in a hydraulic model of the cardiovascular system in which a porcine bioprosthetic valve (Model 242, Hancock Labs, Inc.) was mounted. The tissue annulus diameter of the valve was 29 mm.

The pulse duplicating system has been previously described in detail [6, 10]. The test fluid was mixture of glycerin and saline with a viscosity of 0.04 poise and a density of 1.12 gm/cm^2. The configuration of pressure and flow, were comparable to those seen in human beings (Fig. 1).

Aortic and left ventricular pressure were measured with catheter-tip micromanometers (Millar Instruments). The pressure signals were filtered with a 25-Hz low-pass filter. Both pressure sensors were made equisensitive prior to each study and were referenced to atmospheric pressure. Aortic flow was measured with a cannulating electromagnetic flow transducer (Howell Instruments) placed distal to the aortic test section.

Studies were performed at a pump rate of 65 beats/ min. The stroke volume was 35, 50, and 80 mL. Aortic and left ventricular pressure, aortic flow, and instantaneous fluctuating velocities were recorded simultaneously on a photographic recorder and a magnetic tape recorder.

Velocity fluctuations were measured distal to the valve with a two-channel cross-polarization laser Doppler anemometer which was operated in the differential Doppler mode with forward scattering. The laser Doppler anemometer measured

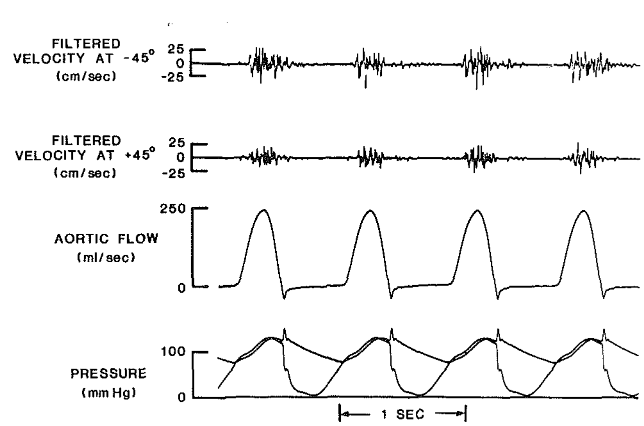

Fig. 1 Velocities and pressures in vitro with a Hancock bioprosthetic valve. From top to bottom are shown fluctuations of velocity at −45 deg to the direction of mean flow; fluctuations of velocity at +45 deg to the direction of mean flow; aortic flow; left ventricular pressure and aortic pressure. The stoke volume was 50 mL.

[1]Supported in part by the U.S. Public Health Service National Heart, Lung and Blood Institute Grant HL30063-01 and HL23669-05.

Contributed by the Bioengineering Division for publication in the JOURNAL OF BIOMECHANICAL ENGINEERING. Manuscript received by the Bioengineering Division, June 7, 1983; revised manuscript recieved March 18, 1985.

Table 1 Peak axial turbulence intensity (cm/s)

Stroke volume (mL)	30 mm from valve ring	45 mm from valve ring	60 mm from valve ring
35	13.9 ± 0.5	9.3 ± 0.3	5.3 ± 0.1
50	16.2 ± 0.3	15.1 ± 0.5	10.5 ± 0.2
80	18.4 ± 0.4	17.0 ± 0.2	15.5 ± 0.4

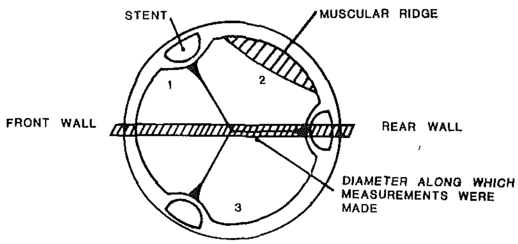

Fig. 2 Sketch (not to scale) of the configuration of the porcine valve relative to the diameter along which velocity measurements were made

velocities that were +45 deg and −45 deg relative to the mean direction of flow (Fig. 1). The method of seeding and dimensions of the measuring volume were previously described [11]. Velocities were measured in a horizontal midline plane. The configuration of the porcine valve relative to the diameter along which velocity measurements were made is shown in Fig. 2.

The simultaneous velocities obtained at +45 deg and −45 deg relative to the direction of mean flow were filtered with a 20-Hz high-pass filter to eliminate the pulse. The filter had a cutoff below 20 Hz of 20 dB per octave. Taylor [12] showed that most of the power spectra of the aortic flow pulse in dogs are below 12 Hz, and the frequency components of flow in human beings of magnitudes greater than 1 mL/s were also below 12 Hz [13]. Some of the frequency components of the pressure pulse in dogs, however, were as high as 20 Hz [12]. The level of 20 Hz was selected based upon these data. Twelve beats at each radial position were digitized using a high-speed analog to digital converter on line with a 21-MX computer (Hewlett-Packard). Each channel was digitized at a rate of 2000 points per second from the tape recorder using an alternating sample and hold (multiplexed) analog-to-digital converter. The Nyquist frequency, calculated at this rate of digitization, was sufficient to show velocity fluctuations as high as 1000 Hz [14].

The absolute turbulence intensity in the axial direction was calculated as the root-mean-square (RMS) value of the axial velocity fluctuation

$$u' = \sqrt{\overline{u^2}} \qquad (1)$$

where u' is the absolute turbulence intensity (cm/s) and u is the instantaneous velocity fluctuations in the axial direction (cm/s). The superscript bar refers to a time average. The axial velocity fluctuations were determined by resolving the velocities obtained at ±45 deg into their axial components. Absolute turbulence intensity was calculated over the entire period of ejection, beginnning at the moment of the rapid rise of aortic pressure and ending at the aortic incisura. The reported values were given as the mean ± standard error of the mean (SEM) of twelve beats.

The instantaneous Reynolds shear stress was calculated as $\rho u_i u_j$ where ρ was the density of the fluid and u_i and u_j represent the instantaneous fluctuations of velocity measured at ± 45 deg relative to the direction of the mean flow. The concept of the instantaneous Reynolds stress has been previously discussed [15]. The reported values of the peak instantaneous Reynolds shear stress were the mean ± SEM of twelve beats of the largest instantaneous shear stress during ejection. The time-average of the Reynolds shear stress was calculated as [6]

$$\mathbf{T} = \rho \overline{u_i u_j} \qquad (2)$$

where the bar refers to a time-average taken over the entire period of ejection. The reported values of the average Reynolds shear stress were the mean ± SEM of the time-average over ejection of 12 beats.

The instantaneous Reynolds normal stress was calculated as ρu^2 where ρ was the density of the fluid and u represents the instantaneous fluctuations of velocity in the axial direction. The reported values of the peak instantaneous Reynolds normal stress were the mean ± SEM of 12 beats of the largest instantaneous normal stress during ejection. The time-average of the Reynolds normal stress was calculated as [6], $\sigma = \rho \overline{u^2}$, where the bar refers to a time-average taken over the entire period of ejection. The reported values of the average Reynolds normal stress were the mean ± SEM of the time-average over ejection of 12 beats.

Results

Turbulence Intensity. The axial turbulence intensity was highest at 30 mm from the valve ring and it decreased as the distance from the valve increased. The peak turbulence intensity occurred at the largest stroke volume (80 mL) and it was 18.4 ± 0.4 cm/s (Table 1). The axial turbulence intensity profile became flat as distance from the valve ring increased for stroke volumes of 35 mL and 50 mL (Fig. 3). At a stroke volume of 80 mL, the turbulence intensity profile was flat 30 mm from the valve ring (Fig. 3). It was skewed at distances of 45 mm and 60 mm from the valve ring (Fig. 3).

Reynolds Shear Stress. The largest instantaneous Reynolds shear stress during ejection was 2540 ± 220 dynes/cm^2 45 mm from the valve ring at a stroke volume of 80 mL (Table 2, Fig. 4). At stroke volumes of 50 mL and 35 mL, the peak instantaneous Reynolds shear stress occurred close to the valve ring (Table 2, Fig. 4). The peak Reynolds shear stress at a stroke volume of 35 mL was 1140 ± 290 dynes/cm^2 and at a stroke volume of 50 mL it was 1710 ± 120 dynes/cm^2 (Table 2, Fig. 4).

At a stroke volume of 80 mL, the instantaneous Reynolds shear stress profiles were skewed at distances of 45 mm and 60 mm from the valve ring (Fig. 4). At the lower stroke volumes, the profiles became flat further from the valve ring (Fig. 4).

The Reynolds shear stress averaged over ejection increased with the stroke volume (Table 3). The highest Reynolds shear stress averaged over ejection was 38 ± 5 dynes/cm^2 for a stroke volume of 80 mL (Table 3).

Reynolds Normal Stress. Values of the peak instantaneous Reynolds normal stress were the largest stresses in the region of the porcine valve. These stresses were more than twice as high as the peak instantaneous Reynolds shear stresses. The peak instantaneous Reynolds normal stress was 6750 ± 470 dynes/cm^2 at a stroke volume of 80 mL (Table 4, Fig. 5).

The peak instantaneous Reynolds normal stress profiles became flat as distance from the valve ring increased for stroke volumes of 35 mL and 50 mL (Fig. 5). At a stroke volume of 80 mL, the profiles became skewed at distances of 45 mm and 60 mm from the valve ring (Fig. 5).

The Reynolds normal stress averaged over ejection was highest at 30 mm from the valve, and values decreased as measurements were made further from the valve ring (Table 5). The maximal Reynolds normal stress, averaged over ejection was 380 ± 16 dynes/cm^2 and this occurred at a stroke volume of 80 mL (Table 5).

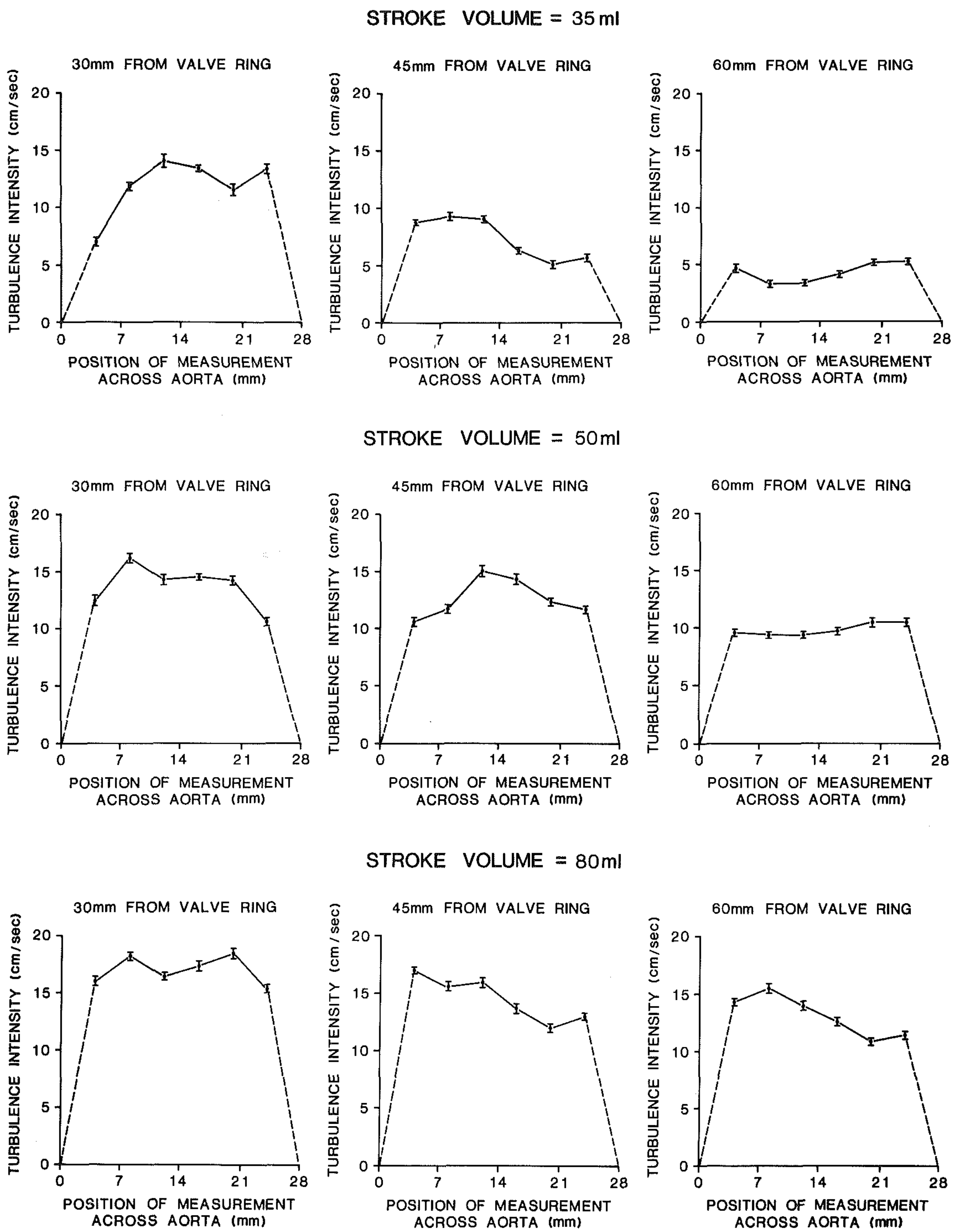

Fig. 3 Distribution of axial turbulence intensity (mean ± SEM) across the diameter of the simulated aorta 30 mm, 45 mm, and 60 mm distal to the valve ring. The stroke volumes were 35 mL, 50 mL and 80mL.

Discussion

The level of the turbulent stresses measured was in the range that affects platelets. The Reynolds shear stress and normal stress averaged over ejection reached levels of 38 dynes/cm^2 and 380 dynes/cm^2 respectively. Stresses in this range have been reported to cause platelet lysis [16, 17]. Adherent single platelets and platelet aggregates have been observed on the surface of leaflets of spontaneously degenerated porcine bioprosthetic valves [18]. In addition, platelets from patients with degenerated porcine bioprosthetic valves have increased reactivity [19]. Whether the platelets deposition and increased reactivity relate to turbulence is conjectural.

Reynolds shear stresses have been measured with x hot film probes in the region of a normal human aortic valve mounted in a pulse duplicating system [3]. Using an ensemble average of 200 beats, a peak instantaneous Reynolds shear stress of 150 dynes/cm^2 was reported with a stroke volume of 70 mL [3]. Shear stresses averaged over ejection would be expected to be lower than the peak instantaneous values. Based upon measurements of turbulence in patients during cardiac catheterization, the estimated Reynolds shear stress in the region of the normal aortic valve, averaged over ejection,

Table 2 Instantaneous Reynolds shear stress (dynes/cm²)

Stroke volume (mL)	30 mm from valve ring	45 mm from valve ring	60 mm from valve ring
35	1140 ± 290	420 ± 50	180 ± 20
50	1710 ± 120	1310 ± 120	570 ± 90
80	2210 ± 220	2540 ± 220	1580 ± 170

Table 3 Average Reynolds shear stress (dynes/cm²)

Stroke volume (mL)	30 mm from valve ring	45 mm from valve ring	60 mm from valve ring
35	15 ± 3	5 ± 1	4 ± 1
50	20 ± 3	30 ± 6	5 ± 1
80	35 ± 5	38 ± 5	12 ± 3

Table 4 Instantaneous Reynolds normal stress (dynes/cm²)

Stroke volume (mL)	30 mm from valve ring	45 mm from valve ring	60 mm from valve ring
35	3250 ± 480	1370 ± 200	490 ± 70
50	4360 ± 250	3600 ± 210	1700 ± 200
80	5820 ± 880	6750 ± 470	4460 ± 310

Table 5 Average Reynolds normal stress (dynes/cm²)

Stroke volume (mL)	30 mm from valve ring	45 mm from valve ring	60 mm from valve ring
35	215 ± 14	97 ± 6	31 ± 2
50	290 ± 9	260 ± 15	123 ± 4
80	380 ± 16	320 ± 82	270 ± 15

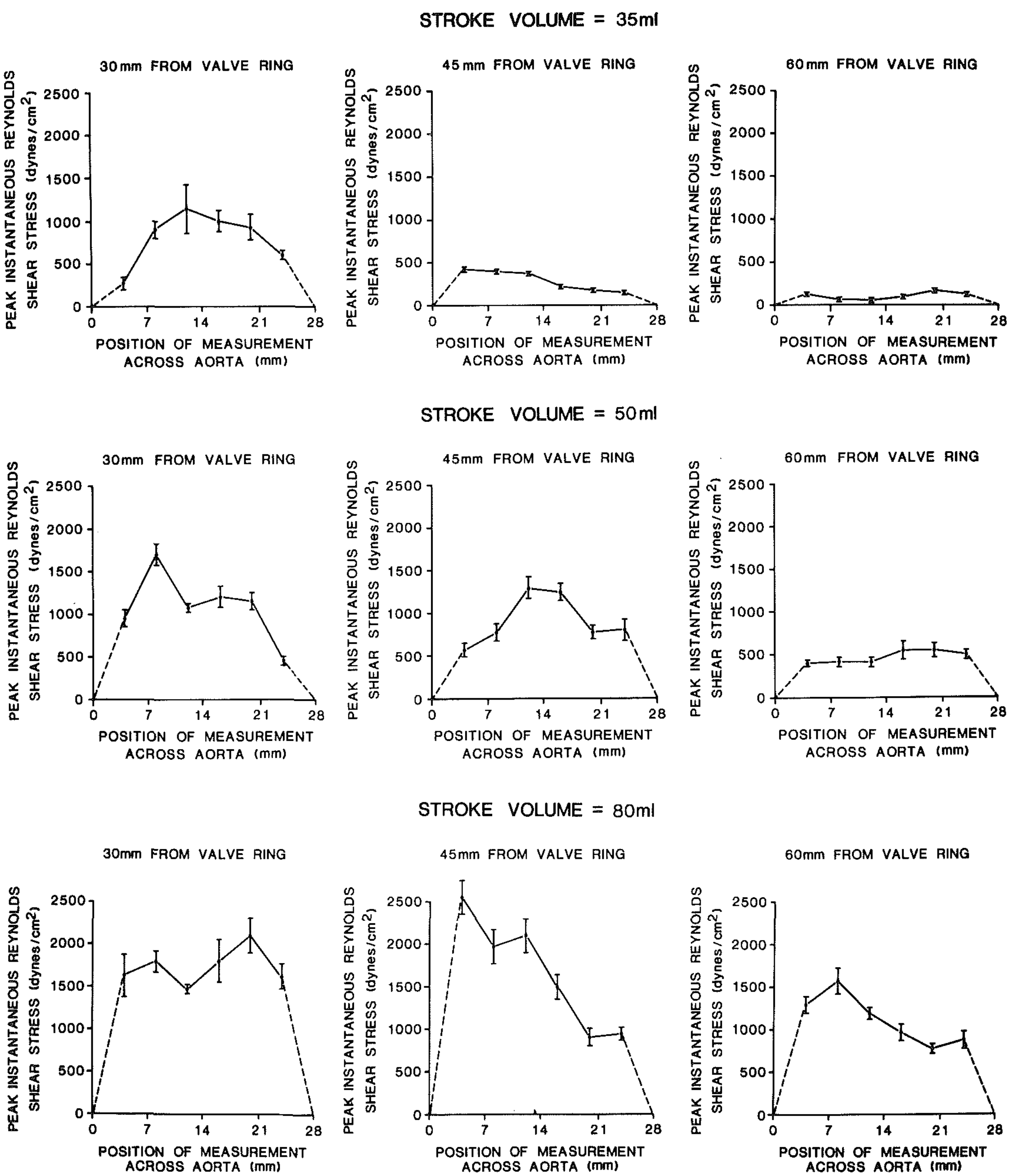

Fig. 4 Profiles of the peak instantaneous Reynolds shear stress (mean ± SEM) distal to the porcine bioprosthetic aortic valve

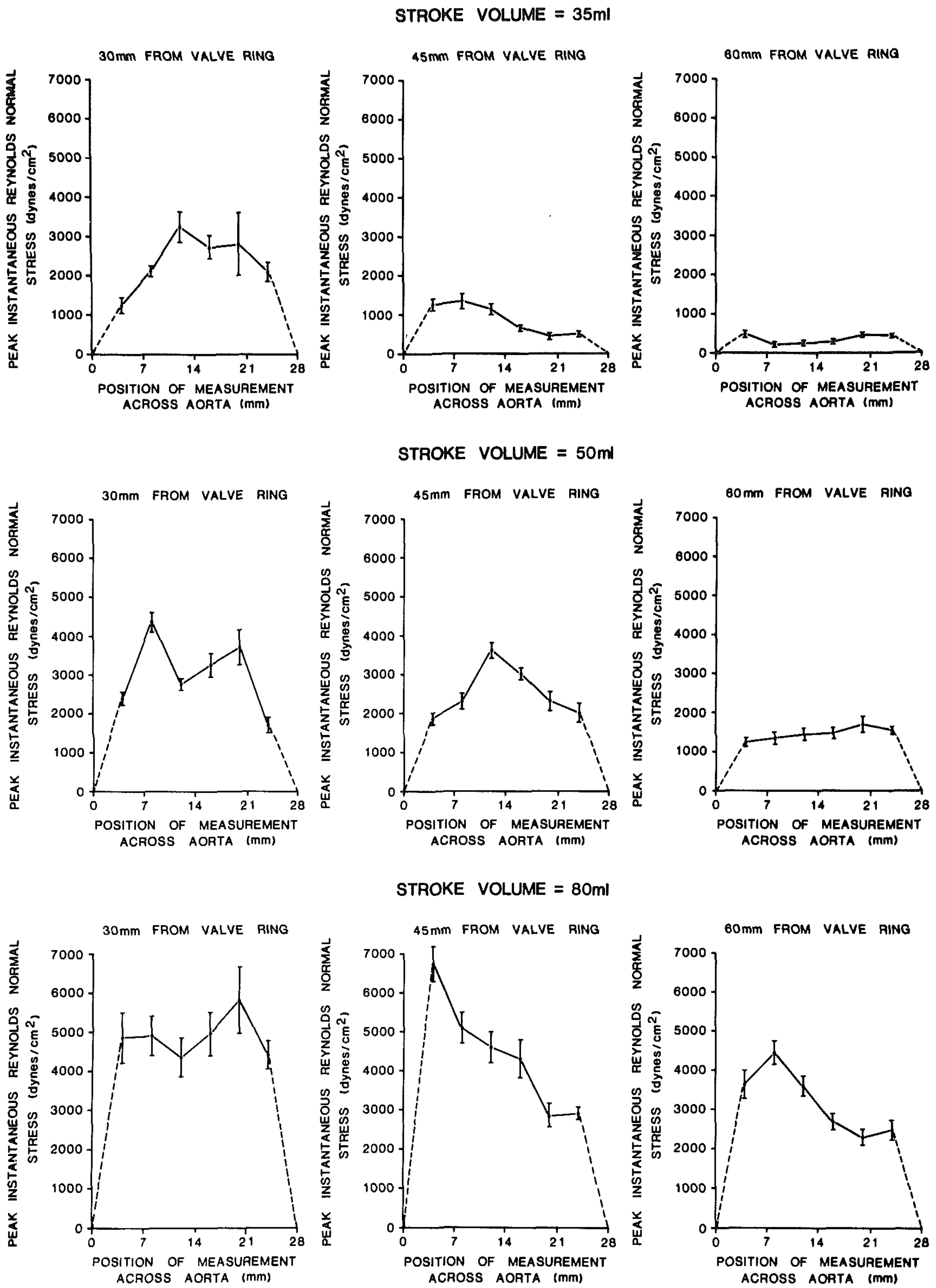

Fig. 5 Profiles of the peak instantaneous Reynolds normal stress (mean ± SEM) distal to the porcine bioprosthetic aortic valve

ranged between 0.1 and 6.1 dynes/cm^2 [10]. The Reynolds shear stress in the region of the normal pulmonary valve was lower, ranging between 0.1 and 0.9 dynes/cm^2 [10]. The turbulent stresses, therefore, seemed to be lower near normal valves than near stent-mounted normal porcine valves.

In the region of mechanical prosthetic valves, the Reynolds stresses are higher than Reynolds stresses in the region of a normal bioprosthetic valve. Measurements were made by others during steady flow in the region of a Kay-Shiley caged disk valve, a Bjork-Shiley tilting disk valve, and two Starr-Edwards ball valves [9]. The maximal turbulent shear stresses ranged between 520 dynes/cm^2 and 816 dynes/cm^2 [9]. It was not clear whether these values were time averaged or instantaneous values.

Other investigators estimated the Reynolds shear stress based upon theoretical considerations of steady turbulent shear flows. Stresses ranging between 100–5000 dynes/cm^2 have been estimated during steady flow through a Starr-

Edwards arotic ball valve [1]. Estimates of the Reynolds shear stresses in the region of a number of mechanical prosthetic valves during steady flow were reported to be on the order of 100–1000 dynes/cm^2 [5]. During pulsatile flow, the Reynolds shear stress was estimated to be 2000 dynes/cm^2 averaged over ejection and 6500 dynes/cm^2 instantaneously during systole in the region of Bjork-Shiley tilting disk and straight disk valves [4].

Reynolds stresses in the region of stenotic human aortic valves have been measured in vitro (10). With valves of orifice areas of 0.33 cm^2 and 0.20 cm^2, the maximal instantaneous Reynolds shear stresses were 3700 and 11,900 dynes/cm^2 and the Reynolds shear stresses averaged over ejection were 93 and 245 dynes/cm^2 [10]. These were comparable to values estimated at cardiac catheterization of patients with arotic stenosis. Peak measured instantaneous Reynolds normal stress reached values as high as 36,000 dynes/cm^2 distal to stenotic aortic valves in vitro [10]. It is apparent, therefore, that severely diseased aortic valves are associated with Reynolds stresses considerably higher than mechanical prosthetic valves as well as bioprosthetic valves.

Reynolds stresses can be calculated from any two orthogonal velocity components. The stresses that we calculated were obtained directly from the velocity components measured at ± 45 deg and act along planes ± 45 deg in the direction of the mean flow. Calculations of the axes of principal stress showed that the 45-deg planes are within ± 2 percent of the planes along which the maximum shear stresses acted in our system. Thus, the Reynolds stresses that we measured were effectively the largest that occurred along any plane of rotation. The choice of calculating the normal stress in the axial direction was made for the same reason; it was the direction in which the largest normal stresses occurred. The stresses reported, therefore, were the largest normal stresses and the largest turbulent shear stresses.

In conclusion, observations made in this study suggest that the turblent stresses distal to normal porcine aortic values may exceed the levels of stress that have been reported to damage platelets.

References

1 Yoganathan, A. P., Reamer, H. H., Corcoran, W. H., Harrison, E. C., Shulman, I. A., and Parnassus, W., "In Vitro Flow Measurements in the Near Vicinity of the Starr-Edwards Aortic Ball Valve Prosthesis," *Proceedings of the 32nd Annual Conference on Engineering in Medicine and Biology*, Vol. 21, 1979, p. 33.

2 Sabbah, H. N., and Stein, P. D., "Contributions of Semilunar Leaflets to Turbulent Blood Flow," *Journal of Biorheology*, Vol. 16, 1979, pp. 101–108.

3 Hwang, N. H. C., "Flow Dynamics of Natural Valves in the Left Heart," eds., N. H. C. Hwang and N. A. Normann, *Cardiovascular Flow Dynamics and Measurements*, University Park Press, 1977, pp. 825–850.

4 Alchas, P. G., Snyder, A. J., and Phillips, W., M., "Pulsatile Prosthetic Valve Flows: Laser-Doppler Studies," ed., D. J. Schneck, *Biofluid Mechanics II*, Plenum Press, 1980, pp. 243–265.

5 Stein, P. D., and Sabbah, H. N., "Turbulent Blood Flow in The Ascending Aorta of Humans with Normal and Diseased Aortic Valves," *Circulation Research*, Vol. 39, 1976, pp. 58–65.

6 Schlichting, H., *Boundary-Layer Theory*, Sixth Edition, McGraw-Hill Book Company, 1968, pp. 527–543.

7 Colantuoni, G., Hellums, J. D., Moake, J. L., and Alfrey, C. P., Jr., "The Reponse of Human Platelets to Shear Stress at Short Exposure Times," *Transactions of the American Society of Artificial Internal Organs*, Vol. 23, 1977, pp. 626–631.

8 Yoganathan, A. P., Corcoran, W. H., and Harrison, E. C., "In Vitro Velocity Measurements in the Vicinity of Aortic Prostheses," *Journal of Biomechanics*, Vol. 12, 1979, pp. 135–152.

9 Figliola, R. S., and Mueller, T. J., "On the Hemolytic and Thrombogenic Potential of Occluder Prosthetic Heart Valves from In-Vitro Measurements," ASME Journal of Biomechanical Engineering, Vol. 103, 1981, pp. 83–90.

10 Stein, P. D., Walburn, F. J., and Sabbah, H. N., "Turbulent Stresses in the Region of Aortic and Pulmonary Valves," ASME Journal of Biomechanical Engineering, Vol. 104, 1982, pp. 238–244.

11 Walburn, F. J., and Stein, P. D., "Wall Shear Stress During Pulsatile Flow Distal to a Normal Porcine Aortic Valve," *Journal of Biomechanics*, Vol. 17, 1984, pp. 97–102.

12 Taylor, M. G., "Use of Random Excitation and Spectral Analysis in the Study of Frequency-Dependent Parameters of the Cardiovascular System," *Circulation Research*, Vol. 18, 1966, pp. 585–595.

13 Nicholas, W. W., Conti, C. R., Walker, W. E., and Milnor, W. R., "Input Impedance of the Systemic Circulation in Man," *Circulation Research*, Vol. 40, 1977, p. 451–458.

14 Bendat, J. S., and Piersol, A. G., *Random Data: Analysis and Measurement Procedures*, Wiley-Interscience, 1975, pp. 1–4.

15 Eckelmann, H., "The Structure of the Viscous Sublayer and the Adjacent Wall Region in a Turbulent Channel Flow," *Journal of Fluid Mechanics*, Vol. 65, 1974, pp. 439–459.

16 Goldsmith, H. L., Yu, S. S. K., and Marlow, J., "Fluid Mechanical Stress and the Platelet," *Thrombos. Diathes. Haemorrh.*, Vol. 34, 1975, pp. 32–41.

17 Hung, T. C., Hochmuth, R. M., Joist, J. H., and Sutera, S. P., "Shear-Induced Aggregation and Lysis of Platelets," *Transactions of the American Society of Artificial Internal Organs*, Vol. 22, 1976, pp. 285–291.

18 Riddle, J. M., Magilligan, D. J., and Stein, P. D., "Surface Morphology of Degenerated Porcine Bioprosthetic Valves Four to Seven Years Following Implantation," *Journal of Thoratic and Cardiovascular Surgery*, Vol. 81, 1981, pp. 279–287.

19 Riddle, J. M., Magilligan, D. J., and Stein, P. D., "Platelet Reactivity in Patients with Degenerated Porcine Bioprosthetic Valves," *Journal of Thrombosis Research*, Vol. 22, 1981, pp. 185–194.