BED-Vol. 48, 2000 Advances in Bioengineering
ASME 2000

LINKING MEASUREMENTS OF CORONARY FLOW RESERVE IN PATIENTS DURING ANGIOPLASTY PROCEDURES TO MYOCARDIAL PERFUSION USING COMPUTATIONAL HEMODYNAMICS

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ABSTRACT

Computational hemodynamics was used to determine the connection between measurements of coronary flow reserve (CFR) and myocardial perfusion in patients with obstructive disease during angioplasty. The 32 patient group (Wilson et al. 1988) had single-vessel, single-lesions with either unstable angina pectoris or stable angina, but no known abnormalities that might affect the vasodilator capacity of the arteriolar vasculature.

The patients' maximal vasodilation-distal perfusion pressure curve (CFR- $\widetilde{P}_{rh}$) was uniquely determined by the intersections of measured values of CFR and computed values of $\widetilde{P}_{rh}$ for the native and residual lesions after percutaneous transluminal coronary balloon angioplasty (PTCA) supplying blood to the same vasculature. Extrapolation of this nearly linear curve to its origin gave a zero-flow mean pressure $\widetilde{P}_{ro}$ of about 20 mm Hg, close to a value of 18 mm Hg known to be associated with ischemia in the subendocardium of dog hearts (Bache and Schwartz, 1982). The corresponding value of $\widetilde{P}_{rh}$ of about 55 mm Hg in the native lesions coincided with the level proposed by Brown et al. 1984 to cause ischemia in the subendocardium of human hearts.

INTRODUCTION

Measurements of CFR and translesional pressure drops, $\Delta\widetilde{P}$, (referred to as pressure gradients in the medical literature) are often made in conjunction with quantitative angiography to assess the physiologic significance of lesions in patients with coronary artery syndromes (eg. Wilson and Laxon 1993). Brown et al. 1984 have proposed that the fall in distal mean coronary pressure, $\widetilde{P}_r$, across lesions to a level of about 55 mm Hg causes ischemia in the subendocardium. Efforts to directly measure pressure losses by catheters spanning lesions introduce a tighter 'artifactual' stenosis, thus elevating the pressure drop and reducing blood flow during mesurements. In this investigation, detailed pulsatile hemodynamic computations for physiologic flow in conjunction with measurements of CFR are used to construct CFR- $\widetilde{P}_{rh}$ curve in a 32 patient group during angioplasty (Wilson et al. 1988), thus linking values of $\widetilde{P}_{rh}$ to the critical zero-flow pressure $\widetilde{P}_{ro}$ important in assessing myocardial perfusion (eg. Klocke, 1987).

METHODS

Dimensions and shape of the coronary stenoses before and after PTCA were obtained from biplanar angiograms (Wilson et al. 1988; Back and Denton 1992). Balloon angioplasty both widened and lengthened the narrowest region of the stenoses (d_m = 0.95 to 1.8 mm, l_m = 0.75 to 3 mm). Despite axial redistribution of the plaque away from the narrowest region, overall stenosis shape and constriction (l_c = 6 mm) and divergence (l_r = 1.5 mm) lengths were roughly unchanged by balloon dilation. Average values of proximal and distal diameter were $d_e = d_r$ = 3 mm, and average percentage diameter stenosis changed from 68% to 40% with angioplasty. Measurements of CFR with a 3F pulsed doppler ultrasound catheter (d = 1.0 mm) with tip positioned proximal to the lesions (with minimal blockage) increased from 2.3 ± 0.1 to 3.6 ± 0.3 in the procedure; mean arterial pressures $\widetilde{P}_a$, measured in the coronary ostium, decreased from 89 ± 3 to 84 ± 3 mm Hg (Wilson et al. 1988). The patients had single-vessel, single-lesion coronary artery disease with either unstable angina pectoris or stable angina. Patients with abnormalities that might affect the vasodilator capacity of the arteriolar vasculature were excluded from the study. Repeated doses of papaverine induced maximal arteriolar bed vasodilation. These mean quantities are summarized in Table 1.

The spatial average coronary velocity waveform $\overline{u}(t)$ used in the flow simulations was obtained in our laboratory from in-vitro calibration (Cho et al. 1983), smoothing the fluctuating Doppler signal, and phase shifting the normal pattern for the proximal left anterior descending (LAD), consistent with Doppler catheter measurements in patients where normal peak diastolic velocity is reduced by significant lesions (eg. Wilson et al. 1988; Segal, 1992) The ratio of peak diastolic to peak systolic velocity was 0.4 before PTCA.

	A_m, mm^2	d_m, mm	% dia. Stenosis	l_m, mm	CFR	$\tilde{P}_a$, mm Hg	$\Delta\tilde{P}_h$, mm Hg	$\tilde{P}_{rh}$, mm Hg
Before PTCA	0.7 ± 0.1	0.95	68	0.75	2.3 ± 0.1	89 ± 3	~34	~55
After PTCA	2.5 ± 0.1	1.8	40	3	3.6 ± 0.1	84 ± 3	8	74 - 76

Table 1: Lesion dimensions, shape, and hemodynamics before and after PTCA. Values of d_e=d_r=3 mm; l_c=6 mm; l_r=1.5 mm.

Details of the finite element method used to solve the mass and momentum conservation equations for the non-Newtonian viscosity of blood have been previously described by Banerjee et al. (1999). Instantaneous pressure differences $\Delta P(t)$ between the stenosis inlet and distal region, thereby including pressure recovery in the separated flow reattachment processes in the distal vessel, were integrated over the cardiac cycle to obtain the mean pressure drops, $\Delta\tilde{P}$. Distal mean coronary pressures $\tilde{P}_r = \tilde{P}_e - \Delta\tilde{P}$ were computed with $\tilde{P}_e \simeq \tilde{P}_a$ since mean flow resistances of proximal vessels were estimated to be small compared to the larger values across the stenoses which increased with flow rate. Computations were carried out for a range of mean flow rates, $\tilde{Q}$, consistent with measurements of CFR and flow limitation. Mean Reynolds numbers $\tilde{\mathrm{Re}}_e$ ranged from 100-230, and 100-360, respectively, before and after PTCA. The frequency parameter $\alpha_e = [(\omega D^2)/4\eta]^{1/2} = 2.25$.

RESULTS AND DISCUSSION

The relationship between relative coronary flow increase $\tilde{Q}/\tilde{Q}_b$ and distal pressure $\tilde{P}_r$ decrease is shown in Fig 1 for the patient group before and after angioplasty. The maximal vasodilation-distal perfusion pressure curve is determined by the intersections of the measured values of CFR and computed values of $\tilde{P}_{rh}$ for the native and residual lesions after angioplasty since blood is supplied to the same distal vasculature, originally with markedly dilated microcirculation. Extrapolation of the nearly linear CFR-$\tilde{P}_{rh}$ relation towards its origin gives a zero-flow mean pressure ($\tilde{P}_{ro}$) of about 20 mm Hg. This value is near a measured value of 18 mm Hg (Bache and Schwartz, 1982) where myocardial blood ceased in the subendocardium layer of dog hearts maximally dilated by infusion of adenosine. A variable occluder was used on the proximal left circumflex (LCX) artery, and distal $\tilde{P}_{rh}$ was measured by cannulation. Myocardial blood flow (ml/min-gm) measured in transmural layers with radioactive microspheres after heart removal decreased linearly with $\tilde{P}_{rh}$, even at pressures close to $\tilde{P}_{ro}$. In contrast, flow ceased in the subepicardium layer at a lower $\tilde{P}_{ro}$ of 10 mm Hg in the dog hearts.

These results show how computational fluid dynamics in conjunction with clinical data in patients with flow limiting lesions may be used to link critical values of $\tilde{P}_{rh}$ of about 55 mm Hg to zero-flow pressures ($\tilde{P}_{ro}$) of about 20 mm Hg, indicative of subendocardium ischemia, and consistent with both angina in the patients, and the phase shift of the Doppler signal to systolic predominance. Bache and Schwartz 1982 postulated that increases in the relative portion of flow during systole would be expected to favor perfusion of the subepicardium where blood flow can occur during cardiac contraction, thus reducing relative perfusion of the subendocardium as indicated in dog studies.

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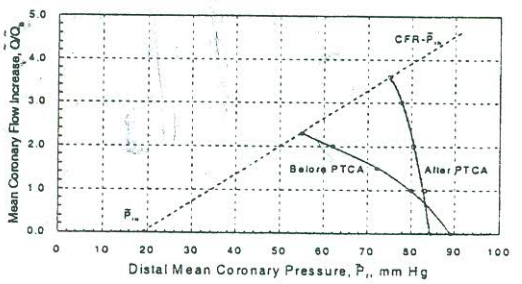

Fig. 1 Relative mean coronary flow rate increase ($\tilde{Q}/\tilde{Q}_b$) versus distal mean coronary pressure $\tilde{P}_r$ before and after PTCA. The maximum vasodilation-distal perfusion pressure relation (CFR-$\tilde{P}_{rh}$) is shown by nearly linear line