Normalization of Coronary Flow Reserve by Percutaneous Transluminal Coronary Angioplasty

FELIX ZIJLSTRA, MD, JOHAN C. REIBER, PhD, YVES JUILLIERE, MD, and PATRICK W. SERRUYS, MD

Fifteen patients undergoing routine follow-up angiography 5 months after successful percutaneous transluminal coronary angioplasty (PTCA) without angina and with normal exercise thallium scintigraphy were selected for analysis. The coronary flow reserves of these patients were compared with those of 24 patients with angiographically normal coronary arteries to establish whether PTCA can restore to normal the coronary flow reserve of patients with chronic coronary artery disease. The quantitative cineangiographic changes and the concomitant alterations in coronary flow reserve as an immediate result of the PTCA and the subsequent changes 5 months later are described. Coronary flow reserve was measured with digital subtraction cineangiography. PTCA resulted in an increase in minimal obstruction area (mean ± standard deviation) from 0.8 ± 0.3 to 3.4 ± 0.7 mm^2 and in coronary flow reserve from 1.0 ± 0.3 to 2.5 ± 0.6. Five months later a further substantial and significant ($p < 0.05$) late increase in obstruction area (3.8 ± 0.9 mm^2) and flow reserve (3.6 ± 0.5) had occurred. In 11 of 15 patients coronary flow reserve was restored to normal. Changes in stenosis geometry are likely to be 1 of the major determinants of this late normalization of coronary flow reserve.

(Am J Cardiol 1988;61:55–60)

Since the introduction of percutaneous transluminal coronary angioplasty (PTCA) in 1977,[1] this procedure has gained increasing importance in the treatment of coronary artery obstructions. The immediate and long-term results of PTCA are usually assessed by coronary angiography. Recently, the measurement of coronary flow reserve has been proposed as a better method of evaluating the hemodynamic repercussions of coronary artery obstructions.[2,3] Three techniques have been developed that allow the measurement of regional coronary flow reserve during cardiac catheterization. The first uses a pulsed Doppler coronary artery catheter that can measure intracoronary blood flow velocity.[4] The second technique is based on the radiographic assessment of myocardial perfusion using contrast medium.[5,6] The third technique is an indicator dilution technique with a platinum-tipped PTCA guidewire, using hydrogen as the indicator.[7] Although PTCA has been shown to result in symptomatic, hemodynamic and functional improvement,[8–10] doubt has remained whether this procedure can restore coronary flow reserve of atherosclerotic coronary arteries to a normal level.[11–14] Therefore, we selected 15 patients who were free of angina and had a normal exercise thallium scintigram 5 months after PTCA and compared their radiographically measured coronary flow reserve with the flow reserve of 24 patients with angiographically normal coronary arteries. We describe the quantitative cineangiographic changes and the concomitant alterations in coronary flow reserve resulting from the acute intervention as well as the subsequent changes as observed 5 months after PTCA.

From the Thoraxcenter, Erasmus University, Rotterdam, The Netherlands. Manuscript received May 19, 1987; revised manuscript received and accepted August 18, 1987.

Address for reprints: Felix Zijlstra, MD, Catheterization Laboratory, Thoraxcenter, Erasmus University, P.O. Box 1738, 3000 DR Rotterdam, The Netherlands.

Methods

Patients: The study population consisted of 24 patients with angiographically normal coronary arteries (data on 12 have been previously published)[5] and 15 patients with 1-vessel coronary artery disease. These 15 patients had undergone successful PTCA for disabling angina refractory to intensive pharmacologic treatment. They were selected on the basis of a normal exercise thallium scintigram and complete relief of chest pain 5 months after PTCA, when coronary angiography and left ventriculography were performed as part of an ongoing study on restenosis after PTCA. Informed consent was obtained for all investigations. Before PTCA, pharmacologic treatment consisted of

TABLE I Results of Coronary Flow Reserve and Quantitative Angiographic Data of PTCA Patients

				PTCA								
				Before			After			5 Months Follow-up		
Pt	Age (yr)	Sex	Vessel	OA	DS	CFR	OA	DS	CFR	OA	DS	CFR
1	54	M	LAD	1.2	53	1.0	5.4	14	3.0	5.2	6	2.9
			LC			3.9			3.7			4.3
2	31	M	LAD	0.5	70	1.0	3.7	15	2.3	3.1	19	2.5
			LC			3.3			2.5			3.1
3	53	F	LAD	0.5	72	0.6	3.3	27	2.8	5.9	7	3.7
			LC			2.6			2.5			2.2
4	36	M	LAD	0.4	70	1.2	3.7	14	3.3	2.8	20	2.9
			LC			3.2			3.4			3.3
5	62	M	LAD	0.8	66	1.0	2.5	44	2.1	3.8	32	3.8
			LC			2.6			2.8			2.9
6	42	M	LC	0.7	66	0.7	3.8	24	1.5	2.6	38	3.4
			LAD			3.8			3.6			4.1
7	53	M	R	1.3	65	0.9	3.6	31	2.2	2.9	35	3.9
8	66	M	LAD	0.7	58	1.4	2.9	26	2.7	3.1	12	2.9
			LC			3.5			3.8			3.4
9	59	M	LAD	1.1	64	1.0	3.5	36	1.4	4.7	21	3.7
			LC			3.2			3.5			3.5
10	52	M	LC	1.4	61	0.9	3.0	32	2.9	3.9	28	4.3
			LAD			3.9			4.0			3.7
11	64	M	LAD	0.6	68	1.0	2.4	38	3.1	4.1	14	4.1
			LC			3.8			3.3			4.6
12	53	M	R	0.7	72	0.9	3.2	49	2.1	3.5	39	3.5
13	47	M	LAD	0.8	76	0.6	3.7	47	1.8	4.2	38	3.9
			LC			4.1			3.6			4.4
14	58	M	R	0.6	71	1.4	2.9	40	2.8	3.6	31	3.8
15	66	M	LAD	0.7	58	1.4	2.9	23	2.7	3.9	13	4.2
			LC			3.3			3.5			3.6

CFR = coronary flow reserve; DS = percentage diameter stenosis; LAD = left anterior descending artery; LC = circumflex artery; OA = minimal cross-sectional obstruction area (mm^2); R = right coronary artery.

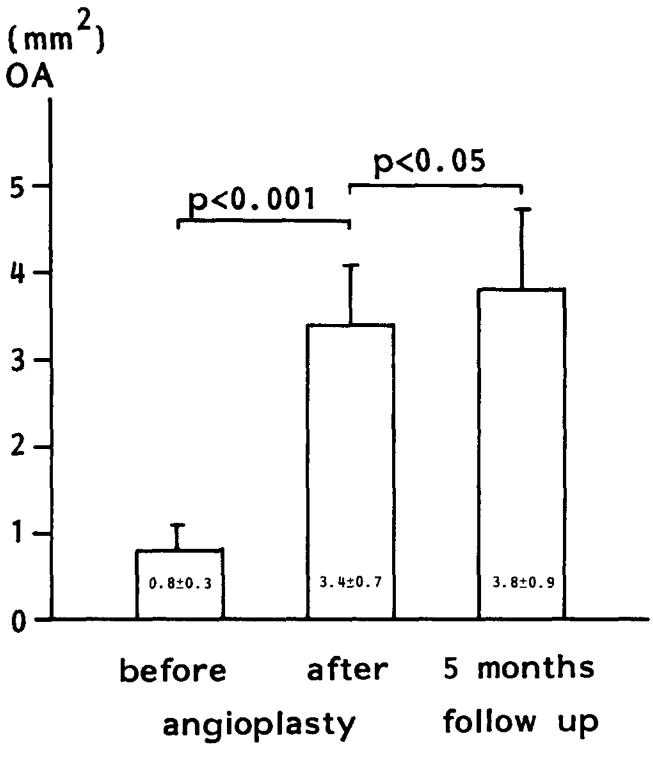

FIGURE 1. Results of quantitative analyses of coronary angiograms, before, immediately after and 5 months after percutaneous transluminal coronary angioplasty. OA = minimal cross-sectional obstruction area (mm^2).

nitrates, calcium antagonist agents and β-blocking drugs, and during the 5 months after PTCA the patients were treated with aspirin 500 mg/day and nifedipine 60 mg/day, which was continued on the day of cardiac catheterization. All 39 patients had normal systolic and diastolic wall motion and an ejection fraction of 55%. Patients with left ventricular hypertrophy, valvular heart disease, angiographic evidence of collateral circulation, anemia, polycythemia or hypertension were excluded because these conditions may influence coronary flow reserve.[15–17]

Exercise thallium scintigraphy: The patients performed a symptom-limited exercise test on the bicycle ergometer with stepwise increments of 20 watts/min. All patients exercised to more than 80% of their expected normal exercise capacity (for age, sex and height). Images were obtained immediately after exercise and 4 hours later and analyzed prospectively by 3 experienced observers without knowledge of the angiographic data. Redistribution and persistent defects were considered abnormal.[18,19]

Quantitative coronary cineangiography: Before PTCA, immediately after PTCA and during repeat catheterization, 2 or 3 identical angiographic projections were filmed. The coronary arterial dimensions were determined with the computer-based Cardiovascular Angiography Analysis System.[5,20,21] In essence, the boundaries of a selected coronary artery segment are detected automatically from optically magnified and video digitized regions of interest of a cineframe. Calibration of the diameter data in absolute values (millimeters) is achieved by detecting the boundaries of a section of the contrast catheter and comparing the mean diameter in pixels with the known size in millimeters.[22] Pincushion distortion is corrected.[21] A computer estimation of the original arterial dimensions at the site of obstruction was used to define the reference region.[21] The interpolated percentage diameter stenosis and the minimal obstruction area (mm^2) were then calculated by averaging the values from at least 2, preferably orthogonal, projections. A mean of 2.2 angiographic projections per patient was used in this study.

Coronary flow reserve measurements: The heart was atrially paced at a rate just above the spontaneous heart rate. An electrocardiographic-triggered injection into the coronary artery 300 ms after the R wave was made with a fixed amount of Jopamidol at 37°C through a Medrad Mark IV infusion pump. This nonionic contrast agent has a viscosity of 9.4 cP at 37°, an osmolality of 0.8 osm · kg^{-1} and an iodine content of 370 mg/ml. The injection rate of the contrast medium was judged to be adequate when back flow of contrast medium into the aorta occurred. In every patient the injection rate was identical for each coronary injection. The field size of the x-ray equipment was 7 inches. The angiogram was repeated 30 seconds after pharmacologically induced hyperemia by a bolus injection of 12.5 mg papaverine into the coronary artery.[5,23] Five end-diastolic cineframes were selected from successive cardiac cycles.

Logarithmic nonmagnified mask-mode background subtraction was applied to the image subset to eliminate noncontrast medium densities. The last end-diastolic frame before contrast administration was chosen as the mask. A contrast appearance time was determined, using an empirically derived density threshold that was constant for each study and all patients.[5] A density image was computed, with each pixel intensity value being representative for the maximal local contrast medium accumulation. The coronary flow reserve was defined as the ratio of the regional flow computed from a hyperemic image (Qh) divided by the regional flow of the corresponding baseline image (Qb). Coronary flow reserve (CFR) was then be calculated as:

$$Qh/Qb = Dh/Th : Db/Tb,$$

where D is the mean contrast density and T the mean appearance time at baseline (b) and hyperemia (h). Appearance time and density were computed within user-defined regions of interest that were chosen in such a way that the epicardial coronary arteries visible on the angiogram, the coronary sinus and the great cardiac vein were excluded from the analysis.[5]

Statistical analysis: Comparisons between groups were made after variance analysis with the Student t test for paired or unpaired observations.

Results

Quantitative cineangiography: The changes in minimal cross-sectional obstruction area are shown in Table I and Figure 1, and the changes in percentage diameter stenosis are shown in Table I and Figure 2. Percentage area stenosis (mean ± standard deviation [SD]) decreased from 89 ± 7 to 51 ± 11% immediately after PTCA. Five months later, percentage area stenosis was further decreased to 42 ± 14% ($p < 0.05$).

Coronary flow reserve: In the 24 patients with angiographically normal coronary arteries, coronary flow reserve ranged from 3.4 to 6.5 (Table II). The mean value was 5.0 (SD ± 0.8). The lower limit for a normal coronary flow reserve is therefore 3.4 (2 × SD below the mean coronary flow reserve). This is comparable to the normal values for coronary flow reserve reported by other groups.[4,14] Coronary flow reserve was measured in the myocardial region supplied by the dilated coronary artery before PTCA, immediately after PTCA and 5 months later. Consecutive measurements were also obtained in 12 adjacent myocardial regions supplied by a nondilated coronary artery (Table I, Figure 3). The coronary flow reserve of these adjacent myocardial regions remained unchanged immediately after PTCA and after 5 months' follow-up. Coronary flow reserve (mean ± SD) in the myocardial region supplied by the dilated coronary artery increased from 1.0 ± 0.3 to 2.5 ± 0.6 immediately after PTCA ($p < 0.001$). In none of these patients was coronary flow reserve restored to a normal level immediately after PTCA. A substantial late improvement ($p < 0.01$) in coronary flow reserve had occurred 5 months later. Coronary flow reserve in the myocardial region supplied by the dilated coronary artery 5 months after PTCA was of the same magnitude as the coronary flow reserve in the myocardial region supplied by a non-

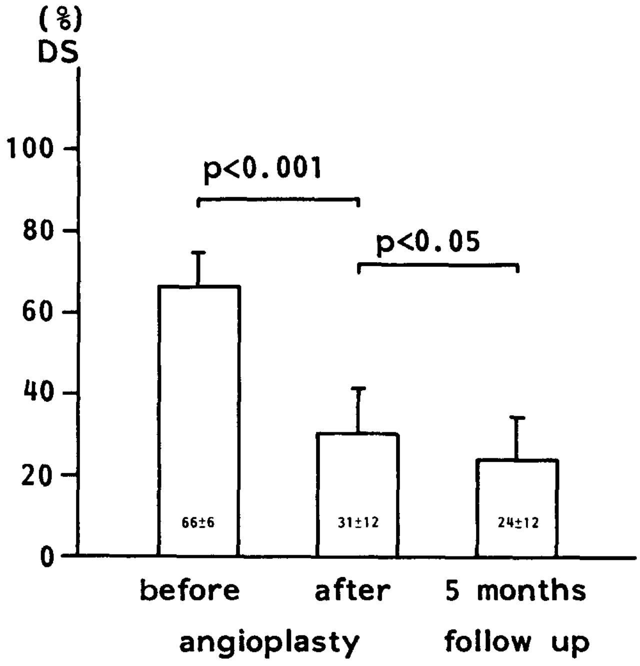

FIGURE 2. Results of quantitative analyses of coronary angiograms, before, immediately after and 5 months after percutaneous transluminal coronary angioplasty. DS = percentage diameter stenosis.

TABLE II Results of Coronary Flow Reserve of Patients with Angiographically Normal Coronary Arteries

Pt	Age (yr)	Sex	Vessel	CFR
1	38	M	LAD	6.5
2	41	M	LC	6.2
3	62	F	LAD	5.3
4	31	M	R	5.2
5	60	M	LC	5.0
6	63	M	LC	5.0
7	54	M	LC	5.0
8	48	M	LC	4.0
9	66	F	LC	4.5
10	52	M	LAD	4.0
11	59	M	LAD	5.0
12	59	M	LC	4.8
13	47	M	LC	4.9
14	58	M	LAD	3.7
15	59	M	LAD	4.3
16	54	F	LC	6.4
17	61	M	LAD	4.9
18	62	M	R	4.8
19	58	M	LAD	4.7
20	57	M	R	4.6
21	64	M	LAD	4.5
22	61	M	LAD	3.4
23	50	M	LAD	6.3
24	58	M	LAD	4.0

CFR = coronary flow reserve; LAD = left anterior descending coronary artery; LC = circumflex artery; R = right coronary artery.

dilated and angiographically not diseased coronary artery. In 11 of the 15 patients (73%) coronary flow reserve of the dilated coronary artery was restored to a normal level of ≥3.4, whereas in 4 of 15 patients (27%) coronary flow reserve was still abnormal (Figures 4 and 5). Coronary flow reserve 5 months after PTCA was related to the change in minimal cross-sectional obstruction area occurring between immediately after PTCA and at follow-up (linear regression analysis: $r = 0.61$, standard error of the estimate = 0.46, Figure 6). In 10 patients the minimal cross-sectional obstruction area 5 months after PTCA was larger than immediately after the procedure (late improvement). Only 1 patient had a coronary flow reserve of <3.4. In 5 patients the minimal cross-sectional obstruction area 5 months after PTCA was smaller than the area immediately after the procedure (late deterioration). The percentage of patients showing normalization of coronary flow reserve 5 months after PTCA is substantially higher ($p < 0.05$, chi-square test) in the group with late angiographic improvement (90%) compared with the group with late deterioration (40%).

Discussion

The purpose of the present study was to establish whether coronary flow reserve in a myocardial region

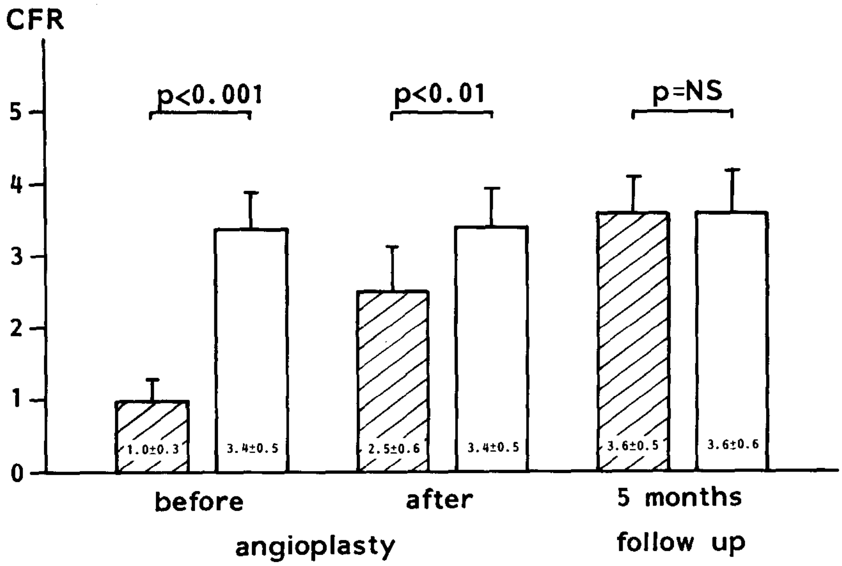

FIGURE 3. Coronary flow reserve (CFR) measured with digital subtraction cineangiography, before, immediately after and 5 months after percutaneous transluminal coronary angioplasty. The *shaded bars* represent the CFR of the myocardial region supplied by the dilated coronary artery. The *open bars* represent the CFR of an adjacent myocardial region supplied by a nondilated and angiographically normal coronary artery.

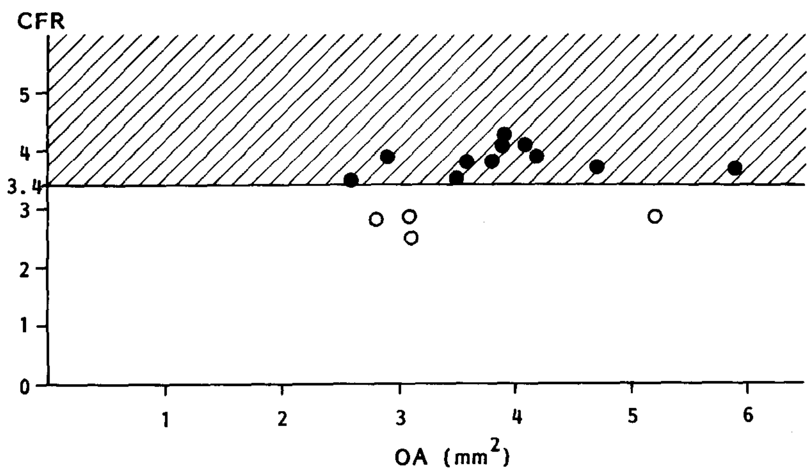

FIGURE 4. Coronary flow reserve (CFR) plotted against minimal cross-sectional obstruction area (OA) 5 months after percutaneous transluminal coronary angioplasty. The lower limit of the normal value for CFR as measured with the digital subtraction cineangiographic technique is 3.4.

supplied by a stenotic coronary artery could be restored to normal by PTCA. Immediately after PTCA, coronary flow reserve is not normalized.[11-14] In 11 of our 15 patients without angina and with normal exercise thallium scintigraphy 5 months after PTCA, coronary flow reserve was normalized. There are several possible explanations for this phenomenon.

First, since coronary flow reserve is a ratio between maximal coronary blood flow and resting flow, an increase in resting flow results in a decrease of this ratio. The radiographic technique we used does not provide us with absolute measurements of volume flow and we therefore cannot draw any conclusion regarding the resting coronary volume flow after the PTCA procedure. However, several investigators using the thermodilution technique in the coronary sinus or the great cardiac vein have reported comparable resting volume flows before and after PTCA.[24-26]

Second, metabolic, humoral or myogenic factors may limit coronary flow reserve after PTCA. The metabolic derangements due to the PTCA seem quickly reversible, as shown by the fast decline of temporarily increased lactate, hypoxanthine and potassium ion concentrations,[24,27] and are therefore not likely to be of major significance. Although humoral factors such as thromboxane release[28] may influence vasoactive regulation in a specific subgroup of patients with complicated PTCA, so far no evidence has been presented for the persistence of humoral derangements after PTCA. The long-standing reduction in perfusion pressure distal to the stenotic lesion may induce alterations in the complex mechanism of coronary blood flow autoregulation,[11] and a prolonged period of time might be needed before these abnormalities subside.[29]

Third, the impaired coronary flow reserve could be directly related to the severity of the residual stenosis. Cross-sectional area as measured immediately after PTCA, generally, is about threefold increased as a result of the procedure, but it remains grossly abnormal.[30,31] In the 6 months after PTCA important morphologic changes may take place. Johnson et al[30] reported a late increase in cross-sectional obstruction area in about one-third of their patients. In our selected group of patients with no angina and a normal exercise thallium scintigram, the percentage of patients with late angiographic improvement was even higher (66%). In a previous study in our laboratory the relation between cross-sectional obstruction area and coronary flow reserve in patients with stable angina

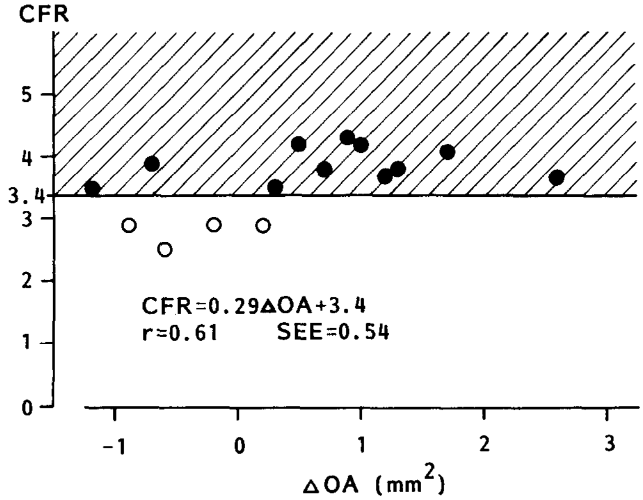

FIGURE 6. Relation between coronary flow reserve (CFR) 5 months after percutaneous transluminal angioplasty and the change that occurred in minimal cross-sectional obstruction area (ΔOA) between immediately after percutaneous transluminal coronary angioplasty and 5 months later. The lower limit of the normal value for CFR as measured with the digital subtraction cineangiographic technique is 3.4.

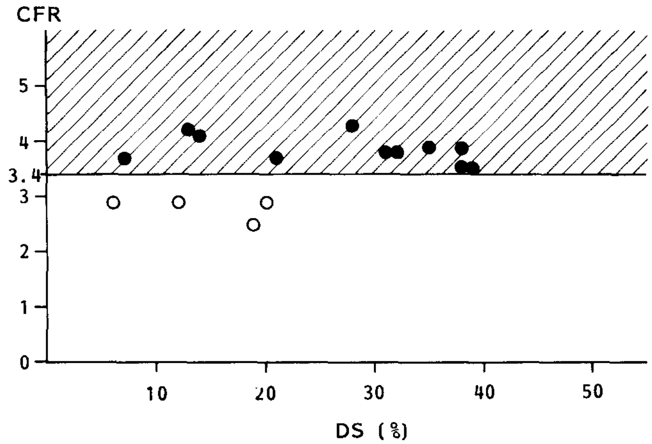

FIGURE 5. Coronary flow reserve (CFR) plotted against percentage diameter stenosis (DS) 5 months after percutaneous transluminal coronary angioplasty. The lower limit of the normal value for CFR as measured with the digital subtraction cineangiographic technique is 3.4.

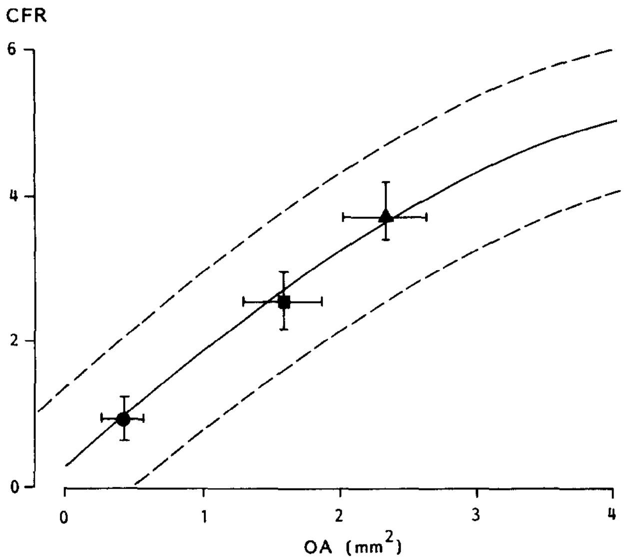

FIGURE 7. Relation between coronary flow reserve (CFR) and cross-sectional obstruction area (OA) as previously reported.[5] The solid line is the best fit curve and the shaded area corresponds to the 95% confidence limits. The mean values and standard deviations of coronary flow reserve and obstruction area as obtained in the present study, before percutaneous transluminal coronary angioplasty (*circle*), immediately after (*square*) and 5 months later (*triangle*), are plotted on this diagram.

and single-vessel coronary artery disease has been established.[5] In Figure 7 this relation is shown with the results of the sequential coronary flow reserve and obstruction area measurements of the present study superimposed. The data of the present study are within the 95% confidence limits of the relation between flow reserve and obstruction area. Therefore, the persisting reduced obstruction area is by itself a sufficient explanation for the limited restoration of coronary flow reserve, although it does not rule out other contributing pathophysiologic mechanisms.

Limitations: There are 2 important limitations of coronary angiography in the setting of PTCA. First, the changes in luminal size of an artery after the mechanical disruption of its internal wall may be difficult to assess by angiographic means.[31,32] The irregular shape with intimal tears that fill with contrast medium to a variable extent will result in some overestimation of the true functional luminal size immediately after PTCA. Second, the extent of coronary atherosclerosis may be difficult to delineate angiographically. McPherson et al[33] documented that substantial intimal atherosclerosis resulting in diffuse obstructive disease that involves the entire length of an epicardial artery is often present, even when angiograms reveal only discrete lesions. As a consequence, relative measurements of stenosis severity are an inadequate approach to assessing the severity of coronary obstructions. This may explain why 4 of our patients with only very mild residual stenoses 5 months after PTCA still had an abnormal vasodilatory reserve.

References

1. Grüntzig AR, Senning A, Siegenthaler WE. *Nonoperative dilatation of coronary artery stenosis: percutaneous transluminal angioplasty. N Engl J Med 1979;301:61–68.*
2. Klocke FJ. *Measurements of coronary blood flow and degree of stenosis: current clinical implications and continuing uncertainties. JACC 1983;1:31–41.*
3. Hoffman JIE. *Maximal coronary flow and the concept of vascular reserve. Circulation 1984;70:153–159.*
4. Wilson RF, Laughlin DE, Ackell PH, Chilian WM, Holida MD, Hartley CJ, Armstrong ML, Marcus ML, White CW. *Transluminal subselective measurement of coronary artery blood flow velocity and vasodilator reserve in man. Circulation 1985;72:82–92.*
5. Zijlstra F, van Ommeren J, Reiber JHC, Serruys PW. *Does quantitative assessment of coronary artery dimensions predict the physiological significance of a coronary stenosis? Circulation 1987;75:1154–1161.*
6. Vogel RA. *The radiographic assessment of coronary blood flow parameters. Circulation 1985;72:460–465.*
7. Vogel RA, Friedman HZ, Beauman GJ, Virano GR, Grines CL. *Measurement of absolute coronary blood flow using a standard angioplasty catheter (abstr). JACC 1987;9:69A.*
8. Kent KM, Bentivoglio LG, Block PC, Cowley MJ, Dorros G, Gosselin AJ, Gruentzig A, Myler RK, Simpson J, Stertzer SH, Williams DO, Fisher L, Gillespie MJ, Detre K, Kelsey S, Mullin SM, Mock MD. *Percutaneous transluminal angioplasty: report from the Registry of the National Heart, Lung and Blood Institute. Am J Cardiol 1982;49:2011–2020.*
9. Scholl JM, Chaitman BR, David PR, Dupras G, Brevers G, Val PG, Crepeau J, Lesperance J, Bourassa MG. *Exercise electrocardiography and myocardial scintigraphy in the serial evaluation of the results of percutaneous transluminal coronary angioplasty. Circulation 1982;66:380–390.*
10. Kent KM, Bonow RO, Rosing DR, Ewels CJ, Lipson LC, McIntosh CL, Bachrach S, Green M, Epstein SE. *Improved myocardial function during exercise after successful percutaneous transluminal angioplasty. N Engl J Med 1982;306:441–447.*
11. Bates ER, Aueron FM, Le Grand V, Lefree MT, Mancini GBJ, Hodgson JM, Vogel RA. *Comparative long-term effects of coronary artery bypass graft surgery and percutaneous transluminal coronary angioplasty on regional coronary flow reserve. Circulation 1985;72:833–839.*
12. O'Neill WW, Walton JA, Bates ER, Colfer HT, Aueron FM, Lefree MT, Ditt B, Vogel RA. *Criteria for successful coronary angioplasty as assessed by alterations in coronary vasodilatory reserve. JACC 1984;3:1382–1390.*
13. Wilson RF, Aylward PE, Talman CL, White CW. *Does percutaneous transluminal coronary angioplasty restore coronary vasodilator reserve? (abstr). Circulation 1985;72 (suppl III):397.*
14. Hodgson JM, Riley RS, Most AS, Williams DD. *Assessment of coronary flow reserve using digital angiography before and after successful percutaneous transluminal coronary angioplasty. Am J Cardiol 1987;60:61–65.*
15. Marcus ML. *Effects of cardiac hypertrophy on the coronary circulation. In: The Coronary Circulation in Health and Disease. New York: McGraw-Hill, 1983:285–306.*
16. Marcus ML. *Effects of anemia and polycythemia on the coronary circulation. In: The Coronary Circulation in Health and Disease. New York: McGraw Hill, 1983:307–319.*
17. Marcus ML, Doty DB, Hiratzka LF, Wright CB, Eastham CL. *Decreased coronary reserve: a mechanism for angina pectoris in patients with aortic stenosis and normal coronary arteries. N Engl J Med 1982;307:1362–1366.*
18. Reiber JHC, Lie SP, Simoons ML, Wijns W, Gerbrands JJ. *Computer quantification of location, extent and type of thallium-201 myocardium perfusion abnormalities. Proceedings of the International Symposium on Medical Imaging and Image Interpretation ISMIII. IEEE, 1982; Cat No 82 CH1804-4:123–128.*
19. Lie SP, Reiber JHC, Simoons ML, Gerbrands JJ, Kooy PPM, Bakker WH. *Computer processing of thallium-201 myocardial scintigrams. Proceedings of the 2nd International Conference on Visual Phychophysics and Medical Imaging. IEEE 1981; Cat No 81CH 1676-6:19–25.*
20. Reiber JHC, Serruys PW, Kooyman CJ, Wijns W, Slager CJ, Gerbrands JJ, Schuurbiers JCH, den Boer A, Hugenholtz PG. *Assessment of short-, medium-, and long-term variations in arterial dimensions from computer-assisted quantification of coronary cineangiograms. Circulation 1985;71:280–288.*
21. Reiber JHC, Kooijman CJ, Slager CJ, Gerbrands JJ, Schuurbiers JHC, den Boer A, Wijns W, Serruys PW, Hugenholtz PG. *Coronary artery dimensions from cineangiograms; methodology and validation of a computer-assisted analysis procedure. IEEE 1984; Trans Med Imaging, MI-3:131–141.*
22. Reiber JHC, Kooijman CJ, den Boer A, Serruys PW. *Assessment of dimensions and image quality of coronary contrast catheters from cineangiograms. Cathet Cardiovasc Diagn 1985;11:521–532.*
23. Zijlstra F, Serruys PW, Hugenholtz PG. *Papaverine: the ideal coronary vasodilator for investigating coronary flow reserve: a study of timing, magnitude, reproducibility and safety of the coronary hyperemic response after intracoronary papaverine. Cathet Cardiovasc Diagn 1986;12:298–303.*
24. Serruys PW, Wijns W, van den Brand M, Mey S, Slager CJ, Schuurbiers JCH, Hugenholtz PG, Brower RW. *Left ventricular performance, regional blood flow, wall motion, and lactate metabolism during transluminal angioplasty. Circulation 1984;70:25–36.*
25. Feldman RL, Conti R, Pepine CJ. *Regional coronary venous flow responses to transient coronary artery occlusion in human beings. JACC 1983;2:1–11.*
26. Rothman MT, Baim DS, Simpson JB, Harrison DC. *Coronary hemodynamics during percutaneous transluminal coronary angioplasty. Am J Cardiol 1984;49:1615–1622.*
27. Webb SC, Rickards AF, Poole-Wilson PA. *Coronary sinus potassium concentration recorded during coronary angioplasty. Br Heart J 1983;50:146–152.*
28. Peterson MB, Machay V, Block PC, Palacios I, Philbin D, Watkins WD. *Thromboxane release during percutaneous transluminal coronary angioplasty. Am Heart J 1986;1:111–119.*
29. Wilson RF, Aylward PE, Leimbach WH, Talman CL, White CW. *Coronary flow reserve late after angioplasty. Do the early alterations persist? (abstr). JACC 1986;7(suppl):212.*
30. Johnson MR, Brayden GP, Ericksen EE, Collins SM, Skorton DJ, Harrison DG, Marcus ML, White CW. *Changes in cross-sectional area of the coronary lumen in the six months after angioplasty: a quantitative analysis of the variable response to percutaneous transluminal angioplasty. Circulation 1986;73:467–475.*
31. Block PC, Myler RK, Stertzer S, Fallon JT. *Morphology after transluminal angioplasty in human beings. N Engl J Med 1981;305:382–387.*
32. Serruys PW, Reiber JHC, Wijns W, van den Brand M, Kooyman CJ, ten Katen HJ, Hugenholtz PG. *Assessment of percutaneous transluminal coronary angioplasty by quantitative coronary angiography: diameter versus densitometric area measurements. Am J Cardiol 1984;54:482–488.*
33. McPherson DD, Hiratzka LF, Lamberth WC, Brandt B, Hunt M, Kieso RA, Marcus ML, Kerber RE. *Delineation of the extent of coronary atherosclerosis by high-frequently epicardial echocardiography. N Engl J Med 1987;316:304–309.*